Soap Based Thermal Insulation as an Environmental Alternative to Petroleum Based Thermal Insulation

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Acronyms List

BREEAM – Building Research Establishment Environmental Assessment Methodology

BS EN – United Kingdom Version of Standardisation of European Standards

CFC- Chlorofluorocarbon

CPD- Construction Products Directive

DEFRA – Department for Environment, Food & Rural Affairs

DEP – Department of Environmental Protection

DIN EN - German institute for standardisation of European Standards

DPM – Damp Proof Membrane

EC – European Community

EPC – Equilibrium Moisture Content

EU – European Union

EUR-lex – Official Journal of the EU

ICAEN – Catalan Energy Institute

ISO – International Organisation for Standardisation

MDI – Reactive Lewis Acid

OFgem – Office of Gas & Electricity Markets

PET – Polyethylene Terephthalate

PEHD - Polythene

pH – Potential of Hydrogen

PIR - Polyisocyanurate

PLA – Canola Oil-Based Plastic

PMDI – Polymeric isocyanate

PSI – Pounds per Square Inch

PUR - Polyurethane

PVC – Polyvinyl Chloride

R-COOH – Carbolic Acid

RH – Relative Humidity

SAP- Standard Assessment Procedure

TDI – Toluene diisocyanate

TSC – Thiosemicarbazide

UK – United Kingdom

UKAS – United Kingdom Accreditation Service

USA – United States of America

UV – Ultra Violet

XPS – Extruded Polystyrene

XPE – Expanded Polystyrene

Units List

^{0}C – Degree Celsius

g - Grams

IU – International Unit

Kg – Kilograms

Kg/m^3- Kilograms per Metre Cubed

m – Metres

m^2 – Metres Squared

m^{3-} Metres Cubed

mm – Millimetres

n/mm^2 – newton's per millimetre squared

V – Volts

W/mk – Watts per Metre Kelvin

W/m^{2}k – Watts per Metre Squared Kelvin

m^{2}K/W – Metres Squared per Kelvin Watt

% - Percent

Acknowledgements

First, I would like to thank my wife Denise for her moral support throughout my doctorate and for accepting the smells and the mess created when manufacturing the soap.

Second, I would like to thank Philip Woodford and Mark Mitton at PWC Building Control Ltd, for their moral and financial support.

Third, but not least, I would like to thank my doctorate supervisor, Yusuf Arayici for his continued support over the previous four years.

Declaration

I hereby state that this thesis is solely based on original work carried out by myself and that references to past research have been appropriately acknowledged.

Lee Read

Abstract

The aim of this doctorate is to investigate an alternative to petroleum based thermal insulations, by using natural and recycled materials. The methodology used is centered on the use of the basic ingredients of waste animal fats, waste oils and a potash derived lye mixture, combined to create a crude soap. This soap is aerated to produce a lightweight structure that is capable of preventing or reducing heat transfer between areas of differing temperatures. Experimental testing reveals that this non-toxic product can be strengthened, made waterproof, vermin proof and fire retardant, whilst the results from the thermal testing laboratory confirm that aerated soap insulation functions as a moderate performer. The step-by-step experimental methodology applied, alongside the thermal conductivity and resistance results contained within this thesis, can be used as a gauge for future potential improvements to build from. Currently there are gaps in knowledge and practice with regards to environmental thermal insulation. There are other environmental insulations, but more research needs to be initiated regarding recyclable, biodegradable, renewable and organic components and ingredients within the insulation make-up. Industry trends are to improve the better performing petroleum insulations, whilst seemingly unwilling to compromise on environmental problem relief. This doctorate provides suggestions on how to reduce some of the environmental problems by replacing or diluting the toxic elements of petroleum insulation.

Soap insulation is unique and as such makes a significant contribution to knowledge. This uniqueness is evidenced through the literature review and the systematic investigation of the research topic. The awarding of a worldwide patent on soap insulation protects the manufacture of thermal insulation comprising of solid aerated soap panels, derived from animal fats and lye. This idea of combining basic soap ingredients, then aerating the mixture to create thermal insulation is new and as such contributes to new knowledge. The publishing of a journal paper titled *"Can Soap be a Sustainable Alternative to Petroleum-Based Thermal Insulation?"* in the journal of *Structural Survey*. (Read & Arayici, 2015) emphasize the contribution of this research. Read & Arayici, (2015) describes the ingredients used, the manufacturing process and the

improvement measures taken to create the soap insulation. Publishing is one method of making this research known to the global community. Academics can then engage with fellow academics or collaborate with industry to further this research or to commercialise this knowledge. Aerated soap research can widen the understanding of possible new alternative thermal insulation ideas. This creates a small yet original and significant opportunity to reduce the associated carbon footprint and environmental costs accrued each time that petroleum insulation is produced.

Chapter 1 Introduction

Thermal insulation is an important topic for consideration, because as a product it will be useful for mankind for the foreseeable future (Torgal et al, 2012). To understand the rationale behind thermal insulation, it is necessary to know what the definition of thermal insulation is, and why it is needed. The primary role of thermal insulation is to achieve energy efficiency throughout a building's lifespan by maintaining comfort for the occupants within the building space (Cezairliyan et al, 2012). Heat transfer will only occur when there is a temperature difference between a warm zone and a cold zone (Bejan, 2013). So in order to stop this heat from leaching, a barrier must be installed, manufactured from a material with low thermal conductivity (Bejan, 2013). Purchasing decisions regarding this insulation can have both positive and negative impacts on the wider environment (Wilson & Piepkorn, 2013), depending on the strength of the environmental credentials (in terms of manufacture and end of life disposal) of the insulation. From a personal perspective, the author of this thesis is employed as a building control surveyor. This means that inspecting thermal insulation placement to walls, floors and roofs to ensure building regulation compliance, is carried out on a variety of buildings, on a daily basis. Observing damaged, end-of-life or unwanted or unusable insulation off-cuts amongst skip waste is also a daily occurrence. The long term problems associated with waste disposal of insulations at landfill and the environmental problems associated with crude oil retrieval and plastic manufacture are amongst the key rationale behind this research quest for a environmental alternative to petroleum insulation.

Attitudes to using natural (organic and/or biodegradable) or recycled insulations must be acquired and developed over the long term. Mind-set changes at local level can universally "snowball". From a theoretical standpoint, this would mean that it is the duty of everyone involved with raw material extraction and fossil fuel processing to step back and observe the bigger environmental picture. This would ensure that through careful waste management, utilising systems of recycling and reuse, the depletion of earth's finite resources may be slowed. This in turn would ensure that eco-systems, natural environments and future generations are not burdened because of present day actions and attitudes encompassing petroleum based insulation manufacture. It should be stated that there are already environmentally friendly alternatives.

One such alternative is a thermal insulation derived from aerated soap. Soap insulation, derived from soap in its most basic form, (fats, oils and wood ash residue) is natural (Grosso, 2013) and could be one possible advancement in a quest to encourage sustainable buildings. Combining fats and lye can create a hard, crude soap mixture that once aerated and left to cool, can be cut into slabs and surrounded in sustainable bio-plastic to create thermal insulation products. Trapped bubbles within the insulation give the insulation its thermal properties (Acton, 2013).

The majority of thermal insulation in buildings tends to be man-made petroleum based products, with limited or no end of life usage (Ryan, 2011). This research targets sustainability simply because the earth's resources are finite and as such are in danger of eventually running out (Price-Smith, 2015). This research targets waste because wastage directly contributes to resources running out and it targets the viability of alternative and recycled plastics because of the ever increasing price and the ongoing scarcity of fossil fuel oils which are required in the manufacture of petroleum based insulations (Price-Smith, 2015). This study will examine alternatives to oil, how the raw ingredients of plastic can be "stretched" or replaced and what happens to these plastic insulations at their end of life.

1.1 Background to Thermal Insulation

In general, insulations were introduced into the UK housing lofts in the 1960's, usually in the form of fibreglass rolls (Goodall, 2012). Polystyrene and fibreglass cavity wall insulation were introduced into dwellings during the 1970's (Long, 2006). This older insulation was often manufactured from formaldehyde and other toxic substances that are released into the atmosphere as the insulation degrades (Kirk, 2010). This can create health problems where human contact and exposure meet. As technology evolved, improvements were made to the thermal insulations. These improved insulations are still in use in 2015 (Goodall, 2012).

There are four main types of foamed plastic wall, floor and roof insulation that are commonly used within the construction industry. Alongside these, multilayered reflective foil and fibreglass insulations are also used, but to a lesser extent (Wilson & Piepkorn, 2013). Environmentally friendly insulations are becoming more popular, but occupy a very small niche in the market generally. The six main insulation types are as follows:

1. Extruded polystyrene (XPS). This insulation is manufactured by liquefying polystyrene pellets with various other ingredients. Gas bubbles are then formed by introducing a blowing agent into the mix. The resulting liquid foam is then cooled to produce closed-cell foam that is both rigid and waterproof (Grinnell, 2015).

2. Extruded polyethylene (XPE) is manufactured by blending polyethylene pellets and various other chemicals. An injected blowing agent is added to the mixture to cause a foaming reaction. When cooled, flexible plastic closed-cell foam is created (Grinnell, 2015)

3. Expanded polystyrene (EPS). Expanded polystyrene is made from pre expanded styrene beads (enlarged with pentane). Heat and pressure is applied to enable the beads to stick together. This insulation is mostly used for floor insulation as it is difficult to achieve the correct wall and roof U values (overall heat transfer coefficient) with the thicknesses manufactured (Wilson & Piepkorn, 2013).

4. Polyurethane (PUR) and polyisocyanurate (PIR) are created by blowing hydro-carbon pentane gas (C_5H_{12}) into a urethane ($C_3H_7NO_2$) mixture. This produces a free frothy insulation that when dry creates an insulation of high thermal efficiency. PUR and PIR insulations are by far the most popular insulations that are used for wall, floor and roof insulations within the UK (Emmitt & Gorse, 2014).

5. Fibreglass insulation is what the name suggests, fibres of glass. Sand and recycled glass are heated to 1,450^{0}C and fused together. The resulting glass mixture is forced through a fine mesh to convert it into fibres. A liquid binder is added to glue the fibres together. Fibreglass insulation remains popular as both loft insulation and cavity wall insulation (Grinnell, 2015).

6. Multifoil insulation is comprised of reinforced top and bottom sheets of foil, with multi-layered reflective sheets between. These sheets are separated by foam, wool or wadding and then sown together to create a thin insulation blanket. The insulation is typically 10mm to 30mm thick (Appleby, 2012).

Environmentally friendly thermal insulation products derived from paper, wool, hemp and cotton fibres etc. have also become available for use in cavity walls and roofs. These products will be scrutinized further into this thesis, although it should be recognised at this stage that advertising products as environmentally friendly is often a way of manufacturers selling them in the best possible light (Rosengren et al, 2013). The exterior walls of a building can actually be built from materials with embodied insulating properties. Examples of building materials that are in their own right natural insulations include straw bales (Racusin & Mc Arleton, 2013), rammed earth (Keefe, 2012), bamboo (Minke, 2012), papercrete, made from a lightweight paper, sand and cement mixture (Kennedy, Smith & Wanek, 2015) and clays mixed with sand or sawdust (Shroeder, 2015). Heriot-Watt University (Edinburgh) have recently been involved with the design and manufacture of a new type of low density thermal insulation derived from coconut husk (the exterior shell of a coconut) and bagasse (a dry, fibrous residue derived from sugarcane). This insulation is manufactured without using chemical binders and gives a thermal conductivity value of 0.046 - 0.068 W/mK, which is close to that achieved by mineral wool insulation (Panyakaew, 2011).

1.2 Environmental impact of Synthetics

Petroleum based plastics (synthetics) are toxic to produce and sometimes toxic to use (Islam, 2008). Additives used in the plastic manufacture often include chlorines (Cl_2), chlorides (C_aC_{12}) and phthalates (C_nH_{2n+1}). All of these are possibly carcinogenic. An object manufactured in PET (polyethylene terephthalate, $C_{10}H_8O_4$) plastic generates approximately 100 times more toxic emissions than a similar object manufactured from glass (Islam, 2008). Brownell, (2013) states that some plastics release endocrine disrupters. These chemicals interfere with the hormones that affect the reproductive process, potentially causing infertility and cancer. It should be noted that the testing of these products has been limited to mice, but also observed in fish and reptiles. There is no recorded data available for the effects on humans, although Sault (2013) is of the opinion that over time, plastics can become toxic, irritant or even carcinogenic to humans.

Oil Sustainability

Regarding sustainability, most of the fossil fuel arguments and opinions by environmental sceptics and believers are based on assumption, estimation and conjecture at this present time and so the *absolute* conclusions regarding the damage created by retrieval, manufacture and their ultimate consequences are merely expert projections and opinions. These estimations are particularly prevalent in the sustainability context considering oil is being consumed at “one million times the rate at which it was laid down” (Phillips & Mighall, 2014). Ayoob (2014) stated that 50% of the world’s energy is provided by oil. On an individual dwelling level, a reduction of 1^0C in the internal set point temperature can create an oil consumption reduction of 6% (Ayoob, 2014). According to Moyer (2010) in his article in “Scientific American” magazine, global oil production would peak in 2012, and by the end of the 2050’s, there will be only 10% of the earth’s oil reserves left. Hamed (2011) agreed and stated that oil will peak between 2012 and 2030. Zebrowski & Zebrowski-Leach (2014) opined that oil discovery has already peaked.

Regarding Moyer and Hamed’s predictions on the amount of time remaining until the oil reserves are depleted, Catty (2010) disagrees. He states that current estimates are too low. Campbell (2013) is of the same opinion. He claims that Saudi oil will not peak for at least 75 years and that the recent discoveries of oil in the Falklands, Russia and Central Asia will sustain the world for many years to come. Learsy (2013) agrees but has differing views as to why there is confusion. Learsy blames OPEC (Organization of the Petroleum Exporting Countries) for scaremongering about the dwindling supplies so as to manipulate the oil markets to keep the oil prices high. According to Learsy (2013), OPEC controls over 80% of the world’s oil exports.

1.3 Potential Environmental Problems with the Insulation Manufacture

There has been a shift away from the use of certain plastic petroleum based thermal insulations. Expanded polystyrene (EPS), Extruded polystyrene (XPS) and extruded polyethylene (XPE) are being replaced by polyurethane / polyisocyanurate (PUR or PIR) insulations (Kutz, 2011).

Most PIR insulations are faced with reflective aluminum foil. According to the

“Sustainable Building Sourcebook” (2010), this foil is used to reflect back radiant heat as part of the insulation’s working process. However, CFC gas, a recognized global warming emission, is released into the atmosphere without it being contained within the insulation by these aluminum facings. This insulation also degrades over time (thermal drift), resulting in the insulation having a substantially lower R-value (thermal resistance) than the R-value advertised (Bradshaw, 2010).

On an environmental level, the impact of petroleum based plastics and refined oil is threefold. Firstly, the retrieval of oil cannot be considered as sustainable. As will be examined further in this thesis, the limited supplies remaining and the damage caused to the environment by retrieval, is in direct opposition to the sustainable energy alternatives. Secondly, the refining process of crude oil and the processes involved in plastic and foamed plastic insulation component manufacture involve high greenhouse gas output emissions as a by-product and high energy consumption throughout the product’s start to finish manufacturing ratios (Chorafas, 2012). The refining process relies on the combustion of fossil fuels for this heating, whilst the recovery units emit large amounts of methane (CH_4) and carbon dioxide (CO_2), making the oil refining industry a significant source of emissions (Chorafas, 2012). (A three stage lifecycle model of plastic insulation is shown in Fig.1.1 below).

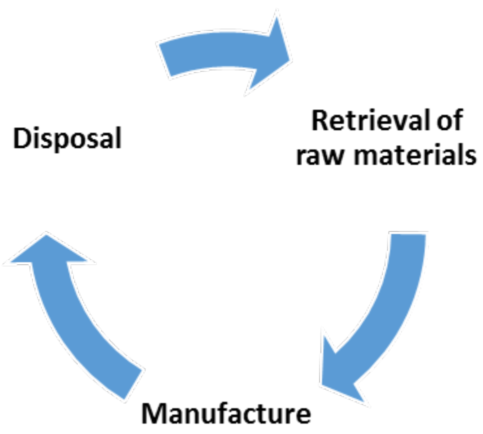


Figure 1.1: Lifecycle Model of Plastic Insulation

End of life disposal of the insulation products is the third phase of this environmental "triangle". Traditional insulations are difficult to dispose of in an ecologically friendly manner (Sault, 2013). In the UK, the majority of insulation finds its way to landfill sites where it leaches toxins into the soil as it degrades (Sault, 2013). Alternative methods of disposal and non-toxic biodegradable insulation waste are explored later into the thesis.

1. 4 Rationale for the Research

There are a number of potential problems associated with the manufacture, use and disposal of petroleum or man-made chemical based insulations. These problems must be understood if they are to be addressed.

Crude oil (and therefore its petroleum derivatives) is a finite commodity. The oil reserves will not last indefinitely. Oil retrieval, refining and the subsequent plastic manufacturing also have high financial and environmental cost implications. Crude oil retrieval and the refining (distillation) process can create both short and long term pollution problems that can be detrimental to both human and wildlife health (Melosi & Pratt, 2014). Worldwide, the manufacture of petroleum plastics and their ultimate end of life disposal can cause problems to the natural environment through airborne toxin release (by incineration) and ground contamination through leachates (from burial at landfill) (Elvin, 2015). An alternative environmentally friendly insulation, manufactured from natural or sustainable components, should combat these problems.

1.5 Research Hypothesis

The research hypothesis for this thesis is that soap based insulation could be a possible alternative to petroleum based insulation. As will be examined in this thesis, the start to finish manufacturing cycle of soap insulation is ecologically sustainable. Soap is pH neutral, non-toxic and non-carcinogenic. Handling and cutting can be performed safely. This is in direct opposition to fibreglass, formaldehyde and urethane based insulations that can create breathing hazards if their fibres are inhaled (Kirk, 2010). The oils and fats used in soap manufacture can be derived from waste animal carcasses. In the UK, thousands of tons of bovine animal fats are a by-product of the slaughter industry that is usually destined for the incinerator each year. Although the actual figure for the incinerated waste is unknown, it is estimated that over 10 million tons of animal waste (meat and fats) derived from healthy animals is created in the EU for waste disposal (Defra, 2012).

End of life disposal for soap based insulation should also be environmentally friendly. The soap can be boiled down and re-moulded for reuse or grated and used as fertilizer. If a bio-plastic insulation casing is used for the soap's protection, then this can be recycled or composted at the products end of life. This is in direct contrast to PIR insulations which tend to degrade slowly when buried at landfill. Soap insulation could also make a positive contribution to creating zero carbon dwellings.

1.6 Research Question

The question that needs to be satisfied is whether sustainable soap based thermal insulation will provide a similar function to the petroleum based alternatives. Will it perform to an equal standard of thermal efficiency and will it equal or exceed the other petroleum insulation qualities? These qualities include being lightweight, uniform, non-toxic and resistant to ultra-violet light (in the event that the insulation is exposed to sunlight for prolonged periods of time).

1.7 Research Aim and Objective

The aim of this research is to develop a soap based thermal insulation for buildings as an alternative to the petroleum based counterparts. Soap insulation should achieve equal or increased efficiency and quality levels as its petroleum counterparts, whilst decreasing (however slight) the environmental costs associated with fossil fuel retrieval, plastic manufacture and end of life waste disposal. The measurable objectives (tasks and activities) are listed below.

1. To explore existing in-situ insulations to expose the insulation limitations and reveal the advantages/disadvantages of each individual thermal insulation type.

2. To identify the pros and cons of existing insulation and insulation materials based on evidence from literature. This will create a reference point for the foundation of the research to build on, and a place where the soap based insulation *ideas* can evolve from.

3. To explore the soap based insulation concept as an alternative insulation and define the criteria for comparative assessment.

4. To produce soap based insulation samples and collect relevant information and data on all of the soap development samples to conduct a comparison study. This will highlight the performance of the insulation types and create indicators that will guide the direction in which the insulation research needs to go (for creating a soap based alternative).

5. To test, compare and refine the soap based insulation samples with established insulations and measure its performance against a selection of the other insulation types (constants) in an iterative manner for continuous improvement of the soap based thermal insulation specification.

6. Validation of the soap based thermal insulation through testing at the thermal testing laboratory. The results will lead directly to the objective, the answer to the original research question.

1.8 Research Methodology

In order to satisfy the objectives, four modes of research must be satisfied for the alignment of the research to the original research question. These are outlined below.

1.8.1 Research Philosophy

Three theories will underpin and help to order and define the philosophical stance of the research:

1. Ontological: A branch of metaphysics regarding the study of things that exist and the specification of a concept (Killam, 2013). Both objectivism and subjectivism fall under the ontology "umbrella" (Killam, 2013). Laboratory based experimental research will form the basis of this thesis and as objectivism is concerned only with the facts derived from results (as opposed to beliefs), it will preside over subjectivism. These facts indicate the direction the research will take.

2. Epistemological: The theory of knowledge. Investigating the origins and methods used and how to use self-reason and others' testimony to acquire further knowledge (Killam, 2013). In relation to the goal of this research, the experiments fill a

knowledge gap. In this respect, the positivist, as opposed to the interpretivist approach is used. This is because, in experimental research, the positivist approach utilizes the manipulation of factors under controlled conditions and identifies causal connections by keeping some variables constant whilst manipulating others (McNab, 2015). This experimental research is measurable. The interpretivist approach is concerned with generating theories as opposed to hypothesis testing, focuses on meaning as opposed to facts and generally tends to produce qualitative data as opposed to quantitative data (McNab, 2015). Reviewing existing literature identifies the strengths and weaknesses of existing insulations, leading to improvements in the soap based insulation.

3. Axiological: The philosophical theory of value, enabling us to identify the systems that influence our actions and decisions, to understand *why* we do *what* we do (Killam, 2013). Value free is the approach used. This is the ability to make impartial, unbiased and balanced assessments of the facts as opposed to the value laden method that imparts personal values based on personal opinions. Continual building upon the facts will create a process of continual improvement until the original research question is answered.

1.8.2 Research Approach

The experimental, observable, inductive approach is ideal for practice based theories and is scientifically robust enough to generate accurate results. Generally, this approach usually begins with detecting patterns in specific observations. This leads to the formulation of hypothesis that will then be explored and tested. From here, broader generalizations and theories can be developed (McNab, 2015). This inductive approach is better suited to the research contained within this thesis, as opposed to the deductive approach, which starts with a broad spectrum of information and works towards a specific conclusion.

1.8.3 Research Strategy

Experimentation is the most appropriate research strategy. According to Saunders et al (2015), research strategy is “the general plan of how a researcher goes about answering the research question”. This method best utilizes the testing of ideas and building of the insulation development theories by focusing on the area of interest (soap insulation), collecting, organizing then interpreting the data, then determining the best way forward. This strategy should highlight the methods used and acknowledge the research limitations. In this case the insulation performance over a prolonged period of time. Limitations for testing the examples would include confirming that the insulation casing remains water and vermin repellent, fire retardant and non-toxic over time. Also, evidence that the soap remains “fit for purpose” over the long term, e.g. will not deform under its own in-situ weight.

1.8.4 Research Process

The research process deals with the stages through a systematic process of gathering information for analysis and objectively reviewing this information in order to reach a conclusion. This research process is divided into three sections.

1. The first stage includes reviewing existing literature on established thermal insulations to determine the strengths and weaknesses of these products. Exploring in-situ insulations and identification of the pros and cons of various insulation types through available literature, as mentioned in points one & two of the objectives listed earlier in this chapter, will create a foundation in which research ideas can evolve from. This should lead to possible improvements in the soap insulation by identifying the shortfalls of the existing plastic insulations and thus incorporating new ideas to reinforce further soap insulation research.

2. The second stage is to manufacture a soap utilising various components and ingredients in order to determine a product of good thermal efficiency. These ingredients could typically include waste animal fats and waste oils (restaurant and engine), potash derived lye and to a lesser extent, animal keratin, bone glue and bio-plastics. These ingredients are to a large extent waste derivatives from other uses. Experimentation will determine which ingredients can be used and comparison with existing insulations will indicate the direction in which the research needs to go.

3. The third stage is a process of continual manufacturing improvement until a thermal insulation is achieved that withstands the thermal conductivity testing requirements of the laboratory to determine possible insulation longevity and degradation issues. This will also determine how the soap insulation compares against established insulations and should provide the answer to the original research question, as revealed in the objectives.

1.8.5 Methods for Data Collection

Background data is available from many sources. These sources include information from literature, the internet, media, corporation or company factsheets and observations. In the context of this research most of this data will be classed as "secondary". Owing to the nature of this research, i.e. experimental, observational data will give the best real-time results and will be most important for experimental modifications and ultimate progression. Experimentation data from the test samples includes identifying the best methods for manufacturing both the lye and the soap. The best methods of strengthening, aerating and making the soap lightweight are also researched. Waterproofing and flammability testing of the soap casing are also explored (in case of future water degradation issues and excessive fire loading to a building when the insulation is fitted), whilst the thermal resistance and conductivity comparisons are acquired via the thermal testing laboratory.

1.8.6 Methods for Data Analysis

Data analysis is a series of actions to systematically apply statistical logical techniques for describing and evaluating data (Berthold & Hand, 2013). Analysing the data will be achieved through a combination of laboratory based testing (to determine measured heat transfer through the insulation to arrive at the R-value figure) and statistical (qualitative) analysis. Salford University Testing Laboratory has the thermal conductivity (hot-box) testing equipment to measure insulation samples of 300mm X 300mm surface area with the soap sample thickness ranging from 50mm – 150mm.

Important points must be recognised to provide accurate, valid and honest analysis. These points include determining the statistical significance from appropriate analysis, e.g. identifying which combination of ingredients will aerate successfully and will remain solid whilst keeping their "elastic" qualities and clearly defining the objectives and drawing unbiased inference from the data collected.

1.9 Scope and Limitation of the Research

There are limitations to this research. Different building types will experience different climatic conditions depending on where the building stands geographically (Watkins, 2011). Over a short time period, the insulation may or may not perform, and this may change over the long term.

It would be infeasible to try to manufacture test samples from every type of oil or fats. It would also be implausible to manufacture the test samples using all of the many variations of soap making that are used throughout the world. For this reason scientific assumptions based on collative evidence will be used, as opposed to the testing of every type of sample for every possible outcome. Each batch of lye may be slightly different to the next. There are many variables to consider in the production of lye. Variations (however miniscule) in the strength and quality will occur, depending on which type of wood is burnt, how long the ashes are soaked for and the quality of the wood, ash and water used (Stokes, 2013).

1.10 Time Programme

The manufacturing stages and the preliminary testing of the soap samples took place within the first year (2011). Variations in the insulation development started in the second year. The basic soap testing and then the laboratory testing took place in the third year. The writing-up process was on-going throughout all four years (see Fig.1.2 on the following page) and the thesis was completed at the end of year four.

Months

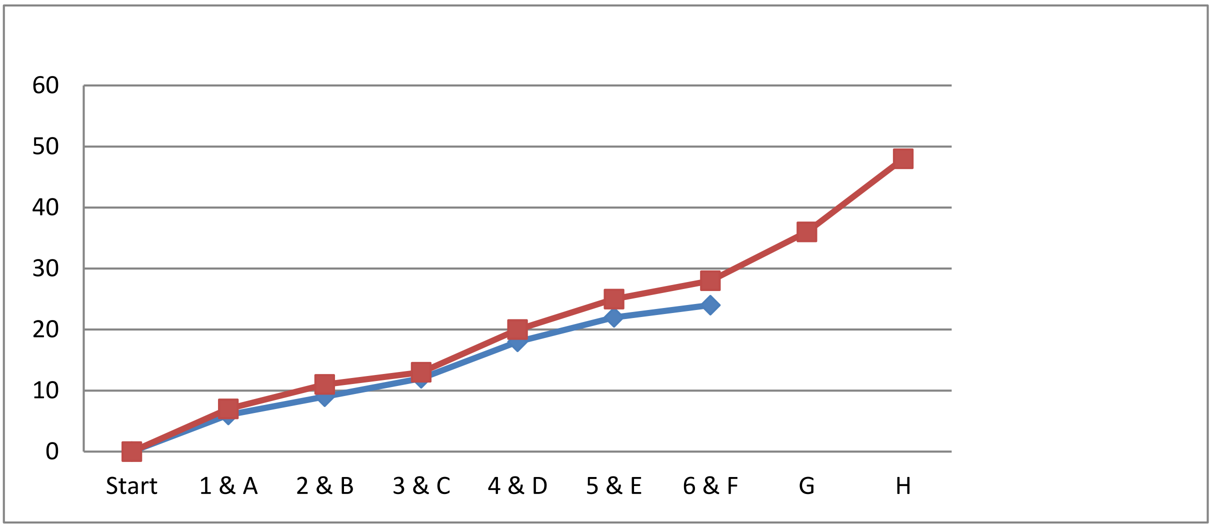


Figure 1.2: Key Milestones of Doctorate Research (Time in Months)

Key to Fig. 1.2

Thesis

Taught Module

1: Module 1 2: Module 2 3: Module 3 4: Module 4 5: Module 5 6: Interim Assessment

A: Research of Soap Manufacture and Thermal Insulations B: Manufacture & Preliminary Testing of Soap samples C: Aeration & Strengthening Techniques of Soap samples D: Variations to the Soap Creation Process and New Ingredients Introduction E: Production of Plastic Protective Casings for Soap Samples F: Laboratory and Real-time Testing of Finished Insulation Samples G: Finish the Sample Production and Writing up of Thesis H: Thesis Submission & Viva

1.11 Ethical Consideration

Generally, this research topic is not ethically sensitive. However, there may be ethical issues over the use of animal products. The data collected from third party sources such as surveys or used laboratory data will be destroyed by incineration or shredding once all of the usable information has been anonymised. A confidentially agreement was signed by all parties (including the testing laboratory staff) and this was adhered to, to maintain the privacy of all parties involved.

1.12 Guide to the Thesis

This thesis includes a number of chapters and these are described below.

Chapter 1 is an introductory chapter and gives information about the research background, rationale, research questions, aim and objectives and outline explanation of the research methodology. It also includes the scope of the research with the related limitations in research and ethical issues.

Chapter 2 critically explains the literature in relation to the thermal insulation in buildings in detail. It shows the broad spectrum of literature coverage in this domain and best practices around the world. It also reveals and explores the relationships between environmental plastics and petroleum based plastics within the built environment.

Chapter 3 gives a detailed description of the research methodology used for the research, which adopts a specific structure at the "heart" of this thesis. This methodology deals with the principles of procedure (data, evidence & information) as part of this research study. This chapter also reveals through manufacture and experimentation, the basic methods of manufacturing the soap, methods of aerating and making the soap lightweight, soap strengthening and methods of manufacturing the plastic case surround for protecting the soap body.

Chapter 4 reveals the further development of the soap insulation and highlights the improvements to the soap samples. Testing and comparisons are conducted with the plastic soap body protective casing and the results from three manufactured soap insulation samples are compared with both polystyrene and polyisocyanurate insulation samples.

Chapter 5 Identifies the final adjustments required to the soap casing and the testing plans that need to be put into place before laboratory testing. The results from the thermal testing laboratory and the comparisons between soap and polystyrene and polyisocyanurate insulations are also revealed.

Chapter 6 Introduces methods of waterproofing the soap insulation body, making the soap insulation vermin proof and making the soap casing fire retardant. In order to make the soap waterproof, three soap samples are blended with three types of waterproofing additives and tested for moisture absorption in timed comparison experiments (see Section 6.2 for experiment description and results). Additives are applied to the insulation casing to make the product vermin proof. Evidence from literature (Dougherty & Guilder, 2012) reveals how natural ingredients can be modified and applied to create an effective vermin repellant (see Section 6.4 for experiment description and results). With regards to making the soap insulation casing fire retardant, the casing is coated with a natural fire retardant product and tested for burning in an ignitability test cabinet (see Section 6.3 for experiment description and results).

Chapter 7 Identifies the contribution to knowledge that this research makes. It also reveals if the original objectives of this research were met. Possible future improvements to the soap are discussed as well as possible future applications that could be initiated. Possible degradation issues and the limits of this research are also recorded for reference.

Chapter 8 Is the conclusion chapter, bringing an end to the research process. Whilst Chapter 9 is the references list.

1.13 Key Stages of the Doctoral Research

A flow chart revealing the key stages of the doctoral research is shown on the following page (Fig. 1.3). The cylindrical shapes indicate the prominent milestones in the thesis and the square boxes indicate the key milestones of the doctoral journey.

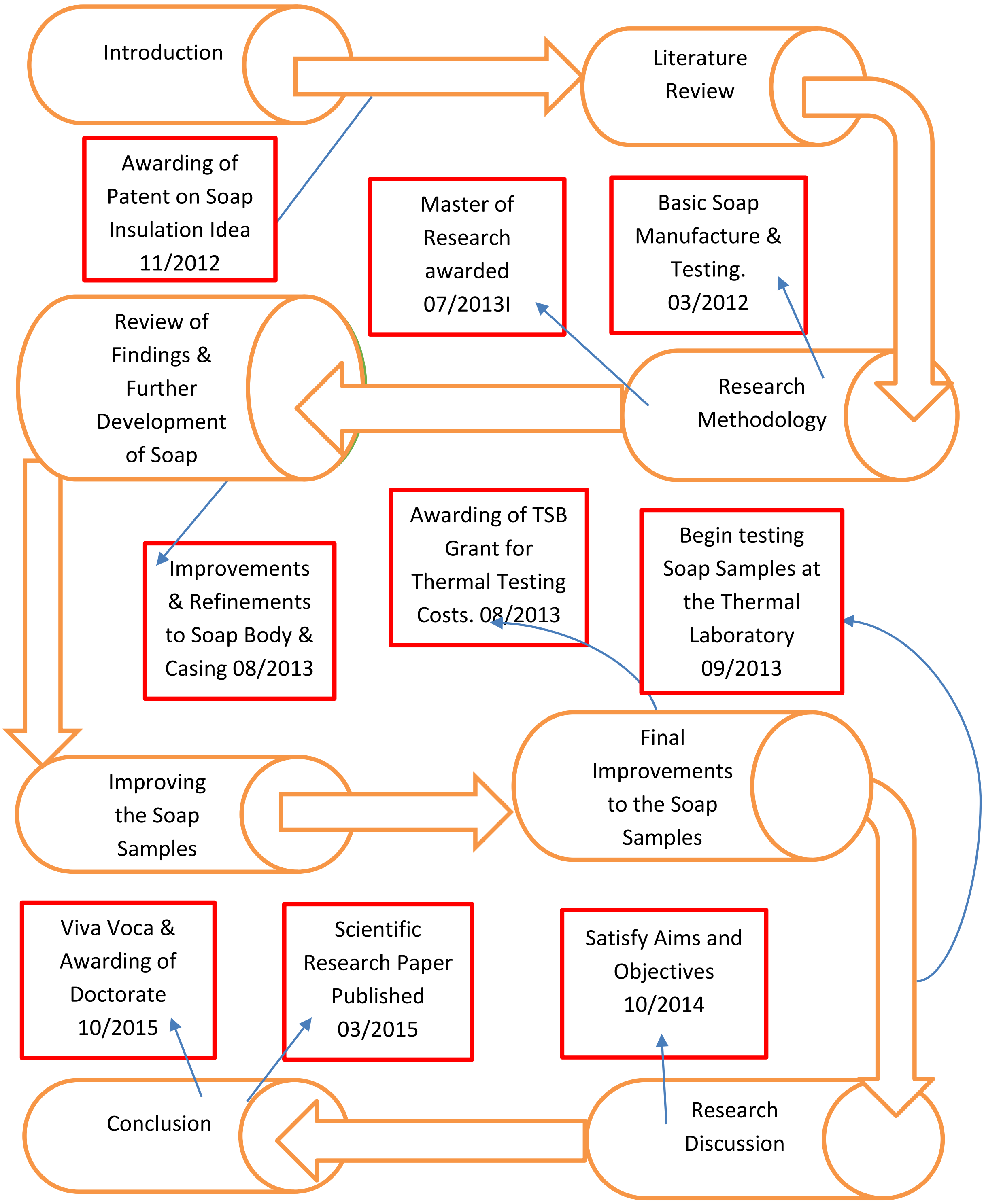


Figure 1.3: Key Stages of Doctoral Research

The scientific research paper titled “Can soap be a sustainable alternative to petroleum-based thermal insulation” (Read & Arayici, 2014) published in the peer reviewed “Structural Survey” journal contained extracts from the first four chapters of this thesis. In effect, it was a condensed version of the introduction, literature review, research methodology and a basic review of the scientific methods employed to manufacture a basic soap body and the methods employed to aerate and strengthen this body. The second research paper (Read & Arayici, 2015) currently under review with “Structural Survey” journal again, is a condensed version of the remaining chapters. These chapters highlight the improvements to the soap and soap casing and reveal the results of the laboratory testing for thermal conductivity and thermal resistance of the soap insulation samples. These peer reviewed articles link this thesis to the contribution of new knowledge by accepting that no other research into soap insulation has been published before.

The patent awarded by the Intellectual Property Office for the soap insulation (GB2486761) is entitled “Soap Based Thermal Insulation” and was awarded to the author of this doctorate on 14th November 2012 (see Appendix Two). The description of the patent was “A wall, floor and roof thermal insulation used within the built environment/ construction industry. The insulation is made from aerated crude soap. The soap is made from a mixture of animal fats and wood ash derived lye. The process undergoes a period of saponification and when dry is cut into large tablets of approx. 900mm X 450mm. The thickness ranges from 100mm, 125mm and 150mm. These tablets are fully enclosed in low grade plastic to protect them from contact damage and moisture ingress”. Once again, the awarding of a patent demonstrates a contribution to knowledge by accepting that this research and development is unique (for example not patented). According to Moir, (2013), “Judges in the UK appeals court have commented that identifying the new knowledge contributed should be an essential part of patent examination”.

Chapter 2 Literature Review - Oil Based Thermal Insulation and Future Challenges

2. 1 Introduction

It would seem that there are arguments both for and against sustainable and fossil materials and these shall be investigated further in this thesis. This literature review aims to create a balanced, unbiased appraisal of the pertinent literature regarding thermal insulations. Thermal insulation as a subject is of interest because of the variations in schools of thought and functional use; for example, to limit heat loss from a building's fabric – thermal insulation is required. Limiting heat loss means broadening natural resource retrieval and consequential wastage. Limiting heat loss can be seen by some as a sustainability "double edged sword." The manufacture of thermal insulations will necessitate the retrieval and burning of fossil products, and it is at this stage where environmental concerns are raised. Regarding toxicity, end of life disposal of the said products can create environmental problems. A lesser known fact perhaps, is that cavity wall insulation can also reduce the risk associated with condensation in a building (Brett, 2012).

The focus of the literature review investigates the pros and cons of various insulation types, the basic conditions or facts of being distinct and the conceptual ideas of the insulation's characteristics and particulars. Petroleum oil and its chemical derivatives feature prominently in this study. This is because petroleum plays a major part in both the composition of plastic insulation, the possible plastic casing surrounding the soap based insulation and as fuel for the insulation manufacture. It is also the main comparable to soap as defined in the research question.

2. 2 Established Insulations: Mainstream, Suitability & Best Practice

2.2.1 Fibreglass and Mineral Wool

Both of these insulations are common worldwide (Dhang, 2014). The manufacturing process is similar for both, except whereas fibreglass contains glass particles, mineral wool contains melted igneous rock and waste slag components (Norton, 2008). The combination of wool and glass and rock fibres make this insulation relatively cheap to manufacture and easy to install. Simply increasing the depth of the insulation increases the insulation performance, hence its worldwide popularity (Pilkington, 2008). However, thicknesses of over 300mm are rare. This is possibly because people adapt to the thermal conditions in which they become accustomed and extra insulation may make the inside living comfort unbearable (Yao, 2013).

Dry thermal insulations have lower thermal conductivity than moisture laden materials. This is especially so for fibreglass insulation. Just 2% added moisture content (by volume) will decrease its thermal conductivity by 100% (Pilkington, 2008). It has been observed that fibreglass cavity wall insulation that has been exposed to precipitation elements for prolonged periods whilst the building is under construction, can have a different R-value from a similar insulation built into a cavity throughout a dry period. This can be more pronounced if the insulation has never properly dried out. Mineral wool however, does have better moisture resisting capabilities and better fire resisting properties than fibreglass (Wilson & Piepkorn, 2013). According to Allinson (2007), damp, dirty or ill-fitting loft insulation of both types can create increased overall U-values up to 20% higher than originally stated.

2.2.2 Multifoil

Multifoil insulation is a relatively new concept, but is available worldwide. When installed it is water vapour resistant. According to “Actis” (2014), Tri-iso super 10 multifoil 35mm thick insulation performs to the same thermal standards as insulation up to five times thicker. The insulation counteracts all three modes of heat transfer: convection, conduction and radiation (Gwynne, 2013). However, this insulation, when used in a roof space, can have a detrimental effect on indoor television aerials due to its metallic foil covering. Also, there are currently no ISO or BS EN testing standards for this insulation (Actis, 2014).

There are some examples on the market of sustainable thermal insulation that seem to help solve the whole man-made/natural and or recycled problem. The “Thermofleece” factsheet, (2011), states that this product contains 85% British wool with a 15% polyester binder. Polyester can include natural chemicals such as cutin (Erdmann & Barciszewski, 2013) but most are a combination of petroleum and acid chloride (Erdmann & Barciszewski, 2013).

"Steico" offer thermal insulations derived from hemp. Hemp is non-hazardous and easily recycled. It grows quickly without the need for pesticides and is inexpensive and low maintenance (Jedlicka, 2009). It is recognized by the UK government as an ecologically friendly crop (Steico, 2011). Along the same lines, coconut and sugarcane fibres have also been tested and have proven to work as thermal insulation (Krishpersad et al, 2000). Corn cob particleboard is a new insulation that has arrived into the retail marketplace and according to Paivaa et al (2012), this also performs well.

"Edenbloc" offer a thermal insulation derived from waste wool fibres from the carpet industry. This insulation contains 60% recycled content mixed with protein based fibres (Edenbloc, 2011).

2.2.3 Expanded Polystyrene

This is an odourless lightweight insulation that is chemically stable and resistant to fungal attack (Gooch, 2010). This insulation is best used in applications protected from birds, as birds have been known to peck at the insulation and or use the styrene beads to line their nests (Wayland & Gooders, 2009). There are case reports, albeit limited, of polystyrene insulation being attacked by termites. This means that the insulation needs to be protected from insects in its finished application (Sykes & Skinner, 2013). However, there are two schools of thought regarding this. Hordeski, (2004) opines that the addition of boric acid (sulphuric acid [H_2SO_4] and sodium borate ($Na_2B_4O_7$) mixture) in some polystyrene brands acts as an effective insect repellent.

Although polystyrene has low water permeability, a vapour barrier must be installed in areas of high humidity (Jackson & Day, 2009). The maximum working temperature is 80^0C which tends to be too low for some applications worldwide. Most organic solvents will attack polystyrene and if polystyrene and PVC come into contact, the polystyrene may partially dissolve and the PVC may become brittle (Joshi, 2008). This can cause problems if contact is initiated between the polystyrene roof insulation and the electrical wiring cables running through a loft space. Polystyrene also has a poor resistance to a naked flame (Buxton, 2015).

2.2.4 Foamed Polyisocyanurate (PIR) and Polyurethane (PUR)

These plastic insulations also act as sound insulation to a certain extent (Gwynne, 2013). The foil backing also goes some way to acting as a vapour barrier (Celotex, 2011). These insulations are popular worldwide because of their excellent low thermal conductivity properties at low temperatures (Gwynne, 2013). These insulations have a better spread of flame characteristics than polystyrene. PIR type insulations are particularly effective at stopping heat entering the building during the day, and limiting the heat loss through the building fabric at night (Brett, 2012). From a human comfort standpoint, this makes the insulation ideally suited to temperate geographical zones rather than tropical type ones in which the temperature might remain constantly hot during the day and night.

2.2.5 Extruded polythene (XPS)

These foam insulations are used on an ever decreasing scale within the UK (Dyplast, 2010). However, this insulation remains popular as an acoustic insulation (Gwynne, 2013). The closed cell structure (sealed pockets of air or gas) is approximately 25% more thermally efficient than its open cell counterpart (Knauf, 2010). This insulation offers reasonably good fire resistance, generating little smoke and toxic gasses when direct flame is applied (Knauf, 2010), perhaps somewhat unusual for plastic.

2.3 Crude Oil: The Dominant Component in Petroleum Based Insulations

Component Description

“Oil refineries are among the top contributors of greenhouse gasses” (Elsbach, 2014). Carbon dioxide accounts for 98% of an oil refinery’s greenhouse gas emissions. (Shine, 2010). Crude oils are the starting point for many different substances, simply because they contain hydrocarbon (molecules of carbon and hydrogen) compounds. 84% of crude oil is made from carbon, whilst 14% is made from hydrogen. The remaining 2% contains sulphur, nitrogen, oxygen and trace amounts of base metals and salts (Smith, 2009).

The hydrocarbons in crude oil need separating in order to create different products. This separation is part of the oil refining process. The hydrocarbons are separated by a method of distillation. In brief, the oil is heated and the different molecular chains are removed by their vaporisation temperatures. Each different molecule chain length has different properties that are used to create different products (Speight, 2011). Petroleum gas, typically methane (CH_4), ethane (C_2H_6), propane (C_3H_8) and butane (C_4H_{10}) are commonly used for plastic manufacture and are present in many rigid board insulations (Spooner, 2012). The oil processing method is numbered below (Speight, 2011). It should be noted that although the plastic manufacturing process remains basically the same, different variations from company to company and country to country do occur.

1. Crude oil is extracted and sent to the oil refinery.

2. Both natural gas and crude oil are distilled (fractioned) into separate hydrocarbon groups.

3. The process of “cracking” and reforming changes the oil at a molecular level to create a more usable product. For example, propane and ethane are transformed into basic propylene ($C_3H_8O_2$) and ethylene (C_2H_4), by subjecting them to high-temperatures.

4. At the next stage, the product is combined with a catalyst, resulting in "fluff," a powdered polymer material.

5. Fluff is blended with additives and then subjected to extraction, hydro-treating and sweetening. The resulting polymer is then fed into an extruder to be melted. When cooled, the plastic is cut into small pellets.

6. The resulting polyurethane ($C_{25}H_{42}N_2O_8$) (or similar) plastic products are manufactured using processes involving extrusion, injection moulding and blow moulding (Speight, 2011; Campo, 2007). A simplified flow diagram (Fig.2.1) showing this process is shown on the following page.

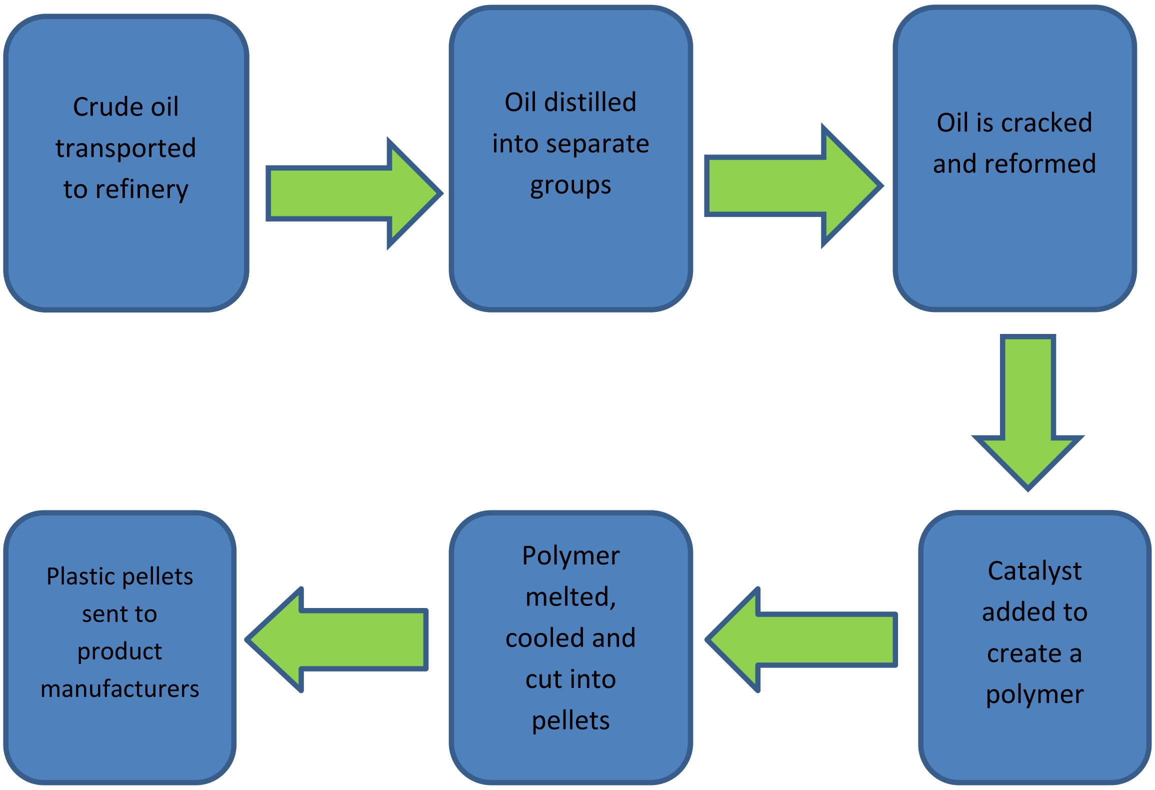


Figure 2.1: Flow Diagram Showing the Oil Refining Process

Polyurethane

Polyurethane ($C_{25}H_{42}N_2O_6$) is the major petroleum ingredient used in polycarbamate thermal insulation. Polyurethanes are synthetic linear polymers (macromolecules that are formed of monomers) that have a molecular backbone containing carbamate groups such as urea, esters, ethers or amide (Speight, 2011). A variety of raw materials are blended with the polymers in polyurethane production. These ingredients include prepolymers, monomers, stabilisers and colorants. Compounds of multiple alcohol groups, usually polyols, are added for the polyurethane fabrication (Speight, 2011). The two most common include PMDI (polymeric isocyanate) and TDI (toluene diisocyanate); which one is used depends on whether foam or thermoplastic is required (Sonnenschein, 2014; McKeen, 2012).

2.4 Environmental Impact of Petrochemical Plastics

To reinforce the academic rigour of the research (by grounding it in an established method of analysis), a life-cycle assessment (analysis) can be used as a tool in the research to reveal the environmental differences between petrochemical based and natural insulations. Assessment of the life-cycle is the ability to assess the impact on the environment of a product's lifecycle (Curran, 2012). The lifecycle steps would usually start from the basic material extraction, to the material's manufacture, then through to the material's eventual disposal. When the greatest environmentally damaging of these three stages has been identified, then the environmental impact can be diminished by making changes to the points recognised. In effect, life-cycle assessment works by gathering data then compiling an itemized record of all relevant energy, material, and environment releases (Curran, 2012). The input and output impacts are evaluated before informed decisions are made by interpreting the results.

2.5: Domain knowledge

In relation to what has been discovered or learned by the systematic study of soap based thermal insulation, each knowledge domain consists of associated key mile-stone associated characteristics within scientific disciplines. These scientific disciplines are commonly divided into four major groups. Natural science, which is the study of natural phenomena and the effects on biological life (Krohn et al, 2012). This is used throughout this thesis to identify and examine the cause and effects of soap based thermal insulation on the natural environment and living planet ecosystem. Research has confirmed that the finalised soap product is environmentally friendly. Formal science is used to establish *reasoning* (Krohn et al, 2012). Used within the context of this thesis, reasoning is used to determine the *direction* the experiments will take based on scientific assumptions in conjunction with the progress from the experimental results. Social science studies human behaviour and applied sciences (Bastow et al, 2014). In this thesis, social sciences are applied to existing scientific knowledge in order to develop improved practical applications (sustainable thermal insulation) and determine if the idea is marketable. Natural science is empirical science (Bastow et al, 2014). This means that the knowledge must be based on observable phenomena and must be capable of being copied or verified by other researchers working with identical ingredients, under the same conditions. The actions contained within this research are clearly identifiable, measured and recorded so that further research can follow on from it.

2.6 End of Life Disposal of Thermal Insulations

End of life scenarios are usually based on a 60 year lifecycle (NNFCC, 2008). Both natural and man-made fibre insulation may have accrued water sorption over this lifespan whilst petroleum based rigid board insulations may have degraded so as to not perform properly (Norton, 2008). It is upon reaching this stage that many insulations are rejected and replaced.

2.6.1 Fibreglass and Mineral Wool

The glass particles and particulates within fibreglass actually originate from recycled sources. The glass originates from recycled glass bottles. The wool used in the insulation is derived from molten raw materials centrifuged into the desired fibrous form (Letcher & Vallero, 2011). These insulations are difficult to recycle, or to salvage any usable components from them, and so they usually find their way to landfill sites (Raviv & Lieth, 2007). However a small percentage of wool waste is used as landfill cover and sometimes mixed with poor clay soils to improve the soil's physical properties (Raviv & Lieth, 2007).

2.6.2 Multifoil Insulation

Although multifoil insulation has been used in France since the 1990's, this is not long enough to generate enough waste from demolition or refurbishment projects to gather reliable data on the product's end of life capabilities. In the future when it does get discarded and replaced, there could be a recycling market for both the metal foils and the felt inner. However, Briggs & Leyworth (2009) opine that the retrieval of foils would not be cost effective when comparing the weight ratios to the collection and sorting costs.

2.6.3 Petroleum Based Insulation

If and when crude oil extraction slows down from current levels, some may see this as a relief from the poisons created from oil based product manufacture to slow down also and as a catalyst for the environmental recovery to speed up (Haigh & West, 2009). However, regarding the end of life disposal of synthetic insulations, an important question would remain. Would the ecosystem suffer as a result of the product being buried in landfill or incinerated, giving off potentially toxic pollutants over time? Typically these pollutants could include petroleum hydrocarbons, heavy metals and solvents. Some of these pollutants have been linked to chronic health conditions (Wilhelm & Bloom, 2012). A summary of the various insulations and their end of life disposal is shown in Table 1 below.

Insulation Type	Reused/Recycled or Landfill
Fibreglass	Landfill
Mineral Wool	Reused/Recycled
Multifoil	Landfill
Polystyrene	Landfill
Polyurethane	Landfill
Soap	Reused/Recycled

Table 1: End of Life Disposal for the Various Insulation Types

It would appear that the shorter the time required for composition, the shorter the time for pollutants to affect the ecosystem. As an example, a plastic bottle can take 100 – 1000 years to decompose in landfill (Jones & Jones, 2013). This figure can be brought down to three months if the bottle is heated to 60^{o}C and introduced to air and digestive microbes (West, 2010). Rae (2009) partially agrees, challenging the idea that plastics will degrade in a thousand years or less, and in fact opines it takes at least double this time frame for petroleum based plastics to biodegrade. According to Fornasieror & Graziani (2006) petroleum plastics have been designed to resist degradation. However, it could be argued that the limited research into plastic degradation means limited damage to the plastic manufacturing industry per se. As previously mentioned, plastic degradation at landfill should be taken into consideration. Also, degraded (waste) oil, the key ingredient of plastic, must also be disposed of when it comes to the end of its useful life. According to the Environment Agency (2012), there are approximately 3000 pollution incidents involving oil and fuels within the UK annually. Waste oils also have to be disposed of according to the controlled waste regulations. In the UK, 16% of all pollution incidents annually involve waste oil (Environment Agency, 2012).

Europe-wide, approximately 67 million tons of plastic waste is dumped in landfill sites annually (Palm et al, 2015). This includes waste plastic thermal insulation. To combat the longevity of landfill plastic waste, additives can be added to the plastic at the manufacturing stage which will degrade the plastic to nothing in a matter of months. (Gho, 2012). Also, according to "Earthtalk" (2012), oil and petroleum-based plastic will rapidly degrade with exposure to water, oxygen or sunlight. However, opinion is divided. According to Massey (2007), neoprene rubber or foam type plastics will resist all three. Because plastic waste is relatively lightweight and landfill reduction targets operate on a weight based tipping system, this can discourage some local authorities from recycling their plastic waste (Davies, 2006). The environmental impact of crude oil retrieval, plastic manufacture and disposal of waste petroleum based insulation could justify the need for environmentally friendly alternatives, using environmentally friendly plastic components as part of the insulation body.

2.6.4 Recycling the Plastic Insulation

Manufacturing from natural and recycled materials helps to preserve natural resources (Palm et al, 2015). After all, the energy needed to produce 1kg of plastic could illuminate a 100-watt lightbulb for 56 hours (Jones & Jones, 2013). In addition, the cost of manufacturing a plastic product from recycled plastic content is four to eight times cheaper than starting from fresh (Jones & Jones, 2013). Recycling also helps to keep the end of life products out of landfill sites, saving money on transportation, tipping and burying costs. It will also reduce the amount of methane given off by the landfill sites as the products rot down. If the product naturally biodegrades, it could also help with the aesthetic appearance of the environment. After all, "the middle of the Pacific Ocean is six times more abundant with plastic waste than zooplankton" (Coburn, 2013).

If the plastic products can be recycled at their end of life for use into an alternative product, a reduction in energy spent and materials sourced mean financial, labour and environmental savings. It could be debated that landfill sites can be used as methane traps to capture the gas to use for energy. Also at the site's end of use the area can be capped and used as parkland, woodland, nature reserves or areas designated for non-food production (bio-oils). From a financial perspective, probably most important for the waste industry, it is ten times more expensive to recycle than to tip at landfill (Coburn, 2013). Recycling waste is just one area of sustainability. There are other alternatives, such as the new build and refurbishment of properties using ecologically friendly methods of construction, adhering to sustainable guidance and legislation.

2.7 Sustainable Plastics

Petroleum based plastics (bio-polymers) are established commodities throughout the world. Recycling waste plastics is already happening (Christensen, 2011), but to actually replace the concept of petroleum plastics will be a difficult process (Graedel & Howard-Grenville, 2010). The concept of "green chemistry" is to manufacture products that are harmless and benign. The green chemistry rationale fuses renewable and fossil raw materials (Hofer & Selig, 2012). The thought process behind green chemistry led directly to vegetable oil derived plastics being introduced into the marketplace and research into plastic manufacture from feather or wool derived keratin, which is happening globally (Defosse, 2010). In theory, these bio-plastics could be developed and adapted to reduce or replace the petroleum element used within thermal insulations. Bio-polymers can be cheaper to manufacture than petroleum plastics and they meet or exceed most petroleum based properties, except for longevity (Goodship, 2007). However, Davies (2006) and Conrad (2013) disagree with this, stating that on a "like for like" basis, green plastics are more expensive than their petroleum counterparts.

2.7.1 Bio-Plastic Lifecycle

A bio-polymer incorporates the composition, structure, bio-compatibility and bio-degradability of the plastic (McGrath & Hickner, 2012). Up to 40% bio-plastic can be added to PEHD (polythene) – reducing the amount of petroleum within the product, whilst not impacting on the material's performance (Royte, 2006). Davies (2006) states that good mechanical properties can be obtained from starch plastics with a 40-60% starch content. However, this mixed product may be difficult to biodegrade (Niaounakis, 2015). West (2010) opines that bio-plastics can bring their own problems. West states that bio-plastics cannot be mixed with petroleum based plastics to be recycled. At their end of life, bio-plastics should go to a composting facility as opposed to a recycling facility.

Literature has been published centered around natural bio-oils, petroleum oils and their subsequent successors (plastics). Interesting theories and widely held beliefs could be construed as established *facts*. Researching sustainability in the printed format is one example highlighting the conflicts of emotions, interpretations, agendas and differing points of view from authors and scientists who share their own opinions and often instill their own emotions onto the subject. The subject data is also open to manipulation (Amstutz, 2013).

Shown below is an example of this conflict. Majer et al (2009) opine that the large areas of deforestation for use by the bio-oil agricultural industry contribute to the global increase of greenhouse gas emissions, thus exasperating climate change. Wool and Sun (2005) state that by switching from petroleum oil to bio-oil cuts down on greenhouse gas emissions and actually slows down the onset of climate change. These two statements highlight one scenario, creating two differing opinions. Whichever statement is factually correct shows that the biofuel industry per se is making a global impact. Because of the ongoing advances in bio-fuel research, it would appear that biofuels are here for the forseeable future (Bullis, 2011). However, their manufacture and end of life scenarios must be environmentally friendly and the true cost of their environmental impact must be considered before these oil products can be truly labeled as sustainable (Bullis, 2011).

From an end of life degradation point of view, because of the contained oxygen content, biofuels degrade four times faster than petroleum fuels (Hamid, 2011). However, this can also create problems. Because of the high oxygen content, biofuels will oxidise at room temperature (Hamed, 2011). This can make them unusable.

2.8 Keratin Plastic as a Component of Thermal Insulation

Plastic derived from keratin is one possible alternative to petroleum based plastic, whilst the vegetable oils and animal fats derived from poultry can also be used in the manufacture of soap (Capua & Alexander, 2009). According to “The Tracing Paper” (2011), there are 88 active poultry abattoirs within the UK alone. Keratin derived from poultry feathers is also being investigated for its uses. Tosik and Wrzesniewska-Adamiec (2007), acknowledged the use of keratin within the cosmetics industry and the possible use of keratin fibres within textile products for use within the sanitary and medical application industry. Plastics derived from feathers should also give poultry producers an income gained from poultry waste, especially as there are over four million tons of waste generated by the poultry industry worldwide each year (Zini & Scandola, 2011).

Keratin is a polymer of strong protein components found in skin, hair, horns, nails, hooves and feathers, in both humans and animals (Urich, 2013). Keratin is the component responsible for making skin waterproof and it also acts as a barrier to prevent bacteria from entering the body through contact. Keratin is insoluble in water and weak acids, making it difficult to dissolve. It is very reactive and as such can be hydrolysed and oxidised (Urich, 2013). Keratin is formed by a process called “keratinocytes”. This is where the body’s living cells push their way outward through the body parts and die, forming a protective layer of dead cells (Lewis & Rippon, 2013). This protective layer acts as an insulation to protect the new keratin cells beneath (Lewis and Rippon, 2013). Every molecule of keratin consists of amino acids, creating, on a molecular level, a collection of fibrous structural proteins (Urich, 2013).

2.8.1 Keratin Derived from Chicken Feathers

Chicken feathers are a good source of keratin, with the composition of feathers being almost entirely constructed from this protein (Fan, 2011). For birds, these feathers are used as an insulant to trap warm air in close proximity to the bird’s skin (Fan, 2011). Due to the increasing amount of worldwide fowl meat production, feathers are available in large quantities (Fan, 2011). The USA produces 1.4 billion kg of chicken feathers annually (Yang, 2011), but only a very small percentage are actually used in manufacturing (Yang, 2011). Most feathers are shipped to landfill.

Because of feathers’ enhanced hydroscopic properties they are being investigated for their use in applications where good sorption rates are required. Norton (2008), in his PhD submission, investigated sorption rates of natural vegetable fibres contained within thermal insulations. Keratin can also be spun into fibres (Fan, 2008) and as such keratin fibre insulation could be investigated as a possible thermal insulation. Keratin is also the major component in animal glue. This glue is explored further, later in this thesis. Keratin resin plastics *are* being produced commercially. Products have been developed with good water resistance (with the addition of methyl acrylate) as well as increased resistance to mechanical and thermal stress. The addition of “hartshorn” has been used as a plastic ingredient (Goldade et al, 2010), and this component could be investigated in the future, for present day use.

Hartshorn is a cooking additive derived from shredded animal horns, hooves or deer antlers. Historically these products were manufactured from the burning or distilling of these waste animal products (Stratford & Kupperman, 2011). Ammonium carbonate $(NH_4)(_2CO_3)$, to give the hartshorn its technical name, is a salt and on a molecular level it is a mixture of three molecules:

1. Ammonium carbonate $(NH_4)_2CO_3$
2. Ammonium bicarbonate $(NH_4)HCO_3$
3. A slightly different second form of ammonium carbonate.

Historically, hartsorn was added to the mixture of pre-1960’s plastics to help achieve a lightweight structure (Goldade et al, 2010) and in theory could be used again for the same purpose. Commercially, man-made ammonium carbonate is still widely used in plastic manufacture, but this is derived from a combination of chemical processes (Goldade et al, 2010). Other component ingredients derived from soil agriculture and from land animals are being investigated for their uses. Oils derived in harmony with the natural environment should be explored and specifically research into organisms within the aquatic environment, may provide many answers.

2.9 Alternative Sustainable Plastic Research

Kim & Netravali (2009) stated that the alternative addition of red algae called “agar” into a soybean plastic mixture would create the same results as the addition of stearic acid. Kim and Netravali stated that this addition “significantly improved” the plastic’s performance at its shape moulding stage. Algae oil as a base for the actual plastic has also been researched and has been proven to perform as a biopolymer plastic (Oilgae, 2012). This plastic will perform better if used as a partial substitute for petroleum based plastic (creating a hybrid plastic). Various plastic types can be manufactured from algae. These include the hybrid plastic mentioned, cellulose based, poly-lactic acid based and polyethylene (Biotech, 2011). There are, however, strengths and weaknesses with using algae based plastics. In the main, algae are a cheap source of raw material. It will grow in virtually any still water, under most conditions and is “around” in abundance (Borrowitzka & Moheimani, 2012). On the negative side it is many more times expensive to create plastic out of algae than from petroleum oil (Biotech, 2011). This is partially due to the fact that this research methodology is still in its infancy and because of continuing problems with filtration clogging and the labour spent cleaning the filters (Borrowitzka & Moheimani, 2012).

2.9.1 Plastics from Agriculture

A plastic has been manufactured that is derived almost entirely from agricultural components. This plastic is known as "agricultural green plastic". The oil is derived from rapeseed (canola), corn starch, soy starch or pea starch (Zini & Scandola, 2011). The designers describe the manufacturing process as low-cost without the need for complicated technology. They also confirmed that canola plastic produces polyurethane sheets with "excellent" mechanical and strength properties (Zini & Scandola, 2011). Biofuel for use in the manufacture of plastic is obtained from vegetable oils via a process of transesterification reaction. This is the process whereby the triglycerides within the oil react with the short chain alcohol molecules in the presence of a catalyst (Hamid, 2011).

However, Lohda and Netravali (2005) state that soybean oil based plastics have low strength and high moisture sensitivity properties and that these plastics can be difficult to process without the addition of glycerol plasticisers. Lohda and Netravali do further state though that by adding stearic acid, these problems can be overcome. Stearic acid is a major ingredient of animal fat (30%) (Wiseman, 2013), and as such is a major ingredient in soap. Waste fibres from sunflower stems, straw and rice husks are being investigated as plastic reinforcing (Majer et al, 2009). Vegetable fibres have similar mechanical properties to glass fibres but they use only one tenth of the required energy production of glass fibres in their manufacture, in addition to having favourable environmental benefits (Van Dam, 2010). Vegetable fibres tend to absorb moisture though (Zini & Scandola, 2011). Also, natural fibres tend to bulk rather than disperse during plastic processing (Zini & Scandola, 2011).This can create problems at the plastic manufacturing stage. However, waste vegetable fibres will easily biodegrade, as opposed to glass and mineral wool fibres.

Fibreglass, when burnt, leaves a 50% un-burnt residue (Corbett & Brannigan, 2013). Fibreglass and mineral wool insulations are both difficult to burn and in fact mineral wool is classed as fire retardant under DIN EN.13501-1 (Pilato, 2010). In addition to their combustible properties, pre-treating vegetable fibres with an alkaline solution will give the fibres high impact, tensile and flexural properties (Zini & Scandola, 2011). However, according to Witten (2010), vegetable fibre reinforced plastic should only be used for non-structural applications (thermal insulation is non-structural). This is because the maximum amount of fibres per product should not exceed 50%, as opposed to glass or petroleum plastic fibres that can be used at up to 95% (Zini & Scandola, 2011). Vegetable fibre production also has a major drawback in that it “steals” resources from food production and requires increased water dispersion and large areas of land for growing (Witten, 2010).

2.9.2 Modification of Sustainable plastics

Nanda et al (2007) stated that soybean plastics could be further modified by the addition of Thiosemicarbazide (TSC). This is a derivative of animal urine and the addition of this will create a plastic on par with petroleum based plastic in its performance. Charlton and Foster (2009) opined that this plastic will also degrade “significantly faster” than petroleum based plastic if buried at landfill. According to Bullis (2011), natural sugarcane additives can be introduced into the plastic at the manufacturing stage to enhance the plastic characteristics through its lifecycle whilst also contributing to its degradation at the plastics end of life.

Bio-based polymers and composites can be used in both rigid and flexible plastics (Wool & Sun, 2011) “It is reasonable to believe that the vegetable-based PUR could be a potential candidate to replace or practically replace petroleum-based PUR, in sensitive and high end applications such as in the biomedical area,” (Lockland, 2007). Biofuels have also been successfully manufactured from crops. Bio diesel and ethanol have been successfully manufactured from corn starch (Wool & Sun, 2011), and both can play their part in the sustainable energy process for plastic manufacturing. Starch is the most favoured option for biofuel production because of its low manufacturing costs and biodegradability (Davies, 2006). Potatoes are the favoured source to obtain starch. Approximately eight tons of potatoes will produce one ton of starch. In the UK, potato crop wastage is equivalent to 1.2 million tons per annum (Davies, 2006). The three major plant based polymers are oil, protein and carbohydrates. Utilising the amount grown globally, there is the potential to produce 400 – 800 million tons of biomass annually (Wool & Sun, 2011). At the plastics end of life, if it does find its way to the incinerator, it does not give off toxic fumes. In landfill it doesn't give off methane, a recognised greenhouse gas (Majer et al, 2009). Wool & Sun also state that crop based oils give off 20-75% less greenhouse gas emissions in their manufacture than their petroleum based equivalents. Davies (2006) confirms that biodegradable plastics are an improvement over the current oil-based plastics. The question is whether their *sustainability* can be sustained.

2.9.3 The Effects of Rising Global Temperatures

According to Dinar and Mendlesohn, (2011), the onset of climate change will have an adverse effect on future agricultural productivity. Changing rainfall patterns and rising temperatures may affect the locations in which crops can be grown. However, other regions may be able to grow crops where once they couldn't. Higher levels of CO_2 actually increase the efficiency of photosynthesis and this accelerates the rate in which plants grow (McDonnell & Pickett, 2012). Arup (2008), states that the growing season for plants in central England has lengthened by 30 days over the last 100 years. Longer growing seasons nationally and globally may also become the norm, meaning that farmers may have to adjust their harvesting times. However, a rise in global temperature may not be harmful everywhere. Within the UK, there can be an average temperature difference of 15^{o}C between Scotland and Southern England (Flood, 2009), yet mankind has successfully adapted to these temperature differences. Humans have been on this planet for 3 million years; this is because of the ability to adapt to changing circumstances.

On the contrary, Sengar & Sengar (2014) disagree, stating that corn production is already down due to higher global temperatures. Sengar & Sengar state that a temperature increase of 1% can result in a 5% drop in the production of corn. A 2% rise in temperature means that crops would require double the amount of water needed to grow the crop. However, Rasul et al (2009) state in their paper, that there has been a 5-7% increase in global temperature in the years from 1914 to 2009, with nothing like the crop problems that should be associated with this increase in temperature. As an alternative or as a partner to vegetable oil based plastics, other sustainable products are under investigation, one of these being soap based insulation, which is biodegradable.

2.10 The Sustainability and Thermal Insulation Link

The UK building regulations have become geared towards promoting sustainability. The recent changes to the Approved Documents Part L1 and L2 (2013) reflect this by promoting air tightness in buildings, the increased use of improved thermal insulations to lower the U-values in heat loss calculations, as well as promoting energy use in more efficient ways (Approved Document L1A, 2013).

Sustainable buildings are low energy buildings created through efficient monitoring of carbon, energy, water and waste performance (Fang, 2010). Fang went on to say that the Brundtland Commission summed up sustainable building when they opined that a building "that meets the needs of the present without compromising the ability of future generations to meet their own needs" is a building that meets people's needs in ways that enhance its positive impacts, whilst minimizing the negative ones. All thermal insulations should contribute to achieving zero carbon homes. The term zero carbon can be defined as a house that creates either zero or possibly negative CO_2 emissions by maximizing the use of renewable energy and energy efficiency (Williams, 2013).

Henson (2007) stated that "the most obvious way to take individual action on climate change is to reduce the size of carbon footprint". Sibley (2011) holds the view that humans can never be truly carbon neutral. "When we breathe we produce carbon, so it's just a nice thing to say". However, the application of thermal insulation to walls, floors and roofs does go a long way to achieving carbon neutrality. It is not the intention for this thesis to explore the arguments for and against climate change and whether man is contributing to that change, but rather to acknowledge the theory behind global warming that states that the atmosphere traps infrared radiation (heat) and holds it. This increases the surface temperature of the earth and the air in the lower atmosphere (Farrar & Mastrandrea, 2007). It is a widely held belief that current greenhouse gas concentrations make up less than 1% of the atmosphere. However, sustainability, in the built environment context, is often mentioned alongside global warming but for the purpose of this thesis, the two are mutually exclusive.

2.10.1 Sustainability Skepticism

Regarding sustainability, every person could help to achieve a difference by buying environmentally friendly products. However, an increasing number of companies are promoting their products as green, when this might not necessarily be the case. “Shoppers are being misled into buying eco-friendly household products, when many of their environmental claims are exaggerated” (Which Magazine, 2010). Thermal insulations are no exception.

According to the Celotex website (2010), Celotex have made an “eco breakthrough” insulation that has received an A+ from the Building Research Establishment Environmental Assessment Method (BREEAM) and the code for sustainable homes. However, when checking the criteria for this award, it soon becomes apparent that the methodology used allows someone to compare the performances of comparable insulations, within a group of the highest performing insulations inside a given category. The highest scoring insulations are denoted as A+. In other words, it has a lower (however slight) environmental impact than the other few PIR insulations within the group. This does not give the insulation sustainable credentials in the true sense, even if that is what is implied in the advertising.

There does seem to be some evidence of “green fatigue” and cynicism. The worldwide recession has been partly blamed because of the trend to market sustainable products at a higher price (Information Resources Management Association, 2014). The trend for “greenwashing” seems to be losing its appeal to the public. In Canada in 2008, 46% of the population had concerns regarding the environment. In 2011 this figure had dropped to 32% (Face the Facts, 2011). Also, “whilst most people are willing to make bold statements about their love of the environment, few are willing to make the major lifestyle changes that are required to make a real difference” (Daley, 2008).

2.11 Considering Soap as an Alternative Insulation

Soap can be used as an environmentally friendly insulation largely due to its inexpensive method of manufacture and the abundance of raw materials to work with (Watson, 2015). Soap does not need heating to high temperatures as part of the manufacturing process and cools at room temperature (Watson, 2015) saving time and energy over its petroleum based counterparts The finished product can be handled safely without the need for economical time limits on the human contact/ maximum exposure time (Watson, 2015).

2.11.1 Assessment of Sustainable Thermal Insulations

Soap insulation is an unknown entity when it comes to placement longevity, but it comes under the same ecological umbrella as other environmental insulations. These environmental insulations can be manufactured from materials such as compressed peat boards, reed and straw boards, hemp, sheep's wool, linen and cellulose fibre board. There has been no associated health risks with organic insulations (Pacheco et al, 2014) and these insulations are suitable for recycling or biodegradation at landfill. When comparing hemp (the soap insulation surround) to petroleum based insulations, three points become apparent. Hemp insulation performs as well as mineral wool insulation (2013, Ashton), the results of a lifecycle assessment analysis reveal that hemp is better than expanded polystyrene, PIR, PUR and mineral wool in terms of respiratory and carcinogenic damage to human health (Pacheco et al, 2014) and although PUR gives the lowest possible thickness of insulation it comes with the highest ecological costs. Polyurethane has the highest negative impacts on the environment, twice as much as mineral wool (2013, Ashton).

Soap based insulation is sustainable, in the sense that sustainability can be likened to a path to improving the ecological footprint, by working with nature as opposed to against it. To be sustainable, products should conform to a number of criteria. Are the components of the product natural or recycled? At the products end of life, can the materials used be broken down and recycled or shipped to landfill to naturally biodegrade harmlessly into the environment? Does the manufacture of the products involve "reasonable" amounts of expended energy usage as opposed to "excessive" amounts? This sustainability definition is open to interpretation. For the purpose of this doctorate sustainability can be defined as recognising the interdependent nature of all things living and the human interaction with these things to ensure that life, as well as the natural environments that sustain life, survives into the long term future. This means that the Earth's finite resources are not depleted. Sustainability can be expressed in three ways. Environmental sustainability (Hill & Gale, 2012), whereby decisions are taken to deliver more benefit than cost over a proposition's complete lifecycle. If the overall environmental costs are deemed greater than the benefits, then the project would be classed as unsustainable. Soap based thermal insulation achieves environmental sustainability by providing a product that does not excessively impinge on the Earth's resources. The manufacture and end of life disposal are nature friendly as they inflict little harm onto the eco-system or the natural environment. Economic sustainability seeks to maintain the environment by utilising strategies for employing existing resources, objectively and quantitatively, so that a responsible environmental balance can be achieved over the long term (Wu & Low, 2013). Soap insulation uses hemp and waste animal fats as its main ingredients. Soap insulation has had its environmental credentials fully researched. It has been tested and compared against petroleum insulation with favourable results. Social sustainability entails living within environmental limits whilst limiting the environmental harm created by this living (Haas & Olsson, 2014). The use of soap insulation as part of a building's thermal envelope will not create environmental problems throughout its lifecycle.

There is an international company called "Bioregional" that advocate's sustainable development globally. In part it does this through its "One Planet Living" framework. This concept utilizes ten guiding principles of sustainability as its core structure. One Planet Living uses ecological footprinting (the impact of human activity, measured in terms of the area of productive land and water, required for the manufacture and application of goods throughout their complete lifecycle) and carbon footprinting (generally defined as the amount of greenhouse gases produced to support human activity) as its headline indicators. OPL subscribes to the notion that to achieve sustainability, it must be made attractive and affordable for people to create an ecological balance as part of their lifestyles.

When comparing soap insulation research with the "one planet living" concepts (Bioregional, 2014), it is clear that soap insulation creates a partial path to sustainable development. Soap insulation is a sustainable and healthy product. It has low embodied energy (the sum of all the energy required to produce the insulation) and is manufactured from renewable and waste resources. It supports sustainable farming by using hemp as the protective casing and waste agricultural products within the soap body and at the insulation's end of life, it can be used as a fertiliser or biodegrade harmlessly in landfill. Soap insulation can contribute to making buildings more energy efficient. This applies to new buildings or the retrofitting of existing properties. In terms of energy efficiency, for example, using less energy to provide the heating and cooling of a building, the concept of "adaptive comfort" can be used effectively.

Both the cooling and overheating of a building will have a bearing on human comfort. Overheating in a building has historically been quantified by the number of occupied hours per year that the indoor temperature exceeds a particular temperature, irrespective of the external temperatures (Das Bhaumik, 2014). This idea has been challenged by the supposition of adaptive comfort. Adaptive comfort builds on the theory that the human connection to the outdoors and their control over the immediate environment, allows people to adapt to a wider range of indoor thermal conditions (partly dependent upon their clothing, activity and physical condition) than is generally considered comfortable. This adaptive approach utilizes the thermal perception and behaviour of the people actively controlling their behaviour to reach satisfaction with their thermal environment. In other words, whereas conventional cooling is based on the occupants of a building adapting the internal temperature and humidity levels to suit, adaptive comfort is achieved by the occupants adapting to the building (Fig.2.2).

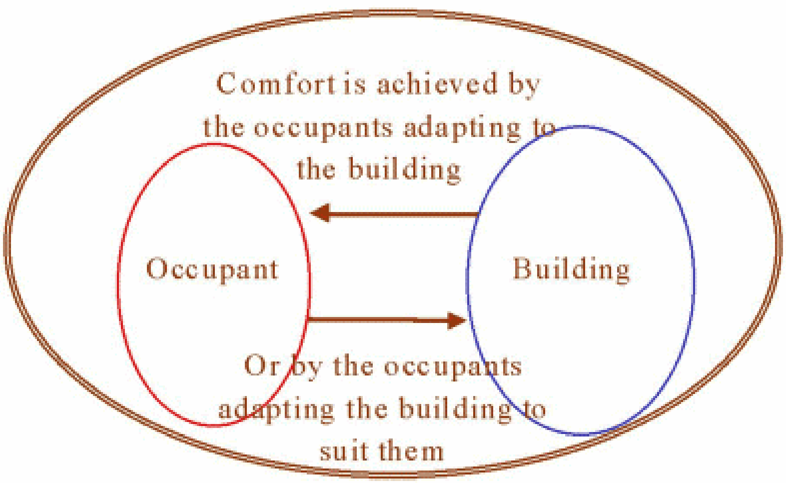


Figure 2.2: Adaptive Comfort Model (CIBSE, 2013)

2.11.2 The Sustainability and Soap Insulation Link

ASHRAE Standard 55, 2013 (Passe & Battaglia, 2015) defines success as meeting the thermal comfort needs of 80% of the occupants in commercial buildings. For example, on a warm day, the occupants may be more accepting of warmer indoor temperatures if they can open a window to reduce the perceived temperature. This gives the building occupants more control over the temperature in their immediate environment and also orients occupants to the outdoor conditions, thus improving occupant satisfaction. On a cold day, the opposite may be true. The occupants may close the windows. These actions may lead to "thermal neutrality" whereby body heat is allowed to dissipate and thus maintain a thermal equilibrium with the immediate surroundings (CIBSE, 2013). Although the role of using these adaptive factors in establishing thermal comfort is recognised, using these factors to design buildings still remains a challenge. The ASHRAE Standard 55, 2013 (Passe & Battaglia, 2015), allows for a warmer range of temperatures in naturally cross ventilated buildings during summer, often linked with minimal low energy fan use, but struggles somewhat to adapt to quantifying buildings with mechanical cooling or heating. However, using thermal mass to manage risks of summertime overheating is one option to regulate the internal climate. Using thicker slabs of soap insulation would aid with this.

Soap based insulation partially meets environmentally friendly criteria through its biodegradable characteristics. Waste bio-polythene can be reconstituted and recycled. Re-using soap insulation makes eco-sense as it reduces carbon emissions. According to "New Sky Energy" (2009), potash lye is carbon neutral. Regarding the waste animal rendering, thousands of tons of waste abattoir animal fats are incinerated each year (Waters, 2013). This could be construed as large scale wastage and could be better served as an insulation ingredient. At the insulations' end of life, the soap component insulation body can be melted down for re-use or possibly ground down to create an alkaline fertilizer (Gowariker et al, 2013), giving the product a 100% end of life recyclability. Because of the soap's pH neutrality, this fertilizer should be compatible with both acid and alkaline soils. Spooner (2012) was of the opinion that tallow and soap refuse can create fertilizer. In itself, this statement appears to be a valid one. However, Baker (2004) states that *liquid* soap is the only soap *proven* to help with turf rejuvenation.

Soap insulation is construed of three component parts: Fats (including oils) and lye (derived from burnt wood ash) for the soap ingredients (Ditchfield, 2012) and vegetable oil based plastic for the soap insulation protective casing, if plastic is deemed a suitable component for the casing after the insulation has undergone testing. Modern rigid board insulations are primarily manufactured from styrenes or cyanurates derived from petroleum. Soap and petroleum insulation component descriptions and their environmental impacts are now explained in more detail.

2.11.3 Lye

Component Description

Burnt wood residue (ash) left to leach in water for a number of days will change the water into a hydroxide alkaline solution known as lye (Tro, 2012). This caustic solution is a strong corrosive metallic base and the primary ingredient of drain cleaners (Tro, 2012). Sodium hydroxide [NaOH] and potassium hydroxide [KOH]) can both be extracted from wood ash, although wood ash typically contains up to 10 times more potassium than sodium (Journey to forever, 2011). It should be explained that both sodium and potassium are soft white metals, in this case derived from common salt (sodium chloride) and potash (Palin, 2014).

Environmental Impact

If lye is not disposed of responsibly, it can cause damage to the environment. Under certain circumstances, lye can react with the water vapour in the air and potentially create a toxic mist (Joye, 2010). If lye is introduced to outside water courses, the pH level of the water can be raised. This could have a detrimental effect on plant and marine life (Joye, 2010). However, according to Ali (2010), if lye is exposed to soil, lye actually neutralises on contact (with the soil and soil organisms). Ali also states that there is no long term proven effect on marine life when in contact with groundwater. This statement was partially confirmed in the USA, when in November 2007 a train of connected rolling stock derailed, spilling 42,000 gallons of lye into the surrounding river and wetland environment. The caustic material spill killed thousands of fish and aquatic life within an 11 mile radius. Staff from the Department of Environmental Protection, (DEP), conducted fish surveys in the area 11 months later and discovered that fish populations had rebounded to near normal levels at the spill site (Environmental News Service, 2007).

2.11.4 Animal Fat

Component Description

Soap insulation must satisfy certain criteria in order for it to achieve mainstream acceptance. Various obstacles must be overcome. Firstly, melted fats or oils must be turned into a solid. At this stage it would be useful to know the definition of oil and fats. Fats are the oily substance occurring in the adipose tissue of some animals and in the fruits, nuts and seeds of some plants (Fantuzzi, 2014). They are usually solid at room temperature (Joachim, 2010). At a molecular level, fat is an ester (organic compound formed from an alcohol and organic acid) of one molecule of glycerol (alcohol) with one, two or three fatty acid molecules bonded to it (esterification) (Fantuzzi, 2014). When fat is exposed to air, it will usually react to the oxygen or water molecules contained within the air and form carboxylic acids (R-COOH). It is these acids that will turn the fat rancid over time (Collins, 2013). Oils have the same chemical structure as fats, but are usually liquid at room temperature.

Environmental Impact

Regarding beef, there are 334 abattoirs in the UK that process carcasses with approximately 46% of each animal not used in human food (The Tracing Paper, 2014). Fats can be separated from the meat and offal manually, or the carcass can be boiled in water and the resulting floating fats can be skimmed off for use. In 2004 it was estimated that rendered animal fat production in the EU equaled 2.6 million metric tons (Woodgate, 2005). Approximately 50 billion kg of inedible rendered waste is generated within the UK annually (Pointon, 2014). Most animal waste is incinerated, which can potentially create pollution problems; but there is an alternative - waste as fertilizer. Animal rendering waste has been used as fertilizer for centuries (Mepham, 2012). Generally, mineral fertilizers including compounds of sodium nitrate, ammonium nitrates/sulphates and phosphates derived from rock have largely replaced these organic fertilizers (Glinski et al, 2011), although according to Mepham (2012), mineral fertilizers can deteriorate soil structure and decline organic content and crop yield. Only disease free rendered waste can be used.

Diseased or potentially diseased bovine carcasses that are not incinerated, but buried “off-site”, need to be disinfected before being placed into burial pits. Covering the carcasses with washing soda (a highly alkaline chemical compound) will ensure that if run-off does occur because of flooding, it does not carry away any "live" viruses or harmful bacteria (Bourne, 2011).

White (2006) stated that organic animal waste decomposes quickly when spread over soil. The actions by the soil micro-organisms work relatively efficiently and so soil contamination or leaching is usually not an environmental issue. Frankx (2009) however, opined that blood wastes should be boiled before application or incinerated. Perera (2010) stated that the high fat content contained within poultry slaughterhouse waste prevents it from being composted by natural microorganisms. Perera (2010) also stated that the addition of sodium lauryl sulphate to act as an emulsifying agent will break down the fats before the waste is used. In contrast to White, Spangberg et al, (2010) were of the opinion that leaching and eutrophication (the process whereby filtration or run-off from fertilised fields causes the water table or lakes to become contaminated with mineral and organic nutrients) will occur when animal waste is spread upon the ground. This process can cause cyanobacteria and algae to grow rapidly and deplete the oxygen supplies within ponds and lakes. Obarska-Pempkowiak et al (2015) agreed, claiming that leachates from landfill also bring problems. Obarska- Pempkowiak et al stated that “The effects on groundwater and soil quality are increasingly large scale and long term.”

2.11.5 Alternative Plastics for the Insulation Protective Casing

Soap based insulation must have a protective casing. The reasons for this are revealed later (in chapter five). This casing may be constructed from plastic. One such plastic is canola oil based bio-plastic (PLA). This sustainable polyurethane is used to prevent the onset of premature degradation to the soap. Bio-plastic is relatively inexpensive, variations are available in abundance, bio-plastic melts at low temperatures and has high impact strength at low temperatures (Crompton, 2006). This makes bio-plastic ideal as a sustainable component for the insulation casing, in the quest for alternative and sustainable thermal insulation. Bio- polyurethanes and sugar or corn based polythenes are not without their problems though. The casing surrounding the soap will have to be moulded to shape, and sealed via a heat weld.

This is because very few glues will adhere to polythene (Tripathi, 2012). This plastic also has poor load-bearing and flammability properties (Tripathi, 2012). Unlike bio-polyurethane, bio-polythene does not biodegrade, but it can be recycled (Gupta, 2014). However, according to Davies (2006), petroleum based polythenes are one of the most toxic of plastics.

2.12 Components of Petroleum Based Insulations

The journey from crude oil to the finished products of polystyrene or polyisocyanurate thermal insulation is somewhat complex when compared to the manufacturing cycle of soap insulation. The component parts of petroleum based insulations can potentially bring both health and environmental problems.

2.12.1 Crude Oil

Crude oil is a mixture of many chemical constituents, although primarily hydrocarbons (chemicals composed of carbon and hydrogen). This oil in its raw form also contains several hundred chemical compounds including mercury, nitrogen, nickel, benzene, iron, chromium, oxygen, xylene and toluene (Kelland, 2014). Crude oil is heated and these chemical compounds are separated according to their density, for example, refined into petroleum, diesel oil, engine and heating oils, bitumen and heavy metals (Rand, 2013).

There are four types of crude oil:

Class A: Light, volatile oils. These are highly fluid thin oils that are toxic to humans and animals (Fingas, 2010)

Class B: Non-sticky oils: These oils are lustrous and less toxic to humans and animals (Fingas, 2010)

Class C: Heavy sticky oils. These oils are sticky tar-like substances of low toxicity. However, the impacts on wildlife and waterfowl can be severe if leaked into the natural environment (Fingas, 2010)

Class D: Non-fluid oils. These oils include heavy crude oils. These are also classed as non-toxic although the impact on waterfowl and wildlife can be severe if spilled. Prolonged exposure to class B-D crude oils can irritate the skin, eyes, and respiratory system. These oils may also cause anemia and may result in allergic skin reactions or rashes, edema, and burning of the skin (Fingas, 2010). The burning of crude oil emits chemicals that can be detrimental to human health. These chemicals include CO_2, carbon monoxide, lead, nitrogen oxides, sulfur dioxides, polycyclic hydrocarbons, and rapidly evaporating organic compounds (Botkin, 2010).

2.12.2 Petroleum

Petroleum is predominately a mixture of cyclo-alkanes, alkanes and arene hydrocarbons, oxygen and carbon gasses, and copper, iron, vanadium and nickel metals (Speight, 2014). Petroleum has the potential to cause pollution at each of its definitive stages, from refining, transportation, and its ultimate end product as a manufacturing ingredient or fuel (Sala et al, 2009). Ground contamination often creates sites that are deemed to be toxic for wildlife and future generations (Sala et al, 2009). Exposure to petroleum may result in skin rashes or irritation to the airways. Studies on animals have revealed that prolonged exposure may lead to cancer of the blood, although it is thought that this is may be due to the benzene and lead content contained within the petroleum (CCOHS, 2011).

2.12.3 Naphtha

Naphtha (C_8H_{18}) is obtained from refined petroleum. It is an intermediate distillate between petroleum and benzene (Speight, 2014). In thermal insulation it is used as a solvent. Naphtha is made from the following chemical components: Hexane, xylene, toluene, cyclohexane, pentane, heptane, ethylbenzene, benzene and sulfur (Speight, 2014). Short term exposure may lead to drowsiness or headaches, but it has no long-term effects. Long-term exposure may affect the skin, liver, kidneys, nervous system and blood (Tesoro, 2010). The effects of naphtha on the wider environment have not been documented.

2.12.4 Polyiso, Polyisocyanurate & Methylene Diphenyl Disocyanate (MDI)

Polyiso is a cellular foam which is also a derivative of distilled petroleum. It is formed when two basic chemicals, polyol and isocyanurate, are combined in the presence of a catalyst (a substance that creates or accelerates a reaction) to help the molecules to rearrange and reform (Szycher, 2012). MDI is a man-made reactive Lewis acid (an acid that will react with a base) which is capable of completing the chemical reaction of the polyiso base, and changing the liquid to polyisocyanurate (Szycher, 2012).

From a health perspective, short-term exposure of MDI may cause dermatitis, asthma or sensitization in humans. Respiratory effects have also been observed in animals. There is currently no adequate information on the carcinogenic effects of MDI in humans (USEPA, 2000). From an environmental perspective, waste polyisocyanurate insulation typically finds its way to landfill, although a small number of specialist companies are recycling the insulation component parts for reuse (Lesco, 2011).

2.12.5 Benzene

Benzene (C_6H_6) is a, volatile, flammable, liquid mixture of various hydrocarbons, obtained from the distillation of petroleum. It is a carcinogenic compound that is present in noxious gasses such as tobacco smoke and car exhaust fumes (National Pollutant Inventory, 2011). Benzene evaporates quickly and so the most common exposure is from breathing benzene contained in air. Benzene is poorly absorbed by the skin, but it can enter the body in this way through physical contact with petroleum (National Pollutant Inventory, 2011). If benzene is released into the ground in low-levels, it will quickly break down in the presence of oxygen and it will not build up elevated concentration levels in animal tissues via plants. However, at high-level concentrations it can have a toxic effect on plant roots and leaves and may ultimately have a detrimental effect on aquatic life through run-off (National Pollutant Inventory, 2011). In humans, long-term benzene exposure can be harmful to the immune system and affect normal blood production. It can cause Leukemia and has also been linked with birth defects in both humans and animals (Spoolman & Miller, 2011).

2.12.6 Ethylene

Ethylene (C_2H_4) is also a derivative of petroleum. It is a hydrocarbon based alkene flammable gas. For its use in plastic manufacture it is first changed to ethylene oxide by adding oxygen at a molecular level. Ethylene oxide is a hazardous substance. At room temperature it is carcinogenic, flammable, and an anaesthetic gas (Dikshith, 2013). Exposure to high concentrations of ethylene oxide may result in increased rates of miscarriages for humans and can mean the death of wildlife and low growth rates in plants. The long-term effects on animal life may include a shortened lifespan and lowered fertility rates. Exposure to ethylene oxide can have moderate long term toxicity to aquatic or marine life (National Pollution Inventory, 2011). Short term exposure to ethylene oxide may cause irritation of the eyes and mucous membranes. Increased levels of exposure may cause difficulty in breathing and contaminated clothing may cause skin burns.

2.12.7 Styrene

Petroleum based styrene (C_8H_8) is usually derived from ethylene and benzene or ethylbenzene. It is a flammable, monomer (a molecule capable of reacting with other molecules to form a polymer) hydrocarbon based liquid (Dikshith, 2013). It dissolves only slightly when mixed with water but it will evaporate when exposed to air. It is thought not to be absorbed through the skin (USEPA, 2009). Humans, animals and plants are unlikely to store styrene, but effects on human health associated with short term exposure are not known (Dikshith, 2013). However, laboratory testing on animals has revealed that repeated long-term exposure may cause cancer of the liver and blood. Styrene alone is unlikely to cause environmental damage at the levels normally found in the environment (Dikshith, 2013).

2.12.8 Polystyrene

Polystyrene (rigid thermoplastic) is obtained through a chemical process which refines styrene into polystyrene. This process is known as polymerization (the act of bonding two or more monomers to form a polymer). This process converts one compound into another. The finished polystyrene article ratio can contain as much as 95% air to 5% foam. It requires 1.5 litres of petroleum oil to manufacture 300mm^3 of polystyrene (Earth Resource Foundation, 2011). Alongside thermal insulation, polystyrene is often used for packaging. Because of the inflexible nature of moulded polystyrene, once used it is difficult to reuse the product for anything else. As such this item is often seen as a “use once and throw away product” (Lesko, 2011). In the US, it is estimated that 25% of the space in landfills is taken up by waste polystyrene (Spangler, 2011). In Hong Kong approximately 135 tons of polystyrene was deposited at landfill every day in 2012 (HKEPD, 2014). This is because recycling polystyrene is not financially viable because of the huge costs involved (CAW, 2010). It can take up to several hundred years for polystyrene to fully decay in landfill sites (Mark, 2013). When incinerated, polystyrene releases toxins including carbon black and carbon monoxide. According to The National Bureau of Standards Centre for

Fire Research (2010), 57 potential toxins are released by polystyrene burning. The cocktail of ingredients that are created from the crude oil base and used to make polystyrene insulation is shown in Figure 2.3 below.

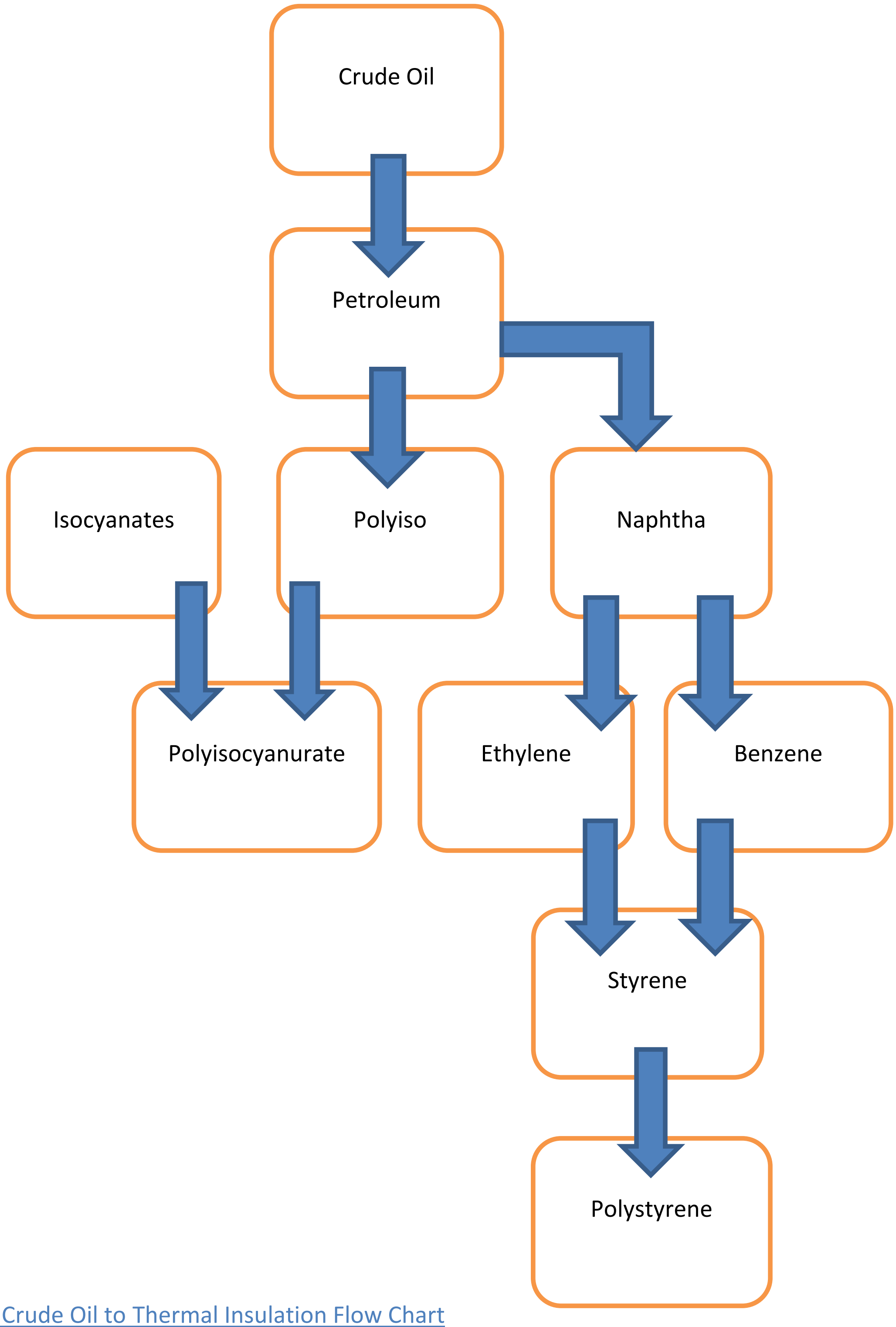


Figure 2.3: Crude Oil to Thermal Insulation Flow Chart

2.13 Means of Disposal for Animal By-Products

Incineration and burial are two means of disposal for animal by-products. However, there is strict legislation governing “what” can be put “where”. The revised regulation, (EC) No. 1069/2009 (EUR-Lex, 2009), provides legislation on food safety, definition of by-products and the by-product categories of animal waste types.

2.13.1 Animal By-Products

Animal by-products are described as “The entire bodies or parts of bodies of animals or products of animal origin not intended for human consumption, including ova, embryos and sperm” (Regulation [EC] No. 1069/2009). For the purpose of human and animal health protection, Regulation [EC] No. 1069/2009 legislation states that waste by-products derived from animals declared unfit for human consumption are prohibited from entering the food chain (Leoci, 2014).

2.13.2 Categories of Animal Waste and Their Disposal Measures

Regulation (EC) No. 1069/2009 is echoed in DEFRA’s (Department for Environment, Food & Rural Affairs) national legislation. DEFRA replaced the Environment Agency for animal waste governance legislation in 2011. There are three by-product categories:

Category 1. This category defines animal waste material as high risk. Typical components will include animals suspected of being infected with communicable diseases, specified risk material likely to carry an infectious agent and animal products that have deemed likely to have absorbed prohibited substances. This material can only be disposed by incineration or by processing in a licensed plant approved to handle category one waste. Category one by-products cannot be disposed of via landfill (Leoci, 2014).

Category 2. Waste defined as category two is of medium risk. This type of waste will typically include manure and digestive tract content, animals that have not been slaughtered for human consumption and animals imported from third countries that fail to comply with EU standards. This material can be disposed of in a similar way as category one waste, but it can also be composted or used in biogas production (Leoci, 2014).

Category 3. This category describes low risk animal waste. Skin, blood, hooves, wool, feathers, hair and fur, originating from healthy animals, fall into this category. This waste can be used in pet-foods or fertilizers (Leoci, 2014).

In certain circumstances animal by-products can be disposed of via open burning or burial, but only in remote areas. The EU Regulation 1069/2009 defines remote areas as “areas where the animal population is so small, and where facilities are so far away, that the arrangements necessary for collection and transport would be unacceptably onerous compared to local disposal.” On-site burial requires control of vermin issues, and ground contamination may result in future land concerns. Open burning will typically require air monitoring and may require public acceptance. Landfill disposal will generally only be applicable to waste that has been treated. Regarding the millions of gallons of waste animal fats and vegetable oils disposed of in the UK via the drains, eight out of ten blocked sewers are caused by this method of disposal (Dirty Britain, 2013). In London, up to 20 tanker loads of fat can be removed in any 12 hour period. This fat is normally buried in landfill sites (Dirty Britain, 2013). With fats being a major component of soap, in theory there is an abundance of raw materials.

2.14 Soap Based Thermal Insulation as a Potential Alternative

As a starting point for further investigation, the following set of propositions should help to explain the background to some of the challenges faced whilst investigating soap as an insulation material.

2.14.1 Keeping the product Lightweight

Building products that are handled on a regular basis should be repetitive lifting safe and as such should be as light as is practicable. Initial laboratory testing reveals that solid soap has a density of approximately 801 Kg/m^3. The challenge is to bring the soap density figure down to between a quarter and one half of this figure (the less dense the soap, the greater the thermal performance). This will be achieved by entraining the soap with air, by utilising various procedures and additives that will enhance the aeration. To be accepted into the retail market, soap insulation would need to compare favourably with both polystyrene and PUR thermal insulations. These insulations have proven to perform and are both easy handling on site.

Expanded polystyrene in general has a density of 1.06 – 1.12 Kg/m^3 (Polysciences, 2013), whilst PUR insulations usually have a density of 30 – 100Kg/m^3 (Hens, 2012).

2.14.2 Thermal Performance

Thermal performance refers to how well the insulation responds to changes in external temperature. Different insulations will give different performances. Soap insulation would need to perform to compete in the marketplace with the established rigid board competition. It is unlikely that soap insulation could ever match or surpass the polyisocyanurate insulations at an equal thickness, however, through a series of experimental refinement it is envisaged that competition with polystyrene may be close. According to Polysciences Inc., (2013) the thermal conductivity measurement of expanded polystyrene is usually between 0.030 W/mK and 0.040 W/mK (watts per metre kelvin). Whilst for PUR insulations, this measurement generally varies between 0.021 W/mK and 0.025 W/mK at 100mm thicknesses (Hens, 2012).

Soap insulation would need to perform at conductivity around 0.060 W/mK or below to have a chance of being successful. Before this literature progresses into the petroleum insulation experimental manufacture and testing stages, it would be useful to reveal the basics of thermal insulation measuring techniques. This will reveal how the calculation results are achieved. Generally U-values are calculated using the methods detailed in BS EN ISO 6946:2007, BS EN ISO 13370 and the conventions set out in BR443 (Conventions for U-value calculations) (Anderson, 2010).

2.14.3 Calculating U-Values of Thermal Elements

A U-value is the measurement of heat loss through a building element. For example, the wall, floor or roof. For the purpose of this research, testing will focus on wall insulation and how this part of a building transfers heat, as opposed to the thermal performance of the roof and floor. The lower the U-value is often indicative of higher levels of thermal insulation (Anderson, 2010).

Thermal conductivity

Thermal conductivity (lambda) is the rate in which heat is transmitted through the insulation. This is measured in watts per square metre of the surface area, with a temperature gradient (the rate at which a physical temperature increases or decreases relative to change in a given variable) of one kelvin per metre of thickness

(Anderson 2010). This is shown as W/mK. Different insulation types offer differing rates of thermal conductivity. Thermal conductivity can also be expressed as a k-value.

<u>Thermal resistance</u>

Thermal resistance (R-value) is equal to the thickness of the material (in metres) divided by the conductivity of the material component. It is measured in m^2K/W. The resistance of each component within an element are added together to reveal the extreme limits of resistance of the element overall. Generally, the higher the R-value is, the greater efficiency of the insulation used (Anderson, 2010). An example of this equation is shown below.

Assuming that a 100mm thermal insulation board has thermal conductivity of 0.022 W/mk. Then the equation would be as follows: (0.022 W/mk 100mm) = 0.1m divided by 0.022. This equals an R-value of $4.54m^2K/W$. Expanded polystyrene insulation at 50mm thick has an R-value generally of $1.25m^2K/W$. At 100mm thick the R-value doubles to $2.50m^2K/W$ (Resene, 2013). Hemp insulation at 70mm thick has an R-value of $1.75m^2K/W$. At 140mm thick the R-value doubles to $3.50m^2K/W$ (Thermofleece, 2012).

<u>Thermal transmittance</u>

Thermal transmittance is expressed as watts per square metre, per degree kelvin (W/m^2k) (Resene, 2013). For the external walls of a building envelope the U-value is calculated from the combined thermal resistance of the insulation *and* the brickwork/ blockwork materials used in the wall construction. An example of how a U-value calculation is conducted is shown below.

R-value of insulation = 4.54 m^2K/W. R-value of 100mm brick wall = 2.27 m^2K/W. The 2 R-values are added together to create a combined R-value: 6.81 m^2W/K. The U-value is the number 1 divided by 6.81. This equals $0.147W/m^2k$.

A general overview of the various insulations and their U-values, as compiled by "The Concrete Company" (2010), are shown in Table two on the following page. The insulation is fitted in the cavity between a 100mm brick outer and 100mm aircrete block inner skin or a solid wall construction with the insulation fitted to the inner skin.

The U value figure is taken from the overall combined thickness of wall construction materials and the insulation.

Insulation Type	Insulation Thickness	Wall type/ Insulation Placement Ratio	U-Values
XPE	50mm	Cavity Wall/ Partial Fill	0.28 W/m^2k
Mineral Wool	100mm	Cavity Wall/ Full Fill	0.28 W/m^2k
Mineral wool	140mm	Timber Frame	0.27 W/m^2k
PIR/PUR	50mm	Cavity Wall/Partial Fill	0.28 W/m^2k
Polystyrene Bead	125mm	Cavity Wall/ Full Fill	0.28 W/m^2k
Expanded/ Extruded Polystyrene	100mm	Inside Face of Solid Wall Construction	0.28 W/m^2k
Hemp	115mm	Inside Face of Solid Wall Construction	0.28 W/m^2k

Table 2: Insulation / Wall Type U-Values (Kruger & Seville, 2012)

Variations in some thermal insulations offered by various manufacturers has increasingly improved thermal conductivity using thinner insulations. Examples of the manufacturers' claims are shown in Table three below. The data is adapted from the various manufacturers' thermal insulation fact sheets and is used in conjunction with a 100mm + 100mm brick and lightweight thermal block wall. The U value claim is for the overall wall thickness, for example, brick outer skin – insulation - block inner skin.

Insulation Type	Insulation Properties	Insulation Thickness	U-Values
Thermafleece Hemp	Hemp Fibre Based. 60% hemp, 40% Recycled Polyester & Binder.	100mm	0.25 W/m^2k
Steico Canaflex	Hemp Fibre Based. Properties as Above.	100mm	0.25 W/m^2k
Glasswool	Fibreglass. Fibres of Glass & Resin.	140mm	0.27 W/m^2k
Extratherm	Polyisocyanurate Rigid Board.	50mm	0.25 W/m^2k
Polyicyene	Spray on Foam	125mm	0.30 W/m^2k
Edenbloc	Recycled Wool. 60% Wool Fibres & 40% Natural Binders	100mm	0.29 W/m^2k
Warmfill Silver	Polystyrene Bonded Bead.	100mm	0.33 W/m^2k
Jablite Dynamic Cavity	Hollow, Rigid Polystyrene	125mm	0.14 W/m^2k
Thermafleece Wool	Wool Fibre Based. 85% Recycled Wool & 15% Polyester Binder.	100mm	0.25 W/m^2k
Ecotherm	Polyisocyanurate Rigid Board	100mm	0.18 W/m^2k

Table 3: U-Value Claims Made by Manufacturers (Kruger & Seville, 2012)

2.14.4 End of Life Disposal

Thermal insulation manufacturers *are* going some way into limiting the amount of waste reaching landfill (Friedman, 2012). Some mineral wool furnace residue is being recycled as a road building component (Worrell & Reuter, 2014). Mineral wool insulation is typically a blend of rock and slag wool. Since 2015, nearly 11 billion pounds of recycled blast furnace slag have been used in the manufacture of slag wool insulation (Naima, 2012). Recycled polystyrene can be manufactured into structural building blocks used for houses and other buildings (Worrell & Reuter, 2014). The recovered foam is clean and dry.

Rastra (2013) is reportedly recycling almost 200 tons per year of plastic foam insulation material. However most petroleum based insulations in their current form are not ideal for possible recycling/reprocessing (Friedman, 2012). This is largely due to financial viabilities which are not commercially available at present. Society also needs to recycle materials to a much greater extent to achieve greater material use efficiency.

2.14.5 Financial Costs of Polystyrene & Polyisocyanurate Insulations

The financial costs of both polystyrene and polyisocyanurate thermal insulation at thicknesses of both 50mm and 100mm were analysed to ascertain the average price per square metre from various retail outlets. A selection of UK trade and DIY building supplies outlets were chosen. For the polyisocyanurate insulations, Celotex, Xtratherm, Quintherm, and Kingspan were chosen because of their variant ranges. For the polystyrene thermal insulation, Jablite, Styrofoam and Foamular were chosen. The mean average purchase price per metre squared (in 2015) is shown in Table 4 below:

Insulation Type	Cost for 50mm Thickness	Cost for 100mm Thickness
Polyisocyanurate	£10.07m^2	£17.36m^2
Polystyrene	£4.69m^2	£9.32m^2

Table 4: Financial Cost of Polyisocyanurate & Polystyrene Insulations

In theory the capital costs of the raw materials for soap production should be low. However, waste handling and hygiene legislation would need to be adhered to.

2.14.6 Environmental Cost

The true cost to the environment cannot be accurately measured on a like-for-like comparison. Chapter two revealed the environment costs for the oil manufacturing industry. Soap production should be more environmentally friendly than oil production, but there are potential problems associated with the soap industry also. Globally, waste created by the animal rendering sector is a source of water and air pollution (WRC, 2008).

The global soap manufacturing industry is responsible for releasing phosphates and surfactants, which remove oxygen from water, into groundwater watercourses. This depletion of oxygen has a detrimental effect on aquatic life (Aichinger, 2004). Both phosphates and surfactants have the power to destroy the external mucus layers of fish (Aichinger, 2004). This mucus layer is key in protecting fish from bacteria and parasites (Aichinger, 2004). It should be clarified at this point that the somewhat low level environmental pollution created by the soap industry, alongside the higher environmental pollution created by the petroleum industry, are outweighed by the fact that thermal insulation is absolutely required to limit wasted heat via the built environment.

2.15 Chapter Summary and Conclusion

The preceding literature review highlights the theoretical overview of existing thermal insulation knowledge, before the research progresses into the experimental observation (empirical) stage. The purpose of this review is to examine the relationship between research into soap based thermal insulation, the petroleum chemical based alternatives, and an investigation into the literature data within this area. Against this background, this literature review also examines recently published and available information regarding oils, insulation derived from oils and bio-plastics from alternative sources. The findings from the literature have been analyzed to reveal the trends, facts, theories and misconceptions within the thermal insulation industry generally. Alongside a review of the components of each insulation type, the environmental impact of each insulation type is critiqued.

This review is justification for the direction this research will follow, and act as a signpost to the present study. The literature has contributed to the approach to this research in the following way. Namely, it offers choices and provides a balanced approach as to why certain sustainable components are environmentally favourable over some others. This may provide the reasoning as to why *natural* can be construed as “better” than the man-made potentially toxic counterparts. Oil, petroleum and its chemical derivatives feature prominently in this research. This is because oil (and petroleum) play a major part in both the composition of plastic insulation, and as fuel for the insulation manufacture. It is also the main comparable to soap as defined in the research question.

The literature review also reveals that the thermal insulation market is large and diverse. Evidence suggests that there is an effort to drive forward the sustainability issues required to bridge the gap between fossil fuel derived as environmentally friendly. Animal rendering waste is only one such material under review, but this does however have the foundation potential for future research to build upon. Regarding the future of insulation research, new discoveries may follow. As will become clear, there are alternatives to fossil fuels and their derivatives, especially oil, which have begun to be explored (Meier et al, 2007). Sustainability encompasses the complete lifecycle from retrieval, manufacture and disposal. This is especially so for the thermal insulations listed. However, available data reveals that new technology research and global mindset change must be implemented to have any long term real effect. Research into the material properties and alternative thermal methodology with regards to soap may yet find its way into mainstream published data. In the main though, the thermal insulation market is still dominated by the bigger petroleum chemical based insulations.

The *potential* environmental implications of the crude oil components is significant because it actually supports the need for a soap alternative. Toxin release at the manufacturing stages and the problems associated with the end of life disposal for chemical waste may also have a bearing on the broader field of other petroleum derived materials. Financially the onus is with soap insulation, although its derivative components i.e. connective animal waste, still needs to be disposed of properly, although the environmental impact of this is dwarfed by petroleum based waste. However, there are limitations to this type of comparison approach. It is relatively simple to document the differences in both insulation types, but harder to identify the reasons as to why insulations made from potentially harmful chemicals dominate the market when other sustainable alternatives are available. One of the implications of identifying the make-up of plastics is that this may lead to the dilution or omission of harmful components in the future manufacturing of petroleum insulations, whilst these insulations still perform to an acceptable standard. However, only testing will determine whether the thermal performance of soap can challenge the dominance of petroleum based plastic insulation in today's market. Chapter three reveals the actual soap manufacturing process and chapter four highlights the basic initial testing that forms the basis for the soap's physical properties and thermal performance improvements to be built upon.

Chapter 3 Research Methodology

3.1 Introduction

The purpose of the research is to test the hypothesis that soap insulation can perform to the same standards as its petroleum counterparts. According to Leedy & Ormrod (2013) research begins with a question (1). This has been defined earlier in this thesis and is central to formulating the research hypothesis. Through research the goal is defined (2). The problem is then subdivided into separate but related sub-problems (3). Next, in this case, the research hypothesis speculates upon the outcome of soap insulation testing, with the aim of creating a workable alternative to the mainstream thermal insulations (4). This inductive reasoning (reasoning from detailed facts to general principles) is collected and organized, leading to the formation of the theory (5). Following this, the *testable* hypothesis is formulated, which will then answer the original research question (Leedy & Ormrod, 2013)

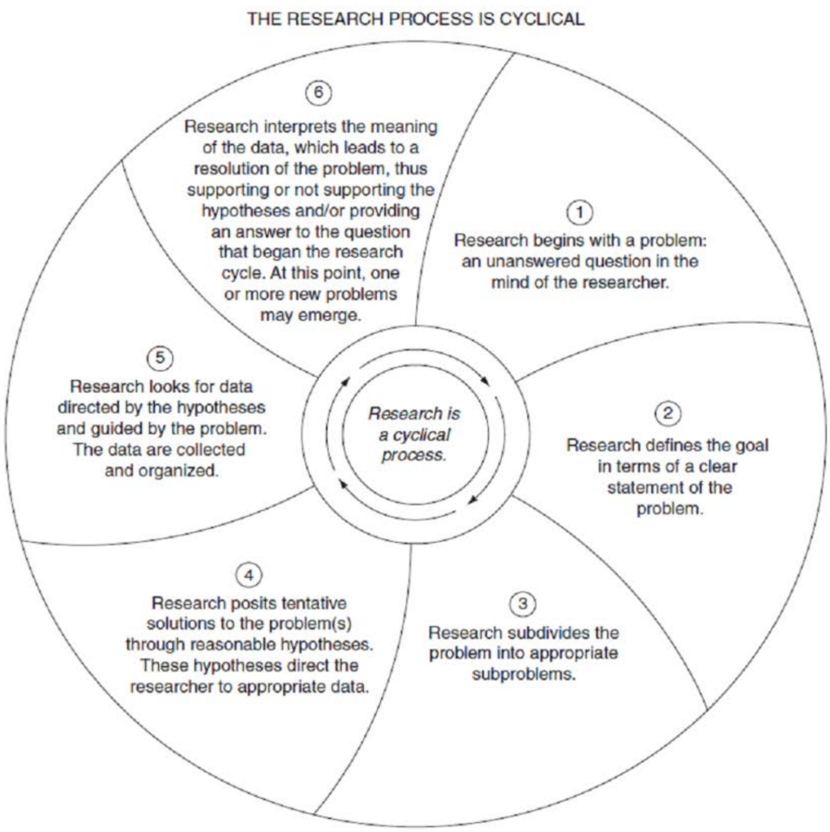


Figure 3.1: Cyclic Research Model (Leedy & Ormrod, 2013)

Ellis & Levy (2008) produced a cyclic research model that broadly follows the same lines as Leedy & Ormrod's model. In the view of the author, this model offers a clearer route to understanding the rationale behind the problem based research cycle. For example, the research problem is the starting point and this establishes the limits or boundaries of the hypothesis. The hypothesis determines the methodology to be used. This in turn creates the results (which can be validated by the literature review). Refining this data leads to the conclusions, thus answering the research questions (Ellis & Levy, 2008). A problem based research model diagram (Fig.3.2) is shown below.

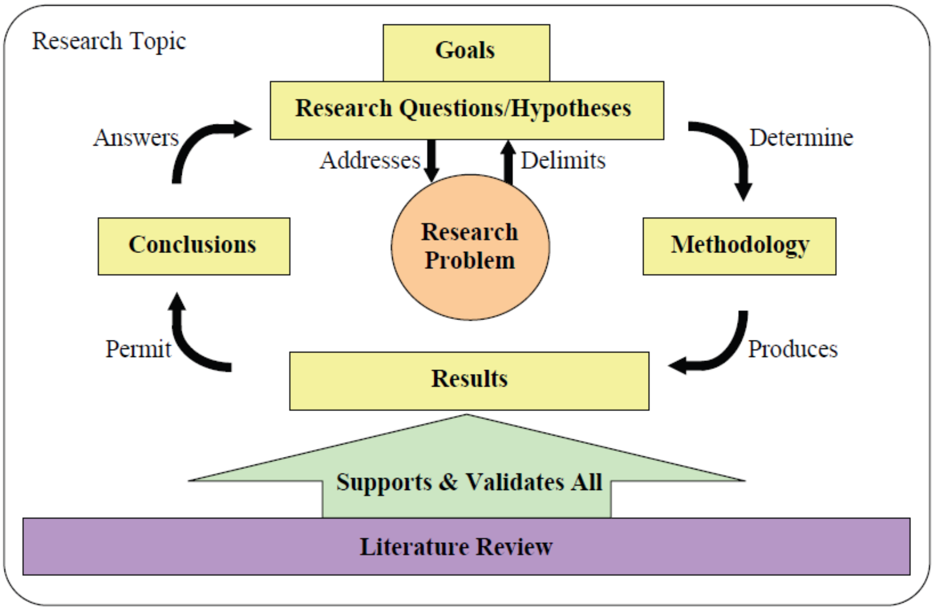


Figure 3.2: Problem Based Research Cycle (Elis & Levy, 2008)

It should be pointed out that the hypothesis can never be proven, but it can be verified or supported, eventually becoming a theory (Ellis & Levy). The thesis conclusion will be based on robust, solid evidential data following established scientific protocols, but the *process* of searching for the solutions to the problems will be achieved via research.

3.2 Formulation of the Research Methodology

In order to define the investigative research and categorize what type is best suited to the topic, a research process concept must be implemented. Although the systematic, methodological search for information is one definition of the art of scientific investigation (McPherson, 2013), a multitude of research methodologies are available to develop and advance the research process in a quest to generate a theory (Kettley, 2010). The research methodology championed for this research question is based on quantitative research methods. This method should lead to a triangulation of the findings. The quantitative approach uses deductive reasoning to arrive at the hypothesis. This method allows for a flexible and iterative approach to solving the research question.

3.2.1 The Research Onion Perspective for the Formulation of the Research Approach

The Research Onion (Fig.3.3) comprises a research approach method to definitively state the ultimate research development. This Research Onion can be likened to a series of layers, (of skin surrounding an onion), leading to the inner layers. The outer ring considers the research philosophy (the belief about the way in which information is collected, analyzed and used). The next layer contemplates the research approach to formulating a testable hypothesis from which strategies can develop the theories and the approaches that will be taken. The third layer reveals the strategy to be used. The fourth layer refers to the choice of methods to be used, whilst the fifth layer reveals the length of time for a project to complete and the sixth layer refers to the data collection and analysis methods for discussion.

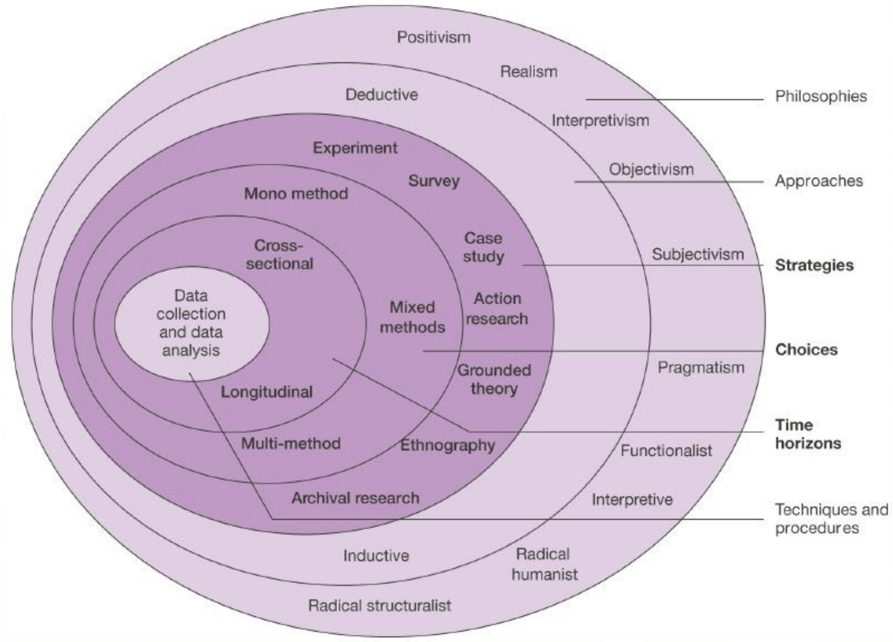


Figure 3.3: Research Onion (Adapted from Saunders et al, 2015)

Other research approaches were considered. For example Yin (2002) takes a similar, if not more basic stance when he states that case study research designs (solid data gathering techniques and methodological paradigms) are built on the research questions. From this comes the proposition stage (the act of suggesting something to be considered). Next comes the analyzing, the act of linking the data to the proportions, and finally the evidence gathering. Blaikie, (2012) agrees, stating that research is a cyclic loop of deduction, observation and inducing (bringing about) (See Fig 3.4).

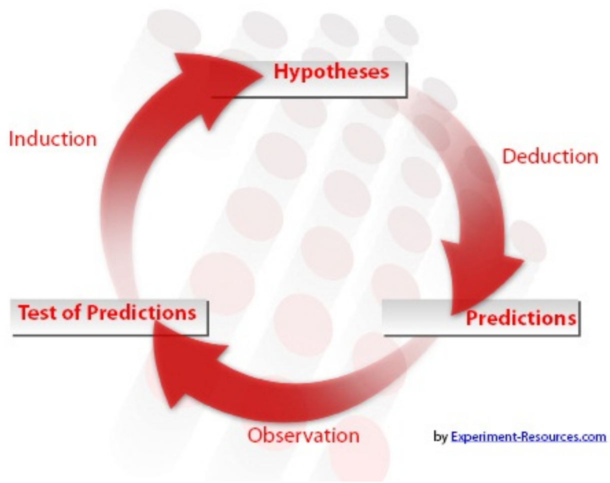


Figure 3.4: Defining a Resource Problem (experiment-resources.com, 2012)

3.2.2 Research Philosophy

The justification and explanation for the choices taken from the research Onion are revealed in the following section within this chapter. The research philosophy (the opinion concerning the way in which this data should be obtained, processed and utilized), is encompassed by ontology (that which is out there to know) and epistemology (how can we know about it)? Objectivism (in relation to ontology) reveals that an objective exists and can be revealed through reasoning and ever more complete information (Leedy & Ormrod 2013). Positivism (in relation to epistemology) acknowledges that the researcher collates facts, gained through observation, that lead to the use of experimental and quantifiable methods of research. The purpose of this research then, is to change what is *believed* into what is *known.* For example, can the *idea* of aerated soap as an effective thermal insulation be turned into reality? The philosophy does this by specifying, then refining the research methods that are to be used, then clarifying the overall research strategy. This helps to enable the researcher to evaluate the different methods and methodologies that can be used, whilst identifying the scope and limitations of some approaches, thus avoiding unnecessary work. Siegel (2012), opined that all true knowledge is acquired through observation and not through belief or conjecture. This scientific method of research makes connections between different facts in order to create theories. This method must demonstrate causality. According to Ramanathan (2009), although the research observer is independent, he is part of what is being observed. On a basic level the positivist approach takes a nomothetic (relating to the study of general scientific laws) approach to science, relying on experimental methods to verify the hypothesis (Ramanathan, 2009). These methods ensure that there is no bias between the researcher and the research. This approach also ensures that the procedure is valid, reliable and able to be replicated outside the context of the study.

Value free is the axiological position taken. Axiology is the philosophical study of values affecting how research is conducted (Li, 2013), the purpose of this research and how this affects the belief in this new knowledge gained. A value free assumption concerns human nature. This questions if the researcher achieves understanding of man as the controlled, or the controller. For example, the research that has been conducted by an impartial researcher and the data collected should be completely independent of the researcher's prejudices, values, opinions and beliefs. This impartiality should then be reflected in the research conclusion. Because there is no external data on developing soap as an insulation, the soap improvements are achieved by a trial and error process. This is recorded and the performance results validated by the thermal testing laboratory.

The quantitative element shown in the flow-chart (Fig.3.5), examines the variables to determine the links and interactions between them (a process of doing *this* to the soap to get *that* from the soap). The research strategy is conducted via a series of progressive step-by-step experiments designed to refine the basic soap body until it becomes a workable thermal insulation. This is accomplished by using the mixed method research choice, meaning that the researcher utilises multiple methods of research (existing literature, experiments and external validation) and then intentionally combines and integrates these so that the validation of the results becomes that much stronger (Li, 2013). Due to the time constraints of the doctorate, cross sectional time horizons is chosen. This identifies a series of particular occurrences at particular points in time to create a workable timeframe to adhere to. These choices made from within the "Research onion" are revealed in Fig.3.5 below.

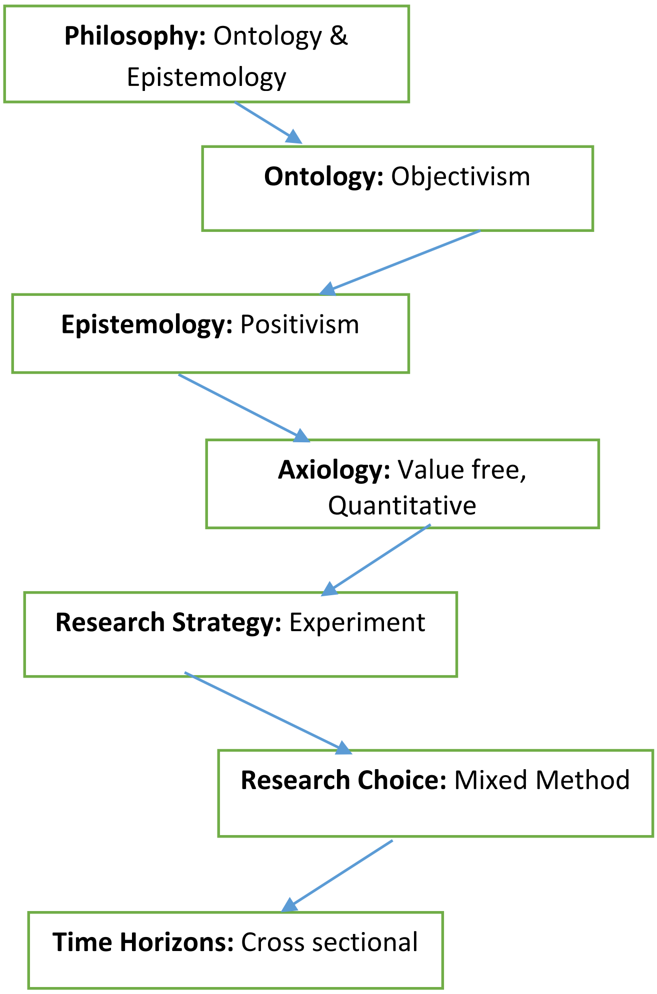


Figure 3.5: Research Process for this Study (Adapted from Dawood & Underwood, 2010)

The key stages taken to complete the soap insulation research are shown in the timeline flow-chart (Fig. 3.6) on the following page. Each stage represents further physical improvements to the soap insulation samples. The date that each stage was started is also revealed in this flow-chart.

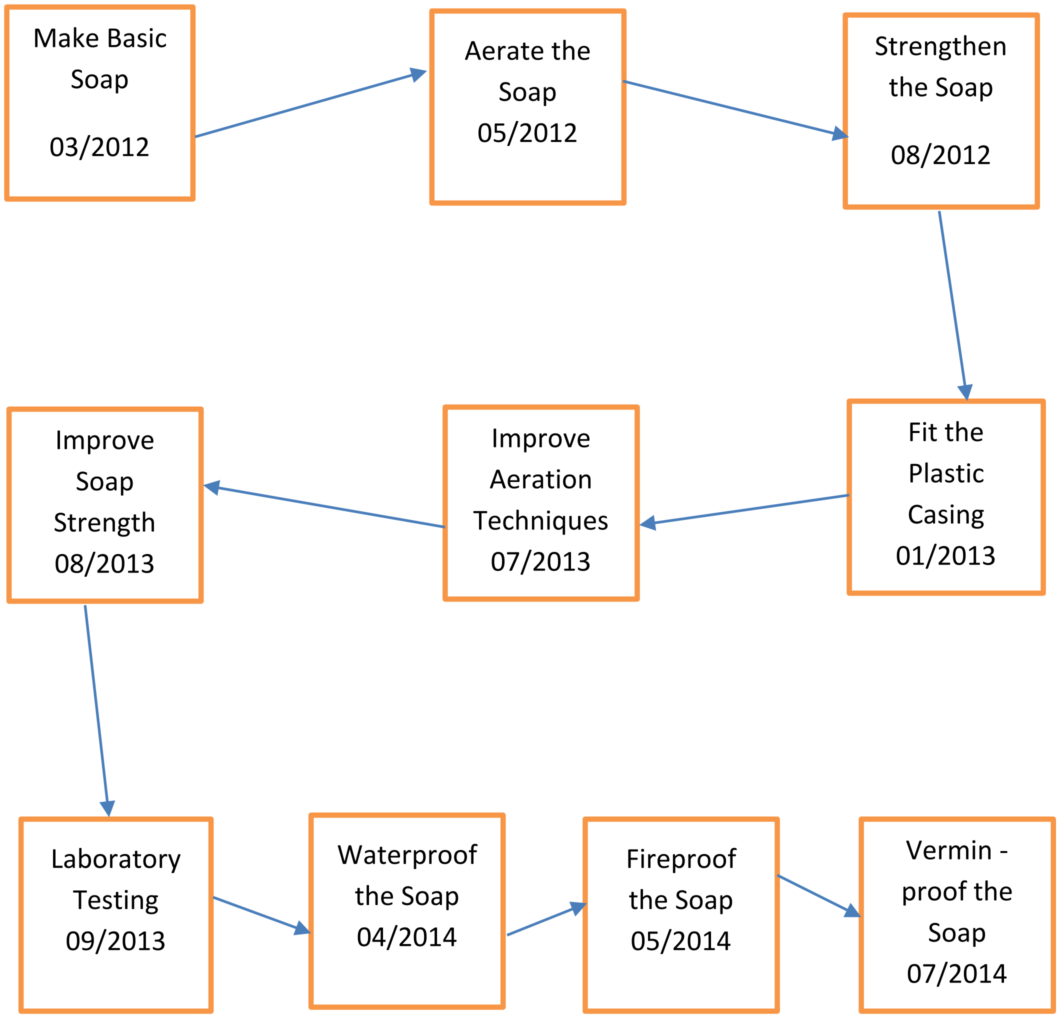


Figure 3.6: Stages of Experimental Research

3.3 Research Approach

The research problem should suggest the research approach. The research approach allows the researcher to satisfy the stated objectives. As described earlier, the research approach to the research question will be one of objectivism and positivism. Easterby-Smith et al (2012) describe objectivism *as* positivism. The traditions associated with objectivist research are shown in Fig.3.7 on the following page.

Assumption approach	The objectivist
Ontology	Realism
Epistemology	Positivism
Human nature	Determination
Methodology	Nomothetic

Figure 3.7: The Objective Dimension (Adapted from Burrell & Morgan, 2012)

Working from an objectivism perspective, House (1970) believed that the research approach should include the following:

1. A presupposed, deductive hypothesis.
2. A presupposed, deductive criterion used to gauge the hypothesis.
3. Control and isolation of the variables under investigation.
4. Techniques of measurement and substantiating of the variables within the systematic examination.

Gill & Johnson (1997) suggest that these preceding points should be challenged on the following grounds:

5. Awareness that no single method exists that generates scientific knowledge in every case.
6. Knowledge generated can be affected by personal influence and validation criteria.
7. Appropriate research methods vary as to which social, physical or natural world area is under investigation.

Yin (2002) went a step further by suggesting that the research approach should also take into account the following considerations:

8. The character or qualities of the enquiry and the type of question asked.
9. The degree or extent of the researcher's control over the actual events.
10. The degree of attention on the characteristics of present events.

With regards to the actual soap processing experimentation, the majority of data will come by means of experiments. The first step is to manufacture some test samples of soap. These soaps will be made with variations to both the soap setting times and the soap ingredients. The finished articles will be evaluated against a set of testing criteria to ascertain if the product needs modifying for improvement or if that particular sample will perform as an insulation. Air, other gases or solid additives may be introduced into the liquid (before setting) mixture for aeration purposes and to create a lightweight structure once set. After this stage the product(s) can be sent for laboratory testing. In this instance, the research approach will be inductive as opposed to deductive. In general this means that the research question will narrow the scope of the study. This method is best suited to scientific study as inductive reasoning adapts one area of data to establish a general theory or assumption (Hughes & Lavery, 2015). The inductive approach often explores new phenomenon through open-ended and exploratory means. A basic inductive approach flow-chart is shown below (Fig. 3.8).

Figure 3.8: Inductive Theory (Adapted from Schutt, 2006)

Deductive theory is concerned with the testing of hypotheses. That is, starting with a theory and then testing its implications with data (Hughes & Lavery, 2015). In effect, moving from the general to the more specific (deducting conclusions from propositions) In general this approach is the opposite to the inductive approach and as such does not relate to this doctoral research. Fig. 3.9 on the following page shows a simplified process model of the deductive theory.

Figure 3.9: Deductive Theory (Adapted from Schutt, 2006)

A diagram depicting the deductive versus the inductive approach is shown in Fig.3.10 below.

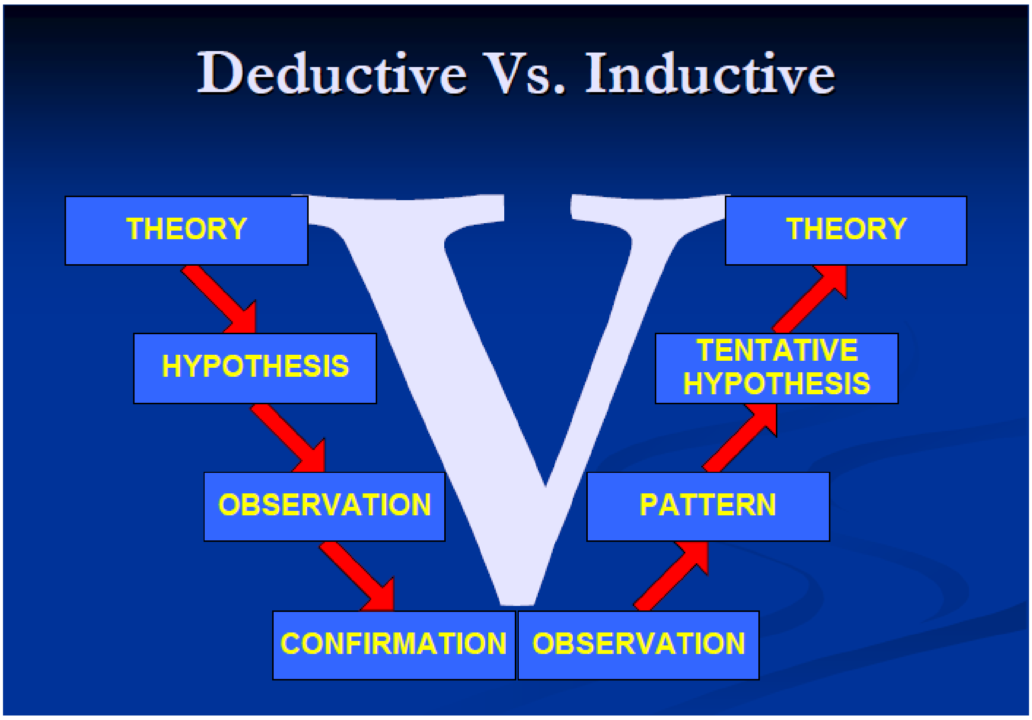


Figure 3.10: Deductive Vs. Inductive Approach (Burney, 2008)

3.4 Research Strategy

Alongside the strategies listed in Saunder's research onion, other research methodologies have also been identified. Table five on the following page reveals some of the methodologies identified by Isaias (2012) that could be useful in experimental research. Table five also reveals that laboratory experiments are the preferred strategies for this study. Along with the variations to the physical research, the design and choice of methods will be constantly modified, dependent upon the ongoing analysis. This will allow investigation into new issues, problems and questions as they arise, and will allow the researcher to progress, whilst dismissing the unproductive areas of research from the original research plan. All of these criteria fall under the remit of experimental research. This carefully controlled research design (experimental design) is the only design capable of allowing the researcher to draw definitive conclusions from the experimental cause and effect relationships (Isaias, 2012). Thus, a planned experimental approach will be exercised to answer the original research question. This scientific approach allows the researcher to manipulate the variables to test a hypothesis and measure the change (cause and effect) (Isaias, 2012). This systematic, objective controlled investigation is ideal for the purpose of controlling phenomena and examining the probability and causality between the selected variables. For the nonprofessional, the independent variable (the cause) is manipulated to assess the impact upon the dependent variable (the effect) (Shuttleworth, 2008). It is through direct intervention into the research problems that the researcher attempts to create practical outcomes, whilst also attempting to anew existing theories within the domain studied.

Scientific/Positivist
Laboratory Experiments
Field Experiments
Case Studies
Theorem Proof
Forecasting
Simulation

Table 5: Table of Research Methodologies (Adapted from Isaias, 2012)

The experimental research used consists of a series of soap related experiments that analyze the cause and effect relationship at each experimental step. For example, conduct an experiment, then measure and observe to assess the outcome (conclusion). In effect the researcher is manipulating the variables in order to control and measure the effect on the dependent variable(s). It should be stated however that experiments and experimental research are not the same thing. The diagram (Fig. 3.11) on the following page represents a typical experimental research cycle.

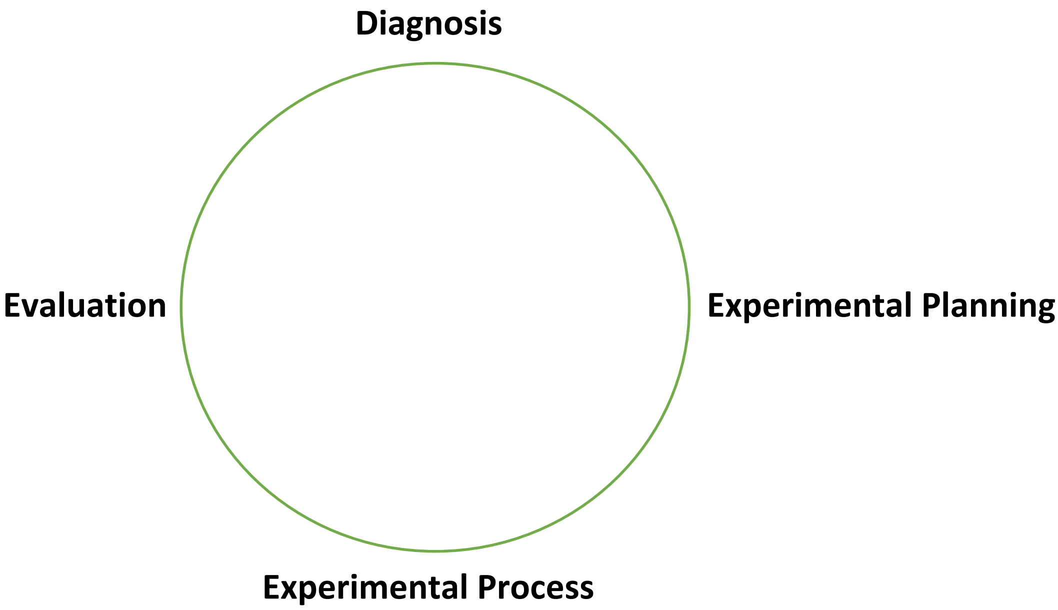


Figure 3.11: Experimental Research Cycle

3.4.1 Diagnosis

This is the stage whereby the background knowledge relating to soap manufacture and established thermal insulation manufacturing methods are scrutinized in an attempt to build upon the existing data. Using both primary (collected first-hand from sources including own literary texts and experiments) and secondary data sources (gathered by researchers and recorded in books, articles, and other publications) (Johnson & Christenson, 2007), the information should help "pave" the way for the experimental stages to begin.

3.4.2 Experimental Planning

This step involves utilizing the information gathered in the diagnosis stage to help in forming the research hypothesis and using it to plan a road map to help organise the experimental program. In this program, the researcher tries to observe phenomena (objectively) which take place in a controlled environment or situation, whereby one or possibly more variables are diversified whilst the rest are kept constant. The program broadly follows the following six steps, (adapted from Fogler & Gurmen's [2008] "Flowchart for experimental projects.") shown on the following page.

1. Define the objectives for the experiments.
2. Recognise the important variables.
3. Design the experiments.
4. Perform the experiments.
5. Analyse the results.
6. Act on the results.

3.4.3 Experimental Process

Comparable U-value studies against existing thermal insulations will provide a means of determining whether soap insulation can be construed as a viable, sustainable alternative. Studies have been conducted into the following areas:

1. Aerated soap derived from animal fats and lye.
2. Aerated soap derived from waste restaurant vegetable oils and lye.
3. Aerated soap derived from waste engine oils and lye.
4. Soap with added ingredients to explore its lightweight capabilities.
5. Soap with added ingredients to explore its overall strength capabilities.
6. Lightweight insulation structures derived from keratin.

Some of the soap samples were surrounded with a plastic casing for protection of the soap contents from moisture, vermin and insect egress. Studies would also be conducted using the following sustainable materials for the plastic casing, if the initial results were favorable.

1. Sugar or corn bio- polythene based plastics.
2. Green plastics derived from vegetable oils.
3. Green plastics derived from algae.

The experiments must be controlled. For example there must be a constant. This will take the form of a control (soap). This will act as the “neutral” and will be the basic comparable to the performance of the experimental products. Confounding variables (variables that the researcher fails to eliminate, potentially damaging the validity of an experiment) will be limited and controlled as best as they can under the circumstances. This should eliminate false explanations or conclusions for any observed effects. The finished products will be tested to ascertain the insulation's performance in the laboratory setting. The Thermal Testing Laboratory at the University of Salford tests the manufactured samples for their thermal resisting properties. The insulation samples were sized at 300mm X 300mm surface area with depths of 50mm. The research will conclude with a thermal conductivity comparison determination to reveal how the soap insulations compares with a selection of established petroleum based insulations.

3.4.4 Evaluation

Evaluation is the disclosure of meaning and structured interpretation to the impacts of the results or proposals (Isaias, 2012). This method uses a host of techniques for scientific research into alternative thermal insulations, whilst acquiring new knowledge into the sustainable components within. This scientific method of inquiry is centered on both measurable and empirical evidence gathered through a procedure of systematic observation, experiments and measurement, with the hypothesis continually being formulated, tested and modified. This scientific inquiry, as with all scientific inquiries, is calculated to be objective to eliminate the chances of bias in the results interpretations.

The main quality which separates this scientific method from the other research methods is the action of positive confirmation when the theories are "proven". For example, supporting a theory upon confirmation of a theory's predictions and challenging theories when the predictions are proven wrong. Both prominent and subtle identifiable features will separate this scientific based inquiry from the other methods of obtaining both data and knowledge. These features include proposing tentative explanations for an observation (as an explanation of a certain phenomenon), and designing experiments to test out the hypothesis via the predictions derived from them. The theories encompassing the wider areas of investigation will group independent hypotheses together in a supportive, coherent, collective structure. In turn, these theories may promote new propositions or at least place the aggregation into context. The conclusion to the experiments will be based on validity (to what degree the research reflects the given research problem) and reliability (how consistent the measurements are). Replication studies will be used to further test the reliability. The observations (empirical evidence) and logic will ultimately lead to the conclusion and it is these two factors that can be checked to validate the conclusion. This research is practice-based.

3.5 Research Techniques for Experimental Data Collection

According to Mertens (2008), there are many methods for data collection. These include observation, experiments and archival and follow-up studies. Observation is used to detect changes in a controlled experiment to isolate the effect of a single factor. The effects would be recorded so that the results can be “built on”. Scientific theories are based upon controlled and repeatable experimental protocols. This allows for the recording of accurate data from solid testable evidence (Mertens, 2008). Conducting experiments gives a clearly defined path to follow in a quest for ongoing improvements. Referring to historic experimental data and archived results from similar products, tested and recorded at the thermal testing laboratory, will create comparison data and may eliminate the need for excessive amounts of experiments. Follow-up studies can be used to collect and evaluate the long-term experimental outcomes. This will help to obtain generalized knowledge about the product and enable developed faults to be “ironed out”.

Defining the experimental unit will help to achieve the detailing of the data collection format. This is the purpose of the research and is the analysis unit within the experiment that is used to collect data. For example, in this research context, the unit will be soap insulation. Once defined, the sources of variability must be identified within the experimental conditions. Trying to improve the precision of the results, in order to investigate the research hypothesis, is the objective. Inconclusive results can occur if the following variables are not sufficiently defined (Mertons, 2008). Fig.3.12, shown on the following page, demonstrates the relationship between the four main variables and the research question.

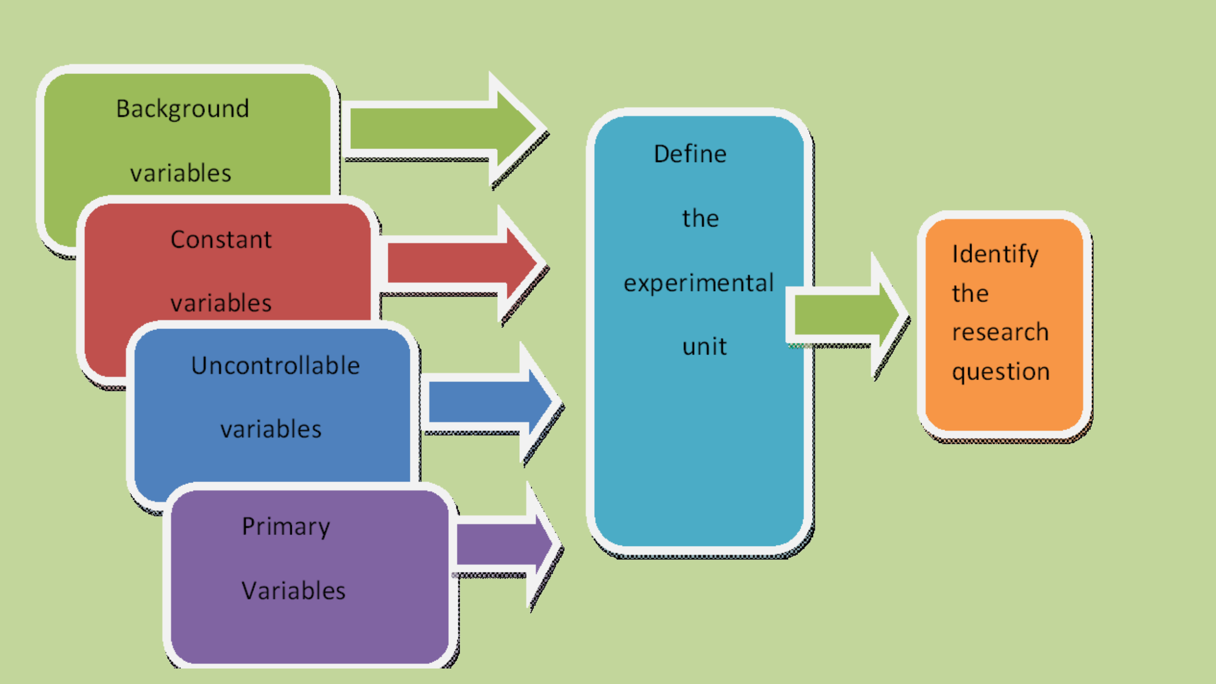


Figure 3.12: Experimental Data Collection

3.5.1 Types of Variables

1. Background Variables

These are both identifiable and measurable but are uncontrollable (Vollmer, 2013). They will have a negligible bearing on the outcome of the experiments undertaken. If background variables are applied to an analysis, a superior estimation of the primary variables may be the result. This is because the variation sources that have been supplied by the control variants have been taken away. The different fats and oils are background variables. The fats all contribute to the soap manufacturing process, but will create soap of differing qualities and texture.

2. Constant Variables

Constant variables can be measured and controlled but will remain constant throughout the continuance of the research (Vollmer, 2013). This action will increase the result's validity by halting or reducing external variation sources and stopping them from "clouding" the data. Soap aeration is a constant variable. Aeration is a key requirement for soap insulation to perform. The size of the air pockets or bubbles is irrelevant in a constant variable context, as any size bubble will allow the soap insulation to perform, although to differing degrees of thermal performance.

3. Uncontrollable Variables

These are variables that refuse to be manipulated and are difficult to measure (Vollmer, 2013). Errors occur in data because of the influential effects of these uncontrollable variables, which affect the evaluations of the background and primary variables. Planned experimental design should control or eliminate uncontrollable variables. This will increase the reliability of, and heighten confidence in the end result. In the ensuing experiments, the controlled variables is the strengthening measures adopted for the accepted soap body. The uncontrolled variable is how the product performs under strength testing. This performance is unknown before the results are revealed and so the strength of the soap is beyond the researcher's control. This is one example. Uncontrollable variables are present in the waterproofing, vermin repelling and fire proofing of the insulation product.

4. Primary Variables

Primary (independent) variables are the usual sources of variations in the responsive reaction (Vollmer, 2013). For example, the values that can be changed in a given model or equation. These primary variables contain the design and treatment structures and provide the "input" which is modified by the model to change the "output." The research question asks if soap can be used as an alternative to petroleum in thermal insulation. The independent variable is the composition of the soap within the experiments. This is controlled by the experimenting researcher. The values that result from the independent variables are called the dependant variables. The actual experiment is a situation in which the researcher attempts to make unbiased and impartial observations in the experimental situation (Johnson & Christenson, 2007). As the experiments progress, samples will be manufactured, tested and remanufactured in a cyclic process of improvement (Fig. 3.13 shown on the following page). This evolution of an idea should incorporate the testing of the hypothesis or null hypothesis (no difference existing between the control and experimental group) for the variables being compared.

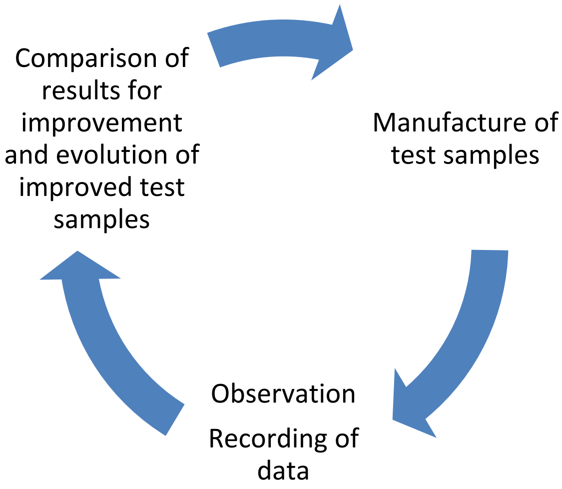


Figure 3.13: Testing & Manufacturing Process Loop

3.5.2 Research Process Design

The research process is based on the cycles of soap sampling and experimental testing. This process will identify the preliminary stages before the thermal laboratory testing and the stages during the thermal laboratory testing.

Preliminary Testing: Different types of fats and oils (including waste engine oil) will be used in the soap manufacture. This identifies a soap body that is the most receptive to aeration and strengthening procedures. At this stage the soap can aerated with different products and by using different aeration techniques to make the soap lightweight and thermally efficient. Strengthening the soap body will take place at this stage to create a soap body that can withstand accidental knocks without breaking. A protective casing will need to be fitted to the outside of the soap body for protection. At this stage the soap casing will made from plastic sheet.

Laboratory Testing: The samples taken forward for laboratory testing had aeration voids of differing sizes. This will identify the optimum size of air void to give the most favourable thermal conductivity and thermal resistance results. Different casings will be tried for the protective casing.

Improvement Testing: The insulation samples will treated to make them moisture, vermin and UV resistant. The casing will also be made fire retardant.

3.5.3 Research Techniques for Data Analysis

Sequential hypothesis testing is the use of a sequence of experiments, whereby the design of each stage depends on the results of previous experiments, including the possible decision to call a halt to the experimenting (Fukunaga, 2013). The soap insulation experimentation is organised along this process. In order that the process runs smoothly, explicit knowledge of prior research must be observed. Alongside this, the know-how of interpreting and recording basic statistics and observations, expertise of constructing databases, alongside knowledge of the implications of the experimental research should be considered (St. Pierre, 2004).

To analyse the data for research techniques, the causal analysis strategy will be employed. This strategy searches for the cause or causes of particular events. A causal factor is a variable which may cause changes in another variable. In a similar way but to a lesser extent, correlational analysis may also be employed. In correlational research, variables are not influenced, but only measured in order to look for relations (correlations) between sets of variables (McNabb, 2008). This will be important for the *control* test samples.

3.6 Basic Soap Manufacture

The preliminary manufacture and testing of the soap ($3HC_3(CH_2)_{14}CO_2N_a$) creates a foundation to support the ongoing refining of the soap insulation product. In order to change the oil to soap, a process of saponification needs to occur. Basically, oils are mixed with an alkaline solution (potassium or sodium hydroxide), derived from lye. This mixture promotes saponification (where the fats are hydrolyzed [broken down], creating a crude soap [i.e. salts of glycerol and fatty acids] (Nielsen, 2010). See Fig. 3.14 below.

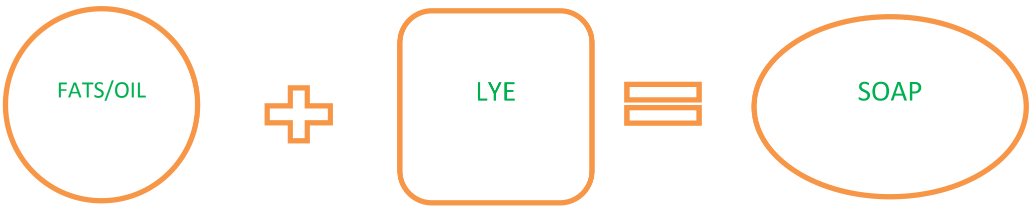


Figure 3.14: Basic Soap Production

Differing quantities or strengths of lye added to different types of fat, i.e. lard (pig), tallow (cow) or vegetable oils will create different types of soap (Phanstiel et al, 2008). These soaps can range from liquid soap to soap that is very hard. The soap that this thesis is concerned with will be very hard. Sodium hydroxide (N_aOH) mixed with animal fats tends to produce a harder soap than soap derived from potassium hydroxide (KOH), but both sodium and potassium soap can be altered at a chemical level, at the initial mixing stage, to create different soap types (Thomssen, 2015). Adding salt to potassium hydroxide will give it sodium hydroxide characteristics (Thomssen, 2015).

Generally the weight ratio for the component parts i.e. lye, water and oil is 1:3:7 respectively (Thomssen, 2015). The actual component weights (in grams) used for the soap samples are revealed in Section 3.9. The resulting mixture sets hard to create the *basic* starting soap samples for the proceeding experiments. These experiments involve strengthening and aerating and are shown in the flow diagram (Fig.3.15) below.

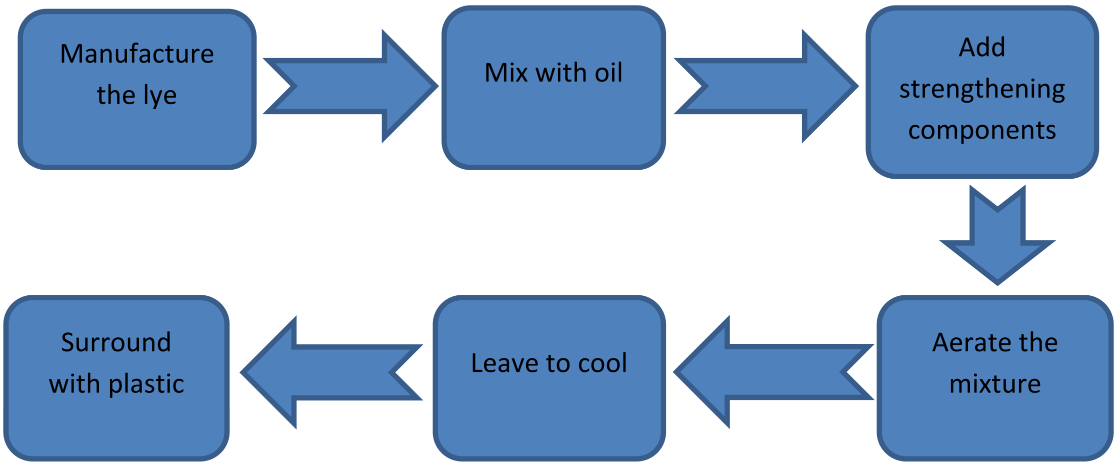


Figure 3.15: Process Diagram Showing Steps of Soap Material Development

3.7. Manufacturing the Lye

Potassium hydroxide was created by adapting the instructions given on the website "Journey to Forever" (2011). Oak branches were burnt because hardwoods leach more lye than softwoods. (Journey to Forever, 2011).The ashes (K_2CO_3) were then collected. A barrel was sourced and a 100mm covering of gravel was placed inside the bottom. 150mm of hay was placed on top of this gravel. This is the filtration system. A small hole was drilled into the bottom of the barrel and a cork fitted to act as a plug. 10 litres of ash were placed into the barrel and 30 litres of rainwater (H_2O) were poured over the ash and allowed to settle. The resulting mixture was allowed to sit for fourteen days, with occasional stirring. The water was then drained off, strained though a nylon sieve and then filtered into a jar. (See Fig. 3.16- 3.19) below and continuing on page 80.

Figure 3.16: Oak Branches

Figure 3.17: Oak Ashes

Figure 3.18: Mixing Barrel

Figure 3.19: Lye

The resulting lye was pH tested to determine its alkalinity and then used for the soap manufacture. The potassium hydroxide lye (KOH) derived from oak ashes is best suited for making soft soap (Practical Action, 2010). For the soap insulation, a block of hard aerated soap will be required. This meant that the potassium hydroxide (KOH) must be changed into sodium hydroxide (NaOH). This was actioned by adding salt to the potassium hydroxide (KOH + N_aCI =N_aOH). The lye was then ready to be blended with the fats (Practical Action, 2010).

3.8 Fats

A selection of fats and oils were required to complete the processing of the various soap types that will be used as the comparables. These fats included beef fat, pork fat, palm oil, used waste vegetable oil and used waste engine oil. The composition of fats and oils varies according to which family of fats they belong to. Typically fats from animal sources tend to be solid at room temperature, whilst fats from vegetable sources tend to be liquid (Thomssen, 2015). Usually oils will contain three types of fats within their structure: Saturated fats (containing carbon atoms saturated with hydrogen atoms in the molecule), monounsaturated fats (containing one double-bonded carbon atom in the molecule) and polyunsaturated fats (containing more than one double-bonded carbon atom in the molecule) (Brown, 2010). Usually, unsaturated fats have a lower melting point than saturated fats (Brown, 2010). The percentage of fats per source type is shown below.

- Beef fat: 50% saturated fats. 45% monounsaturated fats. 5% polyunsaturated fats.
- Pork fat: 40% saturated fats. 50% monounsaturated fats. 10% polyunsaturated fats.
- Palm oil: 50% saturated fats. 40% monounsaturated fats. 5% polyunsaturated fats.
- Vegetable oil: 10% saturated fats. 55% monounsaturated fats. 35% polyunsaturated fats.
- Engine oil: Is the exception. The components of petroleum oil have been revealed earlier into this report.

3.9 Acquiring the Solidified Soap Outputs

There are two processes for making soap. The hot process and the cold process. Both will create soap of good quality (Thomssen, 2015). Hot Process: Oil and lye are mixed then boiled at 80^0 – 100^0 C to initiate saponification. This is the stage where the mixture turns to a gel. Salt is added to the gel to precipitate the mixture and then the excess liquid is removed. The resulting warm, soft soap mixture is then placed into a mould. This mixture is left to cure and harden for approximately 4 weeks (Ditchfield, 2012).

Cold Process: Both the lye and the oil are heated separately then cooled to approximately 40^0C, they are then combined. After blending, the mixture starts to thicken, the viscosity increases, and the mixture achieves “trace” (the sudden thickening of the liquid as it starts to solidify). The mixture is then poured into a mould to harden. As the soap hardens, it loses its causticity and is safe to handle (Stein, 2008). The saponification (conversion of fat to soap) chemical reaction is shown Fig.3.20 below.

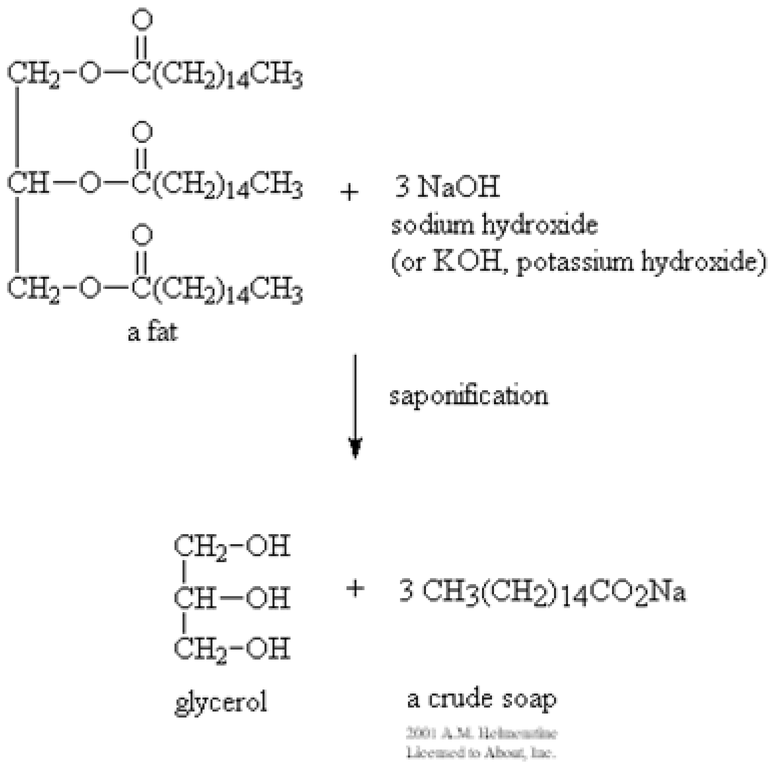


Figure 3.20: Saponification Chemical Reaction

The cold process soap manufacturing method is the method used for the research experiments in this thesis. This method is chosen over the “hot process” because of the speed in which the soap reaches saponification (five minutes as opposed to three hours). As mentioned previously, the cold process involves adding the lye to water and mixing it with heated oil, whilst both ingredients are stabilized at a temperature of 40^0 C. The mixture is blended until it thickens (achieves trace) and then poured into a mould to set (Palmer, 2007). The hot process requires the lye and oil mixture to be cooked (alternating heating and cooling) for three hours in a slow cooker, poured into moulds and left to harden (Grosso, 2013). This method boils off excess water from the mix and negates the need to mix the lye and oil at the precisely the same temperature (40^{0}C). In both processes the saponification setting action reduces the lye soap mixture from a highly alkaline substance to one that is pH neutral. Both methods are shown in the flow charts (Fig. 3.21) below.

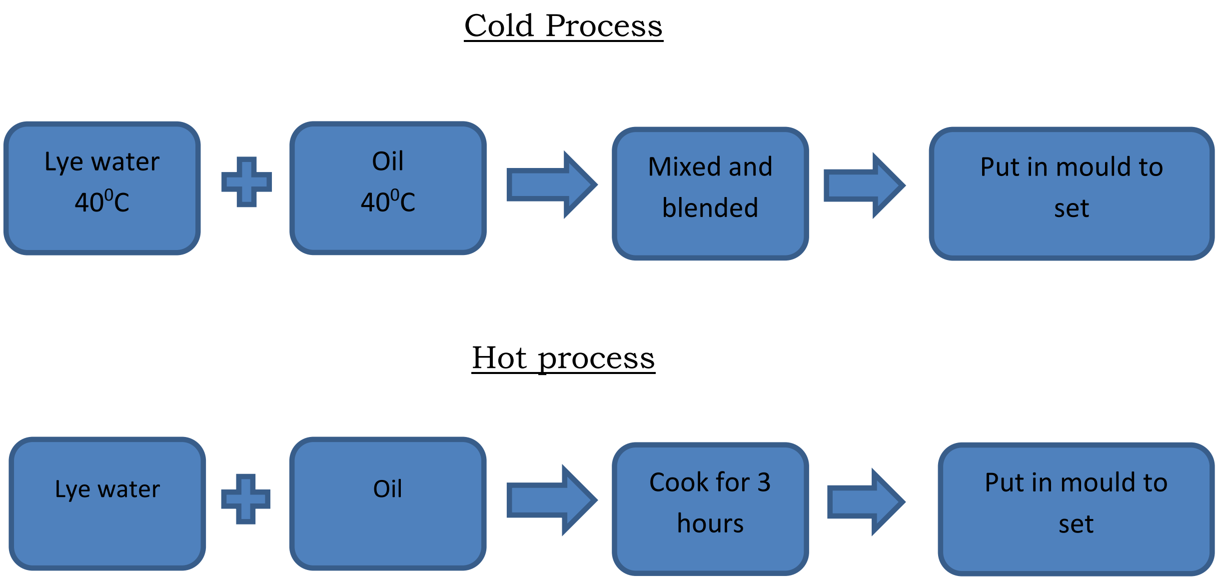


Figure 3.21: Basic Soap Production

Manufactured NaOH powder was used for ease and convenience once the ashes based lye had been proven to perform. The process was repeated five times with different oils. All of the samples were mixed as per the following proportions: 250g of oil. 34g of sodium hydroxide dissolved into 92g of water.

3.10 Preliminary Results from the Soap Development Process

A pH (potential of hydrogen) test was carried out on this lye liquid and the mixture was confirmed as alkaline registering a pH confirmation of 14 on the indicator testing strip. The lye was then placed into containers of water measured at 92g, for use in the manufacture of the soap test samples. (It should be stated that the soap ingredient weight measures were partially achieved through a system of trial and error experiments beforehand, and conversions and adaptions of soap manufacture instructions taken from books). Two soap samples were manufactured using the ashes derived potassium hydroxide and beef fat (92g of KOH and 250g of fat). One sample was blended and left to solidify. 40g of common salt was added to the other sample, then blended and left to solidify. The results were as follows:

- The potassium hydroxide soap without the added salt set to a semi solid state, somewhere between a liquid and a solid.

- The potassium hydroxide soap with added salt (In effect the KOH now converted to NaOH) set solid over a 10 minute period. The manufacturing process was repeated with each of the five oil types listed below and the addition of salt to the ashes based lye. The soap setting time results table is shown in Table six below.

Oil ingredient	Time achieve trace	Setting time (solid)
Beef fat	90 seconds	10 minutes
Pork fat	2 minutes	1 hour
Palm oil	5 minutes	1 hour
Waste vegetable oil	6 minutes	30 hours
Waste engine oil	12 minutes	60 hours

Table 6: Soap Setting Times

As can be seen from the "soap setting time" table, beef, pork and palm oil have similar consistencies and create soap over a broadly similar time-frame. This is because the proportions of fats within the oil have a direct bearing on the length of time required for the soap to set hard. It should be noted that the waste engine oil used in the soap sample failed to set into a hard solid soap, but instead into a soft, flexible, "rubbery" material (Shown in Fig.3.22). It was decided that further research into soap insulation using waste engine oil as the base would be discontinued, as the soap would not perform as thermal insulation unless it set solid. Soap samples manufactured from the other four oils set hard (see Fig. 3.23 on the following page).

Figure 3.22: Waste Engine Oil Set to a “Blancmange” State

Figure 3.23: Block of Hard, Solid, Waste Vegetable Oil Soap

3.11 Making the Soap Lightweight

Mixing oils and lye will create a hard soap mixture that once cooled can be cut into rigid board and surrounded in plastic to create thermal insulation. The air bubbles within the soap give the insulation its thermal properties. The arrangement of the molecules within these air pockets is such to utilize air as the insulator. In relative terms, the molecules in air are not in contact with each other. This makes heat transfer via the molecules difficult. This is because air is a very low density material. The sparsity of atoms per unit volume means that there are few heat transfer type collisions (vibrations). If the air is trapped (and therefore motionless) it cannot transfer heat to another location. The air insulator frustrates the heat transfer mechanism of all three heat transfer mechanisms; conduction, convection and radiation (Pan Global, 2006). The soap based insulation products can be used in walls, floors and roofs to maintain a gradient of temperature by reflecting heat as opposed to allowing its absorption and escape. In order to make this product lightweight (and thermally efficient), it was necessary to aerate the mixtures. The mixing ratios listed previously were used in the manufacture of the following test samples and the weight and weight differential was recorded in the chart (Fig.3.30 on page 93). Various methods of aerating soap were tried. These included the addition of paper fibre balls, polythene balls, ice spheres, straw, expanded Expancel microspheres and the vacuum air removal method. A variation of the Expancel aeration method was also tried using bicarbonate of soda. The methods used to manufacture the test samples are shown on the following pages.

3.11.1 Soap with no Additives

A sample of soap was mixed using the following ingredients. 250g beef fat (Fig.3.24), 36g sodium hydroxide and 92g water. This was an identical ingredients mix as was used for the subsequent soap batches, but in these, no aerating additives were included. The soap with no additives was used as the control.

Figure 3.24: Selection of Raw Beef Fat

3.11.2 Aeration Box

Various methods were tried to aerate the soap. The first was by using an aeration box. Basically, a wooden box (300mm X 300mm) was constructed with a base and four sides 100mm high. Twelve 9mm holes were drilled into the sides, three to each side. A collection of linked plastic piping was connected to all of the holes and this arrangement was connected to a compressor. Liquid soap achieving trace (the point whereby combined fats and lye thicken into the initial soap stage) was poured into the box and the compressor was switched on, pumping air into the soft soap mixture. The compressor was too weak to push air through the tubes and so the soap mixture remained unaffected. The testing was tried again, still using the same box and plastic piping arrangement, but with a more powerful compressor. The results were almost identical. The air pressure was still not strong enough to travel through the pipe arrangement and penetrate the dense soap matter to actually aerate the mixture. An example of the aeration box is shown in Fig.3.25.

Figure 3.35: Aerating Box with Air tubes and 12v Compressor

3.11.3 Soap with Added Straw

Another method of creating a lightweight aerated sample was the introduction of short fibres of straw into the mix. Straw is hollow and is a good insulator (Elpel, 2010). It is a by-product of farming and is totally biodegradable (Elpel, 2010). The dictionary definition of straw is “dry cut stalks of corn” (Elpel, 2010). Straw is the plant material that is left after the crop has matured and been harvested. It is no longer alive. According to Gross & Bauen (2013), the UK produces over 15 million tons of straw annually. The stalks have low animal digestibility and are used for animal bedding as opposed to animal food. The chemical composition of straw reveals that the cell walls are made primarily of a mixture of carbohydrates, protein, silica and lignin. It is the silica and lignin that makes the straw un-digestible. Lignin also acts as a barrier to microbial digestion of the structural carbohydrates (Christensen, 2011). The hollow air containing stems are also well known for their thermal properties and as such, straw bale houses are becoming ever more popular (Jones, 2010). For the soap experiment, 15g of straw cut into lengths of 10mm - 15mm were added to a soap sample mixture (Fig.3.26). The additive equated to 50% of the soap mould’s cubic volume.

Figure 3.26: Straw Cut to 10mm – 15mm

3.11.4 Soap with Added Expancel

Yet another method of aerating the soap was the introduction of *Expancel* microspheres. These microspheres are tiny spherical particles that expand to many times their original size by the introduction of heat (Ash & Ash, 2007). For the heat process to work, the mixture that the spheres are introduced into must reach a temperature of 80^{0}C -250^{0}C (Expancel, 2011). However, soap temperature when mixing and setting peaks at around 50^{0}C. It is the heat that triggers the spheres' expansion. Already expanded microspheres can be introduced into a mixture though. This addition not only aerates the mixture, but also gives the finished structure compressibility and lightweight properties (depending on the amount introduced), ideal for insulation products. The one drawback being that the insulation product is no longer *entirely* natural, recycled or chemical free. The actual ingredients for this product are a manufacturing secret. However research through the Expancel safety data sheets reveal that the microspheres consist of a copolymer and isobutane (C_4H10) combination.

Soap with added Expancel (Fig.3.27) was processed. For this soap mixture, as with the other test samples, the soap ingredients were weighed as per the proportions stated in Section 3.9. The water was heated to 100^{o}C in order to initiate a reaction from the Expancel powder. The Expancel was weighed at 0.5g (4 tablespoons) and added to the water and lye mixture. The normal process of blending to achieve trace, and the pouring of the liquid soap into the mould to cure was completed. The weight of the product was recorded one week later.

Figure 3.27: Expancel Microspheres

3.11.5 Soap with Added Paper Spheres

Small, hollow, dried waste paper based spheres can be introduced into the soap mixture in place of straw. These can be lightweight cellulose fibres and of the type normally used as stabilising additives to stone mastic asphalts and hot rolled asphalts (highways), or the more paper based, as used in art and craft hobbies. The paper can be recycled from low quality products such as newspapers etc. The size of these particles is typically 10mm – 15mm. An identical soap base mixture as listed previously was created, but this time with the addition of 37g of 15mm paper balls (Fig.3.28). This 37g equated to approximately one half of the soap mould cubic area by volume. This left a sufficient volume of soap to bind the mixture together for the product strength.

Figure 3.28: Combination of 10mm & 15mm Lightweight Paper Balls

3.11.6 Soap with PEHD Spheres.

An alternative to paper is to use small (10mm) hollow plastic balls made from waste PEHD (Fig.3.29). These are also extremely lightweight and should also give the insulation good thermal properties. An example of 10mm balls is shown on the following page. This batch of soap was made in an identical way as the previous paper ball additive soap, only this time the paper balls were replaced with 25g of 10mm PEHD hollow spheres.

Figure 3.29: 10mm PEHD Hollow Spheres

3.11.7 Soap with Added Ice

The rationale behind this idea was that ice particles would be another method of aerating the soap. Small ice spheres would be substituted for the straw, paper and "Expancel". The ice would be introduced into the mix and as the temperature of the soap increased, and thus solidified, the melted ice would leave air pockets throughout. This should give the product lightweight properties.

Once again, another batch of soap was mixed but this time 10mm ice cubes were added as an ingredient. The ice was added to a batch of trace soap liquid but the soap immediately solidified on contact (with the ice). A test liquid soap mixture was introduced to a container of cold water and this soap also solidified instantly. Further investigation of ice added to soap was discontinued with a view to possible continuation in the future. Perhaps a temporary soap based sealant could be investigated for use in moist or wet environments, for example, a leaking water pipe or water container. If the liquid soap is applied into the space that the fluid is leaking from, in theory at least, the soap should instantly solidify on contact with the water within, creating a soap plug.

3.11.8 Aerated Soap with Added Sodium Bicarbonate

Aerating with an alternative, more natural additive was tried next. A bicarbonate of soda and vinegar foaming agent was compiled, at a ratio of two teaspoons to four respectively. This mixture foamed violently immediately the vinegar and soda came into contact with each other. This froth was introduced into the soap at the soap's liquid stage, after trace had occurred so as not to let the bicarbonate mix interfere with the actual saponification process (where the fat and lye combined to form the soap). The mixture was blended together and left to cure.

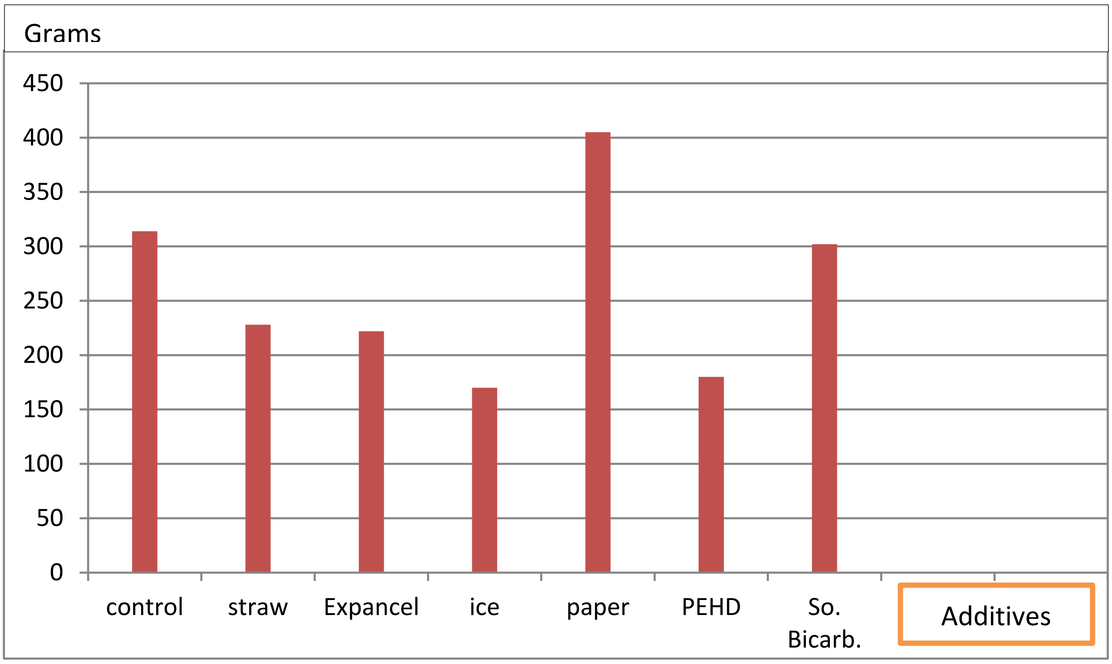
Observation revealed the soap to have separated into distinct layers. Soap occupied the bottom two thirds of the soap mould with ponding on the top third. The top third was a clear liquid with a salt glazed surface. A pH strip revealed the liquid to be an acid with a pH of five, whilst the soap below was alkaline with a pH of thirteen. The liquid was drained off and the soap was left to solidify. However, the soap failed to set firm and remained in a gel state. It also remained in a highly alkaline state.

In effect the addition of the blowing agent had separated the soap into three distinct layers, alkaline at the bottom, acid in the middle and salt on the top surface. Research using this type of mixed foaming agent was discontinued, with the next batch mixed using just sodium bicarbonate alone, in its powdered form. When compared with the control (soap with no additives), the sodium bicarbonate soap was slightly lower in weight than the control. However, the soap did not set hard enough to be considered for use as an insulation material. The soap structure had been considerably weakened by the addition of sodium bicarbonate and so this product was deemed unsuitable for purpose and further research into this particular product was halted.

An alternative to sodium bicarbonate is ammonium carbonate (hartshorn). When this is heated to 60^0C, the molecules within the ammonium carbonate break down into carbon dioxide, ammonia gas and water. In theory, a soap mixture aerated by whisking could retain air bubbles whilst at the same time releasing the two gasses and the water. It was deemed however that sodium carbonate and ammonium carbonate were too much alike chemically to have a positive effect on the soap aeration, and so soap processing going down this route was never started.

3.12 Comparative Analysis of Aeration Methods with the Control Soap

Following manufacture, the soap samples were dried and a moisture content reading was taken for each sample. When all of the samples had an identical reading of 35%, the samples were weighed. The results are recorded in Fig. 3.30.



The vertical axis shows the weight in grams

Figure 3.30: Soap Weight Graph Showing how Additives Affect Soap Weight

Table seven below shows the weight percentage difference between the control soap and the soaps with the aerating additives.

Paper balls*	29%	Heavier than the control
Plastic balls	43%	Lighter than the control
Ice balls*	46%	Lighter than the control
Straw	27%	Lighter than the control
Expancel	29%	Lighter than the control
Sodium bicarbonate*	4%	Lighter than the control

Table 7 Weight Difference Between Soaps

*Discontinued from further study.

Results showed that soap with added paper balls increased in weight. The reason for this is that the lightweight paper balls absorb and retain moisture from within the mixture, thus trapping the moisture inside of the sample, whilst the rest of the soap dries out. The worst performer, soap with the paper ball additives, was discontinued from this study with a view to possible investigation in the future.

3.13 Alternative Aeration Methods

Other aeration methods were also tried but met with only limited success. Soap was mixed and air was introduced whilst the soap was still in its liquid stage. This was achieved by using an off-the-shelf 1000ml clear plastic liquid soap hand pump dispenser. This was used to determine whether the theoretical concept of aeration whilst in a partial vacuum would work. The bottle was part filled with soap and the internal air tube was cut so as not to touch the mixture. The pump was depressed repeatedly to suck out the air above the soap mixture. This concept did work, albeit in a very limited capacity. A few bubbles did appear in the liquid soap, but not enough to aerate it. A 6mm hole was drilled into the side of the bottle midway between the soap's top surface and bottom. A 6mm tube was pushed in whilst the other end of the tube was attached to a 12V air compressor. Air was pumped into the bottle under increasing pressure and the soap bubbled violently and splattered around the inside of the container. However, the soap did not aerate in the true sense, i.e. creating an "aero" bar consistency, but rather fluctuated between two extremes. The soap either did next to nothing (barely registering any movement) or continually "exploded" around the inside of the container.

Another method was tried, a variation on the previous method. Another batch of soap was manufactured and poured into a plastic bottle. An air hose attached to a compressor was fed through the neck of the bottle into the soap mixture. The compressor was switched on, but the results were identical to the previous experimental trial. A lot of soap was splattering around the inside of the container. A second batch of liquid soap was made using potassium hydroxide instead of sodium hydroxide. This was to ensure that the soap remained in a liquid state as opposed to setting hard. The soap was poured into the bottle and the air hose applied. This time the soap did bubble and froth and expanded to an extra 15% of the soap's original volume. A salt solution was added to the mix and blended to try to harden the soap, but this did not work. The initial mix of liquid soap had gone past the point of allowing the salt to change the structure at a molecular level.

3.13.1 Enhancement of the Soap Aerating Process

Research was conducted through the British Library's Electronic Theses Online Service (EthOs), to determine whether previous submissions had mentioned methods of aeration. There was none. Research was then conducted into the patent submission archives to identify any potential aeration/soap insulation ideas from previous patent applications. Only one was listed that was remotely linked to soap insulation. An application was filed for an insulation product comprising of liquid soap bubbles, sandwiched between two sheets of glass which was sealed around the edges. This was marketed as a thermal insulation under the name "Solaroof". However, patent applications of methods to aerate soap for hygiene or cosmetic purposes were found. A Patent filed in 1940 (US2398776) revealed a method of aerating soap for "laundry and toilet use" purposes by aerating soap under pressure. A brief explanation is shown below.

Approximately 70g of soap flakes are fed through the hopper and then these flakes are heated by steam until they reach a temperature of approximately 90^{0}C. This mixture is fed into the chamber (14) and from here into two communicating vacuum chambers (4) & (5) by compressed air pressure acting on the plunger (11). In the first chamber the soap is subjected to steam heating, mixing by the rotors (12) and then forced under pressure through the second vacuum (to prevent air and moisture escaping) through an opening between (7) & (8), (not seen). The pressure used is monitored by the pressure gauge (115). When the soap is cooled, the ratio between bubbles and soap will be approximately 35% bubbles per soap bar. A simplified flow chart of this aeration method is shown below.

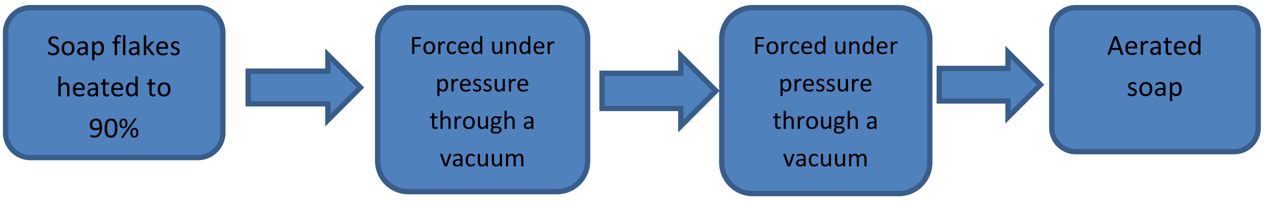


Figure 3.31: Diagram Showing how Soap is Aerated Using the US2398776 Patent Method

A diagram of the apparatus used to create the aerated soap is shown in Fig. 3.32 & Fig. 3.33 on pages 96 and 97.

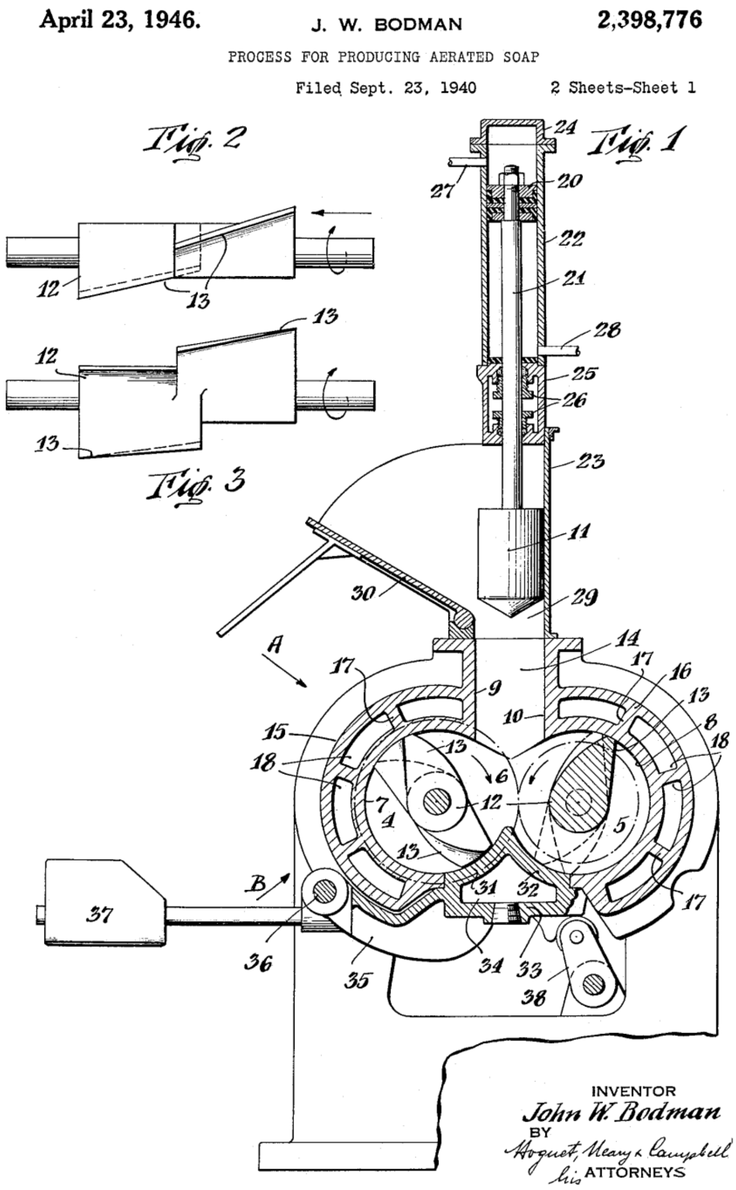


Figure 3.32: US Patent 2398776 Soap Aerating Machine (Bodman, 1946)

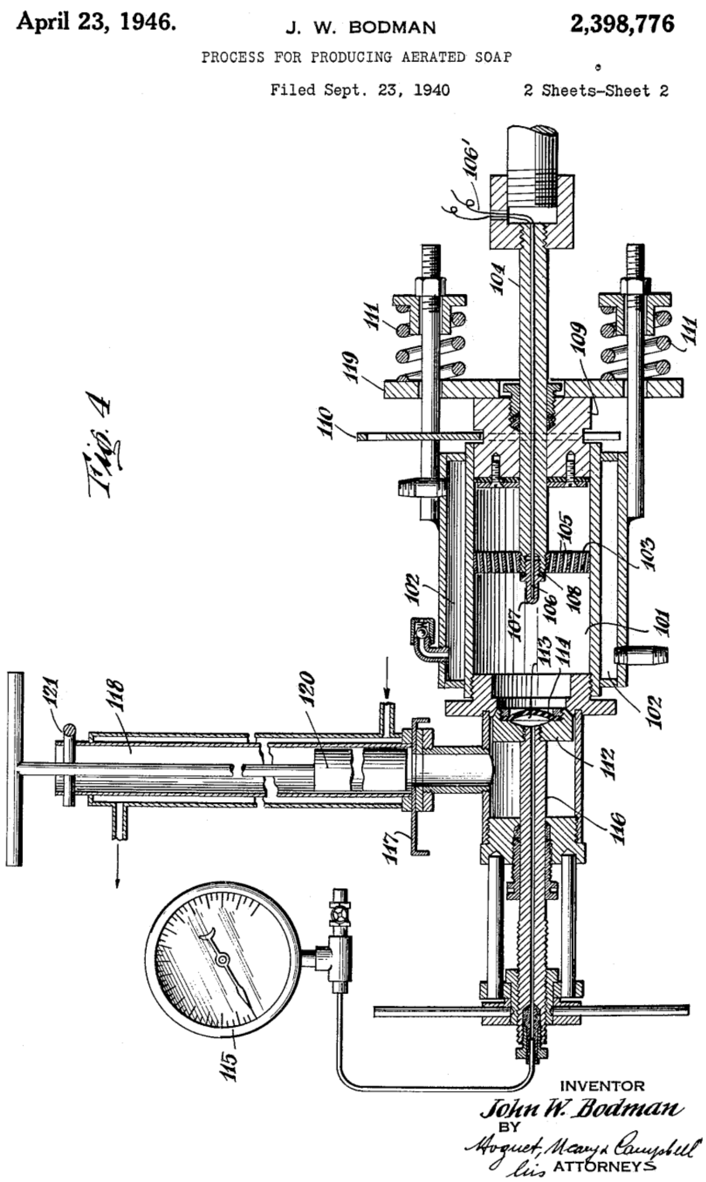


Figure 3.33: US Patent 2398776 Soap Aerating Machine (Bodman, 1946)

Another patent (11/304772) was filed in 2005 by the “Kao Corporation”, Tokyo, Japan. This was a method for producing aerated soap by injecting compressed molten soap, heated to approximately 70^{0}C, under pressure into a cavity. This method uses an inert gas (nitrogen) to produce the bubbles and gives a bubble content of around 80%.

Another batch of soap was mixed and was aerated using a method that is employed when making aerated chocolate (Barrett, 2012). This method would be to introduce air into the mixture under pressure. This would take place in a hermetically sealed container, with the air being sucked out from this container, creating a vacuum inside. This removal of air should create bubbles within the soap before it solidifies. Some brands of bubble chocolate have air introduced into the bar in this way (Chocablog, 2010). Injected molten soap is forced under pressure into a vacuum chamber. This method involves using a compressed gas whipped cream dispenser, a plastic holding container and a plastic vacuum bag. The process is shown on the following pages. Firstly, the liquid soap mixture was poured into a compressed gas (nitrous oxide) whipped cream dispenser (Fig.3.34).

Figure 3.34: Compressed Gas Whipped Cream Dispenser

Next, the soap was then fired under pressure into a plastic box with a sealable lid (Fig.3.35). The lid had a previously cut hole through its surface.

Figure 3.35: Plastic Container with a Hole in the Lid

The box is then placed into a PVC vacuum bag and the bag opening is zipped closed. The vacuum hole in the bag is aligned to the hole in the box lid. A vacuum cleaner sucks the air out of both the bag and the container (Fig.3.36).

Figure 3.36: Photo Showing Air Being Sucked out of Vacuum Bag

The bag was placed into a fridge for one hour (5^0C) and then removed. The soap was taken out and placed into a warm oven (40^0C) to reduce the moisture content to 35%. It was then weighed and the results were recorded (29% lighter than the control soap of equivalent cubic volume). The soap was then dissected to examine the bubble content (Fig 3.37). Although the soap was aerated, the bubbles were small (approximately 1-3mm width generally). However, with the preliminary experimentation into aerating the soap successful, the way was clear to refine and expand on the results to improve its overall thermal efficiency capabilities.

Figure 3.37: Aerated Soap Created by the Vacuum Method

3.14 Increasing the Elasticity of Soap

In order that the insulation can withstand accidental knocks without breaking and retain its shape throughout its lifetime, the soap must be strengthened. This was achieved by the addition of cotton thread fibres, added wool fibres and the addition of animal glue dispersed within the mixture at the soap's liquid stage before it hardens. Animal glue is natural and is derived as a by-product of the meat slaughtering industry (Gooch, 2011).

3.14.1 Polymer Glue Structure

Common glue is made by grinding bones into powder and then dissolving them in boiling water. The resulting mixture is then evaporated and dried into a hard jelly (Gooch, 2011). Animal glue is created by prolonged boiling of animal connective tissue and bone and is formed through the hydrolysis of the collagen contained. The subsequent proteins chondrin and gluten give the glue its strength. Animal glue added to soap creates a polymer (Rhatigan & Gunter, 2007). In theory this could give the soap added strength. This polymer usually takes on a rubbery texture with a solid mass. This process could also be investigated in the future as a base for the manufacture of a more natural acoustic/thermal combined insulation. It was reasoned that glue may have been a *required* addition to the soap mixture if the aerated soap refused to hold its structure whilst setting or became brittle once aerated.

A polymer is an arrangement of molecules strung together to form a chain. The resulting product can be rubbery, sticky or hard. All plastics are polymers, but not all polymers are plastic (Speight, 2011). The atoms that make up the backbone of the chain are repeated along the chain length.

chain	CH_2----	CH----	CH_2----	CH----	CH_2----	CH----	CH_2----	CH----	CH_2
pendant		I		I		I		I	
methyl group		CH_3		CH_3		CH_3		CH_3	(Speight, 2011)

Two carbon atoms make up the backbone of the chain. One carbon atom has two hydrogen atoms attached to it (CH_2). The other carbon atom has one hydrogen atom attached to it (CH) and one “pendant” methyl group (alkyl derived from methane, usually containing 1 carbon atom bonded to 3 hydrogen atoms) hanging from it (CH_3) (Speight, 2011).

Some polymers (branched polymers) may have different branches of molecules attached to the main chain that become inextricably tangled. Some glues and rubbers are an example of this (Speight, 2011).

Blending soap with glue tends to create a “cross-linked” polymer. This is when a molecular bond is formed linking different adjacent polymer chains or different parts of the same chain. The result is a change in the material's physical properties. The soap solution is the cross-linking substance that links the polymer chains of the glue. The effect of this makes the mixture thicken as the chains become ever more bound together and their free flowing movement becomes more restricted. At a molecular level, the more soap added to the glue, the more cross-linking occurs and the more firm the mixture becomes (Spangler, 2010). Products made from cross-linked polymer chains can develop rubber elasticity characteristics. For example, in a liquid, the polymer chains tend to be free flowing. By cross-linking the chains together, this liquid can be turned into a gel or a solid (Spangler, 2010). A simple example of a cross-linked chain is shown below.

chain ----CH----CH_2----CH----CH_2----CH----CH_2----CH----CH_2
link I I I I
chain CH--- CH_2----- CH----CH_2-----CH-----CH_2-----CH---CH_2 (Spangler, 2010)

3.14.2 Soap with Added Glue

The object of manufacturing then testing the reinforced soap was to gauge the strengthening measures of the additives in the soap as a whole (tensile testing was also repeated, but on aerated soap this time). These results are recorded separately, later in this chapter). One soap sample contained no strengthening measures, and this was used as the control. Different soaps will give different readings due to their ingredients and composition. Because of this, all four testing samples were made from the same batch of soap mixture. All four samples were sized at 100mm X 100mm surface area, 25mm thick (it should be noted that the polymer soap failed to achieve trace when mixing, and although clearly mixed, did remain at a "milk" consistency, until eventually setting solid after over 30 hours). The tensile testing of the soap was carried out on a 1970's "Scott" tensile testing machine, with the breaking points of each soap sample recorded in Fig 3.38 on the following page. The conversion of "pounds per square inch" (imperial measurement) to "newtons per square millimeter" (metric measurement) is shown in the conversion table (Table eight) on the following page. As can be seen from Fig. 3.38, soap with a glue additive fared the worst. On cutting into the soap it was revealed that the soap had a denser composition compared to "normal" soap. Research into this soap was discontinued. A soap based *acoustic* insulation might be something to consider in future with this soap composition. It was unclear if the wool fibres would interfere with any future aeration procedures, and so it was deemed that the thinner cotton thread fibres would be preferable for the insulation samples.

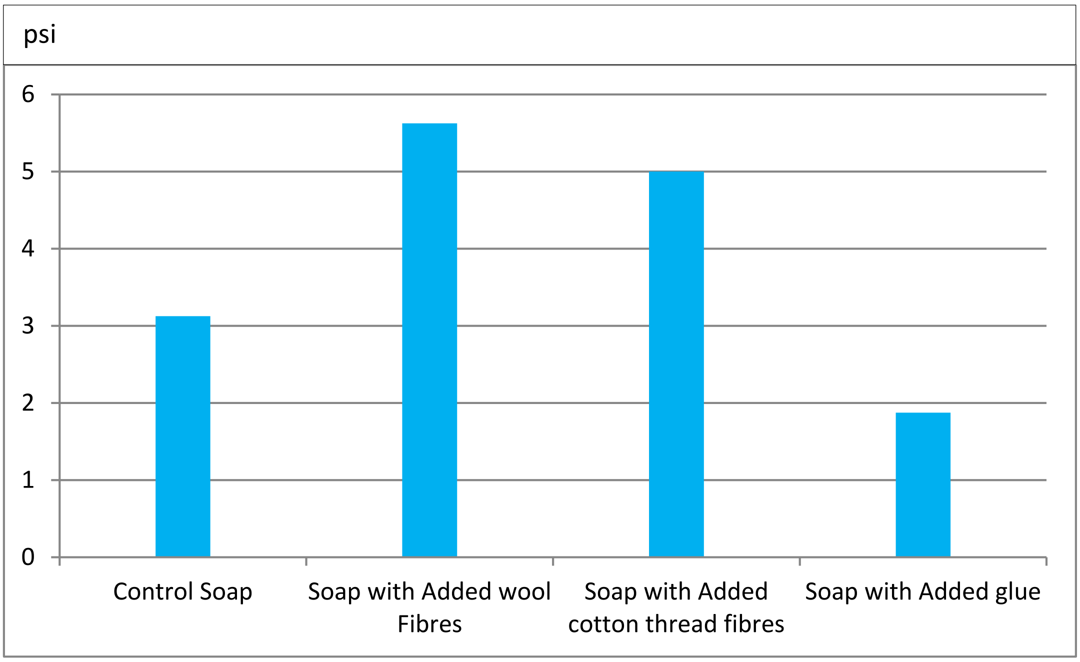


Figure 3.38: Failure of Strengthened Soap Chart

Key to strengthened soap chart

Soap 1: Control (no additives)

Soap 2: Added wool fibres

Soap 3: Added cotton thread fibres

Soap 4: Added glue

Soap type	Failure point (in psi)	Failure point (in n/mm^2)
Soap 1	3.1	0.0213
Soap 2	5.6	0.0386
Soap 3	5	0.0344
Soap 4	1.9	0.0131

Table 8: Failure of Soap (Imperial to Metric Conversion)

3.14.3 Testing the Strength of the Soap for Slump

A second larger batch of soap (29 X the volume of the previous batches) was mixed with the added cotton thread fibres throughout. This was manufactured at 420mm X 840mm surface area and 25mm thick. This was to accentuate any potential slump (the thinner the material the more prone it is to sagging). The length was made greater than the width for two reasons: 1. If the soap based thermal insulation ever came to manufacture, in relative terms, this would be the shape. 2. Downward force appears to increase in relation to the length it is acting upon. This can cause an object to deform as it succumbs to the physical force of gravity along its middle (deflection). Alternatively, also compression due to the objects own settling weight. This sample was placed in a vertical position against a wall and the outline of the soap was drawn on to the wall to act as a horizontal linear gauge (slump line). This would reveal any potential sagging in the soap sample. The sample was left in place for 60 days. If the sample had shown signs of slumping it would have been left in place until the slumping had stopped and then recorded. However, no movement in the sample was observed. Fig.3.39 shows the reinforced soap sample.

Figure 3.39: 420mm X 840mm Soap Sample

3.15 Tensile Testing of the Combined Reinforced and Aerated Soap

Aerated, reinforced soap samples were also used for the tensile testing and the results are shown in Fig.3.40 on the following page. The soap samples consisted of soap mixed as per the previous mixes, with the addition of cotton fibres for strength. The soap samples were aerated with straw, hollow plastic spheres, Expancel and the vacuum method as per the mixtures described earlier in this chapter. Once hardened the soap was tested to ascertain its tensile strength. All four samples performed worse than the un-reinforced samples (shown in Fig. 3.38). The results indicate that aerating the soap samples decreases the tensile strength of the soap, even when the soap has been strengthened. This is a result of the aeration process making the soap less dense, which in turn makes the samples less resistant to compressive force. The molecular bonding could be weakened because of the breaking up of the linear structure as the pockets of air decrease the structural integrity. The soap sample with the added plastic spheres fared the worst. This was because the soap failed to adhere to the plastic to the same extent that it bonded to the straw and Expancel. Research into soap with the addition of plastic spheres was discontinued at this stage. However, research into the other three sample types was continued.

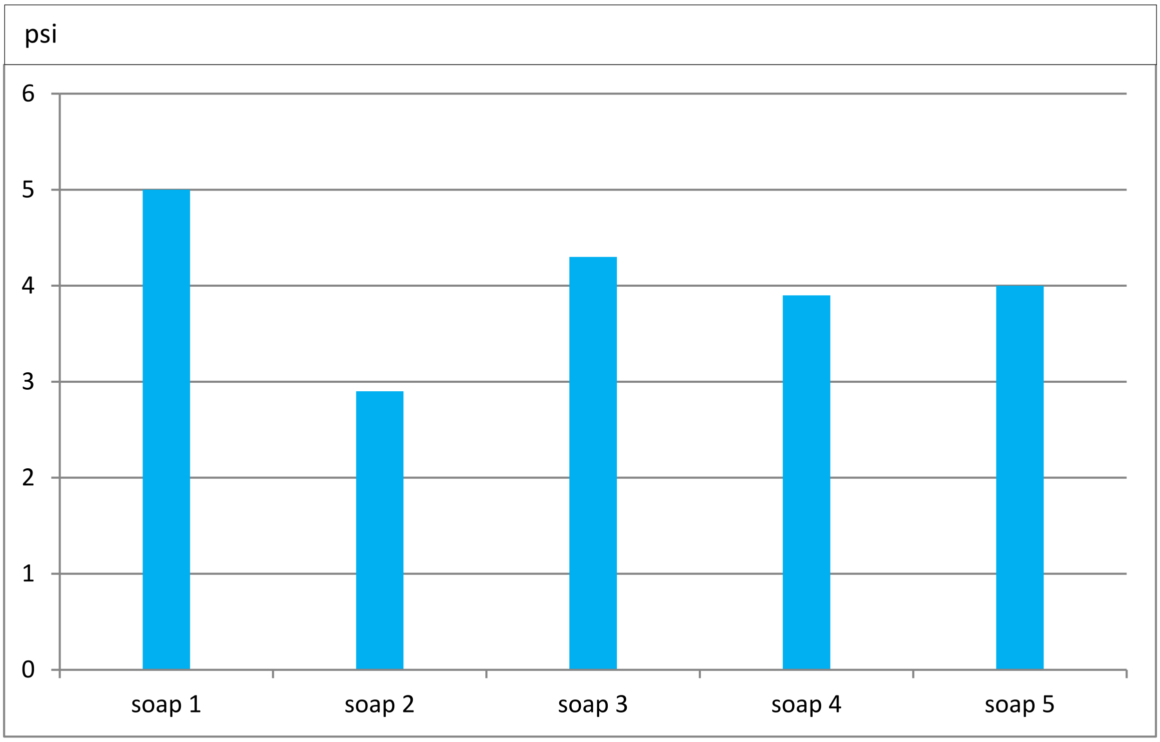


Figure 3.40: Failure of Aerated Soap chart

Key to soap types

Soap 1: Control (added cotton fibres but not aerated). Soap 2: Added hollow plastic spheres.

Soap 3: Added straw. Soap 4: Added Expancel. Soap 5: Aerated via the vacuum method

3.16 Recycling Plastics for the Protective Casing for the Soap

As stated earlier, bio-polythenes may be the product of choice for the insulation outer casing. The rigid insulation boards can be butted together both vertically and horizontally when placed into their final position. They will be connected at the internal and external corners via a 90^0 plastic sleeve. This means that the insulation can be cut and pushed into the corner pieces to seal the insulation ends. Where the insulation stops at a window or door reveal, a stop-end sleeve can be pushed over the cut end. The photographs below (Fig.3.41 – Fig.3.42) show examples of this. A diagram showing the key to the lettering on the samples and how each section fits together is shown in Fig. 3.43 on page 107.

Figure 3.41: Insulation Sample and Sleeve Connectors

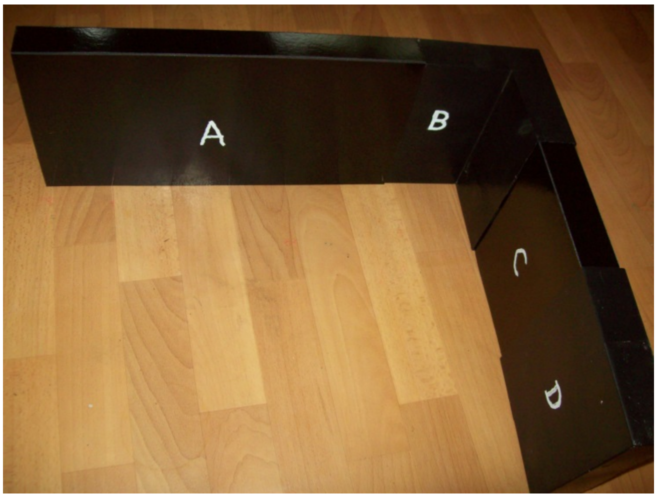


Figure 3.42: Insulation Sample Connection Method

Key to letters on the plastic sections

A. Insulation sample full length. B. Internal / external corner joining sleeve. C. Insulation sample cut to half length. D. Vertical stop-end sleeve. E. horizontal stop-end sleeve could be manufactured to cover and seal the insulation if the insulation is cut along its horizontal length (not shown in photograph but shown in Fig.3.43 below).

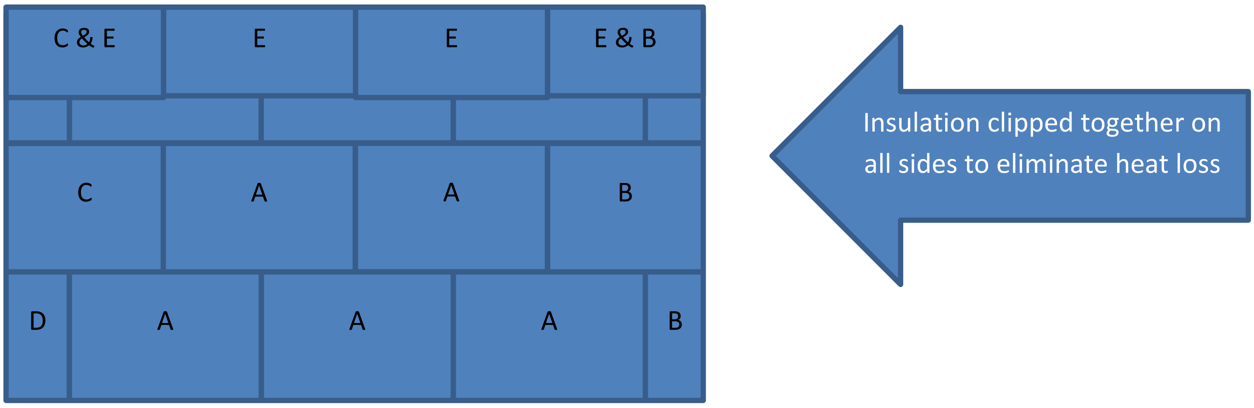


Figure 3.43: Elevation View Showing Fitted Insulation

The properties that are required for the plastic casing are shown in Fig. 3.44 below.

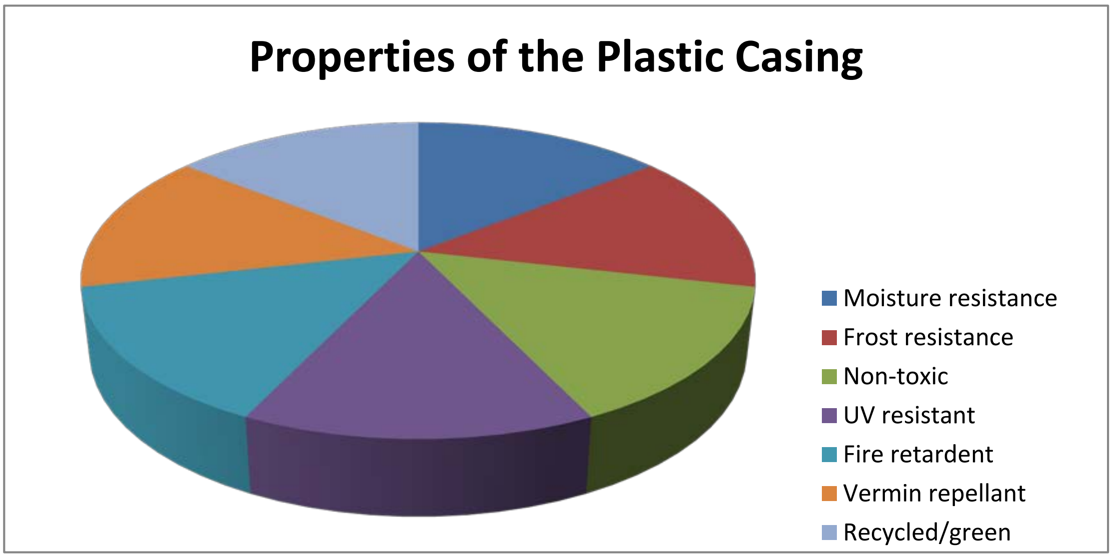


Figure 3.44: Properties of the Plastic Casing

The following criteria are applicable for the recycled plastics. Testing of the plastics derived from algae (agar) based components will follow the same procedures. All three plastic types will be bought from retail outlets but will be constructed into the various sized cases as part of the proposed insulation testing process.

3.16.1 Fire Retardant Casing for Improving the Protective Plastic

The plastic casing should be fire resistant in as far as reasonably practicable. Untreated plastic will ignite easily with a naked flame unless it is chemically treated (McKeen, 2012). A flame retardant solution can be manufactured without the need for expensive or toxic chemicals. Ammonium phosphate $(NH_4)_3PO$ is commonly used as a flame retardant in polymer composites (Weil & Levchik, 2009). It is also used as a fertilizer and used also in bread making to promote yeast growth (Somani, 1989; Toledo, 2007). It is also non-toxic and can be spray applied to the insulation casing. $(NH_4)_3PO$ sprayed plastic will be researched for its fire retarding properties. Ammonium phosphate is a derivative of ammonia (NH_3) commonly found in animal dung or urine and weak phosphoric acid (H_3PO_4) derived from limestone and sea bed sediments. Common materials used throughout the world. Ammonium phosphate salt crystals are water soluble and easy to grow. So easy in fact, that they are one of the main ingredients in children's "grow your own crystals" activity sets (Klipfel & Jahchan, 2005).

3.16.2 Ultra Violet Resisting Casing

The addition of carbon black in the plastic casing would solve the question on whether the plastic would resist UV light. However, according to the World Health Organization (2006), carbon black is possibly carcinogenic. It is also relatively expensive as the price is linked to the ever increasing price of petroleum oil (Ash & Ash, 2007). It is a powdered commercial form of carbon and is the residue of partially burnt oil, usually burnt in an oil furnace. When mixed with plastic, it gives the plastic UV resisting characteristics (Ash & Ash, 2007). There is another product on the market however, a powdered alternative product extracted from waste tyres. It is cheaper and more eco-friendly than the oil derivative, and performs an identical task. One of the trade names for this type of product is "ApexCM" (Science Direct, 2011). Once installed, the plastic casing should not be exposed to excessive heat sources as soap will melt at 60^0C. (Livestrong, 2012).

3.16.3 Creating a Non-Toxic Product

Research must be initiated to determine whether the soap based thermal insulation product is safe to be handled and cut. The pH of soap is recorded as eight (pH neutral). The process of saponification changes the lye, making the soap non-toxic (Thomssen, 2015). The fire retardant coating (ApexCM) applied to the outer casing is also non-toxic. PEHD is a stable compound that is also non-toxic (Thompson & Sorvig, 2007). It is the preferred plastic for the food packaging industry because of its non-toxic properties and purity (Thompson & Sorvig, 2007).

3.16.4 Moisture Resistance

The moisture levels of finished soap were tested with a digital moisture meter. A voltage is conducted into the soap via two sharp probes. These probes are set at a specific distance apart from each other and the meter reads the resistance between these two probes when the test button is pressed. A shop bought control soap was tested and gave a moisture content reading of 35%. Moisture testing is important because the soap has the potential to precipitate moisture if enclosed in a waterproof container and subjected to heat. This is because the soap still contains both glycerol and salt which are both “humectants” (substances that promote moisture retention), and as such will retain a percentage of water. In effect condensation could form on the inside of the polythene case and cause damage over time to the contents. Bio-polythene and petroleum polythene share the same characteristics (Thompson & Sorvig, 2007). Polythene as a material is waterproof.

To test the polythene surrounding the soap, two clear polythene sample boxes were sourced and the insides filled with soap. Clear boxes are preferential for this observation in order to identify any reactions occurring inside. One box acts as the control and is kept indoors and the other is exposed to the outside elements for 60 days. The insulation is not designed to be a stand-alone exposed insulation. Rather it would be fitted into the walls, floors or roof of the buildings, in effect, hidden. On site the insulation would be stored inside or undercover, probably along with the breathable roofing membrane and PVC underground drainage pipes and fittings. This is to protect the materials from UV radiation, which will degrade these products under prolonged sunlight exposure. Polythene has good mould, mildew and bacteria resistance under normal conditions (Thompson & Sorvig, 2007), and has good gas resistant characteristics, also under normal circumstances.

3.16.5 Vermin and Insect Repellant

Both rats and mice will gnaw or eat plastic, especially if there is something edible beyond it (Smith, 2010). They will (and do) eat soap (Garber, 2013). In order to prevent this, a rodent repellant should be used in the insulation manufacture. For a natural repellant, vitamin D3 nutrient will be tested. D3 is essential for human health, but lethal to rodents. “As one of the safest substances known to man, vitamin D toxicity is very rare. In fact, “people are at far greater risk of vitamin D deficiency than they are of vitamin D toxicity” (Vitamin D council, 2012). According to the Krieger (2010), Vitamin D is lethal to rodents because it can cause fatal elevated calcium levels in the blood and or heart attacks (hypercalcemia). When sealed watertight, the plastic casing surrounding the soap will also be enough to prevent even the most determined of insects from gaining entry.

3.16.6 Frost Resistance

Testing the plastic casing for frost resistance will be carried out by subjecting the plastic to intermittent visits to the inside of a freezer. This will expose the insulation to freezing temperatures. This would test the insulations ability to resist the cold. On a construction site the insulation would be stored inside or undercover (as mentioned earlier) and so long term exposure to frost should be minimal. In addition to the qualities required from the soap and casing, petroleum insulations have a relatively high environmental and financial cost compared to basic soap insulation with a recycled plastic casing surround (as revealed in the literature review and the insulation financial comparisons in Table four (Section 2.14.5). These results are shown on the following page in Table nine.

Criteria	Soap Insulation	Polystyrene Insulation	PIR Insulation (Foil faced)
Financial Cost	O	O	O
Environmental Manufacturing Cost	O	O	O
End of Life Disposal	O	O	O

Table 9: Soap Comparison Table

Key:

Good Moderate Poor

3.17 Summary

The aim of this chapter was to convey the research methodology that has been used within this study. In basic terms the research question will be honed down until the question becomes a testable hypothesis. Observation and recording of the research will create the basis for the raw data. This involves observing the effect that the manipulated variables have upon the subject and the recording of the outcomes. Statistical analysis will be performed on the outcomes and then this will be organized into an understandable format. The sample selection, the procedures used, the methods of data collection & analysis have been determined along with the reasons for selecting experimental research as the approach to the methodology have also been described. This chapter demonstrates through the research findings that soap based thermal insulation has passed the preliminary manufacturing and testing stages. Various mixtures and manufacturing methods employed have been discarded. These include pure potassium hydroxide soap, soap derived from waste engine oil and soap mixtures with added paper balls, ice, glue, plastic spheres and sodium bicarbonate. The soaps that will be carried forward to the next stage use the methods that extenuate the soap aeration and strengthening processes. These soaps include NaOH derived soap made with animal and vegetable oils, reinforced and aerated with straw, cotton fibres, Expancel and by use of the vacuum method. Improvements and refinement to the product and manufacturing methods will be demonstrated in the following chapter.

Chapter 4 Critical Review of the Findings and Further Development of the Soap Insulation

4.1 Introduction

This chapter initially highlights the improvements to the soap insulation samples, justifying the reasons as to why the component parts may have been changed and why the key ingredients have been used, briefly elaborating on the possible specification of the soap insulation based on the findings from the preliminary experimentations explained in Chapter three. Following this, this section concentrates on existing petroleum insulations, revealing the most efficient and popular ones, and attempting to explore the reasons why this is so. Furthermore, this section also discusses the detailed environmental and financial costs associated with petroleum based insulations. Finally, this section defines the testing plan and procedures, and describes the testing environment where the samples are to be tested in and explains in more detail how the testing procedures are carried out.

4.2 Refining the Specification of the Soap Insulation

4.2.1 Aerating the Soap

Further experimentation of the soap samples is required to build upon the results from the preliminary tests explained in Chapter three with only the best performing soap samples to be taken forward. These include soap samples i) aerated via the vacuum method and ii) aerated with the addition of straw. Both samples are strengthened with cotton fibres. Since straw can act as a strengthening measure *and* help with aeration, it was investigated further.

It was discovered that using beef fat as the primary soap ingredient made the soap set quickly. This meant that although the soap did aerate to a certain extent, the bubbles never had a chance to fully develop before the soap set hard. Because of this it was decided to change the composition of the fat to prolong the soap setting time. Beef fat was melted and vegetable oil was added at a ratio of 70% - 30% respectively. This slowed down the setting time and allowed the bubbles to form over a longer period. The resulting soap sample is shown in Fig.4.1 on the following page.

Figure 4.1: 100mm X 200mm Improved Aerated Soap Sample

The photograph, (Fig.4.1) above, reveals that the bubbles increased in size to 5mm-7mm. This was an increase in size of approximately 50% over the previous sample aerated with vacuuming. This vacuum method of aeration exceeded expectations and out-performed the added microsphere aeration method. Whilst vacuuming is successful enough for small sized samples such 100mm X 100mm and at a thickness of 25mm, it is not successful enough for larger sized samples such as 300mm X 300mm and at a thickness of 50mm, which is the standard size for laboratory testing at Salford thermal testing laboratory (Simpson, 2011). For testing samples of this size and above, purpose-built bigger sized manufacturing equipment would be required. Therefore, because of the increased size of the insulation samples, a different, more efficient method was adopted to aerate the soap mixture. Hollow, 100% bovine gelatine enteric (dissolved by alkaline contact) capsules were used for aeration purposes in the follow-up testing cycles (see Fig. 4.2 and Fig.4.3 on the following page). These capsules were mixed with the soap at its liquid stage. The mixture was then left to harden and the capsules dissolved, leaving air pockets throughout the hardened soap.

Figure 4.2: Empty Bovine Gelatine Capsules

Figure 4.3: Empty Bovine Gelatine Capsules

4.2.2 Improvements to the Strength of the Soap

Cotton fibres used in the initial experimentations were substituted with fibres of horsehair. This meant that the fibre reinforcing interfered less with the bubbles. Horsehair is keratin derived and thinner than cotton fibres. Because of its smooth molecular surface composition (Fig.4.4), horsehair tends to allow for improved dispersal within the mix, as opposed to "clumping" that can occur with cotton fibres (Fig.4.5). This is because the stray outer fibres can become entangled with the neighbouring fibres. Horsehair is also very strong when comparing its tensile strength to thickness ratio (Sigler, 2011). Also, in decomposition, animal keratin is one of the last biological structures to decay. This is particularly true of hair (Ennos, 2011).

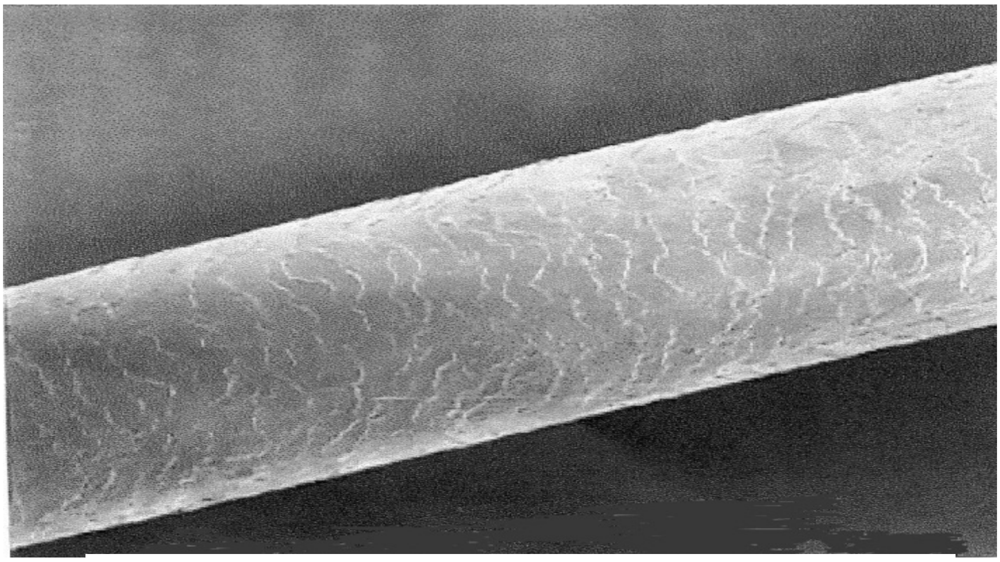


Figure 4.4: Structure of Horsehair (Feughelman, 1997)

Horsehair is built from 16 different amino acids. It is a long chain molecule with a linear structure (Rocaboy, 1990). Its make-up consists of 85% keratin (Dunnett, 2005).

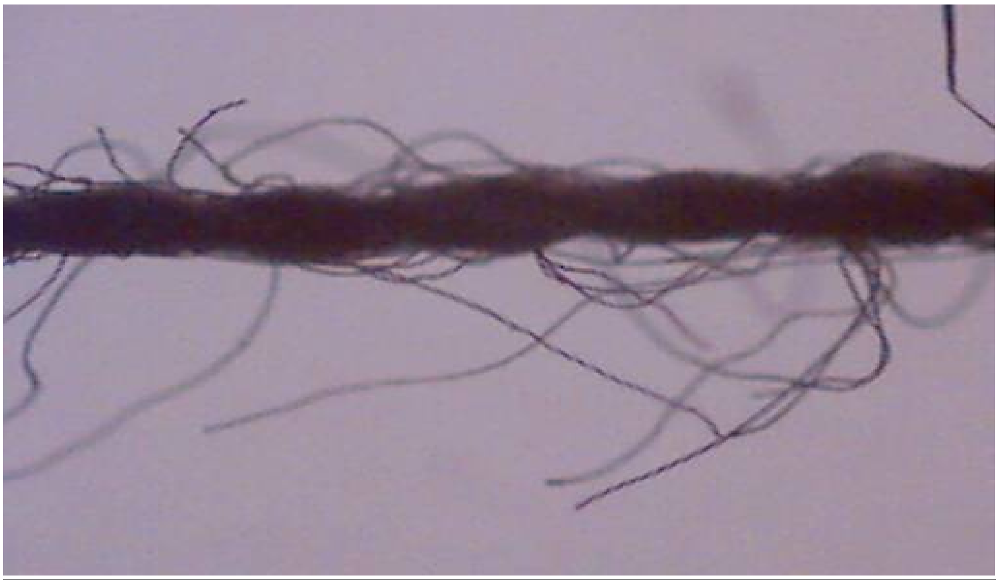


Figure 4.5: Structure of Cotton Thread (Anon.)

A horsehair soap sample was tested for its strength using the identical testing methods and identical soap sample mix as used previously. The horsehair was cut to 20mm – 25mm lengths and was weighed at two grams. The results revealed that this sample had better tensile strength than the soap with added cotton fibres. Furthermore, it actually provided an identical tensile strength with the soap sample strengthened (5.6psi) {0.0386n/mm^2} with wool. Although wool provided better tensile strength than cotton, it was eliminated in the initial tests because it interfered with the aeration process. In effect, this means than horse hair gives tensile strength as good as wool but doesn't interfere with the aeration process.

In summary, in the research findings about the best possible soap sample made up of a lye mixture with 70% beef fat and 30% vegetable oil, combining soap with horsehair for tensile strength and aerating with bovine alkaline capsules seems to be the most effective method so far.

4.3 Suitability of Bio- Plastics for the Insulation Casing

In order to keep the plastic casing as sustainable as possible, it was decided to construct the insulation protective casing from plant based bio-plastic. The main plastics types are listed below:

- Starch based plastics. These plastics are the most widely used and occupy around 50% of the bio-plastic market (Robertson, 2012). However, starch absorbs humidity and because of this, sorbitol (sugar alcohol) and glycerine (vegetable oil) are usually added to create processed thermo-plastics (Fakirov & Bhattacharya, 2007). Thicker sized plastics can be made from starch.
- Cellulose-based plastics. Cellulose plastics can be derived from wood, hemp and cotton (Ebnesajjad, 2012). These plastics are usually used in applications requiring a thin layer of plastic such as cellophane and celluloid (Ebnesajjad, 2012).
- Polylactic acid (PLA) plastics. PLA plastic is produced from sugar cane or glucose. It resembles petroleum based polythene in its characteristics, but is more expensive to produce than its petroleum counterpart (Ebnesajjad, 2012). It is easily processed for a mass production market. PLA is often used for the manufacture of plastic bottles and for film coatings of paper or card (Andrady, 2003).
- Bio-derived polythene. The main component of polyethylene is ethylene (Ducheyne et al, 2011). This monomer is the basic ingredient of ethanol, which can be produced by the fermentation of corn or sugarcane. Bio-derived polyethylene and traditional petroleum based polythene are chemically and physically identical to each other (Ducheyne et al, 2011). Bio-derived polythene does not biodegrade but it can be recycled (Ducheyne et al, 2011). This was the plastic used in the manufacture of the test samples insulation casing.

4.3.1 Testing the Bio-derived Polythene Plastic for Weather Exposure

Bio-derived polythene was chosen over the other three plastics because it is identical to petroleum polythene (Ebnesajjad, 2012). Also, it is cheaper to manufacture than

PLA plastic (Rand, 2013), it is manufactured at thicknesses greater than can be achieved with cellulose plastic and it is better at repelling moisture than starch plastics (Ducheyne et al, 2011). Insulation test samples made from aerated soap surrounded with protective case of bio-derived polythene were constructed (Fig. 4.6) and placed firstly in a freezer and then secondly to an outside area that was exposed to the elements. The temperature of the freezer was a constant -18^{0}C whilst the outside temperature ranged from -4^{0}C to +6^{0}C. Outside the samples were exposed to both sunlight and frost, and snow and rain. The samples remained in both the freezer and outside for 28 days, and then placed in a cavity wall for six months during January 2012. None of the samples showed any adverse effects to the low or fluctuating temperature differences.

Figure 4.6: Soap Sample Surrounded with Clear Plastic Casing

4.4 Molecular Structure of the Plastic Casing

Bio-polythene is a polymer derived from ethane gas (C_2H_6) combined with atoms of carbon and hydrogen (Fig.4.7). Whist in its gas state, increasing the number of carbon atoms in the chain to in excess of several hundreds, will change the material first into a liquid and then into a waxy type solid (Rand, 2013). When the number of carbon atoms in the chain exceeds 1,000 the solid material polythene, with all of its characteristics of strength, flexibility and toughness, is obtained (Rand, 2013). This change in state occurs because as the length of the molecules increases, the total binding forces between molecules also increases (Rand, 2013).

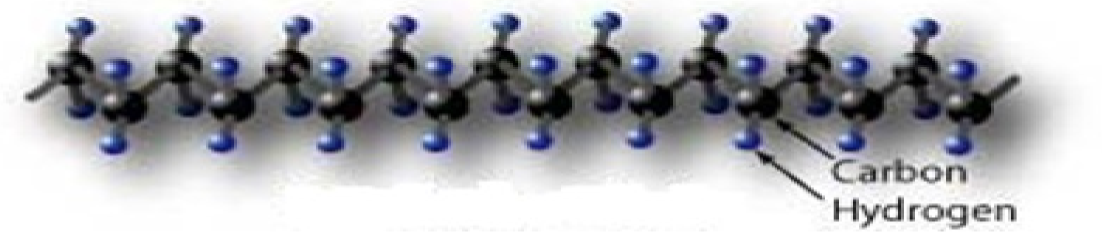


Figure 4.7: Polythene Molecule Chain (Rand, 2013)

The polythene structure comprises of a tangled mass of molecular chains. An example is shown in (Fig.4.8) below.

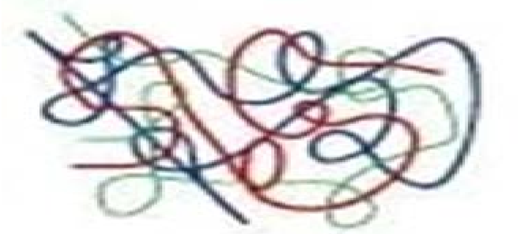


Figure 4.8: Polythene Molecular Mass Example (Ebnesajjad, 2012)

When stress is applied to plastic, the molecule chains stretch and the elongation of the polymers can increase thousands of times greater than the original structures (Rand, 2013). This process will usually weaken the plastic structure. Three plastic samples of differing degrees of thickness were tested to ascertain the rigidity of the plastic to be used for the casing. The samples were sized at 150mm X 150mm with a thickness of 1mm, 2mm and 3mm and were tested on the “Scott” tensile testing machine. The results revealed that plastic 1mm thick failed at 2.1psi (0.0144n/mm^2), at 2mm thick the plastic failed at 4.1psi (0.0282n/mm^2) and at 3mm the plastic failed at 6.2 psi (0.0427n/mm^2). In general these results show that the strength of this plastic increases by approximately 50% for every millimetre increase in thickness. Because the insulation soap content is of a rigid structure it was deemed that a 2mm plastic casing would suffice for the contents protection.

4.4.1 The Colour of the Plastic

The colour of an object depends on the wavelengths of colours reflected from the object. The colour of the plastic casing will have a direct bearing on the insulation's ability to absorb or reflect heat (Bose, 2011). Darker colours absorb light more efficiently and thus they are superior radiators of heat. When a dark object is illuminated by white light, all of the wavelengths are absorbed and few are reflected. This is why the object may appear black. When a dark object absorbs light, the energy carried by the light raises the energy of the object doing the absorbing. This object then releases the absorbed energy by emitting the longer wavelength, lower energy infrared (heat). In effect the light is transformed to heat that is either radiated or retained by the object (Bose, 2011).

4.4.2 Heat Absorption and Reflection Testing

Four coloured plastic samples were tested for their heat absorption. The samples were coloured white, black and transparent and the fourth sample was coated with an aluminium reflective foil. All of the samples were tested by applying a heat source located at a distance of 300mm from the samples, for 60 seconds. A flexible adhesive strip thermometer was applied to the plastic samples after 30 seconds had elapsed (Fig. 4.9). The results are recorded in Table ten on page 120.

Figure 4.9: Flexible Adhesive Strip Thermometer with Plastic Case

Colour	Starting Temperature	Heated Temperature	Temp. Difference
White	18^0C	34.5^0C	91.6%
Clear	18^0C	33^0C	83.3%
Reflective Foil	16^0C	17^0C	6.2%
Black	18^0C	58.5^0C	225%

Table 10 Coloured Plastic Casing Temperature Difference

As seen from Table eight, white plastic absorbs slightly more heat than transparent plastic. Black plastic, however, absorbs almost double the heat of white.

According to Innovative Solutions (2012), aluminium foil absorbs heat at approximately 5% and reflects heat back at 95%. It was decided that black plastic would not be used for the insulation casing because it wouldn't be good enough to reflect heat back. Furthermore, if black plastic is used for insulation, it may cause condensation problems within the cavity wall when the warm temperature from the black insulation, which absorbs heat, meets with the cold temperature from the wall.

Although transparent plastic reflects heat better than white plastic, the soap visible through the clear casing is also white and so this is the surface that reflects or absorbs the heat, which makes the transparent case meaningless. Therefore, the remaining two colour options (white and aluminium) for casing would be considered in the follow-up tests.

4.5 Summary of the Specification of Soap Insulation

The plastic surround for the soap insulation used for thermal conductivity testing comprises of a white polythene casing with 2mm thickness. This was the first alternative. The soap content in this alternative is derived from a beef fat, vegetable oil (70%-30%) mix. This soap was strengthened with horsehair fibres and aerated via the bovine alkaline capsules.

Soap surrounded with aluminium foil over polythene acted as a second alternative sample. This sample was tested as a direct consequence of the positive heat absorption/reflection results aluminium plastic shown in Table eight earlier. The soap mixture in this alternative will be the same as the first alternative.

However, as a third alternative sample, soap also strengthened with straw, aerated with bovine capsules but surrounded with white polythene was used.

Until this stage, soap samples were tested in terms of light-weighting and tensile strength. In the next stage, the testing will concentrate on the thermal performance of these alternative samples.

4.6 Test Plans and Procedures for the Follow-Up Experimentation

A sample testing cycle was established, focusing on the thermal resistance of the soap samples. The test cycle consisted of the five parts listed below.

1. Requirements analysis: necessary factors to be included in the tests to achieve accurate results. These included configuring the testing equipment and stabilising the test samples.

2. Design analysis: identifying which aspects are testable under the test parameters, for example, thermal testing only as opposed to strength testing etc.

3. Test planning: This included the test strategy, test plan and test creation. This helps to identify if soap can perform as insulation and if not, what can be done to improve its performance. Analysing the best combinations / compositions of the soap body will identify the best performer to be taken forward for further stage testing.

4. Test development: This included the design implementation of the test procedures.

5. Test execution: Conducting the tests and recording the findings.

In August 2013, the three alternative soap insulation samples identified on page 119 were then tested at the Salford Thermal Insulation Laboratory to ascertain their thermal resistance. The samples are sized at 300mm X 300mm and at an approximate thickness of 50mm. The three samples sent for R-value testing were as follows:

1. Sample one: Aerated with bovine alkaline capsules and strengthened with horse hair, and surrounded with 2mm white polythene plastic case.
2. Sample two: Aerated with bovine alkaline capsules and strengthened with horse hair, and surrounded with 2mm reflective foil polythene plastic case
3. Sample three: Aerated with bovine alkaline capsules, strengthened with straw and surrounded with 2mm white plastic case.

The method of determining a material's R-value (Thermal resistance) is by using a heat flow meter, similar to the type shown in (Fig. 4.10). The insulation sample is placed between a cold plate and a hot plate inside the calibrated testing apparatus. The heat flow occurring at a defined temperature difference is measured with a heat flux sensor.

Figure 4.10: FOX 600 Heat Flow Meter

4.6.1 Sample 1

The manufacturing procedure for this was exactly the same as it was for sample two, the foil based aerated soap, but without foil being used on the casing faces. During the first meeting at the thermal testing laboratory, it was calculated that soap encased within plastic had a higher density than predicted. The density of aerated soap surrounded with plastic was recorded at 380kg/m^3. Without the plastic casing the aerated soap was recorded at 310kg/m^3. This figure was too high for the insulation to perform at a satisfactory standard as wall insulation and it was reasoned that a thinner, lighter, membrane encasing a more highly aerated soap mixture may be required to improve the insulation for the future stages of testing. The actual test results for sample one are shown below.

Sample one: The sample thickness was 0.0511m and a thermal conductivity of 0.0746 W/mK. This equated to a thermal resistance figure of 0.684m^{2}K/W.

4.6.2 Sample 2

A similar sized case as the one used for sample one was constructed, also with the polythene thickness at 2mm. 1129g of soap was mixed with 264g of gelatine capsules and left to harden within the plastic case. The case was then heat welded along the seams to ensure the contents were fully protected. Both the front and rear faces of the case were faced with metal foil and deposited at the thermal testing laboratory. The testing results were as follows:

Sample two: This sample had a thickness of 0.0513m and had a thermal conductivity of 0.0799 W/mK. This equated to a thermal resistance figure of 0.642m^{2}K/W. Images of the samples tested are shown in Fig. 4.11 and Fig.4.12 below.

	
Figure 4.11: Three Plastic Insulation Samples	Figure 4.12: Section through One of the Samples

4.6.3 Sample 3

The casing for the soap/straw insulation sample was sized at 2mm thick. It weighed 450g. It contained 3kg of fat and 270g of straw at a 50% / 50% ratio by volume. When the soap had dried the sample was weighed. The finished sample weighed 4.650kg. This meant that one (450mm X 1200mm) insulation board at 50mm thick would weigh in at 20.925kg. At 100mm thickness, the insulation sheet would weigh

41.85kg. The maximum recommended manual lifting limit for one man is 25kg and for a woman16kg (Hunt, 2013). However, the sample was sent for testing and the results are shown below.

Sample three: This sample had a thickness of 0.0511m and thermal conductivity of 0.0989 W/mK. This equated to a thermal resistance of 0.516m^{2}K/W.

Regarding the weight of this type of insulation, this would have a bearing on a house foundation. An average, typical new three bedroom detached house has a floor area of 88m^2 (RIBA, 2014). This equates to approximately 260m^2 of wall insulation (Langdon, 2011). This means that the walls would require approximately 482 (450mm X 1200mm) cavity insulation slabs. This would put an additional load on the foundations of 10.122 tons if the soap/straw combination insulation was 50mm thick. Cavity wall insulation ranges from 50mm to 100mm thick generally, dependant if full-fill or partial fill is used. However, the insulation thickness does not determine its thermal conductivity. "Celotex SW3000" will have a lambda of 0.025-0.027W/mK (Celotex, 2014) and "Rockwool Cavity" will have a lambda of 0.037 W/mK (Rockwool, 2011), no matter which thickness is selected. These both satisfy the U–values required for an external cavity wall where standard assessment procedure (SAP) calculations are not required under Approved Document part L1A, (2010).

In an attempt to reduce the weight, various measures were tried:

1. A 1mm plastic protective case was used. This reduced the weight by 225g.

2. The straw was mixed at a 70% / 30% by volume ratio.

3. The setting soap was exposed to a warmer environment to evaporate off extra moisture contained within the soap.

After incorporating these changes, the soap sample still weighed in at 4.130kg. A variation sample of soap and straw insulation was tried. This time dried soap flakes and granules were mixed with straw at the same 70% / 30% ratio. Once again the mixture was tightly packed into a 300m X 300mm case, 50mmm thick. The results over a six month period revealed that over time the soap flakes settled and tended to clump into a solid mass, leaving a 9mm gap at the top of the protective casing. In effect, this is creating a path for air leakage.

Soap/straw insulation could possibly be adapted for floor insulation. The reason for this is because of its improved load bearing capacity as opposed to polystyrene and polyisocyanurate insulations. When tested for its compressive strength, the soap sample withstood 116 psi (0.7997 n/mm^2) before any damage occurred to the casing. The petroleum based polystyrene insulation sample failed at 33 psi (0.2275n/mm^2), forcing the insulation surface to compress by 5mm (one tenth of the original thickness). The foil faced polyisocyanurate failed at 37psi (0.2551n/mm^2). These results indicate that plastic cased soap can withstand over three times more compressive force than the other two; easily strong enough for a person to walk over without damage occurring. Interlocking soap insulation would not require a secondary polythene membrane over the top of the insulation face before the cement screed is poured (Polyisocyanurate insulations require a waterproof barrier on their top surface to prevent wet cement contaminating the insulation and degrading the foam making it "spongy"). Polyisocyanurate insulations will often require a damp proof membrane below the underside of the insulation to prevent moisture degradation to the inner foam. Plastic cased soap insulation may not require this as the casing is waterproof and may act as a damp proof membrane.

4.7 Overall Comparison of the soap insulations with the petroleum counterparts

The three aerated and strengthened soap samples were compared with the petroleum counterparts, polystyrene and polyisocyanurate. This was in order to justify or discount if soap based insulation could be shown to be an effective alternative to those petroleum counterparts. The criteria identified included financial cost, environmental manufacturing cost, thermal resistance, weight, working performance (durability) and end of life disposal. These subjects were utilised for this comparison. Because soap based insulation is a rigid board type, only insulations of petroleum based rigid board types were compared. This meant that both fibreglass and multifoil insulations were omitted from this comparison study. Because of the multitude of performance variant types on sale within the UK, the lowest performing petroleum based insulation, expanded polystyrene was used a comparable, alongside the best performing petroleum based – foil faced polyisocyanurate. This eliminated the need to compare mid-performing thermal insulations such as extruded polythene (XPE). Both expanded polystyrene and polyisocyanurate insulations give a benchmark to aspire to within the same insulation type category, whilst allowing for a scale to be established to show where soap insulation is, compared to these two. The laboratory results revealed that none of the three soap samples gave particularly good thermal resistance results. In comparison with the petroleum based counterparts, plastic covered soap insulation fared better for its end of life disposal and environmental / financial costs. However, petroleum based insulation has a better size to weight ratio, durability and more importantly, it gives better thermal performance. The results are shown in Table eleven below.

Criteria	Sample 1	Sample 2	Sample 3	Expanded polystyrene	Polyisocyanurate (Foil Faced)
Financial Cost	o	o	o	o	o
Environmental Manufacturing Cost	o	o	o	o	o
Thermal Resistance	0.684(m^2K)/W	0.642(m^2K)/W	0.516(m^2K)/W	1.25m^2K/W	2.0m^2K/W
Thermal Conductivity	0.0746W/mK	0.0799W/mK	0.0989W/mK	0.04W/mK	0.025W/mK
Weight	1,084g	1,843g	4,650g	67g	135g
Thickness	51.1mm	51.3mm	51.1mm	50mm	50mm
Working Performance (Durability)	o	o	o	o	o
End of Life Disposal	o	o	o	o	o

Table 11 Soap Comparison Table

Key:

Good Moderate Poor

Small aerated soap samples have been exposed to six months of cavity wall and freezer placement (Section 4.3.1) and have performed without any adverse effects to the either their external or internal composition make-up. However, slabs of soap insulation utilising straw as a component part were too heavy to be stacked upon each other, as would be required in the wall of a building. At a height of 3.3m, the compressive force of 51.150kg acting upon the bottom insulation sample, created a small yet significant split in the plastic casing. This could create a path for possible moisture ingress and as such, the failure of this heavy insulation meant that research into the soap/straw combination was discontinued.

Working on the result that plastic cased insulation could fail with a 51.150kg load applied, it was calculated that at a height of 8.3m, an equal weight of 51.150kg would be produced using Expancel soap with a plastic casing, if the insulation was stacked directly on top of each other. This height is possibly within the realms of a three storey building. This meant that plastic surrounded soap insulation with added Expancel as the bottom supporting slab, could also fail and so this insulation type was also discontinued. Calculations revealed that the lighter plastic surrounded soap insulation aerated via the vacuum method, would be adequate to use in a three storey property but could fail in higher rise buildings if the insulation is stacked as opposed to mechanically supported. The results of the first tests also reveal that 100mm thick aerated soap surrounded with a plastic casing performs to an equivalent level of 50mm expanded polystyrene and 25mm polyisocyanurate generally.

4.7.1 Condensation Risks and Breathability

The plastic casing surrounding the soap could also create problems because of its smooth face. In a capillary active solid brick or stone constructed wall, moisture could condense on the plastic surface and if there is a lack of means for the moisture to be dealt with, problems to the structure can occur. If these walls are insulated internally, heat flow to the external (outside) face can be reduced. This impedes the ability of the brick/stone wall to properly dry out after a wetting from rain and in turn this higher water content increases the thermal conductivity of the masonry (Burberry, 2014)

The vapour resistance of the plastic casing can also reduce the moisture movement and therefore drying potential to the inside of the wall. As the wall establishes its new higher equilibrium moisture content, there is a risk of decay to any organic materials (joist ends or battens) that are in contact with it (Browne, 2012). It is possible that moisture levels in this environment could exceed mould growth and decay conditions, creating an environment that could be detrimental to human health and accelerating degradation to the insulation. After all, “Insulation should offer a reasonable service life” (Aegerter et al, 2011), and be robust enough for the efficient management operation of thermal resistance applications (Turner & Doty, 2007). Because of the potential problems associated with the soap insulation's plastic casing, it was decided to stop research into plastic coated thermal insulation. However, the answer to these problems could be as simple as an air "barrier" to wick away any moisture before it can do any damage, or to use a breathable thermal insulation. Breathable insulation frustrates the dew point from occurring on or within the insulation and thus stops it becoming wet (Allen & Thallon, 2011). This breathability is recognised by built environment professionals as being a useful function for maintaining a durable and healthy building.

4.8 Chapter Conclusion

White or reflective casings were proven to perform better as the soap's protection. However, plastic cased straw soap created a sample that was too dense and too heavy to be used for wall insulation (although laid flat it did exhibit compressive strength that could possibly be used in a floor). Aeration via the vacuum method was preferable to soap aerated and strengthened with straw. Strengthening with horsehair was preferable because of its prolonged decomposition time whilst not interfering with the aeration procedures. Regarding its thermal resistance and conductivity properties, plastic cased soap was also a poor performer when compared with established insulations.

Improvements were required to the soap characteristics of the three samples under test. These latest insulation specimens needed improved strengthening measures, better aeration techniques for lowering the density of the soap body and a perimeter casing for protection. Density decrease was achieved by blending the fat with oil to increase the bubble size whilst adding horsehair meant improved dispersal of the strengthening additive. The bio-polythene casing, whilst recognised as giving good environmental and financial costing, was deemed to bring its own problems in the form of its weight. It was envisaged that the casing could fail under vertical loading (dead load and Impact load) and could precipitate condensation problems. Retrofitting could also cause problems in older properties where the foundations may not be suitable for taking the additional weight. To move forward, the soap needed a more lightweight casing and further improvements with regards to the air void size.

Chapter 5 Refinement to the Soap Samples

5.1 Introduction

As revealed in the previous chapter, the soap body strengthening measures used were deemed adequate, but the plastic casing was unsuitable because of its weight and failure under imposed loading. Further testing was carried out by adhering to an action research methodological cycle (Fig.5.1), (Coghlan & Brannick, 2014). The aerated samples that were tested were surrounded with hemp and cork. Ongoing like-for-like comparisons with the EPS and PIR samples would point the sample manufacture in the right direction. This would become evident after analysing the results from the thermal testing laboratory, where the samples would be tested for their thermal conductivity, thermal resistance and soap density.

5.2 Sample Testing Following the Cycle of Action Research

Information relating to the testing was organised into a cycle of action research (Coghlan & Branick, 2014). There is a cycle for every sample tested and each of these cycles has four stages, as shown in the text of Fig.5.1 below.

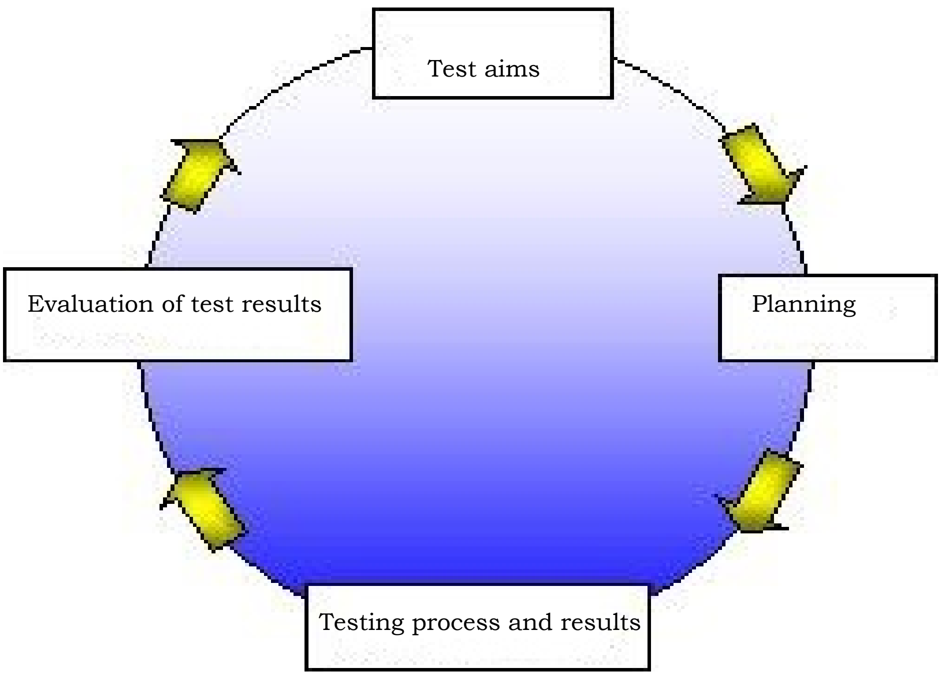


Figure 5.1: Cycle of Action Research (Coghlan & Branick, 2014)

5.2.1 Test Aims

The overall aim is to create a thermal insulation that is capable of performing as a thermal insulation to ISO 8302, BS EN 12667, BS EN 12664 standards and the construction products directive (CPD) for product standard EN13162-EN 13171. This accreditation process is essential for the European Conformity (CE) marking and thus complies with the essential requirements of European health, safety and environmental protection legislation (Graham, 2012). The insulation samples must prove to be resistant to flame, vermin attack and short term direct sunlight exposure. The results should identify a product that fulfils the testing and accreditation criteria and can be used in a variety of different situations, for example walls, floors and roofs. To put it simply, the ultimate goal is to create a soap based thermal insulation that performs to a standard that equals that of petroleum insulation. Failure will be measured by the soap insulation's failure to perform at an acceptable standard. However, if this is the case, at least the research data collected may help to take the soap insulation research into a different direction until it does perform satisfactorily.

5.2.2 Planning

The insulation samples were sized at 300mm X 300mm and 50mm thick. It is possible to calculate the thermal resistance of 100mm thick samples from the results of the 50mm thick samples.

Required Resources

The resources required to complete the testing were in place in the private laboratory and the university laboratory. The samples were initially tested for their thermal resistance and conductivity using the thermal testing equipment at the University of Salford Thermal Testing Laboratory. Here, the testing hardware, software, testing tools and equipment is already in place. The measuring equipment is calibrated for testing the thermal insulation over the required temperature range and capable of accepting industry sized samples of 300mm X 300mm and larger.

When the results from the initial samples had been recorded, the samples were modified for thermal efficiency improvements. This repetition of the sequence of operations would yield results successively closer to the desired result. These modifications were conducted in the private laboratory environment where all the soap sample manufacturing equipment and associated resources (raw ingredients, cooking/manufacturing utensils and heat sources) are kept. From here it was to the testing laboratory where all of the recording and testing equipment was set up for thermal insulation testing. The laboratory staff are experienced and competent in all aspects of thermal testing, including breathability monitoring, recording and interpretation of the resulting data. For example, each staff member is fully trained to work safely in a laboratory environment, deemed competent to perform the given tasks and able to execute the responsibilities associated with thermal testing at a UKAS and Ofgem approved laboratory (Simpson, 2011).

Products That Will Not Be Tested

The current testing regime was not testing for sample strength and elasticity related issues. Extensive testing has been completed on these issues and the results have been recorded. The best practices for improving tensile strength and elasticity have been developed through an on-going process of improvement earlier into the research. Testing of the plastic casings has also been conducted in earlier experiments. Plastic was deemed unacceptable because of the reasons stated in the previous chapter and so was not used for the follow up experiments. Various methods of aerating the soap have been tried and the results have been documented earlier into the research also. Because of this, different aeration techniques and methods would not be tested for.

Documents Produced During Testing

A test report was compiled by the thermal testing laboratory to reveal the results of the thermal testing (see Appendix one).

Risks and Dependencies

The sourcing of the raw materials could have caused potential problems. Although fats/oils and lye are relatively easy to come by, some of the insulation casing materials were harder to source. There had been conflicting reports on the availability of hemp. One of two UK hemp insulation manufacturers had stated that there is a global shortage, whilst the other maintained that stocks were healthy (Fine, 2014).

Due to the fact there is no available data on soap insulation, the performance results were unknown. Whether aerated soap can perform without melting, sweating or degrading whilst in place had yet to be determined. Hemp, cork and cotton thermal insulations are tried and tested as to perform, but not at the thicknesses that would be used to surround the soap samples. These surrounds will breathe and so they should not detract or diminish the breathability of a building envelope or contribute to potential moisture problems (Fine, 2014).

The process of manufacturing soap turns the highly alkaline lye content into a product that is pH neutral. This has been tested for and confirmed. Cutting before the process of transformation has finished, may create problems with toxicity if alkaline soap and skin come into contact. Unknown variables regarding the purity of oils and the strength of lye may mean that different soaps have different strengths.

Identifying the Products for Final Testing

The samples were moved forward to be fire retarded by a spray application of natural ammonium phosphate and then sprayed with a vitamin D3 (essential for human health, but lethal to rodents) compound to deter rodent egress. This was conducted in the private laboratory environment.

5.2.3 Testing Process and results

The first insulation sample (Experiment one) had a protective casing made from cork. This was because the fundamental principle of energy saving is ensuring that the building fabric is intrinsically thermally efficient. However, giving the building scope to breathe without air leakage is important also (Fine, 2014). *Lighter* aerated insulation would be an improvement in the effort to address the weight of the plastic casings. 2mm thick cork sheet was used.

Research indicated that cork as an envelope for an alternative insulation body was yet untried. This meant that there is no available data to draw upon to show how well this product would perform. Cork is the bark of a mature cork oak tree (Wilson, 2012). Regarding sustainability, it can be harvested up to 16 times throughout the tree's lifetime without damage to the tree (Wilson, 2012). The concept of cork as a thermal insulation is not new (Wilson, 2012). Historically cork was used to line freezer walls and is also used as a stand-alone insulation. Cork granules and suberin glue (a natural binder in the cork that activates when the cork is heated) are combined, cooled and cut into the finished product (Wilson, 2012). The make-up of cork is such that the microscopic pockets of air easily compress and expand without collapsing the cork core. In essence, cork is impermeable yet breathable (Greenbuild, 2012). Cork sized at 6mm thick (two faces of an insulation sample) has an R-value of 0.83m^{2}K/W (calculated from figures revealed by “SevilFit”, 2013).

This first sample had aeration bubbles within the soap mixture sized at 2mm^3. The R-value results returned from the lab after testing can also be used to calculate a similar sample surrounded with hemp. This is because a 2mm thick cork casing has only a negligible thermal difference to a 5mm thick hemp covering (Simpson, 2011). The stand-alone R-values of cork and hemp are known. This will create alternative results based on the one test. All of the samples were stabilised to constant mass at 23degC and 50%RH (relative humidity) over periods ranging from 17 to 22 days, before testing. The actual testing was calibrated to ISO 8301, and performed in a “FOX 600 Heat Flow meter”. The time length of each thermal conductivity test was five to fifteen hours to give a % equilibrium of <0.4%. The thermal resistance is evaluated from thickness / thermal conductivity as per the calculation description examples shown previously. As a further example, the thermal resistance for experiment one was calculated thus:

Firstly, the thickness of the sample was measured, in this case 50.1mm. This figure was divided by the thermal conductivity figure measured by the FOX 600 apparatus - (0.0996W/mk). The resulting answer gave the figure for thermal resistance – 0.502m^{2}K/W.

5.3 Further Testing with Breathable Casings

Bio-plastic was chosen originally because of its sustainable and recyclable properties. Interlocking bio-plastic cased thermal insulation could be manufactured for floor insulation because of its strength in resisting compressive force (foot traffic or concrete floor screeds) or surface damage whilst being stored or walked on (for example, small stones wedged in the heal of footwear will not damage the surface, as is the case with foil backed insulations when walked on during initial placement). From the author’s construction site experience, Interlocking plastic cased thermal insulation could provide time saving costs on a warm deck (insulation placed above the roof rafters as opposed to between the rafters) roof. This is because the insulation could be walked on (as with the floor insulation) without using boards to spread the weight to prevent compression damage. The interlocking plastic casing negates the need to tape the abutment joints before the liquid roof covering would be applied. Obviously further research would need to be initiated before the product could be marketed. However, because of the potential problems associated with the plastic casing if used as part of a cavity wall thermal insulation, other materials were considered. There is an abundance of natural materials that could be considered suitable as covering to protect the soap. These breathable materials included cotton, coconut hair matting and wool. However, a combination of time constraints, financial cost and sourcing problems were factors in not going down this route. It was also agreed with the experienced laboratory testing staff that because of the relative thickness of the casing material (only 2mm-6mm) either one would perform equally well. The test sample used in experiment one was surrounded in cork and the results revealed that it did perform on par thermally with the other four generally. However, the cork casing split easily if impacted and stretched and shrunk, as the soap dried out, failing to adhere to the soap. This meant that the cork casing performed like a “baggy overcoat” as opposed to a “well-fitting suit”.

5.3.1: Potential Problems with Cavity Wall Insulations

According to the current version of the BRE Good Building Guide (2000), there can be an increased risk of rain penetration if a cavity is fully filled with insulation. This is because moisture is able to transfer from the outer to the inner leaves resulting in areas of dampness on internal finishes under certain driving rain conditions. The risk can be particularly prevalent in the west facing exposure zones of Scotland, wales and Cornwall (Billington, 2012). The hemp casing that surrounds the soap insulation could be susceptible to transferring moisture from the outside to the inside of a cavity wall in certain wet conditions. However, the insulation body is waterproof and so the actual surface area of the insulation at risk of getting wet is lower than that of full-fill cavity insulations made in their entirety from hemp, fibreglass or mineral wool. The rigid body of soap insulation can prevent the settlement of the cavity insulation (unlike some blown or non-rigid insulations) and thus prevent the creation of air spaces within the cavity that can lead to areas of cold-bridging. However, testing in an actual exposed wall would need to be carried out for verification purposes. If fitting cavity wall insulation to the inside of a solid wall (for example, a wall without a cavity), there is a risk of interstitial condensation. Foil faced rigid board insulations would be more susceptible to this due to their smooth conductive surface area (Wilson, 2012) as opposed to breathable insulations such as hemp (Wilson, 2012). Foil faced insulations can also prevent the building fabric breathing if applied to the external face of a building. This would be particularly prevalent in buildings with their exterior walls made from clays, limes or “wattle and daub” construction which rely on the breathing mechanism to perform (Wilson, 2012). Rigid yet breathable soap insulation may alleviate the problem somewhat, but would have to be tested before any claims could be substantiated.

Because hemp is sustainable and breathable, these are the reasons why hemp was chosen as the preferred covering for the remaining test samples. The first five samples shown are soap/ enteric gelatin capsule combinations. Each sample contained 1kg fats/oils and 142g of lye in 367g of water. The sample sizes were 300mm X 300mm and approx. 50mm thick. To recap, thermal insulation is a material of relatively low heat conductivity used to shield against loss of heat (Pointon, 2014). Many insulators work because they contain trapped air. Trapped air cannot move and so does not convect heat energy. Air bubbles in soap work on this principle. The size and density of these bubbles would have a direct bearing on the insulation’s thermal property.

5.3.2 Results for Experiment 1

Evaluation of the test results for experiment one reveals that physically the soap in this sample closely resembles the sample shown earlier aerated via the vacuum method. The bubble to soap ratio is too strong in favour of the soap, as revealed by the density of 469 Kg/m^3. The thermal resistance figure of 0.502 is too low for the sample to perform satisfactory as a thermal insulation. The actual results are shown in Table twelve on the following page.

Sample	Mean Temperature °C	Thermal Resistance m^2K/W	Apparent Thermal Conductivity W/mK	Mean Thickness mm	Bulk Density Kg/m^3
1. Cork covered soap sample, aerated with 2mm voids	10.0	0.502 ± 5%	0.0996 ± 5%	50.1	469

Table 12: Cork Surrounded Soap Insulation with 2mm Air Pockets

5.3.3 Results for Experiment 2

The evaluation of the test results for experiment two shows that the second insulation sample had a protective casing made from hemp. This was because hemp and flax are natural cellulose fibres that provide unattractive shelter options and food sources for insects and rodents (Fine, 2014). Natural hemp and flax fibres are non-toxic and hemp insulation is non-irritating to the eyes, skin and respiratory system (Williams, 2012). It is usually treated with borax for its fire retardant properties (Lyons, 2012). Hemp insulation absorbs and releases moisture, which can help to regulate internal moisture levels within a building, which can enhance human comfort whilst reducing the risk of the problems associated with condensation (Woolley, 2013). Hemp insulation will typically contain either natural or recycled man-made polyesters as part of its make-up. The results in Table 13 on the following page reveal that a soap insulation sample, 52.5mm thick, containing 4mm voids throughout and encased in 5mm hemp will have an R-value of $0.632m^2K/W$. At 50mm thick this R-value means that at 50mm thickness this insulation would not perform satisfactorily as a thermal insulation. The density is also too great at 425 Kg/m^3 for this sample work effectively.

Sample	Mean Temperature °C	Thermal Resistance m^2K/W	Apparent Thermal Conductivity W/mK	Mean Thickness mm	Bulk Density Kg/m^3
2. Hemp covered soap sample, aerated with 4mm voids	10.0	0.632 5%	0.0830 ± 5%	52.5	425.1

Table 13: Hemp Surrounded Soap Insulation with 4mm Air Pockets

5.3.4 Results for Experiment 3

The evaluation of the test results for experiment three (shown in Table 14 below) reveal that a soap insulation sample, 55mm thick, containing 8mm voids throughout and encased in 2mm hemp will have an R-value of 0.683m^2K/W. This means that 50mm thickness of this insulation would not perform at an acceptable level either, although this is an improvement on the previous sample. The bulk density is an improvement also but is still some way off from getting nearer to an ideal target of below 200 Kg/m^3.

Sample	Mean Temperature °C	Thermal Resistance m^2K/W	Apparent Thermal Conductivity W/mK	Mean Thickness mm	Bulk Density Kg/m^3
3. Hemp covered soap sample, aerated with 8mm voids	10.0	0.683 ± 4%	0.0806 ± 4%	55.1	360

Table 14: Hemp Surrounded Soap Insulation with 8mm Air Pockets

5.3.5 Results for Experiment 4

Hemp sized at 10mm thick (2 x 5mm sides of an insulation sample) has an R-value of 0.25m^2K/W (calculated from figures revealed by “Thermofleece”, 2013). This hemp covered soap sample was aerated with 12mm diameter voids. Table 15 (below) reveals that a soap insulation sample, 61mm thick, containing 12mm voids throughout and encased in 5mm hemp will have an R-value of 0.996m^{2}K/W. This means that 50mm thickness of this insulation performs at approximately 55 - 60% of the thermal resistance of 50mm polystyrene. Showing a bulk density of 225 Kg/m^3, this sample is a substantial improvement over the previous samples. It should be acknowledged at this stage that not all thermal insulations on the market can perform to the UK specification on U-values for walls and roofs on their own. For example, all multifoil insulations have to "backed up" with either 70mm polyisocyanurate or 140mm fibreglass (TLX, 2013). Analysing the results from the previous four tests, it appeared that trapped bubbles of a larger size perform better than smaller ones (for example a higher R-value with sample four as opposed to samples one, two and three). This was as a direct result of more trapped air within the soap matrix. The logical reason at arriving at this decision is based on established evidence of the trapped air principle. These results would help to validate the conclusion of this thesis.

Sample	Mean Temperature °C	Thermal Resistance m^{2}K/W	Apparent Thermal Conductivity W/mK	Mean Thickness mm	Bulk Density Kg/m^3
4. Hemp covered soap sample, aerated with 12mm voids	10.0	0.996 4%	0.0614 ± 4%	61.1	225

Table 15: Hemp Surrounded Soap Insulation with 12mm Air Pockets

5.3.6 Results for Experiment 5

The fifth insulation sample also had a protective casing made from hemp. This was for the reasons mentioned previously, but also because the hemp casing helps to iron out problems arising from the non-uniformities in flatness, required for the testing apparatus. The process for the testing of this soap sample was identical to the other samples in the previous experiments, only this time the bubbles were sized at $14mm^3$. This produced the lowest density so far ($169Kg/m^3$). This sample performed on par with polystyrene at a thickness of 35mm. The results are recorded in Table 16 below.

Sample	Mean Temperature °C	Thermal Resistance m^2K/W	Apparent Thermal Conductivity W/mK	Mean Thickness mm	Bulk Density Kg/m^3
5. Hemp covered soap sample, aerated with 14mm voids	10.0	1.0115 ± 5%	0.0604 ± 5%	61.1	169

Table 16: Hemp Surrounded Soap Insulation with 14mm Air Voids

5.3.7 Evaluating the Results from the Previous 5 Experiments

Although the thermal conductivity and thermal resistance figures for the insulation samples utilizing air voids of *even* numbers (2mm, 4mm etc.) were achieved via laboratory testing, It is possible to calculate the thermal conductivity of other insulations that would be created using *odd* number sized air voids that were not tested in the laboratory. A table of both thermal conductivity and thermal resistance for soap utilizing air pockets of 2mm –14mm is shown in Table 17 (shown on page 140), the method used for calculating the figures not obtained through laboratory testing is shown below.

To calculate the thermal conductivity of soap insulation utilizing 3mm air voids. First subtract the thermal conductivity figure of the 4mm air voids from the 2mm air voids:

0.0996 – 0.0830 = 0.0166. Next divide this figure by 2.= 0.0083. Next subtract this figure from 0.0996 (2mm voids) = <u>0.0913 W/mK</u>

To calculate the thermal conductivity of soap insulation utilizing 5mm air voids, subtract the thermal conductivity figure of the 6mm air void from the 4mm air void and so on. To calculate the thermal resistance figure of soap insulation utilizing 3mm air voids, firstly subtract the 2mm figure from the 4mm figure, for example:

0.632 – 0.502 = 0.13. Next divide this figure by 2 = 0.065. Next add this figure to the 0.502 (2mm voids) figure = 0.567 m^2K/W. This method will not give the precise figure, but the figure will also be close enough to be acceptable.

Size of air voids	Thermal conductivity W/mK	Thermal resistance m^2K/W
2mm	0.0996	0.502
3mm	0.0913	0.567
4mm	0.0830	0.632
5mm	0.0824	0.644
6mm	0.0818	0.657
7mm	0.0812	0.670
8mm	0.0806	0.683
9mm	0.0758	0.773
10mm	0.0710	0.864
11mm	0.0662	0.930
12mm	0.0614	0.996
13mm	0.0609	1.003
14mm	0.0604	1.011

Table 17: Thermal Conductivity & Thermal Performance of Soap

The thermal conductivity and thermal resistance for the previous five experiments are represented in a graph. As can be seen in Fig.5.2, the greater the volume of air entrained within the mix, the higher the thermal resistance and lower thermal conductivity.

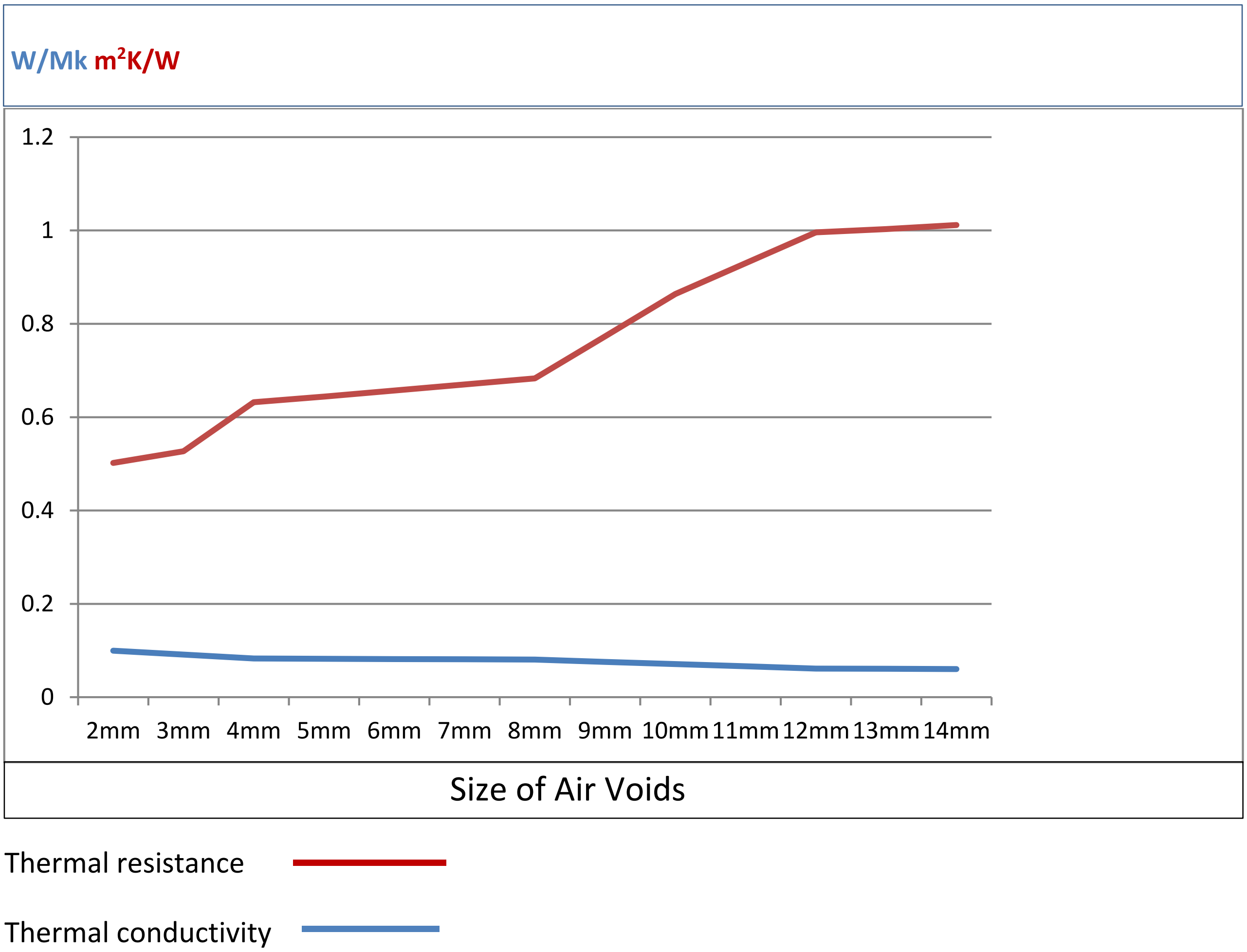


Figure 5.2: Graph Showing Thermal Conductivity and Resistance of Samples 1-5

It should be mentioned at this point that thermal testing was halted at 14mm^3 air voids. This was because previous, archived laboratory testing results, on a wide range of insulations show that 14mm^3 is the optimum size of "bubble" in order to achieve high thermal resistance. Increasing the size to 15mm^3 and greater, actually begins to lower the thermal resistance of the insulation. The reason for this is explained later in this thesis. To evaluate the thermal insulation of a material, it is necessary to know its resistance to heat flow (m^{2}K/W) presented by a material in a given thickness. The higher the thermal resistance, the better insulation is provided by the material. Thermal conductivity or λ is the quantity of heat W/mK that may be transferred into a material, at a given time. The lower the λ value, the higher the insulation of the material. It is generally accepted that Insulating materials that have a thermal conductivity of around 0.030 W/mK are very good and figures of 0.060 W/mK or lower are moderate performers (Pfundstein et al, 2008).

5.4 Results for Experiment 6

The sixth insulation sample also had a protective casing made from hemp. This time, for experimental balance, the aerated soap sample was aerated with 10-15 micron diameter microspheres only. Each sample contained 1kg fats/oils and 142g of lye in 367g of water. The sample sizes were 300mm X 300mm and approx. 50mm thick. The process of testing the samples was identical to the previous five samples tested. The results reveal that microspheres give a reasonable thermal resistance figure at 0.719m^2K/W (see Table 18 below). At 50mm thickness the sample will give a thermal resistance approximately equal to 80/90% of expanded polystyrene of 50mm thickness. However, the density was too high. It was decided to evaluate this experiment and design the seventh sample accordingly. Microspheres at 50% of the soap unit volume were added into the soap mixture.

Sample	Mean Temperature °C	Thermal Resistance m^2K/W	Apparent Thermal Conductivity W/mK	Mean Thickness mm	Bulk Density Kg/m^3
6. Hemp covered soap sample, aerated with expanded microspheres @ 25% per total soap volume	10.0	0.719 5%	0.0792 ± 5%	56.9	369

Table 18: Hemp Surrounded Soap Insulation with Expanded Microspheres

5.4.1 Results for Experiment 7

The results revealed in experiment seven (Table 19) show that soap aerated with 50% of the soap unit volume with microspheres actually works very well. This soap insulation works (in theory) as good as polystyrene. However, it was noted that although the insulation remained rigid, it tends to crumble far too easily when handled. This was due to the fact that the soap binding matrix was weakened by the "excessive" amount of microsphere powder. If the volume of microspheres in relation to soap matrix was increased, then that could improve the soap matrix thermal qualities by lowering its density and making the product lighter. This is partly because the gas in the microspheres is more likely to be "still" with thermal conductivity of 0.025W/mK or less. However, experiments six and seven reveal that soap insulation utilising only microspheres cannot create a *usable* thermal insulation.

The previous sample results indicate that thermal resistance can be improved further by lowering the density of the soap as much as possible, for example, adding larger air voids. However, this could also mean that if the void sizes are increased, i.e. larger than $14mm^3$, there is the possible disadvantage that air convection may start to predominate over air conduction. Basically, the lower the density of the material, the higher the thermal resistance and the lower its thermal conductivity (Li, 2015).

Sample	Mean Temperature °C	Thermal Resistance m^2K/W	Apparent Thermal Conductivity W/mK	Mean Thickness mm	Bulk Density Kg/m^3
7. Hemp covered soap sample, aerated with expanded microspheres @ 50% per total soap volume	10.0	1.073 ± 5%	0.0575 ± 5%	61.7	128

Table 19: Hemp Surrounded Soap insulation with Expanded Microspheres

5.5 Apparent Thermal Conductivity / Density Relationship

The apparent thermal conductivity is plotted as a function of bulk density (in graph form shown in Appendix 1) and compared with the relationship for building materials of comparable density - autoclaved aerated concrete (BS EN 1745), foamed plaster (CIBSE Guide A3, 2015), fibre building board (CIBSE Guide A3, 2015). Standard design data has been taken from BS EN 1745:2002 for the thermal conductivity of aerated concrete over the density range 300 to 1000 kg/m^3 with a probability of 90%. The results for the soap samples are also compared with generic data for mineral wool insulation over a similar density range.

The thermal conductivity of building / insulation materials is strongly dependent on the porosity, pore size and structure, as well as density and thermal conductivity and type of solid contact of the matrix material. Generally, the more air entrainment the lower the density. The thermal conductivity decreases with decreasing density until at very low densities (e.g. loft insulants) radiation heat transfer starts to dominate the conduction processes and the thermal conductivity increases. The soap samples tested were sufficiently dense to avoid this effect. Consequently, the apparent thermal conductivity of the soap samples decreases with decreasing density over the density range tested (128 to 425kg/m^3).

The results for the apparent thermal conductivity of the soap insulation samples over the density range 200-400 kg/m^3 are consistent with a class of structural materials with limited insulation performance, such as aerated concrete, foamed plaster and fibre building board. Lower density soap insulation samples exhibit poorer insulation performance than conventional insulation material over the same density range. The apparent thermal conductivity of soap samples is for example some 70% more than that for mineral fibre of comparable density. This is mainly attributed to the relatively large size of pores and solid conduction component, compared to that for mineral fibres. Generally, the smaller the pores, the smaller are the air conduction component.

5.6 Decreasing the Density of the Soap

As can be proven from experiments one - five and experiments six – eight, the greater the amount of air within the soap sample, the less dense that sample becomes. Graphs depicting this are shown in Fig. 5.3 and Fig. 5.4 on the following page.

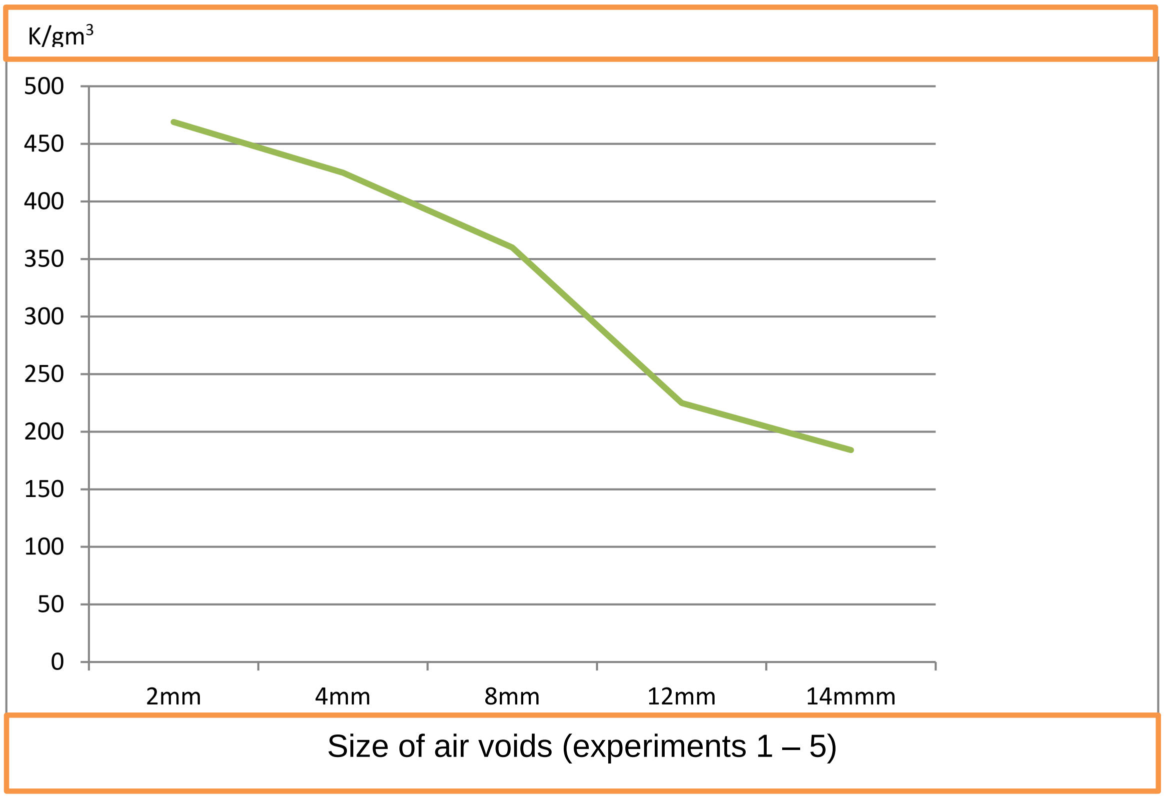


Figure 5.3: Graph Showing how Increasing the Void Size Decreases Density

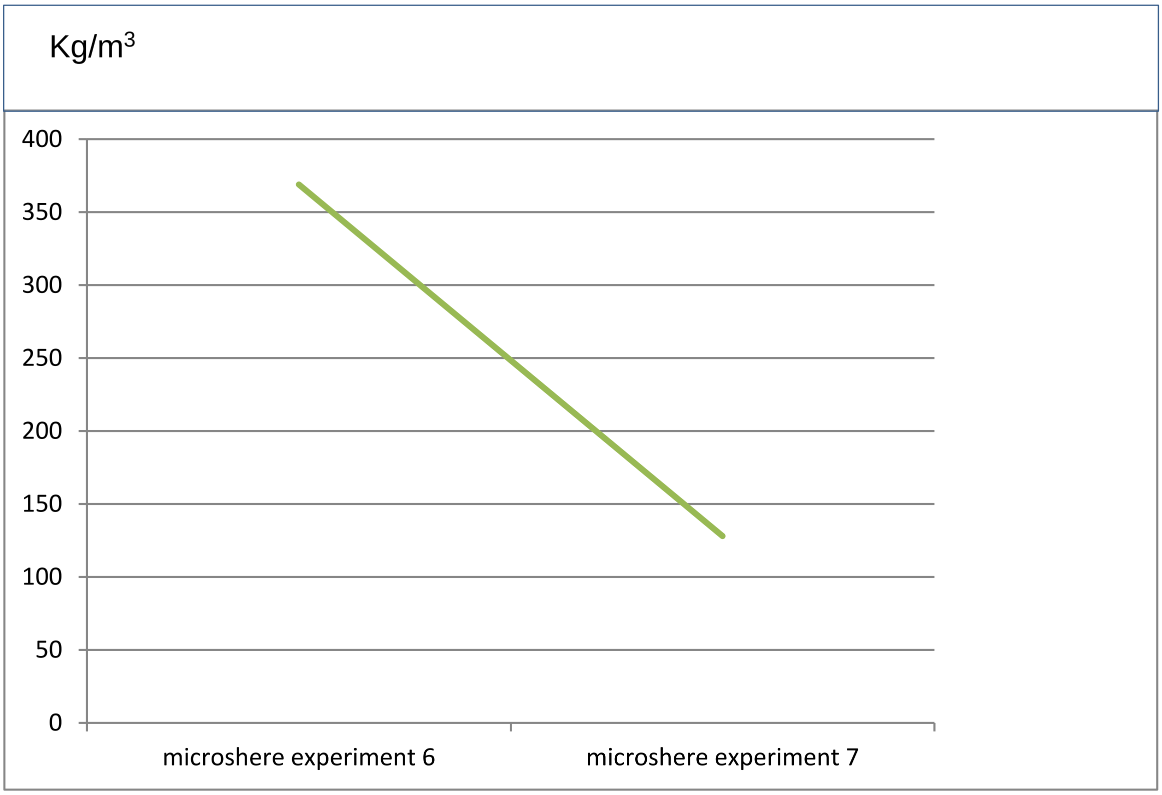


Figure 5.4: Graph Showing how Increasing Void Size Decreases Density

A table indicating the progressive improvements towards finalising the optimised soap insulation specification and comparison of the petroleum counterparts is shown in Table 20 below.

Criteria	Sample: 14mm^3 voids	Expanded polystyrene	Polyisocyanurate (Foil Faced)
Financial Cost	o	o	o
Environmental Manufacturing Cost	o	o	o
Thermal Resistance	1.01(m^{2}K)/W	1.25m^{2}K/W	2.0m^{2}K/W
Thermal Conductivity	0.06W/mK	0.04W/mK	0.025W/mK
Weight	178g	67g	135g
Thickness	61.1mm	50mm	50mm
Working Performance (Durability)	o	o	o
End of Life Disposal	o	o	o

Table 20: Soap Comparison Table

Key: Good Moderate Poor

In summary of the soap sample's performance, the following was noted. Soap containing air pockets of 2mm – 6mm will not perform satisfactory as a thermal insulation. The soap body is too dense. Soap utilising 12mm voids will perform at 55% of the capacity of polystyrene, whilst soap with air voids of 14mm peaked at approximately 70% the capacity of polystyrene. Soap containing voids of over 14mm will actually start to decrease in thermal performance as the void size increases. Soap aerated with 50% of the soap volume using microspheres performs well. This soap insulation performs on par with polystyrene. However, although the insulation remained rigid, it crumbled when handled or moved. Soap with air voids of 14mm is as good as the soap insulation thermal performance will get and so this is the one that will move on to next stage improving.

5.7 Chapter Conclusion

Using hemp insulation as a casing was an improvement over plastic. The insulation samples were lighter and because the hemp is organic, it meant that the hemp could easily be composted at the insulation's end of life. The thermal resistance of the samples increased as the bubble size increased, up to a maximum size of 14mm^3, which meant that the thermal conductivity decreased. This meant that the soap insulation was good, but not as good as the established comparison insulations. In effect, this meant that 65mm of soap insulation would be equal to 50mm polystyrene. The soap insulation couldn't be improved by increasing the bubble size to over 14mm^3 and in reality this put the soap insulation in the position of being a moderate performer under today's UK thermal insulation legislation, but still a useful performer, as revealed later in this thesis. Increasing the void size also decreased the soap density. This made the soap lighter and better able to increase its thermal resistance. Small spheres containing butane gas (expanded microspheres) out-performed spheres containing air on a thermal comparison basis, but because these microspheres have the consistency of powder and their smooth surface area makes it difficult for them to bind with each other or the soap at a molecular level, the resulting sample was unworkable and unusable because of its apt for crumbling and disintegration when handled. Soap insulation also retained its better financial and environmental costs than the polystyrene and polyisocyanurate comparison insulations. The following chapter concentrates on making the soap insulation casing fire retardant and vermin proof whilst waterproofing the soap body.

Chapter 6 Final Improvements to the Soap Insulation: Making the Product Waterproof, Fire Retardant & Vermin Proof

6.1 Introduction

This chapter discusses the improvements to the soap insulation to help it maintain its performance, quality and longevity when placed in a real world situation. The soap based insulation would have to be water repellent. Three samples would be tested to establish their water resistance properties. Each sample would be mixed with a different waterproofing additive and its water immersion properties recorded to establish which additive performed the best. The samples should also be vermin proof and fire retardant to be a viable alternative to established petroleum based rigid board insulations. It should be noted that both polystyrene and polyisocyanurate insulations are not classed as fire retardant, but fibreglass and rockwool are (Wilson, 2012), even though these two insulations are not in direct comparison to soap insulation in terms of the research. Making the soap insulation fire retardant would have to be achieved without the use of toxic or petroleum derived additives. The samples would be tested for their ignitability properties in a draught free test cabinet. Three hemp samples, treated (to reduce the flammability or delay the hemp combustion), partially treated and untreated, would be tested. The hemp casing surrounding the soap body is already anti-microbial, anti-mildew, frost and ultra-violet light resistant (Thermafleece, 2010), and so does not need treating to improve on these characteristics.

6.2 Waterproofing the soap

The marketing of thermal insulation in Europe is regulated by the Construction Products Regulation 305/2011 (Billington, 2012). Manufacturers within the European Union are responsible for compliance of their products with the terms of this regulation. If the insulation carries the European Conformity Assessment (CE) mark, then this shows that the material complies with the standards and therefore fulfills the requirements of the regulation. There are currently no European (or British) standards regarding the waterproofing of thermal insulation and as such there are no benchmarks for soap insulation to aspire to or test against (Billington, 2012).

Keratin is the building block of hair and nails and is the natural waterproofer of skin. Keratin is a natural polymer, made from protein chains, and as with all proteins, keratin contains carbon (C), oxygen (O), nitrogen (N) and hydrogen (H). One other protein found in keratin is cysteine. Cysteine contains the element, sulphur (S). Because of the many different types of keratin (over 50), there is no single chemical formula, for example, KRT1, KRT2, KRT3 etc.

There are variations from animal to animal but the basic molecular structure remains similar, as shown in Fig. 6.1 below.

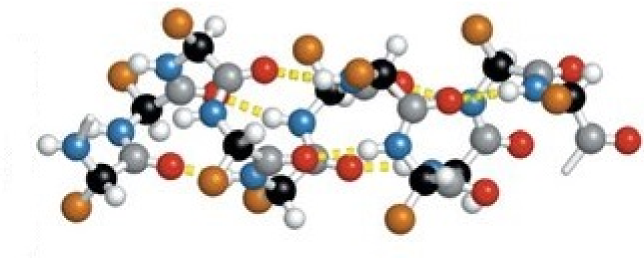


Figure 6.1: Molecular Structure of Keratin (Principles of Bio- Chemistry, 2006)

The next stage testing required an addition of naturally waterproof, pure liquid keratin. This starts as a flexible solid but turns to liquid when heat is applied. This was dispersed within the soap mixture at the soap's liquid stage. The keratin was blended with the soap after the lye and fats had saponified, so as not to interfere with the initial soap saponification process. The keratin was added at a ratio of 15% per soap volume mix. The soap body changed colour from white to coffee brown. The liquid keratin added to the mixture acted as a catalyst and speeded up the initial soap setting time to under two hours. When it had set, the soap body was slightly more "rubbery" than the samples in the previous experiments. When tested with a moisture probe, the soap body contained less water also, 33% as opposed to 35% in the previous samples. The keratin also changed the composition of the soap, making the soap body moisture repellent. This will be essential to the insulation if the protective casing is to be made from lightweight, breathable hemp. The soap was weighed dry and the weight recorded. It was then immersed in water for 48 hours and then removed and weighed. This was to identify how much, if any, water had been absorbed by the soap body. The results are shown in Table 21 on page 151.

Keratin mixes well with soap at a molecular level. This is due to the fact that both keratin and fat molecules are organic. In the interest of balance, another waterproofer called "Wykamol Integral Waterproofer" was used in a second soap sample. This waterproofer is an additive based on an alkaline soap mix of fatty acids. This liquid soap gel's actual composition is based on a potassium hydroxide lye (KOH) and turpentine oil (K12H20O7) mix (Wykamol, 2013). It was reasoned that a soap based waterproofer should be used because a soap additive would not conflict detrimentally with the soap body chemically. The reasoning behind this was because lye can be natural, as explained in a previous chapter, and turpentine oil is distilled from pine tree resin. This soap sample was mixed in an identical way as the previous sample, with 15% waterproof additive used instead of keratin. The water immersion test was also performed and the results were recorded. Two more samples were made using the identical ingredients as above, but this time the first was immersed in keratin and the second was immersed in Wykamol, and then left to dry. The rationale behind this was to coat the soap samples with a waterproof barrier to prevent any moisture ingress. An untreated control sample was also tested in the same way for comparison reasons.

A third soap sample was created using sodium silicate as the waterproofing element. Sodium silicate (water glass) is the common name for compounds with the formula $Na_2(SiO_2)_nO$. It is a clear, colourless liquid that is used in detergents, soaps, adhesives and in waterproofing liquids (Ianakiev & Crabbe, 2014). Sodium silicate is commercially available as a white powder that is readily soluble in water. When mixed the liquid produces an alkaline solution. Sodium silicate is stable in pH neutral and alkaline solutions. However, in acidic solutions, the silicate ions will react with the hydrogen ions in the acid to form silicic acid. This acid will form a hard, glass like substance when heated and cooled (Ianakiev & Crabbe, 2014).

A sodium silicate solution additive will significantly reduce porosity in most masonry products such as concrete, plaster and mortar (Ianakiev & Crabbe, 2014). When mixed with portland cement, a chemical reaction occurs with the portlandite {$Ca(OH)_2$} that permanently binds the silicates with the cement making the product water repellent (Newman & Chew, 2003). When sodium silicate is blended with sodium hydroxide lye, a clear gel is created that mixes easily with soap to create a water resistant product. If sodium silicate is added to a flammable product, it can also make that product fire retardant (Li, 2011).

For the purpose of waterproofing the soap sample, 200g of sodium hydroxide and 300g of sodium silicate gel were blended with 500ml water. This mixture was heated over a hob for 15 minutes until the excess water had evaporated, leaving a clear gel. This gel was mixed with the soap after saponification, but before the soap had set solid, at a volume of 15%. A further soap sample was coated in sodium silicate and left to dry. The results are recorded in Table 21 below.

Soap type	Weight (grams)	After submersion	Weight gain
Control	385	409	6%
Mixed with keratin	385	398	3%
Mixed with Wykamol	385	392	2%
Mixed with sodium silicate	385	39.5	1.5%
With keratin coating	385	389	1%
Wykamol coating	385	385	0%
sodium silicate coating	385	385	0%

Table 21: Results of the Waterproofing Testing

As can be seen from the Table 21 above, soap mixed with, and coated with sodium silicate, (along with Wykamol), created the best performing water resistant insulation bodies. Soap mixed and coated with keratin came second.

6.3 Fire Retardant Soap Casing

The soap casing should be fire resisting in as far as reasonably practicable. This is because it would be unwise to knowingly increase the fire load, for example, on a timber frame building. A flame retardant solution was manufactured from ammonium phosphate $(NH_4)_3PO$. As mentioned previously, it is non-toxic and was applied to the insulation casing. The hemp casing was then performance tested in relation to fire ignition. Pictures of ammonium phosphate and an ammonium phosphate coated sample are shown in Fig. 6.2 and Fig.6.3 on the following page.

Figure 6.2: Ammonium Phosphate Powder Figure 6.3: Section through Hemp Sample

Combustibility of building products are rated in European classes from A to F, with A classified as the most fire retardant and F being classified as the worse (or the manufacturer has not provided the fire properties for the product) (Domone & Illston, 2010). Under Approved Document B (2007), Class 0 relates to products of non or low combustibility, whilst Class three relates to products with poor resistance to fire. With regards to thermal insulation, Rockwool insulation achieves a Class A, whilst expanded polystyrene will achieve a Class F (Domone & Illston, 2010). The standard fire resistance tests for these Euroclasses are EN ISO 9239-1 and EN ISO 13823 (Scidali, 2014). These test methods measure the ignitability of building products when exposed to a small flame. The testing takes place inside a test cabinet that creates a draught free environment, as shown in Fig.6.4 below.

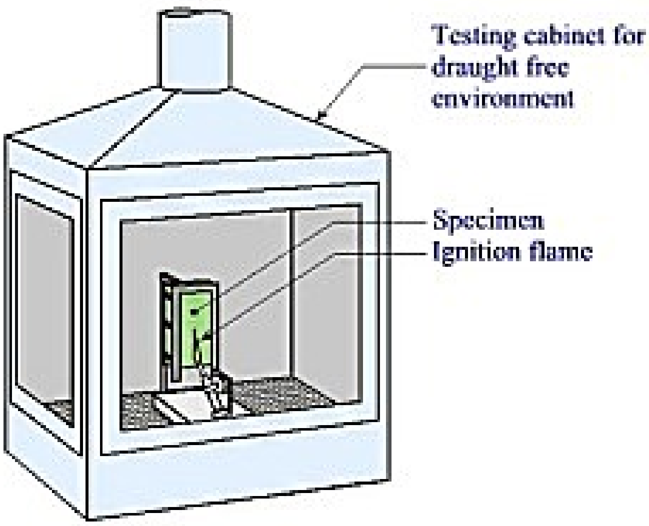


Figure 6.4: Ignitability Test Cabinet (Science Partner, 2014)

An ignitability test cabinet was constructed (Fig.6.5 below) for the hemp insulation samples to be tested in. The steel and glass box was constructed with a steel flue and was placed on a fibre cement heat resistant base before the testing was carried out. The results from the testing revealed that basic untreated hemp insulation will ignite after three seconds if exposed to a naked flame. If the hemp casing is sprayed with ammonium phosphate, then the hemp casing takes 12 seconds to ignite. If the hemp casing is fully immersed in ammonium phosphate liquid, then removed and left to dry, it will not ignite. It will char however. It may be possible to improve the casing by using rockwool as opposed to hemp. Rockwool is fully fire retardant (Horrocks & Price, 2008) and at a thermal level performs slightly better than hemp on an equal thickness basis.

Figure 6.5: Ignitability Test Cabinet

There is currently no harmonised European methodology for testing and evaluating the toxicity of building products in a fire. The toxic gases that can be produced by combustion of insulation materials at the early stages of a fire can create their own hazards but these potential problems would normally be dealt with at the building development or planning stage (Horrocks & Price, 2008). Continuous glowing combustion and smouldering fire relates to fire development of a product that has resulted from prolonged, low-intensity heat exposure. This can occur in thermal insulation in a ceiling void, for example, above a recessed lighting fixture. As yet there is no harmonised European testing method for smouldering fire or continuous glowing combustion, although a European test method (CEN TC127) is under development (Smith, 2014).

6.4 Making the Soap Vermin Proof

Vitamin D can be lethal to rodents. So obviously the more vitamin D mixed into the soap mixture, the better the rodent repellent. A product called “Now Vitamin D3” was added to the soap mixture at the mixing stage.

“Now Vitamin D3” is an extra strength vitamin liquid. It contains 1,000 iu’s (international units) per drop (one IU is the biological equivalent of 0.025 μg). Although vitamin D was added to the soap, it was not added to the hemp casing. This was because it was reasoned that although in theory rodents could use the hemp for nesting purposes, it would be unlikely to be ingested as food as hemp insulation is naturally both insect and vermin repellent (Naturepro, 2014). Studies have shown that ammonium phosphate, the fire retarding additive to the hemp casing, could give rise to gastro-intestinal disorders in rodents if ingested (Toxicology Data Network, 2007). This could be aggravated further because of a rodent’s inability to vomit (Dougherty & Guilder, 2012). For a “belts and braces” approach for repelling rodents, mustard powder would be mixed with the ammonium phosphate. Mustard powder is a natural repellent to rodents (Klein & Wenner, 2001).

6.4.1: Description and Results from the Rodent Test

Hemp is a natural insect repellent due to its compounds of pinene, limonene, terpenoid, and borneol (McPartland, 2009), and so does not require any additional treatment to deter insects. However, ammonium phosphate mixed with mustard powder was used to deter rodent activity with the hemp casing. To verify that rodents will avoid treated hemp, a small portion of hemp was placed into the corner of a cage containing two tame white mice. For animal cruelty prevention reasons, the hemp was treated with a liquid mustard powder solution only and then left to dry. In the other corner was placed a portion of “Animal Dreams” hamster wool. The mice were observed over a period of five days. The hemp was avoided and untouched, whilst the hamster wool was occasionally used for bedding purposes (see Fig. 6.6 on page 155).

Figure 6.6: Caged White Mice

6.5 Chapter Conclusion

In relation to waterproofing the soap insulation, Wykamol and sodium silicate added to the soap body during the mixing stage gave good results. Even better results were achieved when these were painted on to the exterior face of the soap body also. When the hemp casing was immersed into an ammonium phosphate solution and dried, the casing became fire retardant. The same ammonium phosphate treated hemp casing would also act as a rodent repellent, especially when the phosphate was mixed with mustard powder. The final soap sample contained air voids of $14mm^3$. The hemp casing was treated with ammonium phosphate mixed with mustard powder. The soap body contained extra strength vitamin D, horsehair fibres and Wykamol waterproofer which were blended with the soap body at the soap mixing stage. The soap body was also coated with Wykamol waterproofer once the soap had dried.

Chapter 7 Research Discussion

7.1 Chapter Introduction

This discussion chapter brings together all of the salient points about how and why the soap insulation was created and tested. In addition, it also seeks to establish whether the original aims and objectives were satisfied, what contribution to knowledge is contained within this thesis, what is required for potential future improvements to the soap based insulation and it highlights the key findings from the comparison and testing results where soap insulation is compared against polystyrene and polyisocyanurate insulations. The journey from theory to execution has been one of systematic improvements based on trial and error, with the results analysed within this chapter.

7.2 Contribution to Knowledge

The topic of this thesis was an idea that demonstrates through literature review and the systematic investigation into the research topic, that soap insulation is unique. This is evidenced by the awarding of a worldwide patent on the product, the Technology Strategy Board funding the thermal testing laboratory fees by means of a research grant and by having a peer reviewed paper published on the soap insulation research. The first paper published by Emerald Publishing contains extracts from the first half of this thesis, whilst a second paper under review for publication by Emerald Publishing includes the results contained in the second half of the thesis. With regards to practice, a patent to a certain extent, can stifle independent, external practical innovation. This can inhibit further contributions to practice. If further research is initiated in practice, where questions and challenges can be identified and the research strategy carried out through practice based methodologies, formed by the needs of the practice, then this can be seen as an agreeable scenario. This probably would not happen if the patent is still in force. For this reason the patent for soap based insulation will not be renewed in 2016. So the real question is, what is the importance of the research question and what is the significance of the findings?

7.3 Results from the Previous Chapter Investigations

Whether soap insulation can be an alternative to petroleum insulation is an important question to ask in so far that soap processing and manufacture is better for the environment than crude oil retrieval, crude oil processing and insulation manufacture. Soap will never replace petroleum derived foamed insulants because soap cannot compete with the high level of thermal resistance that the petroleum based insulations can achieve. However, it is within the realms of possibility for a small niche market to be established amongst the other eco-friendly insulations to accommodate sustainable soap. As revealed in the literature review, the abundance of waste fats and oils would ensure that there is a consistent flow of raw materials to fuel the manufacture, whilst the low capital outlays and associated manufacturing costs can be passed on to the retailer. The use of biodegradable and sustainable components for the finished article make soap an attractive alternative to insulations derived from fossil fuels. The lower environmental costs achieved by the hemp and soap combination is a desirable alternative also. On an environmental level the difference is clear. The literature review section of this thesis reveals that soap insulation can certainly compete favourably with petrochemical based insulations on this level. Weight wise, soap insulation satisfies the Health and Safety manual handling requirements. The process of soap manufacture and waste disposal is unlikely to create long, mid or short- term damage to the environment. Whilst investigating soaps sustainability credentials, it is worth remembering that soap based insulation can create a use for waste animal by-products that would otherwise be destined for incineration or landfill.

It is an inescapable fact that crude oil is a finite commodity that *will* run out someday. For this reason it is worthwhile investigating soap's environmental credentials. In theory soap lends itself favourably to other natural or sustainable insulations. Natural additives and ingredients can be incorporated in part to create effective hybrid insulation barriers to resist heat transfer. Soap insulation is toxic chemical free and although hemp insulation in its current form is still in its infancy somewhat, research and manufacturing results are positive. It has been proven that soap can be aerated, strengthened and in theory protected with a hemp covering. If the instructions shown in the previous chapters are followed, soap insulation can be made fire retardant and vermin repellent, whilst remaining non-toxic. In a life-cycle assessment scenario, soap does compare favourably to petroleum based products. It is commendable to the petrochemical industries that some waste insulation products are recycled. However, as revealed within the literature review, worldwide a large amount of petroleum insulation still finds its way to landfill, meaning that soap insulation compares favourably with petrochemical based insulations on an end of life disposal basis. To sum up, soap insulation uses renewable resources, is sustainably sourced and benefits from innocuous disposal.

7.4. Possible Future Improvements and Applications of the Soap Insulation

Aerated soap insulation could be improved by replacing the pockets of air with pockets of butane or similar petroleum derived gases. This works on the same principal as the “Expancel” microspheres used in the earlier experiments. However, this takes the soap insulation research down a different direction because although the thermal performance would be improved, the soap body would depend on a petroleum based derivative to function. Using lighter, inert (not chemically reactive) gasses such as helium (which is both non-toxic and fire retardant) or neon (which is two thirds the density of air) would decrease the weight and help to improve the thermal performance of the soap.

If the soap insulation was factory manufactured using regularised sizing and shaping with regularised and measured ingredients, the insulation product would be uniform and consistent throughout. A uniform insulation creates a uniform thermal barrier that eliminates temperature cold spots and thermal bridging discrepancies within the building envelope. Regularised raw ingredient quantities of a consistent standard would eliminate any minor indiscretions with the thermal conductivity measurements due to mixing more, less or slightly different ingredients into the soap mixture. Temperature controlled drying rooms at the final manufacturing stage would prevent any minute discrepancies in the insulation’s thermal conductivity readings. This is because the moisture contained within the soap body would be evaporated off at the same rate, giving a uniform body matrix to contained moisture ratio.

With outside investment and product promotion, soap insulation could become marketable as a sustainable product. Part of its selling features would be that soap thermal insulation is sustainable and non-toxic. Also, because soap is mouldable, it lends itself to fitting intricate shapes and niches. Buildings that are earmarked for thermal upgrading, can, and often are allowed by building control bodies to be thermally upgraded to a lower standard than the building regulations require (Barritt, 2014). This discretion is commonly used when properties are difficult to insulate without major structural or expensive alterations are required. Grade II listed buildings or properties contained within a conservation belt often fall under this remit.

Soap based insulation is viewed as a *moderate* thermal performer (as opposed as an *excellent* performer) and as such should not be viewed as a failure. As mentioned previously, although thermal insulation over 200mm thick is unlikely to be accepted as a mainstream standalone wall thermal insulation, it could be used as part of a *combination* to achieve a wall's overall U-value. Multifoil insulation, a common type of insulation used throughout the world, does not perform on its own and requires a back-up insulation to help it achieve the correct U-values for the UK legislation. Soap based thermal insulation would probably be best suited for roof and floor insulations where insulation thickness is not so much of an issue.

In an environment where thermal performance legislation is not such so stringent, for example in a country with a warmer climate, soap insulation could come to the fore. This especially applies to an environment where low capital manufacture and retail costs are important, where elevated sustainability issues are important and to countries without a need for such high, stringent thermal performance requirements from their buildings. In effect, by using up the thousands of tons of waste oils and fats that are accumulated annually, soap insulation would actually give this waste a purpose.

In some Asian countries, for example, Thailand, India, Korea, China and Indonesia etc., solar heat gain is an important a problem as heat loss. This is especially so in the overcrowded factories where human comfort in crowded conditions can lead to manufacturing production issues. Roof insulation can reduce solar gain in factories to combat overheating, but the insulation must have a cheap overall retail cost for it to be considered (Desjarlais & Zarr, 2012). To limit solar gain to the factory roofs, traditional methods of solar reflection or absorption are still in use.

A 100mm thick mud layer spread over a factory roof can reduce the interior by 10^{0}C (Utgikar, 2009). However this can lead to structural problems due to the extra loading to the roof. Painting the roof white can reduce internal heat by 11% but will eventually become ineffective through dust accumulation over the surface and ultraviolet degradation (Utgikar, 2009). 25mm polystyrene will reduce the internal heat gain by 12% (Utgikar, 2009). This means that 40mm soap insulation should produce the same results. Obviously the thicker the soap insulation used, the less internal heat gain.

Insulation in new buildings is a legal requirement in many former Eastern Bloc countries, but because of financial cost issues, only 30% of new buildings actually contain it (Ries et al, 2009). Cheap aerated soap insulation, made from cheap animal fats, could help to combat this.

Most abattoirs and rendering facilities have to pay to have their animal waste removed. If the fats are separated from the offal at source, removal to a tallow manufacturing plant could be carried out a reduced cost to the abattoir. Worldwide, 60 billion farmed animals are slaughtered every year, with this figure predicted to double by 2050 (Cross, 2013). This will create a colossal amount of waste animal fats. In London alone, Thames Water removes 30 tonnes of fats, oils and grease (fog) from the sewer system every day (Messenger, 2013).

7.5 Achievements of Research Aim and Objectives

The aim of this research was to develop a soap based thermal insulation for use within buildings as a sustainable alternative to the petroleum based counterparts. The objectives were to expose soap and petroleum insulation performance limitations and reveal the advantages/disadvantages of each thermal insulation type. This was achieved by an ongoing process of refining the soap based insulation samples and measuring their performance against both polystyrene and polyisocyanurate insulation. The soap based thermal insulation was validated through observation and testing in the thermal testing laboratory. The objectives and how they were subsequently satisfied are listed below.

Objective 1: To explore existing insulations to identify the advantages and disadvantages of each thermal insulation type.

Satisfying this objective was achieved by recognizing the facts and duly accepting the indications that soap insulation would perform. This recognition and acceptance was achieved by testing the thermal insulation samples in a thermal testing laboratory. However, what is not known is how this insulation will function over a building's lifespan.

Objective 2: To identify the pros and cons of existing insulation and insulation materials based on evidence from literature.

The objective satisfaction was achieved via a number of literary sources. Literature reveals that regarding the thermal performance of both polystyrene and polyisocyanurate insulations, they both perform well, with minimal adverse effects over the insulation's in-situ duration. Both insulations are effective for the purpose they are designed for. However, polystyrene uses large quantities of petroleum based additives at its manufacturing stage. The finished product is difficult to reuse and will often finish up in landfill at its end of life. Polyisocyanurate insulations are also difficult to recycle and long term exposure to the cocktail of chemical ingredients used in PIR insulations can be detrimental to both human and animal health.

Objective 3: To explore the soap based insulation concept as an alternative insulation and define the criteria for comparative assessment.

This objective was achieved via measured systematic observation of the similarities or dissimilarities between soap insulation and petroleum insulations. This included ensuring that soap insulation was moisture and frost resistant, vermin repellent and fire retardant. This was the criteria for soap insulation but not necessarily the requirements for the established petroleum insulations. Environmental and financial costs were compared and the thermal performance of the insulations was measured also.

Objective 4: To produce soap based insulation samples and collect relevant information and data on all of the soap development samples to conduct a comparison study.

To achieve this objective, a definitive, characteristic declaration of the similarities and differences was initiated to guide the direction of the research. This was to help ascend from the initial level of exploratory case studies to a more advanced level of theoretical causality.

Objective 5: To test, compare and refine the soap based insulation samples with established insulations and measure its performance against a selection of the other insulation types.

Satisfying this objective meant trying to achieve the desired results of the soap insulation body to enhance its performance. The soap insulation was refined on a continual basis with regular comparison stages against other established petroleum insulations. These refinements and improvements are documented throughout the body of this thesis.

Objective 6: Satisfying this objective was achieved by analyzing the results from the thermal testing laboratory. These results have answered the original research question on whether soap based thermal insulation can perform in buildings.

7.6 Limitations of the Research

As can be determined through the previous chapters, manufacturing a soap based product has been a journey of continual, ongoing improvement. As wall insulation, the results from the thermal laboratory are somewhat disappointing. It is difficult to see how soap based insulation can improved enough to compete with petroleum based insulations on a like for like basis with regards to thermal resistance, whilst keeping the product synthetic chemical free. As revealed in Table 16, (page 139), the thermal resistance of soap insulation peaked with the 14mm air voids. Increasing the air void size even further would not improve on this. Larger voids have a detrimental effect on insulation performance as they encourage micro convection within the air pockets, whereas the smaller ones maintain still air conduction. Void sizes over 14mm would result in this micro convection (Simpson, 2014). Without having tested the insulation in a real world environment, for example in an actual cavity wall, only assumptions can be made about the insulation's air pocket stability and the consequential thermal performance over a prolonged time period. Whether the insulation remains waterproof and vermin proof over the long term is also conjecture derived from educated guesswork.

7.7 Human Comfort

In addition to creating a thermal barrier to a building's envelope, the external environment surrounding a building can make a significant difference to how much energy is required to heat the building. For this reason, external weather condition factors such as wind, rain and temperature ranges should be monitored. Ideally over the time period, wind up to 10m/s and outside temperatures from -12ºC to +30ºC will be encountered to accommodate the full temperature range experienced in the UK (Simpson, 2011). The insulated cavity wall could be monitored for in-situ U-value fluctuations and the soap insulation's thermal conductivity and resistance measurements over time, achieved via a series of needle probes inserted through the wall and into the cavity insulation. These probes utilize the principle of the transient hot wire method. The heated wire, in addition to a thermocouple sensor, are encapsulated in the probe that electrically insulates the hot wire and the temperature sensor from the test material. For accurate results the room to which the cavity wall forms part of would need to have a constant, stable and uniform temperature. The results would be logged through a custom time program, providing data feeds and real time analysis (Simpson, 2011).

A building needs to air tight to benefit fully from thermal insulation. Data analysis from "Innovate UK" shows a strong correlation between good air-tightness, lower CO^2 emissions and maintained human comfort within a building. The testing procured by Innovate UK revealed that buildings benefited from reduced energy costs if an effective air tightness and thermal insulation combination to the building envelope is created. This will usually keep the building within "comfortable boundaries" for temperature and relative humidity (Innovate UK, 2014). Controlling humidity is important for human health. Maintaining human comfort in a building is achieved through a process of heating, ventilating and/or air conditioning (HVAC) (Vaillencourt, 2014). When the outside temperatures fall, adding heat to counterbalance internal heat loss is usually the answer. Removing heat from a building when the occupants encounter heat gain is often the response to warm outside temperatures. However, everyone's comfort levels are different and so maintaining a precise internal temperature will not satisfy everybody. In general, for human comfort, relative humidity should not exceed 60% or drop below 20% (Merrit & Ambrose, 2012). The generic indoor temperature for the winter months should usually range between 18^0C and 25^0 C and for the summer months, the indoor temperature should generally be in the temperature range of 22^0 C and 27^0 C (kruger & Seville, 2012).

7.8 Using Soap Insulation in Different Contexts

This section is concerned with possible future research of the finished soap insulation product after it has been placed in an actual cavity wall environment or used as a different insulation type. When used as wall insulation, the physical features of the insulation would be observed and recorded before placement into an external cavity wall of a building and then again after a period of at least twenty four months (Simpson, 2011). This timeframe would ensure that the external wall is exposed to the complete cycle of seasonal weather variations observed in the UK. The room that the cavity wall was part of would need to be kept at a temperature for normal living or working conditions. Testing could also be put into execution with regards to other sectors of industry. Different industry sectors could benefit from soap insulation. Metal clad buildings, typically of the types used for warehouses and distribution centres, usually incorporate thermal insulation between both sheets of external cladding. This can be fitted separately between the metal sheets or bonded to one of the sheets. Additional testing would be required to ascertain the suitability of a soap insulation that is only surrounded by thin metal sheeting, whereby it may rapidly heat and cool when exposed to the outside elements. Moulded soap insulation could also be used to sleeve hot or cold water pipes. Soap lends itself well to being moulded but would require a different range of testing to establish the viability of soap when exposed to these more extreme temperatures of heat and cold. The insulation would need to be tested over the long term at the differing water temperature levels required for each application type. Heating, ventilation and air conditioning ducting usually requires insulating. Once again, mouldable aerated soap could be used. Additional testing would be required to determine if the insulation performs at the required temperatures, over the lifecycle of the ducting.

Changing use from an established product to a different product should not present major problems, especially if the size and weight of the product are similar. This should be true with thermal insulation. From the author’s own experience, the swap-over should furnish only a negligible impact on productivity when using different products or utilising different methods of use. As with most new products, training would be required to gain familiarity with the legal requirements and regulations for its use and for the actual operational methods for operating and putting the product into service. Manufacturing the soap insulation in the ways researched in this thesis would create a sustainable approach to managing the stages of the product's existence. This would mean that the soap should still be made from waste oils or fats, lye from burnt wood residue and the product disposed of by being recycled at its end of life. This would ensure that any negative impacts on the environment are minimized.

7.9 Insulation Degradation Whilst in Storage

7.9.1 Solar Radiation

Before the insulation is fitted into the building envelope fabric, problems can arise from incorrect on-site storage, for example, exposure to the sun (Staff, 2013). Insulation materials can undergo both physical and chemical changes when exposed to heat or ultra violet radiation (Staff, 2013). This can result in undesirable changes to the insulation properties at a molecular level of the material. In theory, thermal expansion can create permanent cracking damage to an insulation body. According to Kutz (2012), thermal degradation is “a process whereby the action of heat or elevated temperature on a material causes loss of physical or mechanical properties”.

7.9.2 Applied Stress

Compressive stress is the stress state caused by applied loading that causes a squeezing of the material. A simple case of compression is the uniaxial compression caused by non -uniform stacking, induced by the action of opposite, pushing forces (Hyde & Ollerton, 2012). Compressive strength for insulation materials is generally higher than their tensile strength (Hyde & Ollerton, 2012). However, structures loaded in compression can be subject to additional failure modes, such as buckling, but this is dependent on the insulation's geometrical shape and composition.

Shear stress is the stress state created by the combined energy of a pair of opposing forces acting along parallel lines of action through the material, for example, the stress caused by the internal faces of the material *sliding* relative to each other (Hyde & Ollerton, 2012). If rigid board type insulation is not stored with its body fully supported, the overhanging parts may try to bend downwards because of the action of gravity. It is along this “bend” line where shear stress forces will act.

7.9.3 Moisture Degradation

Even a product that is considered waterproof will eventually fail if exposed to prolonged water submersion (Wendt et al, 2013). Hydrolysis (the separation of chemical bonds by the addition of water), is a chemical process in which molecules of water added to a substance causes both the substance material and water molecules to split into two parts. This is achieved because the complex molecules are broken down into their constituent parts by the insertion of ions of water that get between the atoms and loosen the bonds that hold the building blocks together (Wendt et al, 2013). In this environment, soap fat acids and salts will eventually undergo molecular rearrangements (degradation) and be destroyed.

7.10 Insulation Degradation whilst in Fitted in a Cavity Wall

Soap based thermal insulation would be protected from the elements if placed within a wall cavity, or within an internal floor or roof space. However, prolonged exposure to the elements, as with all thermal insulations, will result in insulation degradation (Staff, 2013). If the insulation degrades whilst in situ, then its thermal performance will be compromised. There are four main reasons as to why the thermal insulation may degrade when it is fitted into its place:

1. Moisture Content. Moisture will damage most insulations under prolonged exposure conditions. This is because moisture is a poor insulator (Aksamija, 2013) and will fill the voids once occupied by air. Damp conditions may also give way to favourable conditions for bacteria and mould growth, which can accelerate the degradation of the insulation, causing it to rot (Brett, 2012). Moisture can also interact with insulation material at a molecular level giving the material different properties, for example , making the material soft or “spongy” (Hagger, 2010).

2. Air Infiltration. This term refers to the unintentional introduction of outside air into a building. This air can also damage insulation to the extent that it impacts on the insulation’s thermal performance. Infiltration is usually caused by wind, negative pressurization of the building, and by air buoyancy forces (McElroy & Tye, 2011).

3. Densification. This is the term used when insulation becomes compressed. If a thermal insulation is compressed then it becomes denser (Hagger, 2010). The trapped air within it is compressed also, reducing the insulation’s effectiveness

(Kruger & Seville, 2012). Insulation can compress under additional layers or can slump under its own weight.

4. Convection Currents. Air movement, within a cavity or roof space for example, can also impact on the insulations ability to perform. Air expands when it is heated. This is because the particles in air move faster when they are heated than they do when they are cold (Pickett, 2012). Because of this, the particles take up more volume. Air in hot areas is less dense than the air in cold areas, so it rises into the cold areas. The denser cold air falls into the warm areas. In this way, convection currents transfer heat from one area to another (Pickett, 2012).

7.11 In Situ Testing for Insulation Degradation

If hemp dries out it may lose some of its thermal properties (Naima, 2012). Natural fibres are a heterogeneous mixture of organic materials and applied heat can result in a variety of chemical and physical changes. These physical changes include enthalpy (the amount of heat content used or released in a system at constant pressure), weight loss, changes in colour, strength and the structural order of the atoms or molecules of the hemp matrix. It is extremely unlikely that the hemp surrounding the soap insulation could lose all of its moisture. According to Shahzad (2013), Hemp loses moisture quite rapid initially but starts to stabilise after about 1500 minutes as the amount of moisture in the fibres starts to decrease. After five days it is possible for the fibres to lose up to 4% of their moisture, but the fibres must be exposed to prolonged constant heat for that to happen. The process by which hemp insulation absorbs and releases moisture, can help to regulate internal moisture levels. The type of wall construction that the insulation is fitted to will also have a bearing on this movement of moisture.

When retrospectively insulating solid brick walls (walls without a cavity, often found in houses pre 1950) a vapour barrier should be installed (see Fig. 7.1 on the following page). This reduces the permeability rate at which water vapour can move through the wall. To a certain extent, the wall itself will limit moisture penetration and temperature between the outside and inside of the building envelope, but the insulation is the actual thermal barrier.

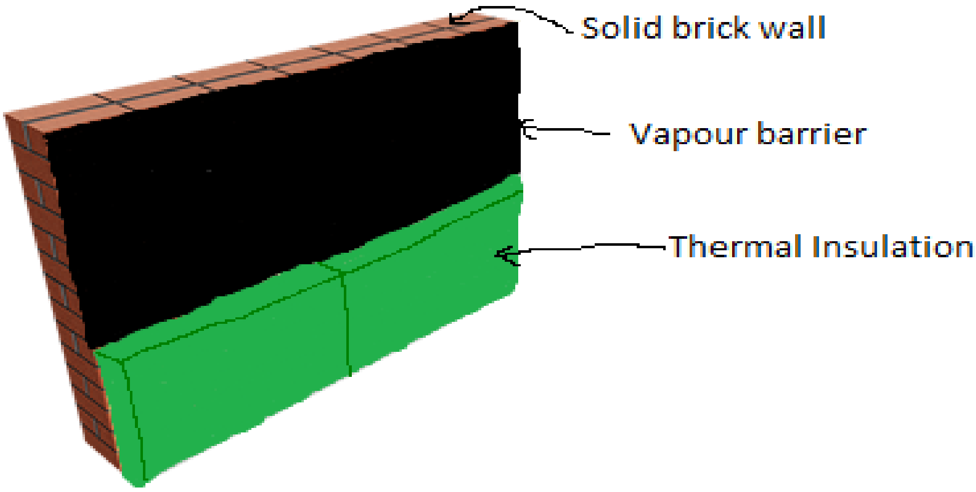


Figure 7.1: Solid Wall Construction

In a cavity wall (as shown in Fig.7.2 below) or timber framed construction, air barriers would be installed to limit air and moisture movement within the cavity, whilst the thermal insulation will have an effect on vapour diffusion.

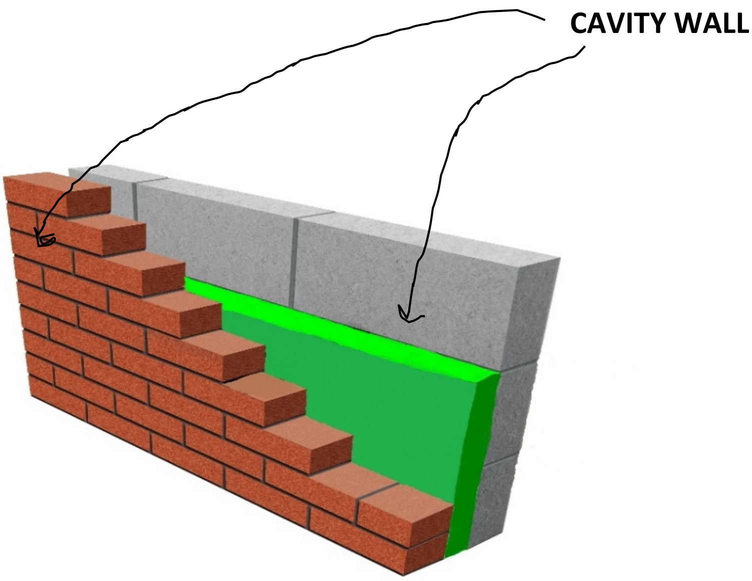


Figure 7.2: Cavity Wall Construction

Vapour diffusion is the movement of water vapour molecules through porous materials as a result of the vapour pressure differences (occurring as a result of moisture content and temperature differences within the air). The vapour permeability of the thermal insulation will control the vapour diffusion flow (Means, 2011). Without a moisture barrier, porous masonry can suck moisture from the outside, bringing the water vapour inwards. This process can lead to elevated humidity levels within buildings and can lead to condensation on colder surfaces within walls, leading to fungal growth (Means, 2011). Fibrous hemp is hygroscopic (absorbs moisture from the air) but the actual limits of its water absorption are well known. The thermal conductivity of hemp insulation does not change significantly until it is exposed to very high humidity conditions and will usually average 40% relative humidity (RH) with water absorption at 100%. It is important to ensure relative humidity does not fall below 40% as the risk of disease is increased when relative humidity falls below this level (Means, 2011). For a pleasant living or working environment, the hemp should reach a state of moisture equilibration (neither gains nor loses moisture). Because the soap body will be made waterproof, it will not equilibrate with the moisture content of the environment. An explanation is shown in the diagram (Fig.7.3) below.

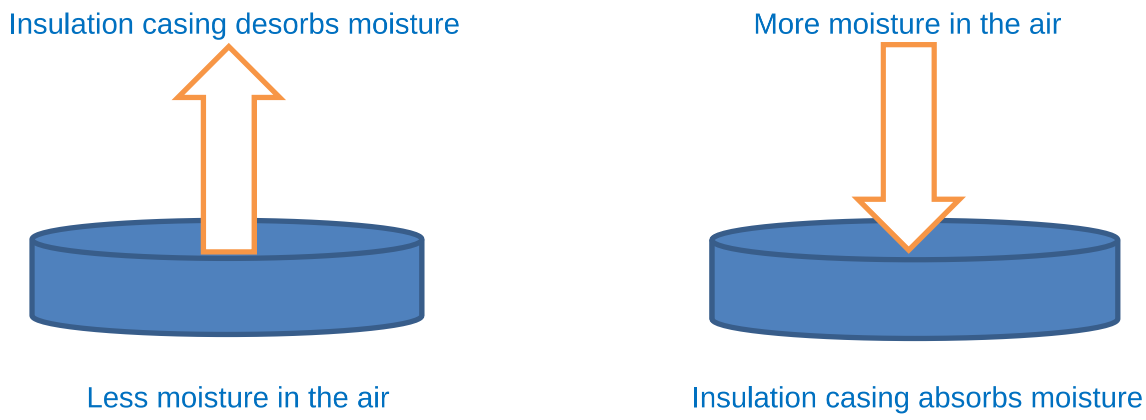


Figure 7.3: Insulation Casing before Reaching a State of Moisture Equilibration

The equilibrium moisture content (EMC) is the amount of moisture a material contains when it has reached equilibrium with its environment (Means, 2011). It is determined by the inherent properties of the material and the temperature and relative humidity of the immediate environment (Means, 2011). It is expressed as a percentage. The EMC describes what percentage of the material's mass is made up from water. For example, if an object is determined to have an EMC of 8% at 16^{0}C and 40% RH, then there are eight grams of water in every 100 grams of material when the material has reached equilibrium with that environment. An example of how to calculate the EMC of hemp is shown in the equation below. The moisture content (*M*) of hemp is defined as:

$$M = \frac{m - m_{od}}{m_{od}}$$

Where *m* is the mass of the hemp (with moisture) and m_{od} is the oven-dry mass of hemp (i.e. no moisture). If the hemp is placed in an environment at a particular temperature and relative humidity, its moisture content will generally begin to change until it reaches an equilibrium with its surroundings, and the moisture content no longer changes over time (Means, 2011). This moisture content is the EMC of the hemp for that temperature and relative humidity.

7.12 In Situ Testing Plan

The specification of the soap sample that could be taken forward for cavity wall placement and subsequent testing is shown in Table 22 below.

Sample Size	300mm X 30Omm X 50mm
Sample Covering	Hemp
Air Void Size	14mm^3
Soap Strengthening Measures	Horsehair Fibres
Fire Retarding Measures	Ammonium Phosphate
Vermin Repellent Measures	Extra Strength Vitamin D3/ Mustard
Soap Waterproofing Measures	Wykamol Waterproofer

Table 22: Specification of the Soap Insulation Product used for the In-Situ Testing

The aim of the in-situ testing is to determine whether soap based insulation performs in a real world environment. The observations and testing would be constructed in such a way as to be able to explain the causation of the results. The physical characteristics of the soap insulation sample would be recorded before and after the insulation has been inside a cavity wall for eighteen months and the differences (if any) would be revealed and compared. The scope of the testing would include a critical evaluation of stress degradation, moisture, bacterial & biological deterioration and insect/vermin infestation. These steps would define the work that needs to be done to delineate the extent of the subject matter to which it is relevant in regards to making further improvements or modifications to the soap sample. The soap insulation must be dry when first fitted and the hemp would be treated to the specifications shown in the previous chapter. The conditions of the in-situ testing require a sealed, dry cavity wall with the outer skin exposed to the outside elements and the inner wall exposed to a heated and cooled room area. Accurate testing of the cavity insulation requires the outside environment to experience temperature differences ranging from freezing to hot and both dry and wet weather conditions. Improvements to the loop factors (as shown in Fig. 7.4 below) defining the aim, scope, conditions and the environment would continue until the desired results are achieved.

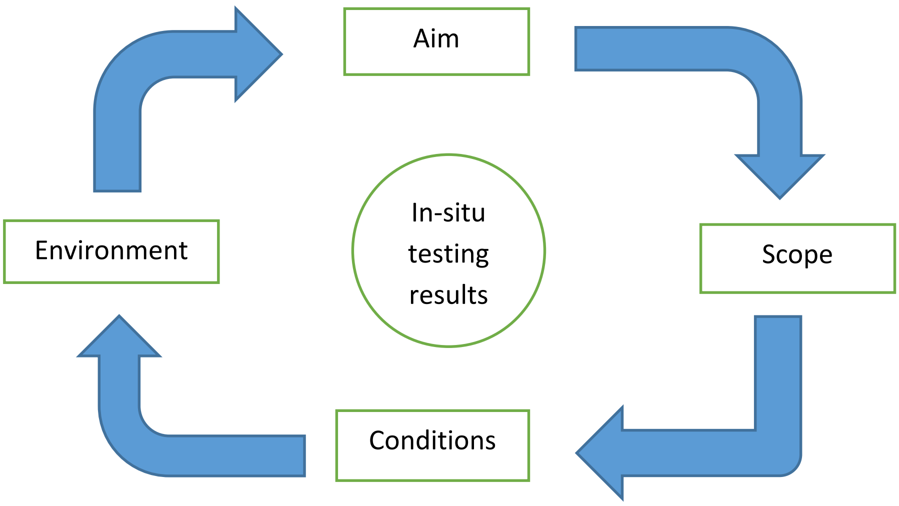


Figure 7.4: Factors impacting on the In-situ Testing Results

The findings of the in situ testing would validate the final thermal insulation product. Both polystyrene and polyisocyanurate insulations are proven to work over the long term. Polystyrene has an expected lifespan of 50 years and the thermal resistance figure of polystyrene may be used without adjusting it for the product aging (Green & Randles, 2006). According to Celotex, PIR/PUR insulation products are expected to remain efficient for the life of the building they are fitted into, although PIR/PUR insulation companies will not reveal the actual decrease in thermal performance figures (over time) that are shown in this efficiency. Soap insulation, being a waterproof matrix of air pockets and scaffolding, should remain constant over the long term. Hiscox, 1914, recommended that liquid soap mixed with turpentine (a key ingredient of “Wykamol” waterproofer) should be used to impregnate timber railway sleepers to make them waterproof for longevity purposes. Metal foil can be easily torn or punctured (Allen & Thallon, 2013). This is especially so if the foil face of PUR insulation is walked on. This could be construed as a weakness in the insulation. The foil could be improved by using reinforced, untearable foil, similar to the foils used in multi foil insulation. The soap insulation casing could be an improvement on the foil covering that is used on rigid board insulations. Plastic is robust (if used as floor or roof insulation), whilst the hemp surround is also difficult to damage under normal handling. Some polystyrene insulations have no protective covering. This can make them compressible or broken if walked on, if used as floor insulation. Reinforced soap has good tensile and compressive strength, making it difficult to damage under normal placement situations. Polystyrene and PUR insulations are also solid type insulations that are used as thermal barriers only. Hemp acts as a thermal barrier *and* helps a building to breathe (as revealed earlier into this chapter) and so in this respect, soap insulation is an improvement over rigid board types.

7.13. Key Findings from the Comparison Results

The bulk of insulation performance in buildings is provided by low density insulants (<40kg/m^3), such as polyisocyanurate foams (PIR) and expanded polystyrene (EPS). A comparison has been made of the best performing soap insulation sample against these two mainstream insulations that are on general sale to the building industry. Sample five, the hemp covered soap sample aerated with 14mm^3 air voids, had the lowest thermal conductivity out of the workable aerated soap samples. The thickness of this soap sample required to match the thermal resistance of both 50mm and 100mm white EPS and aged PIR board, is compiled in Table 23 on the following page.

	50mm Insulation Board		100mm Insulation Board	
Insulation Board	Thermal Resistance at 50mm thickness (m^2K/W)	Thickness of Soap insulation sample required to give same thermal resistance as 50mm insulation (mm)	Thermal Resistance at 100mm thickness (m^2K/W)	Thickness of Soap insulation sample required to give same thermal resistance as 100mm insulation (mm)
White EPS board (thermal conductivity 0.04W/mK)	1.25	74.1	2.50	148.3
Aged PIR board (thermal conductivity 0.025W/mK)	2.00	118.6	4.00	237.2

Table 23: Soap Comparrison with Mainsteam Insulation Materials (Simpson, 2014)

It is clear that a greater thickness of soap insulation is required to match the thermal performance of the two conventional insulation boards. In order to compete with the *best* performing insulation materials, it is clear that an even greater thickness of soap insulation would be required. However, this research was compiled to test the hypothesis on whether aerated soap could be used as an alternative to petroleum to accomplish a specific task, for example, achieving equal or increased efficiency and quality levels as the petroleum counterparts, whilst decreasing the environmental costs associated with fossil fuel retrieval and end of life waste disposal. The reply to this question is yes, soap insulation does perform to a degree in certain situations. Soap can replace polystyrene and polyisocyanurate insulations in applications where a thicker insulation would not be an issue.

7.14. Key Findings from the Testing Results

The best performing soap sample was compared to polystyrene. It is clear that for practical purposes, it would be difficult to use aerated soap insulation as a stand - alone cavity wall insulation and comply with the UK building regulations. For example, trying to fit a 250mm aerated soap board insulation into or attached to a cavity wall would not be practical in most circumstances or situations. In the UK, 50mm polystyrene insulation is not used as a stand-alone insulation for walls, floors or roofs. However, it can be used as part of an overall insulation *combination* to help the building envelope achieve thermal compliance. A comparison between soap insulation and expanded polystyrene is shown in Table 24 below.

Criteria	Soap Sample: 14mm^3 voids	Expanded Polystyrene
Thickness	74.1	50
Financial Cost	o	o
Environmental Manufacturing Cost	o	o
Thermal Conductivity	0.04W/mK	0.04W/mK
Thermal Resistance	1.25(m^{2}K)/W	1.25m^{2}K/W
Weight	263g	67g
Working Performance (Durability)	o	o
End of Life Disposal	o	o

Table 24: Soap Comparison with Expanded Polystyrene (50mm thick)

Key to soap insulations

Good: (suitable for insulating walls, floors and roofs). Moderate: (suitable for insulating floors and roofs). Poor: (not practical as thermal insulation).

7.14.1 Soap Insulation and Polyisocyanurate (50mm) Insulation Comparison

In a cavity wall, 50mm polyisocyanurate within a 100mm cavity (partial fill) will satisfy the building regulations. With 50mm partial fill aerated soap insulation within a wall cavity *and* 70mm aerated soap insulation fixed to the inner skin of the cavity wall will also satisfy the building regulations for external wall U values. Multifoil insulation fixed to the underside of roof rafters with 50mm polyisocyanurate fitted between the rafters will satisfy the building regulations for roof insulation. It is easily within the realms of possibility to fit 120mm soap insulation between the rafters with multifoil insulation fitted below to achieve the same roof U value. 50mm soap insulation samples were compared against 50mm polyisocyanurate samples and the results are shown in Table 25 on the following page.

Criteria	Soap Sample: 14mm³ voids	Polyisocyanurate (Foil Faced)
Thickness	118.6	50
Financial Cost	o	o
Environmental Manufacturing Cost	o	o
Thermal Conductivity	0.025W/mK	0.025W/mK
Thermal Resistance	$2.0m^2K/W$	$2.0m^2K/W$
Weight	422g	135g
Working Performance (Durability)	o	o
End of Life Disposal	o	o

Table 25: Soap Comparison with Polyisocyanurate (50mm thick)

7.14.2. Polystyrene (100mm) and Soap Insulation Comparison

100mm polystyrene can be used as floor insulation under certain circumstances, although the corresponding U value would be on the limit of building regulation compliance. 150mm aerated soap insulation would achieve a similar U value. A comparison is shown on the following page (Table 26) between polystyrene & Soap based insulation.

Criteria	Soap Sample: 14mm^3 Voids	Expanded Polystyrene
Thickness	148	100
Financial Cost	o	O
Environmental manufacturing Cost	o	O
Thermal Conductivity	0.04W/mK	0.04W/mK
Thermal Resistance	2.50(m^{2}K)/W	2.50 (m^{2}K)/W
Weight	526.88g	134g
Working Performance (Durability)	o	O
End of Life Disposal	o	O

Table 26: Soap Comparison with Expanded Polystyrene (100mm thick)

7.14.3 Polyisocyanurate (100mm) and Soap Insulation Comparison

100mm foil faced polyisocyanurate insulation can be used on a warm deck roof to satisfy the UK building regulation legislation. For a flat roofed commercial building it may be possible to use 250mm aerated soap insulation to meet a similar thermal target. 75mm polyisocyanurate can be used to achieve the correct u value for a floor. 180mm soap insulation could easily slot between 200mm X 47mm floor joists on a suspended or floating timber floor. A comparison between 100mm polyisocyanurate insulation and 100mm soap based insulation is shown in Table 27 on the following page.

Criteria	Soap Sample: $14mm^3$ voids	Polyisocyanurate (Foil Faced)
Thickness	237.2	100
Financial Cost	o	o
Environmental Manufacturing Cost	o	o
Thermal Conductivity	0.025W/mK	0.025W/mK
Thermal Resistance	$4.0m^2K/W$	$4.0m^2K/W$
Weight	422g	135g
Working Performance (Durability)	o	o
End of Life Disposal	o	o

Table 27: Soap Comparison with Polyisocyanurate (100mm thick)

Chapter 8 Conclusion

The key findings in response to the original research question are shown in the numbered list below.

1. Soap based insulation can be made from waste animal fats or waste restaurant oils, combined with lye made from burnt wood ashes. Using these waste fats and oils as key ingredients in the soap body, will decrease the amount of waste fats and oils otherwise disposed of via incineration or landfill.

2. The soap insulation was manufactured from natural ingredients and the samples were tested at a thermal testing laboratory to ascertain their thermal performance. The final sample was revealed as a moderate performer. This testing satisfies Objective One of the Aims and Objectives. The results from the thermal testing laboratory reveal that polystyrene insulation performs approximately 33% better than soap insulation, whilst polyisocyanurate insulation is an improvement of more than 100% over the best performing soap insulation

3. Objective Two was satisfied via the literature review. The literature review revealed that both polystyrene and polyisocyanurate insulations contain petroleum derivatives that can be detrimental to health. Both of these insulations are difficult to recycle and often finish up in landfill sites at their end of life. Environmentally friendly soap insulation can be disposed of safely in landfill sites. Soap insulation creates a smaller ecological footprint than petroleum based insulation.

4. Soap insulation is non-toxic and lightweight and thus can be handled safely. The hemp casing surrounding the aerated soap insulation body is natural and breathable. This breathability of the soap insulation has benefits for the building envelope by reducing elevated humidity levels within the building.

5. The soap body casing, alongside natural additives, ensured that the soap insulation samples were made frost and moisture resistant. The samples were also made fire retardant, vermin repellent and strengthened with horsehair fibres to ensure their longevity capabilities. Both the financial and environmental costs were compared against polystyrene and polyisocyanurate insulations, alongside their thermal performance (Objective Three). The lower manufacturing financial costs

associated with soap insulation ensures that soap insulation could retail at lower prices than petroleum based insulation of equivalent thicknesses.

6. Research into soap insulation was via step-by-step development stage improvements. These improvements and comparisons are documented in progressive chapters within this thesis. These improvements and subsequent testing satisfies both Objectives Four and Five.

7. Analysing the results from the thermal testing laboratory satisfies Objective Six and answered the original research question. Aerated soap can be used as an alternative to petroleum based insulations in certain situations where the thickness of the insulation slabs is not such an issue.

8. Soap can be moulded to fit awkward and intricate spaces and shapes.

9. The way forward for soap insulation would be to actually test the insulation in an outdoor located building. The building perimeter envelope would contain the soap based insulation and this is where the results would be generated from. The results of this exposure can be monitored and recorded, which would create a better understanding of how the insulation would perform over time.

10. Aerated soap insulation could be further improved by replacing the contained air pockets within the soap body with inert gasses. These gasses, for example helium and neon, will improve the insulation's thermal performance but would create an aerated soap that is not entirely natural in its composition.

11. Soap based thermal insulation represents new knowledge. This can be evidenced by the awarding of a patent on the aerated soap insulation idea and the publishing of a journal paper in the "Structural Survey" journal. The research contained within this thesis also offers a foundation for further research to build from.

Chapter 9 References

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Appendices

Appendix 1: Test Report from Thermal Testing Laboratory

Test Report Internal Reference No.: TT13/251 Page 1 of 6 pages

Thermal Measurement Laboratory, University of Salford UKAS Accredited Testing Laboratory No. **1660**

Issued by
Thermal Measurement Laboratory
School of Computing, Science & Engineering
Newton Building, The University of Salford
Salford, M5 4WT, England.
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University of Salford MANCHESTER

Date of Issue: 10 April 2014
Your Order No.: SI-01-1325

Approved Signatory: Dr.A.Simpson CEng (Head of laboratory)

Thermal Resistance / Conductivity of Soap Samples

Client Sustaintherm Insulations, 13 Peaselands, Desborough, Kettering, Northants, NN14 2JY

1. Samples*

1.	Cork covered soap sample, aerated with 2mm voids
2.	Hemp covered soap sample, aerated with 4mm voids
3.	Hemp covered soap sample, aerated with 8mm voids
4.	Hemp covered soap sample, aerated with 12mm voids
5.	Hemp covered soap sample, aerated with 14mm voids
6.	Hemp covered soap sample, aerated with microspheres @ 25%
7.	Hemp covered soap sample, aerated with microspheres @ 50%

Product Standard – N/A

2. Method LaserComp FOX 603 Instrument single specimen heat flow meter apparatus Heat flow meter method to ISO 8301:1991 / BS EN 12667
Heat flux direction – vertically upwards. Edge heat losses minimised by additional edge temperature controls and an edge insulation mask. All temperature, dimensional and heat flow measurements have traceability to national standards.

3. Testing The samples (lateral dimensions 300 – 310mm square) were supplied and identified by the client as in section 1) above. The samples were conditioned over a period of weeks to constant mass at 23^{o}C and 50% RH, in order to eliminate any residual preparation water, and then wrapped in a 5 micron thick plastic envelope before testing to prevent moisture ingress.
Additional dessicant was placed in the FOX 603 to prevent moisture gain during test. The thermal resistance was measured after thermal equilibrium had been reached after about 5-24 hours, at a mean temperature of 10.0^{o}C and a temperature difference of 12.0^{o}C.

The mean thickness was determined by the FOX 603 Instrument by measuring the hot and cold plate separation at each corner, when the sample was compressed between the plates. The separation was checked with calibrated electronic calipers.

4. Thermal Resistance / Conductivity Results

1). The results only apply to the samples tested as described in this report.
2). Since the soap insulation samples were hemp or cork covered, the thermal resistance of a composite layered material was measured, and the apparent thermal conductivity of this composite has been evaluated as in Table 1. It is estimated that based on a hemp/cork thickness of 2mm the thermal conductivity of the soap samples is some 3-6% more than the apparent thermal conductivities below.

Table 1

Sample & Date of Test	Mean Temperature ^{0}C	Thermal Resistance m^2K/W	Apparent Thermal Conductivity W/mK	Mean Thickness mm	Bulk Density Kg/m^3
1. Cork covered soap sample, aerated with 2mm voids (15/09/13)	10.0	0.502 ± 5%	0.0996 ± 5%	50.1	469
2. Hemp covered soap sample, aerated with 4mm voids (4/10/13)	10.0	0.632 ± 5%	0.0830 ± 5%	52.5	425.1
3. Hemp covered soap sample, aerated with 8mm voids (6/11/13)	10.0	0.683 ± 5%	0.0806± 5%	55.1	360
4. Hemp covered soap sample, aerated with 12mm voids (12/12/13)	10.0	0.996 ± 5%	0.0614 ± 5%	61.1	225
5. Hemp covered soap sample, aerated with 14mm voids (14/01/14)	10.0	1.0115 ± 5%	0.0604 ± 5%	61.1	169
6. Hemp covered soap sample, aerated with microspheres @ 25% soap volume (20/02/14)	10.0	0.0719 ± 5%	0.0792 ± 5%	56.9	369
7. Hemp covered soap sample, aerated with microspheres @ 50% soap volume (12/03/14)	10.0	1.073 ± 5%	0.0575 ± 5%	61.7	128

(The reported expanded uncertainty is based on a standard uncertainty multiplied by a coverage factor k=2, providing a level of confidence of approximately 95%. The uncertainty evaluation has been carried out in accordance with UKAS requirements).

5. Date of Last Heat Flow Meter Calibration Check

The heat flow meter calibration was checked approximately twice a month over the period of the measurement programme between 9 September 2013 and 4 April 2014, with calibrations traceable to national and international standards and found to be within specification.

Calibrations are used that are based on

1) 25 mm EPS material (EPS#1108112, traceable to IRMM-440) with thermal resistance at 10^{O}C of 0.78 m^2K/W. EPS#1108112 was last calibrated at LaserComp, Inc. in July 2012 and is due to be recalibrated in July 2017.
2) stable 20 year aged 50 mm EPS with thermal resistance at 10^{O}C of 1.41 m^2K/W, which was last calibrated in the Salford University UKAS accredited guarded hot plate during September 2012, and is due to be recalibrated in September 2017.
3) stable 20 year aged 100 mm EPS with thermal resistance at 10^{O}C of 2.82 m^2K/W, which was last calibrated in the Salford University UKAS accredited guarded hot plate during September 2012, and is due to be recalibrated in September 2017.

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6. Name of Test Operator/s A. Simpson

7. Apparent Thermal Conductivity / Density Relationship

The apparent thermal conductivity is plotted as a function of bulk density in Figure 1 and compared with the relationship for building materials of comparable density - autoclaved aerated concrete (BS EN 1745), foamed plaster (CIBSE Guide A3), fibre building board (CIBSE Guide A3). Standard design data has been taken from BS EN 1745:2002 for the thermal conductivity of aerated concrete over the density range 300 to 1000 kg/m^3 with a probability of 90%. The results for the soap samples are also compared with generic data for mineral wool insulation over a similar density range.

The thermal conductivity of building / insulation materials is strongly dependent on the porosity, pore size and structure, as well as density and thermal conductivity and type of solid contact of the matrix material. Generally, the more air entrainment the lower the density. The thermal conductivity decreases with decreasing density until at very low densities (eg. loft insulants) radiation heat transfer starts to dominate the conduction processes and the thermal conductivity increases. The soap samples tested were sufficiently dense to avoid this effect. Consequently, the apparent thermal conductivity of the soap samples decreases with decreasing density over the density range tested (128 to 425kg/m^3).

The results for the apparent thermal conductivity of the soap insulation samples over the density range 200-400 kg/m^3 are consistent with a class of structural materials with limited insulation performance, such as aerated concrete, foamed plaster and fibre building board. Lower density soap insulation samples exhibit poorer insulation performance than conventional insulation material over the same density range. The apparent thermal conductivity of soap samples is for example some 70% more than that for mineral fibre of comparable density. This is mainly attributed to the relatively large size of pores and solid conduction component, compared to that for mineral fibres. Generally, the smaller the pores the smaller is the air conduction component.

8. Comparison with Mainstream Insulation Materials

The bulk of insulation performance in buildings is provided by low density insulants (<40kg/m^3), such as polyisocyanurate foams (PIR) and expanded polystyrene (EPS). It is clear from the table that a significantly greater thickness of soap insulation would be required to match the thermal performance of conventional rigid board type insulation. In order to compete with the best performing insulation materials, an even greater thickness of soap insulation would be required.

Table 2

	50mm Insulation Board		100mm Insulation Board	
Insulation Board	Thermal Resistance at 50mm thickness (m^2K/W)	Thickness of Soap insulation sample required to give same thermal resistance as 50mm insulation (mm)	Thermal Resistance at 100mm thickness (m^2K/W)	Thickness of Soap insulation sample required to give same thermal resistance as 100mm insulation (mm)
White EPS board (thermal conductivity 0.04W/mK)	1.25	74.1	2.50	148.3
Aged PIR board (thermal conductivity 0.025W/mK)	2.00	118.6	4.00	237.2

A. Simpson

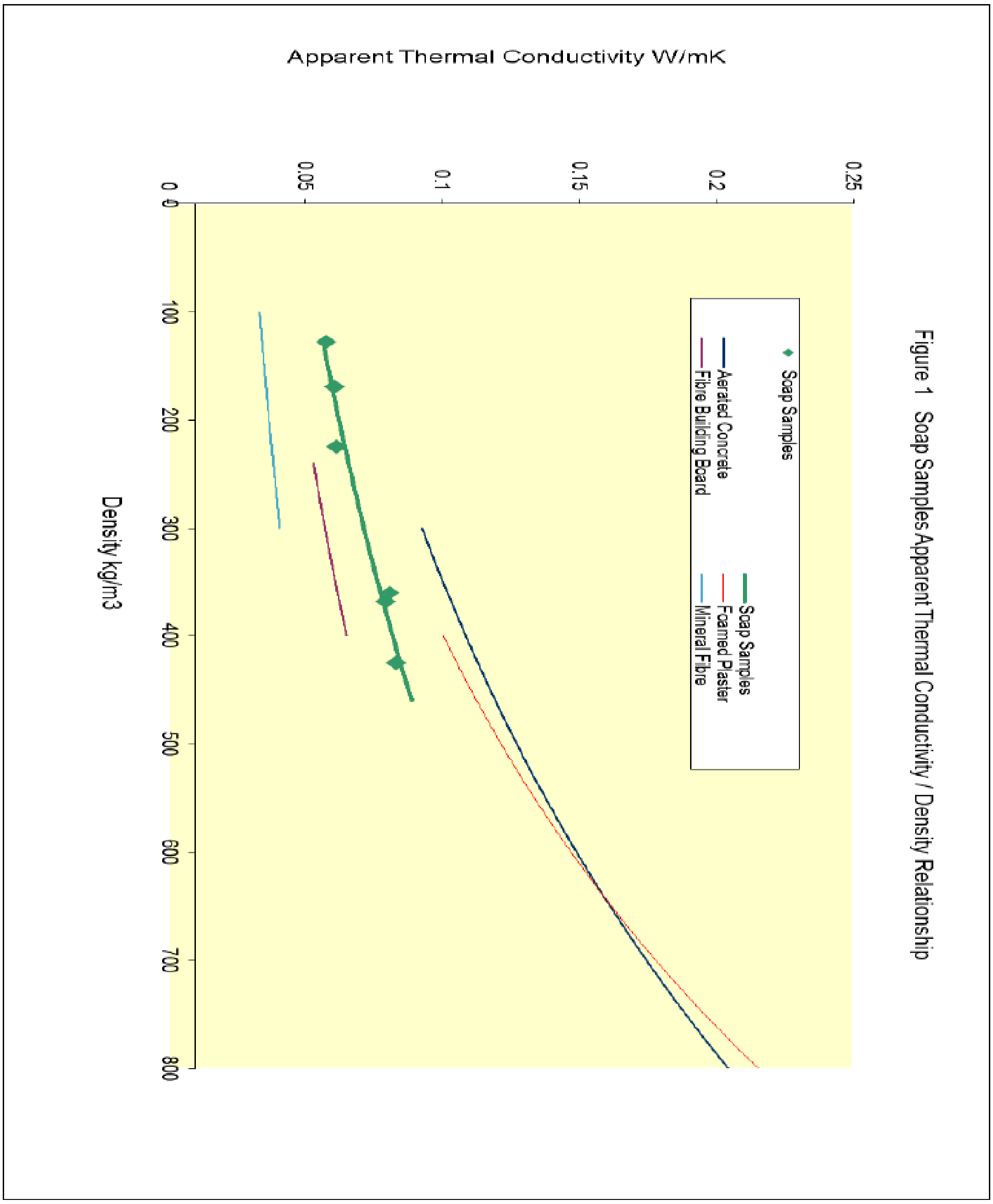

Figure 1 Soap Samples Apparent Thermal Conductivity / Density Relationship

FOX 603 Apparatus

Appendix 2: Patent Certificate

INTELLECTUAL
PROPERTY OFFICE

Certificate of Grant of Patent

Patent Number: GB2486761

Proprietor(s): Lee Read

Inventor(s): Lee Read

This is to Certify that, in accordance with the Patents Act 1977,

a Patent has been granted to the proprietor(s) for an invention entitled **"Soap based thermal insulation"** disclosed in an application filed **22 November 2011**.

Dated 14 November 2012

John Alty
Comptroller-General of Patents, Designs and Trade Marks
Intellectual Property Office

The attention of the Proprietor(s) is drawn to the important notes overleaf.

Intellectual Property Office is an operating name of the Patent Office