Chapter 2

Literature Review

2.1 The Sustainability Issue

In 2002 the British government published “Waste Not Want Not” (2002), which set out an action plan for sustainable waste management. This action plan has resulted in the introduction of landfill allowance trading scheme which further underlined the movement away from landfill disposal. The overall aim of this action plan is to ensure that by 2020 England has a world-class waste management system for the nation to prosper whilst reducing harm to the environment and preserving resources for further generations. Another key point in the action plan was to boost recycling by developing the infra-structure needed for increased recycling (including non-biodegradable waste such as plastic and rubber waste). The United Kingdom government “Waste Strategy for England 2007” is the strategy for complying with the European Union landfill directive. Its aim is to boost recycling and value recovery from waste and in turn reducing reliance on landfill (Waste Strategy for England, 2007).

The landfill tax escalator was introduced in 1996, starting at a tax rate of £7 per tonne. In 2005 the rate reached £18 per tonne, and will rise to £48 per tonne by 2010/11, other forms of end disposal are becoming more attractive promoting a shift away from landfill.

2.2 Acoustic material markets and some indication of the costs

One particular application of granulated polymeric and elastomeric waste is the production of materials with good acoustic performance. The range of acoustic materials which can be made from this waste is vast; the application of these materials falls in to three distinct categories: (i) the building industry; (ii) transport; (iii) and machinery/white goods manufacturing.

This section is devoted at looking into the above three categories in more detail.

1. Uses of acoustic materials in the building industry include:
   i. In ceilings to reduce air borne and structure borne noise through floor/ceiling system.
   ii. In walls and partitions to absorb sound between cavities.
   iii. In flooring to reduce impact and airborne transmitted sound

2. Uses of acoustic materials in the transportation industry include:
   i. Absorption of noise from engine compartment
   ii. Reduction in the transmission of air borne sound from engine and road into vehicle
   iii. Isolation of moving components from vehicle shell structure

3. Uses of acoustic materials in the white goods manufacturing include:
   i. Reduction of noise field inside cabinet
   ii. Anti-vibration mounts and supports
   iii. Reduction in the reverberant noise field.

Several potential market segments are identified for acoustic materials (National Industrial Symbiosis Programme, 2008). The technical parameters are associated with the acoustic materials function, and non-acoustic requirements such as fire behaviour, price, physical and mechanical properties etc.

For example, the materials for the automotive industry can be split into three categories:

i. Isolation layers are used within the engine compartment to isolate mechanical components. Typical materials include foamed rubbers, polyethylene, polypropylene, felts, impregnated foams, these materials normally have a dynamic stiffness resonance frequency less than 100 Hz, and cost around £2.00/m^2.

ii. The absorbing materials are used in the interior of automotives to absorb the structure borne noise, e.g. materials with high porosity, low flow resistivity and high tortousity and these materials cost £3.00/m^2.

iii. The barrier materials are heavy layers and have high transmission loss greater than 30 dB, for example mineral loaded PVC barrier costs £3.50/m^2.

The materials used in the building and construction industry can also be split into three categories.

i. The absorbing materials for example medium/high density mineral wool used in suspended ceiling tile infill, cavity wall infill, the cost of this type of material is around £4.00 – 6.00/m^2.

ii. Barrier materials are used to improve airborne noise reduction in floor cavities, these materials should meet Building Regulations Document E requirements (2003). A combination of a barrier/absorber material is used in walls for example rigid Polyurethane for wall/cladding, such a material would cost around £2.50 - 3.50/m^2.

iii. Isolation layers are used to improve impact performance in flooring such materials include Cloud 9, felts, chipfoam. Isolation layers are also used under screed and include mineral wool, polyethylene and rubber, to improve the impact performance in flooring. These materials cost around £2.00 - 3.00/m^2.

Acoustic materials can also be used in equipment enclosures and white goods. For example, in the casing of washing machines to absorb noise, materials for this purpose would include composite and laminated foams (PVC, PU faced), felts, polyurethane foams, the cost of these materials would be around £1.60 - 3.00/m^2.

According to the national industrial symbiosis programme, the building and construction market is high volume and low price. However, tougher legislation is an incentive for specifiers to look into higher performance products that have higher pricing. Similarly, the automotive industry is generally high volume and low price. However, the ELV (End of Life Vehicle Directive, 2003) and tougher noise requirements are pushing the material market move towards higher performance and higher price. The heavy automotive industry typically offers lower volumes but higher margins than mainstream automotive.

In summary, for the new acoustic products made from recycled materials, market focus should be driven towards the flooring in the building and construction industry, and in the heavy automotive industry. Other segments in the building, industrial noise and white goods industry should also be explored. There could also be a potential for the new materials made from recycled waste in the building services industry, marine and offshore but the materials will require high fire performance.

2.3 Acoustic materials

A majority of materials used for noise and vibration control are porous. Porous materials are generally excellent absorbers. The complex pore structure of the porous material acts as a sound trap. Two main parameters which influence the performance of absorbing materials are pore size and open porosity. It is a common requirement for a good acoustical absorber to have a relatively high open porosity in order to enable the incident sound wave to penetrate the porous space. The pore size controls the viscous and thermal effects which are responsible for the dissipation of the energy in the acoustic wave which penetrates the porous structure. If the pore size is relatively small then the attenuation of sound per unit distance is relatively large, but it is difficult for sound wave to penetrate the porous structure. If the pore size is relatively large, then it is easy for sound to penetrate the porous structure but the acoustic attenuation is relatively small. The pore size and open porosity control the air flow resistivity of the porous structure. In both extreme cases, there exists an air flow resistivity for which the acoustical absorption is optimal. Therefore, an air flow resistivity for which the acoustical absorption is maximum across a broad frequency range is shown in Figure 2.1.

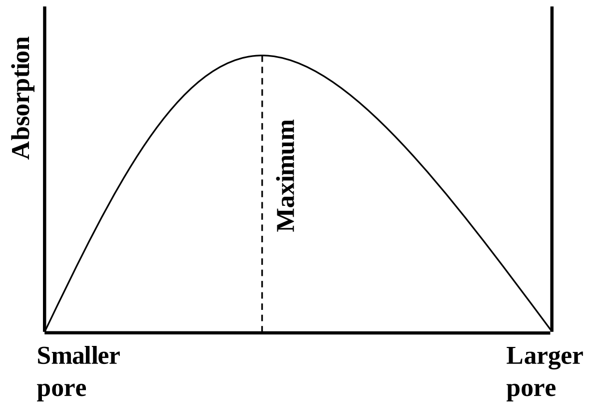

Figure 2.1: Absorption in a porous material

Porous materials which have an elastic frame are good for impact damping. When an object impacts a resilient floor, its speed is reduced in a fraction of a second. This process is accompanied by the conversion of the kinetic energy in the impacting body into the potential energy in the compressed resilient layer and the heat generated as a result. By careful selection of the elastic and damping properties of the resilient layer it is possible to maximise the amount of the kinetic energy dissipated on the impact.

Materials with high porosity also exhibit good thermal insulation properties. In materials with high porosity and high proportion of close non-connected pores the heat transfer by conduction (transfer of heat within the material, from molecule to molecule) is low. In these materials, the heat transfer by convection (transfer of heat by displacement of gas) is also low because the air is trapped in the pores and is unable to move freely. Therefore, the thermal insulation of a porous, low density material increases if the material is composed of small pores which are closed and not interconnected.

2.4 Resources used for making vibro-acoustic and thermal insulation materials

Porous materials in the form of foams are made from raw materials and a large proportion of them originate from crude oil. The raw materials chart in Figure 2.2 shows how foams are produced from crude oil. Crude oil is used for producing an enormous variety of products. A majority of polymeric materials are non-biodegradable or the biodegradation process is very slow. This means that post-manufacturing polymeric waste is often the most objectionable kind of waste in landfills and sits in landfill sites for hundreds of years without degrading.

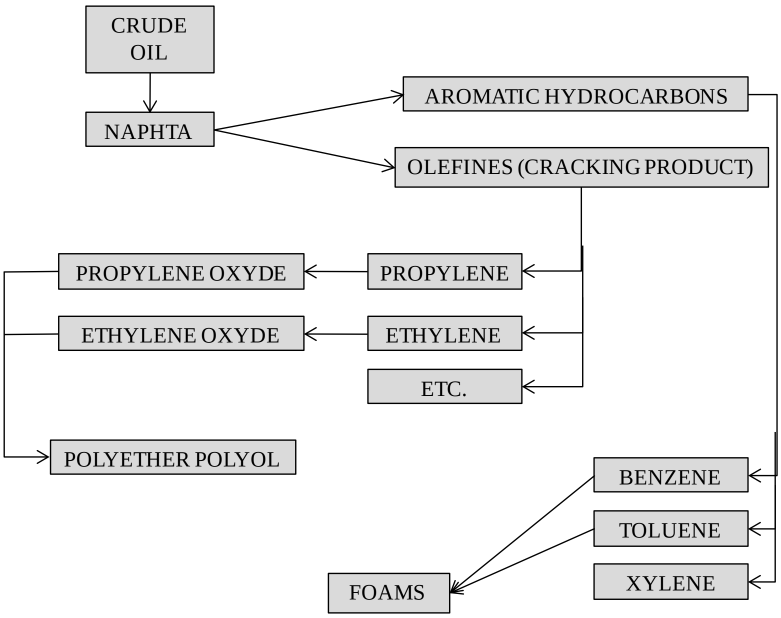

Figure 2.2: Flow diagram showing the origin of acoustic materials

Many manufacturing processes produce waste fragments in cuttings and shaping products. Without recycling this is a costly disposal problem for manufactures and the environment. Using the trimmings for making porous products with good vibro-acoustic and thermal insulation properties for the building, transport and white goods manufacturing industries can provide both environmental and financial benefits. In the next section the processes used to manufacture porous materials from virgin ingredients is described.

As it is pointed out in the previous sections, the function of vibro-acoustic materials is extremely diversified. The analysis of the function for any new acoustic material is therefore an important step before developing a new formulation or a new product. All the functions can be related to this general mechanism:

Action Acoustic Material Reaction

A raw material selection analysis was carried out in order to identify three key raw material streams for further development from the list shown in Table 2.1. These materials were selected on consideration of raw material source properties (e.g. volume, post consumer or post manufacturing, health and safety, contamination etc.) and also on the technical performance (e.g. absorption, impact performance, transmission loss).

Table 2.1: Summary of material waste streams

Waste Stream Name	Supplier	Quantity tonnes/yr	Ready Granulated
Carpet Tiles Post consumer - Bitumen backed	Various	280,000	No
Carpet Tile Manufacturing Waste - Bitumen backed	-	-	No
Carpet Tile Manufacturing Waste - PVC backed	Interface	70-100	No
Carpet Tile Manufacturing Waste - PVC backed	Milliken	-	No
Carpet Tile Manufacturing Waste - Rubber backed	Duttons	-	No
Nonwoven Dust	Anglo Felt	30-50	Yes
Nonwoven Dust	John Cotton	-	Yes
Nonwoven Dust	Various	50+	Yes
Tyre shred residue	Various	254,400	Yes
Reclaim Dust	James Robinson	50-60	Yes
Carpet production dust	William S Graham	50	Yes
Carpet Wool Flock	William S Graham	113	Yes
Nonwoven Edge Trim / waste	Edward Clay	150-200	No
Auto dashboard-semi rigid PU Manufacturing waste	Various	50-200	No
Auto dashboard-semi rigid PU Post Consumer	Various	25000	Yes
PVC Window frames	Various	-	No
Lorry tyres-Post Consumer	Various	>200,000	Yes
Cable covering	Various	-	-
Ground sawdust	Various	Large	Both
PVC Flooring	Gee Graphite	70-80	No

2.5 Manufacturing methods

Several manufacturing methods exist to produce porous materials with elastic frame. The inclined conveyor system is a continuous system developed by Cannon Viking

Limited (2000). The method involves vigorous mixing of the raw materials and then pouring onto a rolling conveyor with vertical variable walls (Figure 2.3). After a few seconds, a cream is foamed, the volume expands and the foam reaches in about one to three minutes its maximum height. Polyether, polyester and polyurethane foams may be produced by this technology.

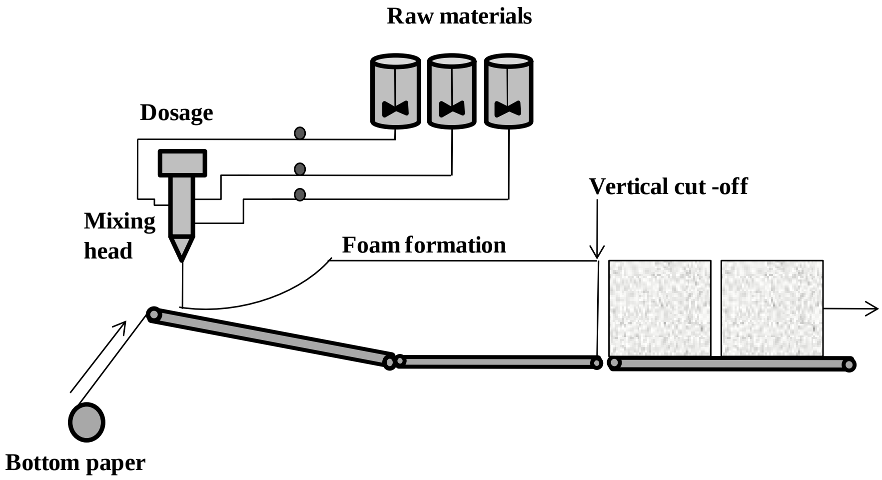

Figure 2.3: Inclined Conveyor System

Moulding is another process which can be used for the manufacture of porous products. Here, the mix is poured into a closed or open mould in which the product is produced (Figure 2.4). The process allows a one-step production of a finished porous panel. The mould is a hollowed-out block that is filled with the raw ingredients. The mix hardens inside the mould, adopting its shape (BPF, 2007) .

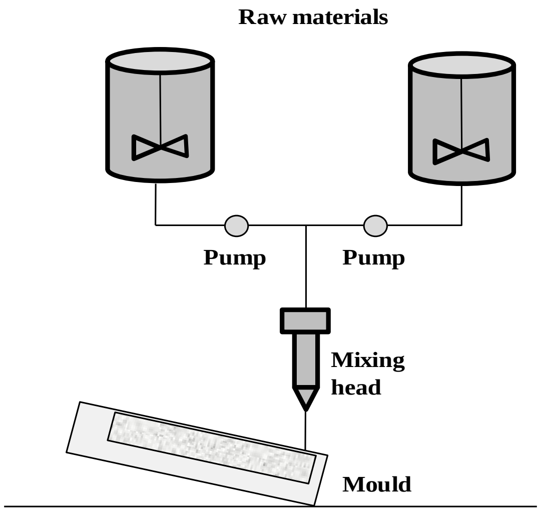

Figure 2.4: The Moulding System

An alternative method to produce porous materials is by reticulation (Figure 2.5). The flexible materials obtained from slab stock production partially contain closed pores. By a thermal process, explosion of oxygen-hydrogen mixer in a closed reactor, all the residual pore membranes are melted and a completely open cellular network is obtained (Engnet, 2007).

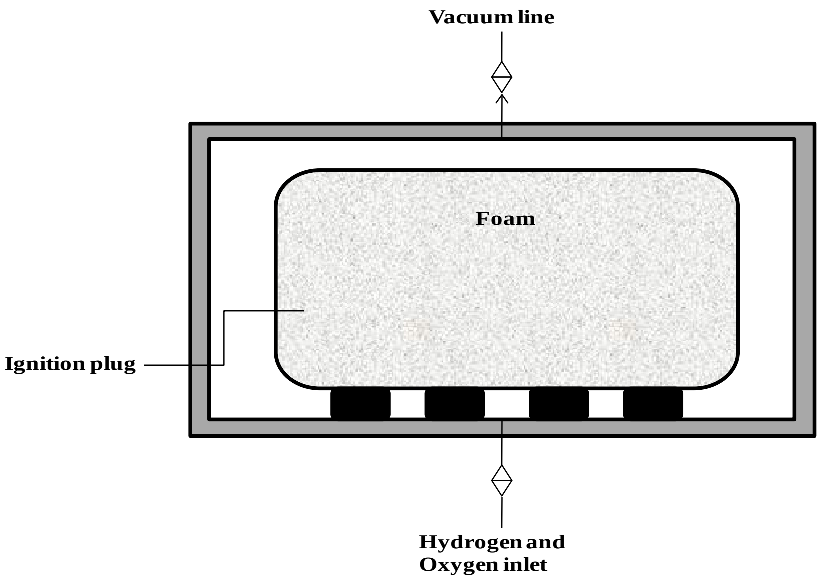

Figure 2.5: The Reticulation System

Dipping the acoustic material into a bath, squeezing and drying it afterwards in an oven constitute the impregnation process of manufacture (Figure 2.6). Following the nature of the chemicals used for the impregnation, specific new properties are achieved i.e. flame resistance, smell reduction etc.

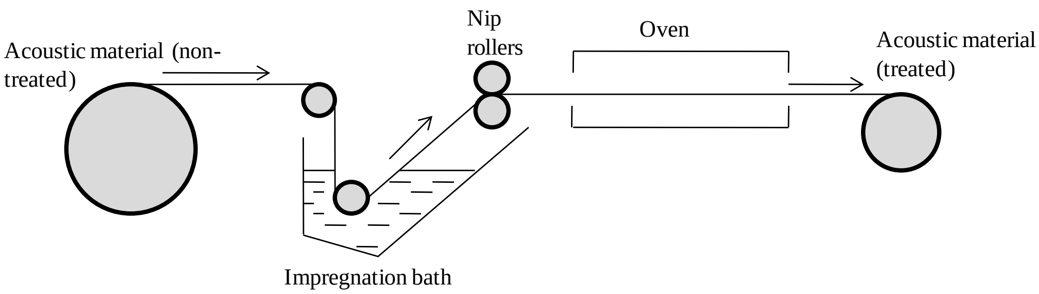

Figure 2.6: The Impregnation System

Densification process relates to compression and heating the material up to a permanent deformation so that a new pore structures are created with a higher density (Figure 2.7). Densification may be alternatively limited to the surface of the acoustic material, leading to a skin formation on one or both sides.

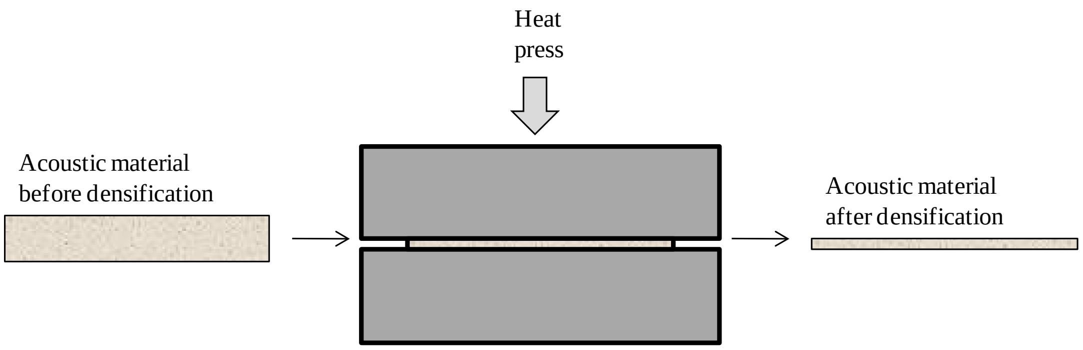

Figure 2.7: The Densification System

2.6 Chemical methods for recycling polymeric waste

Many technologies exist for recycling polymeric materials, including chemical processing, and mechanical processing. Many technologies require further development to tolerate higher contamination and to be cost effective. Four main types of recycling are:

i. Chemical recycling
ii. Thermo chemical processing
iii. Mechanical recycling
iv. Energy recovery

Figure 2.8 shows the overview of the options to recycle polymeric waste.

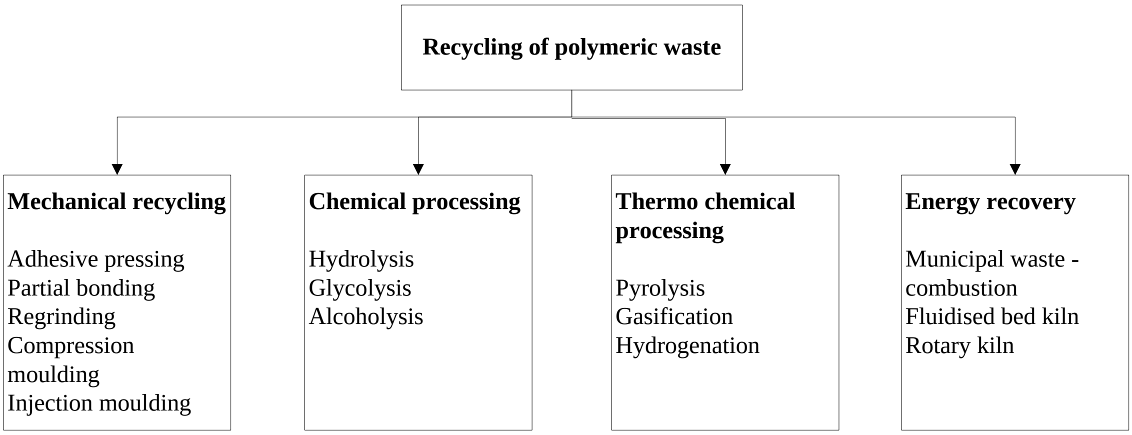

Figure 2.8: Overview of existing methods used to recycle polymeric waste

Mechanical recycling is done by regrinding polymeric waste into powders allowing them to be reused in the production of new products. In the production of some underlay materials foam pieces are adhered together to make underlay products.

Adhesive pressing is where the polymeric material is coated with a binder then cured under heat and pressure to make parts like floor mats.

Energy recovery is a method in which the polymeric waste can be burned. This process produces heat, power, and by-products such as ashes, chars, oils which still need to be disposed.

Chemical recycling involves chemical treatments that produce feedstock chemicals for the chemical process industry (Weigand et al. 1996). It involves complete or partial oxidation of the material producing heat and gaseous fuels. The by-products that must be disposed of include ashes, chars and oils. Chemical recycling consists of several different methods such as glycolysis, hydrolysis, pyrolysis, hydrogenation etc.

Glycolysis is where the polymeric waste is chemically mixed and heated to 200^{o}C to produce polyols (Scheirs, 1998), which can then be used to make new polymers or used as fuel. The aim of this process is the recovery of polyols for the production of new polyurethane materials. Figure 2.9 shows the summarised chemistry of glycolysis.

Figure 2.9: Chemistry of glycolysis of a polymer resulting in the formation of ether polyol

After the chemical reaction is complete, the material is cooled, filtered, blended with virgin polyol and formulated into polyol and isocyanate systems that is marketed to manufactures of polyurethane products e.g. for the manufacture of diphenylmethane diisocyanate adhesives.

Hydrolysis is similar to glycolysis however it produces polyols and amine intermediates that can be used for fuel and for the production of polyurethane (Figure 2.10). Hydrolysis is the reaction of polyurethane with water, and can produce both polyols and amine intermediates from polyurethane scrap, when recovered the polyols can be used as effective fuels. This method uses a heated, oxygen free environment to break down polyurethane and plastics into gases, oils and solids. Superheated steam of 200^{o}C is used to convert polyurethane into a two phase liquid. Figure 2.10 shows the summarised chemistry for the hydrolysis process.

Figure 2.10: Chemistry of hydrolysis of a polymer resulting in the formation of diamines like diphenyl methane diamine (MDA)

The chemical processes mentioned in this section involve considerable technical and economic investment to recycle small amounts of polymeric waste, which make these economically infeasible on a larger scale. These technologies remain underdeveloped and have not yet proven to be sustainable in a competitive material production market.

The aim of this work is to develop a recycling process that is sustainable, more economical on a larger scale and yet be flexible to handle many types of existing polymeric, elastomeric and textile waste.

2.7 Wave propagation through porous media

Common porous absorbers include fibrous mineral wools and open-cell foams. Generally, all of these materials allow air to flow into a cellular structure where sound energy is converted into heat. There are several mechanisms by which an incident sound wave is absorbed in a porous material:

i. By viscous losses as the pressure wave results in the friction of air on the solid frame of which the material is composed

ii. By thermal exchanges in the pores

iii. By destructive interference of sound waves in a porous layer

iv. By direct mechanical damping in the material frame.

Other types of acoustic materials include:

i. Panel absorbers

   Panel absorbers, are typically non-rigid, non-porous materials, which are placed over an airspace that vibrates in a flexural mode in response to sound pressure exerted by adjacent air molecules. Common panel (membrane) absorbers include thin wood panelling over framing, lightweight impervious ceilings and floors, glazing and other large surfaces capable of resonating in response to sound. Panel absorbers are usually most efficient at absorbing low frequencies (Sakagami, 2008).

ii. Resonators

Resonators typically tend to absorb sound in a narrow frequency range. Resonators include materials that have openings (holes and slots). The classic example of a resonator is the Helmholtz resonator, which has the shape of a bottle. The size of the opening, the length of the neck and the volume of air trapped in the chamber govern the resonant frequency. Typically, perforated materials only absorb in the narrow frequency range.

iii. Acoustic Insulators

Porous materials are not good at insulation. The degree of insulation is generally controlled by the material density. This means that the heavier the material and less porous it is the better it insulates against sound. Heavy panels and doors are typically used to guarantee good acoustic insulation between spaces.

iv. Vibration Isolation

Solid materials can transmit locally generated vibrations throughout a structure. Introducing a resilient layer with damping can reduce the amplitude of transmitted vibration and convert part of the vibration energy into heat. This is achieved through a careful selection of the elastic properties of the resilient layers and the amount of damping. Porous materials are generally good vibration isolators and the air trapped in the pores can provide additional damping mechanism.

This chapter provides the basic theory for sound absorption and transmission in the porous media. Further, this chapter addresses the issue of tailoring of acoustic materials using waste. Finally, the technology used to recycle the polymeric mixes is considered and its relevance to the acoustic properties of the materials discussed.

2.8 Classification of porous materials

Porous materials may be either homogeneous (e.g. glass wool) or composite as in the case of ceiling tiles, which have perforated coverings of semi rigid porous material. In either case, the performance of the whole material depends on the manner in which acoustic disturbances are propagated in the homogeneous porous medium.

Theories of Helmholtz and Kirchoff were extended by Rayleigh (1894) that relate to the transmission of sound along tubes to deduce the absorption coefficient at the surface of such a material in terms of the propagation of the surface area occupied by open pores, the radius of the tubes and the physical constants of the air (Rayleigh, 1894).

The theory developed by Rayleigh is important in that it shows that the attenuation of a sound wave falling on the absorber is determined by the viscosity as well as by the density and the elasticity of the air. Majority of porous materials used in acoustics are composed of an almost random entanglement of fine fibres in three dimensions, rather than of a collection of similar parallel tubes, and it is clear that conclusions drawn from Rayleighs theory would not be applicable to such materials. Works by Morse and Bolt have shown that it is possible to remove the restriction of a cylindrical shape for the pore whilst still retaining wave propagation in the material (Morse, 1944).

In general sound absorbing materials commonly consist of many small particles which are packed together so as to leave between them interconnected pores of irregular shape. A sound wave falling on the bounding surface of such a material must necessarily set up disturbances, not only of the air filling the pores but also of the particles themselves.

Porous materials may be classified as follows:

i. Rigid – When the solid phase does not move significantly compared to the motion of the fluid (air) phase, because the frame is immobilised by the stiffness of interconnecting filaments, or because the frame is much denser than the fluid (Horoshenkov, 2007).

ii. Limp – When the frame making up the material is sufficiently unconstrained and light that it can move freely as a result of viscous coupling with the fluid, i.e. when the density of the material is comparable with the density of fluid and/or the structure is not self supporting.

iii. Elastic – When the bulk modulus of elasticity of the expanded solid phase is greater than that of the fluid but the material density is comparable with the fluid density. In these materials the frame can interact with the fluid filling the pores and the resultant frame vibrations cannot be ignored (Horoshenkov, 2001).

The exact analysis of the performance of such a system would require knowledge of the forces of restraint of the particles i.e.

i. The motion of the particles under the action of the forces exerted upon them by the moving air.

ii. The motion of the air in the irregular pore space under the combined influences of the pressure in the initial sound wave, the movement of the particles, and the inertial, compressive and viscous forces associated with the confined air.

This research work has focused mainly on achieving tailored porous materials through manipulation of processing parameters then through understanding of the physical mechanisms that influence the material porosity and pore size distribution. As a result, the tailoring of porous materials has proceeded largely in an experimental fashion.

Porous materials are not generally useful as noise barriers because of their relatively low density, but make efficient sound absorbing or thermal insulating materials. Porous materials have two phases, the solid referred to as the frame and the fluid (air) contained within the pores formed by the frame. The porous materials dissipate acoustical energy largely by the interaction of their solid and fluid phases. In particular they convert acoustical energy into heat by thermal means (irreversible heat flow within the porous space and from the fluid to the frame), viscous means (associated with oscillatory shearing of the fluid in the vicinity of the solid surface), and by structural means (irreversible losses associated with flexure of the frame).

A majority of porous materials are spatially inhomogeneous, i.e. their macroscopic properties vary randomly throughout the material. It is not uncommon for the flow resistivities of two closely spaced samples taken from a single piece of porous material to differ significantly; the same tends to be true of stiffness properties. The properties of a porous material are usually estimated by averaging the results for a number of individual samples; it is doubtful that the macroscopic properties of a single sample of porous material are likely to represent the average properties of the whole material.

Direct measurable non-acoustical properties of porous materials are crucial for their accurate acoustical characterisation. A particular set of physical parameters can be specified that will result in a porous material having a specified level of acoustical performance. There is a direct link between the microscopic structure of a porous material (e.g. the morphology of the solid frame or particle shape and size) to its macroscopic properties. There have been a number of studies in which porous materials microscopic and macroscopic properties and the effects of particle consolidation have been linked (e.g. Stinson (1991) and Lafarge (1997)). The most important macroscopic physical properties of a porous material are:

i. Air flow resistivity
ii. Porosity
iii. Pore tortuosity
iv. Elastic modulus

These three properties together constitute largely the pore fluid properties which are needed to describe the material acoustical behaviour.

2.9 Fundamentals of sound propagation through porous materials

The first work on the mathematical explanations of the physical nature of sound absorption relate to the behaviour of rigid-frame porous media. The first dedicated textbook on the theory and application of sound absorbing materials was published by Zwikker and Kosten (1949). These works laid the foundation for a range of theoretical acoustic models for sound propagation in porous materials which started to appear in the second half of the 20th century (e.g. Biot (1956), Attenborough, (1971). The majority of existing models for the acoustic properties of rigid frame porous materials assume that these materials could be modelled as a stack of parallel capillary tubes (Stinson et al. (1992). The fluid trapped in these tubes is typically presented as a homogeneous, equivalent fluid with complex, frequency dependant characteristic impedance (z_b) and complex wavenumber(k_b). The value of the characteristic impedance and the boundary conditions at the back of porous layer determine the ability of sound waves to enter the porous space. The value of the complex wavenumber relates to the speed of sound in the porous space and the rate of its attenuation.

In order to model the frequency dependant behaviour of the characteristic impedance and propagation constant two separate approaches can be adopted, (i) theoretical and (ii) empirical. Theoretical models tend to treat separately the viscous and thermal effects by introducing complex expressions for the dynamic, frequency dependant density $(\rho_b\ (\omega))$ and compressibility $(C_b\ (\omega))$ of the fluid, $\omega = 2\pi f$ being the angular frequency and f being the frequency of sound in Hertz. The influence of these two characteristics on the sound speed, attenuation and the impedance of the porous medium have been known for a long time and analytical formulae have been developed to predict their frequency dependent behaviour as a function of macroscopic parameters of the porous space (Kirchhoff, 1876). It has been shown that the viscous friction losses in the oscillatory flow in a material pore are controlled by the non-zero imaginary part of the dynamic density and are pronounced at frequencies below the so called Biot frequency,

$$\omega_v = \frac{\eta}{s^2 \rho_0 \alpha_\infty} \tag{2.1}$$

where $\eta \cong 1.84 \times 10^{-5}$ Pa.s is the dynamic viscosity and $\rho_0 \cong 1.21$ kg/m^3 is the equilibrium density of air. Above this frequency the viscous friction is relatively small and the inertial forces are predominant. Therefore, the value of this frequency is of importance as it separates the viscous (low frequency, $\rho_b \cong \rho_0 + \frac{\eta}{i\omega s^2}$) and inertial (high frequency, $\rho_b \cong \alpha_\infty \rho_0$) flow regimes in the pore which are controlled by the characteristic pore size (s) and the pore tortuosity (α_∞), respectively. Similarly, the thermal losses are controlled by the non-zero imaginary part of the complex compressibility and are pronounced around the characteristic thermal frequency,

$$\omega_B = \frac{\kappa}{s^2 \rho_{0C_p}} \tag{2.2}$$

where, $\kappa \cong 26 \times 10^{-3}$ W m^{-1} K^{-1} is the thermal conductivity of air and $C_p \cong 1000$ J kg^{-1} K^{-1} is the specific heat of air at constant pressure. This frequency separates the isothermal (low frequency, $C_b \cong P_0^{-1}$) and adiabatic (high frequency, $C_b \cong (\gamma P_0^{-1})^{-1}$) regimes. Here γ is the ratio of specific heats and P_0 is the ambient atmospheric pressure. There is a considerable amount of experimental evidence which confirms that the above assumptions are valid for the accurate prediction of the acoustic properties of a porous surface.

The acoustic absorption is controlled by the characteristic impedance, wavenumber and the geometry of the porous layer. For some known values of the dynamic density and complex compressibility the characteristic impedance and complex wavenumber can be determined from the following relations,

$$z_b(\omega) = \sqrt{\frac{\rho_b(\omega)}{C_b(\omega)}} \quad \text{and} \quad k_b(\omega) = \omega\sqrt{\rho_b(\omega) C_b(\omega)} \tag{2.3}$$

The characteristic impedance is an important quantity related to reflection and transmission of sound at boundaries. The characteristic impedance of a medium is defined as the ratio of the acoustic pressure to the particle velocity in a progressive plane wave propagating through the medium.

The proportion of the acoustic energy absorbed by a porous layer of thickness h backed by an acoustic impedance z_m is determined from,

$$\alpha(\omega) = 1 - \left|\frac{z_s - \rho_0 c_0}{z_s + \rho_0 c_0}\right|^2 \qquad z_s = z_b \frac{z_m + z_c \tanh(ik_b h)}{z_c + z_m \tanh(ik_b h)} \tag{2.4}$$

where c_0 is the sound speed in air and z_s is the surface impedance of the porous layer. The characteristic impedance of the surrounding medium is $z_c = \rho_0 c_0$ and $z_m = \rho_b c_b$ is the characteristic impedance of the material. The absorption coefficient α, is defined as the ratio of absorbed energy to the incident energy, also given as,

$$\alpha = \frac{E_i - E_r}{E_i} = \frac{E_\alpha}{E_i} \tag{2.5}$$

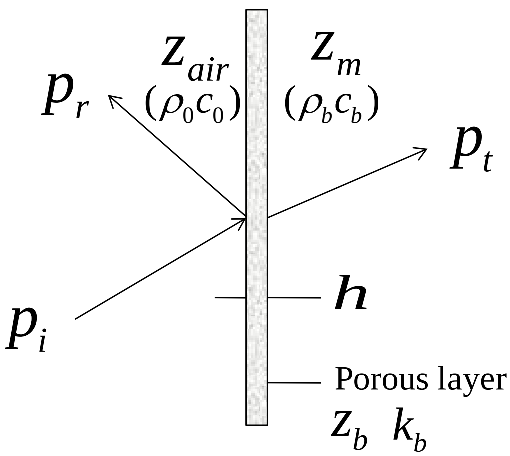

Figure 2.11: Sound wave reflection and transmission through a porous layer

The proportion of the acoustic energy transmitted through the porous layer is shown in Figure 2.11,

$$\tau(\omega) = \left|\frac{2z_s}{z_s+\rho_0 c_0}\right|^2 \qquad (2.6)$$

Obviously, many materials are not rigid enough and their frame can vibrate, in this way sound gets transmitted through a porous layer because of the energy seepage through the material pores and because of the frame vibration (equation 2.6). This phenomenon also affects the absorption coefficient because of the frame resonance.

2.10 Modelling acoustic wave propagation through elastic porous media

Several works have been done on poroelastic properties of materials; Horoshenkov (2001) has studied the effect of consolidation on the acoustic properties of loose rubber granulates, in his work four models were adopted to predict the acoustic performance of loose and consolidated rubber granulates, the Pade approximation model (Horosenkov et al., 1998), the Miki empirical model (1990), the Wilson relaxation model (1997) and the Voronina empirical model (1999). Dauchez et al have studied the behaviour of a poroelastic material bonded onto a vibrating plate in the low frequency range. They found that viscous dissipation is the major phenomenon within soft materials and thermal dissipation is negligible, they concluded that viscoelastic dissipation is dominant within soft materials such as foams. Allard in his book (1993) discusses Biots theory of sound propagation in porous materials having an elastic frame. His porous structures such as foams, fibreglass are much more complex than a stack of parallel capillary tubes as modelled by Lord Rayleigh. In order to cope with this complexity it has been common in a theoretical model to introduce semi-empirical adjustable factors, which together with the measured macro structural data are able to account for any deviation of the realistic porous structure from the assumed stack of cylindrical pores of identical size. The very idea of using a semi-empirical factor in a theoretically-founded model sounds flawed as it illustrates the fact that most theoretical models are unable to characterise fully the complexity of real porous media. An excellent, physically-founded model proposed by Johnson-Allard (1992) relies upon knowledge of the viscous and thermal characteristic lengths, which are difficult to measure. As a result, a number of simple empirical models have been proposed (Delany and Bazley (1970), Voronina (2003)). On the other hand, there are models of ever increasing complexity based around a large number of macro- and microstructural parameters which, when carefully characterised, are able to describe accurately the acoustical processes in a complex porous medium.

The most widely used class of models for porous materials, is based on the Biot formulation, who developed a general three dimensional theory for elastic porous media. According to the Biot theory of sound propagation in poro-elastic solids, the presence of fluid within a porous solid results in the existence of two compressional waves and one transversal wave. The theory takes into account fluid density, flow resistivity, porosity, tortuosity, viscous length, and thermal length. Biots early theory is similar in nature to the works by Zwikker and Kosten, but with the important difference that Biot also included effects of shear in the elastic frame of the porous medium. The resulting equations may be written in several different forms; here they will be given using the sign convention shown in Figures 2.12 and 2.13. The theory for wave propagation in elastic porous media proceeds from dynamic and stress stain equations for the two phases of the porous material, the solid frame and the fluid.

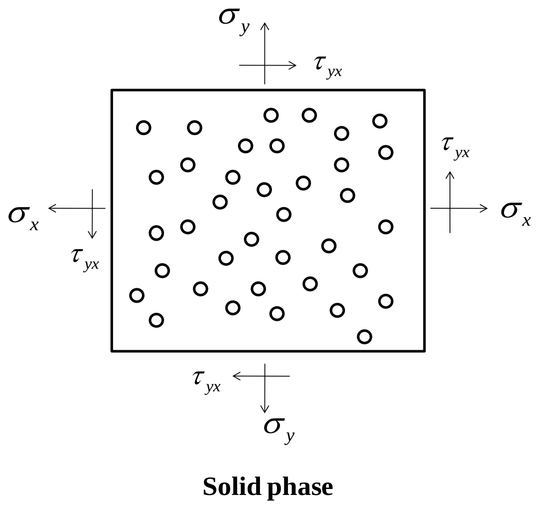

Figure 2.12: Stresses acting on the solid phase

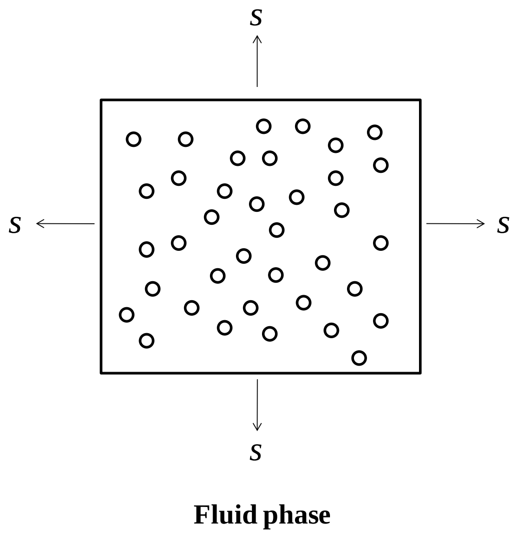

Figure 2.13: Stresses acting on the fluid phase

where P is the pressure in the exterior acoustic field at the interface, v_y is the normal component of the acoustic particle velocity in the exterior medium at the interface, S is the fluid stress within the porous material, σ_y is the solid stress within the porous material, τ_{xy} is the shear acting on the solid phase, and u_y and U_y are, the solid and fluid displacements, respectively.

In the dynamic relations there appear fluid structural coupling terms proportional to the relative acceleration of the two phases. The coupling is directly related to the pore tortuosity, while the viscous coupling can be related to the flow resistivity. After combining the two sets of relations and performing a sequence of vector operations, one obtains two wave equations that govern the propagation of volumetric and rotational strains within the material,

$$\nabla^4 e_s + A_1 \nabla^2 e_s + A_2 e_s = 0 \tag{2.1}$$

$$\nabla^2 \varpi + k_t^2 \varpi = 0 \, , \tag{2.2}$$

where e_s and ϖ are the volumetric and rotational strains, respectively, and k_t is the wave number of the rotational wave. The forth order wave equation having the form of equation 2.1 indicates the existence of two longitudinal wave types, and a second order wave equation having the form of equation 2.2 governs the propagation of a single transverse wave.

At the open surface of the elastic porous layer there are four boundary conditions to be satisfied (Figure 2.14), two normal stress continuity conditions, a normal volume velocity continuity condition and one stress free condition. These conditions are, respectively,

$$S = -hP \tag{2.3}$$

$$\sigma_y = -(1-h)P \tag{2.4}$$

$$v_y = j\varpi\,(1-h)u_y + j\varpi\,hU_y \tag{2.5}$$

$$\tau_{xy} = 0 \tag{2.6}$$

Where h is the porosity, P is the pressure in the exterior acoustic field at the interface.

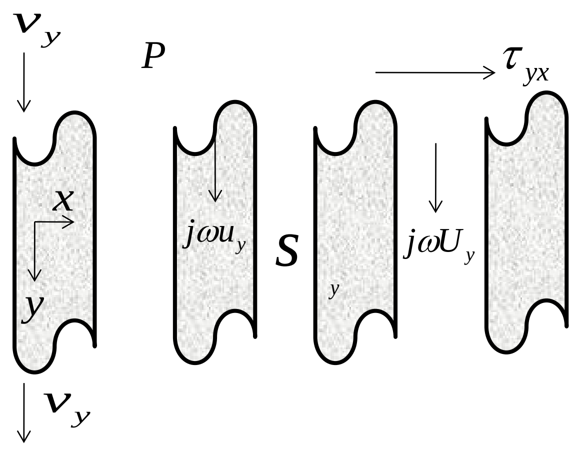

Figure 2.14: Boundary conditions for open surface

At an open surface of this type there is no constraint placed on the individual velocities of the solid and fluid phases of the material, only the volume velocity must be continuous at the interface. As a result, the partial impedance of the fluid and solid phases add in parallel, and the motion in the external fluid region (i.e. the external sound field) primarily drives the phase of the porous material that has the lowest impedance, which would normally be the fluid phase of the porous material. Therefore, at an open surface, airborne incident sound couples most directly to the airborne wave within the material. This is usually advantageous since the airborne wave is usually much more heavily damped than is the frame wave.

In majority of cases materials with an elastic frame have poor absorption compared with materials with a rigid frame, but the positive aspects of the frame elasticity can be attributed to the impact sound insulation properties of resilient materials with elastic frames (resilient materials designed for use in acoustic flooring systems must comply with Building Regulations Approved Document E and ISO 140 part 8).

2.11 Tailoring of Acoustic Materials from Polymeric Waste

The tailoring of acoustic materials from polymeric waste poses a broad challenge that is perhaps best appreciated by considering the range of applications where specific types of new porous materials are needed for use in devices or systems that perform specific functions for example in buildings, vehicles, white goods etc. These applications will require tailoring of the polymeric waste not only on the molecular size and chemical process scales, but also on the meso and macroscopic size scale.

Tailoring porous materials from recycled polymeric waste raises the question of how porosity can be controlled. In general, the creation of porosity within the structure requires study of the physical and chemical processes at a molecular level. In this way the grains/fibres are allowed to be securely bonded together to achieve a porous product with good acoustical properties. It may be possible in this fashion to prepare tailored materials from waste that have a specific absorbance to serve a specific function. Recycled granular media for acoustic applications has been studied in the past (e.g. Swift, (2000) and Horoshenkov (2001)). Given the amount of previous work it is surprising that recycling granular waste has still limited use for manufacturing acoustic products.

This research investigates an entirely new approach to the tailoring of porous materials with controlled pore size distribution. For acoustic applications the pore size distribution plays a major role, how this is controlled will be presented in the following chapter. The knowledge gained in batch process mixing will be applied to develop a continuous extrusion process that will not require heat. The extruder will be used as a solid conveyor, solid mixer, and reactor. The hopper and screw design and the way the binder is added will be discussed in general in the next section.

2.12 Processing consideration

The function of a standard extruder is to convert solid feedstock into a homogeneous melt and to pump it through a die at a uniform rate. The hopper is fed by cold polymer granules; the solid feedstock is transported by a screw which rotates within a heated barrel (Figure 2.15). The melted extrudate is compressed, homogenised, moulded, and pressurised to generate sufficient pressure to pump the melt against the resistance of the die.

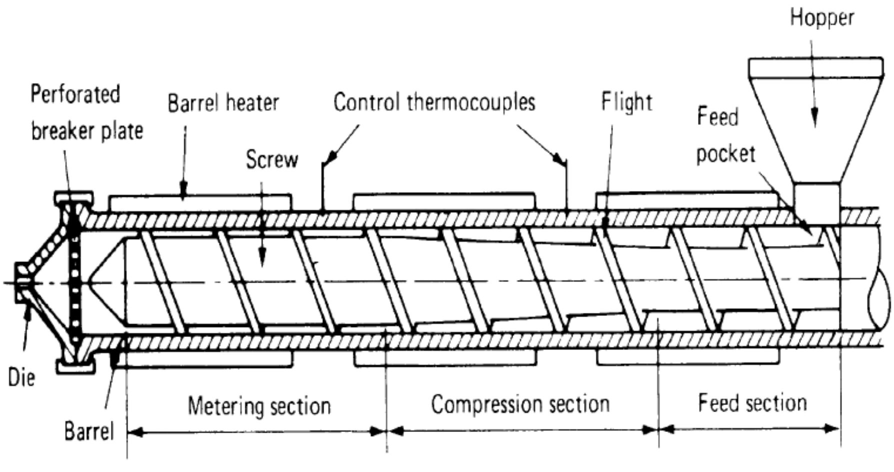

Figure 2.15: Schematic diagram of a standard extruder (Crawford, (1992))

The process developed to recycle polymeric waste was cold extrusion based on the hot extrusion notion. For the production of the initial prototype extruder the following design considerations were needed to be taken into account:

i. Feeding of the raw materials

- Fibrous/grain particulate,
- Binder
- Water

ii Mixing of the raw materials

- Premixing
- Extruder mixing

iii Extruder characteristics

- Width, Capacity
- Diameter and length of extruder barrel
- Screw design, variable pitch, channel length
- Die width and thickness, back pressure issues

iv Curing

- Dwell time
- Effect of temperature

v After processing

- Compression/calendaring time (cold/hot)
- Sheeting size

vi Services needed and consumption of

- Electricity
- Water

In general the performance of the extruder is related to several aspects including the quality of the product it produces, energy consumption, rate of production and pressure profiles within the extruder. The quality of the extrudate is defined in terms of the ability of the extruder to homogenise the mixture before it reaches the die and to achieve a uniform delivery rate. The compositional inhomogeneity of the extrudate affects the appearance, the porosity pore size distribution, mechanical properties and acoustic properties of the extrudate. It is important to balance the addition of binder, water, PVC granulates and fibres. Instabilities occur if the water and binder are unable to coat the grains and fibres due to a high output rate from the hoppers. Material break up occurs when the material pumping rate is higher than the binder feed. The total output rate is a function of the screw speed, diameter of the barrel and the screw geometry. The cold extrusion equipment was designed to run with a range of screw speeds, which allowed a range of flow rates to be produced.

A detailed description of the experimental equipment used in the cold extrusion process is presented in the next chapter together with a description of the binder and the chemical process chosen to create the pore size distribution within the material.

2.13 Summary

In this chapter a literature survey has been carried out on the selection of raw materials and manufacturing methods. The fundamental of sound propagation in porous materials has been discussed. This theory is used to model acoustic wave propagation through elastic porous media and hence predict the acoustic absorption properties of porous material.