DEVELOPMENT OF LOW COST THERMAL INSULATING MATERIALS

By

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ABSTRACT

The disadvantaged people in South Africa are unfortunate, by virtue of their financial status. It was estimated in 1992 that 20 % of the South African population live in informal settlements. The houses in these settlements are found to be very energy inefficient. This study was aimed at developing low cost thermal insulating materials that can be used to increase energy efficiency of the houses in these informal settlements. This was done by firstly studying the properties of thermal insulation materials. Furthermore, common thermal insulating materials in South Africa were studied and evaluated. Only recycled polymeric based materials were examined for selecting the raw materials that were used to investigate the feasibility of the thermal insulating materials from waste material.

The experimental work was extended to construct a thermal conductivity rig that was to be used in measuring the thermal conductivity of both the developed and existing thermal insulating materials. The expanded polystyrene obtained from Sagex (Pty) Ltd and polyester obtained from Isotherm (Pty) Ltd. were evaluated and compared to the manufactured recycled polymer slabs and expanded polyethylene foams (EPEF). Expanded polyethylene foam and recycled polymer slab samples were subjected to mechanical and physical testing. A temperature comparison test and thermal conductivity determination were conducted on both the expanded polyethylene foam (EPEF) and recycled polymer slab (RPS) samples. The scanning electron microscope (SEM) was used to reveal the micro-structures of all the developed thermal insulating material samples. The expanded polystyrene and polyester thermal insulating materials were also examined using the SEM. Optical microscopy was only used on RPS samples.

It was found in this research, that the properties that govern the viability of thermal insulating materials are: thermal conductivity (k-value), thermal resistance (R-value), combustibility, moisture absorption and the presence of hazardous gases during burning. The temperature comparison test showed that the recycled polymer slab (RPS) and expanded polyethylene foam (EPEF) retards the flow of heat to levels comparable to that of the locally obtained thermal insulation. The comparative cut bar method was found to be relatively cheap to design and it was ideal for the measurement of the thermal conductivity of polymeric based materials. The k-value of all the EPEF samples was measured to be around 0.04 $W.m^{-1}K^{-1}$ and the RPS k-value was found to be 0.05 $W.m^{-1}K^{-1}$. This is attributed to air pockets with lower conductivities values, found within the structure of the polymeric thermal insulating materials. The porous structure is evident from the SEM micrographs of both the EPEF and RPS samples. One grade of expanded polyethylene foam, the SPX80, had accumulated less moisture when moisture absorption was compared with other EPEF samples. The RPS material did have a propensity for absorption of water. The flammability retardant tests have showed that gypsum board has to be incorporated during service for the RPS and SPX80. The mechanical testing results also suggest that both the EPEF and RPS need to be supported when installed in a ceiling, for example.

NOMENCLATURE

WHO	**World Health Organization**
CSIRO	**Commonwealth Scientific and Industries Research Organisation**
RDSM	**Residential Demand Side Management**
U.S	**United States of America**
k-value (k)	**Thermal Conductivity**
k_R	**Thermal Conductivity of the References**
k_s	**Thermal Conductivity of the Unknown Sample**
R-value (R)	**Thermal Resistance**
U-value	**Thermal Transmittance / Conductance**
K	**Kelvin**
m	**Meter**
mm	**Millimetre**
W	**Watt**
kg	**Kilogram**
^{o}C	**Degrees Celsius**
J	**Joules**
t	**Thickness**
T	**Temperature**
σ	**Flexural Stress**
E	**Flexural Modulus**
Pa	**Pascal**
R_AL	**Rand Loss per Unit Area**

$R_{A(UHE)}$	**Rand per Unit of Heat Energy**
SiO_2	**Silica**
CaO	**Calcium Oxide**
MgO	**Magnesium Oxide**
K_2O	**Potassium Oxide**
CFC	**Chlorofluorocarbon**
HCFC	**Hydrochloride-Fluorocarbons**
HFC	**Hydro-Fluorocarbon**
HFR	**Heat Flow Rate**
CO_2	**Carbon Dioxide**
CO	**Carbon Monoxide**
B_2O_3	**Boron Oxide**
R_A	**South African Rand**
$	**U.S. Dollar**
h	**Hour**
G	**Giga**
M	**Mega**
c	**South African Cent**
Q	**Heat**
A	**Area**
UFFI	**Urea Formaldehyde Foam Insulation**
PMDI	**Polymeric Methylene Diisocyanate**
HVAC	**High Voltage Alternating Current**
EPA	**Environmental Protection Agency**
CIMA	**Cellulose Insulation Manufacturers Association**

EPS	**Expanded Polystyrene**
XPS	**Extruded Polystyrene**
EPEF	**Expanded Polyethylene Foam**
RPS	**Recycled Polymer Slab**
SIK	**Standard Insulation Kit**
SEM	**Scanning Electron Microscope**
PE	**Polyethylene**
PP	**Polypropylene**
RDP	**Residential Development Program**
WVP	**Water Vapour Permeability**
LWP	**Liquid Water Permeability**
EHC	**Effective Heat of Combustion**
HRR	**Heat Release Rate**
RFS	**Rate of Smoke Formation**
MLR	**Mass Loss Rate**
PIMA	**Polyisocyanurate Insulation Manufacturers Association**

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CHAPTER 1

INTRODUCTION

1.1 BACKGROUND TO THE PROJECT

This research project is a partnership project comprising the City of Cape Town, the Environmental Evaluation Unit and Centre for Materials Engineering at the University of Cape Town and the Wood Science Department at the University of Stellenbosch. This project can be viewed in the broader context as a South African government initiation to deliver sustainable settlements under Agenda 21 and the Habitual Agenda. The South African government's housing policy has the objective of ensuring that every South African has access to housing, hence providing thermally efficient houses would be consistent with the policy[1].

The disadvantaged people in South Africa are unfortunate, by virtue of their financial status. As a result they are forced to reside in dwellings of sub-standard materials. These are however, the only form of accommodation they can afford. The structures, such as shacks are extremely energy inefficient and in turn give rise to several other problems[2]. Most shacks are built from wood, corrugated iron, fibre cement, or a combination of the three. There is potential of saving energy by closely examining how heat is lost from corrugated structures[3].

It was estimated in 1992 that 20 % of South African population is living in informal settlements[4]. The houses in these settlements are found to be very energy inefficient. The inhabitants can spend up to 20 % of their disposable income on heating and they use mainly low energy content fuels, bio-fuels and inefficient heating methods that also contribute to energy wastage[5]. The burning of low energy content fuels further result in high personal exposure to total suspended particulates. A study on low cost houses in South Africa indicates that extremely high levels of exposure of between 3 and 12 times higher than that prescribed by the World Health Organization (WHO), are currently experienced[6].

1.2 THERMAL INSULATION IN SOUTH AFRICA

Low income communities deem thermal performance an important standard for housing in South Africa. Acceptable indoor thermal conditions result in greater user satisfaction, better health and lower electricity accounts[7]. Residential Demand Side Management (RDSM) of South Africa and the City of Cape Town aim to improve electrical use in residences by promoting energy efficiency and load shaping. Load is the amount of electric power or energy delivered or required at any specified point or points in a system and load shaping is the adjustment of storage releases so that generation and load are continuously in balance. From the electricity supply point of view, space heating with electrical resistance heaters presents a particular problem. In South Africa, there is evidence that this end-use is largely to blame for annual peak load and poor daily load shape[8]. The situation will rapidly deteriorate further in the near future, as a result of massive housing construction driven by the South African Government, and this coincides with the "electricity for all" campaign requiring that every South African has electricity connected to their homes. Another important issue is the design of more than 1000 new houses that must be built per year in South Africa to alleviate South Africa's housing crisis[9].

The new houses have to be prudently designed and built to ensure the optimum use of energy resources. For this reason, this thesis evaluates energy efficiency design factors based on thermal insulation that should be incorporated in the design of the new low cost houses. Electricity suppliers and the Government are also interested in electrical energy savings, so that capital expenditure on new generating equipment can be postponed, and also, to minimise the impact on the environment.

South African residential consumers, on the other hand, see affordable electricity as a requirement for an improvement in their standard of living. The convenience of small, portable, inexpensive, electric resistance heaters makes these appliances ideal mass consumer items for households. This problem is worsened by the mildness of the South African climate, which allows houses to be built with complete disregard for thermal response considerations. The fact that the heating season is relatively short makes the adoption of the unplanned space heating measures popular[10].

1.3 INTERNATIONAL EXPERIENCE ON THERMAL INSULATION

The ‘‘demand side” of the electricity market can be divided into the industrial, commercial and residential sectors. In each sector the typical use of electricity is different. Studies have indicated that the opportunity for demand management in these sectors is substantial[8]. International experience, particularly in the United States of America, shows that considerable electrical savings are possible for the residential sector. Many countries have programs targeting the residential sector, particularly, with the aim of improving the load factor. Most of the overseas experience is in cold climates and therefore they are not applicable in South Africa. However, experience in other countries shows energy savings of above 20 % in residential areas are achievable[8]. It also appears possible to improve the residential load shaping. In this case the measures that have been employed include thermal insulation of residences.

Thirty years after the introduction of compulsory thermal insulation in most European countries, insulation materials still form the major tool for the improvement of a building’s energy behaviour. The use of insulation materials has increased, both in terms of buildings being insulated and in the minimum values of insulation required by the national regulations. This degree of insulation necessary becomes clear when considering the thermal conductivity values foreseen in various European countries for the building envelope of presently built residential buildings and they are presented in table 1.1[11]. The k-values in table 1:1 were derived from computer simulations that were based on the regions estimated temperature and building traditions. This indicates that the k-values for insulating materials depend on the adaptability of an insulating material for particular national, regional or even local building methods and traditions. In that sense, the k-values foreseen theoretically for specific regions are different because the materials used in buildings can alter the performance of thermal insulating materials.

Table 1.1: Typical thermal conductivity ($W.m^{-1}K^{-1}$) values for the building envelope of presently built residential buildings in various European countries[11].

	Roofs	Outer Walls	Ground Floors	Windows
Austria	0.2-0.3	0.3-0.4	0.4-0.5	1.0-1.5
Belgium (Flanders)	0.4-0.5	0.5-0.6	0.6-0.6	1.5-2.5
Denmark	0.1-0.2	0.2-0.3	0.1-0.2	1.5-2.5
Finland	0.1-0.2	0.2-0.3	0.2-0.3	1.5-2.0
France	0.2-0.3	0.5-0.6	0.4-0.5	1.5-2.5
Germany	0.2-0.3	0.5-0.6	0.4-0.5	1.0-1.5
Greece	0.4-0.5	0.5-0.7	0.7-1.9	2.5-3.5
Ireland	0.1-0.2	0.2-0.3	0.2-0.3	1.5-2.5
Italy	0.3-0.4	0.4-0.5	0.4-0.5	2.5-3.5
Lithuania	0.1-0.2	0.2-0.3	0.2-0.3	1.5-2.5
Norway	0.1-0.2	0.2-0.3	0.1-0.2	1.0-1.5
Portugal	0.6-0.6	0.6-0.6	0.6-0.6	2.0-3.0
Russian Federation	0.1-0.4	0.1-0.2	0.1-0.4	1.5-3.5
Spain	0.6-0.6	0.6-0.6	0.6-0.6	2.5-3.5
Switzerland	0.3-0.4	0.3-0.4	0.6-0.6	1.0-1.5
UK	0.1-0.2	0.3-0.4	0.2-0.3	1.5-2.5
The Netherlands	0.2-0.3	0.2-0.4	0.2-0.3	1.5-2.5
Sweden	0.1-0.2	0.1-0.2	0.1-0.2	1.0-1.5

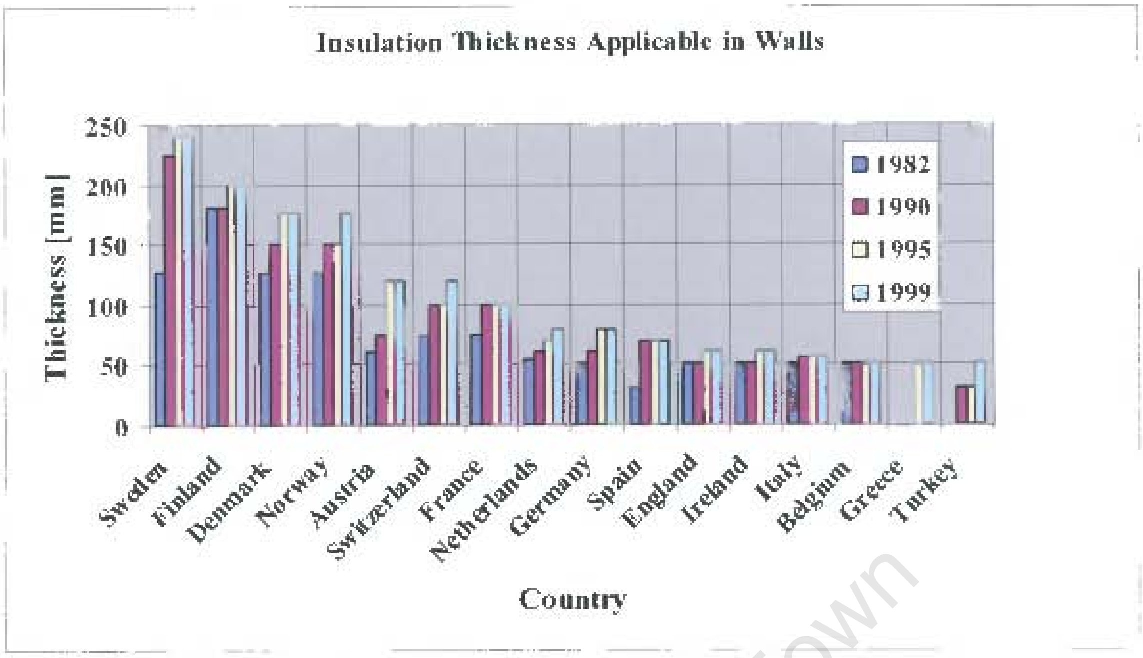

Figure 1.1: Comparison of the evolution of insulation thickness applicable in walls in European countries[12].

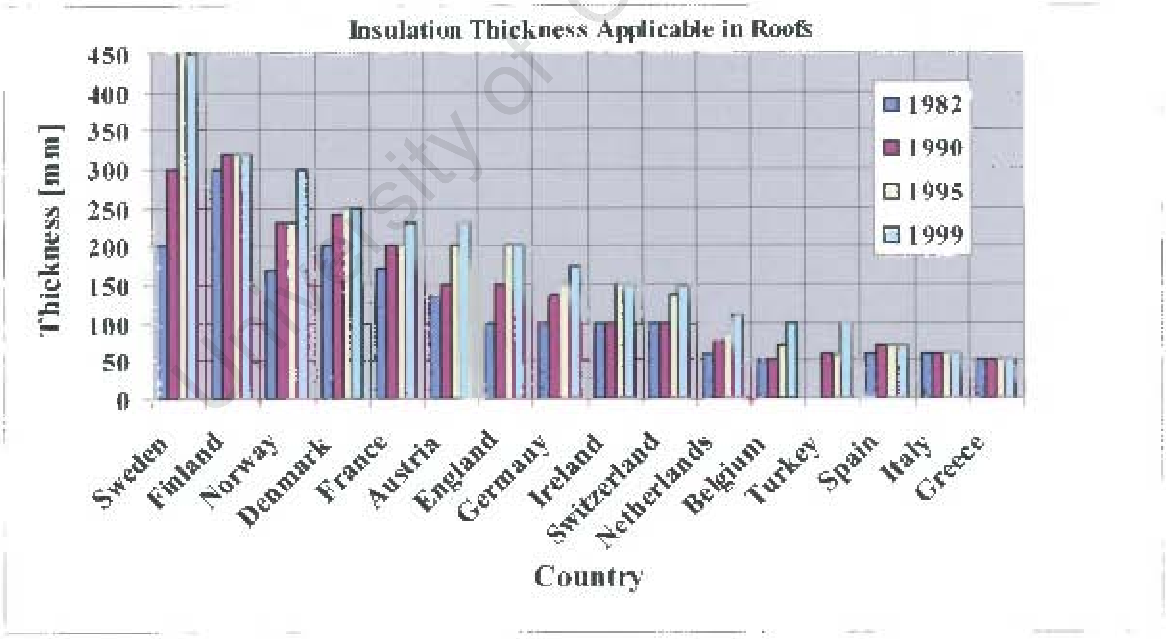

Figure 1.3: Comparison of the evolution of insulation thickness applicable in roofs in European countries[12].

The evolution that has taken place since the early 1970's becomes evident when considering the increase in the typical insulation thickness required in European countries over the past years. These are depicted for walls and roofs in figure 1.1 and figure 1.2, respectively[12]. It is interesting to note that whilst in some countries, mainly in Northern Europe, the requirements have almost doubled during this period, in others like in Greece, the standards have remained unaltered.

1.4 ENERGY SAVING ASSOCIATED WITH THERMAL INSULATION

As climate modifiers, buildings are usually designed to shelter occupants and achieve thermal comfort in the occupied space backed up by mechanical heating and air conditioning systems as necessary. Significant energy savings could be achieved if they are properly designed and operated. For every unit of energy saved by a given measure of technology, resources will be saved and annual operating costs associated with producing that unit of energy will be reduced or even eliminated. Therefore, building designers can contribute to solving the energy problem if proper early design decisions are made regarding the selection and integration of building components. Thermal insulation is a major contributor to energy savings. It is an obvious practical and logical first step that can be used to achieve energy efficiency in envelope-loading dominated buildings located in places with harsh climatic conditions[13].

Space air conditioning uses a large share of the energy used to operate buildings. In the average American home, for example, space heating and cooling account for 50 %-70 % of its energy usage[14]. This percentage could be higher in other parts of the world with more harsh climatic conditions and less energy efficient buildings. The amount of energy required in cooling or heating a building depends on how well the envelope of that building is treated thermally, especially in envelope dominated structures such as residences. The thermal performance of the building envelope is determined by the thermal properties of the materials used in its construction. This performance is characterized by its ability to absorb or emit solar heat[14].

The placement of the insulation material within the building component can affect its performance under transient heat flow. The best performance can be achieved by placing the insulating material close to the point of entry of heat flow. This means that the placement of the insulation on the inside of the building's wall is efficient where winter heating is dominant and on the outside of the building's wall where summer cooling is dominant, for different climatic condition in the world. However, for practicality, it is common to use insulation on the inside or between wall cavities.

1.5 PROJECT MOTIVATION

This project was motivated by the living conditions of low income communities living in informal settlements, and formal low-cost housing in South Africa. Since informal low-cost houses are poorly sealed from the outdoor environment, heat streams occur inside the house during summer months and outside during winter months. In winter months, up to 20 % of the occupant's income can be spent on heating. To provide heat by burning bio-fuels leads to high levels of indoor pollution. This situation is undesirable for the occupants as it poses a serious health risk. Indoor pollution, health risks, and depletion of natural resources as a result of the high space heating requirements, are a problem. This can be addressed simultaneously by increasing the energy efficiency of these low cost houses.

The domestic sector is one of the largest electricity consumers in South Africa[15]. Households alone consume approximately 29 % of municipal electricity. This figure is expected to increase to 37 % by the year 2015[16]. One of the reasons for this expected rise is the recently electrified urban townships. South Africa is also experiencing a rapidly increasing peak demand, of which households contribute over 20 % to this peak demand[17]. To forestall the building of costly new power stations, the peak demand must be reduced. Electricity savings in the domestic sector could therefore have a significant impact. The environment will also benefit from these savings.

Recent studies indicate that South Africa's contribution to the additional radiation load on the global atmosphere though emissions are roughly 1.2 %[18]. This is very high when considering South Africa's contribution to the world economy and population. Electricity generation accounts for a large portion of these unwanted emissions, which are mostly greenhouse gases[18]. Effective energy management is the cheapest alternative to decreasing pollution in the energy industry[19]. A better approach is to improve the thermal performance of the house shell. Passive design aspects such as building orientation, insulation, window sizes and exterior colour should be investigated. The main benefit of this strategy is that once a house is designed to be thermally efficient, no further effort is required. Matthews *et al.* had shown in their research that thermal insulation gives maximum savings in energy when compared to other forms energy savings[3].

1.6 AIMS OF THE PROJECT

The aims of this project were to:

1. Study the material parameters contributing to the thermal insulating properties of a material.

This will be achieved by studying the existing thermal insulating materials on the South African market. This is done in order to understand what makes a material a good thermal insulating material and to know what types of the thermal insulating materials are available on the South African market.

2. Develop a low-cost thermal insulating material.

This is to be achieved by examining the polymer based materials that can be used as raw materials to develop a reasonably inexpensive thermal insulating material(s) that is simple to install, user-friendly, practically safe, moisture resistant, and non-flammable. The developed insulating material(s) is further intended to reduce energy heating costs and increase comfort levels in South African residential houses, mainly in formal low-cost housing and be produced with low technology.

3. Measure accurately the thermal conductivity of developed thermal insulating materials.

This will be achieved by constructing a thermal conductivity device (rig) that will measure thermal conductivity. This thermal conductivity will be used to calculate the R-value, and to illustrate the material's ability to resist heat conduction through it. The R-value is the thickness of the panel divided by the thermal conductivity.

1.7 LIMITATIONS TO THIS THESIS

The limitations of this thesis are:

This project is mainly experimentally based. In this regard no simulation or modelling software has been used. Any built device will only be applicable to polymer based materials.

1.8 OUTLINE OF THIS THESIS

The work that was carried out in the current study is reported in different chapters. *Chapter 2* gives the literature review. The literature review discusses the background into insulation, different forms of insulation and insulating materials, energy saving methods through insulation, a comparison of insulating materials on environmental impact, the thermodynamics behind heat transfer and the relevant terminology. *Chapter 3* describes all the test methods that were followed to achieve the aims of this project research. The results obtained in this investigation are given in *Chapter 4* and discussed in *Chapter 5*. The conclusions that can be drawn from *Chapter 4* and *Chapter 5* are then stated in *Chapter 6*. Recommendations for the future work are listed in *Chapter 7*.

CHAPTER 2

LITERATURE REVIEW

2.1 INTRODUCTION

Thermal insulation is the use of special materials that retard the flow of heat energy. It prevents the loss of heat, so saving on fuel and money, and contributing to safety and comfort. In general insulation is a barrier that minimizes the transfer of heat energy from one material to another by reducing the conduction, convection and radiation effects. There is a wide variety of insulating materials, including minerals-based materials. Insulation is mainly measured in R-values, the resistance to heat flow. Therefore the higher the R-value (a measure of the material's ability to resist heat flow through it) the better the insulating material is to restrict heat flow. Although insulation can be made from a variety of materials, it is usually used in four different types *viz.* batts, rolls, loose-fill and rigid foam boards. Each type is made to fit in a different part of a building. The choice of the material depends on cost, temperature, application, environment and safety. The thickness of insulation should be calculated so as to optimise the cost of the insulation against the savings in energy.

2.2 BACKGROUND INTO INSULATION

From caves to super insulated houses, human beings have demonstrated the need for protection from the elements. The true origins of the science of thermal insulation, however, are difficult to identify. Organic materials have served as the natural prototype for thermal insulators. Evolutionary examples include fur covering the polar bear or feathers on a bird, cotton, wool, straw and even hair. Prehistoric human beings clothed themselves with wool and skins from animals. They built homes of wood, stone, earth and other materials for protection from the cold winter and the heat of summer[20].

For thousands of years, house structures were designed to best suit the climate of their location. For example, using the earth as an insulator, the Egyptians retired to the coolness of subterranean chambers and caves on hot days[20]. Historians believe that the ancient Greeks and Romans discovered asbestos and found many uses for it because of its resistance to heat and fire. The Romans even used cork for insulation in shoes in order to keep their feet warm. Pliny, in the first century, referred to the use of cork as an insulating material for roofs. Early inhabitants of Spain lined their stone houses with cork bark, and North African natives used cork mixed with clay for the walls of their dwellings[21].

2.3 THERMAL INSULATING MATERIALS

Thermal insulating materials are dependent energy productions that depend on the structure they are insulating. They form part of complex structural elements which form a building's covering. Based on the fact that they are not independent energy production systems they cannot be evaluated in the same way as energy producing systems *e.g.* solar, thermal or photovoltaic systems. They have to be evaluated as an integral part of a building's design and construction. The quality of a thermal insulating material depends on its adaptability to local building methods. In that sense, materials are widespread in specific regions, even though from the scientific point of view, any material could be used instead. When high specifications are set on certain mechanical properties and humidity resistance or where the initial cost factor is less important, there are certainly very expensive different thermal insulating materials. A further point of interest is the development of alternative materials, like sheep wool and cotton wool and the so called intelligent materials, such as transparent insulation and dynamic materials with temperature dependent thermal conductivity properties[11].

Insulating materials are dominated by inorganic fibrous materials, glass wool and stone wool, which account for 60 % of the European market[9]. Organic foamy materials such as expanded and extruded polystyrene and a lesser extent polyurethane account for 27 % of market. The remaining 13 % is accounted for by other insulating materials like combined materials. Insulating materials are classified according to their chemical or physical structure. The mostly widely used building insulating materials are classified in table 2.1[11].

Table 2.1: Classification of the most used insulating materials[11].

Insulating Materials			
Inorganic Materials	**Organic Materials**	**Combined Materials**	**New Technological Materials**
{Foamy} Foam Glass	{Foamy} Expanded Polystyrene Extruded Polystyrene Polyurethane Foam	Siliconeted Calcium Gypsum Foam Wood Wool	Transparent Materials Dynamic Materials
{Fibrous} Glass Wool Stone Wool	{Foamy Expanded} Cork Melamine Foam Phenol Foam		
	{Fibrous} Sheep Wool Cotton Wool Coconut Fibre Cellulose		

The thermal insulating materials growth in the market is an issue of economics, with further development depending on both improvements in the production processes and on achieving economies scale. There is a series of new ready-to-use thermal insulation building components that have been developed for specific constructions. These components are mainly prefabricated thermal insulation panels for commercial and office buildings and prefabricated thermal insulation panels for residential buildings. The performance of the insulating material itself in these products (be it organic foamy or inorganic fibrous) remains the main determinant of such a component's energy behaviour. The measure of their success, however, depends on criteria such as adaptability, handling and cost[11].

2.3.1 BLANKETS

Blankets (batts or rolls) are divided mainly into three types, fibreglass, rock wool and polyethylene.

2.3.1.1 Blanket Fibreglass

Sand and recycled glasses are mainly used as raw materials to manufacture fibreglass thermal insulation. Fibreglass has good fire resistance and an excellent resistance to direct sunlight with a maximum service temperature range from -4 °C to 260 °C as well as high sound absorption. When compressed, its R-value decreases and produces irritating dust during installation of the fibreglass insulation. It has a thermal conductivity range from 0.033 $W.m^{-1}K^{-1}$ to 0.04 $W.m^{-1}K^{-1}$. It is typically applied to frame walls or ceilings, partitions, prefabricated houses, irregularly shaped surfaces, ducts and pipes for insulation[12,13].

2.3.1.2 Blanket Rock Wool

Rock wool which is extracted from natural rocks has density values between 40-200 $kg.m^{-3}$. The larger proportion of rock wool is from steam injection into molten slag. It is applied to the same places as fibreglass. It has good fire resistance, excellent resistance to direct sunlight and a very high sound absorption factor with a maximum service temperature of 800 °C. Like fibreglass it produces irritating dust during installation and the R-value decreases on compression[13]. It has a low thermal conductivity of 0.037 $W.m^{-1}K^{-1}$.

2.3.1.3 Blanket Polyethylene

The service temperature of polyethylene is 90 °C. It has poor resistance to fire with good resistance to direct sunlight. It is mainly placed in ceilings, hangers, wrapping, carpet underlay and expansion joints. It has a low thermal conductivity of approximately 0.041 $W.m^{-1}K^{-1}$ and it emits toxic organic smoke when burning[13].

2.3.2 LOOSE FILL

Loose-fill blow-in or poured-in thermal insulation is divided into five different thermal insulating materials. Open cell structure fibreglass, open cell structure rock wool, cellulose, vermiculite and perlite.

2.3.2.1 Open Cell Fibreglass and Rock Wool

Even though open cell structure fibreglass and open cell structure rock wool share the same properties as normal fibreglass and rock wool as described above, they are mainly applied to cavities and around obstructions. Adhesives are added to both of them to provide more resistance to air infiltration[22].

2.3.2.2 Cellulose

Cellulose produced from ground waste paper has a very good fire resistance when fire resisting chemicals are added to it. Its maximum operating temperature is 80 °C with good resistance to direct sunlight and it is mainly used in cavities. It is a good insulating material with a thermal conductivity value in the range of 0.046 $W/m^{-1}K^{-1}$ to 0.054 $W.m^{-1}K^{-1}$ [22,23].

2.3.2.3 Perlite

Perlite is a volcanic rock containing 2 to 5 % bonded water. It is a chemically inert substance composed mainly of SiO_2 and Al, but some impurities, such as Na_2O, CaO, MgO and K_2O, which are hygroscopic, can absorb moisture easily. Therefore, depending on the storage conditions and the quality of the perlite, moisture absorption can be minimized.

2.3.2.3.1 Expanded Perlite

The average density of expanded perlite is about 130 $kg.m^{-3}$ and its thermal conductivity is about 0.047 $W.m^{-1}K^{-1}$. The perlite is expanded by means of rapid heating to a temperature between 800 °C and 1200 °C. The vaporization of the bonded water and the formation of natural glass results in the expansion of the perlite particles, which have a granular shape[23].

The main parameters that define the characteristics of expanded perlite are:

- The origin of the volcanic rock.
- The granulometric characteristics of the mineral before the expansion process.
- The temperature of expansion.

However, despite its good insulating efficiency, it is only effective when it is dry or in a loose granular state. As these granules tend to absorb moisture and settle after installation, it becomes less effective as an insulation material with time. The most common way of applying perlite is to pour the granules and spread them manually. It can fill small spaces more completely than fibrous insulation materials. Loose fill insulation, such as expanded perlite, may be used in combination with other types of insulation material (*e.g.* slabs of cellular plastics) for filling awkwardly shaped areas where cutting of slabs to the desired shape would be time consuming and incomplete. Caution is needed during handling and installation of expanded perlite, as perlite dust can cause chronic poisoning.

2.3.2.3.2 Unexpanded Perlite

Unexpanded Perlite is produced from natural glassy volcanic rock. It has excellent resistance to open fire with a thermal conductivity value in the range of about 0.040 $W.m^{-1}K^{-1}$to 0.06 $W.m^{-1}K^{-1}$. The maximum service temperature of perlite is 760 °C. Unexpanded perlite is mainly mixed with Portland cement for walls, roofs, floors and plastering when it is used[23].

2.3.2.4 Vermiculite

Vermiculite is made from expanded mineral called mica. When mica is exposed to high temperatures it expands to form vermiculite. Vermiculite is used mainly as an insulating material. Vermiculite has a relatively high density (64 $kg.m^{-3}$-130 $kg.m^{-3}$), with a relatively low thermal conductivity (0.063 $W.m^{-1}K^{-1}$-0.068 $W.m^{-1}K^{-1}$). It also has excellent resistance to fire, good resistance to direct sunlight and its maximum service temperature is 1315 K. It is mainly poured into ceiling, cavity walls, and the cores of hollow core bricks[13].

2.3.3 RIGID BOARDS

Rigid board is another form of thermal insulating material that is mainly divided into four types, *viz.*: fibre glass (open cell structure), expanded polystyrene (closed cell foam), extruded polystyrene (closed cell foam), polyisocyanurate (closed cell foam) and polyurethane[13]. Both expanded and extruded closed cell foam polystyrene have a maximum service temperature value of 100 °C. Through polymerization styrene can be made into white pearls or beads of polystyrene plastic. These beads can then be expanded to form foam known as expanded polystyrene.

2.3.3.1 Rigid Board Fibreglass

The rigid board fibreglass has a higher maximum service temperature of approximately 350 °C compared to the batts and loose fill equivalents and is more rigid than batts. It is applied mainly on roofs, cavity walls and prefabricated structures. In general fibreglass matting is also used as a thermal insulating material and offers the following advantages:

- High resistance to fire.
- High resistance to microbiological attack.
- Good resistance to most chemicals.
- High heat resistance.
- Available in a variety of presentations (*e.g.* blankets, mats, loose fill and boards).
- Low thermal conductivity.

The thermal conductivity of rigid board fibreglass depends on density as indicated in table 2.2.

Table 2.2: Values of the thermal conductivity and density values of the fibreglass thermal insulation at 273 K where "Type" signifies the difference in densities[24].

Type	Density	Thermal Conductivity
	kg/m^3	W/mK
Type I	**10-18**	**0.044**
Type II	**19-30**	**0.037**
Type III	**31-45**	**0.034**
Type IV	**46-65**	**0.033**
Type V	**66-90**	**0.033**
Type VI	**91**	**0.036**
Glass Fibre, Resin Bonded	**64-144**	**0.036**

Rigid board fibreglass insulation is available in rolls of different thicknesses, which are also called blankets or mats. The width of the blankets and mats will depend on the way they are to be installed and some are faced on one side with aluminium foil or Kraft paper, which serve as vapour barriers. Kraft paper is a relatively heavy, high strength sulphate paper used mainly in electrical insulating materials. However, the main technical limitations of fibreglass matting as insulation are:

- Poor structural strength or compression resistance.
- A tendency to settle after installation if not properly installed.
- Its permeability to moisture.

Rigid board panels can be made with compressed fibreglass. These lightweight insulation boards have relatively high R-values for their thickness[24].

2.3.3.2 Extruded Polystyrene

Extruded foams are made by mixing the polystyrene with a solvent, adding a gas under pressure and finally extruding the mixture to the required thickness. The extrusion process improves the characteristics of the final foam, such as its mechanical resistance, producing non-interconnecting pores and a more homogeneous material. Mechanical resistance here refers to resistance to tensile, compression, creep and flexural loadings. The mechanical resistance of extruded polystyrene foams can vary as the density of the foam varies from 0.4 kg.m^{-3} to 1.1 kg.m^{-3}. There are several grades of foams available with densities ranging from 10 kg.m^{-3} to 33 kg.m^{-3}, with thermal conductivities that are lower with an increase in density[24].

2.3.3.3 Expanded Polystyrene

Table 2.3: Thermal conductivities and densities of expanded and extruded polystyrene insulation at 273K[24].

Type	Density	Thermal Conductivity
	Kg/m^3	W/mK
Expanded Foam Type I	10	0.057
Expanded Foam Type II	12	0.044
Expanded Foam Type III	15	0.037
Expanded Foam Type IV	20	0.034
Expanded Foam Type V	25	0.033
Rigid Extruded Foam	33	0.033

Expanded polystyrene foams have a number of technical limitations:

- They are flammable, although fire-retardant grades are available
- They break down gradually when exposed to direct sunlight
- They react with solvents used in the installation of fibreglass-reinforced plastic (such as styrene-formulated polyesters) as well as with other organic solvents such as petrol, kerosene and acetone.

Table 2.3 gives an indication of the effects of density on polystyrene insulation[24]. Rigid board panels can be made with expanded polystyrene of different densities, various thicknesses and sizes. Density plays a major role in the thermal conductivity values of polystyrene insulation.

2.3.3.4 Polyurethane Foam

Table 2.4: Thermal conductivities and densities of polyurethane at 293-298 K[24].

Type	Density	Thermal Conductivity
	kg/m^3	W/mK
Foam	**30**	**0.026**
Rigid Expanded Board	**30**	**0.020-0.025 (Average of 0.0225)**
Rigid Expanded Board	**40**	**0.023**
Rigid Expanded Board	**80**	**0.04**
Foamed in Place	**24-40**	**0.023-0.026 (Average of 0.0245)**

Polyurethane foam is effective as an insulator because it has a high proportion (90 % minimum) of non-connected closed micro cells, filled with inert gas. Until recently, the non-reactive gas most commonly used in polyurethane foams was R-11 (trichlorofluoromethane). The Montreal Protocol on Substances that Deplete the Ozone Layer organisation has called for the phasing out of the use of CFC's such as R-11. Replacement foaming agents are being investigated at the present time, with hydrocarbons, hydro fluorocarbons and inert gases such as carbon dioxide. Table 2.4 gives density and thermal conductivity values of foamed polyurethane[24].

Polyurethane and closed cell foam polyisocyanurate both have poor fire and direct sunlight resistance and they have a maximum service temperature of around 95 °C. They are both used on areas like roofs and walls, but they too have to be covered in the inside for fire and against outside weather. They both have thermal conductivity values of 0.023 $W.m^{-1}K^{-1}$.

2.3.4 OTHER COMMON FORMS OF THERMAL INSULATING MATERIALS

2.3.4.1 Cork

Table 2.5: Values of the thermal conductivity and density for cork thermal insulation at 293-298 K[24].

Type	Density	Thermal Conductivity
	kg/m³	W/mK
Granulated Loose, Dry	115	0.052
Granulated	86	0.048
Expanded Cork Slab	130	0.040
Expanded Cork Board	150	0.043
Expanded Bonded with Resin/Bitumen	100-150	0.043
Expanded Bonded with Resin/Bitumen	150-250	0.048

Cork is probably one of the oldest insulation materials used commercially, and in the past it was the most widely used insulation material in the refrigeration industry. At present, due to the scarcity of cork-producing trees, its price is relatively high in comparison with other insulating materials. Therefore, its use is very limited, with the exception of some machine foundations where it is used to reduce the transmission of vibrations. It is available as expanded slabs or boards as well as in granular form. Its density varies from 110 $kg.m^{-3}$ to 130 $kg.m^{-3}$. It can only be used up to temperatures of 65 °C. It has good thermal insulating properties, is fairly resistant to compression and is difficult to burn. Its main technical limitation is the tendency to absorb moisture with an average permeability to water vapour of 12.5 $g.m^{-2}day^{-1}$. Table 2.5 gives some typical characteristics of cork[24].

2.3.4.2 Aluminium Thin Sheet

Aluminium thin sheet is made of reflective foil separated by air spaces. It mainly works by reducing radiant heat transfer. It has a high maximum service temperature with good resistance to both fire and direct sunlight. It is used in ceilings, walls and floors. It is most effective in reducing downward heat flow. Reflective systems are the other form of insulation and are divided into two forms, aluminised thin sheet and ceramic coating[13].

2.3.4.3 Ceramic Coating

Ceramic coatings are mainly acrylic paint filled with ceramic micro-spheres. It is used for radiant control because it has excellent resistance to fire and direct sunlight. It requires protective clothing and eye protection when applied to metal roofing, built-up roofing, walls, storage systems, ducts and pipes.

2.3.5 SELECTION OF INSULATING MATERIAL

Some the most important properties which must be considered in the selection of an insulating material are as follows:

- Thermal resistance: the higher the value of thermal resistance, the better the insulating capability of the material.
- Combustibility: this becomes significant as it provides an indication of the insulating material's contribution to fire hazard.
- Toxicity: certain insulating materials are combustible and release toxic fumes when they burn. This must be avoided where there is a danger of fire in a confined space.
- Appearance: Appearance is significant in exposed areas and for the purpose of identification.
- Density: the density of an insulating material affects many of its other properties, especially its thermal properties.

2.4 FORMS OF INSULATION

Insulation is mainly defined as the control of heat flow and the distinguished forms of insulation are:

- Reflective insulation.
- Resistive insulation.
- Composite insulation.
- Capacitive insulation.

2.4.1 REFLECTIVE INSULATION

The primary function of reflective insulation is to reduce radiant heat transfer across open spaces, which is a significant contributor to heat gain in summer and heat loss in winter. The only practical reflective insulating material is aluminium foil. Reflective insulation is employed mainly where the dominant heat transfer is radiation. The low emissive metal foil (usually aluminium) surface of the product blocks up to 97 % of radiation and therefore a significant part of the heat transfer[25].

Aluminium foil has a low absorbance and low emission[26]. Reflective insulation systems are fabricated from aluminium foils with a variety of support such as Kraft paper, plastic films, polyethylene bubbles, or cardboard. Supports are applied to provide a series of closed air spaces. Its insulating value is derived from heat reflective surfaces separated by air spaces into which the radiation is reflected. The resistance to heat flow depends on the heat flow direction, and this type of insulation is most effective in reducing downward heat flow.

Reflective systems are typically located between roof beams, floor joints or wall studs. If a single reflective surface is used alone and faces an open space, such as an attic, it is called a radiant barrier. Radiant barriers are sometimes used in buildings to reduce summer heat gain and winter heat loss. When compared to mass insulation materials like fibreglass, reflective foils offer some advantages. They are not affected by humidity or moisture, they do not lose their effectiveness when compressed, and they do not irritate the skin, nose, or eyes and require no special handling or clothing to install.

Reflective systems are more effective in hot climates than in cool climates. They can be used on their own, but they are frequently laminated with building paper, either single sided or double sided and even on plasterboards. They must be installed in cavities or air spaces for them to be effective. They differ from other insulating materials in the manner in which they retard heat transfer. Reflective insulation works by reflecting incident infrared radiation, thus reducing radiant heat transfer[27].

2.4.2 RESISTIVE INSULATION

Resistive insulation is the most common type of insulation, often referred to as bulk insulation. Resistive insulation insulates against the transfer of heat simply through its resistance to conduction. Because air has one of the highest resistances to conduction, the best resistive insulators are those that trap small pockets of air within themselves. Insulators such as glass fibre, mineral wool and expanded polystyrene work extremely well as long as the air within these pockets cannot move and thus transfer heat by convection. Resistive insulation includes mineral wools, strawboard, wool slabs, glass fibre, cellulose fibre and kapok. They also include expanded and extruded polystyrene and polyurethane, urea formaldehyde, vermiculite and perlite[28].

2.4.3 COMPOSITE INSULATION

Composite products are a range of composite insulation products that combine a reflective foil with bulk insulation, combining the benefits of both types of insulation.

2.4.4 CAPACITIVE INSULATION

Capacitive insulation has virtually no effect to steady-state heat flow when temperatures are relatively constant on each side of a material. If the temperature on either side fluctuates however, capacitive insulation effects become important. Daily variations between the outside and inside temperatures of the building takes time to reach a steady because heat transfer is not instantaneous as heat takes time in passing through the building elements. For some materials like glass this is not that noticeable, however, for double brick or rammed earth walls this can take up to eight or nine hours. This delay is termed thermal lag and is measured as the time difference between peak outside temperature and the peak temperature on the inside surface of an element[28].

2.5 ROLE OF THERMAL INSULATION

A building of any kind is essentially a space surrounded by the building envelope. A building envelope may include sub elements such as windows and doors, but its main elements are the floor, walls and roof. Heat will flow through the building envelope from a high temperature side to a lower temperature side if the interior space is maintained at a temperature different from the outdoors by heating or cooling. Heating is provided by some energy installation during winter. If the indoor temperature is to be maintained, a steady state must be reached where heat input is equal to the heat loss. The heat flow rate from the heat input must balance the heat loss through the building envelope. If the sum of the heat lost through all the leaks is greater than the flow from the input, the indoor temperature will drop. Conversely, when the inside temperature is at the same temperature as the outside and heating up, the building will require the heat flow rate from the heat input to be greater than the heat loss. If energy is to be conserved or the heating cost is to be kept down then heat loss through the envelope should be reduced. This is maintained through thermal insulation[29].

Inadequate insulation and air leakage are the leading causes of energy waste in most buildings. Thermal insulation saves money and the nation's limited energy resources. It can make a house or building more comfortable by helping to maintain uniform temperatures throughout the house. Hence walls, ceilings and floors will be warmer in winter and cooler in summer. The thermal and energy performance of buildings depends on the thermal characteristics of the building envelope and particularly on the thermal resistance of the insulation materials used[29]. With the general acceptance of global warming as a continuing problem, energy efficiency is becoming a higher priority in industry and residential houses. One aspect of energy efficiency is to improve the insulation of buildings by using materials of a low thermal conductivity. In temperate and polar climates this will result in reducing heating requirements, whilst in equatorial areas air conditioning energy consumption is decreased. Additionally, in order to reduce CO_2 and other emissions, legislation and standards concerning insulation levels in buildings and other applications involving heat transfer are becoming more stringent world wide[30].

The electricity savings potential as well as the economic and environmental impact of ceiling insulation on South Africa have been well established. A previous study has shown that if all existing high income houses in South Africa are insulated, (where the term "insulated" here is taken to mean an insulated ceiling as well as additional insulation wrapped around the outside of the geyser), almost 3000 GWh of electricity can be saved in winter heating per year. This is equivalent to an annual monetary saving of R_A740 million. The corresponding reduction in greenhouse gas pollution from power stations is roughly one million tons per year[31]. Furthermore, ceiling insulation has the potential to reduce evening peak electricity demand in the winter by more than 1900 MW[32]. This will result in an even greater saving for the country as it will allow the building of a new power station to be postponed. The study conducted in 1996 has indicated that South Africa will save around $2 billion through thermal insulation[33].

2.5.1 ENERGY SAVING METHODS

In South Africa there are a large number of energy inefficient buildings. This is mainly because of a high percentage of low income communities living in informal low cost houses (shacks). Extensive research has already been conducted to determine the characteristics of a typical informal low cost house[34]. According to this research, the typical informal low cost house is built with two windows, one on the south side and one on the west. Winter heating requirements are lowest when the windows are placed on the northern facing equator and eastern walls[34]. The requirements of different orientations are negligible. The exterior colour of a building can play a very important role in determining the building's thermal performance. Shacks with a dark exterior colour require less indoor heating to achieve acceptable indoor temperatures during winter. This is because the darker surface absorbs a lot more heat from the sun than the light surface does. It was found that in the absence of any wall insulation, applying a dark colour to the exterior of the shack could lower the winter heating requirements by 24 %[3]. An increase of this magnitude hardly compensates for the winter energy saving. Summer indoor conditions however are affected by a dark exterior. . Interestingly, it was found that shacks inhabitants prefer light exterior colours, silver particularly[34]. Exterior colour control is thus not really a feasible energy control option for shacks.

A recent study showed that the natural infiltration into a leaky building is of the order of 0.9 air changes per hour. This infiltration rate can be increased dramatically as most shack inhabitants use coal stoves[35]. Although significant energy savings can be achieved by limiting infiltration, the idea is not really practical. Coal stoves generate indoor pollution and adequate volumes of outdoor air are thus required for health reasons. Limiting ventilation is not recommended as an option for increasing energy efficiency in informal low-cost houses[35]. In contrast to all the options discussed thus far, the addition of thermal insulation is an extremely effective option for increasing energy efficiency for shacks. Placing a thermal insulation on the walls and roofs of a house increases the resistance to heat flow to and from the building. As a result, outdoor heat may be kept away from the shack in summer and the warmth is kept inside the shack in winter. It was found that adding 25 mm of glass wool, which has a thermal resistance of 1.05 $m^2K.W^{-1}$, that the winter energy requirements were reduced by 78 %. The option of installing thermal insulation is thus clearly much more effective than others[3]. The important role of insulation is shown in figure 2.1 compared to other options[36].

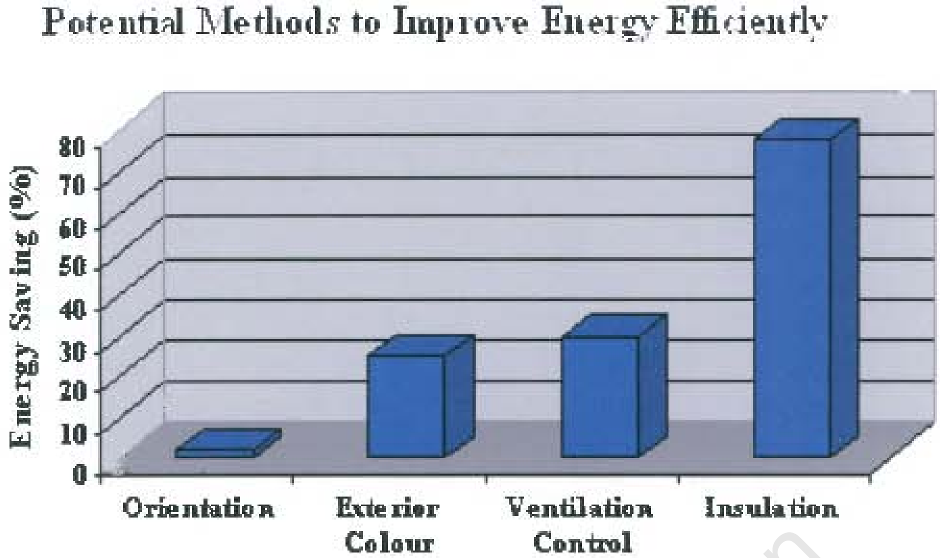

Figure 2.1: Comparisons of the effect on energy saving options through different methods[3].

Table 2.6: Comparison of the effect of different methods of energy savings in different types of houses[8].

Options	Shacks	Matchbox	Suburban
	[%]	[%]	[%]
Exterior Colour	8	26	10
Building Orientation	2	22	14
Ventilation Control	6	16	10
Window Size	0	2	35
Insulation	90	50	35

Van Wyk *et al.* investigated building materials, building orientation, exterior colour, ventilation control and insulation in formal low-cost housing (matchbox houses) and informal low-cost housing (shacks). It was found that thermal insulation provided the most effective energy saving of up to 75 %[3]. There are many forms of energy conservation and methods of conserving energy by means of thermal insulation are the most effective ones. Taylor and Kleingeld improved the work of Van Wyk by including suburban houses. Their findings are summarised in table 2.6. In general the role played by thermal insulation in buildings can lead to a number of benefits, which are summarized as follows[13,37]:

- Using thermal insulation in buildings helps to reduce the reliance on mechanical or electrical systems to operate buildings comfortably. Resources, like coal associated with energy, are conserved.
- The use of thermal insulation not only saves energy operating costs, but also results in environmental benefits and as a result dependence upon mechanical means with the associated emitted pollutants is reduced.
- An energy cost is an operating cost, and a significant energy saving can be achieved by using thermal insulation with little capital expenditure of only about 5 % of the building construction cost.
- This does not deal only with the reduction of operating cost, but also reduces high voltage alternating current (HVAC) equipment cost due to a reduction of the equipment size required.

The use of thermal insulation in buildings not only reduces the reliance upon mechanical air conditioning systems, but also extends the periods of indoor thermal comfort of installed buildings. This enhances the acoustic comfort of insulated buildings. High temperature changes may cause undesirable thermal movements, which may result in damage of the building and structure. Hence insulation can increase the building structural integrity of buildings by minimising temperature fluctuations. This can be achieved by the use of proper thermal insulation and so helps in increasing the lifetime of building structures[13].

Proper design and installation of thermal insulation helps in preventing vapour condensation on building surfaces. However, care must be taken to avoid adverse effects of damaging a building structure, which can result from improper insulation material installation or poor design. Vapour barriers are usually used to prevent moisture penetration into thermal insulation. If a suitable insulation material is selected and properly installed, it can assist in retarding heat and preventing flame spread into the building in the case of fire[13].

2.6 COMPARISON OF THERMAL INSULATING MATERIALS

Table 2.7: Some common thermal insulations material's R-values, advantages and disadvantages[24].

Insulating Material	R-Value per 2.54 cm	Advantages	Disadvantages
Polyurethane	6.25	**Very good R-value; can be used with fibreglass resin**	**Not always easily available; relatively expensive**
Polyurethane (Spray on)	7.0	**Very good R-value; can be used with fibreglass resin; easy application with spray equipment**	**Not always easily available; requires special spray equipment**
Polyurethane; Poured (two-part chemical)	7.0	**Very good R-value; can be used with fibreglass resin; relative ease of application**	**Not always easily available; expensive; require very careful volume calculation**
Polystyrene, Sheets (smooth) Trade Name "Styrofoam"	5.0	**Readily available; low cost; reasonable R-value**	**Cannot be used with fibreglass resin unless protected; easily damaged**
Polystyrene foamed in Place and Expanded Moulded beads, known as Isopor , Polypor	3.75 to 4.0	**Reasonable R-value; lower cost than smooth surface sheets**	**Cannot be used with fibreglass resin unless protected; easily damaged**
Cork Board	3.33	**Availability in many markets; reasonable cost; can be covered with fibreglass**	**Lower R-value than polyurethane; and styrene foam**
Fibreglass Wool Batts	3.3	**Low cost; ease of installation**	**Readily absorbs water or other fluids; loses insulating value when wet**
Rock Wool Batts	3.7	**As above**	**As above**
Wood Shadings	2.2	**Readily available**	**Absorbs moisture and loses R-value when wet; decays**
Sawdust	2.44	**Readily available; low cost**	**Absorbs moisture and loses R-value when wet; packs down under vibration**

Over the years, there have been many health concerns that have arisen due to insulation materials such as asbestos and urea formaldehyde foam insulation. Nevertheless different types of insulations that have been and are being used, have their advantages and disadvantages. Some of the more common materials used for insulation are compared in table 2.7 with their relative insulating values and the advantages and disadvantages of each particular type. In general, the more expensive materials, such as the polyurethane foams are more efficient insulators for given thicknesses. Using the "R" system of grading, it is possible to arrive at equivalent R-values for a variety of insulating material types[24].

2.6.1 ASBESTOS

Asbestos is a mineral fibre that has been used commonly in a variety of building construction materials for insulation and as a fire retardant. It was commonly used before 1970 in building products because it was fireproof, a good thermal insulator, and easily made into pipe covering fabric and other materials. Asbestos was commonly found in pipe and furnace insulation materials, especially in homes built between 1930 and 1950. Oil and coal furnaces and door gaskets may also have asbestos insulation. Hot water and steam pipes in older houses may be coated with an asbestos material or covered with an asbestos blanket or tape. Asbestos was an excellent thermal and electrical insulator for more than 50 years, but the manufacture and use of asbestos is now prohibited in many countries in the world. It is known to cause several cancers such as a type of lung cancer called mesothelioma and cancers of the gastrointestinal tract[38].

2.6.2 UREA FORMALDEHYDE FOAM INSULATION (UFFI)

In the 1970's there were concerns about health effects of insulation materials, when improperly installed UFFI caused high levels of formaldehyde emissions in tens of thousands of homes. No insulation materials in use today exhibit indoor air quality problems approaching those of UFFI, but the rapidly growing interest in healthy homes is spurring a close examination of health impacts. Urea formaldehyde is one of the main resin mixtures of formaldehyde and of all the formaldehyde compounds. It contributes the most to indoor air problems because of its water solubility[39].

2.6.3 FIBREGLASS

Fibreglass is a soft wool-like material that is usually pink or yellow. It is used as insulation, in weatherproofing and as textile material. It was originally used as a "safe" substitute for asbestos. The modern technique of making fibreglass insulation, developed in 1931, involves jetting of molten glass through tiny heated holes into high speed air streams, wherein the resulting fibres are drawn very thin and to great lengths[40]. Fibreglass was used as a liner inside air supply ducts and air handler compartments of the ventilation system of homes and buildings built from the early 1960's through to the late 1980's. It was used in ventilation systems as an insulator to prevent the loss of ventilation pipes cold air and to reduce the noise from the blower fan. Fibreglass liners inside ducts were a problem because if it got wet it could become a breeding ground for micro organisms.

There are a few more problems with fibreglass. One is there are some health problems associated with it. For example, it can cause a skin allergy and there is debate on whether or not fibreglass may cause cancer. It may also trigger reactions in people who are chemically sensitive since most fibreglass insulation is produced using a phenol formaldehyde binder to hold the fibres together. These binder materials may release offending amine or "dead-fish" odours in high humidity situations. Another factor that should be considered when choosing insulation is the ingredients that go into it. The largest fibreglass insulation manufacturers all use at least 20 percent recycled glass in their insulation products to comply with the U.S. Environmental Protection Agency (EPA) recycled content guidelines, which is adopted world wide. One of the raw materials that are used to make fibreglass more flexible and fire retardant is boron. However, there are only two large deposits of boron in the world: one in the southwest U.S. and one in Turkey. Since the total known U.S. reserves of boron are just 200 years, other renewable alternatives should be considered[41].

2.6.4 MINERAL WOOL

Mineral wool was at one time the most common type of insulating material and its market share was largely lost to fibreglass in the 1960's and 1970's. In the past few years, however, the product appears to have made a comeback. There are currently several manufacturers of mineral wool in the U.S. and about eight plants that produce it. Mineral wool actually refers to two different materials, slag wool and rock wool. Slag wool is produced primarily from iron ore blast furnace slag, an industrial waste product. Rock wool is produced from natural rocks. Slag wool accounts for roughly 80 % of the mineral wool industry, compared with 20 % for rock wool. Given the relative use of these two materials, mineral wool has, on average, 75 % post-industrial recycled content[41].

2.6.5 CELLULOSE

Cellulose is perhaps the best example of recycled material that is used in insulation. Most cellulose insulation is approximately 80 % post-consumer recycled newspaper by weight; the rest is comprised of fire retardant chemicals and, in some products, acrylic binders. The biggest long term performance concern with cellulose insulation is possible loss of fire retardant chemicals because borates are water soluble and they can leach out if the insulation gets wet[41].

2.6.6 COTTON

Cotton is a type of insulation that uses cotton and polyester mill scraps with plastic fibre added for three dimensional lofts and borates added are for pest and combustion resistance. This insulation costs about 15 % to 20 % more than comparable fibreglass insulation. Of course, precautions need to be taken to prevent insect infestation as well as moisture intrusion[41].

2.6.7 FOAM INSULATING MATERIALS

There are different types of foam insulation materials. These include polyisocyanurate, polyurethane and polystyrene. Styrene, like that used in polystyrene insulation, can cause irritation of the eyes, nose and respiratory system. It can also cause headache, fatigue, dizziness, confusion, malaise (vague feeling of discomfort), drowsiness, weakness, unsteady gait and possible liver injury. Many foam insulations use recycled plastic resin such as that found in some extruded and expanded polystyrenes (EPS).

Of the foam insulations, polystyrene is easier to recycle than polyisocyanurate or polyurethane since it can easily be melted down and reformed into other products. The simplest recycling involves crumbling the old EPS into small pieces and re-moulding them into usable shapes. Polystyrene used to be blown with chlorofluorocarbons, or CFC's, that destroy the earth's protective ozone layer. Modern extruded polystyrene (XPS) uses hydrochloride-fluorocarbons (HCFC's) that are not as harmful. EPS is the only common rigid foam board stock insulation made with neither CFC's nor HCFC's. During manufacture, polystyrene beads are expanded with pentane, which is a flammable gas. An advantage of board stock insulation is that if it can be removed without breaking up, it can often be reused.

Two new types of foam insulations that do not use CFC's or HCFC's are Icynene and Air Krete™. Icynene is a foaming agent that uses a mixture of carbon dioxide and water. Though it does not have polyurethane's HCFC-related environmental problems, it also has a lower insulation rating (R-value). Like polyurethane, Icynene is foamed into wall cavities, but the resultant open-cell foam is soft, not rigid. Air Krete™ is inorganic foam produced from magnesium oxide (derived from sea water). It is foamed under pressure with a microscopic cell generator and compressed air and no CFC's or HCFC's are used[41].

In some parts of the country, foam insulation materials are prone to infestation of wood boring insects, such as carpenter ants. Tunnels and nesting cavities will reduce thermal performance and may affect the structure as well. Foam insulation materials that contain HCFC's must be avoided. Though HCFC's are less destructive to stratospheric ozone than CFC's, they are still damaging to the environment[41].

2.6.8 LOOSE FILL

Other considerations regarding insulation are that some loose fill fibre insulation will settle and get displaced because of wind and rodent pestilence. It is also possible that, over many years, dust and dirt accumulation could reduce the R-value by either compressing the insulation or by filling air pockets[41]. Insulating materials should be durable so that they do not have to be replaced every few years, thus contributing to the solid waste problem. Provision must be made so that a home or a building is well insulated to save energy. Reducing the energy use of a building is usually the single most important factor that can be done to reduce the building's overall environmental impact. If an insulating material that has a lower R-value (insulation rating) is being used then the thickness of the insulation can be increased. The insulation materials that have large amounts of recycled materials are a better choice. For example, with cavity-fill insulation, cellulose and mineral wool have a higher recycled content than fibreglass. Also, as far as possible, an insulation contractor who recycles scrap insulation must be chosen[41].

2.7 ENVIRONMENTAL COMPARISONS OF INSULATION MATERIALS

Decisions about insulation are among the most important that must be made relative to the environmental impact of buildings. Because insulation reduces the energy consumption, it provides ongoing environmental benefits throughout a building's life. However, not all insulation materials are equally environmentally friendly. In assessing the environmental characteristics of insulation materials, there is a need to consider a broad range of issues relating to the resources going into their production.

These include manufacturing processes, pollutants given off during their lifecycle, durability, recyclables and impact on indoor air quality.

2.7.1 RAW MATERIAL ACQUISITION

The raw materials used to produce insulation vary widely, ranging from the sand used in fibreglass to the petrochemicals in foam plastic insulation and old newspaper in cellulose insulation. Environmental concerns with raw material acquisition include, on the negative side, depletion of limited resources and pollution resulting from mining. On the positive side is the recycled content of many common insulation materials[42].

2.7.2 LIMITED RESOURCES

The most obvious resource limitation among materials used to produce insulation is the availability of fossil fuels used in foam plastic insulation.

2.7.2.1 Polystyrene

Polystyrene is produced from ethylene, a natural gas component and benzene, which is derived from petroleum. Polyisocyanurate and polyurethane are made from polymeric methylene diisocyanate (PMDI) and polyol, both of which are derived from petroleum. While fossil fuels are not going to run out any time soon, the reserves are finite, and as they decrease in the next century, costs are likely to rise[42]. While other insulation materials are not made from petrochemical feed stocks, most require fossil fuel energy for mining, manufacture, and transport, so they lead indirectly to fossil fuel depletion. Another raw material that is potentially in short supply is the boron used in fibreglass insulation and as a fire retardant in some cellulose insulation[42].

2.7.2.2 Fibreglass

Fibreglass insulation is the biggest consumer of boron, most of which comes from two primary deposits: the largest in the south-western U.S. and Turkey. Boron improves the flexibility of fibreglass. Fibreglass insulation is approximately 6 %-8 % boron oxide (B_2O_3) by weight. At present levels of extraction and with current economics, U.S. Bureau of Mines data shows a 54 year reserve of boron in the U.S., and total known U.S. reserves of about 200 years[42].

2.7.3 POLLUTION FROM RESOURCE EXTRACTION

Environmental impacts from raw material acquisition include air pollution, water pollution and erosion from mining of minerals. For example, sand and limestone used in fibreglass, diabase rock used in rock wool, and bauxite for the aluminium used in foil facings and radiant barriers. Often these environmental impacts are combined. For example, mining usually produces tailings waste, which results in runoff with high levels of suspended solids. This increases turbidity in surface waters, which can cause deoxygenating of these waters, which in turn can kill fish. Pollution from oil spills and well-head leaks occurs when extracting and transporting the fossil fuels used to make plastic foam. The same fuels provide the energy for mining and other resource extraction[42].

2.7.4 RECYCLE CONTENT

Recycled content is the most recognized environmental feature of building products. Materials with recycled content have three advantages:

- They require less natural resource.
- They divert materials from the solid waste stream.
- They use less energy during manufacturing.

The insulation industry is abundant with good examples of recycled material use. Considerable use of recycled materials in producing insulation has been investigated in other countries. As an example, the U.S. Environmental Protection Agency's recycled-content procurement guidelines specify minimum recycled contents for construction projects receiving over $10 000 in federal funding. Table 2.8 shows the minimum recycled content percent by weight for common insulating materials[42].

Table 2.8: The recycled-content acquired by EPA guidelines[42].

Material Type	Minimum Recycled Content (% by Weight)
Cellulose (Loose –fill and Spray-on)	75% post-consumer recovered paper
Fibreglass	20%-25% cullet (post-industrial or post-consumer glass)
Mineral Wool	75% recovered materials
Polyisocyanurate Rigid Foam	9% recovered material (polyol resin contents)
Polyurethane Spray Foam	5% recovered material (polyol resin contents)

2.7.4.1 Cellulose

Cellulose is perhaps the best example of recycled material use in insulation. Most cellulose insulation is approximately 80 % post-consumer recycled newspaper by weight. The rest is comprised of fire retardant chemicals and in some products acrylic binders. The cellulose industry used approximately 381 million kg of recycled newspaper in 1994, according to the Cellulose Insulation Manufacturers Association (CIMA)[42].

New cellulose insulation technologies are helping recycled newspaper to go further. There is increasing use of lower density cellulose produced by breaking newspaper down into individual fibres that are fluffier. The industry is switching to this process from the older hammer mill process because it results in a better product that is cleaner, has less dust, and slightly higher R-value. More manufacturers are offering stabilized cellulose to prevent settling of loose fill attic insulation.

2.7.4.2 Mineral Wool

While mineral wool was at one time the most common type of insulation, its market share was largely lost to fibreglass in the 1960's and 1970's. Over the past few years, however, the product appears to have made a comeback. There are currently several manufacturers of mineral wool in the U.S. and about eight plants that produce it. Slag wool is produced primarily from iron ore blast furnace slag, an industrial waste product. Rock wool is produced from natural rocks, such as basalt and diabase. Slag wool accounts for roughly 80 % of the mineral wool industry, compared with 20 % for rock wool. Given the relative use of these two materials, mineral wool has, on average, 75 % post-industrial recycled content. According to the North American Insulation Manufacturers Association, 425 million kg of blast furnace slag were used in 1992 to produce slag wool[41].

2.7.4.3 Fibreglass Insulation

Fibreglass insulation manufacturers Owens Corning, Schuller International and Certain Teed in the U.S. use at least 20 % recycled glass cullet in their insulation products to comply with the EPA recycled-content procurement guidelines. Schuller's fibreglass is certified by the Scientific Certification Systems (SCS) to contain 25 % recycled glass (18 % post-consumer bottles and 7 % post-industrial cullet), and it has most actively promoted that environmental benefit. Schuller's manufacturing equipment readily handles colour glass, making it easier for the company to use post-consumer recycled cullet. Certain Teed and Owens Corning rely primarily on post-industrial cullet from flat glass manufacturers[42]. Recycled glass content in excess of 90 % is feasible. Each percent of glass cullet (over 10 %) substituted for raw sand reduces energy use by about 1 %. The company has one plant using 40 % recycled glass, but they claim a 20 % average among all their plants. Owens Corning, the largest producer of fibreglass insulation, is now averaging 30 % recycled glass and one of their foreign plants is using in excess of 90 %[42].

2.7.4.4 Extruded and Expanded Polystyrene

Recycled plastic resin is used in some extruded and expanded polystyrene. Expanded polystyrene (EPS) can also be made out of recycled polystyrene. The simplest recycling involves crumbling the old EPS into small pieces and re-moulding them into usable shapes. Any polystyrene can be recycled into building insulation, but because of fire retardants, old building insulation cannot usually be recycled into non-building applications[42].

2.7.4.5 Polyisocyanurate Foam

The polyisocyanurate foam insulation industry also uses recycled material in its products. In addition to the raw chemicals having recycled content, the foil facings used on polyisocyanurate are typically 70-80 % recycled aluminium. Like foil facings on polyisocyanurate insulation, the aluminium used in radiant barriers is also mostly recycled. The 6mm polyethylene foam insulation in the product is 10 % recycled high-density polyethylene[42].

2.7.4.6 Cotton Insulation

Cotton insulation is the new thermal insulating material in the fibre insulation industry. Promoted initially as a non-irritating alternative to fibreglass, early market research revealed an interest in the use of recycled fibre. The present product is approximately 95 % post-industrial recycled fibre, 25 % of which is polyester fibre. The polyester improves tear strength and recoil characteristics[42].

2.7.5 CHEMICAL PRECURSORS OF SOME INSULATING MATERIALS

With some insulation materials, there are industrial processes that result in non-energy-related pollution. To manufacture isocyanate, a precursor of polyisocyanurate and polyurethane insulation, two chlorine-based chemical intermediates are used: phosgene and propylene chlorohydrins. The styrene used in polystyrene insulation is identified as a possible carcinogen, mutagen, chronic toxin, and environmental toxin. Further, it is produced from benzene, another chemical with both environmental and health concerns.

Most fibreglass insulation is produced using a phenol formaldehyde (PF) binder to hold the fibres together. Though exact quantities of binder used in manufacture of fibreglass are not disclosed by industry, it comprises 5-7 % of typical residential fibreglass insulation products, and they may account for 10-15 % of the total material cost. During manufacturing, most of the binder apparently dissipates and is captured with pollution control equipment. A new type of fibreglass that does not require a binder is being introduced. Because there are no binders or other chemicals (such as colorants) in this product, pollution control equipment is not required, and pollution emissions during manufacturing will be much less of a concern[42].

2.7.6 CHLORO-FLUOROCARBONS AND HYDROCHLORIDE-FLUOROCARBONS

The most significant pollutants found in insulation materials are chlorine based chemicals that destroy the earth's protective ozone layer. Chlorofluorocarbons, which are also greenhouse gases, were used until recently as blowing agents in extruded polystyrene, polyurethane, polyisocyanurate and phenolic foam as indicated in table 2.9[42]. As revelations about the role CFC's play in ozone depletion came to light and regulations to restrict their use were enacted, however, these industries have turned to other, less damaging, foaming agents.

Table 2.9: Blowing agents used in rigid board stock and spray polyurethane insulation[42].

Product	Original Blowing Agent	Current Blowing Agent	Date of CFC Phase-out	Date of HCFC Phase-out
Extruded Polystyrene	CFC-12	HCFC-142b	1990-1993	2020
Polyisocyanurate	CFC-11	HCFC-141b	1993	Dec. 2002
Spray Polyurethane	CFC-11	HCFC-141b (or water, HCFC-22b, HCFC-134b)	1993	Dec. 2002
Phenolic Foam Board Stock	CFC-11	HCFC-141b and or recycled CFCs	1992	Dec. 2002
Expanded Polystyrene	Pentane	Pentane	N.A	N.A
Rigid Fibreglass	None	None	N.A	N.A

Among building insulation materials, extruded polystyrene (XPS) led the shift to less damaging hydrochloride-fluorocarbons (HCFC's). XPS manufacturers were able to switch quickly because HCFC-142b had already passed toxicity testing and companies were able to produce it without additional testing. Other CFC users were not so fortunate. Polyisocyanurate, polyurethane, and phenol foam were all foamed with CFC-11, and the best replacement found, HCFC-141b, had not been tested for toxicity, so was not on the market. Thus, those industries could not shift away from CFC's as quickly. In mid 1993, PIMA announced that the POLYISO-industry had completed the shift from CFC-11 to HCFC-141b. HCFC's are only 5 % to 11 % as damaging to ozone as CFC's because they do not last as long in the atmosphere. However, they are almost as damaging for the period of time when they are present and all are significant greenhouse gases believed to cause global warming. Foam insulation manufacturers and chemical producers are working hard to find zero-ozone-depletion alternatives[43].

2.7.7 CFC'S FREE FOAM INSULATION

Among foam insulation materials, there are several alternatives to those made with ozone exhausting chemicals.

2.7.7.1 Expanded Polystyrene (EPS)

Expanded polystyrene (EPS) is the only common rigid foam board stock insulation made with neither CFC's nor HCFC's. During manufacture, polystyrene beads are expanded with pentane, a hydrocarbon that contributes to smog but is not implicated in ozone depletion or global warming; the pentane quickly leaks out of the insulation and is replaced by air. Several EPS manufacturers have redesigned their plants to recover up to 95 % of the pentane used in production and some manufacturers have shifted to a low pentane formulation[42].

2.7.7.2 Polyurethane

The polyurethane industry as a whole has gone the route of replacing CFC-11 with HCFC's. Some producers and insulation contractors have stopped the use of CFC-11 and gone to a non-ozone-depleting hydro-fluorocarbon (HFC). Others use HFC-134a as the foaming agent in polyurethane foam[44]. The higher cost of this foaming agent results in an increase of about 10 % over conventional polyurethane. While HFC's are ozone-safe and they are significant greenhouse gases.

2.7.7.3 Icynene

Icynene is another type of foamed insulation. The foaming agent is a mixture of carbon dioxide and water. This eliminates polyurethane's HCFC-related environmental problems but also means a lower R-value. Like polyurethane, Icynene is foamed into wall cavities, but the resultant open-cell foam is soft not rigid. In fact, it is marketed as much for its air sealing characteristics as its insulation properties. A recent development with Icynene is a second formulation that can be foamed into closed cavities.

2.7.8 EMBODIED ENERGY

Table 2.10: Embodied energy values for common insulation materials[42].

Material	Embodied Energy (MJ/kg)	Weight per Insulation Unit (kg)	Embodied Energy per Insulation Unit (MJ)
Cellulose	1.75	0.37	0.6
Fibreglass	27.9	0.17	4.8
Mineral Wool	15.1	0.21	3.1
EPS	11.6	0.17	19.0
Polyisocyanurate	69.8	0.22	15.1

State of the art, energy-efficient, passive solar houses built today may consume less heating and cooling energy over 30 or even 50 years of operation than was required to build it. This means that if society wants to continue the impressive gains that have been made over the past 20 years in reducing energy usage, they will need to focus attention on embodied energy as well as operating energy. Embodied energy is the energy required to produce and transport materials. If two insulation materials insulate equally well and other manufacturing factors are comparable, then the one with lower embodied energy is environmentally preferable.

While the embodied energy of insulation materials is usually quite low when compared with the energy a given amount of insulation will save over its lifetime, it is nonetheless important. Embodied energy values for common insulation materials are compared in table 2.10[42]. Because these values were obtained from different sources and may have been obtained using different assumptions, they should not be considered to be highly accurate. They do however provide useful order of magnitude comparisons. Just how embodied energy values relate to environmental performance of a product is complicated by the fact that different fuels have different environmental impacts. For this broad comparison, it is reasonable to assume that a Joule of energy used by one industry is roughly comparable in terms of resource use and resultant pollution to a Joule used by another industry[42].

2.7.9 DURABILITY

Durability of building materials, including insulation, is a very important environmental consideration. Clearly, more durable materials are environmentally superior to less durable ones. Most insulation materials will perform very well over the lifetime measured in decades or even centuries. There are exceptions, however, and various factors affect performance over time.

The biggest long term performance concern with cellulose insulation is possible loss of fire-retardant chemicals. Borates are water soluble; hence they can leach out if the insulation gets wet. There is a shift within the industry towards ammonium sulphate fire retardants, which actually improve in fire resistance performance over time. A concern with ammonium sulphate, however, is corrosion of metals in contact with the insulation, particularly with wet-spray applications[42]. Other concerns with loose fill fibre insulation are settling, displacement as a result of wind and infestations of rodents. It is also possible that, over many decades, dust and dirt accumulation could reduce the R-value either by compressing the insulation or by filling air pockets. Insulation materials that rely on reflectivity for their thermal performance are prone to reduced performance as accumulating dust reduces reflectivity.

Rigid foam insulation materials that are produced using low conductivity blowing agents (CFC's and HCFC's) are prone to R-value decreases as the blowing agents leak out of the cell structure and air leaks in. In some parts, foam insulation materials are also prone to infestation of wood boring insects, such as carpenter ants. Tunnels and nesting cavities will reduce thermal performance and with foam-core panels, may affect the structural performance as well[42].

2.7.10 REUSABILITY AND RECYCLABILITY

Most insulation materials reach the end of their life not because it has worn out or has ceased to function properly, but because the building it was installed in is altered or taken down. An exception of this is commercial roofing. Many built-up roofing systems incorporate both rigid insulation and an adequate amount of roof surfacing. When re-roofing becomes necessary, the whole roof surface including insulation is often removed.

The reusability of insulation materials is dependent on how these materials were installed. To facilitate re-roofing without replacing the insulation, a layer of sheathing between the insulation and the roofing membrane is recommended. If rigid board stock insulation can be removed without breaking it up, it can often be re-used. The performance of reused polyisocyanurate insulation will not be as good as that of new material, because some of the low-conductivity gases will have escaped and because of nail holes. Extruded polystyrene, expanded polystyrene and all fibre insulation materials should not appreciably change in their insulating performance, though dust in fibre insulation materials will make working with the material at best disagreeable and at worst hazardous[45].

Because of dust and dirt, it is unlikely that any fibre insulation materials could be easily recycled into products other than insulation. Of the foam insulation materials, polystyrene (expanded polystyrene and extruded polystyrene) is easier to recycle than polyisocyanurate or polyurethane. Polystyrene is a thermoplastic and can be melted and reformed into other products with minimal chemical modification. Polyisocyanurate and polyurethane are thermosetting plastics that do not melt. Most of the research being done on recycling of these materials is focusing on grinding the insulation and using the resultant powder as an additive in various unrelated materials.

Another issue of concern relating to disposal of insulation is the CFC blowing agents that are within the foamed thermal insulating materials in our existing buildings. A large portion of the CFC blowing agents that have been used in building insulation over the past 20 years have not yet been released into the atmosphere and are still in the insulation. If studies show that even phasing out new production of CFC's and HCFC's is not enough to stem the ozone depletion that is occurring, there might be pressure to capture and thermally destroy CFC's in foam insulation that is being disposed of. This is already happening to a limited extent with refrigerators that are being recycled by utility companies through demand side management programs[45].

2.7.11 INDOOR AIR QUALITY

Though indoor air quality issues are different from environmental issues, they are related and should be considered at the same time. Health effects of insulation materials have been a concern since the 1970's, when improperly installed urea formaldehyde foam insulation (UFFI) caused high levels of formaldehyde emissions in a large number of homes. No insulation materials in use today exhibit indoor air quality problems approaching those of UFFI, but the rapidly growing interest in healthy homes is spurring a close examination of health impacts[45].

Some argue that the fibres released from fibreglass insulation may be carcinogenic, like asbestos. A spate of recent technical articles about the carcinogenicity of glass fibres has been damaging to the image of the fibreglass industry, as has the requirement for cancer warning labels. To address health concerns, fibreglass batts that have been covered are available in perforated polyethylene. While touted as a convenience feature for do-it-yourselves, most industry observers consider it a reaction to growing health concerns about glass fibre. The use of binder in loose-fill fibreglass insulation has been increased to reduce the amount of loose fibres escaping into the air, but higher levels of phenol formaldehyde binder raise concern among some about formaldehyde off-gassing. The fibres are stronger and less brittle in fibreglass. The product may not have to carry the cancer warning label. Also, this type of fibreglass contains no chemical binders or dyes, so there should be no off-gassing[45].

Table 2.11: Summary of Environmental and Health Impacts for some commonly used fibre thermal insulating materials[45].

Fibre Insulation					
Type of Insulation	**Insulation Methods**	**R-value (m^2K/W)**	**Raw Material**	**Pollution from the Manufacture**	**Indoor Air Quality Impact**
Cellulose	**Loose fill, wet spray, dense pack stabilized**	**21-26**	**Newspaper, borates, ammonium sulphate**	**Negligible**	**Fibre and chemicals can be irritants, should be isolated from interior space**
Fibreglass	**Batts, loose fill, stabilized rigid board**	**15-28**	**Silica, sand, limestone, boron, PF resin, cullet**	**Air pollution from energy**	**Same as cellulose**
Mineral Wool	**Loose fill, bats**	**19-26**	**Steel slag, PF natural rock**	**Same as fibreglass**	**Same as cellulose**
Cotton	**Batts, loose fill**	**21-26**	**Cotton and polyester, mill scraps**	**Negligible**	**Considered very safe**
Perlite	**Loose fill**	**17-23**	**Volcanic rock**	**Negligible**	**Some skin irritation dust**

There are also claims that the fire retardant chemicals or reparable particles in cellulose insulation may be hazardous. Much of the concern about fibreglass and cellulose has been generated by competing manufacturers or trade associations, and it has become difficult to pick out areas of real concern as it appears that some of the issues are unnecessarily exaggerated. When properly installed, neither fibreglass nor cellulose should pose any health risks.

Some individuals have acute chemical sensitivity to the small quantities of chemicals that off gas from nearly all common insulation materials. The binders used in conventional batt insulation, inks from the recycled newspaper in cellulose, and VOC's released from foam insulation are examples of such off gassing. This has led to increasing interest in such products as Air Krete$^{(TM)}$. Tables 2.11 and table 2.12 below summarise the health risks that are posed by different common insulating materials[45].

Table 2.12: Summary of Environmental and Health Impacts for some commonly used foamed thermal insulating materials[45].

Foam Insulation					
Type of Insulation	**Insulation Methods**	**R-value (m²K/W))**	**Raw Material**	**Pollution from the Manufacture**	**IAQ Impact**
Expanded Polystyrene (EPS)	Rigid boards	25-31	Fossil fuels, pentane	Pentane emission contribute pollution	Concern only for those with sensitivities
Extruded Polystyrene	Rigid boards	35	Fossil fuels, HCFC-142b	Ozone depletion, global warming, energy use	Same as EPS
Polyisocyanurate	Foil-faced, rigid boards	39-53	Fossil fuels, HCFC-141b	Same as Extruded Polystyrene	Same as EPS
Phenols	Foil-faced, rigid boards	55	Fossil fuels, HCFC-142b	Same as Extruded Polystyrene	Same as EPS
Polyurethane	Spray in	40-47	Fossil fuels, HCFC-142b	Same as Extruded Polystyrene	Same as EPS

2.7.12 POLLUTION FROM MANUFACTURE AND USER

Nearly all manufacturing processes generate pollution. Much of the pollution generated by insulation production is a result of energy use (generally fossil fuel combustion), so a simple way to compare manufacturing impacts of different insulation materials is to compare the manufacturing energy required[45].

2.8 MOISTURE CONTROL

Moisture transfers into the building structure from many sources. If enough quantities of moisture accumulates in the building envelope and cannot escape, it becomes a good environment for mould and other moisture-related problems. Different materials have different moisture storage capacities which are a function of time, temperature and material properties. If moisture penetrates into the building, thermal insulation will cause physical damage and will adversely impact on its performance by increasing its thermal conductivity. Four conditions are necessary for moisture to accumulate in a building component and pose a source of problems. These include a moisture source, a moisture route for travel, a driving force, and a material susceptible to moisture damage. Moisture can ideally be controlled if one of these conditions is eliminated. The most practical approach to controlling moisture in buildings is through careful design and material selection[43].

There are different sources and transport mechanisms of moisture into building assemblies, including[14, 43].

- Liquid water flow from rain and plumbing leaks. Rain can penetrate through leaks around doors, windows and other cracks in the building envelope.
- Water vapour convection from air infiltration through openings and cracks in the building envelope. This is a major cause of interstitial condensation in the building envelope.

- Water vapour from internal sources such as cooking, shower, laundry and indoor plants.
- Water vapour diffusion from parts with higher moisture levels (higher vapour pressure) to other parts with lower moisture levels.
- Liquid water movement due to capillarity from the ground through porous materials in the basement, foundation, ground floor slab and walls.
- Released moisture which was previously stored in the building structure during slow air drying construction process. This normally plays a role only in the first few years after building construction.

In reality, multiple moisture sources and transport mechanisms normally act together. Every moisture transport mechanism can cause moisture problems and can help dry building materials and alleviate such problems as well. Therefore, it is not always the best approach to prevent moisture transport mechanisms but rather to control moisture sources, control moisture transport and accumulation mechanisms, and encourage moisture removal (drying) in a building assembly[43]. Many factors affect moisture problems in buildings. These include:

- Local climate at the building site.
- The difference between the indoor and outdoor climate.
- The type and quality of construction. Different materials will hold and transport moisture differently. For example, concrete will allow more moisture to pass and be stored than wood or aluminium.
- The amount of moisture generated indoors.
- The ventilation process.
- The type and position of the insulation used.
- The use and location of vapour retardants.

In order to control moisture in buildings, it is important to understand the climate at which the building is designed, its thermal systems, and consider the following:

- Select proper building materials and construction methods.

- Prevent rain water penetration into the building envelope by proper roofing and caulking around all penetrations and cracks.
- Control infiltration by sealing all air leakage pathways around the building envelope.
- Use proper ventilation and dehumidification. However, in humid climates make sure that the incoming ventilation air is not a moisture source where it might be more humid than the inside air.
- Use and properly locate vapour retardants in the building envelope when applicable.

2.9 VAPOUR RETARDANTS

A vapour retardant is a special material (treated papers, paints, plastic sheets, and metallic foils) that reduces the passage of water vapour. The material permeability determines the extent to which water vapour can pass through it. The lower the permeability, the better the material is as a vapour retardant. Materials can be classified based on their permeability as follows:

- Vapour barriers which are very impermeable to water vapour (≤1 % permeable). These include polyethylene films, aluminium foils, oil-based paints, vinyl wall coverings, sheet metal, foil-faced insulation, glass and rubber membranes.
- Vapour retardants which are semi-vapour permeable to water vapour (1<10 % permeable) and include plywood, un-faced expanded polystyrene, paper and bitumen facing on fibreglass insulation and most latex-based paints.
- Breathable materials which are permeable to water vapour (≥10 % permeable) such as unpainted gypsum board, un-faced fibreglass insulation, cellulose insulation, cement, and other similar building materials.

When vapour retardants are used when there is high level of moisture in the air of a living space, such moisture can cause a lot of problems. When such moist air touches a cold surface with a temperature that is below or equal to the dew point of that air, condensation will start to occur on that surface which could accumulate and create problems. If this moisture penetrates into the wall or the ceiling it could create an environment for mould and mildew growth resulting in health problems and damaging building materials. If it gets into the insulation material, it will adversely impact on its performance. Thermal insulation can help cure or complicate moisture problems. The temperature inside an insulated component is changed and the new temperature profile can either prevent condensation or make a surface inside that component colder during winter than it would be if un-insulated. Therefore, water vapour travelling through that component can condense and cause problems[46, 47].

The type and location of the vapour retardants to be used in a building depends greatly on the prevailing climatic conditions and whether moisture is expected to move into or out of the building. For example, in regions with prevailing cold climates, moisture tends to diffuse through the building envelope from warmer and more humid inside air to colder and drier outside air. The exterior surfaces should be permeable to allow drying towards the outside. In regions with prevailing hot and humid conditions, on the other hand, moisture is expected to diffuse through the building envelope from outside warmer and humid air to the colder and drier inside conditioned air. Therefore, vapour retardants should generally be placed towards the outside surface of the insulation. In mixed climates, where moisture is expected to move both into and out of the space without predominance of either, it is better not to use vapour retardants at all and allow water vapour by diffusion to flow through the building envelope into and out of the space without accumulation. Rigid foam insulation boards do not require added vapour retardant treatment when placed onto the interior of stonework walls[47].

2.10 PREFERRED INDOOR AIR TEMPERATURES

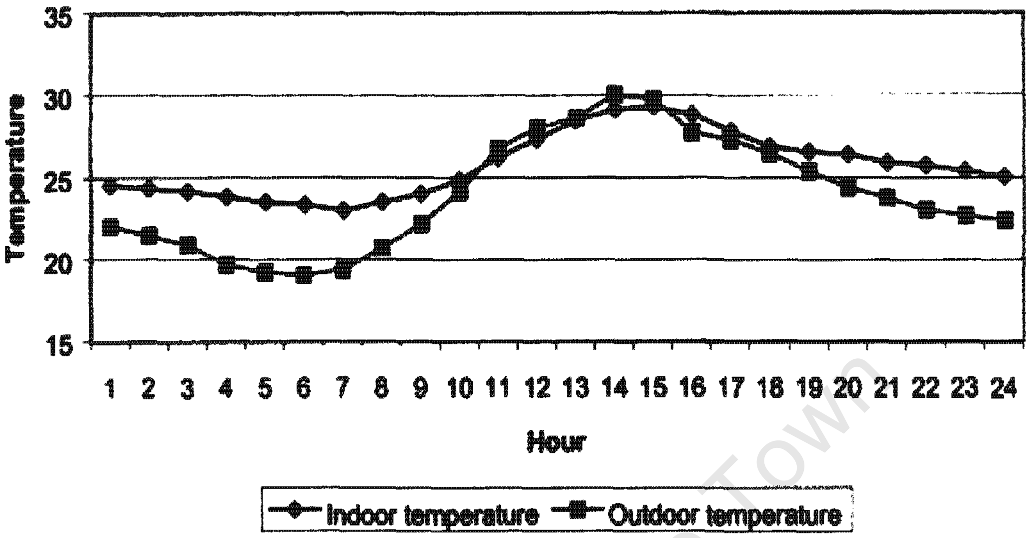

Figure 2.2: A temperature comparison of a typical middle class house before insulation[50].

Mathews *et al* conducted a study on preferred conformable indoor air temperature in different regions of South Africa. It was found that an indoor air temperature of approximately 28.5 °C was acceptable for 80 % of the participants taking part in the survey. For an indoor temperature of around 30.5 °C, only 27 % were of the opinion that the indoor environment was acceptably comfortable. These tests were conducted without the consideration of humidity. A study was also conducted on six different houses in the Pretoria region[48, 49]. It was also found that when thermal insulation is installed in the ceiling of the house these comfortable temperatures can be approximately achieved. Fibreglass insulation was installed in each house's ceiling. To provide a control, two further non-insulated houses were also measured during the measurement of other six insulated houses. The six houses used were chosen to fit the profile of an average middle to high income household in South Africa.

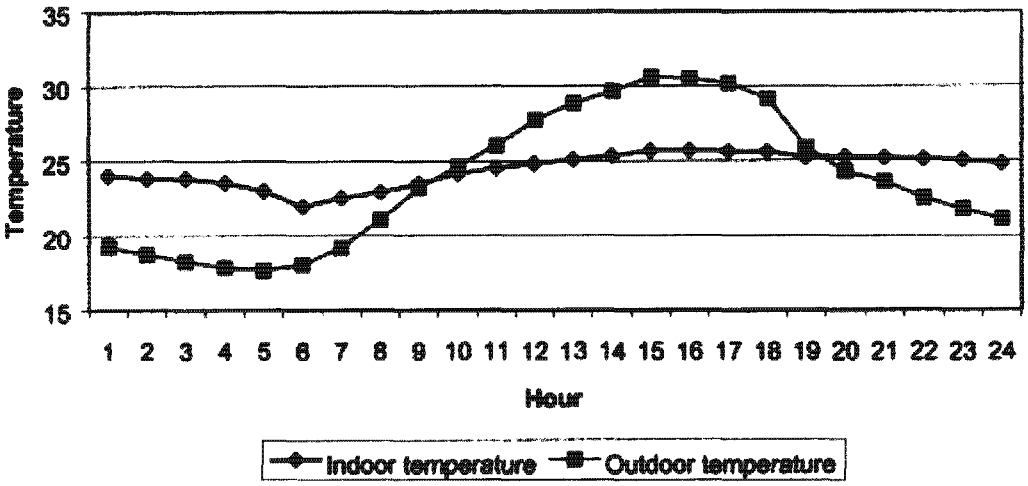

Figure 2.3: A temperature comparison of typical middle class house after insulation[50].

The measured indoor temperatures for each house were then compared with the outdoor temperatures. The results are shown in figure 2.2 and figure 2.3. It is interesting to note that the maximum indoor and outdoor temperatures were close to each other when no ceiling insulation present. However, a significant difference occurred after the ceiling insulation was installed[50]. A better indoor temperature can be achieved with a different thermal insulating material. The results found here are not total representations of the South African climatic conditions. However they give an idea of the significance of thermal insulation in the ceiling of buildings.

2.11 MODES OF THERMAL HEAT TRANSFER

To change the temperature of an object, energy is required in the form of heat generation to increase the temperature, or heat extraction to reduce temperature. Once the heat generation or heat extraction is terminated a reverse flow of heat occurs to reverse the temperature back to ambient. To maintain a given temperature, considerable continuous energy is required. Thermal insulation can be used to reduce this energy loss. Heat may be transferred via three modes: conduction, convection and radiation. All heating applications involve each mode to a greater or lesser degree.

Convection is the mode of energy transfer between a solid surface and the adjacent liquid or gas that is in motion. It involves the combined effects of conduction and fluid motion. The faster the fluid motion or gas motion, the greater the convection heat transfer. Convection of heat occurs in liquids and gases, whereby flow processes transfer heat. Free convection is flow caused by differences in density as a result of temperature differences. Forced convection is flow caused by external influences (*e.g* wind or ventilators).

Radiation is the transfer of heat energy by electromagnetic (infrared) waves and is very different from conduction and convection. Conduction and convection take place when the material being heated is in direct contact with the heat source. In infrared heating, there is no direct contact with the heat source. Infrared energy, like light travels in straight lines through space or vacuum and does not produce heat energy until absorbed. Thermal radiation mechanism occurs when thermal energy is emitted similar to light radiation[51]. It occurs generally where the mode of heat transport is a gas.

Glass, ceramics and polymers are relatively poor conductors of heat energy and are frequently used as thermal insulators. All gases are poor conductors of heat energy. The atoms or molecules are widely separated and interact rarely compared to solids and liquids. This is illustrated in figure 2.4, where two substances at different temperatures are separated by a barrier which is subsequently removed[53]. When the barrier is removed, the fast high energy atoms collide with the slower lesser energy ones. In such collisions the faster atoms lose some speed and the slower ones gain speed; thus, the fast ones transfer some of their kinetic energy to the slow ones. This transfer of kinetic energy from the hot to the cold side is called a flow of heat through conduction. The red box represents fast atoms, blue represent slow atoms and yellow the temperature achieved after removing the barrier. A combination of expanded polymer or ceramic fibre filled with air is an excellent thermal insulation. Generally, conduction in a solid, a liquid, or a gas is the movement of heat through a material by the transfer of kinetic energy between atoms or molecules.

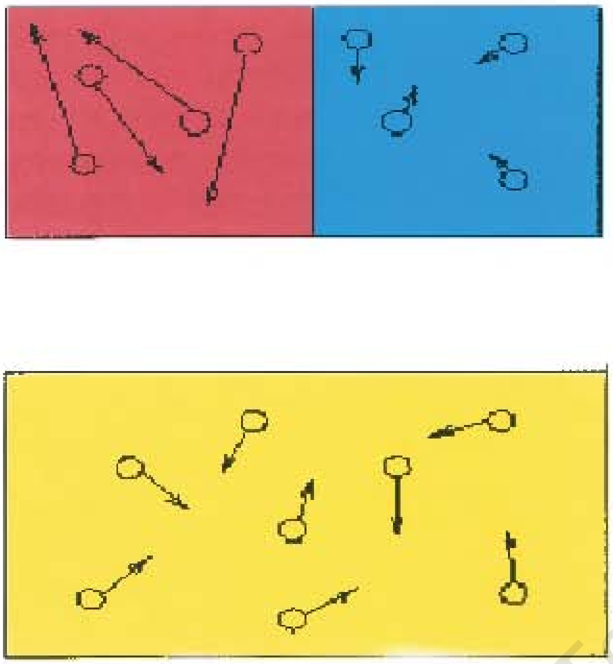

Figure 2.4: Heat is conducted by conduction between gas molecules[52].

Thermal conduction is the molecular transport of heat under the influence of a temperature gradient. This mode of heat transfer is more clearly defined when a metal rod is heated at one end and heat is conducted through the rod by conduction as figure 2.5 illustrates[52].

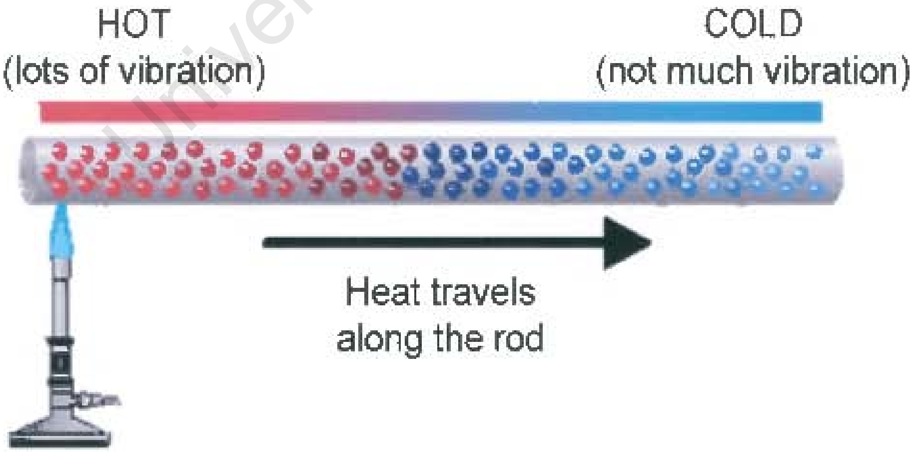

Figure 2.5: A schematic representation of how heat is conducted through a heated rod[52].

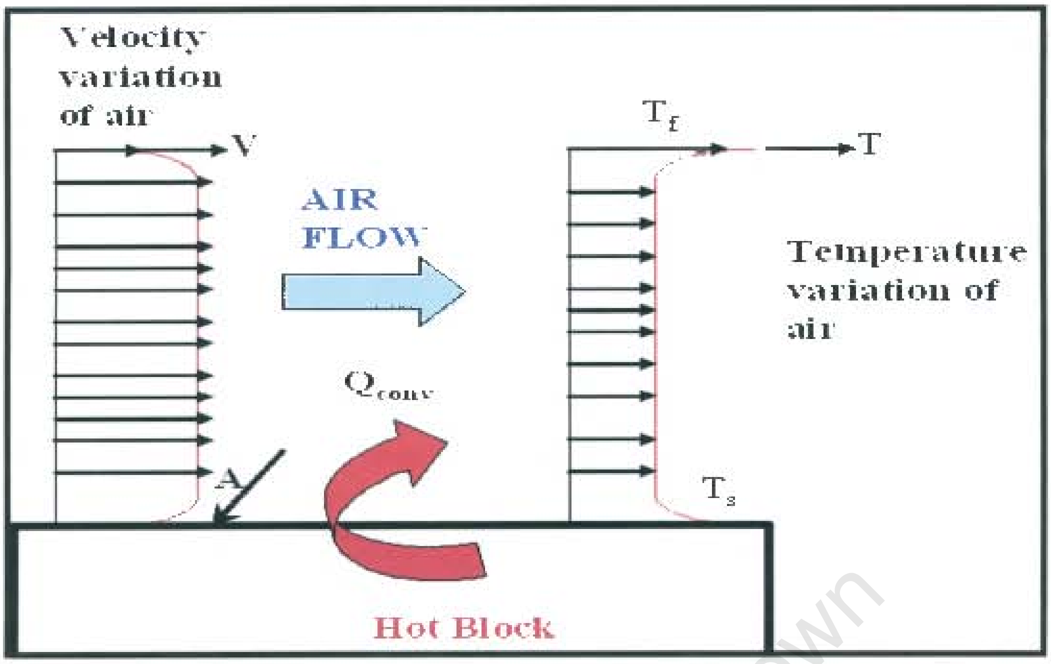

Figure 2.6: Heat transfer from a hot surface to air by convection represented schematically[51].

In the absence of any bulk fluid motion, heat transfer between solid surfaces and the adjacent fluid is pure conduction. The presence of bulk motion of the fluid enhances the heat transfer between solids and the fluid, but it also complicates the determination of heat transfer rates. Consider the cooling of a hot block by blowing of cool air over its top surface as indicated in figure 2.6[51]. Energy is first transferred to the air layer adjacent to the surface of the block by conduction. This energy is then carried away from the surface by convection. The effects of conduction within air due to random motion of air molecules and microscopic motion of air that removes the heated air near the hot surface and replaces it by the cooler air, results in convection effects.

All materials transfer heat by conduction as their component atoms or molecules exchange energy through collisions. Solids are the most effective conductors of heat. Although the atoms in a solid have fixed positions, they constantly vibrate and interact with their neighbours. In hot areas the atoms vibrate more strongly, so the interactions tend to pass energy to cooler regions resulting in heat flow. Some solids conduct heat much better than others, depending on the way the atoms are bonded together. Liquids are generally worse conductors of heat than solids. The interactions are weaker than in solids and this makes energy transfer less efficient.

Different materials transfer heat by conduction at different rates and this is measured by the material's thermal conductivity. Consider a material placed in between two reservoirs at different temperatures, as in the indicated in figure 2.7[52]. The flow of heat through the material over time can be measured. But more practically the heat flow rate (HFR) through the insulation for a flat surface may be calculated using equation 2.1[53].

$$\mathbf{HFR(in \cdot an \cdot hour) = \frac{DT \times A}{R}} \qquad \mathbf{[Wh]} \qquad \mathbf{(2.1)}$$

where, **DT** (K) is temperature difference across the insulating material and **A** is the surface area (m^2). The term heat flow in general, refers to the rate at which heat moves from an area of higher temperature to an area of lower temperature.

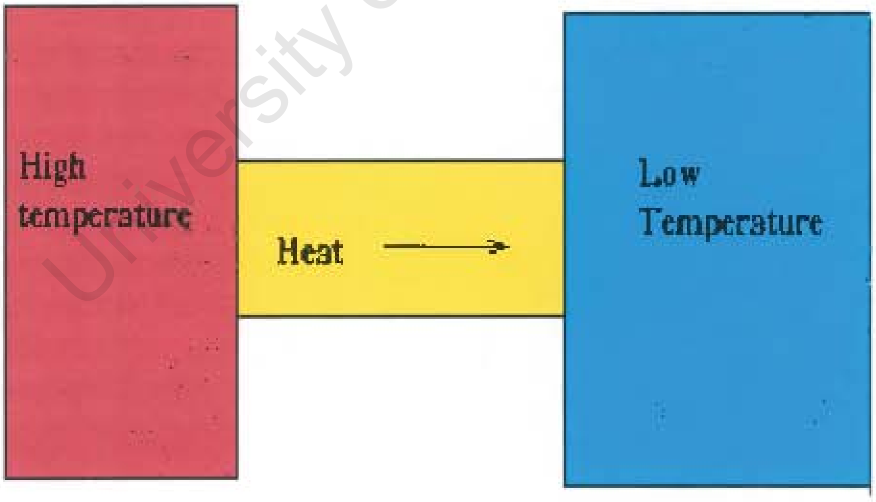

Figure 2.7: Schematic illustration of how thermal conductivity can be measured[52].

The purpose of any insulating material is to retard heat flow. The term thermal conductivity is used to express the quantity of heat, which will flow across a unit area when a temperature deference of one degree exists. Thus, for a given temperature difference between the reservoirs, materials with a large thermal conductivity will transfer large amounts of heat over time. Such materials, for example, copper, are good thermal conductors. Conversely, materials with low thermal conductivities will transfer small amounts of heat over time and these materials, like concrete, are poor thermal conductors. For this reason, fibreglass, feathers or fur as insulation have air pockets and still air is a poor thermal conductor. These air pockets aid in cutting back on the heat loss through the material. Home insulation is thus a poor thermal conductor, which keeps as much heat in as possible. Instead of being rated in terms of thermal conductivity, insulation is usually rated in terms of its thermal resistance (R), which is defined as:

$$\mathbf{R = \frac{t}{k}} \qquad [\mathbf{m^2.K.W^{-1}}] \qquad \mathbf{(2.2)}$$

where **t** is the insulation thickness, and **k** is the thermal conductivity[53]. Materials which have a high thermal conductivity have, by definition, a low thermal resistance and they are poor heat insulators. Good insulating materials therefore should have a high thermal resistance. In fact, the R-value quoted for insulation is the thermal resistance.

2.12 THERMAL QUANTITIES

Heat is a form of energy, appearing as molecular motion in a substance or radiation in space. It is measured in the same units as any form of energy: the SI unit being the joule (J). Temperature can be considered as a symptom of the presence of heat in a substance; it is a measure of the thermal state of that substance. This is measured in the Celsius scale or Kelvin scale. Specific heat capacity of a substance expresses the relationship between heat and temperature: it is the amount of heat energy that causes a unit temperature increases for a unit mass of the substance, measured in units of

J.kg^{-1}K^{-1} [25]. The most common quantities that are used to describe thermal properties of insulating materials are thermal conductivity, thermal resistance, thermal conductance and thermal transmittance[13]. Thermal conductivity is the time rate of steady state heat flow (W) through a unit area of 1m thick homogeneous material in a direction perpendicular to isothermal planes, induced by a unit (1K) temperature difference across the sample[48]. Thermal conductivity which is the k-value is expressed in W.m^{-1}K^{-1}. It is a function of the material's mean temperature and moisture content. Thermal conductivity is a measure of the effectiveness of a material in conducting heat. Hence, knowledge of the thermal conductivity values allows quantitative comparisons to be made between the effectiveness of different thermal insulation materials.

Thermal resistance is a measure of the resistance to heat flow as a result of suppressing conduction, convection and radiation. It is a function of the material's thermal conductivity, thickness and density. Thermal resistance, R-value, is expressed in m^{2}K.W^{-1}. Thermal conductance is the rate of heat flow (W) through a unit surface area of a component with unit (1K) temperature difference between the surfaces of the two sides of the component. It is the reciprocal of the sum of the resistances of all layers composing that component without the inside and outside air film resistances. It is similar to thermal conductivity except it refers to a particular thickness of material. Thermal conductance, U-value, is expressed in W.m^{-2}K^{-1}. Thermal transmittance is the rate of heat flow through a unit surface area of a component with unit (1K) temperature difference between the surfaces of the two sides of the component. It is the reciprocal of the sum of the resistances of all layers comprising that component plus the inside and outside air film resistances. It is often called the overall heat transfer coefficient and is expressed in W.m^{-2}K^{-1} [54].

2.13 PRINCIPAL METHODS OF THERMAL CONDUCTIVITY MEASUREMENTS

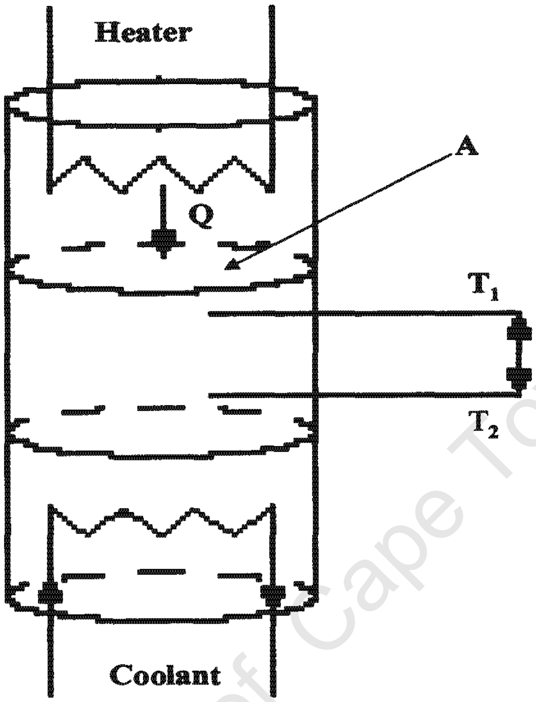

Figure 2.8: A schematic illustration procedure of how thermal conductivity can be measured[55].

According to the illustration in figure 2.8, thermal conductivity can be defined by the following equation[55]:

$$\mathbf{k} = \frac{\mathbf{Q}/\mathbf{A}}{\Delta\mathbf{T}/\Delta\mathbf{L}} \qquad (2.3)$$

where, **Q** is the amount of heat passing through a cross section, **A**, and causing a temperature difference, **Δ*T***, over a distance of **Δ*L***. **Q / A** is therefore the heat flux which is causing the thermal gradient, **Δ*T* / Δ*L***. The measurement of thermal conductivity has always involved the measurement of the heat flux and temperature difference. The difficulty of the measurement is associated with the heat flux measurement. The measurement is called absolute when the measurement of the heat flux is done directly by measuring the electrical power going into the heater. When the flux measurement is done indirectly through comparison techniques, the method is called comparative[55].

2.13.1 AXIAL FLOW METHODS

Axial flow methods have long established and have produced some of the most reliable, highest accuracy results reported in the literature. It is the method of choice at low temperatures. Key measurement issues are mainly centred on a reduction of radial heat losses in the axial heat flow developed through the specimen from the electrical heater mounted at one end. The power dissipation of this heater is used in calculating column heat flux. The losses are minimal at low temperatures. As the specimen temperature moves above room temperature, control of heat losses becomes more difficult to eliminate. Of importance are the experimental parameters such as the ratio of effective specimen conductance to lateral insulation conductance and to the quality of guarding. Guarding is the match of the axial gradient in the specimen to that of the surrounding insulation. In practice, only cylindrical symmetry heat transfer is used[55].

2.13.2 COMPARATIVE CUT BARS

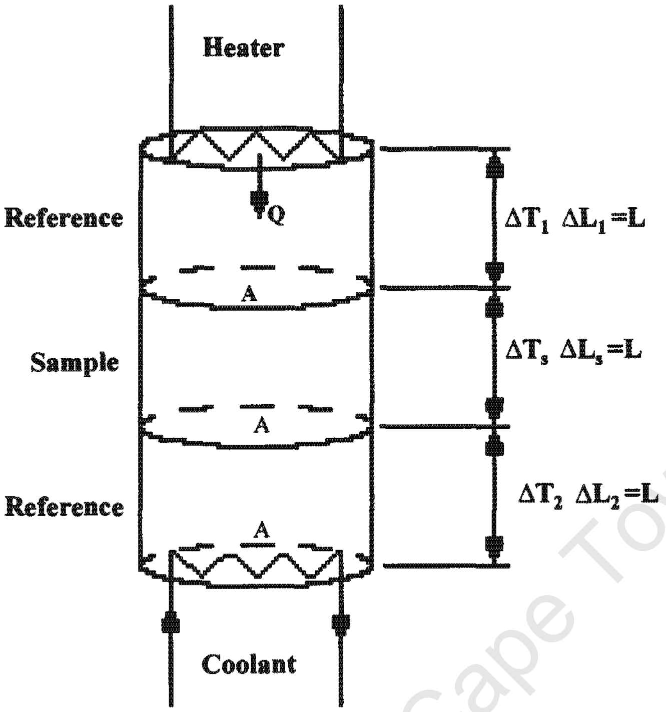

Figure 2.9: The axial comparative cut bar thermal conductivity testing method[55, 56].

This is perhaps the most widely used method for axial thermal conductivity testing. The principle of the measurement lies with passing the heat flux through a known sample and an unknown sample and comparing the respective thermal gradients, which will be inversely proportional to their thermal conductivities. In most cases the unknown is sandwiched between two known samples (the references) to further account for minor heat losses that are very difficult to eliminate. This type of thermal conductivity measurement method it is outlined in figure 2.9[55, 56]. If k_R in figure 2.9 is the thermal conductivity of the references, then the thermal conductivity of the unknown sample can be calculated from:

$$Q = k_s \times \left(\Delta T_s / L \right) = \frac{k_R \times (\Delta T_1 + \Delta T_2)}{2L} \tag{2.4}$$

Through mathematical manipulations equation 2.4 resolves to the following equation:

$$k_s = \frac{k_R \times (\Delta T_1 + T_2)}{2\Delta T_s} \qquad (2.5)$$

Guarded or unguarded heat flow meter methods involve the use of a flux gauge[57, 58]. The flux gauge is very similar, in its purpose, to the references in the comparative cut bar method. In practice the reference material has a very low thermal conductivity and can be made very thin. Thermocouple pairs are located on both sides of the reference material. They can be connected differentially to yield directly an electrical signal proportional to the differential temperature across it. This type of flux gauge is mostly used with instruments testing very low thermal conductivity samples, such as building insulations. In a similar fashion, flux gauges can be constructed from a wide variety of materials, thick or thin, depending on the material's thermal conductivity. Common requirements for all flux gauges are that the material used for the measuring section be stable, not affected by the thermal cycling, and the gauge be calibrated by some method independently. A very large variety of testing instruments use this method.

2.14 MECHANICAL TESTING

All materials require some degree of standard testing to ensure the proper execution for the desired application. There are various standard test methods introduced to determine the mechanical behaviour of insulating materials. This section will briefly discuss some of the test methods mostly used. The methods include three-point bending testing, compression testing, and creep testing. These methods are employed in industry to develop mechanical property data mainly taken over a short period of time at standard temperature and strain rates.

2.14.1 THREE-POINT BENDING TESTING

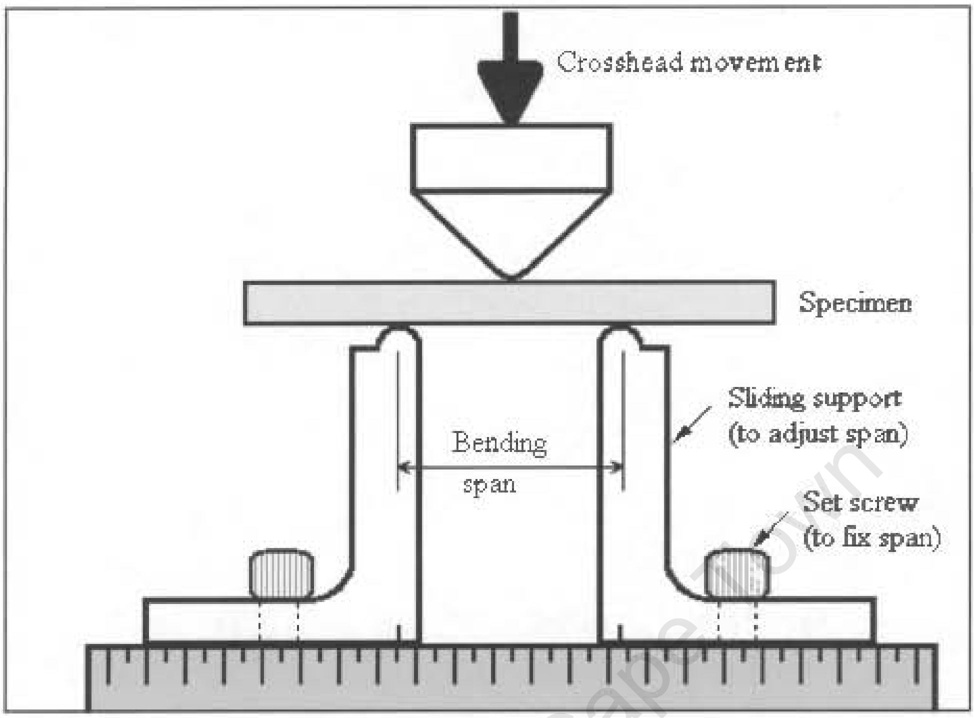

Figure 2.10: Experimental set-up for the flexural test illustrated schematically, where the test speed is 5 mm/min[61].

The three-point bending testing introduces flexural stresses onto the test samples. Therefore materials are subjected to flexural testing in order to determine the mechanical behaviour. During the three-point bending testing the material experiences both compression and tensile forces[59]. The test specimen used is a rectangular bar, which is placed on fixed supports near each other. The load is applied from the top at the middle of the specimen (see figure 2.10[60]). In the three-point bending test the flexural stress (σ), deflection and the flexural modulus (E) of the material can be determined. The following equations are used to calculate these parameters[60]. The top part of the specimen is under compression and the bottom part is under tension.

$$\sigma = \frac{(3FL)}{(2bd^2)} \qquad \textbf{Flexural Stress} \qquad (2.5)$$

$$E = \frac{\left(3FL^3\right)}{\left(4bd^3D\right)}$$ **Flexural Modulus** (2.6)

where, F, L, b, d and D are the load, support span, specimen width, specimen thickness and deflection at the centre of the beam (see figures 2.10 and 2.11[60]), respectively.

Flexural properties are important in assessing the resistance of materials to bending. If the load recorded corresponds to the value at which failure occurs, then σ corresponds to the flexural strength[61].

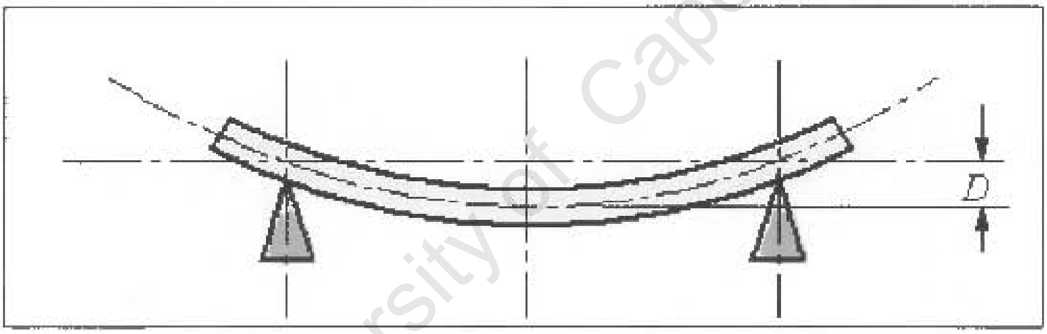

Figure 2.11: Schematic drawing showing the maximum deflection during flexure [62].

2.14.2 COMPRESSION TESTING

The compressive strength of a material is the compressive force per unit area that it can withstand without failing. This is in contrast to the more commonly measured tensile strength. ASTM D 695 is the most commonly used test method. Figure 2.12 shows the test geometry[62].

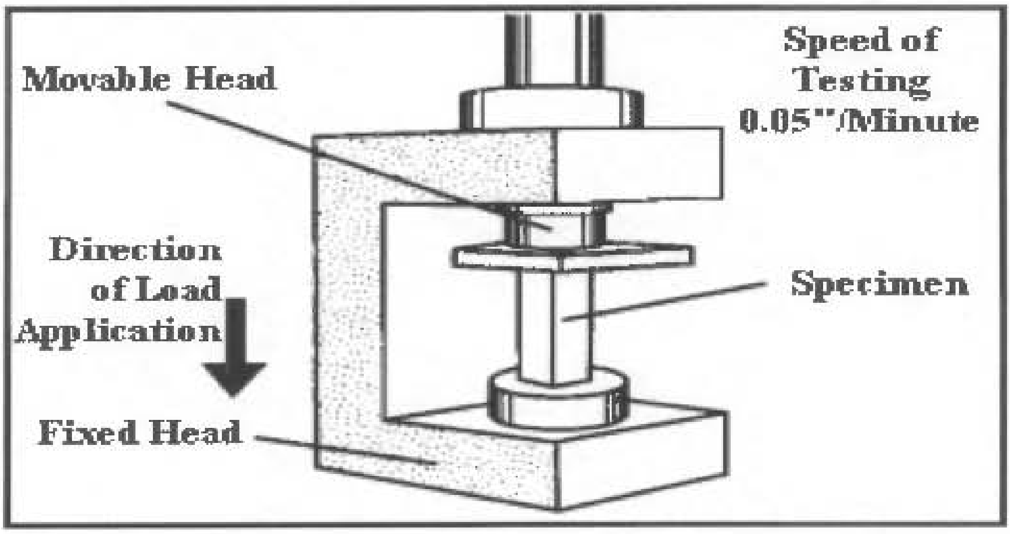

Figure 2.12: The test geometry of ASTM D 695 for compressive strength testing represented schematically[63].

The compressive yield strength is the stress measured at the point of permanent yield where the slope is zero, on the stress-strain curve. The ultimate compressive strength is the stress required to rupture a specimen. Materials such as most plastics that do not rupture can have their results reported as the compressive strength at a specific deformation such as 1%, 5%, or 10% of the sample's original height. The compressive strength is calculated by dividing the maximum load by the original cross-sectional area of a specimen in a compression test. Polystyrene, as a common insulating material, has a compressive strength of around 70 kPa[63, 64].

2.14.3 CREEP TESTING

A crucial challenge when designing products to be made from polymeric materials is the prediction of performance over long periods of time. The amount of deformation after short or long term loading has to be known reasonably accurately in advance, *i.e.* at the design stage. During long term service, creep and stress relaxation are the main deformation mechanisms that is of concern. Creep is particularly common in polymers. Creep occurs when a force is continuously applied to a component, causing it to deform gradually. For polymers, the delayed response of polymer chains during deformations is the cause of creep behaviour. If a load is slowly applied to a polymeric body, the chains in the polymer have time to unfold and stretch.

Deformation stops when the initially folded chains reach a new equilibrium configuration (*i.e.* slightly stretched). This deformation is recoverable after the load is removed, but recovery takes place slowly with the chains retracting by folding back to their initial state. The rate at which polymers creep depends not only on the load, but also on temperature. The temperature at which a polymeric body is loaded is very important with respect to its mechanical behaviour. In general, a loaded component creeps faster at higher temperatures[60].

2.15 ECONOMICS OF INSULATION

Insulation can be considered as a long term investment with associated financial benefit, following a relatively short initial payback. There are number of computer programs available to aid in selecting the most economic insulation thickness. The thickness provides the highest insulation value for the lowest cost. Economics is the primary concern in evaluating investment alternatives. When applied to an insulating system, economics can be used mainly to establish the following items.

- Evaluation of two or more thermal insulating materials for the lowest cost for a given thermal performance.
- Selection of the optimum insulation thickness for a given insulation type.

Knowing the value of heat energy, the cost of lost heat at the various thicknesses can be determined by the equation:

$$\mathbf{R\ L = HFR \times R_{UHE}} \qquad \mathbf{(2.7)}$$

where RL (R_A) is the Rand loss per unit area and R_{UHE} is Rand per unit of heat energy[53]. HFR is the heat flow rate through an insulating material.

2.16 FIRE TESTING OF POLYMERIC MATERIALS

When thermoplastics and elastomers are exposed to external or internal heat fluxes, they generally undergo softening and melting. This is followed by the release of vapours to the environment without significant surface charring. When thermosets are exposed to external and internal heat flux in a fire, they generally result in surface charring and form a combustible or a non-combustible mixture, depending on the chemical composition of the polymer vapour[65]. The polymer vapours generated during exposure to fire mix with air and form a combustible or a non-combustible mixture, depending on the chemical composition of the polymer vapours. As the polymer vapour-air mixture come into contact with the hot surface or the flame, the combustible mixture ignite and a flame is established at the surface, while the non-combustible mixture does not ignite. The establishment of the sustained flame at the surface is termed ignition. After ignition, the burning polymer continues to generate vapours, whereas the non-combustible mixture continues to release vapours without burning. The two processes are called flaming and non-flaming combustion, respectively[65].

The polymer surface location for ignition and the establishment of a sustained flame is defined as the ignition zone. The sustained combustion extends beyond the ignition zone if the heat flux from the burning polymer is of sufficient magnitude to ignite the polymer surface ahead of the flame front. The continuous extension of the sustained combustion on the polymer surface is defined as the flame spread. The release of heat, smoke and combustion and charring of the polymer in the flame is called fire propagation. Under all three fire stages of ignition, combustion and fire propagation, heat and products of complete and incomplete combustion are released into the environment around the fire periphery. The release of heat in the fire is responsible for thermal hazards and the release of complete and incomplete combustion and polymer vapours are non-thermal hazards[66].

CHAPTER 3

EXPERIMENTAL METHODS

3.1 INTRODUCTION

This chapter outlines all the experimental methods used in this research project. The South African thermal insulating material market was examined by evaluating various thermal insulating materials. The recycled streams were also considered for possible raw materials that could be used to develop low-cost thermal insulating materials. Several mechanical tests where conducted in order to carry out the objectives of this research work. The developed expanded polyethylene foam (EPEF) and recycled polymer slab (RPS) samples where subjected to flexural (three-point bend), creep, liquid water, water vapour permeability, flammability and compression tests. A temperature comparison test and thermal conductivity determination were conducted on both the EPEF and RPS samples. The SEM (scanning electron microscope) was used to reveal the micro and macro structures of the samples and some of the already exciting thermal insulating materials on the South African market. Optical microscopy was only used on RPS samples. This chapter is aimed at providing the reader with an understanding as how the results of this research work, outlined in chapter 4, were obtained.

3.2 REVIEW OF EXISTING INSULATING MATERIALS

The South African thermal insulation market was studied to look at the thermal insulating materials available to local household communities and the industrial sector. This was done by visiting the Building Centre in Cape Town and obtaining the products from insulating companies that had their products displayed.

3.3 RECYCLED MATERIALS SELECTION

3.3.1 INTRODUCTION

Different polymer based materials were evaluated for the purpose of the research project objectives. Recycled glass wool, recycled polymeric container bottles (*e.g.* PE and PP), recycled foamed polyethylene and recycled rubbers (tyres) were the materials considered. In considering the thermal insulating material, factors such as the method of production, assembly and the requirements for the end users were taken into account. Apart from the insulating properties, the most important consideration in developing the low-cost insulating materials is of course cost.

3.3.2 EXAMINED MATERIALS

Approximately 360 tons of scrap glass wool is produced each year during the manufacture of glass wool insulation. This scrap is available free of charge from the manufacturers[5]. The thermal properties, fire retardant, UV-resistance, and low-density of these materials are all very attractive. Glass wool was not chosen for this project since glass wool irritates the skin upon contact, it cannot be used in an exposed application, and it provides no waterproofing and above all the technology upon upgrading it to a low-cost thermal insulating material has been proven to involve expensive binding resins.

Roughly 600 000 tons of used tyres are produced in Belgium, Germany, France, Luxembourg and the Netherlands on a yearly basis. These tyres are either dumped in landfills, or burnt in power stations as a coal supplement[67]. The latter however, has caused a loud outcry from environmentalists, and increasing pressure from various environmental groups is likely to put a stop to this practice. A possibility also exists that an environmental tax may be placed on tyres in Europe. This tax would then be used to process tyres at the end of their lifetime[67]. Tyres could thus easily be imported from Europe using the environmental tax. These tyres could then be processed into a base material for insulation at the expense of the original buyer. Studies have shown that rubber is an effective domestic insulator, and it is both UV-resistant and waterproof[68]. The major drawback of rubber (tyres), however is that it requires binding agents in its base form, which is quite expensive. The high density of a rubber compound could pose a problem for the flimsy structure of a RDP houses[5].

There is a large quantity of recycled polymeric bottles in the South African recycled sector. These used bottles include mainly PE and PP and they can be easily collected from the recycled facilities all over South Africa. Sondor industries (Pty) Ltd. is a company that produces expanded polyethylene foam (EPEF), ethylene vinyl acetate (EVA), closed cell rubber and foamed plastic. The company's polyethylene off-cuts were mainly used in the developed insulating materials[69]. The recycled polypropylene and polyethylene bottles and tops were chosen from other recycled polymeric materials, as they can be inexpensively collected from the recycling structures. The EPEF samples were also selected for this research project. The insulation kit (polyester and gypsum board) was chosen as a standard insulating material.

3.4 PRODUCTION OF SOLID POLYMERIC SLABS

The selected recycled polypropylene and polyethylene bottles and tops were granulated to fine particles at Plastamid (Pty) Ltd. in Cape Town. The reactor that was built in the Centre for Materials Engineering (CME) was modified for this purpose. Figure 3.1 shows the final reactor that was to be used whilst figure 3.2 shows a picture of the mould. The granules were fused to form a compacted slab using this rig. The components in figure 3.1 are: (1) temperature controller (2) heating elements (3) mould (4) and (5) base and top metal blocks (6) and (7) cooling pipes on base and top blocks (8) pressure applying block (9) hydraulic press (10) pressure gauge (11) pressure applying lever. The detailed procedure of using the rig to produce the slabs is outlined in Appendix I.

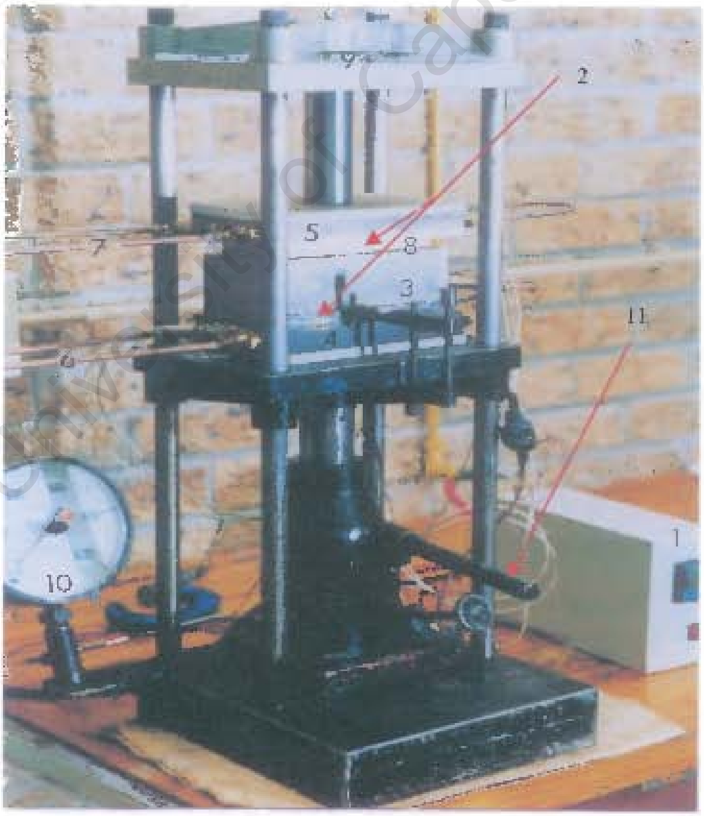

Figure 3.1: Photograph showing the rig used to produce the solid recycled polymer slabs.

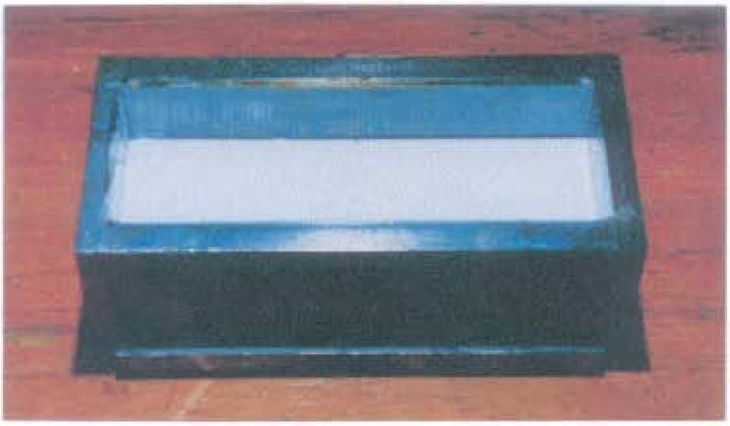

Figure 3.2: A photograph showing a closer view of the mould.

To see if the rig was working properly, the PP (virgin polypropylene) was fused in the mould of the rig following the procedure in Appendix I. The produced slab of PP is shown in figure 3.3. Slabs were then produced from granulated recycled PP and PE bottles and tops. The slabs where produced by using a mould temperature of 80 °C for a period of 30 minutes. The slabs were further laminated with two layers of fibreglass on both sites.

Figure 3.3: Photograph showing a sintered polypropylene slab.

3.5 THERMAL PROPERTIES

3.5.1 TEMPERATURE COMPARISON TESTING

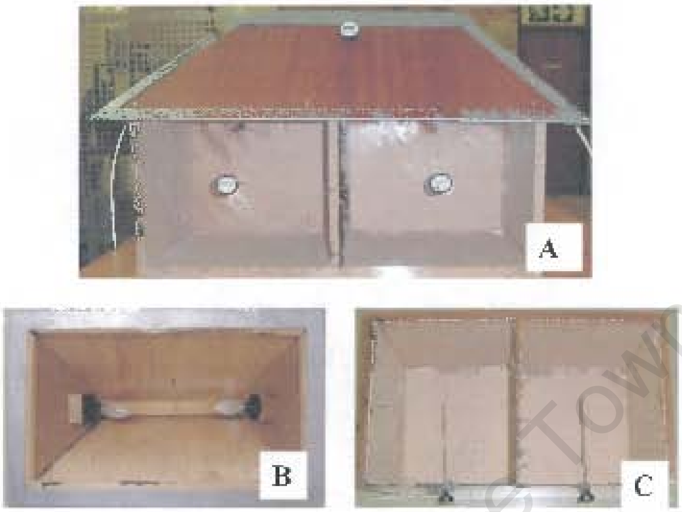

Figure 3.4: Photograph showing (A) the front view, (B) top view of the inside of the roof and (C) top view of the inside of the two rooms.

The hot box that was built in CME was used to compare the samples with a standard insulating kit. The standard insulating kit is a combination of Isotherm's thermal insulating material and gypsum board. The Isotherm thermal insulating material is made mainly of polyester. The hot box was constructed using wood and Perspex. Three thermometers and two 60 W light bulbs were used. Figure 3.4 show the two rooms of the hot box. The ambient temperature was not controlled during this experiment and it was varied between 20 and 25 °C.

In figure 3:4 **A** is the front view of the entire hot box, **B** is the roof with two light bulbs and **C** is the two separated rooms. The procedure for operating the hot box is outlined in Appendix II. The temperature comparison test was conducted for all the insulating material samples. This was done by firstly leaving the roof of one room un-insulated while the other room was insulated with the standard insulating kit. This was followed by placing the insulating material samples in the ceiling, and comparing the temperature curve with that of the standard insulating kit. The equivalent temperature for each room was noted for every 15 minutes. These comparison tests were conducted three times for each of insulating material samples and the average recorded.

3.5.2 MEASUREMENTS OF THERMAL CONDUCTIVITY

To measure the thermal conductivity of the insulating materials samples, a thermal conductivity testing rig was built in the CME. The instrument was constructed based on the comparative cut bar (ASTM E1225 Test Method) method. Figure 3.5 shows the thermal conductivity measuring rig. The thermal conductivity of expanded polystyrene was measured in order to determine if the rig was working properly which was then compared to its known thermal conductivity value from literature.

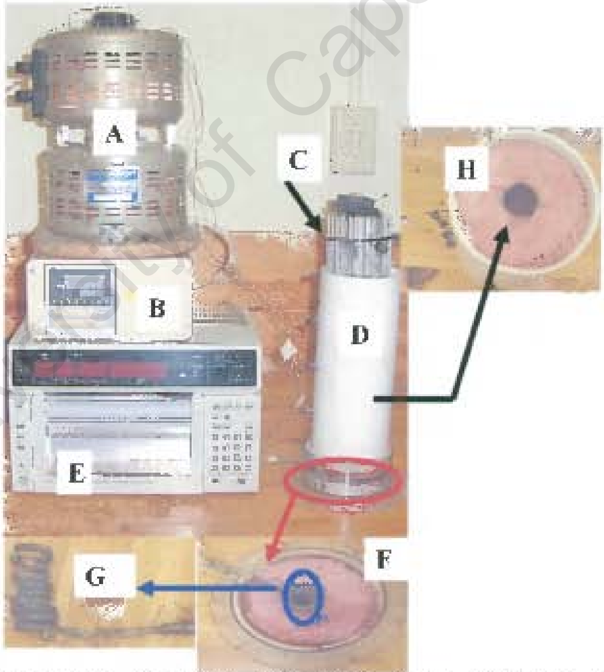

Figure 3.5: Photograph showing (A) step-down voltage converter, (B) programmable voltage and temperature controller (Rex-P90), (C) aluminium heat sink, (D) specimens holder, (E) portable hybrid recorder (Model 3087), (F) heating element holder, (G) heating element, and (H) top view of specimen holder.

The step-down voltage controller reduces the 240 volts input from the mains to 80 volts, which is suitable for the Rex-P90 to control the heating element within the required range. The Rex-P90 is programmed to supply the heating element with power to reach a temperature of 80 °C in five minutes. After five minutes has elapsed, the Rex-P90 allows the temperature of the heating element to be between 79 °C and 81 °C by switching the power supplied to the heating element on and off for a period of thirty minutes.

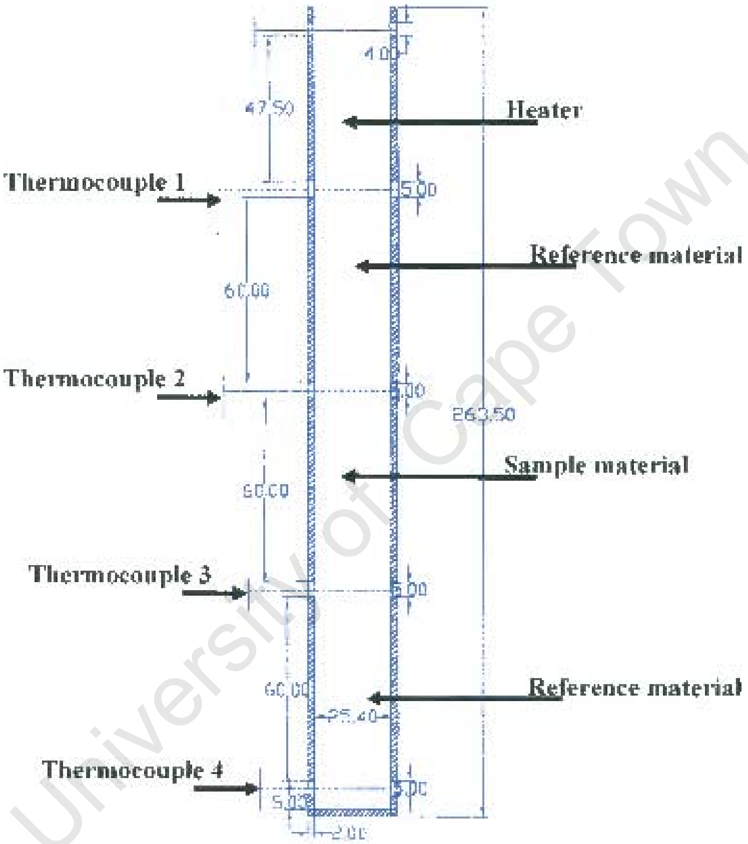

Figure 3.6: A schematic illustration of the copper tube specimen holder showing positions of the thermocouples, reference and sample materials and the heating element (heater).

After thirty minutes has elapsed, the Portable hybrid recorder reads and prints the temperature in four different points on the specimen holder. Figure 3.6 shows the positions were the thermocouples are placed on the copper tube specimen holder. All the dimensions in figure 3.6 are in mm. The Portable hybrid recorder uses K-type thermocouples to read the temperature. The Rex-P90 switches off the power to the heating element after the temperatures are recorded by the Portable hybrid recorder.

The heating element is placed at the bottom of the specimen holder, into the hollowed copper tube so that it can introduce heat to the specimens that are placed above it. The aluminium heat sink is placed at the top of the specimen holder to encourage the heat to move upwards through the specimens. The specimen holder has three different parts, the high thermal conductivity copper tube (specimen holder) at the inside, non-flammable Aerolite thermal insulation blanket in between and PVC (polyvinylchloride) on the outside. The Aerolite thermal insulating material has a thermal conductivity of 0.040 $W.m^{-1}K^{-1}$ and it was used as a reference material. The thermal blanket is used reduce the radial heat loss by insulating the copper tube. Three sets of temperature measurements where performed for each sample and an average calculated to give the thermal conductivity of the insulating material sample.

3.6 MATERIALS USED

The thermal insulating materials samples used together with those developed for the research purposes were:

- Sagex's EPS (expanded polystyrene).
- Isotherm's polyester thermal insulating material.
- Sondor's developed expanded polyethylene foam (SPX25, SPX33, SPX33FRA, SPX45 and SPX80). The two digits in front of the SPX- represent the density ($kg.m^{-3}$) of the sample and SPX is the trade name used at Sondor (Pty) Ltd.
- Polypropylene and polyethylene fused solid slabs (recycled polymer slabs).

3.7 SCANNING ELECTRON MICROSCOPY

The thermal insulating materials samples collected together with those developed were examined under the SEM. The materials include:

- Sagex's EPS (expanded polystyrene).
- Isotherm (polyester).
- EPEF samples (SPX25, SPX33, SPX33FRA, SPX45 and SPX80)

- Polypropylene and polyethylene fused solid slabs (recycled polymer slabs).

A LEO STEREOSCAN 440 SEM operating at an acceleration voltage of 10 kV was used to quantify the cells and their spatial distribution. This analysis was carried out on cryogenically fractured surfaces. In preparing samples for the technique, specimens were first mounted on aluminium stubs. Before analysis, the samples were sputter coated with a gold / palladium mixture for 10 minutes to render them conductive.

3.8 PHYSICAL PROPERTIES

3.8.1 WVP AND LWP TESTS

WVP (water vapour permeability) and LWP (liquid water permeability) tests on the insulating materials were performed in the Wood Science Department at Stellenbosch University. The water vapour permeability (WVP) of the materials was measured as mass increase per exposed square metre, after exposure of one side of the sample to a 100 % RH atmosphere for 7 days. The test areas were 200 cm^2. Liquid water permeability (LWP) was measured as mass increase per exposed square metre after exposure of one side of the sample to a liquid water for 24 hours. The test areas were 200 cm^2 and all tests were done at 25 ^oC.

3.8.2 FLAMMABILITY TESTS

The flammability tests for the EPEF and RPS samples were performed by CSIRO in Australia. The cone calorimeter, as depicted schematically in figure 3:7, was used to examine the fire retardant performance of all the samples. By observing the change in the fire parameters measured during this test, the fire retardant effectiveness of the materials was determined. Parameters that were considered in this test included the following:

- Effective heat of combustion in $MJ.kg^{-1}$.
- Ratio of CO to CO_2 (based on weight of the material burned).

- Heat release rate in kW.m^{-2}.
- Mass loss rate in %.s^{-1}.
- Rate of smoke formation in cm^{2}.s^{-1}.

The effective heat of combustion (EHC) is a measure of the efficiency with which the emitted gaseous products are combusted. A lower EHC indicates a less efficient combustion process in the gas phase, suggesting a better flame retardant. The heat release rate (HRR) is one of the most important parameters for characterising the material's fire behaviour. It is an indicator for the rate of fire growth and the intensity of the fire. A more effective fire retardant has a lower HRR. A high production smoke rate (RFS) may be used an indicator of uncompleted combustion of volatile products. The CO to CO_2 ratios may be considered an indicator of the degree of efficiency of the combustion processes. A high CO with respect to CO_2 confirms an inefficient combustion.

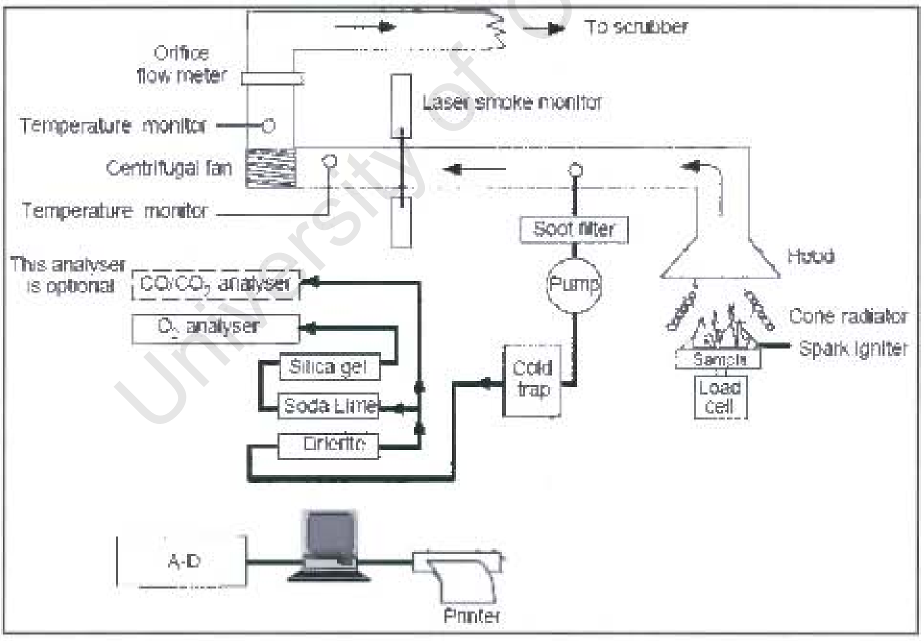

Figure 3:7. A Schematic representation of a Stanton Redcroft cone calorimeter used by CSIRO to perform the fire tests.

A Stanton Redcroft cone calorimeter was used in accordance with ISO 5660-1. Under the standard conditions, the sample dimensions were 100 mm X 100 mm with a thickness of 6 mm and were contained within an aluminium tray during the testing.

The aluminium tray was taller on the sides than the tray specified in ISO 5660-1 to ensure of the entire specimen and mass loss was only via volatilisation and combustion. The specimens were positioned horizontally on the load cell within the cone calorimeter and tested at a heat flux of 25 kW.m^{-1}. The other variation to the standard was the use of a radiation of 25 instead of 50 kW.m^{-1}.

3.9 ECONOMICS OF INSULATION

3.9.1 ECONOMIC INSULATION THICKNESS

The thickness of insulation can provide the highest insulation value. As a result of this a cost analysis was conducted on the experimental thermal insulating material samples. A cost analysis was done to determine the optimum thickness with the lowest energy lost for the thermal insulating materials under investigation. This cost analysis, which is based on thickness, R-value and thermal conductivity, helps to evaluate the insulating material for the lowest cost for a given thermal performance. As a result the optimum insulation thickness will be selected for given insulation type.

Equation 2.1 in chapter 2 was used to calculate the heat flow rate (HFR), which is the equivalent of the heat loss through an insulating material. Equation 2.2 was used to calculate the thermal resistance (R-value). The charge rates of Eskom were used in calculating the Rand loss per unit area (RL) (equation 2.7) for the insulating materials. The calculation was done on all the EPEF samples and the RPS insulating materials. The EPS thermal insulating material from Sagex was also evaluated. The last audited average price that Eskom charged was 16.08 cents(c) / kWh in 2003. The price in 2005 should be around 2.5 % higher, putting it around 16.5 cent (c).kW^{-1}h^{-1}, where kWh is kilowatt hour[70].

A recent study that was conducted indicated that the most acceptable indoor temperature was found to be around a temperature of approximately 301.5 K[48, 49]. The study showed that the most common maximum outdoor temperature is approximately 32 °C (305K) in regions around Gauteng province (South Africa)[51]. The difference between the indoor and outdoor temperature values (DT) of the house was about 3.5K (305K-301.5K).

3.10 MECHANICAL PROPERTIES

Several mechanical tests were conducted at room temperature to determine the mechanical properties of the insulating materials samples. The insulating materials samples were subjected to flexural, compression and creep testing. The flexural test and the compressive tests were conducted at the Centre for Materials Engineering, while the creep test was conducted at the Stellenbosch University Wood Science Department.

3.10.1 COMPRESSION TESTING

Figure 3.8: Photograph showing the grip set-up for the compression test on the ZWICK Universal tensile machine.

The Universal ZWICK tensile tester was used for the compression testing by using suitable compression testing grips. The grip set up is illustrated in figure 3.8. In figure 3:8 the arrow points to the position where the specimen is placed during testing.

The dimensions of the EPEF specimens used for these tests were 25 mm X 34 mm for the diameter and thickness, respectively. For the recycled polymer slab the thickness used was 14 mm and the diameter was 27 mm. The ASTM standard D-695 was used for conducting the compression tests. Ten specimens were tested for each type of material. The test speed was set to 0.05 mm/min. Ten samples were done for each material.

3.10.2 CREEP TESTING

Creep testing on the insulating materials was performed in the Wood Science Department at Stellenbosch University. Creep was measured as the downward deflection (in mm) of the centre of a 30 mm X 30 mm board due to a 200 g weight placed at that centre point for a period of 14 days and under RH of 100 %. The tests were conducted at 25 °C.

3.10.3 THREE POINT BEND TESTING

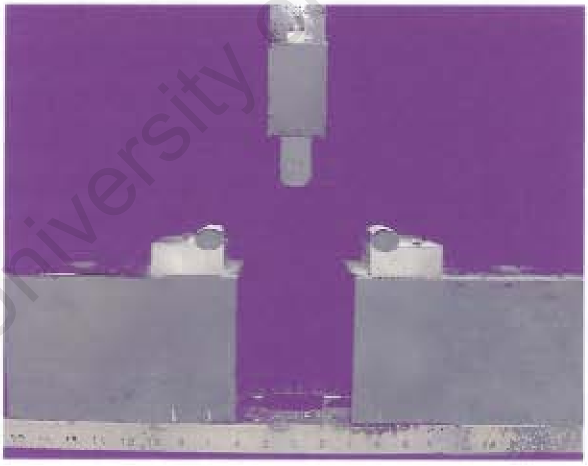

Figure 3.9: Photograph showing a the grip set up on the Universal ZWICK tensile tester machine for the three-point bend testing of samples.

The Universal ZWICK tensile tester was used for the three-point bend tests by using suitable three-point bend flexures as shown in figure 3.9. The ASTM standard D 5023 was used for conducting the three-point bend tests. This test was used to determine the mechanical properties of the materials subjected to flexural forces. The dimensions of the EPEF specimens used for these tests were 800 mm X 100 mm X 18 mm for the length, width and thickness, respectively. The recycled polymers slab thickness was 14 mm and that of the gypsum board was 9 mm. The test speed was set at 5 mm/min. Ten specimens were done for each material.

3.11 INSULATING MATERIAL PROPERTIES

There are few companies in South Africa that are involved in manufacturing and distributing of thermal insulation materials. These companies include Aerolite (ceiling insulation), Sagex (Pty) Ltd., Insulation Solutions (Pty) Ltd., Nampack L & CP (super Sisalation®), and Isotherm (Pty) Ltd. (thermal roof insulation).

3.11.1 AEROLITE

Table 3.1: The thermal and physical properties of Aerolite thermal insulating material[71].

Density (kg.m^{-3})	Thickness (mm)	Thermal Resistance (m^{2}K.W^{-1})	Thermal Conductivity (W.m^{-1}K^{-1})	Noise Reduction Coefficient NRC value
10	50	1.25	0.040	0,70
10	75	1.88	0.040	0,80
10	100	2,50	0.040	0,85

Aerolite thermal insulating material is made from pure spun glass that is bonded with an inert thermosetting resin. It reduces heat flow by up to 87 % and it can lower the temperature in summer by up to 5 °C. It is a non-combustible material that conforms to SABS 0177 part V and SABS 0177 part III (class I). Aerolite can easily and inexpensively be installed in both existing or new homes and buildings as ceiling insulation. Table 3.1 tabulate the properties of Aerolite thermal insulating material[71].

3.11.2 SAGEX

Table 3.2: The thermal, mechanical and physical properties for Sagex EPS 16D and 24D thermal insulating material[72].

Properties	Grade	
	16D	24D
Density (kg.m^{-3})	15-17	22-26
Thermal conductivity at 10°C (W.m^{-1}K^{-1})	0.036	0.033
Compressive strength (kPa)	85	170
Tensile strength (kPa)	200	310
Water absorption (%Vol)	0.5 to 1.5	0.5 to 1.5
Temperature limits in °C	-150 to 80	-150 to 80

Sagex (Pty) Ltd. has four different thermal insulating products. All four products have expanded polystyrene (EPS) as the core material. These four different thermal insulating materials are EPS, Megaspan, Kulite and Koolspan[73]. The Sagex's EPS is a polymerised styrene and is produced from benzene and ethylene. The polymerisation is accomplished in the presence of catalysts using organic peroxides. The thermal and physical properties of Sagex EPS are tabulated in table 3.2.

Megaspan is an insulated roof panel. The standard Megaspan panel comprises of a wide span metal roof sheet bonded to a core of 16 kg.m^{-3} Sagex EPS, finished with a chromadek steel ceiling board. The overall thickness of Megaspan is 79 mm with 50 mm of EPS and has a mass of 10.5 kg per square meter. This whole Megaspann component has an average R-value of 1.712 m^2.K.W^{-1}. Kulite is a rigid laminated insulation board consisting of a core of Sagex flame retardant EPS, faced on both sides with a variety of combinations of reflective aluminium foil, lacquered foil, and vinyl and bituminised kraft paper. Kulite is resistant to both moisture and most acids and alkalis found in normal environments[72]. Koolspan insulated ceiling panels are a derivative of the Megaspan range of composite insulated roof panels. It consists of an EPS sheet laminated to a ceiling board. The overall thickness of Koolspan is 34 mm with 30 mm of EPS and is has a mass of 6.4 kg per square meter. This whole Koolspan component has an average R-value of 0.855 $m^2.K\ W^{-1}$.

3.11.3 ISOTHERM

Isotherm thermal roof insulation is made from 100 % polyester. It is safe and easy to install in roofs. Table 3.3 list the Isotherm performance data[73].

Table 3.3: Isotherm insulating material performance data[73].

Thickness (mm)	Density ($kg.m^{-3}$)	Reduction in Heat Flow (Downwards)	Thermal Resistance ($m^2K.W^{-1}$) (as tested by the SABS)	Noise Reduction Coefficient NRC Value (as tested by the SABS)
40	10	69%	0.88	10
50	10	72%	1.10	10
75	10	78%	1.65	8
100	10	83%	2.20	6

3.11.4 INSULATION SOLUTIONS CC

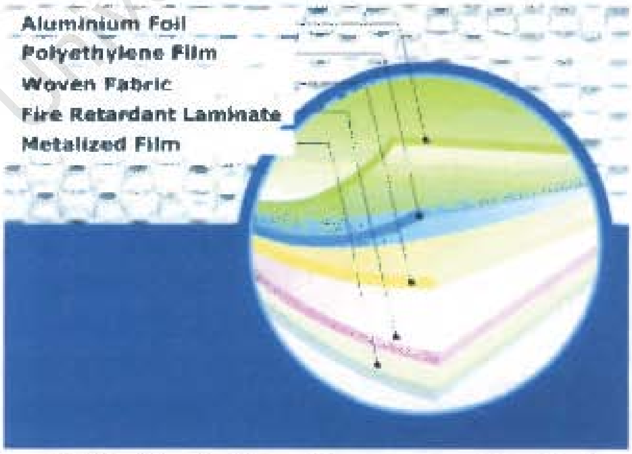

Figure 3.10: Illustration of a cross-sectional view of the Polyminium 202 insulating material[74].

Polyminium 202 is a reflective foil insulation product that is supplied by Insulation Solutions (Pty) Ltd.[74]. Polyminium 202 is a light, super strong roof, waterproofing and dust proofing buildings. It is a double sided reflective foil with super strong woven polyethylene reinforcing as illustrated in figure 3.10. In the longitudinal direction Polyminuim has a tensile strength of 12.2 kN.m^{-1} and in the transverse direction it has a tensile strength of 8.9 kN.m^{-1}. Its thermal resistance (R-value) is 1.4 m^2.K.W^{-1}.

3.11.5 NAMPAK L & CP (SUPER SISALATION®)

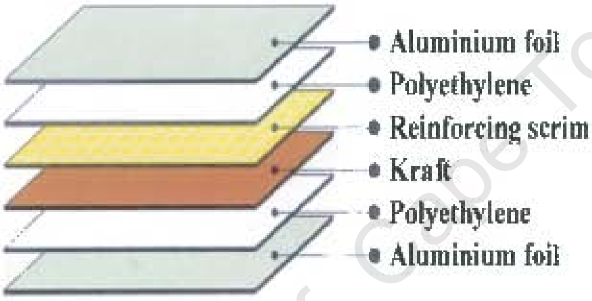

Figure 3.11: Illustration of the Nampak L & CP (Super Sisalation®) 400 industrial grade [75].

Nampak L & CP (Super Sisalation®) manufacture and distribute four different thermal insulating materials. Their products are all based on the principle of reflective insulation. Super Sisalation® is a reinforced aluminium foil insulation material, made from a lamination of aluminium foil, Kraft paper, reinforced synthetic fibre and polyethylene. It is used in factories, warehouses, schools, hospitals and commercial and residential dwellings. Super Sisalation® reduces heat gains in summer and retains heat losses in winter. The material also acts as a waterproofing membrane when used under roof tiles. Super Sisalation® has a high light reflectivity. When installed in industrial building as an exposed internal roof lining, the reflectivity of the ceiling is increased by up to 40 %[75].

CHAPTER 4

EXPERIMENTAL RESULTS

4.1 INTRODUCTION

This chapter presents the results of all the experiments outlined in chapter three. The results obtained from temperature comparison tests are included. Mechanical and physical testing results are presented. Macro- and micro-structural investigations results are also presented. The results from constructing the thermal conductivity measuring device are also outlined in this chapter. The thermal properties of existing thermal insulating materials are then compared with the thermal insulating materials developed during the research. This comparison will indicate which developed thermal insulating material could feasibly be selected for low cost housing applications.

4.2 MICRO- AND MACRO-STRUCTURAL ANALYSIS

4.2.1 POLYESTER (FROM ISOTHERM)

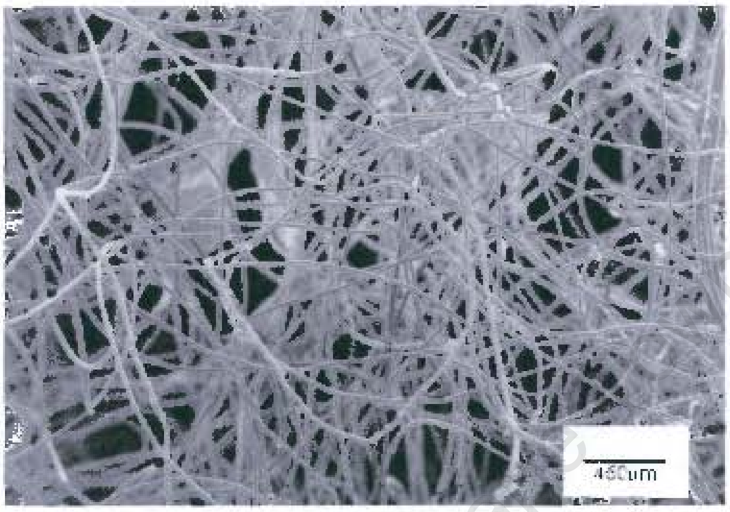

Figure 4.1: SEM image showing the structure of the fused fibres of the polyester insulating material obtainable from Isotherm. Note the porous nature of this material.

The SEM micrographs in figure 4.1 show the polyester fibres and the numerous air spaces between the polyester fibres. The micrographs show clearly white 100 % polyester fibres that were thermally bonded from long organic chains of synthetic polymer fibre. It is apparent from figure 4.1 that the air gaps play a significant role in the low thermal conductivity of this material.

4.2.2 EXPANDED POLYSTYRENE (FROM SAGEX)

Figure 4.2 show the closed cell expanded polystyrene microstructure at two different magnifications. The microstructures in figure 4.2 also shows the bonding between the polystyrene beads. This foamed microstructure in figure 4.2 reveals clearly how air can be trapped within the closed cell structure of expanded styrene. Collisions within the gas molecules are reduced significantly by this form of microstructure.

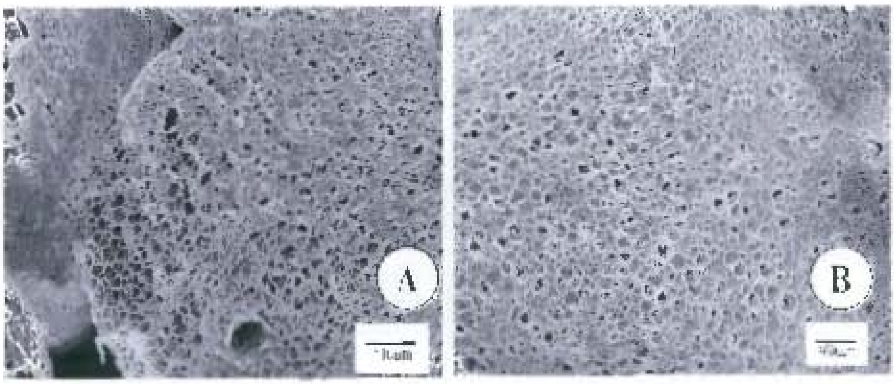

Figure 4.2: SEM images showing (A) Sagex's expanded polystyrene closed cell microstructures structure and (B) the microstructure at different magnification.

4.2.3 RECYCLED POLYMER SLABS (RPS)

Figure 4.3: The photograph showing the produced recycled polymers slab without the woven glass fibres reinforcement.

The rig described in section 3.4 of chapter three was used to produce the polymer slabs obtained by fusing together granulated polymer particles. Figure 4.3 shows a picture of such a recycled polymer slab (RPS). Figure 4.4 shows a higher magnification optical micrograph of the produced RPS, without the glass fibre reinforcement. It is apparent from figure 4.4 that the granules of recycled PP and PE have been bonded together, but bonding is not fully attained. Therefore the granules can be easily removed from the solid slab by abrading it against another surface. Woven glass fibres were laminated on the solid slab to prevent this disintegration of the granulates from the slab and to improve the mechanical strength to the RPS. Figure 4.5 shows this laminated solid slab and a higher magnification micrograph is presented in figure 4.6.

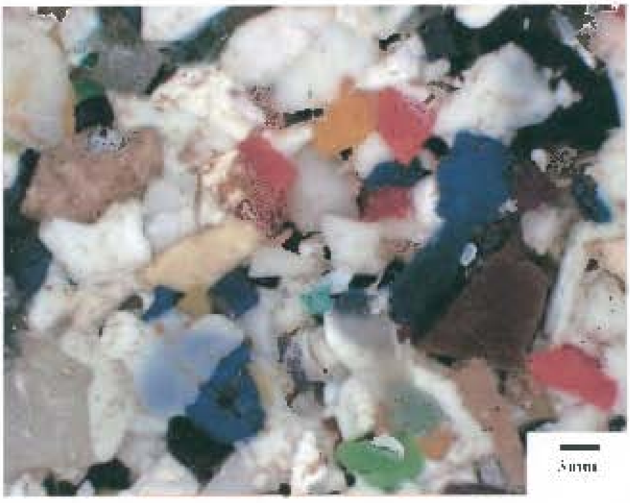

Figure 4.4: An optical micrograph showing the recycled slab morphology without the woven glass fibres reinforcement.

Figure 4.5: Top view of the produced recycled polymers slab laminated with two layers of glass fibres on the top and bottom faces.

Figure 4.6: An optical micrograph showing the morphology of the recycled polymers slab with the reinforcement of the woven glass fibres.

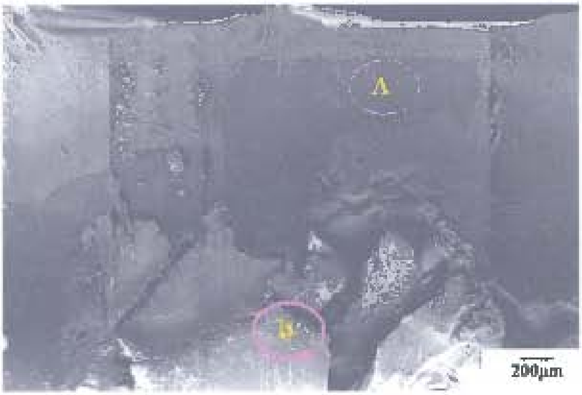

Figure 4.7: SEM micrograph of the recycled polymer slab showing the glass fibre + resin area (A) and an area of granulates (B).

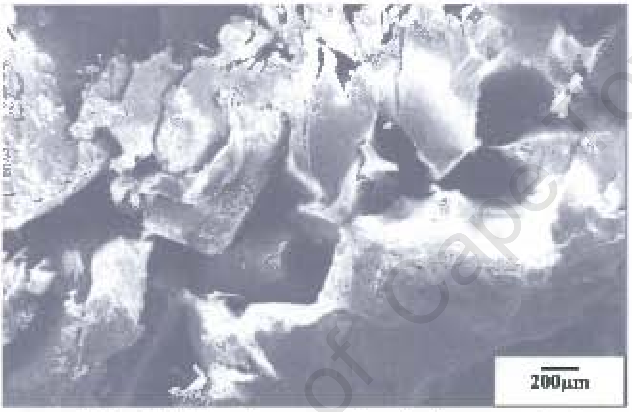

Figure 4.8: SEM micrograph of the recycled polymer slab showing the bonding between granulates.

The SEM micrographs in figures 4.7 and 4.8 illustrate the morphology of the recycled polymer solid slabs at a microscopic level. The letter **(A)** in figure 4.7 indicates the area around the surface of the slab where the glass fibre, thermosetting resin, and granulates bonds together, while **(B)** indicates the area of the polymers (PP and PE) granulates bond as a result of heat applied during the fusion process. This is more clearly illustrated in the optical micrograph in figure 4.9. It is apparent from the two micrographs that the polymer granulates did not melt during the process of fusion, but only softened and bonded as they were cooled. It is also noticeable in figure 4.9 that the type of bond formed between the granulated polymers had resulted in a formation of structure that has air spaces between the polymer particulates. Hence air is separated in these polymer slabs structures and there is a significant reduction in gas molecule collision.

Figure 4.9: Optical micrograph of the recycled polymer slab picture showing the glass fibre and resin area (A) and (B) the area of granulates.

4.2.4 EXPANDED POLYETHYLENE FOAM (EPEF) SAMPLES

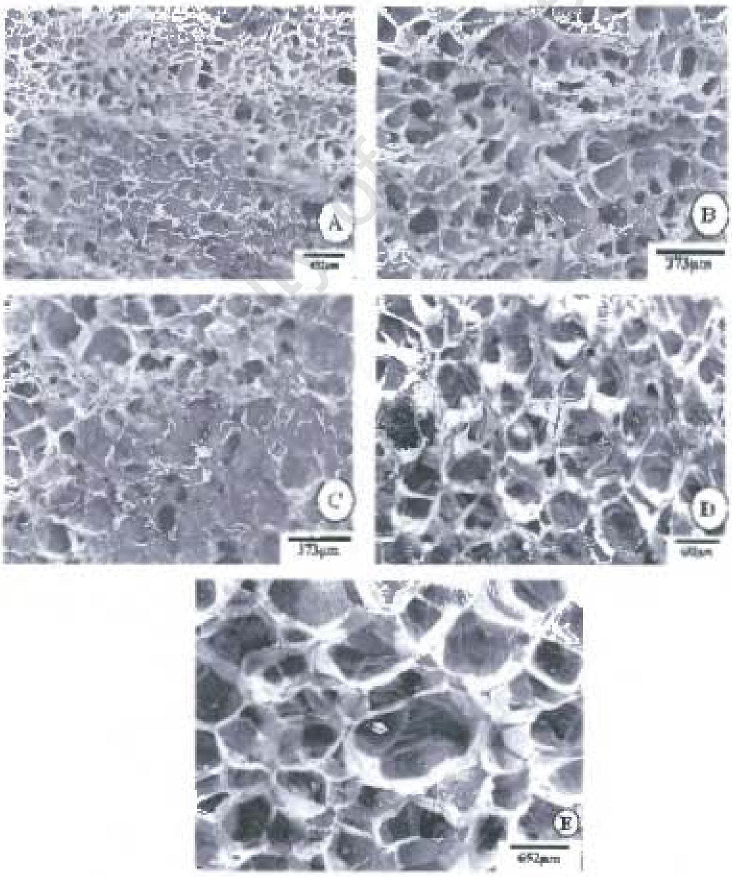

Figure 4.10: SEM images showing the closed-cell foamed microstructure of (A) SPX25, (B) SPX33, (C) SPX33FRA, (D) SPX45 and (E) SPX80.

SPX, in general, is a closed cell, crossed-linked expanded polyethylene foam (EPEF). The SEM images in figure 4.10 illustrate the morphology of the EPEF with respect to their different densities. The numbers at the end of the letters "SPX" signify the density (kg.m^{-3}) of the material. A closed cell foamed structure can be observed in all of these micrographs in figure 4.10. These closed cell microstructure indicates that air is easily trapped in this cell preventing maximum collisions between gas molecules.

4.3 THERMAL INSULATION PROPERTIES

4.3.1 RELATIVE TEMPERATURE COMPARISON TESTING

The temperature comparison test was chosen to compare temperatures obtained form the two chambers in the hot box. The standard insulating kit polyester (obtained from Isotherm) and gypsum board is placed in the roof of the one chamber while the various insulating materials samples under investigation are placed in the other chamber. The temperature comparison tests were conducted on all samples *viz.*, the recycled polymers slabs (RPS), and all of the Sondor crossed linked EPEF (expanded polyethylene foam) samples.

4.3.1.1 Recycled Polymer Slab Results

The graphs in figure 4.11 show a gradual increase in temperature as a function of time. Temperature (in degrees Celsius) is plotted against time (in minutes). It is apparent from figure 4.11 that there is a significant difference in temperature between the curve of the roof, un-insulated room whilst the curves for RPS sample and standard insulation kit are similar. The difference increases slightly as temperature increases with time. It is clear from figure 4.11 that the temperature rises rapidly in the roof, followed steadily by that in the un-insulated room. The temperatures of the room insulated with the standard insulation kit and that insulated with the RPS sample were below 30 °C for the duration of the test (figure 4.11).

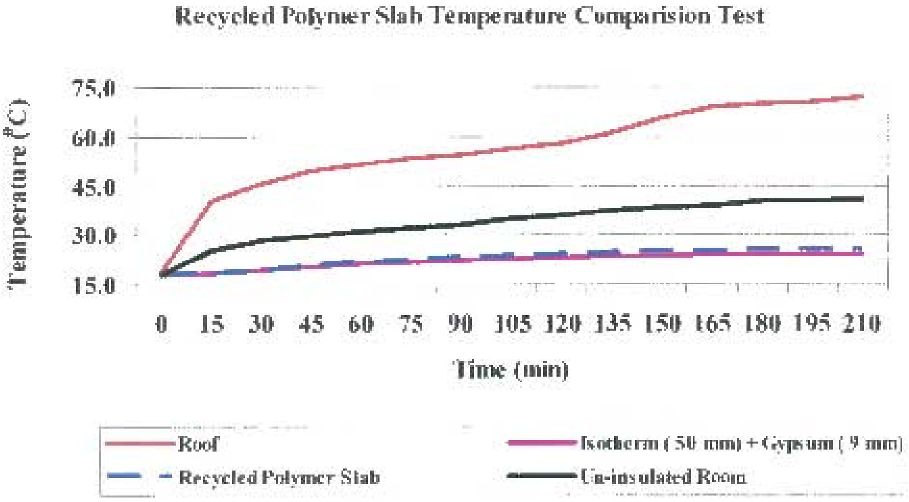

Figure 4.11: The graphs of the temperature *vs.* time of the thermal insulating material samples (RPS) compared with temperature profile of the standard insulation kit (Isotherm + Gypsum board).

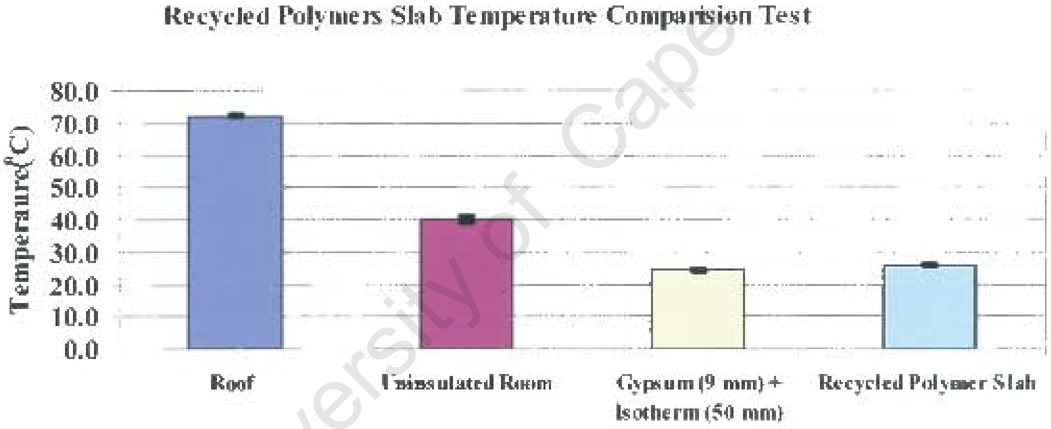

Figure 4.12: Bar chart representation of the 'equilibrium' temperatures for the thermal insulating material sample (RPS) compared to the standard insulation kit.

There is a small difference in the 'equilibrium' temperatures between the RPS and standard insulation kit (SIK). This is apparent in the bar chart graphs of figure 4.12. The roof temperature reached the highest of approximately 71.4 °C on average followed by approximately 40 °C for the un-insulated room. The RPS room temperature is around 26 °C and the standard insulation kit is at around 25 °C. The bar chart graphs for the RPS samples also shows that the error bars for the insulated and un-insulated room do not overlap indicating that there is a significant difference in temperatures between the two. It is also apparent from the bar chart graphs in figure 4.12 that the RPS and SIK had significantly reduced the temperature of the rooms they were insulating. All this temperatures are the maximum values of the test at steady state.

4.3.1.2 Sondor EPEF Samples

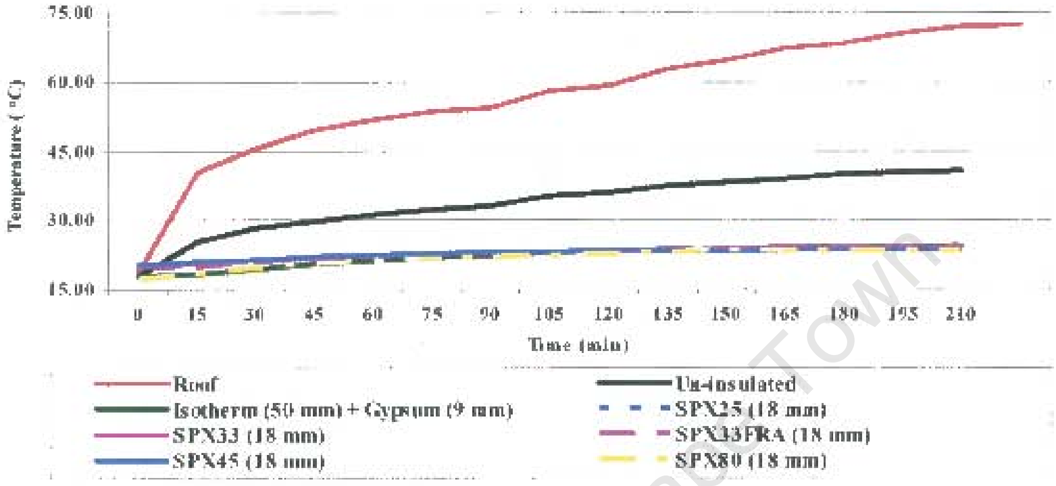

Figure 4.13: Temperature profiles of the thermal insulating material sample (EPEF [18mm]) compared with the standard insulation kit temperature profile.

The graphs in figure 4.13 and figure 4.14 show the rise in temperature as a function of time for the EPEF samples with thicknesses of 18 mm and 34 mm, respectively. Temperature (in degrees Celsius) is plotted against time (in minutes). It is noticeable from figure 4.13 and figure 4.14 that there is a significant difference in temperature between the curve of the roof, the un-insulated room, and the curves for the EPEF sample and the standard insulation kit materials. It is also clear from figure 4.13 that the temperature in the roof and un-insulated rooms rises rapidly and then levels off. The temperatures of the room insulated with the standard insulation kit and all of the EPEF samples, managed to stay well below 30 °C for the duration of the test.

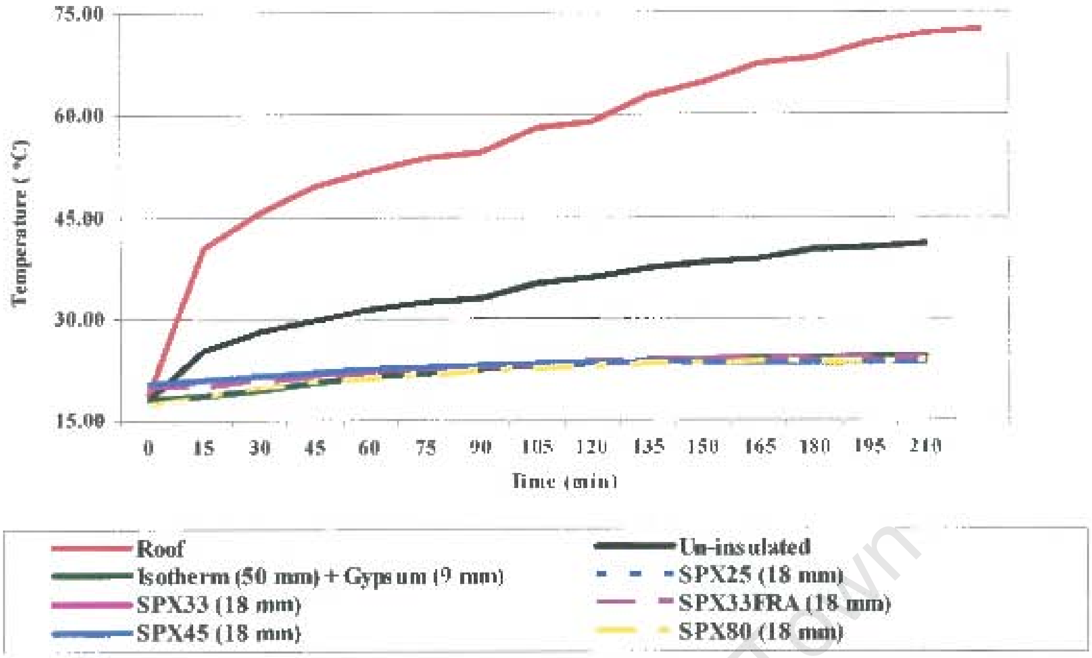

Figure 4.14: Temperature profiles of the thermal insulating material sample (EPEF [34mm]) compared with the standard insulation kit temperature profile.

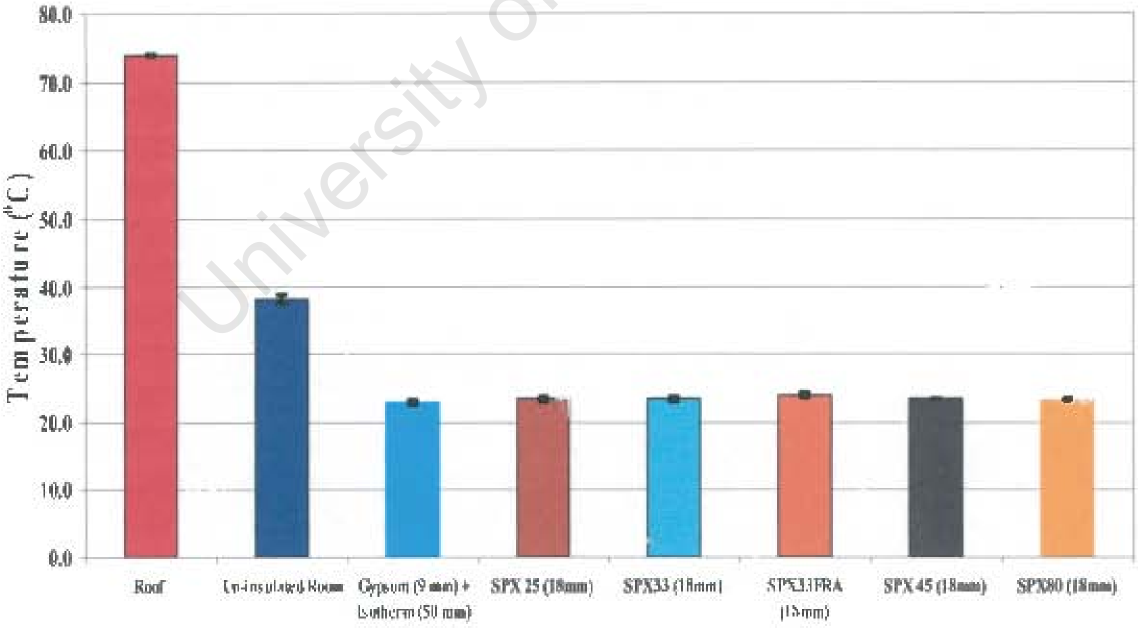

Figure 4.15: Bar chart representation of the equilibrium temperature for the thermal insulating materials samples (EPEF [18 mm]) compared with the standard insulation kit room temperature.

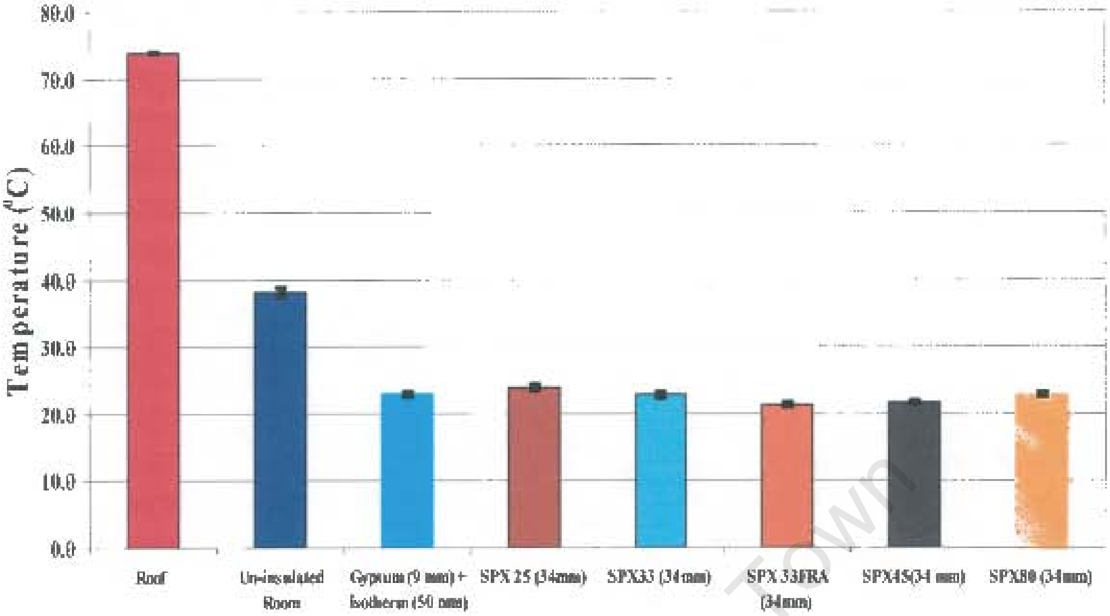

Figure 4.16: Bar chart representation of the equilibrium temperature for the thermal insulating materials samples (EPEF [34 mm]) compared with the standard insulation kit room temperature.

There is a small difference in room temperatures for the EPEF samples and standard insulation kit (SIK) combination. This is apparent in bar chart graphs of figure 4.15 and figure 4.16. The roof temperature reached approximately 71.4°C on average whilst the un-insulated room reached approximately 40 °C. Table 4.1 tabulates the temperature recorded for the Sondor EPEF insulating materials samples with respect to their thicknesses. It is apparent from table 4.1 that for the SPX33FRA (34mm) insulation the lowest temperatures were recorded compared to the other EPEF samples which were are all below 25 °C. From the bar charts, the error bars for all the EPEF samples do not overlap. There is a significant difference between the temperature for the roof and the un-insulated roof as indicated again by the error bars that do not overlap. It is again apparent from the bar chart graphs in figure 4. 15 and figure 4.16 that the EPEF insulating materials and SIK had significantly reduced the temperature of the rooms they were insulating. The thickness of the EPEF samples showed no significant difference with respect to the maximum temperatures recorded. All these temperatures are at the maximum point of the test duration when the steady state was observed (table 4.1).

Table 4.1: The maximum room temperature of the hot-box insulated with different Sondor EPEF insulating material samples.

EPEF Samples	Thickness	
	18 mm	34 mm
SPX25	23°C	24°C
SPX33	23°C	22°C
SPX33FRA	23°C	21°C
SPX45	23°C	22°C
SPX80	23°C	22°C

4.3.2 THERMAL CONDUCTIVITY

The thermal conductivity measurement was chosen in order to better understand the insulating ability of the materials. The thermal conductivity was conducted on all the Sondor EPEF insulating material samples and the RPS samples. The thermal conductivity for Sagex's EPS was also measured. The results of all the insulating materials under investigation together with the EPS from Sagex are tabulated in table 4.2. It is evident from table 4.2 that the EPEF samples have considerably low k-values compared to the EPS and RPS material. The standard error was considered to be significantly small for all samples tested. The difference in the thermal conductivity values of all the EPEF and the RPS samples is not highly significant as compared to that of the expanded polystyrene.

Table 4.2: Values of the thermal conductivity for the EPS, EPEF and RPS thermal insulating material samples.

Materials	k (W.m^{-1}K^{-1}) Given	k (W.m^{-1}K^{-1}) Calculated	Standard Deviation
EPS (SAGEX))	0.040	0.047 (±0.0003)	0.001
SPX25 (Sondor)	0.037	0.045(±0.001)	0.002
SPX33 (Sondor)	0.037	0.043(±0.001)	0.002
SPX33FRA (Sondor)	0.037	0.039(±0.001)	0.001
SPX45 (Sondor)	0.042	0.043(±0.001)	0.001
SPX80 (Sondor)	none	0.040(±0.0003)	0.001
Recycled Polymer Slab	none	0.054(±0.0003)	0.001

4.3.3 FLAMMABILITY TESTING

4.3.3.1 Mass Loss Rate (MLR) and Mass Loss (ML)

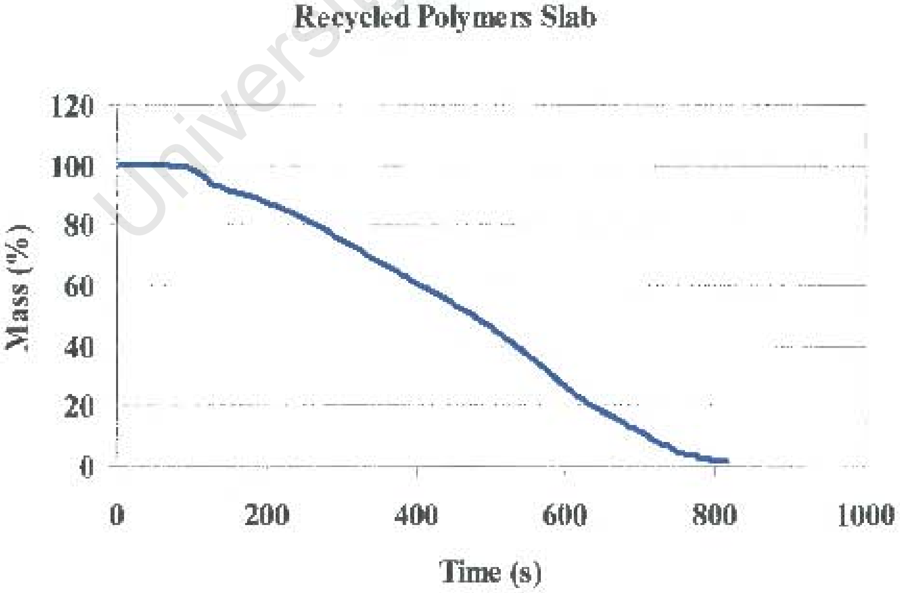

Figure 4.17: A graph of the average mass loss versus time for the RPS samples after the ignition had been initiated.

After ignition, there is a relatively rapid mass loss for the recycled polymers slab followed by a constant rate of mass loss until full decomposition. This constant rate of mass loss is observable in figure 4.17 and the maximum time for full decomposition for the RPS sample is approximately 13 minutes. Two samples were tested for the recycled polymers slabs and their average mass loss is plotted in figure 4.17.

For all of the EPEF samples after ignition, there is relatively slow mass loss followed by a relative constant rate of mass loss until full decomposition (figure 4.18). It is apparent from figure 4.18 that it took less than 150 seconds for SPX25 and SPX33 to undergo full decomposition. It took about 200 seconds for the SPX33FRA and SPX45 to experience full decomposition (figure 4.18). Figure 4.18 shows that it took slightly above 200 s for SPX80 to undergo decomposition and full decomposition did not appear to occur (figure 4.18).

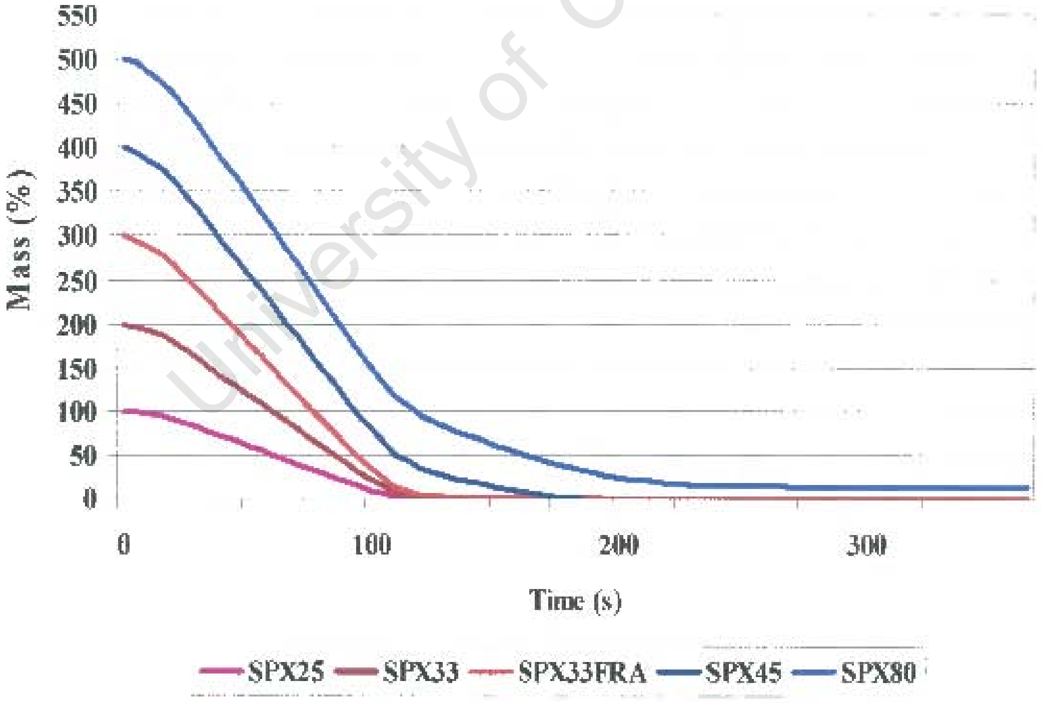

Figure 4.18: The graphs of the average mass loss versus time for the EPEF samples after the ignition had been initiated.

Table 4.3: The mass loss rate range and the time it took for the EPEF samples to decompose.

Material	Mass Loss Rate (MLR) % sec^{-1}	Time Elapsed sec
SPX25	1.00-1.13	160
SPX33	0.89-0.87	150
SPX33FRA	0.87-1.00	146
SPX45	0.70-0.73	219
SPX80	0.47-0.50	347

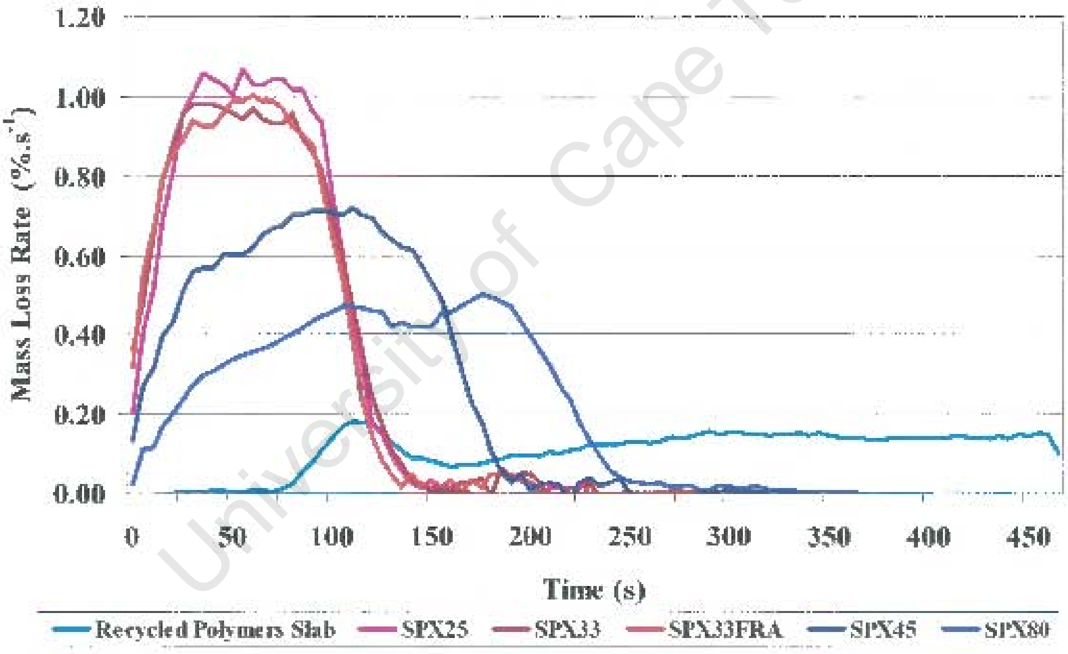

Figure 4.19: The graphs of the average mass loss rate versus time for the EPEF samples and RPS samples after the ignition had been initiated.

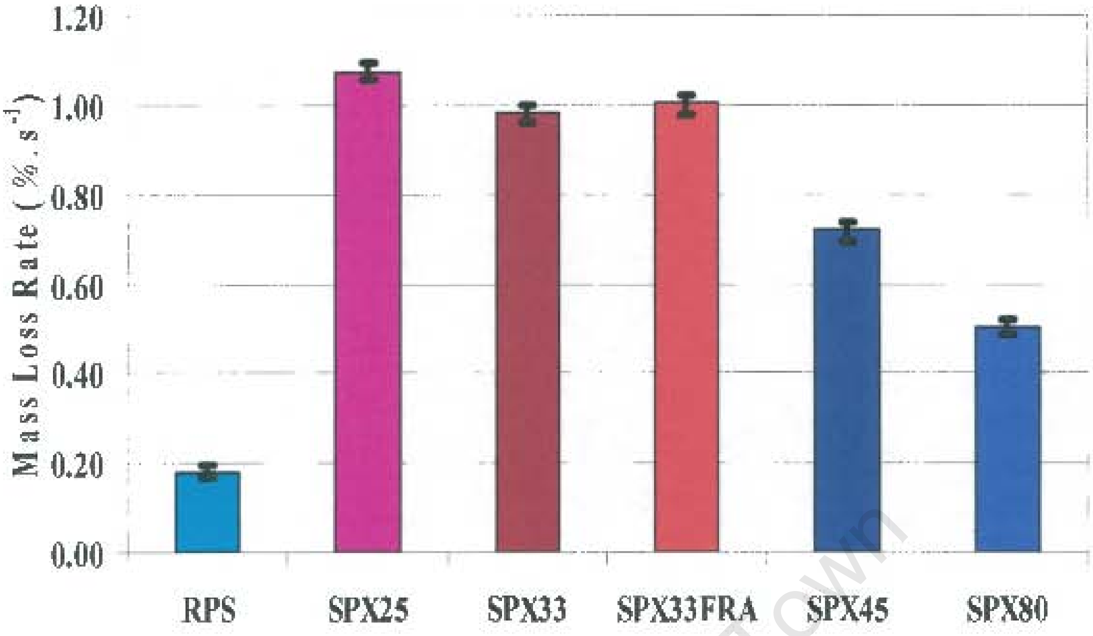

Figure 4.20: Bar charts of the average mass loss rate versus time for the EPEF samples and RPS samples after the ignition had been initiated.

It is evident from the curves in figure 4.19 that the average peak mass loss rate ranges roughly between 0.18 %.sec^{-1} and 0.15 %.sec^{-1} for the two RPS samples tested and it lasted approximately for a period of 440 seconds. From table 4:3 and figure 4.19, it is seen that SPX80 has the lowest average peak mass loss rate (0.50 % sec^{-1}) compared to other EPEF samples. Its MLR is higher than the maximum peak MLR value recorded for RPS (0.18 %.s^{-1}). This is more clearly evident in the bar chart representation of all the samples (figure 4.20). SPX25 has the highest peak MLR value of 1.02 %.s^{-1} (figure 4.19 and figure 4.20, table 4.3). The SPX33FRA sample peaks at around 1.0 %.s^{-1}, whilst SPX33 has recorded a MLR value of 0.89 %.s^{-1} and SPX45 an MLR of about 0.73 %.s^{-1}.

4.3.3.2 Heat Release Rate (HRR)

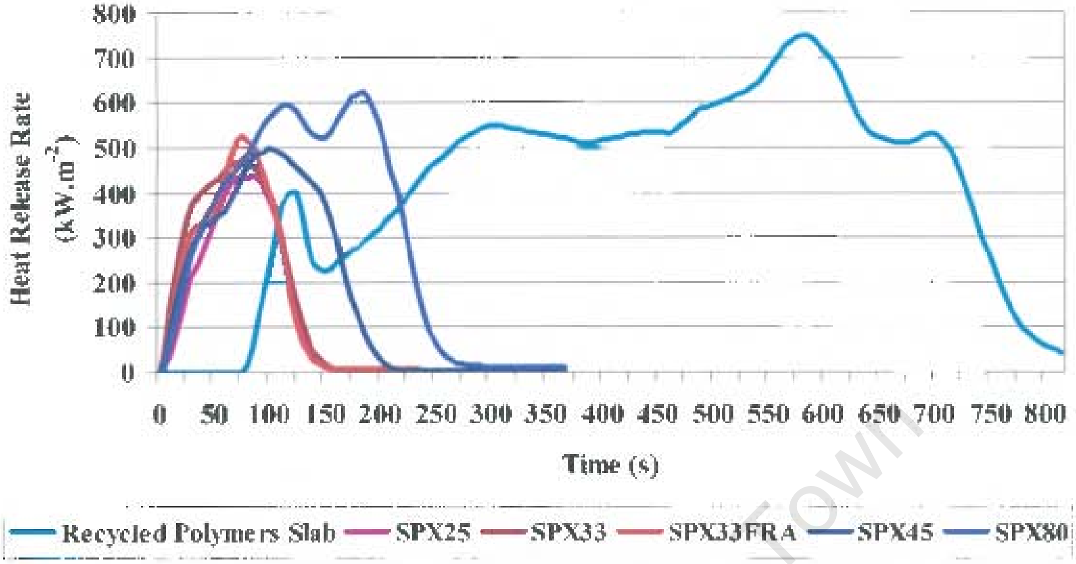

Figure 4.21: Graphs of the average heat release rate (HRR) as a function of time for the EPEF and the RPS samples.

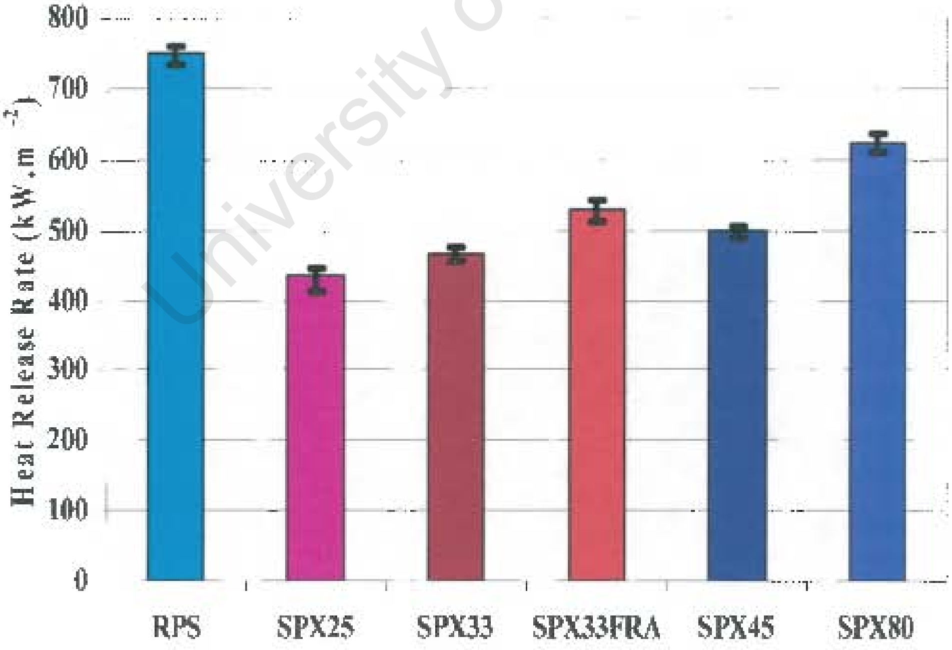

Figure 4.22: Bar chart graphs of the average heat release rate versus time for the EPEF samples and the RPS sample after the ignition had been initiated.

The curve of recycled polymers slabs in figure 4.21 shows a number of stages. There is an initial rapid increase in HRR to a peak of around 400 kW.m^{-2}, which is followed by a trough and then a steady incline up to about 500 kW.m^{-2}. This is followed by a slight trough until another peak of 750 kW.m^{-2}-800 kW.m^{-2}, followed by another trough and a peak of around 500 kW.m^{-2}. It is apparent from figure 4.21 that there are no multiple HRR peaks occurring for SPX25, SPX33, SPX33FRA, and SPX45 except for the curve of SPX80 that shows an initial rapid increase of HRR to a peak of 600 kW.m^{-2}, followed by a trough and then a steady incline to a peak that is just above 600 kW.m^{-2}, which is the highest as compared to other EPEF samples, but lower than that of RPS (750 kW.m^{-2}). The lowest maximum HRR value of approximately 420 kW.m^{-2} was recorded for SPX25 (figure 4.21), with SPX33 at approximately 460 kW.m^{-2}. SPX33FRA and SPX45 had HRR values of around 500 kW.m^{-2}. The HRR values recorded for the different samples tested is more clearly illustrated in the figure 4.22, which is a bar chart representation in terms of the maximum HRR values observed.

4.3.3.3 Effective Heat of Combustion (EHC)

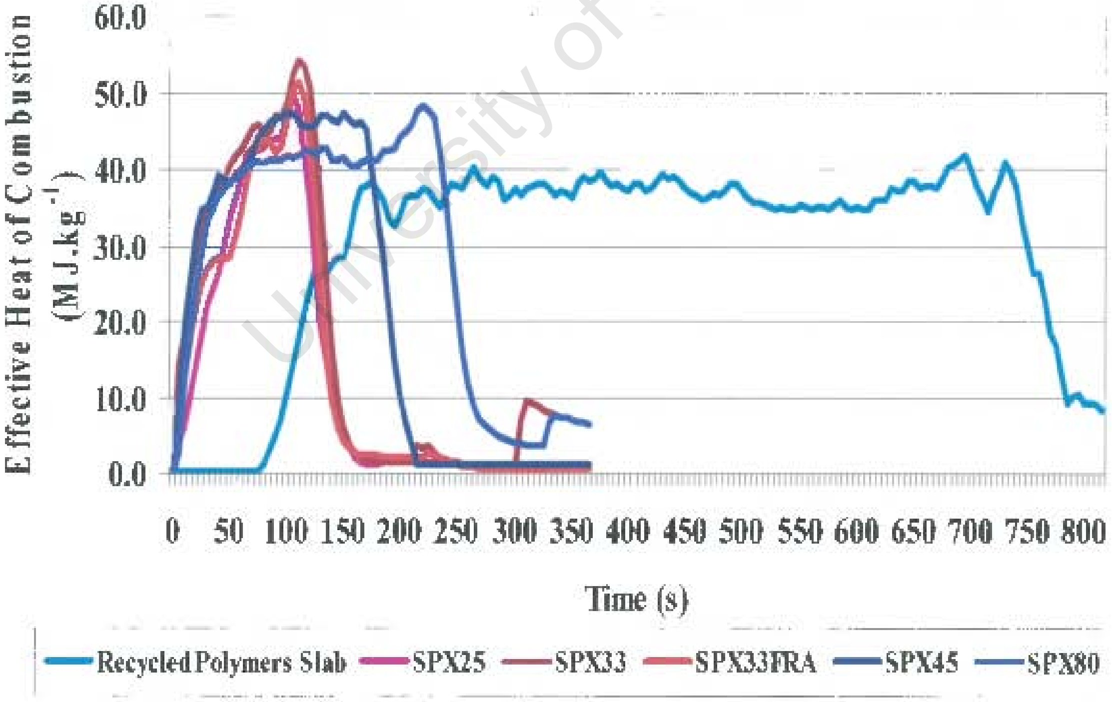

Figure 4.23: The graphs of the average effective heat of combustion versus time for the EPEF samples and RPS sample after the ignition had been initiated.

It clear from figure 4.23 that the EHC for the RPS is fairly constant at between 30 and 40 MJ.kg^{-1}, during the main burning period. It is also apparent from figure 4.23 that the EHC values for SPX25, SPX33, SPX33FRA, SPX45, and SPX80 are moderately constant between 40 and 55 MJ.kg^{-1}, during the main flaming period and the EHC values for all the EPEF samples are slightly higher than that of the RPS sample. These maximum EHC values recorded during the flaming period are presented clearly in the bar chart graphs in figure 4.24 for the samples tested. The burning period for the RPS sample is long compared to the EPEF samples (figure 4.23).

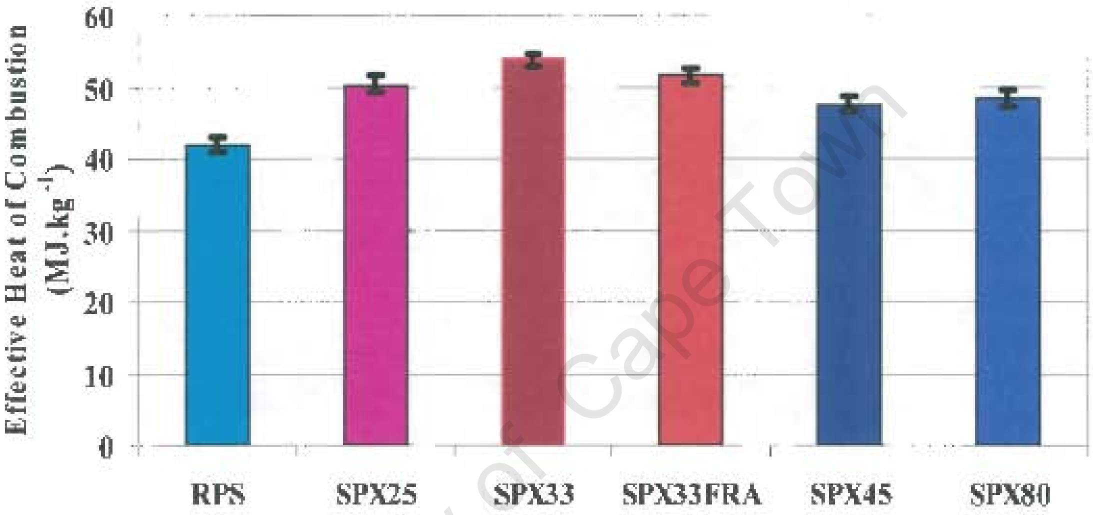

Figure 4.24: Bar charts of the average effective heat of combustion versus time for the EPEF samples and RPS sample after ignition had been initiated.

4.3.3.4 Rate of Smoke Formation (RSF)

It is apparent from figure 4.25 that the smoke formation in the RPS samples commenced after ignition with a peak at about 0.1 m^2.s^{-1}. Because of the slowing of combustion after initial burning, the smoke formation decreased, and then rose steadily with the burning of the material to a maximum slightly above 0.1 m^2.s^{-1} and reduced to zero at the end of the test. All of the SPXS samples showed a rapid formation of smoke, because of their relatively fast combustion after ignition. SPX80, SPX33FRA, and SPX25 reached a maximum RSF values that are between 0.1 and 0.12 m^2.s^{-1}, while SPX45 and SPX33 reached maximum RSF values that are between 0.08 and 0.1 m^2.s^{-1}. Figure 4.26 shows clearly the maximum RSF values for all samples tested and it is clear that the highest rate was experienced with the SPX33FRA. These show a relatively low smoke formation within all the EPEF samples and the RPS sample.

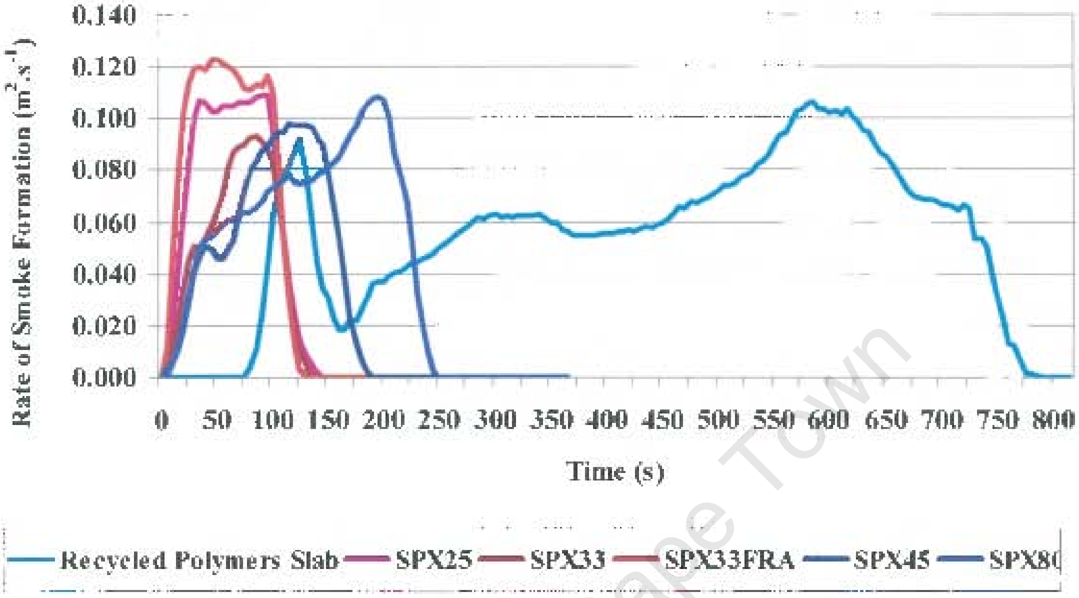

Figure 4.5: The graphs of the average rate of smoke formation versus time for the EPEF samples and RPS sample after ignition had been initiated.

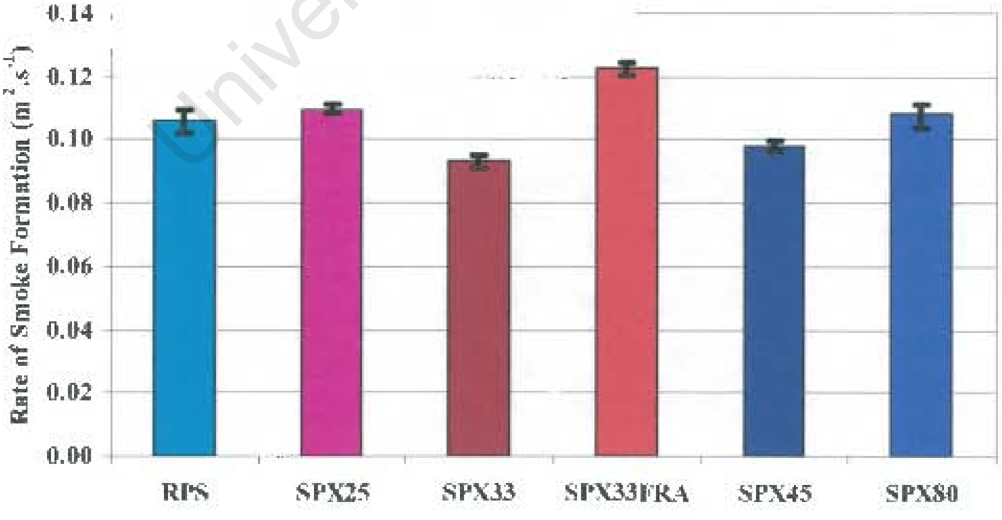

Figure 4.26: Bar charts of the average rate at which the smoke was formed versus time for the EPEF samples and RPS sample after ignition had been initiated.

4.3.3.5 Carbon Monoxide (CO) and Carbon Dioxide (CO_2) Formation

At the onset of combustion of the RPS samples, a peak of around 0.06 $kg.kg^{-1}$ (mass of CO per mass of the sample) was reached. After the maximum level of 0.06 $kg.kg^{-1}$, the level of CO had reduced and stayed between 0.04 and 0.05 $kg.kg^{-1}$. This is clear in figure 4.27. It is also apparent from figure 4.27 that among the EPEF samples the SPX25 has a highest amount of CO recorded. The graph of SPX25 in figure 4.27 has an initial peak of 0.14 $kg.kg^{-1}$ and a trough of around 0.04 $kg.kg^{-1}$ which is followed by a peak that is around 0.19 $kg.kg^{-1}$ at the end of combustion. SPX80 had the lowest value of CO formed during combustion (figure 4.27). The bar chart graphs in figure 4.28 indicates clearly the maximum CO recorded for each sample tested and these graphs makes it clear that the SPX25 has the highest value, followed by SPX33FRA, while SPX33, SPX45 and RPS are more less at the same level in terms CO produced during combustion.

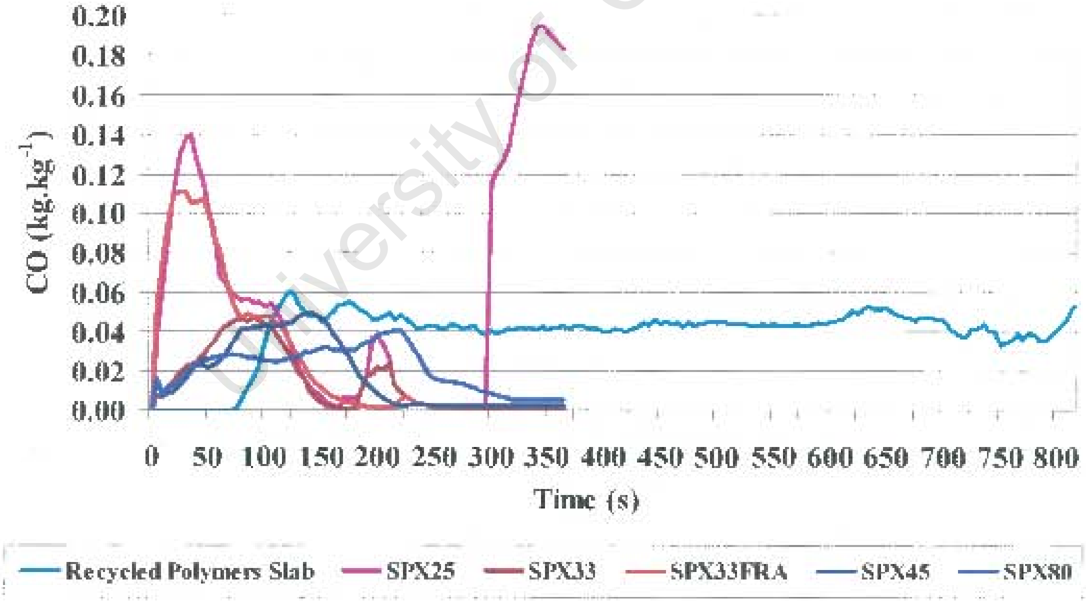

Figure 4.27: Graphs of the average rate CO formation versus time for the EPEF samples and RPS sample after ignition had been initiated.

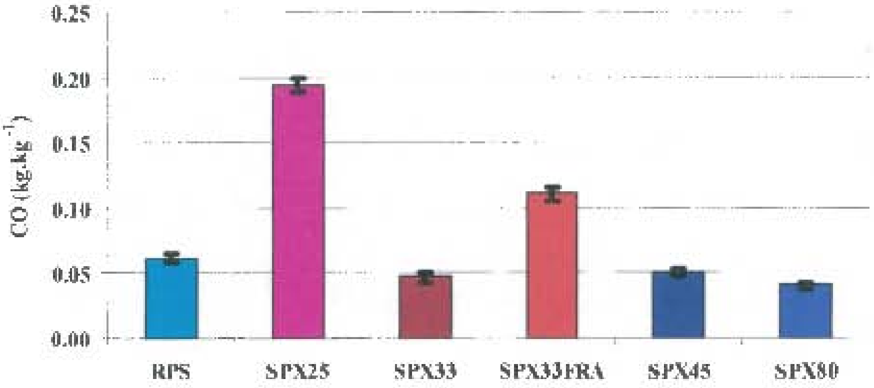

Figure 4.28: Bar charts of the average carbon monoxide formed versus time for the EPEF samples and RPS sample after ignition had been initiated.

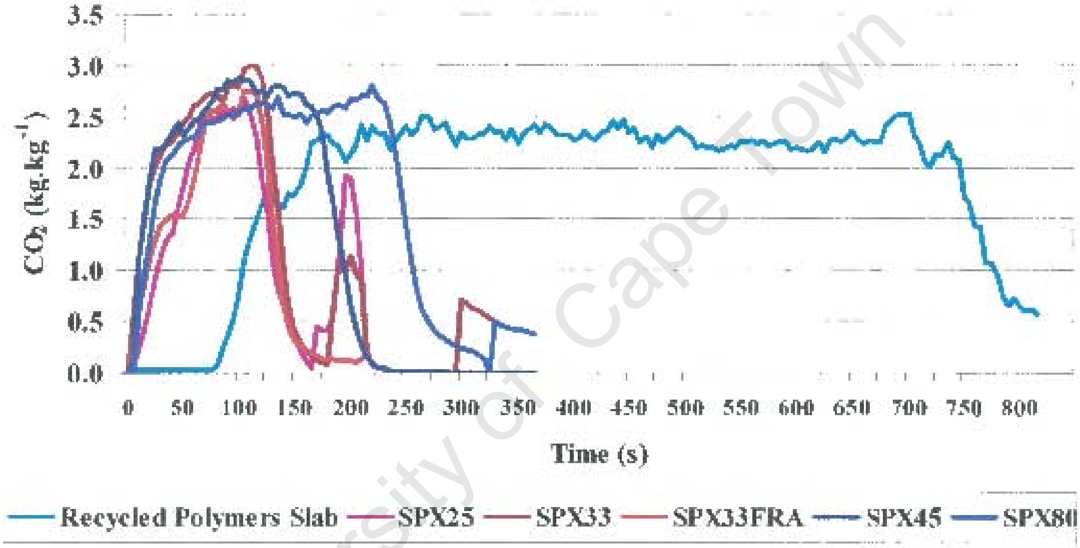

Figure 4.29: Graphs of the average rate CO_2 formation versus time for the EPEF samples and RPS sample after ignition had been initiated.

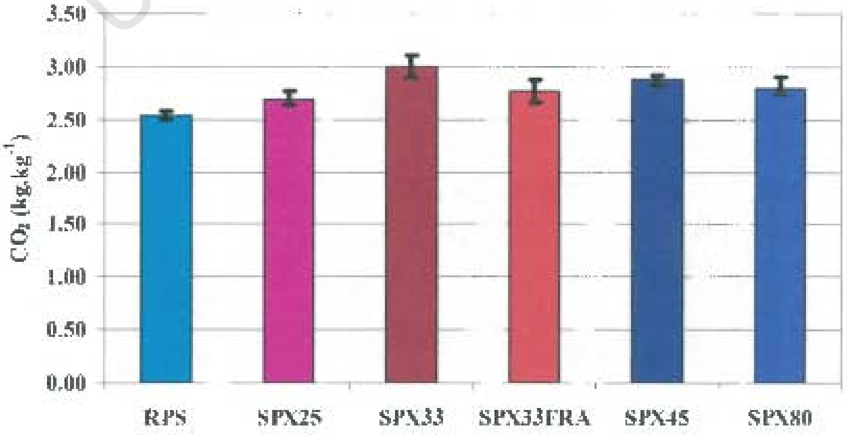

Figure 4.30: Bar charts of the average carbon dioxide formed versus time for the EPEF samples and RPS sample after ignition had been initiated.

Table 4.4: Maximum average quantity of carbon monoxide and carbon dioxide formed during the combustion process for the EPEF samples.

Materials	Maximum CO (kg.kg^{-1})	Maximum CO_2 (kg.kg^{-1})
SPX25	0.190	2.63
SPX33	0.047	3.00
SPX33FRA	0.110	2.73
SPX45	0.050	2.84
SPX80	0.043	2.75
Recycled Polymers slab	0.060	2.51

The CO_2 level for the RPS is reasonably constant between 2 and 2.51 kg.kg^{-1} (figure 4.29) for the main part of combustion. SPX25 has the highest CO_2 formed compared to all the samples tested and this is clear from the bar chart graphs in figure 4.29. The CO_2 level for all the samples, including SPX25 is between 3.00 kg.kg^{-1} and 2.50 kg.kg^{-1} (figure 4.30). It is clear from table 4.4 that for all the samples, the amount of CO_2 formed is higher than CO formed during combustion process.

4.4 MECHANICAL PROPERTIES

4.4.1 COMPRESSION TESTING

4.4.1.1 Sondor EPEF Samples

The compression test gives the applied force as a function of the deflection of the material in compression. The results of these tests are represented by compressive stress versus deflection curve. The compressive stress was derived from the force and the specimen's dimensions as discussed in chapter 2 section 2.14.3 where the compressive stress is calculated by dividing the load (force) by the cross-sectional area (A). The specimens used for testing were cylindrical. It is apparent from figure 4.31 that the SPX80 has the highest resistance to crush load compared to SPX25, SPX33, SPX33FRA and SPX45. The SPX80 has maximum compressive strength of

0.040 MPa whilst the average compressive strength for the SPX25, SPX33, SPX33FRA and SPX45 is about 0.02 MPa. This is more clearly illustrated in figure 4.32 where the error bars for the EPEF samples overlaps, showing no significant difference in their maximum compressive strength. For all the samples the test was stopped as the materials were deforming plastically without breaking to failure. These EPEF samples recovered completely after the compressive loading.

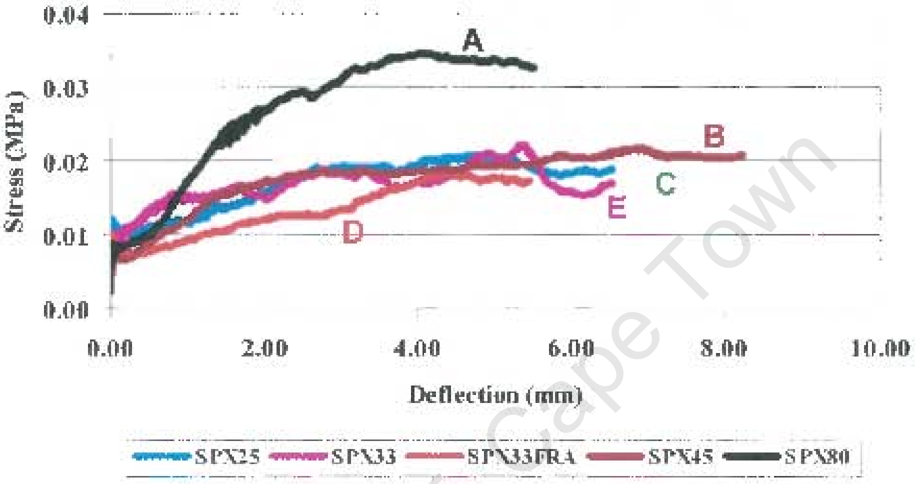

Figure 4.31: The compressive test stress / deflection curves for (A) SPX80, (B) SPX45, (C) SPX33FRA, (D) SPX33 and (E) SPX25.

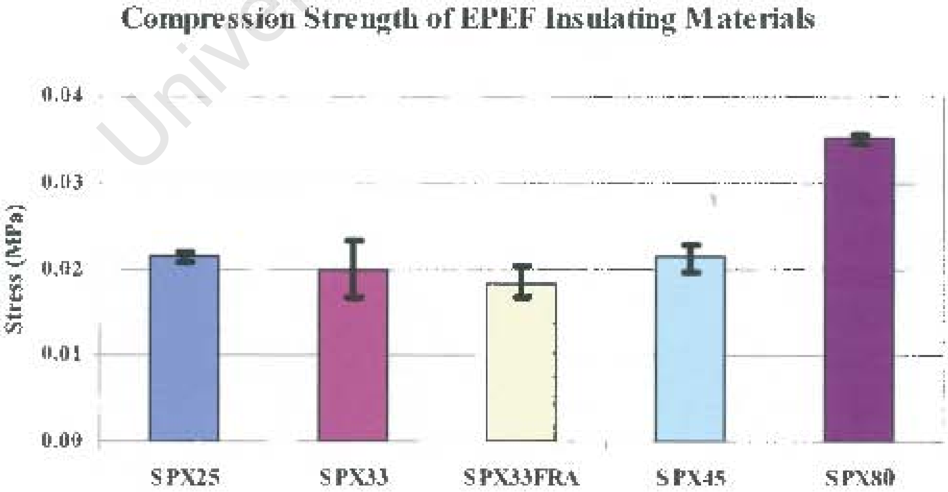

Figure 4.32: A bar chart representation for compression tests for the EPEF insulating materials.

Table 4.5: Average compressive strength for the EPEF insulating materials, RPS insulating material, together with their standard deviation (STDEV) and standard error values.

Insulating Materials	Maximum Stress (MPa)	STDEV (for Max.Stress)
SPX25	**0.021 (±0.001)**	**0.004**
SPX33	**0.020 (±0.001)**	**0.002**
SPX33FRA	**0.018 (±0.0004)**	**0.0013**
SPX45	**0.021 (±0.0003)**	**0.0010**
SPX80	**0.035 (±0.001)**	**0.003**
Recycled Polymers Slab	**8.13 (±1.39)**	**2.79**

Ten samples were tested in compression for each material. A statistical analysis was performed for each EPEF thermal insulating material and the RPS thermal insulating materials. The results are tabulated in table 4.5. It is clear from table 4.5 that there is less deviation from the average maximum compressive strength as the values for the standard deviation (STDEV) are relatively low.

4.4.1.2 Recycled Polymer Slab

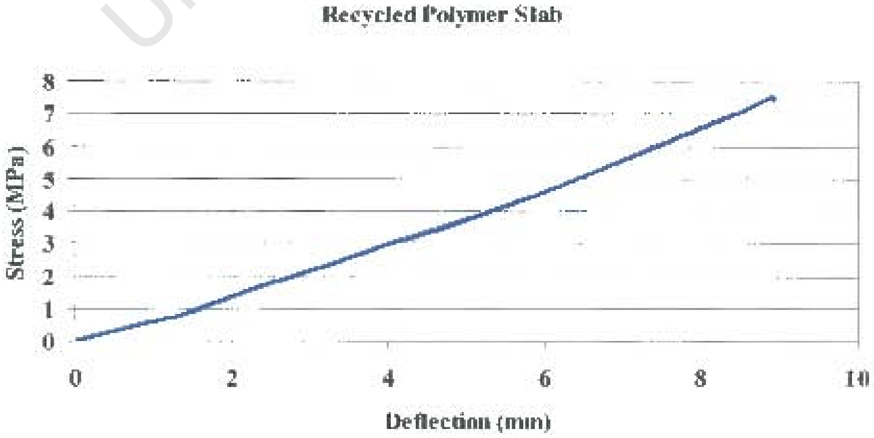

Figure 4.33: Typical compressive stress / deflection curves for the recycled polymer slabs.

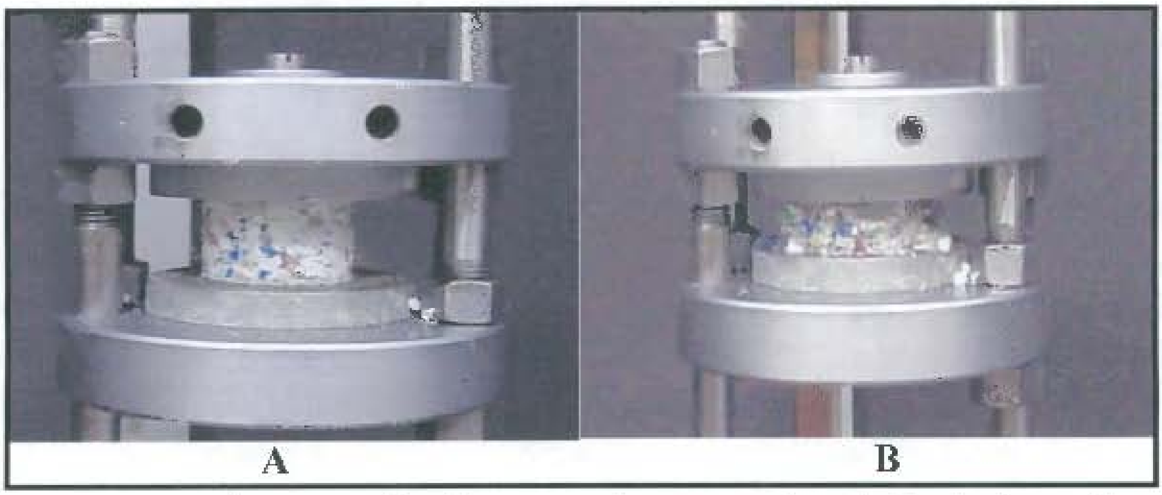

Figure 4.34: Pictures showing the compression test specimen holder before testing (A) and when the test was stopped (B) for the RPS material.

It is apparent from figure 4.33 that the maximum compressive strength of approximately 7.2 MPa for the RPS is significantly higher than that of SPX80 (figure 4.31, table 4.5). The tests were stopped when the RPS material crumbled. Figure 4.34 shows the specimen just before the point of failure.

4.4.2 CREEP TESTING

Table 4.6: Creep test results for expanded polyethylene foam and the recycled polymers slab samples.

Thickness	Sample Description	Deflection (mm) t = 14 days
18mm	SPX33FRA	2
18mm	SPX80	0
18mm	SPX45	1
18mm	SPX25	3
18mm	SPX33	2
18mm	Recycled Polymers Slab	0

The creep tests were conducted by the Department of Wood Science at the University of Stellenbosch. The creep test was conducted on all of the EPEF samples and the recycled polymers slab. The test results for creep are tabulated in table 4.6. The test results for creep reveals that the SPX80 and the recycled polymers slabs did not show deflections after 14 days of testing. The maximum value of 3mm was recorded for SPX25. The SPX45 deflected by only 1mm after 14 days. The SPX33 and SPX33FRA managed a 2 mm deflection. The creep of the deflected samples was not permanent as the samples had returned to their original shape after the test load was removed.

4.4.3 THREE POINT BEND TESTING

The three-point bend test gives the applied force as a function of deflection of the material in flexure. The results of these tests are represented by flexural stress versus deflection curve, where the flexural stress was derived from the force using equation 2.5 of section 2.14 in chapter 2. It is apparent in figure 4.35 that the SPX80 (A) has the highest value of ultimate flexural stress. There appears to be no significant difference in ultimate flexural stress for SPX33, SPX33FRA and SPX25, inferred from the overlapping of the error bars in figure 4.36. The error bars for SPX45 and SPX80 are not overlapping with any of the other EPEF samples

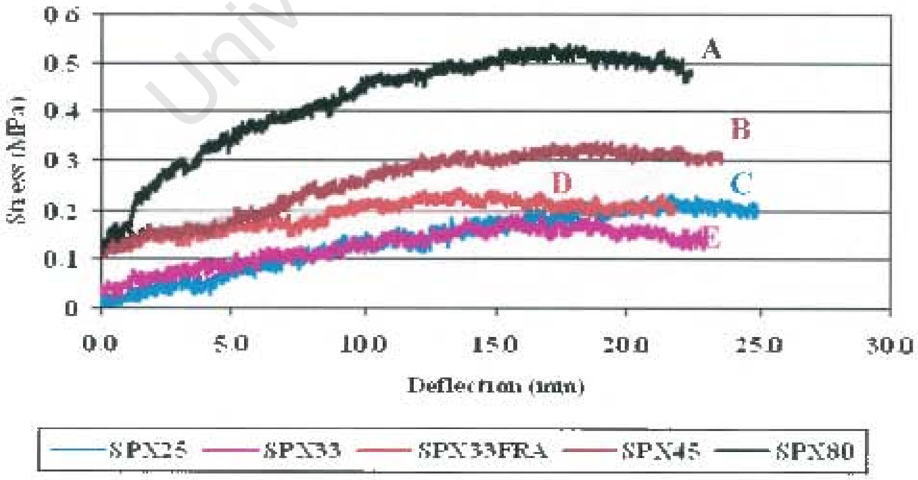

Figure 4.35: Three-point bend stress/deflection curves for (A) SPX80, (B) SPX45, (C) SPX33FRA, (D) SPX33 and (E) SPX25 for the EPEF insulating materials.

The true failure stress and strain for all of the EPEF are not known since the tests were stopped before failure. They all demonstrated the same behaviour of continuous plastic deformation. This is illustrated in figure 4.37 where the SPX25 was used as an example of this common behaviour of the EPEF samples. The tests were stopped because all of the EPEF samples were continuously deforming plastically after the UTS (ultimate tensile stress) during the test until the grips of the testing machine where about to touch.

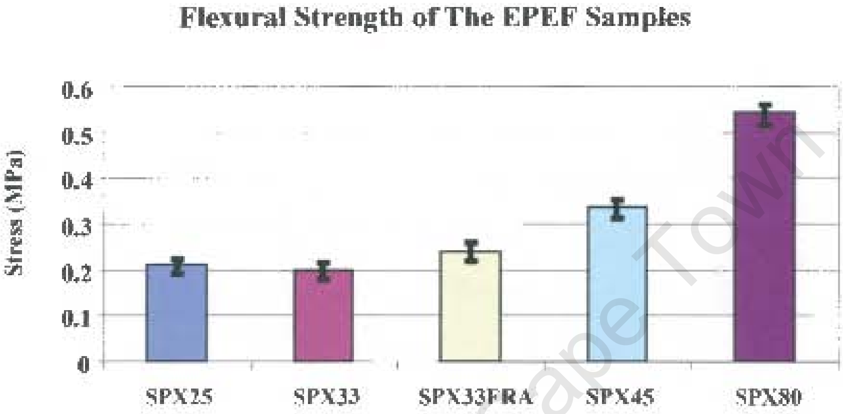

Figure 4.36: The bar chart representation for the three-point bend tests of EPEF insulating material samples.

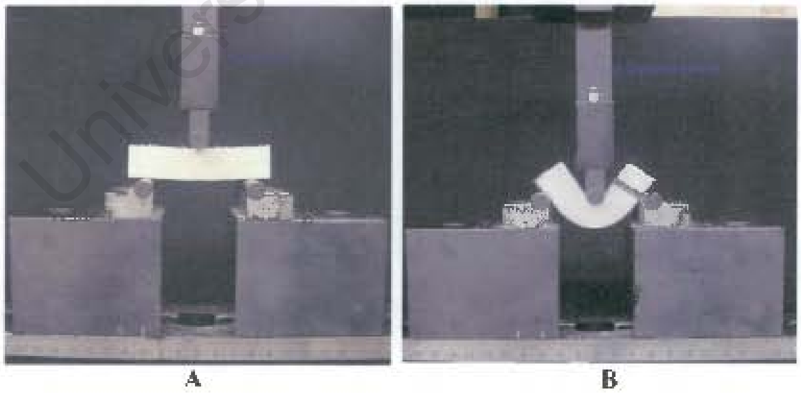
A
B

Figure 4.37: Photograph showing the 3-bend testing of the SPX25 before (A) and after the test was stopped (B).

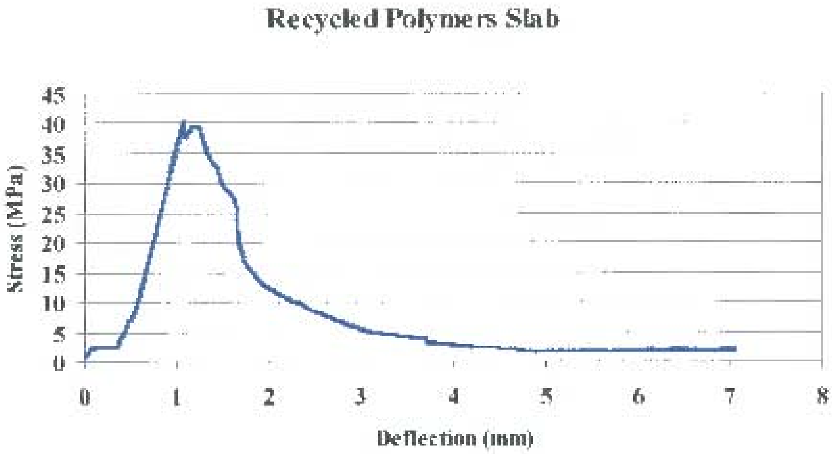

Figure 4.38: Three-point bend stress versus deflection curves for the recycled polymers slab.

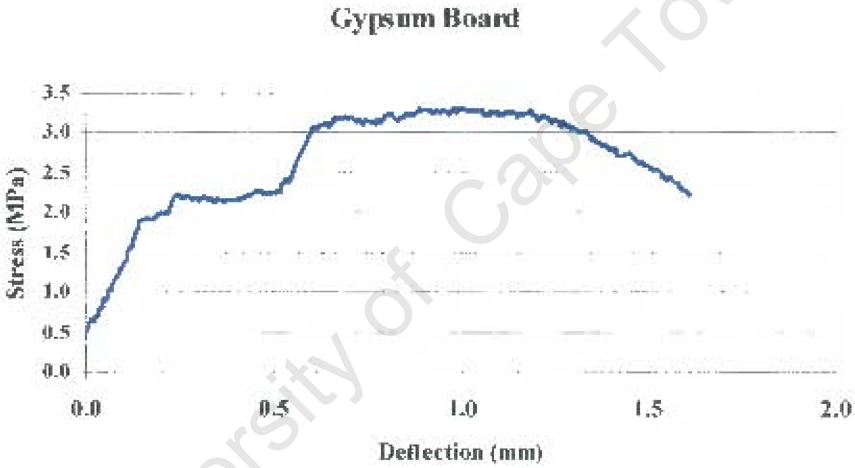

Figure 4.39: Three-point bend stress/deflection curves for the gypsum board.

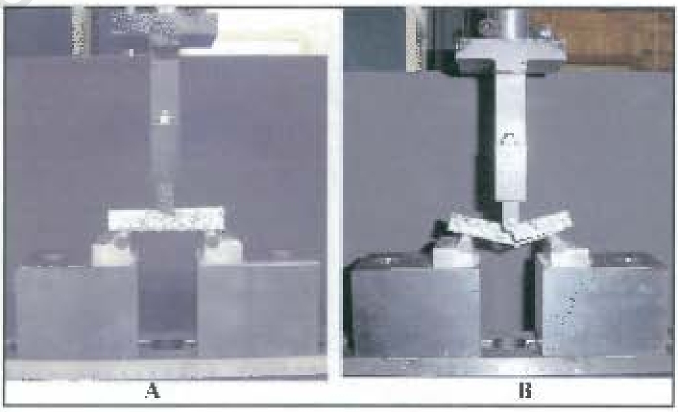

Figure 4.40: The pictures showing the 3-point bending test specimen grips before testing (A) and when the test was stopped (B) for the RPS material.

Figure 4.38 shows the flexural stress versus deflection for the recycled polymers slab (RPS) samples. The RPS has the highest flexural stress compared to all of the EPEF samples and the gypsum board. The gypsum board has a UTS flexural stress that is higher than that of the EPEF samples, but smaller than the flexural value for insulating material (figure 4.39). Figure 4.40 illustrates the RPS specimen during the bend test.

Table 4.7: Average flexural stress and modulus for the expanded polyethylene foam (EPEF) samples, recycled polymers slab (RPS) samples, and the gypsum board together with their standard deviation (STDEV) and standard error values.

Insulating Materials	Maximum Stress (MPa)	STDEV (for Max.Stress)	Flexural Modulus (MPa)	STDEV (for F.Modulus)
SPX25	0.21 (±0.01)	0.04	0.95 (±0.06)	0.18
SPX33	0.20 (±0.01)	0.03	0.89 (±0.03)	0.10
SPX33FRA	0.24 (±0.01)	0.02	1.09 (±0.03)	0.11
SPX45	0.34 (±0.004)	0.01	1.50 (±0.03)	0.10
SPX80	0.54 (±0.01)	0.04	2.46 (±0.05)	0.16
Recycled Polymers Slab	39.40 (±0.17)	3.37	44.77 (±1.45)	3.83
Gypsum Board	3.34 (±0.11)	0.36	3.79 (±0.13)	0.40

Table 4.7 tabulates the maximum flexural stress and maximum flexural modulus for the EPEF samples, recycled polymers slab insulating material and the gypsum board. Ten samples were tested for each material and a statistical analysis was performed on the data for all the samples. The standard error (the ± value), in table 4.7, shows that there is no significant difference between the 10 samples tested for each material. The standard deviation (STDEV) values for all materials in table 4.7 indicate that there is a small amount of scatter from the mean values of flexural stress and flexural modulus. The RPS insulating material has the highest flexural stress and flexural modulus, compared to all EPEF samples and the gypsum board. It is evident from table 4.7 that the SPX80 has the highest flexural stress and flexural modulus compared to the other EPEF samples. The second highest second flexural stress and modulus was recorded for SPX45 whilst much lower values were recorded for SPX25, SPX33 and

SPX33FRA. There appears to be no significant difference in the values for flexural stress and modulus for the EPEF samples. The gypsum board, since it not an insulating material, had higher values of both flexural stress and modulus.

4.5 WATER VAPOUR PERMEABILITY (WVP) AND LIQUID WATER PERMEABILITY (LWP) TESTING

The results obtained for the water vapour permeability (WVP) and liquid water permeability (LWP) from experimental tests that were conducted at Stellenbosch University are tabulated in table 4.8 (WVP) and table 4.9 (LWP). The results of the WVP test in table 4.8 shows that the SPX80 sample had the lowest value (11.0 g.m^{-2}) for mass uptake per square meter compared to the other insulating materials samples. There is a small difference between the water vapour uptake for the remaining insulating materials. SXP33FRA and SPX33 have an uptake value of 24.50 g.m^{-2} whilst the highest value of 26.00 g.m^{-2} was recorded for SPX45. All the tests on the specimens where performed for a period of 7 days.

Table 4.8: Water vapour permeability test results for the EPEF thermal insulating material samples over a period of 7 days.

		Date in 07/06/05	Date out 14/06/05	Difference (g)	Mass Uptake /7days/m^2 (g.m^{-2})
Thickness	Sample Description	Mass (g)	Mass (g)		
18mm	SPX25	16.19	16.68	0.49	24.50
18mm	SPX33	17.26	17.78	0.52	26.00
18mm	SPX33FRA	17.17	17.66	0.49	24.50
18mm	SPX45	28.29	28.79	0..50	25.00
18mm	SPX80	43.86	44.08	0.22	11.00

Table 4.9: Liquid water permeability test results for the EPEF thermal insulating material samples over a period of 24 hours.

		Date in 07/06/05	Date out 08/06/05	Difference (g)	Mass Uptake /24hrs/m^2 (g.m^{-2})
Thickness	Sample Description	Mass (g)	Mass (g)		
18mm	SPX25	16.15	16.78	0.63	31.50
18mm	SPX33	17.31	17.83	0.52	26.00
18mm	SPX33FRA	17.32	17.58	0.26	13.00
18mm	SPX45	28.41	28.89	0.48	24.00
18mm	SPX80	43.95	44.15	0.20	10.00

In the LWP test, the SPX80 has the lowest value (10.00 g.m^{-2}) for the mass uptake per square meter. The highest value of 31.50 g.m^{2} was recorded for SPX25. The second lowest value of 13.00 g.m^{-2} was recorded for SPX33FRA, while there is not much difference between the SPX45 and SPX33 samples, as indicated table 4.9. The result for the RPS slabs could not be obtained. The recycled polymers slab could not be measured for LWP as it was leaking. Water could not settle inside the specimens. A WVP test was not conducted as relatively little water was expected to be absorbed by the recycled polymers slab.

4.6 ECONOMICS OF INSULATION

4.6.1 ECONOMIC INSULATION THICKNESS

Table 4.10 shows the calculated values for the heat flow rate or the heat loss through an insulating material (HFR) and their corresponding Rand loss (RL) values per unit area (1m^2) for EPS, RPS and all of the EPEF thermal insulating material samples. Their R-values were also calculated. It is noticeable from table 4.10 that the EPEF samples have lower values of HFR and RL and higher R-values than the RPS material. The SPX33FRA (34 mm) and SPX80 (34 mm) samples have the lowest HFR values of 0.0040 kWh and 0.0041 kWh, respectively. It is also seen in table 4.10 these two materials also show lower values of HFR at the smaller thicknesses (18 mm), at 0.0076 kWh and 0.0078 kWh, respectively. The R-values for the EPEF samples increased when the thickness was increased from 18 mm to 34 mm. SPX33FRA (34 mm in thickness) has the highest R-value of 0.87 $m^2K.W^{-1}$ whilst the SPX80 (34 mm) has an R-value of 0.85 $m^2K.W^{-1}$. The EPEF samples of 18 mm thickness have R-values ranging between 0.4 and 0.46 $m^2K.W^{-1}$. This can be compared with the R-value of the RPS which was calculated to be 0.26 $m^2K.W^{-1}$. In table 4.10, the RL values for the SPX insulating materials of thickness 34 mm is of the order 7-8 $x10^{-4}$ and increases with decreasing thickness. SAGEX EPS (50 mm) have an RL value of $5x10^{-4}$ R_A while that of the RPS (14 mm) was calculated to be $2.2x10^{-3}$ R_A.

Table 4.10: Tabulated calculated values of the R-value, HFR and R_AL for the EPS (SAGEX), RPS (developed) and all of the SONDOR EPEF samples.

<table>
<tr><th>Material</th><th colspan="2">Thickness (m)</th><th>R-Value ($m^2 K.W^{-1}$)</th><th colspan="2">k-value ($W.m^{-1}K^{-1}$)</th><th>HFR (kWh)</th><th>RL (R_A)</th></tr>
<tr><td>EPS (SAGEX)</td><td colspan="2">0.050</td><td>1.06</td><td colspan="2">0.047</td><td>0.0033</td><td>0.0005</td></tr>
<tr><td>RPS Sample</td><td colspan="2">0.014</td><td>0.26</td><td colspan="2">0.054</td><td>0.0135</td><td>0.0022</td></tr>
<tr><td colspan="8">SONDOR EPEF Thermal Insulating Material Samples</td></tr>
<tr><td colspan="4">Thickness (18m)</td><td colspan="3">Thickness (34m)</td><td rowspan="2">k-value ($W.m^{-1}K^{-1}$)</td></tr>
<tr><td></td><td>R-Value ($m^2 K.W^{-1}$)</td><td>HFR (kWh)</td><td>RL (R_A)</td><td>R-Value ($m^2 K.W^{-1}$)</td><td>HFR (kWh)</td><td>RL (R_A)</td></tr>
<tr><td>SPX25</td><td>0.40</td><td>0.0088</td><td>0.0014</td><td>0.76</td><td>0.0046</td><td>0.0008</td><td>0.045</td></tr>
<tr><td>SPX33</td><td>0.42</td><td>0.0084</td><td>0.0014</td><td>0.79</td><td>0.0044</td><td>0.0007</td><td>0.043</td></tr>
<tr><td>SPX33FRA</td><td>0.46</td><td>0.0076</td><td>0.0013</td><td>0.87</td><td>0.0040</td><td>0.0007</td><td>0.039</td></tr>
<tr><td>SPX45</td><td>0.42</td><td>0.0084</td><td>0.0014</td><td>0.79</td><td>0.0044</td><td>0.0007</td><td>0.043</td></tr>
<tr><td>SPX80</td><td>0.45</td><td>0.0078</td><td>0.0013</td><td>0.85</td><td>0.0041</td><td>0.0007</td><td>0.040</td></tr>
</table>

CHAPTER 5

DISCUSSION

5.1 INTRODUCTION

There are several factors that influence the performance and adaptability of polymeric based thermal insulating materials. These factors are mainly thermal resistance, thermal conductivity, combustibility, mechanical properties, moisture resistance and density. It is evident from the literature study that the key to maintaining a comfortable temperature in a building is to reduce the heat transfer out of the building in winter and reduce heat transfer into the building in summer by introducing thermal insulation materials into the building envelope. The building envelope is mainly formed by the floors, walls and roof, which may include elements such as windows and doors. The roof was found to be the major contributor to reducing heat loss in the building envelope when it is insulated. Buildings, as they are designed and used today symbolise unrestrained consumption of energy and other natural resources with its consequent negative environmental impact. This chapter deals with a discussion of the experimental findings outlined in chapter 4.

5.2 EXISTING INSULATING MATERIALS

As mentioned in chapter 3 section 3.11, existing thermal insulating materials in the South African market were used in this investigation. This was done in order to understand and study the properties that would make a material a good thermal insulating material. It is evident from section 3.11 that the properties that govern the viability of thermal insulating materials are:

- Thermal conductivity (k-value): This is the fundamental property governing heat flow through a thermal insulating material from a higher temperature to a lower temperature.
- Thermal resistance (R-value): The higher the value of thermal resistance, the better the insulating capability of the material.
- Density: The density of an insulating material affects its thermal insulating capability.
- Combustibility: This is a significant parameter as it provides an indication of the insulating material's contribution to fire hazard.

The second priority is given to physical properties such as moisture absorption and the presence of hazardous gases during burning. It is evident that polymeric based materials are mainly used in developing these thermal insulating materials, although reflective aluminium foils are also sometimes used. When cost as the determining factor is ignored, both the polymer and the metal (Al) foil are combined. In a general sense the market is dominated by organic, inorganic and reflective thermal insulating materials.

In section 2.4 different forms of insulation were defined and it was explained in section 2.3 that insulating materials are energy dependent products. As a result of this they should be evaluated as part of a building when they are developed or evaluated, not as energy independent products. It was also found that South African residential consumers see affordable electricity as a requirement for an improvement in their standard of living[9]. As result of this, convenient small, portable, inexpensive, electric resistance heaters are mainly used in households to keep warm. This is practiced mainly because of the mildness of the South African climate and the fact that the heating season is relatively short. This has been the driver for the production of thermal insulation materials in South Africa. Thermal insulation is perceived to be a luxury. With this in mind, it is evident that most insulating materials on the South African market have been developed based on affordability and not on sustainable criteria.

The products from Isotherm, Aerolite and Sagex are mainly resistive thermal insulating materials. The Sagex and Isotherm products are based on the composite insulation principle, where resistive and reflective insulation materials are combined. Insulation Solutions (Pty) Ltd and Nampak L & CP products are reflective thermal insulating materials and they are mainly used in industry although they are relatively expensive.

Reflective systems are more effective in hot than in cool climates. Reflective insulation is employed mainly where the dominant heat transfer is through radiation[27]. It is apparent from the South African thermal insulation market that foamed materials are mostly used in preference to reflective insulation. This is because solid raw polymeric materials can easily be developed into inexpensive foamed thermal insulating materials compared to the conversion of solid metals into reflective thermal insulating materials.

Foamed thermal insulating materials fall under the group called resistive (bulk) insulating materials. Resistive insulation insulates against the transfer of heat simply through its resistance to conduction. Because air has one of the highest resistances to conduction, the best resistive insulators are those that trap small pockets of air within themselves. Figure 5.1 show a plot of the thermal conductivity of air as a function of temperature. It is apparent from figure 5.1 that the thermal conductivity of air is low even at high temperatures. Insulators such as glass fibre, mineral wool and expanded polystyrene work extremely well as long as the air within these pockets cannot move and thus transfer heat by convection[28].

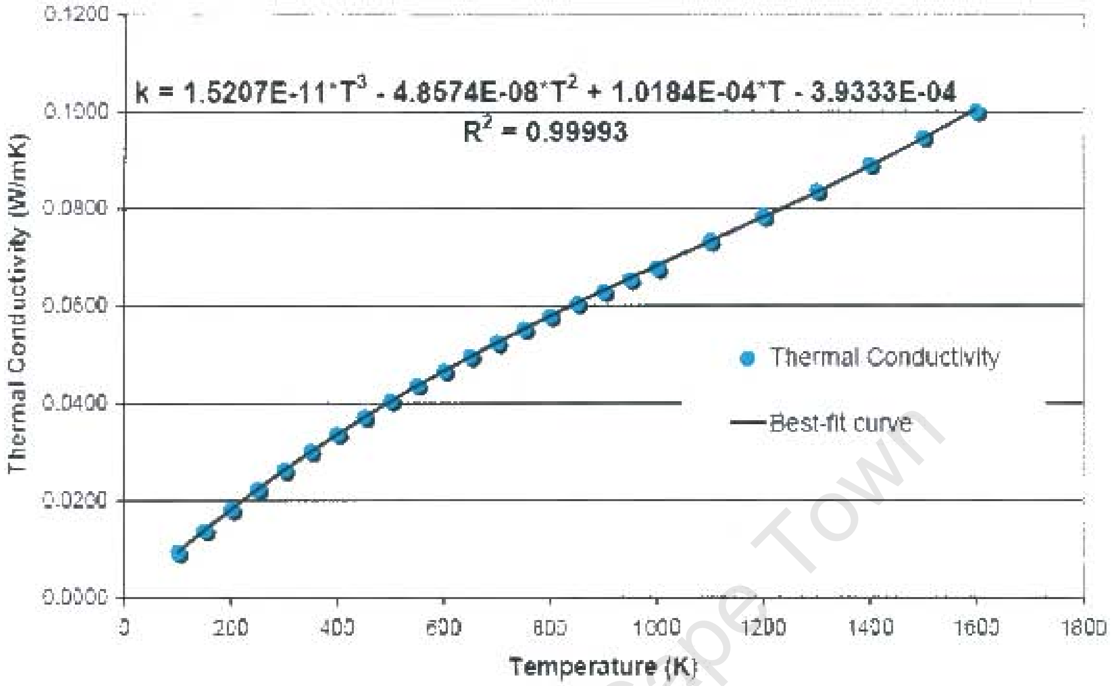

Figure 5.1: Graph of thermal conductivity as a function of the temperature for air[78].

Foaming dramatically extends the range of properties for engineering applications. Cellular solids have physical, mechanical and thermal properties which are measured by the same methods as those used for fully dense solids. Figure 5.2 shows the range of properties that foamed materials can offer[77]. The bar with the dotted shading shows the range of properties spanned by conventional solids and the solid bars show the extension of this range made possible by foaming. The low densities and thermal conductivity of foams has given a starting point for the development of low-cost thermal insulating materials. This is because in foamed polymeric materials, the low thermal conductivity allows cheap, reliable thermal insulation even though this can sometimes be achieved by expensive vacuum-based methods.

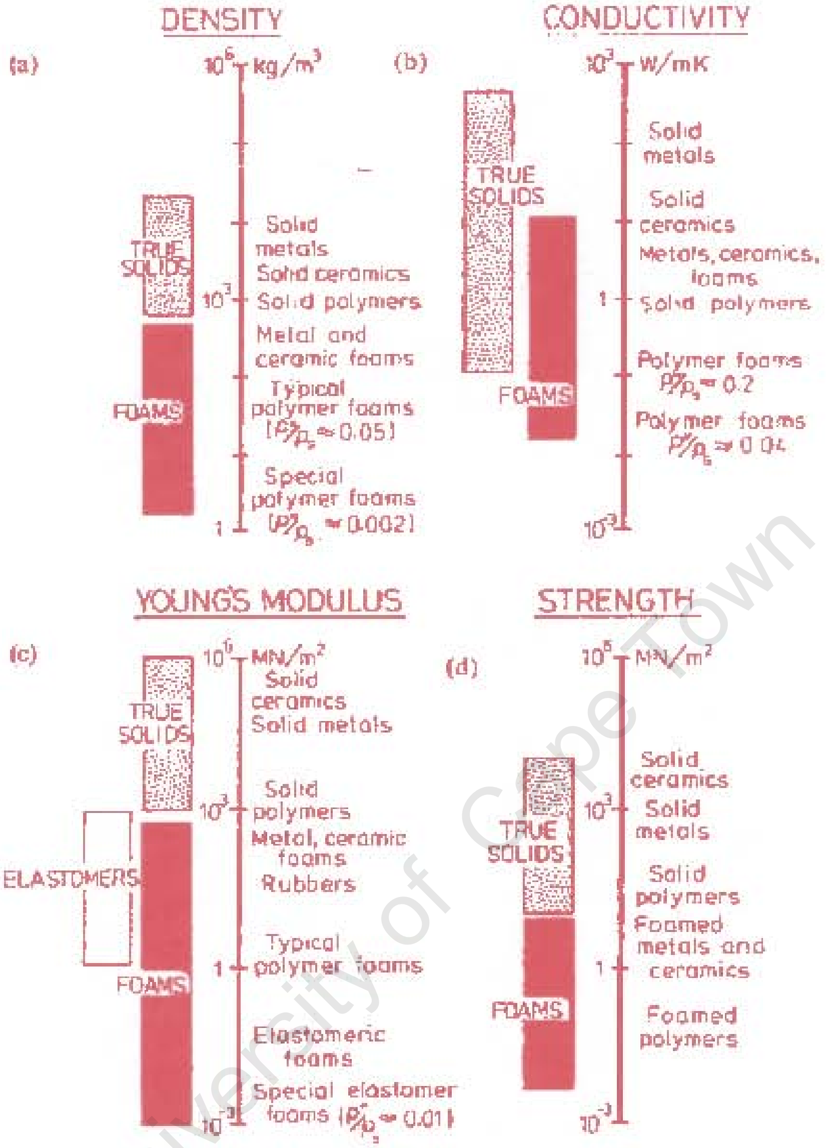

Figure 5.2: The range of properties available to engineering applications through foaming: (a) density (b) thermal conductivity (c) Young's modulus (d) compressive strength[77].

5.3 MATERIALS SELECTION

A low cost thermal insulating material was developed during this research project and only polymeric based raw materials were considered. Recyclable materials were investigated as possible raw materials because of the fact that the thermal insulating material had to be relatively inexpensive. Only a few polymeric raw materials were selected for evaluation and these included recycled glass wool, damaged car tyres, polypropylene and polyethylene bottles and caps as well as expanded polyethylene foams (EPEF) obtained from Sondor (Pty) Ltd.

Some work has been done by Mathews *et al.* on recycled glass wool and tyres[5]. It was evident from their research that in order to change or transform recycled glass wool to be a good thermal insulating materials one must use expensive binders or thermosetting resins and the technology behind it is relatively expensive to maintain. Besides this expensive procedure, the glass wool posses a health risk such as skin allergy and there is debate over whether or not fibreglass may cause cancer[5,40]. The same can be said of tyres as they too need expensive binders and are highly flammable. Recycled PP and PE caps and bottles were chosen in order to see if it possible to transform them cheaply into a low cost thermal insulating materials. These low cost thermal insulating materials will have to have the same thermal properties as some of the existing thermal insulating materials. The recycled PP and PE caps and bottles can easily be collected from the recycling factories around Cape Town.

Sondor (Pty) Ltd. is company that is based in Cape Town, produces different grades of closed cell, cross-linked expanded polyethylene foams (EPEF) and offered to provide off-cuts from their manufacturing processes. Five different foamed polyethylene products were obtained. The difference can be found in their densities. The PE recycled bottles and tops were mainly selected because of their excellent thermal properties. The Sondor EPEF samples were accepted because they are expected to have a lower k-value, since they have a foamed structure. Solid polyethylene has a low thermal conductivity value that ranges between 0.35-0.52 $W.m^{-1}K^{-1}$ whilst solid polypropylene has a thermal conductivity of 0.2 $W.m^{-1}K^{-1}$ [12,13]. This indicates that when they are foamed they will have an even lower thermal conductivity.

5.4 THE MORPHOLOGY OF THE RESEARCH SAMPLES

As outlined in chapter 4, section 4.4, the recycled PP and PE particulates were fused together into a solid polymer slab (recycled polymer slab). Prior to the fusing process, the recycled PP and PE materials were granulated into fine granules. This was done using a granulator at Plastamid (Pty) Ltd. The polymer granules were then washed before they were used in the project. Polypropylene (PP) and polyethylene (PE) are both thermoplastics and soften by the application of heat. PP has a softening temperature of about 100 °C and melting point of 176 °C whilst low density PE has a melting point of 115°C and high density PE melts at 135 °C. They both soften at temperatures between 70 °C and 80 °C[81]. When heated the PE softens and bonds the particulates together as cooling occurs. Since the granulated material contained both PP and PE (low and high densities) the mould temperature was set at 80 °C for 30 minutes. This process created a porous structure with many air pockets. It is the air pockets formed in this RPS structure which minimises air collisions within the slab (see SEM micrographs in figure 4.7 and 4.8). All materials transfer heat by conduction as their component atoms or molecules exchange energy through collisions[53]. The produced RPS has perforations in the structure which reduces collisions between air particles which results in a reduction of heat transfer within gas molecules. The low thermal conductivity of the solid particles (PP and PE) maximises the resistance to heat conduction within the RPS slab. This technique of preventing heat conduction by using the high thermal resistance of air is evident in the EPS (Sagex) microstructure.

The produced recycled polymers slab was laminated with two layers of woven glass fibres on either side. This was done in order to prevent the granules from falling apart and at the same time to increase the mechanical properties of the slab. This process also prevents water from seeping into the slab. A hand lay-up process without vacuum forming was used to make the laminates of the woven glass fibres onto the polymer slabs. Both the RPS and EPEF samples have a structure that can easily trap air (see SEM micrograph in figure 4.10). The same principle that is used by EPS and polyester for minimising the transfer of heat by conduction is evident in the EPEF samples. In general more foam materials are used for thermal insulation than for any other purpose. Closed cell foams have a lower thermal conductivity than conventional non-vacuum insulation[76]. Several factors combine to limit heat flow in foams: the low volume fraction of the solid phase, the small cell size which virtually suppresses convection and reduces radiation through repeated absorption and reflection at the cell walls, and the poor conductivity of the enclosed gas (air has a k value of 0.025 $W.m^{-1}K^{-1}$ [77, 78]). All these factors are evident in the micrographic structures of RPS, EPS and all of the Sondor EPEF samples.

5.5 THERMAL PROPERTIES

The hot box construction (figure 3.4, chapter 3) uses the principle that a temperature gradient exist in the roof and the rooms of the box. The performance of the standard insulation kit (Isotherm + gypsum board) can then be compared with other materials *e.g.* the RPS and all of the Sondor EPEF samples. Heat is a form of energy that appears as molecular motion in a substance or radiation in space[55]. Radiation is the transfer of heat energy by electromagnetic infrared waves and is very different from conduction and convection. When the light bulbs in the roof of the hot-box are switched on it radiates heat. Heat will travel from the bulbs by forced convection into the surrounding air[52]. Since convection is the mode of energy transfer between the solid surface and the adjacent liquid or gas that is in motion. The heat is absorbed by the air molecules and they will collide with one another. In such collisions the faster molecules lose some kinetic energy and the slower ones gain some. This transfer of kinetic energy from the hot to the cold side is called a flow of heat through conduction. Finally heat is transferred to the surface of the thermal insulating materials by conduction and convection.

Temperature can be considered to be a symptom of the presence of heat in a medium (air), and is a measure of the thermal state of that medium[54]. Thermometers were placed in roof and the other two rooms of the hot-box to measure the temperature of the air as a function of time. It is apparent from figures 4.11, 4.13 and 4.14 that the temperature of the un-insulated room reached a maximum of around 40 °C, the roof at about 70.4 °C and the standard insulation kit room around 25°C after approximately 210 min. It is also clear from figure 4.11 that the temperature of the un-insulated room was reduced to below 30°C after an introduction of RPS for the same period of time (210 min). Both the standard insulation kit and RPS act as ceilings for their respective rooms. Similar results were achieved with all the Sondor EPEF samples when they were evaluated in the hot-box (figures 4.13 and 4.14, in chapter 4). The difference in thicknesses for the Sondor EPEF samples did not make a significant difference in terms of temperature obtained of the room they insulated (table 4.1).

The open spaces in the RPS and the closed-cell structure in Sondor EPEF samples retard the flow of heat by conduction and radiation as a result of the temperature difference between the roof and the room they are insulating. The air particles within the RPS slab and the Sondor EPEF samples are not colliding with molecules in adjacent cells and this slows down the transfer of heat from the roof into the room. The same principle happens with the standard insulation kit, where the polyester reduces collision between the air molecules. Figure 4.1 shows the open structure of polyester. In the standard insulation kit, the gypsum board was incorporated for strength and flammability purposes.

5.5.1 THERMAL CONDUCTIVITY

Thermal conductivity in simple terms is a measure of the capacity of a material to conduct heat through its mass. When heat is applied to one surface of the polymer it diffuses inwards at a rate that is determined by the thermal conductivity of the polymer. Heat increases the local amplitude of vibration of the atoms and groups of atoms which are bonded together in the polymer chain. The thermal conductivity measures how strongly the vibrations of adjacent atoms or groups are coupled[76]. This is the principle behind the use of the comparative cut bar explained in chapter 2, section 2.13. The comparative cut bar was found to be relatively cheap to design and it was ideal for the measurement of the thermal conductivity of polymeric based materials. Hence it was designed and used to measure the thermal conductivity of all the samples under investigation.

Expanded polystyrene as a foamed thermal insulating material was chosen and its thermal conductivity was measured using the comparative cut bar. EPS uses the foamed structure to trap air and uses the low thermal conductivity of air together with that of the solid styrene to retard the flow of heat and this is similar for the RPS and Sondor samples. Expanded polystyrene (EPS) was also chosen to see if the designed thermal conductivity device can indeed produce the same values reported in the literature. The thermal conductivity value for the EPS was found to be 0.047 $W.m^{-1}K^{-1}$ (table 4.10) and this has indicated that the EPS used has a density range between 10-12 $kg.m^{-3}$ (table 2.3, chapter 2). This is because of the fact that, as the relative density of the foamed structure increases, the contribution from conduction of the solid walls increases while that from radiation decreases[76]. The k-value of all the Sondor EPEF samples was measured to be around 0.04 $W.m^{-1}K^{-1}$ and the RPS k-value was found to be 0.05 $W.m^{-1}K^{-1}$ and this is attributed to the type of bond in polymeric materials. Covalent bonds in a crystallographic ordered array give strong coupling (so diamond, for instance, is a good thermal conductor) and the weak bond and disordered packing, like those in EPS, RPS and Sondor EPEF samples give poor coupling with their crystallographic structure. Ordinary polymers like styrene, polyethylene and polypropylene, contain weak bonds and are disordered, and for this reason their thermal conductivities are lower than those of any other class of dense solids. Only polymeric foams have lower conductivities[76].

5.6 PHYSICAL PROPERTIES

5.6.1 WVP AND LWP

The durability of building materials, including thermal insulating materials, is a very important environmental consideration. Increasing attention is being given to the long term performance of insulation materials. Thermal insulating materials that are more durable are environmentally superior to less durable ones[42]. Even though many thermal insulating materials perform well with time, moisture was found to reduce the insulating performance of these materials. Moisture can gather in the insulating material structure through vapour or pure liquid migration. Moisture transfers into the building structure from many sources, for example from cooking or boiling water. The reality here is that if moisture penetrates into building thermal insulation materials, it will cause it physical damage and will adversely impact on its performance by increasing its thermal conductivity[47]. Water vapour and liquid water are the most serious moisture contributors in buildings, especially residential buildings.

Water vapour and liquid water permeability tests were performed on all the Sondor EPEF samples and their results were outlined in section 4.5. It is clear from table 4.8 in chapter 4 that of all the EPEF samples, SPX80 accumulated the least amount of moisture after being exposed to water vapour for a period of 7 days. The movement of water vapour in an insulation system is dependent upon changes in relative humidity, temperature and vapour pressure. The SPX80 sample also had the smallest mass uptake in the liquid water permeability test (table 4.9). High levels of moisture can results in the formation of water droplets within the insulating material structure. Water has a high thermal conductivity and its build up in the foam structure results in a decrease in overall thermal insulation properties.

The amount of water that can penetrate into the structure of the foam by vapour condensation or by pure liquid water under a temperature gradient can be surprisingly high as values of over 100 % weight increase having been reported in the literature[78]. At such high levels of absorbed water, a relatively large number of foam cells must be substantially filled with liquid water. In immersion testing, by comparison, a closed cell foam structure like polyurethane and polystyrene gives a relatively high rate of water uptake in the early stages of the test but this rapidly reaches a plateau absorption value[79]. This was found with the EPEF foams samples during the tests. Condensation testing under vapour pressure gradients penetration can therefore be considered to be a more severe test protocol than immersion testing and has been stated to be more appropriate for construction applications such as roofing[80]. The driving force for water vapour diffusion through an insulating material can be very low in households. Liquid water will penetrate any insulation without this driving force, when insulation is directly exposed to water. This shows that insulating materials have to be protected entirely from direct water.

The nature of the RPS made it difficult to perform the WVP and LWP tests as water does not settle in this material, because PP and PE are water repellent and the samples were not closed at the sides of the specimens. Water could diffuse through the polyester coating in the samples. This indicates that, the problems encountered by insulation due to water settling in them, will be relatively low with the RPS samples.

5.6.2 FIRE RETARDANCY

Combustion is the process where the polymer vapour reacts chemically with oxygen in the reaction zone of the flame, generating heat and products of complete and incomplete combustion. The effective heat of combustion (EHC) is a measure of the efficiency with which the emitted gaseous products are combusted. A lower EHC indicates a less efficient combustion process in the gas phase, suggesting better flame retardancy in the material. The heat release rate (HRR) is one the most important parameters for characterising a material's fire behaviour. It is an indicator of the rate of fire growth and the intensity of the fire. A more effective fire retardant has a lower HRR. Release rates of heat and the products of complete of combustion (CO_2) increase with a decrease in oxygen available, whereas the release of products of incomplete combustion (smoke and CO) increase with an increase in the oxygen content. High smoke production rates (RSF) may be considered an indicator of incomplete combustion of volatile products. The CO to CO_2 ratio may be considered as an indicator of the degree of efficiency of the combustion process. A high CO with respect to CO_2 confirms an inefficient combustion[82].

The key results are the heat release rate data. The lowest HRR value within the EPEF samples was recorded for SPX25 while SPX80 have the highest HRR value. Even though the SPX80 shows a rapid release of HRR after a rapid ignition, the curve in figure 4.20 indicates that SPX80 is the only material within the EPEF samples that forms a relatively large trough (or a slowing down in the HRR) after the maximum HRR peak. The trough suggests the formation of a charred layer which interrupts the ingress of air to the burning SPX80 thermal insulating material. The relatively low rate of smoke formation after rapid ignition and low CO relative to CO_2 during the main weight loss period indicates an efficient burning process during this time. The SPX80 had a longest time with respect to the lowest mass loss rate. Therefore the HRR curve for the SPX80 shows a long period of relatively low smouldering, during which the CO production is relatively low, compared to other EPEF samples. The results show that SPX80 does not burn with a great intensity compared to the other EPEF samples. The EHC values for the EPEF samples have plateaus at about 40-53 $MJ.kg^{-1}$, indicating a relatively efficient combustion process with respect to the RPS.

The recycled polymer slabs (RPS) go through a number of burning phases, after ignition which is relatively late compared to the EPEF materials. The HRR curve shows a trough (or slowing down in the HRR) suggesting the formation of a char layer which interrupts the ingress of air to the burning material. A second charred layer is formed again after the first as indicated by a slowing in the HRR. The shape of the HRR curve (figure 4.21) suggests the possibility of the third char layer just before the end of the burn. The peak HRR is relatively high at around 750 $kW.m^{-2}$. Another indicator of good and efficient burning of the RPS material is indicated by the relatively high effective heat of combustion, and a low CO with respect to CO_2. The EHC of the RPS material plateaus at about 35-40 $MJ.kg^{-1}$, indicating a relatively less efficient combustion, with respect to the EPEF samples.

5.7 MECHANICAL PROPERTIES

When a thermal insulating material is installed in a building it will experience some kind of mechanical loading. The three well known mechanical loadings that can be experienced by a thermal insulating material are creep, bending and compression. Creep, compression and bending (flexural) stresses are important factors to consider. This is because thermal insulating materials are subjected to creep when placed in roofs. Compression and flexural loading is experienced when loads are placed on these materials and may result in a loss in the insulating material properties. During this period of mechanical loading thermal insulating materials can loose their insulating properties.

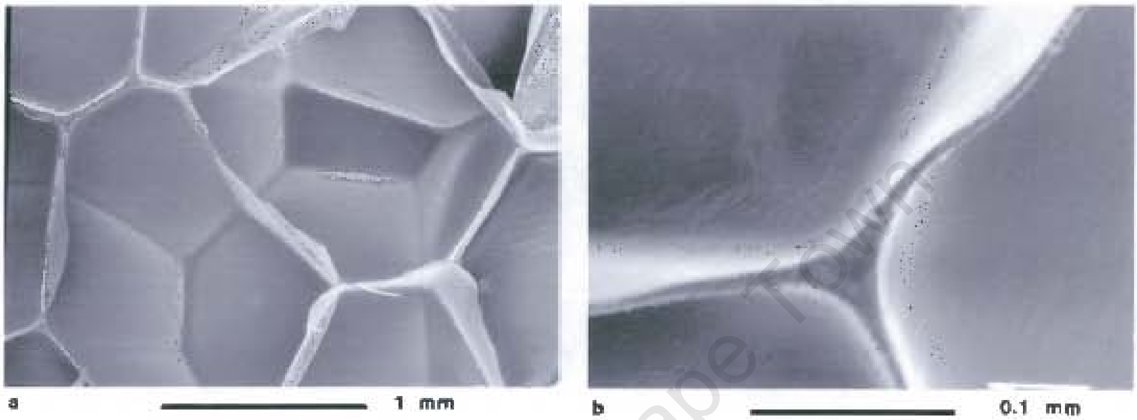

Figure 5.3: SEM micrographs of LDPE foam of density 24 kg.m^{-3} (a) complete cells showing the flat faces (b) section through an edge of the cell and the 2 adjoining faces[83].

Closed cell foams are complicated to study because the cell faces do not rupture during testing and there are contributions to the mechanical properties from the compression of the cell gas and from the stretching (tension) of the cell faces. Computer modelling software is mainly used to study and predict the behaviour of foamed polymeric materials. The polymer response in closed cell foams varies substantially. For example, low density polyethylene (LDPE) foams recover completely when the compressive stress is removed after some time. This indicates that the polymer response is viscoelastic for the LDPE samples and this is general for all the polymeric foams. Figure 5.3 shows a picture of the cells before and after the material was compressed. There is a little deformation in the cell structure where the cell separates (figure 5.3 (b)).

The same behaviour was exhibited by the EPEF samples as they recovered fully when the loading was removed. This indicates that if the EPEF samples experiences compression during application, they will loose their thermal insulating properties. However, they will regain the insulating properties as soon loading is removed because the cell structure will be filled with gas (air) again. SPX80 has the highest resistance to compressive loading compared to the other EPEF samples. This is because of its high density (80 $kg.m^{-3}$) as compared to other EPEF samples. The denser the polymeric material is in a foam structure the higher will be stretching along the face of the cells[83]. For approximately the same deflection as the EPEF sample, the recycled polymers slab has shown the highest resistance to compressive loading. The RPS compression test was stopped because the failure was sudden. The recycled PP and PE's original ductility has been reduced as a result of impurities and regrinding. These impurities were incorporated into the RPS during fusing. The woven glass fibres and the thermosetting resin in the RPS had increased the compression strength of the slab.

During flexural testing (bending) the samples experience tension (stretching) and compression at the same time. This test was done to see if the samples under investigation will require support during installation. This result will complement those from the creep tests. SPX80 has the highest flexural stress and flexural modulus as compared to other EPEF samples as a result of its high compression strength. All of the EPEF samples were stopped during these tests as they were deforming continuously after the maximum flexural strength was reached and this shows that they all have an elastic behaviour under tension. The RPS flexural stress and flexural modulus are very high as compared to the SPX80. The gypsum board flexural stress and flexural modulus values are higher than those of EPEF samples, but lower that the RPS values. The gypsum board was not evaluated for thermal properties, but for flexural support. Above their glass temperature, polymers show slow, permanent, time-dependant deformation (creep)[76]. Both SPX80 and RPS showed no deflection attributed to creep after 14 days of testing.

5.8 ECONOMICS OF INSULATION

Thermal insulation of buildings is a long term investment. This suggests that when selecting a thermal insulation material, the optimum results have to be achieved by using low cost thermal insulating materials with high R-values. Economical financial benefits are achieved when a thermal insulating material is used with the smallest thickness possible. When the thickness of an insulating material is increased for optimum results, then the cost of manufacturing it will also increase. An increase in the manufacturing cost will make the thermal insulating material more expensive. Computer software can be used to evaluate the optimum thickness for thermal insulating materials[53]. An alternative way that is not based on computer simulations was found and used. This was achieved by calculating the amount of energy that will be lost through a thermal insulating material and the corresponding amount of money that will be lost.

Table 4.10 shows the calculated R-values, heat lost through an insulating material (HFR) and Rand loss (RL) per unit area. This was calculated for all the EPEF samples, the RPS and EPS. EPS values were calculated for comparison purposes. Among the expanded polyethylene foams (EPEF samples), the SPX33FRA and SPX80 (34 mm) performed better in terms of the HFR and RL. The RPS has shown higher values of HFR and RL values compared to the SPX33FRA and SPX80. The HFR and RL values for the RPS, SPX33FRA and SPX80 are relatively higher than the expanded polystyrene's (EPS's) HFR and RL values. The R-values for the EPEF samples are higher than that of the RPS and relatively lower than that of the EPS.

CHAPTER 6

CONCLUSIONS

Based on the study undertaken the following conclusions can be drawn:

- The properties of thermal insulating materials are complex and difficult to evaluate and measure. The most significant properties that cause a material to be a good insulator are the thermal conductivity (k-value), thermal resistance (R-value), combustibility, density and moisture resistance. The thermal performance of the thermal insulating material is sensitive to small changes in one of these properties and could lead to a poor performance of the thermal insulating material. There are three main different forms of thermal insulating materials on the South African market, *viz*: reflective, resistive and composite. Aluminium foil is the only reflective metal that is used in the development of reflective thermal insulation products. Polyester, glass fibre and styrene (foamed) are the most commonly used materials in the construction of resistive thermal insulating products. Composite thermal insulating materials developed for the South African market are mainly a combination of reflective and resistive insulating materials.
- The procedure in the production of a low-cost thermal insulating material is rather challenging. Polymeric materials have the excellent thermal properties compared to any other solid materials. Their thermal properties are enhanced when they are foamed. In the production of the recycled polymers slabs (RPS) a relatively low technology process was used. The RPS is affordable when compared to Sondor's SPX80 (expanded polyethylene) product, for example. The recycled polymers slab (RPS) and SPX80 are relatively low in cost, practically safe, and moisture resistant developed thermal insulating materials. When RPS and SPX80 are used together with the gypsum board during installation they will not combust. The RPS and SPX80 as thermal insulating materials will reduce energy heating costs and increase the comfort levels in houses where they are installed. These two

chosen thermal insulating materials, RPS and SPX80, have to be supported when in place, especially when installed in the roof. The compression and flexural strength of SPX80 are very low and no permanent loading stress must be present in service. The heat loss rate through SPX80 (18mm) and RPS (14mm) are relatively low and the Rand losses per unit area for these two samples are considerably low.

- The measurement of the thermal conductivity is highly complex. The comparative cut bar method is relatively cheap to design and it is ideal for the measurement of the polymeric based materials' thermal conductivity. The thermal conductivity of the expanded polystyrene was accurately measured using the comparative cut bar and accurate k-values of the RPS and EPEF samples were obtained.

RECOMMENDATIONS FOR FUTURE WORK

Based on the complex nature of the processes involved in the production of a low-cost thermal insulating material, the following recommendations are made:

- Although the recycled polypropylene and polyethylene have shown good results in developing a low-cost thermal insulating material, more research should be done on other remaining recycled polymer materials. This will further help to evaluate the possibility of finding a raw polymer based material that could also be applicable to a low-cost thermal insulating material.
- Foamed polymers have shown good thermal properties in this study. The recycled polymer slabs were not foamed using blowing agents, because the process is rather complex and needed time. A study should be conducted on finding an inexpensive process of using blowing agents to form a foamed structure. The foamed polymers were found to absorb moisture into their cells and this reduced the thermal performance of the materials. Even though moisture resistance mechanisms are rather expensive to be incorporated into the foamed thermal insulating material, a study should be conducted in order to find a cheap method of reducing the susceptibility of foamed thermal insulating materials to moisture.
- The chosen thermal insulating materials from the investigated samples are relatively flammable. Fire retardants are relatively expensive and alternative methods of reducing the flammability of this product should be investigated. A study should be conducted on the possibility of incorporating cheap fire retardants into the thermal insulating materials.

CHAPTER 8

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APPENDIX I

THE PROCEDURE TO MAKE A POLYMER SLAB

The procedure to be flowed to make slabs is as follows:

- Fill the mould with the material *e.g.* powder.
- Set the target pressure on the pressure gauge with the red needle. Put the mould on the metal base; insert the thermocouple into the bottom wall of the mould, and tighten the pressure release valve and jack up to the target pressure using the pressure-applying lever.
- Set the target temperature on the temperature controller. Heating begins as soon as the voltage is applied to the controller.
- The pressure continuously falls during heating. This must therefore be accordingly adjusted during the entire heating process.
- After heating for the required time, switch off the controller and open the tap for water to flow through the cooling pipes. Do not apply any pressure anymore.
- Once fully cooled, open the hydraulic release valve. Remove the mould and remove the sidewalls of the mould to remove the slab.

APPENDIX II

THE PROCEDURE OF USING THE HOT BOX

The house (hot-box) is divided into three portions:

- The roof
- Room A
- Room B

The light bulbs in the roof supply the heat to increase the temperature in the rooms. The temperature in each room is monitored by a small (Mini) thermometer, where the tip of the stem must protrude at least 30 mm into the room. Table.1 below tabulates the technical data for Mini-Thermometer.

Table 1. Technical data for the Mini-Thermometer

Measuring range	$-50...+150^{0}C$
Accuracy	$\pm 1^{0}C(-10...+100^{0}C)/ \pm 2^{0}C$ (rest of range)
Resolution	$0,1^{0}C(-19.9...-150^{0}C)/ \pm 1,0^{0}C$ (rest of range)
Measuring rate	1 sec
Material of stem	Stainless steel
Battery life	Approx.1 year

The temperature of the rooms and the roof is recorded after fixed time intervals, *e.g.* after every 15 minutes. Room A must totally be covered in the roof with the tested (insulating) material and Room B with the standard insulating material (gypsum board and Isotherm Polyester).

APPENDIX III

Temperature Comparison Tests

THE GRAPHICAL REPRESENTATION OF ALL THE SONDOR EPEF AND RPS THERMAL INSULATING MATERIALS SAMPLES FOR THE TEMPERATURE COMPARISON TESTS

Table 1. Tabulation of the average temperature (°C) values recorded for the recycled polymers slab during the temperature comparison test.

Time	Temperature (°C)			
	Roof	Standard Insulation Kit	Recycled Polymers Slab	Un-Insulated
0	18.8	17.9	18.0	18.0
15	40.3	18.5	18.4	25.3
30	45.6	19.4	19.5	28.1
45	49.7	20.5	20.7	29.7
60	51.7	21.3	21.8	31.3
75	53.6	22.0	22.5	32.3
90	54.6	22.5	23.2	33.0
105	56.2	23.0	23.9	35.1
120	57.8	23.3	24.3	36.0
135	61.2	23.6	24.7	37.5
150	65.5	23.8	25.1	38.3
165	69.1	24.1	25.4	38.9
180	70.0	24.2	25.6	40.2
195	70.8	24.4	25.8	40.3
210	72.0	24.5	25.9	40.9

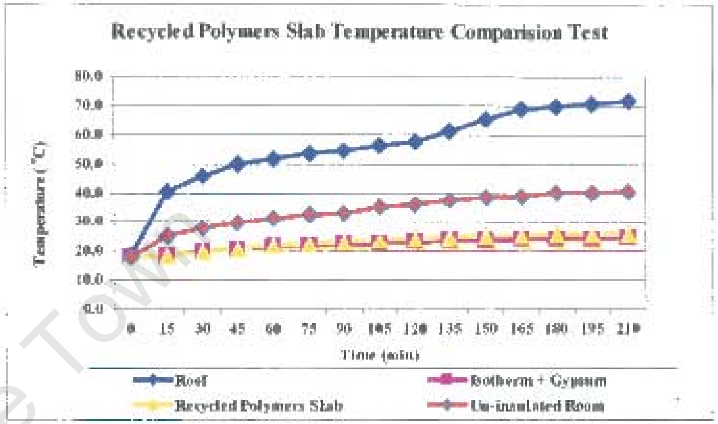


Figure 1: Temperature vs. time graph for the RPS (14mm).

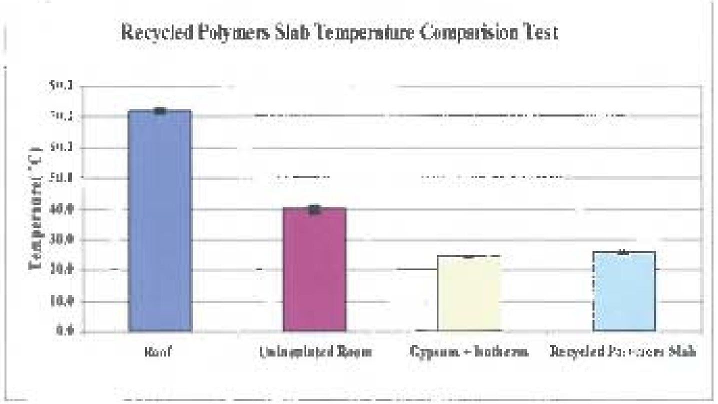
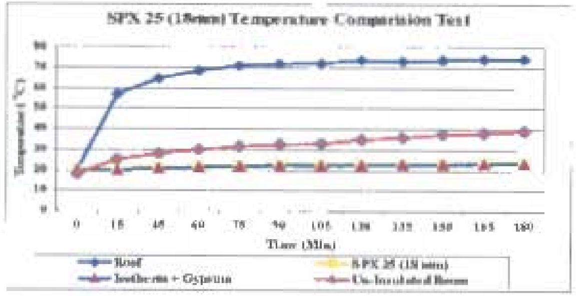
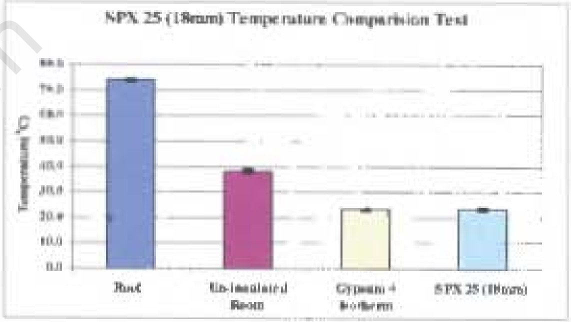


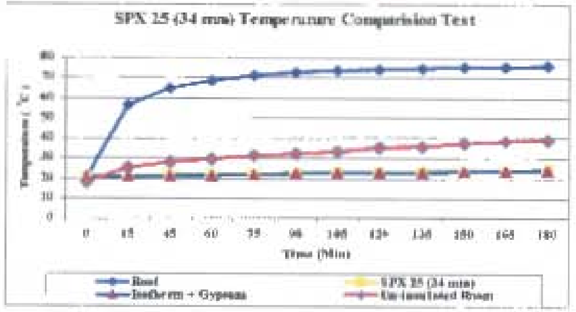
Figure 2: The bar chart representation of temperature comparison test for the RPS (14mm).

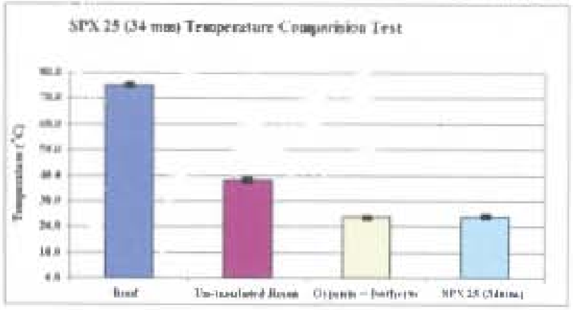
Time	Temperature (°C)			
	Roof	Standard Insulation Kit	SPX25 (18mm)	Un-Insulated
0	19.9	19.8	19.9	18.0
15	56.9	20.0	20.7	25.3
30	64.7	20.5	21.2	28.1
45	68.5	21.1	21.7	29.7
60	71.0	21.5	22.2	31.3
75	71.6	22.0	22.6	32.3
90	72.4	22.3	22.8	33.0
105	74.0	22.7	23.0	35.1
120	73.4	23.0	23.2	36.0
135	73.9	23.2	23.4	37.5
150	74.1	23.2	23.5	38.3
165	74.2	23.3	23.7	38.9

Time	Temperature (°C)			
	Roof	Standard Insulation Kit	SPX25 (34mm)	Un-Insulated
0	21.0	20.6	20.8	19.0
15	57.0	20.7	21.0	25.3
30	65.1	21.1	21.6	28.1
45	69.2	21.5	21.9	29.7
60	71.0	21.9	22.3	31.3
75	73.1	22.3	22.6	32.3
90	74.3	22.6	22.9	33.0
105	74.0	22.9	23.1	35.1
120	75.0	23.1	23.5	36.0
135	75.1	23.6	23.6	37.5
150	75.3	23.7	23.8	38.3
165	75.9	24.0	24.2	38.9



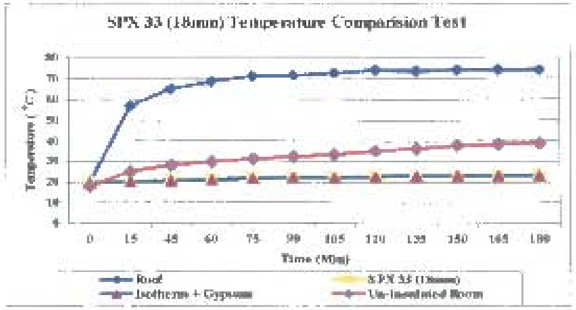


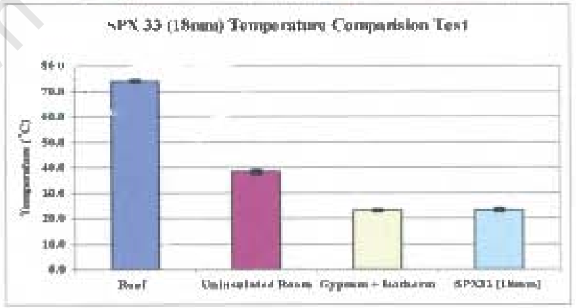


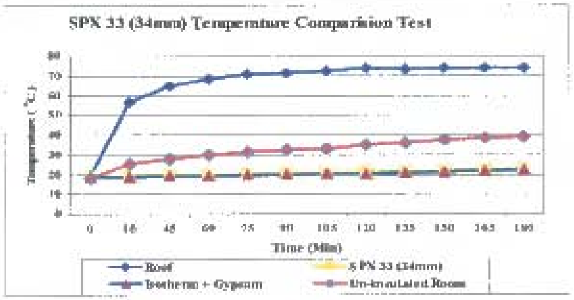


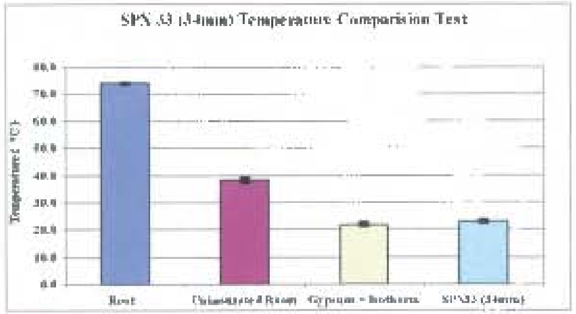
Time	Temperature (°C)			
	Roof	Standard Insulation Kit	SPX33 (18mm)	Un-Insulated
0	20.0	19.8	19.9	19.0
15	57.1	20.0	20.7	25.3
30	65.2	20.5	21.2	28.1
45	69.0	21.1	21.7	29.7
60	71.3	21.5	22.2	31.3
75	72.1	22.0	22.6	32.3
90	72.3	22.3	22.8	33.0
105	74.2	22.7	23.0	35.1
120	75.2	23.0	23.2	36.0
135	74.3	23.2	23.4	37.5
150	74.0	23.2	23.5	38.3
165	74.2	23.3	23.7	38.9

Time	Temperature (°C)			
	Roof	Standard Insulation Kit	SPX33 (34mm)	Un-Insulated
0	19.9	18.9	19.4	19.0
15	56.9	18.9	19.8	25.3
30	64.7	19.2	20.2	28.1
45	68.5	19.5	20.5	29.7
60	71.0	19.7	20.7	31.3
75	71.6	19.9	21.0	32.3
90	72.4	20.2	21.3	33.0
105	74.0	20.4	21.7	35.1
120	73.4	20.6	22.0	36.0
135	73.9	21.2	22.4	37.5
150	74.1	21.8	22.7	38.3
165	74.2	22.5	23.2	38.9



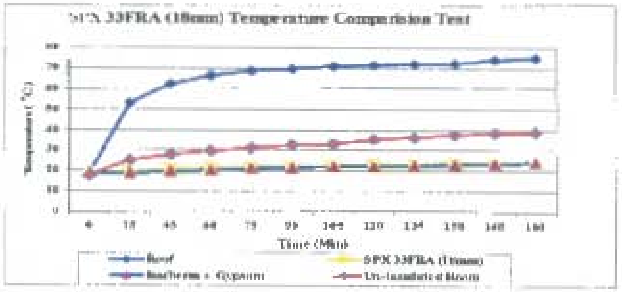


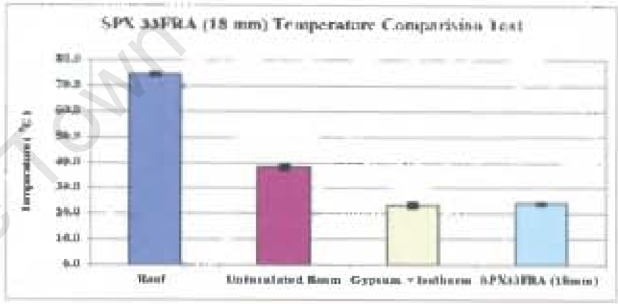


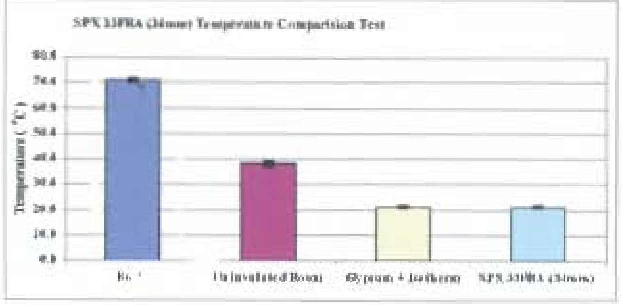


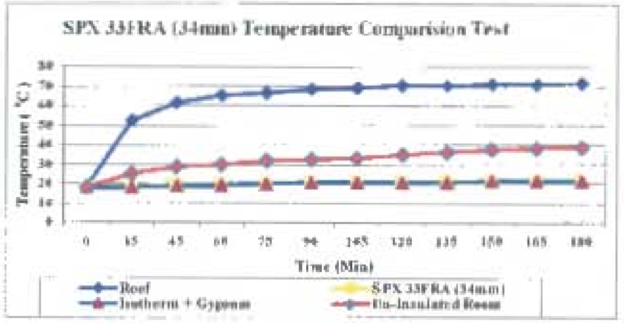
Time	Temperature (°C)			
	Roof	Standard Insulation Kit	SPX33FRA (18mm)	Un-Insulated
0	19.1	19.2	19.7	19.0
15	53.2	19.0	19.9	25.3
30	62.1	19.7	20.8	28.1
45	66.2	20.3	21.3	29.7
60	68.4	20.9	22.0	31.3
75	69.6	21.4	22.4	32.3
90	70.7	21.7	22.8	33.0
105	71.3	22.1	23.2	35.1
120	71.8	22.3	23.5	36.0
135	72.2	22.7	23.8	37.5
150	74.1	23.3	23.9	38.3
165	74.9	24.1	24.2	38.9

Time	Temperature (°C)			
	Roof	Standard Insulation Kit	SPX33FRA (34mm)	Un-Insulated
0	18.5	18.1	18.1	19.0
15	52.5	18.2	18.5	25.3
30	61.3	18.8	19.2	28.1
45	65.0	19.0	19.6	29.7
60	66.7	19.9	20.1	31.3
75	68.5	20.3	20.5	32.3
90	69.2	20.6	20.7	33.0
105	70.1	20.8	20.8	35.1
120	70.5	21.0	21.0	36.0
135	70.7	21.1	21.2	37.5
150	71.0	21.3	21.3	38.3
165	71.3	21.4	21.6	38.9









Time	Temperature (°C)			
	Roof	Standard Insulation Kit	SPX45 (18mm)	Un-Insulated
0	19.7	20.4	20.1	19.0
15	53.9	20.4	20.7	25.3
30	61.8	20.8	21.3	28.1
45	66.4	21.3	22.0	29.7
60	69.4	21.7	22.4	31.4
75	69.7	22.1	22.8	32.3
90	70.7	22.4	23.1	33.0
105	70.1	22.7	23.2	35.1
120	71.1	22.9	23.4	36.0
135	71.5	23.0	23.5	37.5
150	71.9	23.1	23.3	38.3
165	72.6	23.2	23.4	38.9

Time	Temperature (°C)			
	Roof	Standard Insulation Kit	SPX45 (34mm)	Un-Insulated
0	19.9	17.8	18.3	19.0
15	48.4	18.4	18.7	25.3
30	57.9	19.1	19.2	28.1
45	62.6	19.8	19.6	29.7
60	65.3	20.4	20.3	31.3
75	66.7	20.9	20.8	32.3
90	68.1	21.2	21	33.0
105	68.9	21.4	21.3	35.1
120	69.5	21.7	21.5	36.0
135	70.0	21.8	21.6	37.5
150	70.4	22.0	21.8	38.3
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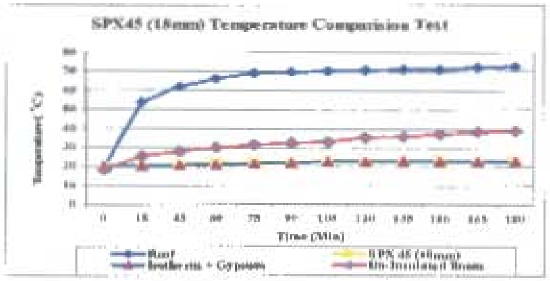
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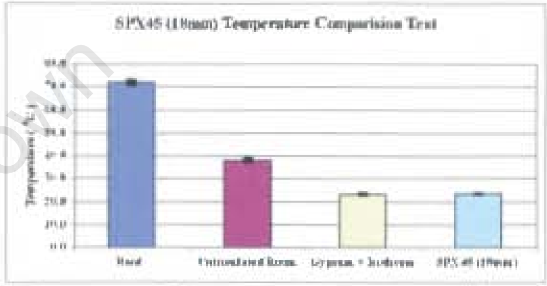
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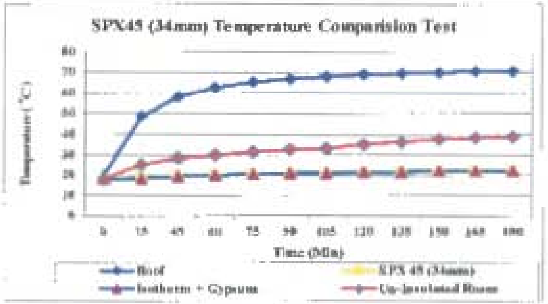
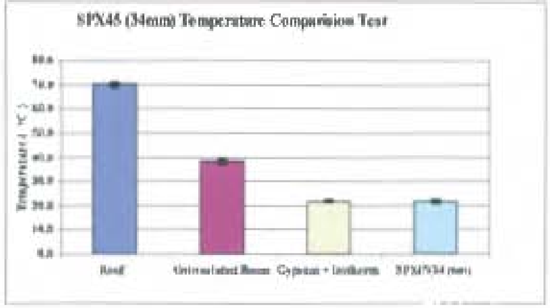
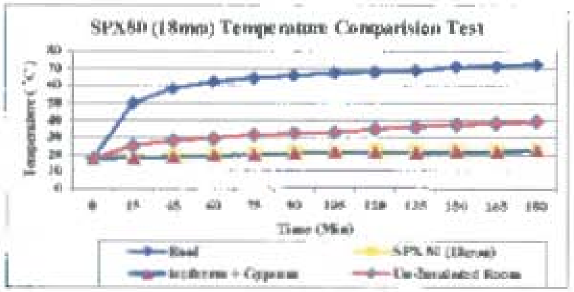
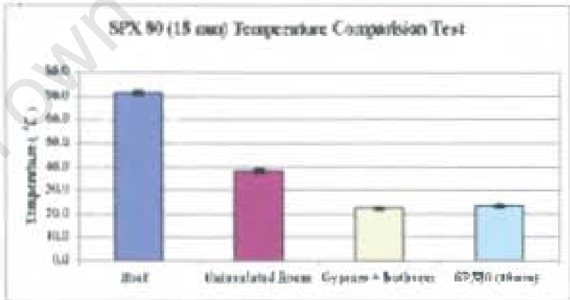

SPX45 (34mm) Temperature Comparision Test

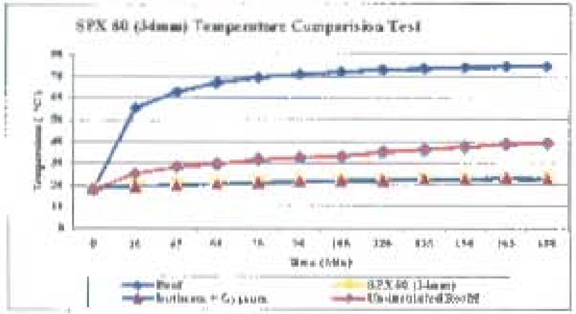

SPX45 (34mm) Temperature Comparision Test

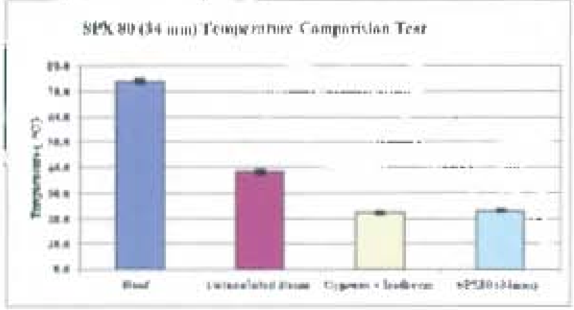
Time	Temperature (°C)			
	Roof	Standard Insulation Kit	SPX80 (18mm)	Un-Insulated
0	17.9	17.1	17.3	19.0
15	49.7	17.5	18.3	25.3
30	58.1	18.4	19.6	28.1
45	62.4	19.2	20.5	29.7
60	64.5	20.0	21.2	31.3
75	65.9	20.5	21.7	32.3
90	67.1	20.9	22.1	33.0
105	67.9	21.2	22.5	35.1
120	68.4	21.4	22.8	36.0
135	70.8	22.0	23.2	37.5
150	71.1	22.1	23.3	38.3
165	71.6	22.4	23.5	38.9

Time	Temperature (°C)			
	Roof	Standard Insulation Kit	SPX80 (18mm)	Un-Insulated
0	18.5	18.3	18.63	19.0
15	55.2	19.2	19.9	25.3
30	62.4	20.0	20.4	28.1
45	67.1	20.5	21.0	29.7
60	69.2	21.0	21.4	31.3
75	70.8	21.3	21.8	32.3
90	71.9	21.6	22.1	33.0
105	72.5	21.9	22.4	35.1
120	73.2	22.1	22.6	36.0
135	73.5	22.3	22.8	37.5
150	74.0	22.6	23.0	38.3
165	74.4	22.4	23.1	38.9









APPENDIX III

Temperature Comparison Tests

THE GRAPHICAL REPRESENTATION OF ALL THE SONDOR EPEF AND RPS THERMAL INSULATING MATERIALS SAMPLES FOR THE TEMPERATURE COMPARISON TESTS

Table 1. Tabulation of the average temperature (°C) values recorded for the recycled polymers slab during the temperature comparison test.

Time	Temperature (°C)			
	Roof	Standard Insulation Kit	Recycled Polymers Slab	Un-Insulated
0	18.8	17.9	18.0	18.0
15	40.3	18.5	18.4	25.3
30	45.6	19.4	19.5	28.1
45	49.7	20.5	20.7	29.7
60	51.7	21.3	21.8	31.3
75	53.6	22.0	22.5	32.3
90	54.6	22.5	23.2	33.0
105	56.2	23.0	23.9	35.1
120	57.8	23.3	24.3	36.0
135	61.2	23.6	24.7	37.5
150	65.5	23.8	25.1	38.3
165	69.1	24.1	25.4	38.9
180	70.0	24.2	25.6	40.2
195	70.8	24.4	25.8	40.3
210	72.0	24.5	25.9	40.9

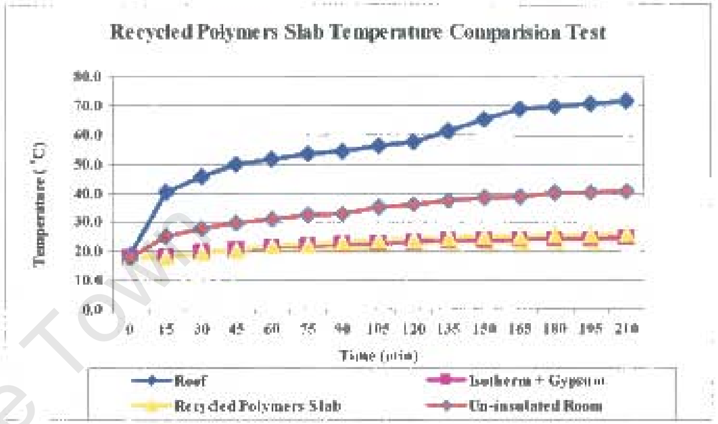


Figure 1: Temperature vs. time graph for the RPS (14mm).

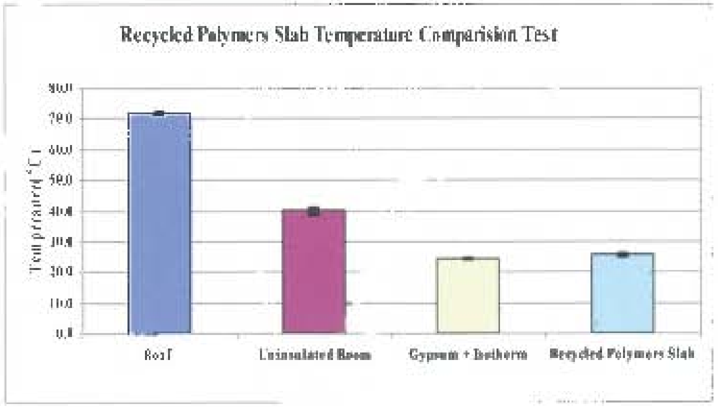
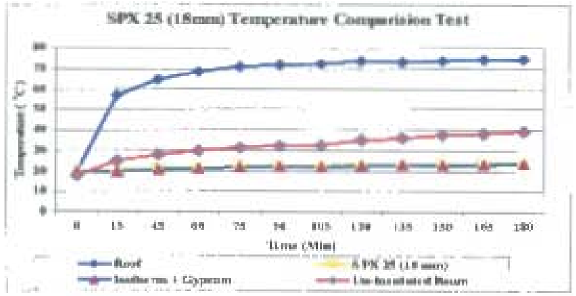
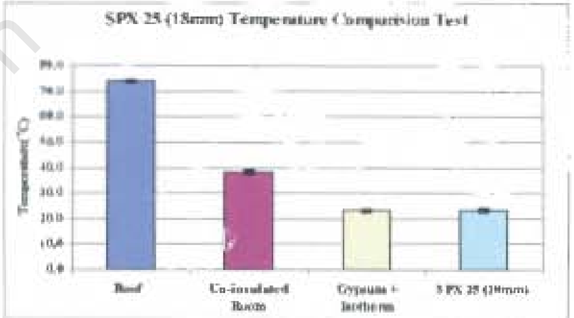


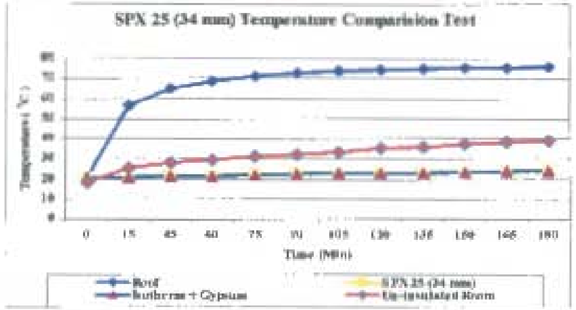
Figure 2: The bar chart representation of temperature comparison test for the RPS (14mm).

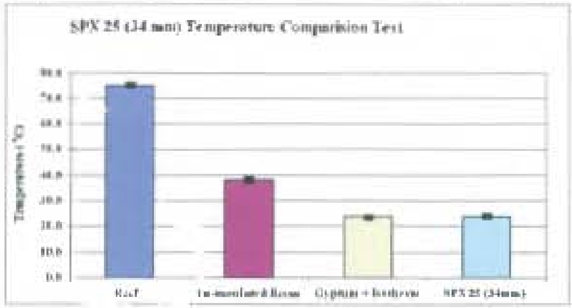
Time	Temperature (°C)			
	Roof	Standard Insulation Kit	SPX25 (18mm)	Un-Insulated
0	19.9	19.8	19.9	18.0
15	56.9	20.0	20.7	25.3
30	64.7	20.5	21.2	28.1
45	68.5	21.1	21.7	29.7
60	71.0	21.5	22.2	31.3
75	71.6	22.0	22.6	32.5
90	72.4	22.3	22.8	33.0
105	74.0	22.7	23.0	35.1
120	73.4	23.0	23.2	36.0
135	73.9	23.2	23.4	37.5
150	74.1	23.2	23.5	38.3
165	74.2	23.3	23.7	38.9

Time	Temperature (°C)			
	Roof	Standard Insulation Kit	SPX25 (34mm)	Un-Insulated
0	21.0	20.6	20.8	19.0
15	57.0	20.7	21.0	25.3
30	65.1	21.1	21.6	28.1
45	69.2	21.5	21.9	29.7
60	71.0	21.9	22.3	31.3
75	73.1	22.3	22.6	32.3
90	74.3	22.6	22.9	33.0
105	74.0	22.9	23.1	35.1
120	75.0	23.1	23.5	36.0
135	75.1	23.6	23.6	37.5
150	75.3	23.7	23.8	38.3
165	75.9	24.0	24.2	38.9



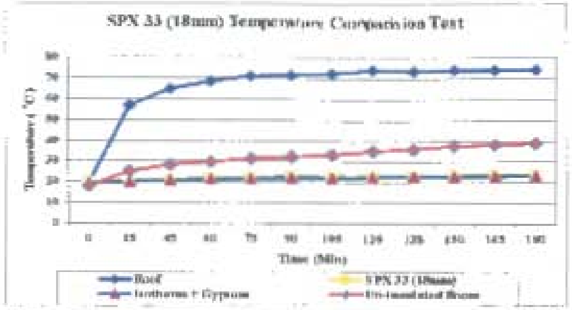


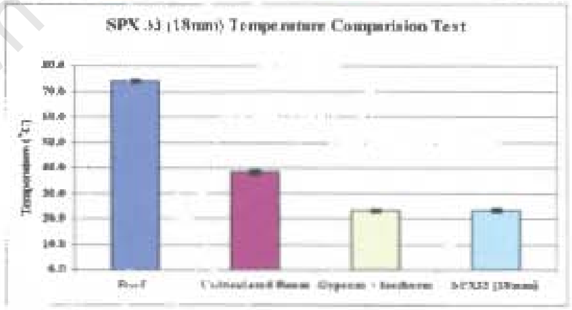




Time	Temperature (°C)			
	Roof	Standard Insulation Kit	SPX33 (18mm)	Un-Insulated
0	20.0	19.8	19.9	19.0
15	57.1	20.0	20.7	25.3
30	65.2	20.5	21.2	28.1
45	69.0	21.1	21.7	29.7
60	71.1	21.5	22.2	31.3
75	72.1	22.0	22.6	32.3
90	72.3	22.3	22.8	33.0
105	74.2	22.7	23.0	35.1
120	73.2	23.0	23.2	36.0
135	74.3	23.2	23.4	37.5
150	74.0	23.2	23.5	38.3
165	74.2	23.3	23.7	38.9

Time	Temperature (°C)			
	Roof	Standard Insulation Kit	SPX33 (34mm)	Un-Insulated
0	19.9	18.9	19.4	19.0
15	56.9	18.9	19.8	25.3
30	64.7	19.2	20.2	28.1
45	68.5	19.5	20.5	29.7
60	71.0	19.7	20.7	31.3
75	71.6	19.9	21.0	32.3
90	72.4	20.2	21.3	33.0
105	74.0	20.4	21.7	35.1
120	73.4	20.6	22.0	36.0
135	73.9	21.2	22.4	37.5
150	74.1	21.8	22.7	38.3
165	74.2	22.5	23.2	38.9


SPX 33 (18mm) Temperature Comparision Test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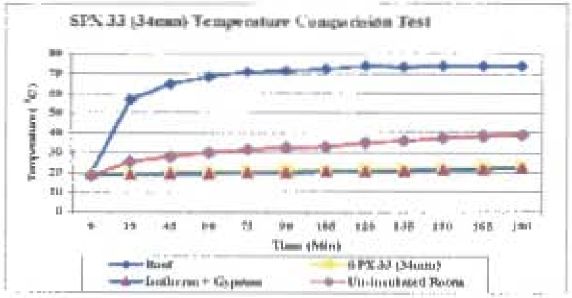
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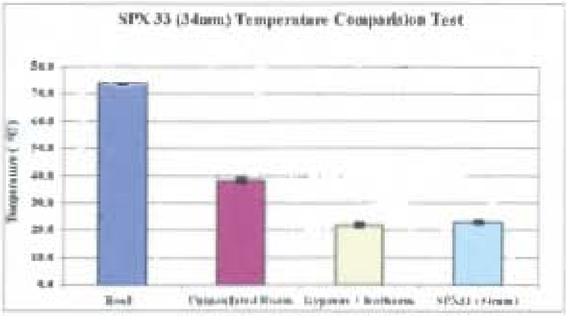
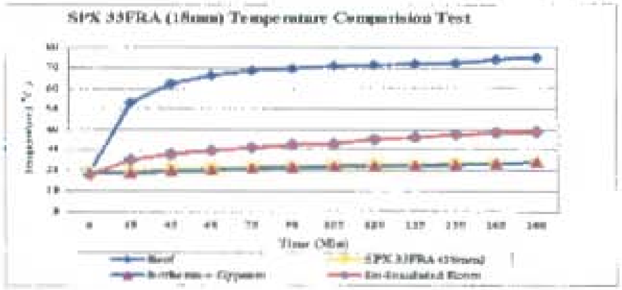
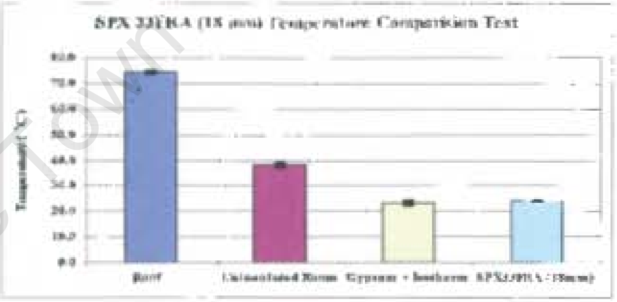
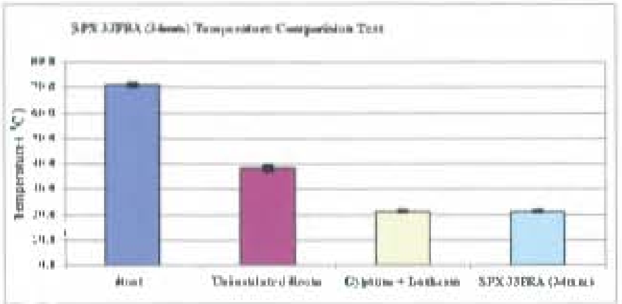

SPX 33 (34mm) Temperature Comparision Test

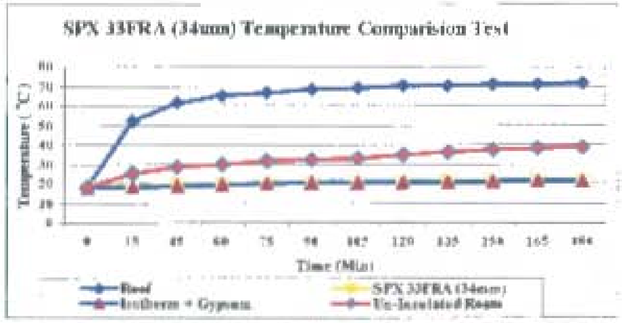
Time	Temperature (°C)			
	Roof	Standard Insulation Kit	SPX33FRA (18mm)	Un-Insulated
0	19.1	19.2	19.7	19.0
15	53.2	19.0	19.9	25.3
30	62.1	19.7	20.8	28.1
45	66.2	20.3	21.3	29.7
60	68.4	20.9	22.0	31.3
75	69.6	21.4	22.4	32.3
90	70.7	21.7	22.8	53.0
105	71.3	22.1	23.2	35.1
120	71.8	22.3	23.5	36.0
135	72.2	22.7	23.8	37.5
150	74.1	23.3	23.9	38.3
165	74.9	24.1	24.2	38.9

Time	Temperature (°C)			
	Roof	Standard Insulation Kit	SPX33FRA (34mm)	Un-Insulated
0	18.5	18.1	18.4	19.0
15	52.5	18.2	18.5	25.3
30	61.3	18.8	19.2	28.1
45	65.0	19.0	19.6	29.7
60	66.7	19.9	20.1	31.3
75	68.5	20.3	20.5	32.3
90	69.2	20.6	20.7	33.0
105	70.1	20.8	20.8	35.1
120	70.5	21.0	21.0	36.0
135	70.7	21.1	21.2	37.5
150	71.0	21.3	21.3	38.3
165	71.3	21.4	21.6	38.9

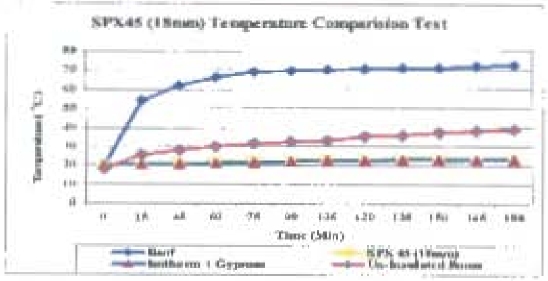


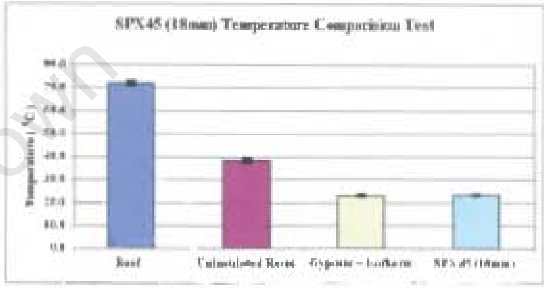




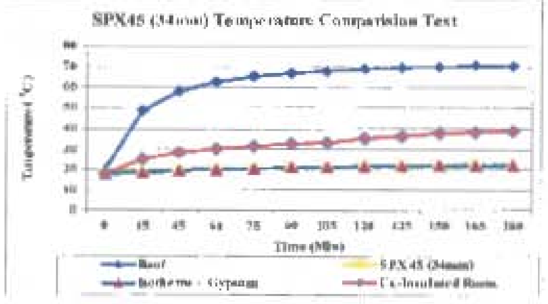


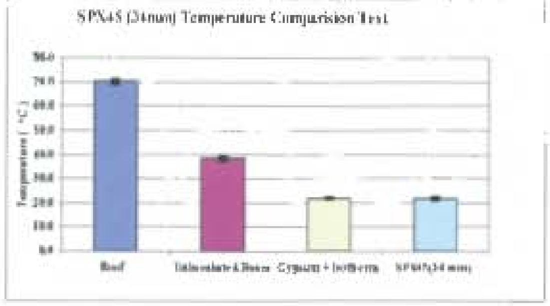
Time	Temperature (°C)			
	Roof	Standard Insulation Kit	SPX45 (18mm)	Un-Insulated
0	19.7	20.1	20.1	19.0
15	53.9	20.4	20.7	25.3
30	61.8	20.8	21.5	28.1
45	66.4	21.3	22.0	29.7
60	69.4	21.7	22.4	31.3
75	69.7	22.1	22.8	32.3
90	70.7	22.4	23.1	33.0
105	70.1	22.7	23.2	35.1
120	71.1	22.9	23.4	36.0
135	71.3	23.0	23.5	37.5
150	71.9	23.1	23.3	38.3
165	72.6	23.2	23.4	38.9





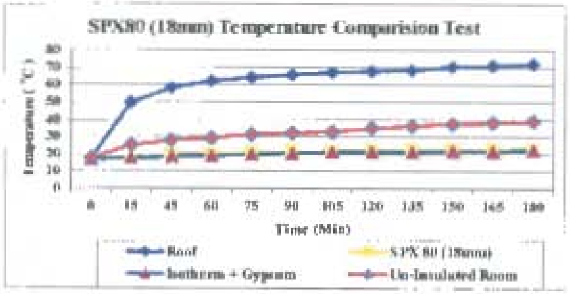
Time	Temperature (°C)			
	Roof	Standard Insulation Kit	SPX45 (34mm)	Un-Insulated
0	19.9	17.8	18.3	19.0
15	48.4	18.4	18.7	25.3
30	57.9	19.1	19.2	28.1
45	62.6	19.8	19.8	29.7
60	65.3	20.4	20.3	31.3
75	66.7	20.9	20.8	32.3
90	68.1	21.2	21	33.0
105	68.9	21.4	21.3	35.1
120	69.5	21.7	21.5	36.0
135	70.0	21.8	21.6	37.5
150	70.4	22.0	21.8	38.3
165	70.7	22.1	22.0	38.9

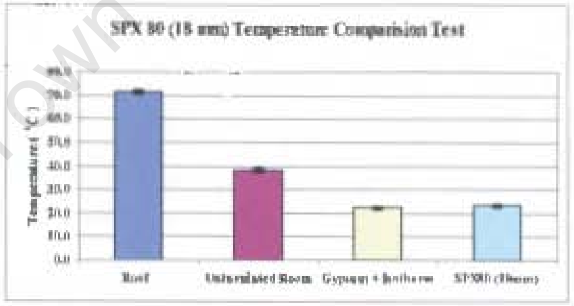


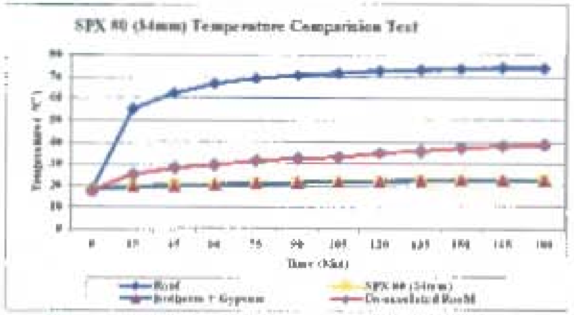


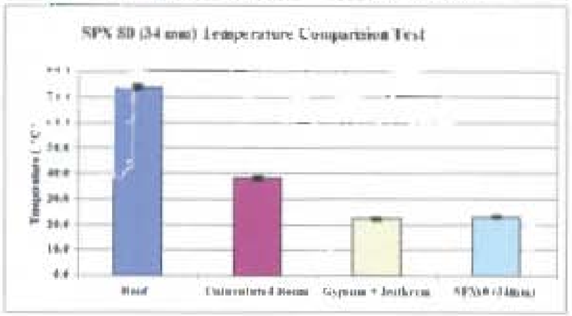
Time	Temperature (°C)			
	Roof	Standard Insulation Kit	SPX80 (18mm)	Un-Insulated
0	17.9	17.1	17.3	19.0
15	49.7	17.5	18.3	25.3
30	58.1	18.4	19.6	28.1
45	62.4	19.2	20.5	29.7
60	64.5	20.0	21.2	31.3
75	65.9	20.5	21.7	32.3
90	67.1	20.9	22.1	33.0
105	67.9	21.2	22.5	35.1
120	68.4	21.4	22.8	36.0
135	70.8	22.0	23.2	37.5
150	71.1	22.1	23.3	38.3
165	71.6	22.4	23.5	38.9

Time	Temperature (°C)			
	Roof	Standard Insulation Kit	SPX80 (18mm)	Un-Insulated
0	18.5	18.3	18.63	19.0
15	55.2	19.2	19.9	25.3
30	62.4	20.0	20.4	28.1
45	67.1	20.5	21.0	29.7
60	69.2	21.0	21.4	31.3
75	70.8	21.3	21.8	32.3
90	71.9	21.6	22.1	33.0
105	72.5	21.9	22.4	35.1
120	73.2	22.1	22.6	36.0
135	73.5	22.3	22.8	37.9
150	74.0	22.6	23.0	38.3
165	74.4	22.4	23.1	38.9


SPX80 (18mm) Temperature Comparision Test


SPX 80 (18 mm) Temperature Comparision Test


SPX 80 (34mm) Temperature Comparision Test


SPX 80 (34 mm) Temperature Comparision Test

APPENDIX IV

Thermal Conductivity Calculations Data

Temperatures (°C) values recorded using the constructed thermal conductivity rig for the samples and EPS																					
	RPS			SPX25			SPX33			SPX33FRA			SPX45			SPX80			EPS		
	1st Set	2nd Set	3rd Set	1st Set	2nd Set	3rd Set	1st Set	2nd Set	3rd Set	1st Set	2nd Set	3rd Set	1st Set	2nd Set	3rd Set	1st Set	2nd Set	3rd Set	1st Set	2nd Set	3rd Set
T_1	62.3	57.1	58.6	49.8	52.4	49.3	54.4	53.8	53.6	61.0	65.4	62.7	43.0	64.3	54.2	66.9	61.5	59.3	64.0	64.2	64.7
T_2	48.6	44.5	45.9	41.9	44.6	42.0	45.9	45.4	45	51.4	54.4	50.8	36.4	51.9	45.1	57.6	53.2	48.9	50.4	50.4	51.2
T_3	40.6	37.5	38.9	36.5	38.8	37.3	40.1	39.8	39.5	43.0	45.5	41.5	31.6	43.2	38.3	50.6	47.1	40.7	41.6	41.3	42.2
T_4	32.8	31.0	32.6	32.3	34.1	33.5	36.4	36.1	35.7	36.8	38.9	34.7	28.1	36.4	33.0	46.0	43.0	34.5	34.5	33.9	35.1
Where $\Delta T_1 = T_1 - T_2$, $\Delta T_s = T_2 - T_3$, $\Delta T_2 = T_3 - T_4$																					

Recycled Polymers Slab (RPS)

Thermal Conductivity of the standard (k_R=0.04W/mK) And the formula used in calculating the thermal conductivity of RPS : $k_s = k_R \times (\Delta T_1 + \Delta T_2)/2\Delta T_s$	First Set of Temperatures (°C)		Second Set of Temperatures (°C)		Third Set of Temperatures (°C)	
	ΔT_1	13.7	ΔT_1	12.6	ΔT_1	12.7
	ΔT_s	8.0	ΔT_s	7.0	ΔT_s	7.0
	ΔT_2	7.8	ΔT_2	6.5	ΔT_2	6.3
Calculated k_{RPS} (Recycled Polymers Slab) (W/mK)	0.054		0.055		0.054	
Average k_{RPS} (W/mK)	0.054					

Expanded Polyethylene Foam (SPX25)

Thermal Conductivity of the standard (k_R=0.04W/mK) And the formula used in calculating the thermal conductivity of SPX25 : $k_s = k_R \times (\Delta T_1 + \Delta T_2)/2\Delta T_s$	First Set of Temperatures (°C)		Second Set of Temperatures (°C)		Third Set of Temperatures (°C)	
	ΔT_1	13.7	ΔT_1	12.6	ΔT_1	12.7
	ΔT_s	8.0	ΔT_s	7.0	ΔT_s	7.0
	ΔT_2	7.8	ΔT_2	6.5	ΔT_2	6.3
Calculated k_{SPX25} (SPX25) (W/mK)	0.054		0.055		0.054	
Average k_{SPX25} (W/mK)	0.054					

Expanded Polyethylene Foam (SPX33)

Thermal Conductivity of the standard (k_R=0.04W/mK) And the formula used in calculating the thermal conductivity of SPX33 : $k_s = k_R \times (\Delta T_1 + \Delta T_2)/2\Delta T_s$	First Set of Temperatures (°C)		Second Set of Temperatures (°C)		Third Set of Temperatures (°C)	
	ΔT_1	8.5	ΔT_1	8.4	ΔT_1	8.6
	ΔT_s	5.8	ΔT_s	5.6	ΔT_s	5.5
	ΔT_2	3.7	ΔT_2	3.7	ΔT_2	3.8
Calculated k_{SPX33} (SPX33) (W/mK)	0.042		0.045		0.045	
Average k_{SPX33} (W/mK)	0.045					

Expanded Polyethylene Foam (SPX33FRA)

Thermal Conductivity of the standard (k_R=0.04W/mK) And the formula used in calculating the thermal conductivity of SPX33FRA: $k_s = k_R \times (\Delta T_1 + \Delta T_2)/2\Delta T_s$	First Set of Temperatures (°C)		Second Set of Temperatures (°C)		Third Set of Temperatures (°C)	
	ΔT_1	9.6	ΔT_1	11.0	ΔT_1	11.9
	ΔT_s	8.4	ΔT_s	8.9	ΔT_s	9.3
	ΔT_2	6.2	ΔT_2	6.6	ΔT_2	6.8
Calculated $k_{SPX33FRA}$ (SPX33FRA) (W/mK)	0.038		0.040		0.040	
Average $k_{SPX33FRA}$ (W/mK)	0.039					

Expanded Polyethylene Foam (SPX45)

Thermal Conductivity of the standard (k_R=0.04W/mK) And the formula used in calculating the thermal conductivity of SPX45: $k_s = k_R \times (\Delta T_1 + \Delta T_2)/2\Delta T_s$	First Set of Temperatures (°C)		Second Set of Temperatures (°C)		Third Set of Temperatures (°C)	
	ΔT_1	6.6	ΔT_1	12.4	ΔT_1	9.1
	ΔT_s	4.8	ΔT_s	8.7	ΔT_s	6.8
	ΔT_2	5.5	ΔT_2	6.8	ΔT_2	5.3
Calculated k_{SPX45} (SPX45) (W/mK)	0.042		0.044		0.042	
Average k_{SPX45} (W/mK)	0.043					

Expanded Polyethylene Foam (SPX80)

Thermal Conductivity of the standard (k_R=0.04W/mK) And the formula used in calculating the thermal conductivity of SPX80: $k_s = k_R \times (\Delta T_1 + \Delta T_2)/2\Delta T_s$	First Set of Temperatures (°C)		Second Set of Temperatures (°C)		Third Set of Temperatures (°C)	
	ΔT_1	9.3	ΔT_1	8.3	ΔT_1	10.4
	ΔT_s	7.0	ΔT_s	6.1	ΔT_s	6.2
	ΔT_2	4.6	ΔT_2	4.1	ΔT_2	6.2
Calculated k_{SPX80} (SPX80) (W/mK)	0.040		0.041		0.040	
Average k_{SPX80} (W/mK)	0.040					

Expanded Polyethylene Foam (EPS)

Thermal Conductivity of the standard (k_R=0.04W/mK) And the formula used in calculating the thermal conductivity of EPS : $k_s = k_R \times (\Delta T_1 + \Delta T_2)/2\Delta T_s$	First Set of Temperatures (°C)		Second Set of Temperatures (°C)		Third Set of Temperatures (°C)	
	ΔT_1	13.6	ΔT_1	13.8	ΔT_1	13.5
	ΔT_s	8.8	ΔT_s	9.1	ΔT_s	9.0
	ΔT_2	7.1	ΔT_2	7.4	ΔT_2	7.1
Calculated k_{EPS} (EPS) (W/mK)	0.047		0.047		0.046	
Average k_{EPS} (W/mK)	0.047					

APPENDIX V

Name and Function Component for the Portable Hybrid Recorder (Model 3087)

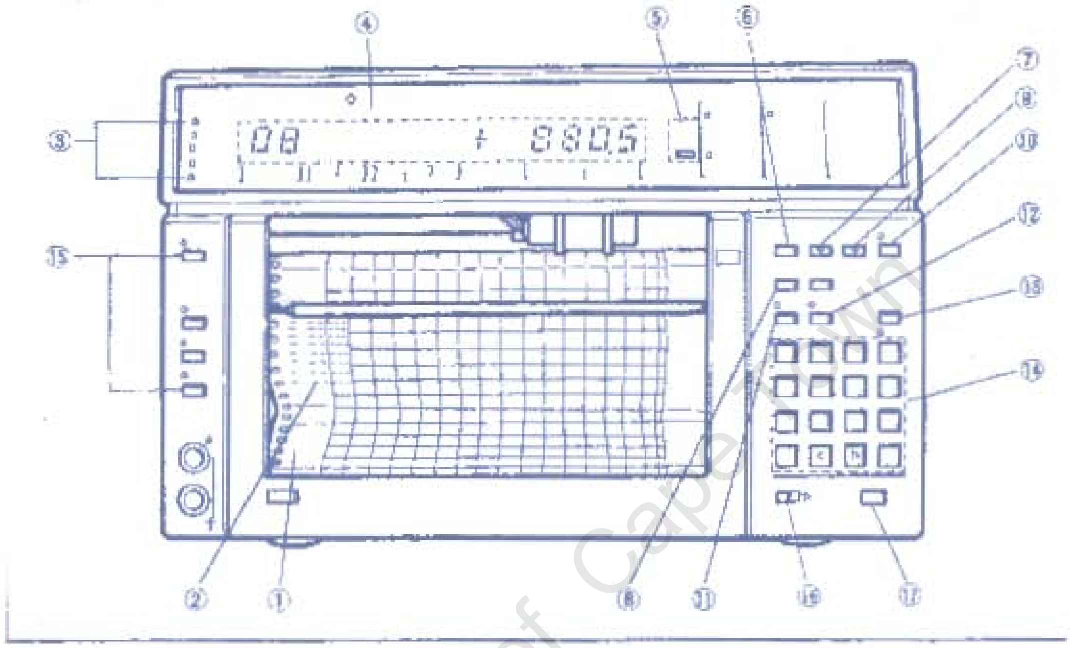


Figure 3-1. Names and Functions of Components (1).

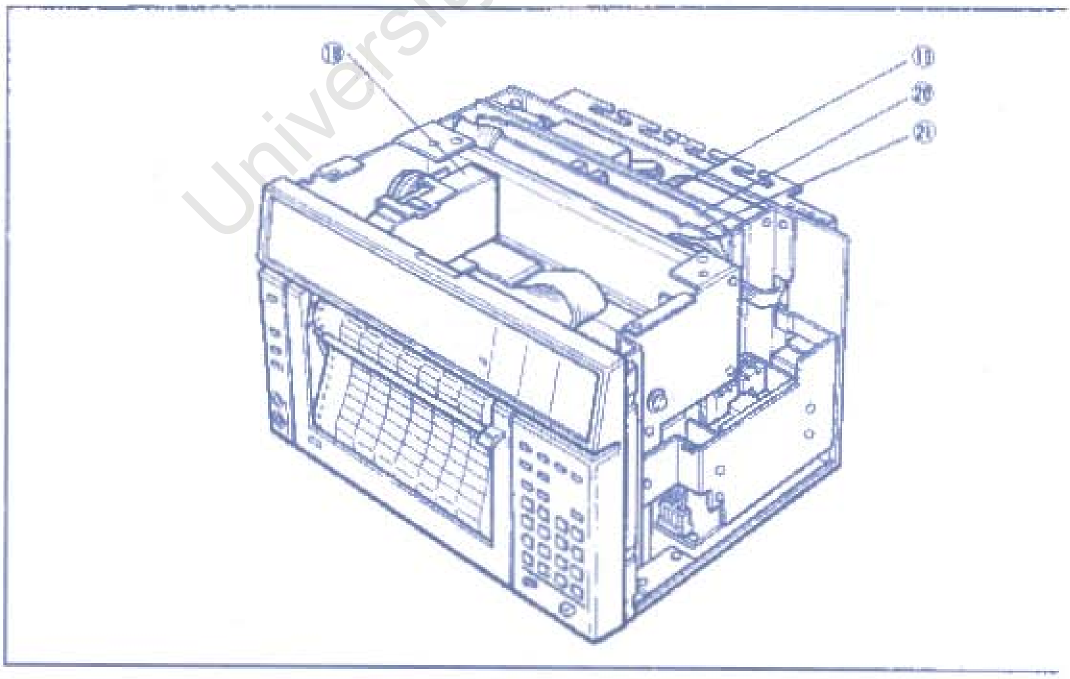


Figure 3-2. Names and Functions of Components (2).

① Chart

2-fold chart (total width 210 mm, analog recording width 150 mm, digital printing approx. 20 mm in the left margin of the chart, total chart length 16 m) 100 uniform divisions.

② Digital measurement data printout

Measurement data are also digitally printed in the left margin of the chart. Such digital printing is executed automatically at fixed time intervals e.g. hourly (depends on the selected chart speed)

Relationships between Chart Speeds and Printouts.

Chart speed (mm/h)	CH No.	Date, Chart speed, Measurement data	Alarm Setpoint
1 to 9	printable	unprintable	printable
10 to 500	printable	printable	printable
501 to 1200	unprintable	unprintable	unprintable

Digital Measurement Data Printing Interval

Chart speed (mm/h)	Digital measurement data printing interval (h)
10 to 24	12
25 to 49	4
50 to 99	2
100 to 500	1

③ LED indicators

(1) ALARM: When any of the preset alarm conditions occurs, the red "ALARM" LED indicator lights.

(2) FAIL: The red "FAIL" LED indicator lights if the recorder function is abnormality.

(3) BATTERY: When the batteries for memory back-up are exhausted, the red "BATTERY" LED indicator flashes (batteries back up the memory for approx. three months).

(4) CHART: The red "CHART" LED indicator lights when chart end is sensed. Recording stops when the chart is fed 60 mm after this indicator lights.
When the CHART FEED key is pressed after this indicator lights, recording stops immediately. However, after the RENEW CHART mark on the chart paper, the LED becomes possible to operate occasionally ON/OFF

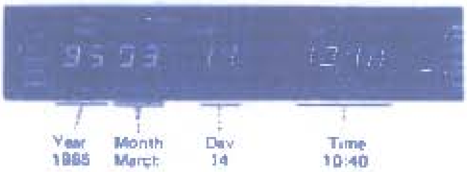
(5) REMOTE: The green "REMOTE" LED indicator lights when remote control is executed via the GP-IB interface bus (optional).

④ Displays

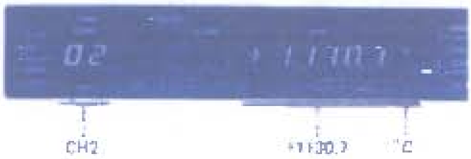
Year/month/day, time, measured data, chart speeds and various settings are displayed (LED 13 digits).

Examples:

(1) Year/month/day and time display
10:40 AM, March 14, 1985



(2) Data display Channel No. 2, 1130.7°C



⑤ Engineering Unit Display

Any one of the following engineering units lights according to the measuring range. However, when time, chart speed or scanning interval is displayed, engineering unit does not light.

mV	V
°C	°F
Ω	kΩ
MΩ	■

Lights when "scaling" set in performed.

Figure 3-3. Engineering Unit Display.

⑥ Mode Selector Key (MODE)

(1) TREND:
When MODE key is pressed and "TREND" LED indicator lights, the TREND mode is set.
When the TREND mode is set, analog printing and analog/digital printing can be executed.

(2) LOGGING:
When MODE key is pressed and "LOGGING" LED indicator lights, the LOGGING mode is set.
When the LOGGING mode is set, digital printing can be executed at fixed intervals.

⑦ Display Selector Key (DISPLAY)

Pressing DISPLAY key, you can select display any of DATA (AUTO), DATA (MAN) and CLOCK.

(1) DATA (AUTO): Displays CH No. and measurement data in order at 3 second intervals.

(2) DATA (MAN): Displays data only for the CH currently designated by the CH key. Pressing the CH key allows CH Nos. to be processively incremented, and the desired CH is called.

(3) CLOCK: Displays the year, month, day and time.

⑧ Scanning Interval Selector Key (SCAN)

By pressing SCAN key, either AUTO or FIX (5S) mode can be selected.

(1) AUTO: In TREND mode, the scanning period varies with the chart speed. Recording chart is fed 0.25 mm each scan. In LOGGING mode, input scanning is performed every scanning interval.

(2) FIX (5S): Keeps the scanning period constant (5 seconds) regardless of the chart speed selected.

⑨ **Data Set Selector Key (SET)**

By pressing SET key, any of RANGE, ALARM CLOCK, CHART SP/INTVL and **PRINT TIME** setting can be selected.

(1) RANGE: Measuring input range can be selected.

(2) ALARM: Alarm setting can be performed.

(3) CLOCK: Year, month, day and time may be set.

(4) CHART SP/INTVL: In TREND mode, chart speeds (at any point between 1 and 1200 mm/h) can be selected.
In LOGGING mode, intervals to print out measurement data (digital) on the chart can be set (for 1 min to 24h: in min unit).

(5) PRINT TIME. In TREND mode, the digital printout time can be set in minutes at any time. The digital printout interval complies with Item (2) above.

⑩ **LIST Key (LIST)**

The LIST key permits measuring range, alarm setting of each channel, chart speed, date and time, to be printed out on the chart paper.

⑪ **PRINT Key (PRINT)**

The PRINT key permits, analog/digital or digital printing. Printing operation (both in TREND and LOGGING modes) is possible only when the LED indicator lights. By pressing this key, input scanning is performed once.

⑫ **MAN PRINT Key (MAN PRINT)**

Digitally prints measurement data of all channel (except for SKIP CH.).

⑬ **CHART FEED Key (CHART FEED)**

The CHART FEED key permits chart feeding.

⑭ **Data Set Keys**

(1) SHIFT Key (SHIFT): When the LED above the SHIFT key lights, the characters and mark above the numeral keys are effective.

(2) Numeral Keys (0 to 9): Numeric characters (0 to 9) can be set. In addition, these keys allow alphabetic characters A to F, H, L, and P to be set with the **SHIFT** key pressed.

(3) Sign Key (+/−): Sign key to change sign + or −.

(4) Brightly Lit Position Shift Keys (◄, ►): When the set data currently displayed are to be changed, these keys are used to shift brightly lit positions so that characters or numerals to be changed are brightly lit.

(5) Entry Key (ENT): Enters RANGE, ALARM, CLOCK, CHART SP/INTVL and PRINT TIME settings when pressed at the end of the entry.

(6) OFF Key (OFF/(−)): Designates channel skip (in RANGE setting) and alarm OFF.

(7) ⊢/⊣ Key: When the RANGE set data are displayed, this key is used to switch the LEFT END value to the RIGHT END value or vice versa. Pressing this key highlights the LEFT END value mark (⊢) or RIGHT END value mark (⊣) displayed and switching is completed by pressing SHIFT key and 0 (zero) key abusequently to display the other end value.

⑮ **DMM Operation Keys**

(1) DMM Operation Keys (DMM): Displays measured data of DCV, ACV or OHM (Ω) applied to terminals H and L on the recorder front panel.

(2) DCV, ACV and Ω Keys (DC, AC, Ω): When the DMM key is turned on, these keys are operated to select the type of input to be measured.

(3) Terminals H and L: Input terminals on the front panel. (Use the measurement lead supplied with the recorder).

⑯ **Key Lock Switch:** When this switch is slid to KEY LOCK position, the keys other than DISPLAY key will be disabled.

⑰ **POWER Switch:** Turns the instrument ON/OFF.

⑱ **Ink Ribbon Cassette**

⑲ **A/D Card**

⑳ **MAIN CPU Card**

㉑ **SUB CPU Card**

APPENDIX VI

Thermal Properties of Building Materials

		Conductivity (W/m.K)	Density (kg/m^3)
Wall Materials			
Adobe block		1.250	2050
Brickwork	Outer Leaf	0.840	1700
Brickwork	Inner Leaf	0.620	1700
Concrete, Cast	Dense	1.400	2100
	Lightweight	0.380	1200
Concrete Block	Heavy	1.630	2300
	Medium	0.510	1400
	Light	0.190	600
Fibreboard (Soft board)		0.060	300
Fibrous Cement	Sheet	0.360	700
	Decking	0.580	1500
Glass		1.100	2500
Plasterboard		0.160	950
Plywood		0.138	620
Stone	Marble	2.000	2500
	Sandstone	1.300	2000
	Granite	2.300	2600
Tile hanging		0.840	1900
Timber	Softwood	0.130	610
	Hardwood	0.150	680
Wood Chipboard		0.120	660
Surfacing			
External Rendering		0.600	1300
Plastering	Dense	0.500	1300
	Lightweight	0.160	600
Roof and Floor Materials			
Asphalt or Bitominous Felt		0.500	1700
Concrete Slab	Dense	1.130	2000
	Aerated	0.160	500
Metal Deck		50	7800
Screed		0.410	1200
Stone Chippings		0.960	1800
Tiles		0.840	1900
Thatch	Straw	0.070	240
Timber Board or Wood Blocks		0.140	640
Insulating Materials			
Cellulose Fibre	Fireproofed	0.039	42
	Same	0.047	83
Cork		0.038	144
Eel Grass	Zostera Marina	0.046	21
Glass Fibre	Quilt	0.040	12
	Batts (slab)	0.035	25
EPS (Exp. Polystyrene Slab)		0.035	25
Perlite	Loose Fill	0.046	65
Mineral Fibre Slab	Slab	0.035	35
	Dense	0.044	150
Phenolic Foam		0.040	30
Polyurethane Board	New	0.016	24
	Aged	0.025	30
Strawboard		0.037	250
Compressed Paper Faced		0.081	320
Urea-Formaldehyde	Foam	0.040	10
Vermiculate	Exfoliated	0.069	128
Wood Wool	Slab	0.100	500

MOISTURE MOVEMENT DATA

INDOOR MOISTURE PRODUCTION

one person	at rest	40 g/h	
	sedentary	50 g/h	
	active	200 g/h	
cooking (gas)	breakfast	400 g	
	lunch	500 g	3000 g/day
	dinner	1200 g	
dishwashing	breakfast	100 g	
	lunch	100 g	
	dinner	300 g	
floor mopping		1100 g	
clothes washing		2000 g	
clothes drying		12 000 g	
shower		200 g	
bath		100 g	

PERMEABILITY OF SOME MATERIALS

brickwork		0.006 -	0.042	mg/s.m.kPa
cement render			0.010	
concrete		0.005 -	0.035	
cork board		0.003 -	0.004	
expanded ebonite (Onozote)			< 0.0001	
expanded polystyrene		0.002 -	0.007	
fibreboard (softboard)		0.020 -	0.070	
hardboard		0.001 -	0.002	
mineral wool			0.168	
plastering		0.017-	0.025	
plasterboard		0.017-	0.023	
plywood		0.002-	0.007	
polyurethane foam	closed cell		0.001	
	open cell		0.035	
			0.022	
timber	air dry	0.014-	0.022	
	wet	0.001 -	0.008	
wood wool slab		0.024 -	0.070	

PERMEANCE OF SOME ELEMENTS

aluminium foil		< 0.006	mg/s.m^{2}kPa
bituminous paper		0.09	
brickwork	105 mm	0.04- 0.06	
concrete blocks	200 mm hollow	0.14	
cement render or screed, 25 mm	4:1	0.67	
	1:1	0.40	
corkboard	25 mm	0.40-0.54	
paint, 2 coats, oil	on plaster	0.09-0.17	
paint, 3 coats, oil,	on wood	0.02-0.06	
plaster on lath	25 mm	0.63	
	20 mm	0.83	
	12 mm	0.93	
plasterboard	10mm	1.7- 2.80	
plywood, 6 mm	external qual.	0.026-0.041	internal
	qual.	0.106-0.370	
polyethylene film	0.06 mm 0.004	25	mm
softwood (pine)		0,08	12
	mm	0.10- 0.47	
strawboard wood	50 mm	0.13- 0.26	
wool slab	25 mm	3.08- 4.14	

[any layer of less than 0.067 mg/s.m^{2}kPa permeance is a vapour barrier]

THERMAL PROPERTIES OF SURFACES AND CAVITIES

RADIATION PROPERTIES		for 6000° solar radiation abs.& emittance	reflectance	at 50°C abs.& emitt.
brick,	white, glazed	0.25	0.75	0.95
	light colours	0.40	0.60	0.90
	dark colours	0.80	0.20	0.90
roofs	asphalt or bitumen red	0.90	0.10	0.96
	tiles white tiles aluminium	0.65	0.35	0.85
	(oxidised)	0.40	0.60	0.50
paint	white	0.20	0.80	0.11
	matt black	0.30	0.70	0.95
weathered surfaces:		0.96	0.04	0.96
	light	0.50	0.50	0.60
	medium	0.80	0.20	0.95

SURFACE RESISTANCES (m^2K/W)			normal surfaces	low emittance surfaces
inside,	walls		0.12	0.30
	ceiling, floor: heat flow up		0.10	0.22
		heat flow down	0.14	0.55
	ceiling, 45° heat flow up		0.11	0.23
		heat flow down	0.13	0.38
outside, walls,		sheltered	0.08	0.11
		normal exposure	0.06	0.07
		severe exposure	0.03	0.03
roofs		sheltered	0.07	0.09
		normal exposure	0.04	0.05
		severe exposure	0.02	0.02

CAVITY RESISTANCES (m^2K/W)		mm	DIRECTION OF HEAT FLOW: horizontal	upward	downward
		1	0.035	0.035	0.035
0.11	0.11	0.11			
	normal	10	0.15	0.13	0.15
		20	0.17	0.14	0.20
non-ventilated		50	0.17	0.14	0.21
		1	0.07	0.07	0.07
	low emissivity	5	0.22	0.22	0.22
		10	0.30	0.25	0.30
		20	0.35	0.28	0.40
		50	0.35	0.28	0.42
		1	0.17	0.17	0.17
		5	0.05	0.05	0.05
	normal	10	0.07	0.06	0.07
		20	0.08	0.07	0.10
		50	0.08	0.07	0.10
ventilated		1	0.35	0.35	0.35
	low emissivity	5	0.10	0.10	0.10
		10	0.14	0.12	0.14
		20	0.16	0.14	0.20
		50	0.16	0.14	0.20