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ENERGY STORAGE COMPOSITE WITH AN ORGANIC PCM

Muslim Abbas Khan

A Thesis

in the

Centre for Building Studies

Faculty of Engineering and Computer Science

Presented in Partial Fulfillment of the Requirements

for the Degree of Master of Engineering (Building)

Concordia University

Montréal, Québec, Canada

August 1988

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ABSTRACT

Energy Storage Composite with an Organic PCM

Muslim Abbas Khan

This research is primarily aimed at exploring possibilities of storing an organic phase change material (PCM) in a composite. Phase change materials have previously been successfully stored in gypsum wallboard.

During the present research work certain aggregate and filler materials were selected after detailed laboratory tests as possible constituents for the proposed composite. Absorption of PCM and retention there-of in materials like expanded shale, volcanic rock, activated charcoal, gypsum and vermiculite etc. was determined. Efforts were made to prepare polymer concrete composites from pre- PCM impregnated aggregates, fillers and polyester resin but the results were not promising.

Composite specimens were then prepared using coarse aggregates, gypsum, sand, cement, sawdust, vermiculite etc. and water. Several mix compositions using different proportions of these materials were prepared. The gypsum concrete specimens so prepared were cured, dried and impregnated with PCM. The absorption capacities of PCM in the specimens were determined and compressive strength tests, DSC analysis infrared spectroscopy and thermal conductivity tests were performed.

The composite, depending upon the mix composition, is capable of storing 15-30 weight % of PCM. In order to ensure complete encapsulation of PCM, the composite specimens were coated with a film of polyester resin. This, however, resulted in lowering of the heat transfer capability of the composite. Thermal conductivity tests showed great improvement on introduction of aluminum powder in the resin.

The composite can be produced in the form of floor, ceiling or wall tiles capable of storing heat @ 480-766 KJ/m². The cost of such tiles with built-in-energy is approximately \$15.00 per square meter.

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LIST OF SYMBOLS

<u>SYMBOL</u>	<u>Description</u>
Al	Aluminum
ASTM	American Society of Testing Materials
BS	British Standards
Btu	British Thermal Unit
Bu St	Butyl Stearate
DSC	Differential Scanning Calorimetry
g	gram
kg	kilo gram
°K	degree Kelvin = $273 + ^\circ\text{C}$
J	Joules
kJ	Kilo Joules
J/g	Joules per gram
J/kg	Joules per kilogram
K-factor	Thermal Conductivity
m	Mass
MPa	Mega Pascal
PC	Polymer Concrete
PIC	Polymer Impregnated Concrete
PPCC	Polymer-Portland Cement Concrete
R-factor	Resistance
R.H	Relative Humidity
T	Temperature swing

SYMBOLDescription

t	Time
ΔH	Heat of Transmission
Q	Quantity of Heat
ΔQ	Heat of flux
wt	Weight
[]	Reference

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CHAPTER 1

INTRODUCTION

1.1 GENERAL

The objective of this research work is to study the possibilities of encapsulating a phase change material in a composite for conservation of energy in buildings.

Previous works on the subject of conservation of energy for passive heating and cooling of buildings has shown that phase change materials can be successfully stored in gypsum wallboard. Phase change materials were introduced in $\frac{1}{2}$ inch wallboard and no exudation of the liquid PCM occurred below 25% by weight. For a temperature swing of $\pm 4^{\circ}\text{C}$, thermal storage capacities up to 350 kJ/m^2 are available [1]. The results of PCM - impregnated wallboard show that impregnated gypsum wallboard can function as an inexpensive means of thermal storage and reduction of up to 30% in space conditioning energy consumption costs. A product of high latent heat storage was thus produced [2].

The Institute of Energy Conservation (IEC) of the University of Delaware has designed and constructed a modular collection and storage unit, called 'thermal wall panel' for application in passive and hybrid solar system [3].

Another research work has demonstrated that polypropylastic wax sheets could be made using paraffin, stearic acid or other waxes. These sheets can absorb solar energy effectively so that a useful inexpensive collector could be built [4].

In the present research work efforts have been made to prepare a new kind of composites, from various aggregate materials, fillers and polyester resin, capable of storing a phase change material.

1.2 DEVELOPMENT OF STUDY

In the first phase of this work, a number of aggregate materials were selected and tests performed to study their absorption capacities for the phase change materials. Thermal analysis were performed for analysing transition temperatures and heats of fusion and crystallization of the phase change material inside the aggregates.

It was now possible to choose some of the dependable materials having good absorbing capabilities. In the second phase, attempts were made to prepare polymer-concrete composites using aggregates impregnated with phase change material, fillers like sand and calcium carbonate and polyester resin, the resin being a binder.

In the third phase of the research, specimens were prepared like ordinary concretes from aggregates, fillers and water using different mix compositions. No phase change materials were introduced at this stage. The specimens were allowed to dry and cure before being impregnated with the phase change material. A thin film of polyester resin was then applied to completely seal-off the composite. Strength tests and thermal analysis were performed on various specimens in the following state:

- 1) Plain specimens with no phase change material or polyester resin.

- 2) Specimens impregnated with phase change material.
- 3) Specimens impregnated with phase change material and coated with polyester resin.

Chapter 2 of this report deals with the study of literature, origin, selection, availability and properties of aggregates and fillers. Since the aggregate materials constitute a major portion of the composite, the selection of such materials compatible with the requirements of this research work was an extremely important aspect. The aggregate and filler materials for the proposed composite have dual purpose viz:

- provide necessary strength to the composite
- to ensure performance properties i.e., absorption as well as being capable of retaining a phase change material for thermal storage.

A number of phase change materials such as fatty acids are available in the market. Fatty acids are already known commercially important products and are in extensive use in cosmetics, pharmaceutical, textile, plastic and automobile industries. A detailed study of such materials was conducted by the Centre for Building Studies and a report titled "Energy Storing Wallboard" prepared. The salient features of this report on phase change materials have been adapted in Chapter 2.

As per recommendations of this study commercial Butyl Stearate, henceforth referred as PCM, was used as the phase change material

throughout this research work.

Since polyester resin is proposed as a constituent of our composites, a brief résumé of polymers is also included in Chapter 2.

Experimental work on absorption of PCM in aggregates has been summarized in Chapter 3. The aggregate materials were impregnated under different conditions of temperature and pressure. Certain materials like shale, volcanic rock and activated charcoal showed best results when impregnated at 70°C under a vacuum pressure of 50 mm of mercury. Hardened and dried gypsum pastes showed greater absorption when the water: gypsum ratio was increased, while expanded vermiculite would absorb large amounts of PCM even at room conditions.

After the preliminary research, certain materials were available which had sufficient absorbing capacities were selected for further investigations before these could be used as composite constituents.

Chapter 4 of this thesis takes up the "Composite" in which the experimental work on preparation of specimen composites with various combinations of materials have been described in detail. Several tests such as absorption of PCM, compressive strength, thermal analysis, infrared spectroscopy, specific heat and thermal conductivity were performed on various specimens. The chapter includes details of all the tests performed and the results obtained. Cost analysis of a specimen tile has been worked out in Chapter 5. Conclusions drawn from this research work and some suggestions for the future are described in the final chapter of this thesis.

CHAPTER 2

SELECTION OF MATERIALS

2.1 INTRODUCTION

Aggregates constitute almost two thirds of the volume of any concrete mix and they not only influence the strength of the composite but also affect its other properties of which the performance properties are of greatest importance for the present research work. The selection of the aggregate materials is determined by several factors such as:

- size
- shape and texture
- availability
- cost
- composition and compatibility with the particular requirements.

Aggregates and fillers have been usually considered as cheap extenders or diluents which are dispersed throughout a mix largely for economic reasons. The primary objective for use of these materials in the present research work has been to impart certain functional properties to the composite rather than being materials simply forming bulk mass of the end product.

2.2 GENERAL CONSIDERATIONS

2.2.1 The Particle: Size, Shape & Texture

The particle shape and the manner in which the particles are

packed together are important considerations for selection of any aggregate material [5]. The size of the largest aggregate will be controlled by the thickness of the composite so as to provide sufficient cover. Most fillers and aggregates are usually minerals which are ground rock or ores processed to obtain materials in different forms and sizes. These may range from fine powders of gypsum and sand to solids like crushed stone or the irregular shapes of expanded vermiculite.

Aggregate shape and texture also affect the workability of the mix through their influence on the paste requirements. Sufficient paste is required to coat the aggregates and to provide lubrication to decrease interactions between aggregate particles during mixing. Natural sand and gravel are spherical in shape, well rounded and compact. Crushed stone is angular with sharp edges and corners and rough surface texture. The surface texture of aggregates is important for workability as rough surfaces require more lubrication for movement than smooth surface materials. There are no specified tests or detailed definitions prescribed by ASTM for surface texture and particle shape. A classification system of BS 812 :Part 7 (Table 2-1 and 2-2) provide classification system for aggregates [6].

2.2.2. Chemical Composition [5]

Chemical composition of the candidate materials is important consideration towards their use in this research work. The requirements of the composite are such that any chemical reaction between its

TABLE 2-1
Classification of Aggregate Shape (BS 812: Part 1) [6]

Classification	Description	Examples
Rounded	Fully water-worn or shaped by attrition	River or seashore gravel; desert, sea-shore & windblown sand
Irregular	Naturally irregular or partly shaped by attrition having rounded edges	Other gravel; sand or dug flint
Angular	Possessing well-defined edges formed at intersection of roughly planar faces	Crushed rock of all types; talus; crushed slag
Flaky	Material of which the thickness is small relative to other two dimensions	Laminated rock
Elongated	Material usually angular in which length is much larger than the other two dimensions	
Floky and elongated	Material having length much larger than the width and the width much larger than the thickness	

TABLE 2-2

Classification of Aggregate Texture (BS 812: Part1) [6]

Group	Surface Texture	Characteristics	Examples
1	Glassy	Conchoidal fracture	Black flint, obsidian and
2	Smooth	Water-worn or smooth due to fracture of laminated or fine-grained rock	Gravel, chert, state, marble
3	Granular	Fracture showing more or less uniform rounded grains	Sandstone, oolite
4	Rough	Rough fracture or fine or medium grained rock containing no easily visible crystalline constituents	Basalt, felsite limestone
5	Crystalline	Containing easily visible crystalline constituents	Granite, gabbro, gneiss
6	Honeycombed	With visible pores and cavities	Brick, pumice, foamed slag, clinker and expanded clay

constituents and the phase change material may render it unfit for the purpose of a thermal storage mass. It is desired that the filler materials should have no chemical reaction what-so-ever with the phase change material.

2.2.3 Physical

Density of the materials to be used is a fundamental and important physical property since it affects the strength of the composite and also has direct effect on its cost. General rules which apply are that densities for solids vary from organics to metals in ascending order. Porous or cellular fillers fall in the lowest density range. Dry and non absorbant materials like gravel, crushed stone and sand provide density and strength to the composite.

Densities of some of the aggregate materials are presented in Table 2-3.

Hardness or the resistance to wear is another important physical property to be considered in aggregates in concrete for use in roads and floor surfaces. Moh's scale (Table 2-4) which rates one material against another for its ability to scratch or to be scratched by an adjacent member in the series by a knife or file is a useful abrasiveness index [5].

Porosity of the filler materials is by far a very important consideration for the present research work. The absorption capacity of the fillers for the PCM and their capability to retain the same was

comprehensively studied and tests performed in the laboratory for confirmation.

TABLE 2-3

Densities of some Aggregate materials [6]

Type of Aggregate	Density of Aggregate kg/m ³
Expanded Vermiculite	64-240
Pumice	480-880
Natural Aggregate	1360-1600
Expanded Clay or Shael	560-1040
Volcanic Rock	850-1250

2.2.4 Thermal

As stated earlier, the primary objective of this research work is to study possibilities of production of thermal storage composite for conservation of energy in buildings.

Since the composites will be exposed to thermal influence, therefore these properties are important to the aggregates and fillers. Thermal conductivity (K), which is the ability of a material for transferring heat through the material from a region of higher temperature to a region of lower temperature, is of great significance for our proposed composites.

TABLE 2-4
Moh's Scale of Hardness [5]

	Value	Material
Softest	1	talc, vermiculite 1.5
	2	kaoline, gypsum, tin, mica 2-2.5 serpentine asbestos 2.0-5.0 fingernail 2
	3	calcite, barite, copper, gold, anhydrite 3-3.5
	4	aragonite, fluorite, iron 4.5
	5	tremolite 5-6, wollastonite 5-5.5 steel knife, window glass 5.5
	6	feldspar 6-6.5, nepheline 6-6.5 titanium dioxide pigment 6-6.5 file steel 6.5
	7	silica, zircon 7.5
	8	topaz
	9	corundum (alumina)
Hardest	10	diamond

2.2.5 Economics

The cost of the end product is greatly influenced by the choice of fillers and aggregates to be used in the composite forming. Cost per unit weight of the composite will depend upon the type, density

and other factors mentioned earlier. The cost criterion in selection of fillers, aggregates and phase change materials will therefore be a very important factor. Cost of certain composite materials is shown in Chapter 5.

Based on the criteria described in the earlier paragraphs of this chapter, a number of aggregate materials which could form constituents of our proposed composite were selected for further tests.

The following paragraphs briefly describe general characteristics, properties, and other relevant information about the candidate materials for our proposed composite. The information contained here is based on study of the available literature on the subject.

2.3 AGGREGATES AND FILLERS

2.3.1 Expanded Shale [7]

Porous materials of cellular structure are produced by heating clays, shales, and slate etc. to a suitable temperature. After crushing and screening to the desired size, these materials have been used as good light weight aggregates. Expanded shale is basically formed from slate waste. Slate is the general name for microcrystalline silicate rocks that can be split along parallel surfaces into smooth surfaced sheets. The major portion of the microcrystals consist of quartz, mica, and clay minerals such as "illite" (an aluminum silicate of iron, magnesium, and potassium) and "chlorite" (a hydrated

aluminum silicate or iron and magnesium). Small quantities of calcite, dolomite, felspar and iron oxide are also present in the rock. As a matter of fact slate is a metamorphic rock which has actually been formed from shale which itself, is a microcrystalline sedimentary ground-mass deposited mainly in the sea. Shale may occur in loose or consolidated form. In loose form, it has a structure like clay but contains large quantities of very finely divided quartz, mica and other non clay minerals. Slate has been formed from shale by directional pressure built up by intense folding of the shale deposits. As a result sheets like crystals of mica and clay minerals have recrystallized and oriented to form a hard state rock with a laminar structure.

Chips of slate waste are crushed and heated to 1200°C to form an expanded cellular product known as expanded shale. It has a density of $560 - 1040 \text{ kg/m}^3$ and is an excellent aggregate for light weight concrete.

2.3.2 Volcanic Rock

All minerals and rocks are primarily formed by solidification of the molten silicate slag, called magma, which developed on the earth a few thousand million years ago. In large regions this magma melted and solidified again and again when masses, already solidified, sunk to hotter regions or have been heated again by hotter magma moving upwards. This process is still repeated today. Because of pressure difference in earth's interior, great earth movements occur periodically, and consequently the pressure may change locally. If a pressure

drop occurs at a depth at which the temperature is high enough, a large mass of magma may be formed since a pressure drop lowers the melting point of the rocks. Nowadays these magmas occur mainly at a depth between 40 and 100 km in the earth's crust. When the pressure increases the magma can be squeezed upward, dissolving rocks above it, and solidify again either as a result of the increasing pressure or by cooling [7,8].

Volcanic rock is a general name of the rock materials erupted after a volcanic activity. Explosive volcanic eruptions give rise to many products such as pyroclastic rocks which embrace fragments of different origins, many shapes and sizes. Some accumulations of volcanic debris are uniform in composition and texture while others are heterogeneous mixtures. Pyroclastic deposits include fragments of rocks shattered by explosions and materials derived from rapid cooling of ejected lava. On final consolidation the coarser fragments mixed with lava and volcanic dust form the agglomerates and the finely divided dust and fragments of rock form the tuffs.

The volcanic rocks have loose packing, low density and high porosity and permeability.

2.3.3 Activated Charcoal

The adsorbent properties of certain carbons have been known since ages, however, their manufacture began only during the present century. The expanding technology has ever since continued to find new uses of carbon.

A large number of carbonaceous substances are available as starting materials for manufacture of active carbons. The present day production is based on coconut shell, wood, charcoal, lignite, peat, pulp waste, and bituminous coal. A large surface area per unit volume ($300 - 2000 \text{ m}^2/\text{g}$) is necessary to be created to produce an active carbon. Carbonaceous materials such as wood and coal have a system of pores but in their natural state these pores are extremely small. These pores can barely permit access to nothing but smallest gas molecules. The art of making active carbon is therefore to enlarge these pores as well as develop new ones. This is accomplished by thermal treatment in steam or other gases followed by some chemical treatment with or without the process of steaming.

Active carbons are used mainly in the purification and decolorization of liquids. In the sugar industry it finds its use as decolorizing agent, in the pharmaceuticals for concentrating components and to remove peroxides from the food stuff and edible oils. It is also used in the water treatment and many other similar applications [9].

Due to its known high porosity, the material was tested for its absorption capabilities for our phase change material and its subsequent possible applications as a useful material for thermal storage in buildings.

2.3.4 Gypsum. [7,9,10]

The importance of gypsum is based on the fact that when heated to about 175°C and powdered, it forms a solid mass when mixed with water

and allowed to set. This phenomenon has been known since ancient times when Egyptians used the material as mortar, wall plaster, plastic arts and most of all for preservation of dead bodies. In the middle ages it was extensively used for decorative purposes in houses, churches, memorials and in plastic arts.

The mechanism of hardening of gypsum was critically studied by Lavoisier in 1775. He discovered that gypsum is a salt that loses three quarters of its water of crystallization on heating i.e. calcination of gypsum. The hardening of calcined gypsum in presence of water was described as due to recombining of water in the form of water of crystallization.

Gypsum in its natural form is a constituent of sea water which contains about 0.14 % by weight of calcium sulphate. Solid gypsum is widely distributed occurring commonly in beds composed of almost pure gypsum. In Canada, on the island of Nova Scotia gypsum is found close to the surface over a large area of about 1000 square kilometers.

Gypsum rock consists of a white crystalline mass and is the principal commercial form of gypsum. Gypsum is calcined at temperatures between 120 - 160°C to remove about three quarters of its water of crystallization. The resulting product is the calcined gypsum well known as "Plaster of Paris".

In the present research, gypsum powder has been one of the principal constituents of our proposed composite, it will therefore be of

interest to look into some of its physical and chemical properties.

Calcium sulphate dihydrate, the common natural form of gypsum forms colorless crystals, has a density of 2.3 g/cm^3 , and a hardness of 1.5 to 2 on the Moh's scale. The naturally occurring masses of very small crystals are white or very nearly white. The solubility in water is 2 g/litre at 20°C (in terms of CaSO_4).

Gypsum is relatively inert towards chemicals such as acids, alkalis and oxidising agents. This property has been one of the big factors for selection of gypsum for this work as it will be seen in the subsequent chapters of this thesis that how important it is to ensure no chemical reaction between the phase change material and the rest of the constituents of the composite.

On heating to $120 - 130^\circ\text{C}$ the hydrate ($\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$) expels water and is converted into the hemihydrate (also called calcined gypsum, Plaster of Paris, plaster, $\text{CaSO}_4 \cdot 0.5\text{H}_2\text{O}$).

The hardening of gypsum is based on two processes:

- the chemical process of combining with water to form calcium sulphate dihydrate, and
- the physical process of crystallization of the dihydrate from the aqueous solution.

Experiments show that 40 - 50% of water by weight of calcined gypsum is required to obtain a hardened product with a setting time of about 5 minutes.

The compressive strength of hardened gypsum depends on the quantity of water used in the paste as well as presence of other fillers.

Gypsum finds its use as a building material in a variety of ways such as:

- It is used as a retarder in cement to prolong setting time of concrete and mortar [11].
- A number of prefabricated building products like gypsum wallboard, wall panels, floor tiles, and bricks are manufactured from calcined gypsum.
- Insoluble anhydrate or dead-burnt gypsum in finely divided form is constituent of plasters which form a hard mass with high compressive strength. Plasters of insoluble anhydrite are used in flooring for production of imitation marble.

2.3.5 Vermiculite [9,12]

Vermiculite is the name of a group of minerals consisting of hydrous magnesium alumino-silicate and hydrous ferro-magnesium alumino-silicates, which have been formed by alteration of the mica minerals biotite and phlogopite. Since mica is a parent material, it is important to know more about it.

Mica is a well known common name of a group of alumino-silicate minerals forming flat crystals with a remarkable cleavage, which

permit the crystals to be split into thin films. The name mica was first used in 1546 by G. Agricola, but Romans knew the product so well that it was used as a costly glazing material. The mica minerals biotite and muscovite are essential constituents of igneous rocks as granite, of metamorphic rocks and various sedimentary deposits formed from igneous and metamorphic rocks containing mica minerals.

Economic deposits of muscovite which contain large crystals of these minerals are only found in granite or acidic pegmatites. The larger crystals of mica are often called "books" because of their highly developed cleavage and laminar structure (Fig. 2.1). The name vermiculite is derived from the Latin "vermiculus" meaning little worm and was given in 1824 to a mineral occurring in Massachusetts because of the fact that a small particle of it could be expanded on heating to a worm-like thread.

In the USA, vermiculite, resulting from alteration of biotite is found in basic or ultrabasic igneous and metamorphic rocks or at contact surfaces of these rocks with acid rocks. Irregular concentrations containing upto 95% of vermiculite and having a length of 300 m and width of 6 to 30 m are commonly found in these rocks.

Vermiculite is mined by open-cast methods as well as through underground mining in certain places in the U.S.A. The crude material from these deposits varies in sizes from almost dust to plates or books several square inches in area and is mixed with various rocks. The crude product is screened to size at the mine, air-dried in a

rotary kiln at a temperature of about 80°C and passed through crushers. The soft and flaky vermiculite passes through these without much destruction whereas rock fragments are crushed to dust and removed by air separation.

Vermiculite, like mica, forms flat crystals with good cleavage. Its color varies from yellow through various shades of brown to black. The hardness of vermiculite ranges between 1.5 to 3.0 on the Moh's scale.

Vermiculite has a capacity to expand when heated to high temperatures. On heating the water of crystallization is liberated and evaporated. The evaporating cleaves the vermiculite crystals into a number of layers, and the vermiculite expands at right angles to the plane of cleavage. This process is called exfoliation.

Hydrated magnesium iron aluminum silicate when heated to about 1100°C is capable of expanding six to twenty times. The platelets exhibit active curling movement when heated; hence the name "expanded vermiculite". Figures 2.1, 2.2, 2.3 and 2.4 show vermiculite in the normal state and how it looks like after expansion.

Vermiculite has crystalline structure with high porosity and high void volume to surface area ratio. The density of the material is low, ranging from 56-72 Kg/m³ for 16 mm to 104-160 Kg/m³ for 0.5 mm sizes.

It is insoluble in water and all the known organic solvents. The absorption capacity of vermiculite for liquids ranges between 200-500%

depending upon the particle size. This property was extremely important for selection of vermiculite for use in this research work.

Vermiculite has been used for light weight concrete aggregate, in insulating concrete, fire proofing, refractory, filler in rubber, paint and plastics, absorption of oil spills and packing [12].

Wood sawdust, burnt clay bricks and certain other materials were also tested as possible constituents of the proposed composite.

2.3.6 Clay

Clay is a kind of natural earth which can be readily recognized. When sub-divided and mixed with water it becomes coherent, sticky and moldable. When mixed with small proportions of water the mixture, although still moldable under pressure, shows little or no tendency to adhere to the fingers. If mixed with larger proportions of water the clay forms a suspension with water from which the coarser particles settle out fairly quickly but from which the finer particles settle only after prolonged sedimentation.

The most characteristic property of clay is its property of plasticity or moldability. Plastic clays with proper addition of water are readily moldable into test pieces, slabs or bars.

2.4 METAL FILLERS [5]

When polymers are used in a composite, they enhance the adhesive properties, corrosion resistance, resistance to abrasion, and also maintain excellent electrical and thermal insulation. In the present

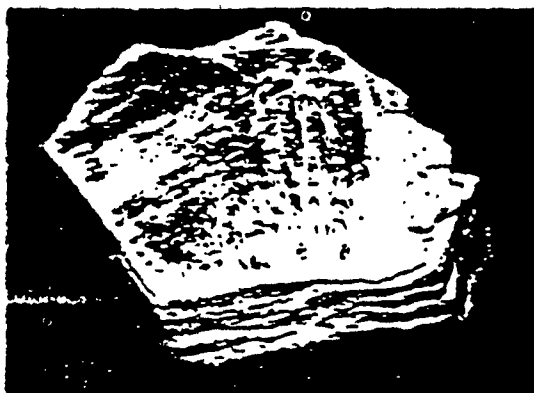


Figure 2.1 A large slab of Mica

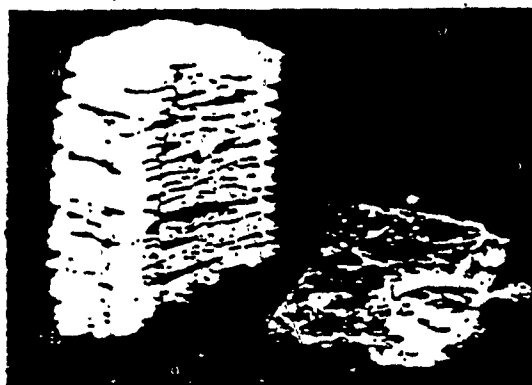


Figure 2.2 Vermiculite before and after exfoliation

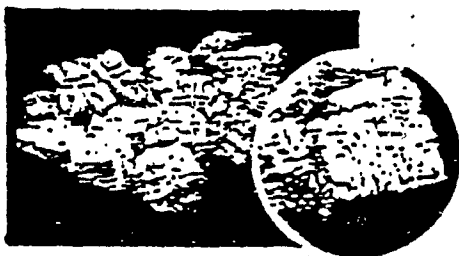


Figure 2.3 Crude Vermiculite



Figure 2.4 Exfoliated Vermiculite

application, however, we desire a polymer with high thermal conductivity in order to allow phase transition of the phase change material encapsulated in the composite. The problem of the insulating properties of the conventional polymers can be overcome by introduction of metallic powders in the polymer to improve their thermal conductivity.

Metallic powders are produced in large quantities for powder metallurgical purposes. These powders can also be used to impart special qualities to plastics by enhancing their properties like those of thermal conductivity, electrical conductivity and heat capacity.

Almost all pure metals and most alloys can be obtained in powder form. Iron is the most common metal in the use of powder metal for fabricating parts of automotive equipment, appliances, office machines, power tools and hardware. Copper and its alloys are extensively used as powders in porous filters and bearings. Aluminum, a light weight corrosion resistant metal has been widely used for high tension electric cables, metal foils and a host of other applications [13]. The metal has low cost as compared to many other metals and has high conductivity. The use of aluminum in construction industry has found huge consumption and the metal is now extensively used in all construction projects. Aluminum powders is available in various grades and sizes. These and copper powders, when used as fillers can greatly improve thermal properties of resin bound composites. Gold and silver are also excellent candidates for the purpose but because of their tremendous cost, would not be considered for such use.

Metallic fillers also improve physical properties such as impact strength, reduction of moisture transmission and fire retardancy.

2.5 PHASE CHANGE MATERIALS (PCM)

Phase change materials can be used for thermal storage in space heating and cooling. Heat is stored and released by melting and freezing of the phase change material by utilizing solar and internal heat gains from lights and people. At lower temperature, the PCM freezes thereby releasing energy in the process and will absorb energy when it melts at higher temperature. This is the basic phenomenon of storage and release of energy of the phase change materials.

The phase change materials which have been developed for energy storage from the vast number of potential products have a number of important similarities. They all have the following basic properties [14].

1. Both phases are condensed, either solids or liquids.
2. The temperature of phase change is useful in energy storage application, typically 0°C to 200°C.
3. The phase change process can be repeated without loss in storage capacity.
4. The latent energy of the phase change is substantial.
5. The materials are not expensive, highly toxic, or noxious.

A number of energy storage materials some in the form of salts [15,16] are available in the market, Centre for Building Studies of

Concordia University conducted a detailed study of such materials during a research project on energy storing wall-board. A portion of this chapter regarding selection of the phase change material has been adapted from the report titled "Energy Storing Wall-board (Phase I), Part of the Solar Energy Development Program.

2.5.1 Selection Criteria

The selection criteria of the phase change materials were based on the following considerations:

- Thermal Properties
- Physical Properties
- Kinetic Properties
- Chemical Properties
- Economic Factors

A summary of each of these criterion is described in the following paragraphs.

2.5.1.1 Thermal Properties

(a) Transition temperature

The phase transition temperature of the material should be such that melting process should be complete at its upper limit. For storage and release of energy, a range between 17-23°C is considered most appropriate. The initial melting and freezing temperatures should be within 4°C of each other to prevent excursions outside the comfort zone.

(b) Latent Heat

In order to meet the thermal requirements of buildings with least amount of phase change material, it is essential that it should have highest possible latent heat of fusion.

(c) Heat Transfer Properties

The ability of the phase change material to transfer heat from within the mass in which it is encapsulated is a very important factor influencing its selection.

2.5.1.2 Physical Properties

(a) Physical Stability

When a phase change material changes from one phase to the other, it is desired that the composition of both phases must be identical under all conditions of operation. As such the material should be such that the melting of components is congruent and that they do not segregate during the process.

(b) Vapor Pressure

The phase change material should have high boiling point (above 200°C) in order to have low vapor pressure necessary for containment of the material.

(c) Volumetric Change

The volumetric changes associated with the phase change of the material should be such that no damage to the container is caused.

(d) Density

The material should have greatest possible density to maximize heat storage per unit volume.

Physical properties of some fatty acids like Palmitic acid have been investigated in details by Southern Regional Research Laboratory, New Orleans to cover the specific volume temperature relationship, expansibility of the solid and liquid states and melting dilation [17].

2.5.1.3. Kinetic Properties

(a) Avoidance of Super Cooling

Some materials remain in liquid state even when their temperature drops below freezing point, the latent heat is therefore not released at the desired temperature. It is important that the phase change materials should be devoid of this super cooling tendency.

(b) Crystallization Rate

The rate of crystallization of a substance is controlled by the kinetics of incorporation of the molecules in the crystal lattice and by the rate of heat transfer. Both of these processes must proceed at such a speed so as to ensure the exchange of heat within an acceptable period of time for effective temperature conditioning.

2.5.1.4 Chemical Properties

(a) Chemical Stability:

A phase change material incorporated in a building material must have long life. This will be achieved only when any chemical reaction

and thermal decomposition of the material is limited to an acceptable low rate.

(b) Compatibility:

The phase change material should be compatible with the materials in which it is encapsulated as well as those with which it will come into contact. These include building materials, wiring, pipings, paints, wall coverings, adhesives, and others.

(c) Non-toxicity:

The material should be non-toxic so that injury cannot result from skin contact, ingestion or inspiration.

(d) Flamability:

The material must be non-flamable.

(e) Elimination of Nuisance:

The material selected should not cause unpleasant odour or allergic reactions due to any vaporization.

2.5.1.5 Economic Factors

(a) Availability:

The material should be readily available in abundance.

(b) Cost:

Any stable phase change materials which is encapsulated in a composite must have low cost per unit of heat storage as compared to the total of a central storage system.

After thorough consideration of all the factors, certain phase change materials were selected by the Centre for Building Studies for detailed research and investigations. These materials also included certain fatty acids.

2.5.2 Fatty Acids

The use of fatty acids has been growing steadily as commercially important products. These chemicals are obtained primarily from naturally occurring fats and oils and hence the name "fatty". Their most important applications so far have been in cosmetics and pharmaceutical industries where these are used in varnishing creams, ointments, lipsticks and nail polishes etc; in textile and fibre technology, in the manufacture and processing of plastics, metal treatments and lubricants, automobile tires, soaps and detergents [17,18].

Fatty acids because of their thermal properties may have found new dimensions as low cost energy savings materials for use in buildings. These acids meet thermodynamic and kinetic criteria for low temperature latent heat storage. Their melting points are in low temperature range with high latent heat of transitions per unit mass. The studies show that the freezing points of these materials are higher than the melting points i.e., freezing and melting ranges overlap. This may be due to the impurities present in commercial grades of these materials [16]. Saturated fatty acids exhibit small volume changes during the phase transition and have little or no super cooling during freezing. They have good chemical stability, low vapor

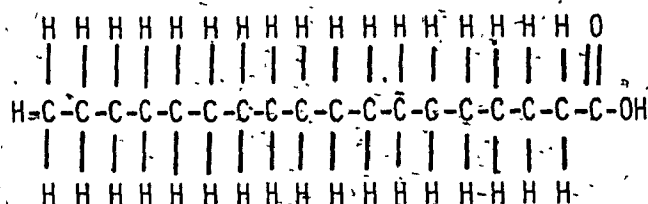
pressure at room temperature, are non-toxic and also non-corrosive. Principal physico-chemical properties of some fatty acids are shown in Table 2-5.

2.5.2.1 Butyl Stearate [20,21]

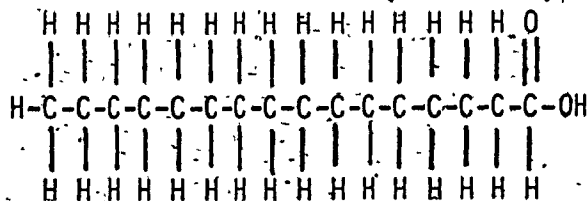
Commercial Butyl Stearate, a product of Emery Industries Ltd. Canada and marketed under trade name of Emery 2325 has been used as phase change material (PCM) throughout this research work. The major components of the product are:

- Butyl Stearate 50%
- Butyl Palmitate 48%

The raw material for Emery 2325 is stearic and Palmitic Acid. Commercial Stearic $\text{CH}_3(\text{CH}_2)_{16}\text{COOH}$ and Palmitic $\text{CH}_3(\text{CH}_2)_{14}\text{COOH}$ are straight chain, saturated nonobasic acids and are found in abundance



Stearic Acid



Palmitic Acid

TABLE 2-5
Principal Physico-Chemical Characteristics of Fatty Acids [20,21]

Fatty Acid	Formula	Molecular weight	Melting Point C°	Freezing Point C°	Latent Heat of Melting J/g
Stearic	$\text{CH}_3(\text{CH}_2)_{16}\text{COOH}$	284.7	69.2	69.4	222
Palmitic	$\text{CH}_3(\text{CH}_2)_{14}\text{COOH}$	256.42	62.9	62.4	212
Capric	$\text{CH}_3(\text{CH}_2)_8\text{COOH}$	172.27	31.6	31.2	163
Lauric	$\text{CH}_3(\text{CH}_2)_{10}\text{COOH}$	200.32	44.2	43.8	183

in animal fats and in varying degrees in cotton seed, corn, soya, coco and palm oils. In the pure form these acids are solid crystalline opaque white materials. Physical composition of some common fatty acids are shown in Table 2-6. The chemical properties like fire hazzard, toxicity and the price range of the products are listed in Table 2-7.

Thermal analysis of the product were conducted to determine thermal characteristics. It is derived from the analysis curves (Fig. 3.3) that:

- the PCM, Butyl Stearate, starts melting at 17.1°C with peak temperature of crystallization of 21.6°C
- freezing of this PCM starts at 20.4°C with peak temperature of crystallization of 18.8°C
- latent heat of melting = 140 J/g
- latent heat of crystallization = 143 J/g

TABLE 2-6
Fatty Acids Proportions of Common Fats & Oils [20,21]

Fatty Acid	Carbon Number	Composition %								
		Lard	Tallow	Castor	Coconut	Corn	Cotton Seed	Lin Seed	Palm	Soya
Stearic	C18	8-16	15-25	0-3	2-4	2-4	1-4	2-4	3-6	2-6
Palmi- tic	C16	20-28	20-35	1-3	7-11	7-19	17-29	5-8	38-48	7-12
Capric	C10				4-9					
Lauric	C12				43-50					

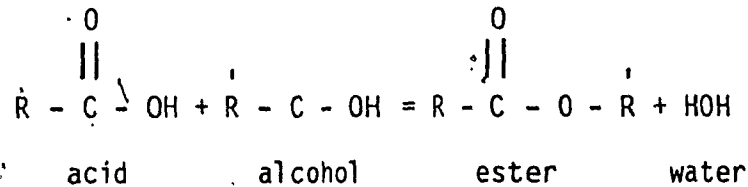
TABLE 2-7
Toxicity, Fire Hazard and Prices of some PCM's [9,20-22]

Material	Hazard Analysis		Price
	Toxic Hazard Rating	Fire Hazard	\$/kg
Butyl Stearate	Details known, limited animal experiments suggest low toxicity	Slight when exposed to heat or flame, can react with oxidizing materials	1.10
Capric Acid	Moderately toxic, limited animal experiments suggested moderate toxicity and irritation		1.20
Lauric Acid	Animal data suggests low toxicity for lauric acid esters, details unknown	Slight when exposed to heat or flame, can react with oxidizing materials	1.20

2.6 POLYMER MATERIALS [23-28]

The engineering materials commonly known by the term plastics are in fact polymers. The name polymer is derived from the Greek words "poly" meaning many and "meros" which means parts, as these substances are composed of long chain repeating molecules (mer). Carbon forms the backbone of the repeating chains and the atoms in the molecules are strongly bonded. The common polymer polyethylene is composed of repeating ethylene (C_2H_4) molecules. The term "polyester" is analogous

to the term "steel" because of the fact that there are multitudes of polyesters just as there are numerous types of steels. A polyester is formed by the reaction of a polybasic acid and a polyhydric alcohol to form a series of ester linkages.



According to the type of acid and alcohol used, one of the following will be formed:

- Alkyd or oil modified polyesters used for coatings
- Unsaturated polyesters based on dibasic acids and dihydric alcohols capable of cross-linking with vinyl monomers to form thermosetting copolymers
- Saturated polyesters which are used as plasticizers
- Fibers and films which are high molecular weight highly oriented saturated polyesters
- Polyester foams formed with polyesters with a high concentration of hydroxyl groups which are cross-linked to form foams, elastomers and coatings.

2.6.1 Unsaturated Polyester Resins

The construction industry is a major consumer of polyester resins in as much as these products are used in the production of cultured

marble and onyx, sanitary wares, glass-fiber reinforced tub shower units, building facades, special types of floors and floor tiles, polymer concrete and many decorative building elements.

Since the beginning of the early 1960s, cultured marble and onyx have grown to be one of the major applications of unsaturated polyesters. These synthetic stone products are cast into either flat stock or complete bathroom items. The flat stock can also be used for wall applications. The pigmentation and appearance duplicate the appearance of the finest onyx and marble with the advantage of greater durability.

Polymer concrete is a more recent development and was first introduced in Europe. With correct fillers such as silica and chemically resistant resins, mortars and aggregate filled polymer concrete mixes can be formulated. Some of the applications of polymer concrete are shown in Figures 2.5, 2.6 and 2.7.

Polyester resins are viscous, pale yellow colored materials of low degree of polymerisation (8-10). These are produced by condensation of a glycol with both an unsaturated and a saturated dicarboxylic acid. The polyester resin which may vary from a very highly viscous liquid to a brittle solid depending upon its composition is mixed with a reactive diluent such as styrene. Addition of styrene eases working, reduces cost of the product and enhances its reactivity.

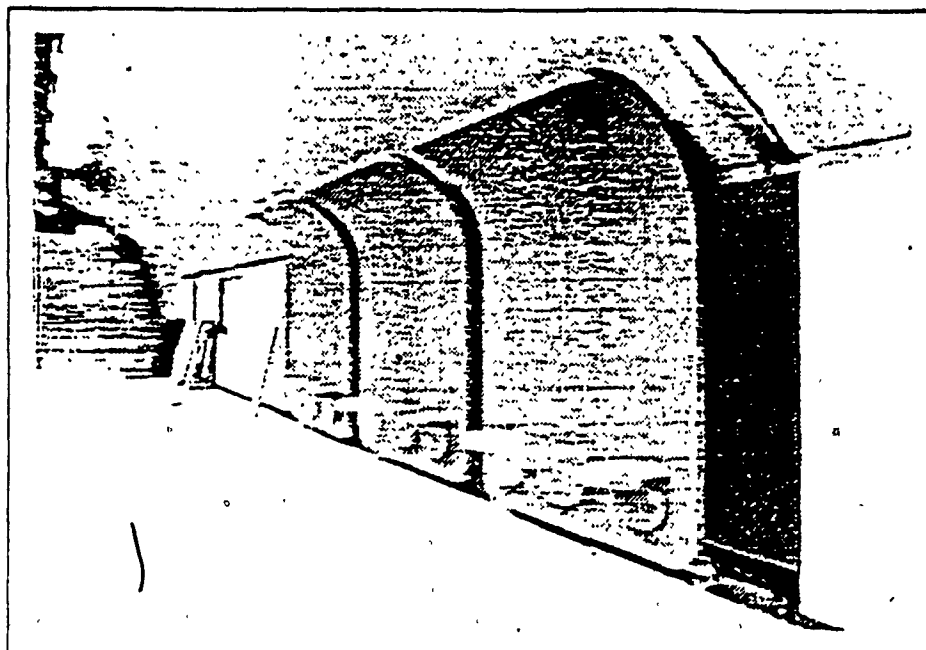


Figure 2.5 Polyester Concrete Seats & Panels at Plamondon Station of Montreal Metro System

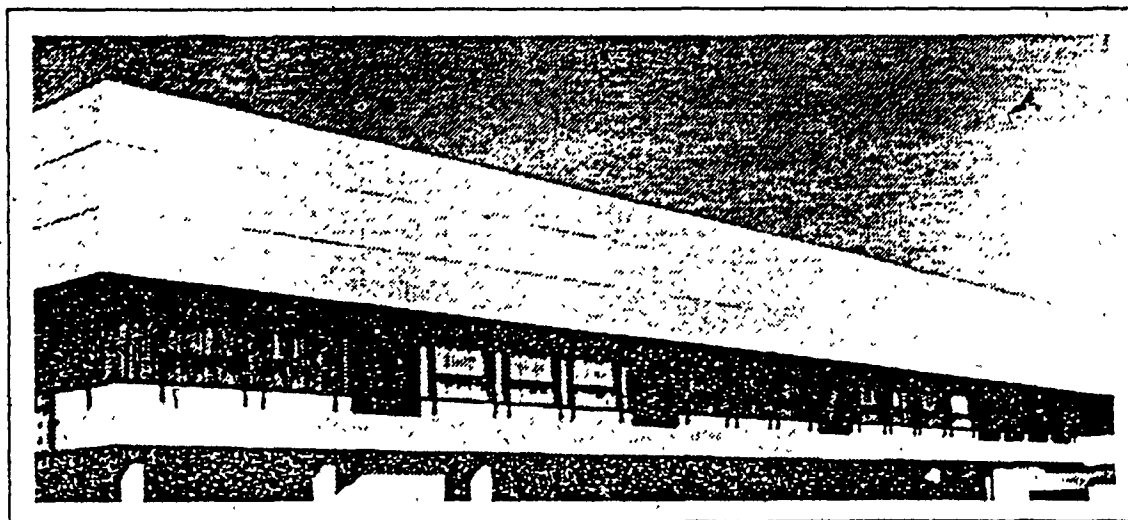


Figure 2.6 Polyester Concrete Panels for a Building

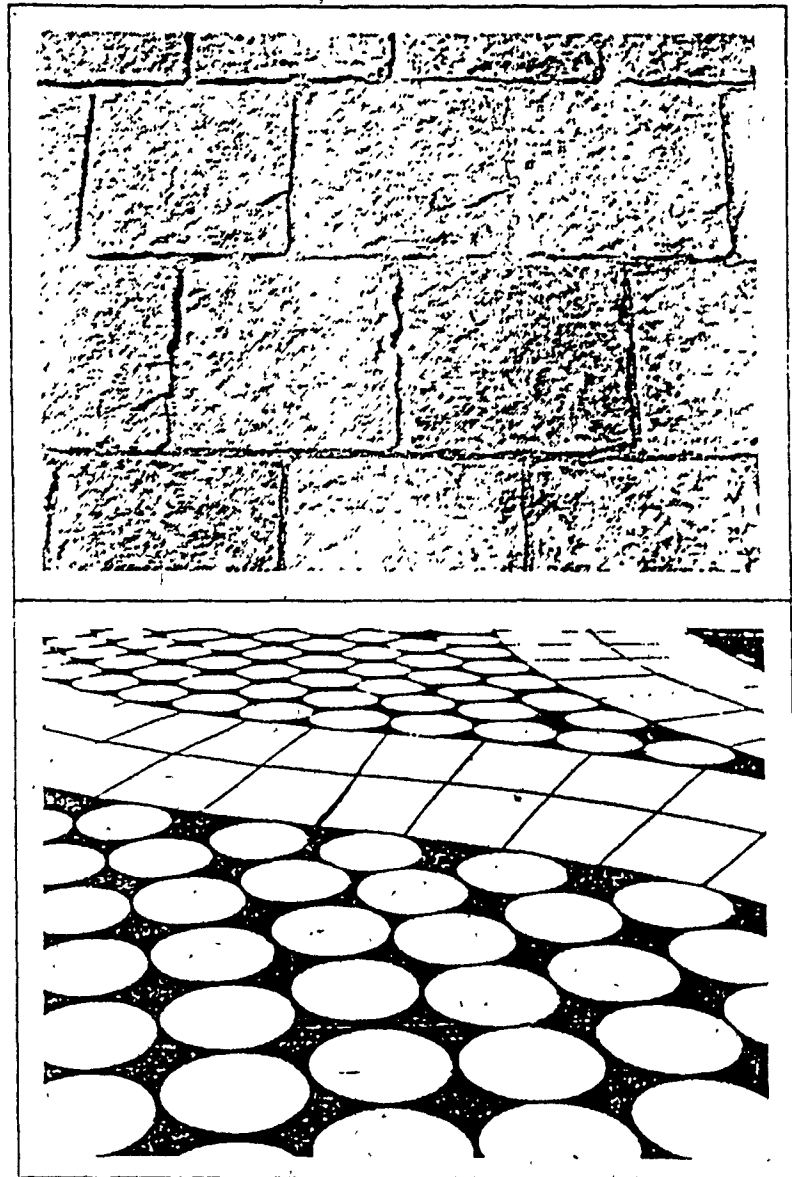
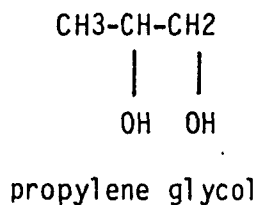


Figure 2.7 Floor Tiles imitating stone & Tiles geometrically shaped for interior or exterior use

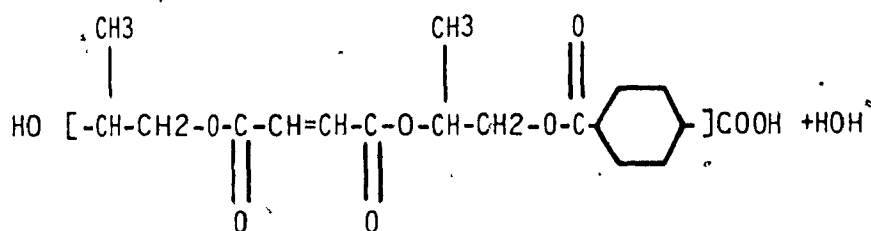
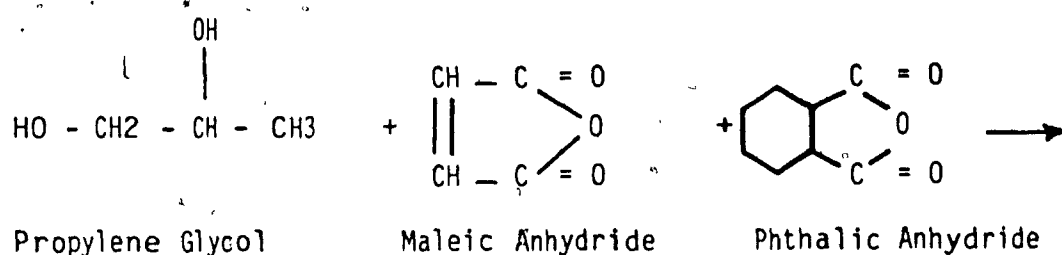
The raw materials used in the preparation of polyesters are:

- Propylene glycol is the most important glycol used in the manufacture of the resin



- Saturated acids have the prime function of spacing out the double bonds thereby reducing the density of the cross-linking. Phthalic anhydride is the most commonly used acid, which because of its low cost enables production of cheap resins.
- Diluents: Styrene is the most preferred diluent because of its compatibility, low cost and ease of use.

Orthophthalic polyester resins, isophthalic polyester resins, vinyl esters and blends of one or more types of these represent some of the variant forms that are utilized commercially.



Unsaturated Polyester (Alkydal)

2.6.1.1 Production and Properties

Unsaturated polyester resins are produced by the polycondensation process; glycols and acids are esterified, water is driven off, and polymers evolve. The type of starting materials used, the quality of the process control employed, and the time and temperature of cooking all influence final resin performance. Generally speaking, orthophthalic resins are cooked on a relatively short cycle time; these resins find a variety of applications where high performance requirements are not of the first magnitude. Corrosion-resistant products such as isophthalic polyester resins require extended cooking time to develop maximum chemical resistance. End-use properties are tailored to the

specific market place into which the resins are sold. For instance, the automotive market demands for its appearance parts that the resins perform well with low profile and shrink-control agents to produce smoother than steel molded surfaces. Propylene glycol maleate resins are preferred for this application.

In buildings, for sanitaryware and floor tiles etc., it is required that the resin system mix well with a variety of fillers cure bubble-free and resist the effects of exposure to stains and mechanical impact. Orthophthalic, dicyclopentadiene, and isophthalic resins, as well as blends are used for this purpose. Cultured onyx and marble bathroom sinks and tubs are produced by the open mold and low pressure molding processes. Reinforced panels are produced in a continuous process in large production plants.

A wide range of polyesters are available in the market. For the purpose of this research work products of Mia Chemicals - Fiber Glass of Canada were used. Manufacturer's specifications and properties of the products are listed in Appendix "A".

CHAPTER 3

ABSORPTION OF PCM IN AGGREGATES

The previous chapter describes an overview of the aggregate materials in which the origin, characteristics, properties, availability and their usefulness as construction materials was described in some details.

The conventional task of aggregate materials is to provide the back bone of a composite by forming its bulk and imparting stability, durability and necessary physical and mechanical properties to the composite. In the present research work an additional and prime responsibility of the aggregates and filler materials is to provide adequate storage facility to the Phase Change Materials inside a composite.

3.1 FUNCTIONS OF AGGREGATES AND FILLERS

Aggregates and filler materials in the proposed composites are required to:

- absorb PCM
- retain the absorbed PCM without leakage
- no chemical reaction should take place between the aggregate materials and the PCM
- provide necessary strength to the composite
- cost of these materials should be acceptably low

3.2 MATERIALS SELECTED

Most common aggregates used in civil engineering works are obtained from hard solid rocks which are devoid of any absorption capability for liquids. Crushed and broken sandstone which forms the major constituent of most concrete mixes has little or no absorption capacity.

Since the present work is the first of its kind in which low cost materials will form the composite constituents, and because of the ~~typical requirements of our proposed composite of encapsulating a PCM,~~ it was important to explore availability of porous materials. After detailed study of the literature and discussions with experts in the field of materials and based on criteria described in Chapter 2, following materials were selected for further laboratory tests and investigations:

- Expanded Shale
- Volcanic Rock
- Activated Charcoal
- Crushed Stone
- Gypsum
- Clay
- Expanded Vermiculite

3.3 TEST EQUIPMENT

3.3.1 Temperature Controlled Heating Bath

Controlled Temperature Heating Bath, a laboratory apparatus from Lab-line Imperial 3 was used for absorption of the PCM in aggregates at a controlled temperature.

3.3.1.1 Method

Butyl Stearate (PCM) was heated in a flask at a controlled temperature of 70°C. Weighed quantities of specimen aggregates were then introduced in order to allow absorption under a vacuum pressure of 50 mm of mercury.

The process continued for 30 minutes after which the aggregate specimens were taken out and allowed to drain off excessive PCM. The specimen were left for drying for 48 hours. Apparently dry but fully absorbed specimen were weighed and the percentage gain in weight calculated.

Preliminary experiments showed that the aggregates absorbed maximum PCM at a temperature of 70°C over a period of 30 minutes.

3.4 ABSORPTION RESULTS

3.4.1 Expanded Shale

Test results of 5 specimens each of 6 mm, 9 mm and 12 mm size of the material, are shown in Table 3-1. These sizes were selected considering the thickness, weight and ultimate cost of the proposed composite. The material was found to absorb:

TABLE 3-1

Absorption of PCM in different sizes of Expanded Shale

Expanded Shale

Specimen No. and Size	Weight of dry specimen (g)	Weight of impreg- nated specimen (g)	Gain (g)	% Gain
--------------------------	----------------------------------	--	-------------	--------

12 mm

S1.1	50	55.8	5.8	11.6
S1.2	50	55.7	5.7	11.4
S1.3	50	55.7	5.7	11.4
S1.4	50	55.9	5.9	11.8
S1.5	50	56.1	6.1	12.2

Average absorption of 5 specimens : 11.68%

Standard deviation (Appendix B) : 0.335

Probable error (Appendix B) : 2.8%

9 mm

S2.1	50	55.7	5.7	11.4
S2.2	50	55.3	5.3	10.6
S2.3	50	55.7	5.7	11.4
S2.4	50	55.6	5.6	11.2
S2.5	50	55.5	5.5	11.0

Average absorption of 5 specimens : 11.1%

Standard deviation (Appendix B) : 0.335

Probable error (Appendix B) : 3%

6 mm

S3.1	50	54.1	4.1	8.2
S3.2	50	54.0	4.0	8.0
S3.3	50	53.8	3.8	7.6
S3.4	50	54.0	4.0	8.0
S3.5	50	54.0	4.0	8.0

Average absorption of 5 specimens : 8.0%

Standard deviation (Appendix B) : 0.219

Probable error (Appendix B) : 1.2%

- 8.2% for 6 mm size
- 11.3% for 9 mm size and,
- 11.5 for 12 mm size aggregate

The impregnated specimens were weighed again after every 24 hours to see if the weight remained constant.

It was observed that the expanded shale is not a good storage material for the PCM as it was not able to retain the PCM over a period of time. A considerable loss of weight because of the leakage of the PCM was noticed.

3.4.2. Volcanic Rock

Volcanic rock specimens of 6 mm; 9 mm; and 12 mm size were impregnated under vacuum at 70°C. The results (Table 3-2) show average absorption of 13.8%, 16.0% and 18% respectively for each size of the material.

3.4.3 Activated Charcoal

Activated charcoal impregnated under vacuum at 70°C was able to absorb almost 40% of the PCM (Table 3-3).

Comparative results of absorption of Expanded Shale, Volcanic Rock and Activated Charcoal are graphically presented in figure 3.1.

3.4.4 Crushed Stone

The material showed negligible absorption for the PCM.

TABLE 3-2

Absorption of PCM in different sizes of Volcanic Rock

Volcanic Rock

Specimen No. and Size	Weight of dry specimen (g)	Weight of impreg- nated specimen (g)	Gain (g)	% Gain
--------------------------	----------------------------------	--	-------------	--------

12 mm

R1.1	50	60.3	10.3	20.6
R1.2	50	59.4	9.4	18.8
R1.3	50	59.3	9.3	18.6
R1.4	50	58.1	8.1	16.2
R1.5	50	59.1	9.9	19.8

Average absorption of 5 specimens : 18.8%
 Standard deviation (Appendix B) : 1.66
 Probable error (Appendix B) : 3.9%

9 mm

R2.1	50	58.1	8.1	16.2
R2.2	50	57.9	7.9	15.8
R2.3	50	57.9	7.9	15.8
R2.4	50	58.4	8.4	16.8
R2.5	50	57.8	7.8	15.6

Average absorption of 5 specimens : 16%
 Standard deviation (Appendix B) : 0.47
 Probable error (Appendix B) : 1.3%

6 mm

R3.1	50	57.2	7.2	14.4
R3.2	50	57.0	7.0	14.0
R3.3	50	56.9	6.9	13.8
R3.4	50	57.2	7.2	14.4
R3.5	50	56.5	6.5	13.0

Average absorption of 5 specimens : 13.9%
 Standard deviation (Appendix B) : 0.576
 Probable error (Appendix B) : 1.8%

TABLE 3-3

Absorption of PCM in Activated Charcoal

Activated Charcoal

Specimen No.	Weight of dry specimen (g)	Weight of impregnated specimen (g)	Gain (g)	% Gain
C1	50	69.1	19.1	38.2
C2	50	70.3	20.3	40.6
C3	50	68.9	18.9	37.8
C4	50	70.5	20.5	41.0
C5	50	70.4	20.4	40.8
Average absorption of 5 specimens : 39.7%				
Standard deviation (Appendix B) : 1.54				
Probable error (Appendix B) : 1.45				

3.4.5 Gypsum

Gypsum rock is calcined at temperatures of 120 to 160°C to remove almost three quarters of its water of crystallization. This product is commercially known as Plaster of Paris and is available in the powder form in market. Gypsum paste samples were prepared with varying quantities of water. The pastes were allowed to harden and then dried at 70°C for 48 hours.

The hardened material was impregnated with the PCM. The results are shown in Table 3-4. It is observed that the absorption capacity

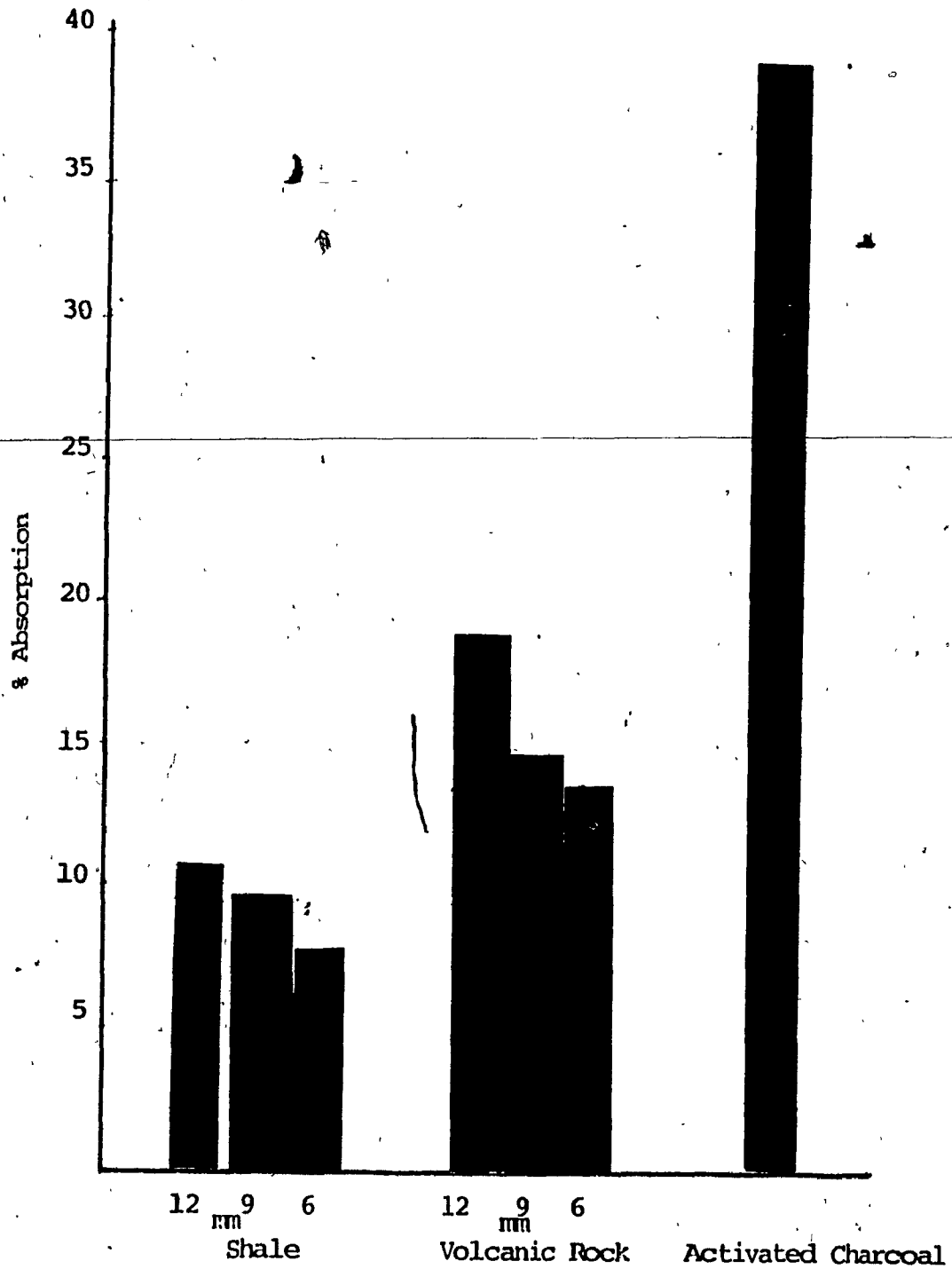


Figure 3.1 Comparative Results of absorption of PCM in some Aggregates

TABLE 3-4

Absorption of PCM in Gypsum pastes prepared with
different water: Gypsum ratios

Gypsum

Specimen No.	Water: Gypsum Ratio in the paste	Absorption of PCM wt. %
P1	0.50	40.0
P2	0.60	40.8
P3	0.70	42.8
P4	0.80	50.0

of the material increased with the increase of water content in the paste (Figure 3.2) from 40% for a water: gypsum ratio of 0.5 to 50% for a ratio of 0.8.

3.4.6 Clay

Clay bricks were prepared in the laboratory with 5% water content. Absorption results show that an average of 8.1% of the PCM was absorbed in these clay bricks.

3.4.7 Expanded vermiculite

This light weight aggregate has tremendous absorption for liquids. It can absorb more than 200% of the PCM at room temperature.

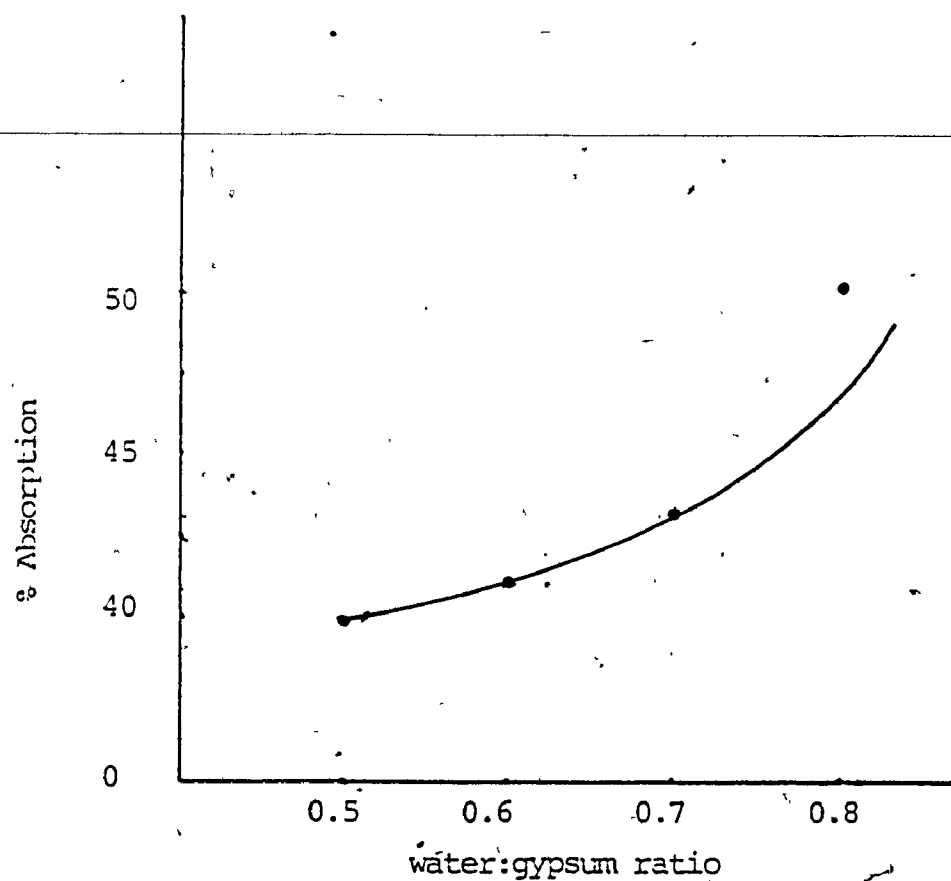


Figure 3.2 Absorption of PCM in hardened gypsum pastes prepared with different water : gypsum ratios

3.5 DIFFERENTIAL SCANNING CALORIMETRY

Thermal analysis were conducted on various PCM - impregnated aggregate specimens in order to:

- determine transition temperatures and heats of fusion and crystallization
- see the affects, if any, of Butyl Stearate (PCM) on the specimens

DuPont Model 910 Differential Scanning Calorimeter was used for the thermal analysis of the specimens. The equipment consists of a cell base module directly connected to a programmer-recorder DuPont 1090 Thermal Analyzer. The specification of the instrument are:

- Temperature interval -: -160 to +160°C
- Heating rate : 0.1 to 20°C/min
- Repeatability of latent heat:- 1% with identical choices for the ends of the base line
- Absolute Reference Temperature repeatability $\pm 0.3^{\circ}\text{C}$ at 2 °C/min scan rate.

The DSC cell has a constant disk as a primary heat transfer element which conducts heat to both the sample and reference pan which are positioned on raised portions of the disk. The temperatures of the sample and reference pans are measured by chromel-constant thermocouples.

Since the areas and materials of the two pans are identical, the difference of heat flow is directly proportional to the difference in temperatures when the magnitude of the specimen is small enough. This measurement can be stored or plotted as a DSC curve.

The DSC curve is analyzed by the 1090 DuPont Thermal Analyzer using the Interactive Data Analysis Program (V.2.0). This program calculates the temperatures and heats associated with transitions in the specimen materials.

The method consists of heating and or/cooling a weighed quantity of the specimen material and a reference empty pan both at the same controlled rate of temperature. When a given heat related change takes place in the specimen but none-so in the reference pan, the resulting difference in temperature between the two is directly related to the heat flow to and from the specimen. This differential heat flow is quantitatively measured and plotted in the form of a DSC curve. This diagram, because of the high calorimetric sensitivity of the equipment, provides accurate measurement of the temperatures of transition. The values of the heats of transition are calculated by automatic peak integration of the related heat flow versus time curve which is available in the microcomputer memory.

A typical thermogram of heating and cooling cycle for a test specimen of Butyl Stearate is shown in Figure 3.3. The list of parameters calculated by the Interactive Data Analysis Program are:

Date: 17-Dec-86 Time: 8:11:13
 Operator: 0.4SEC/POINT
 Sample: BU. STEARATE
 Size: 5.406MG
 Rate: 2C/MIN
 Program: Interactive DSC V2.0

DSC

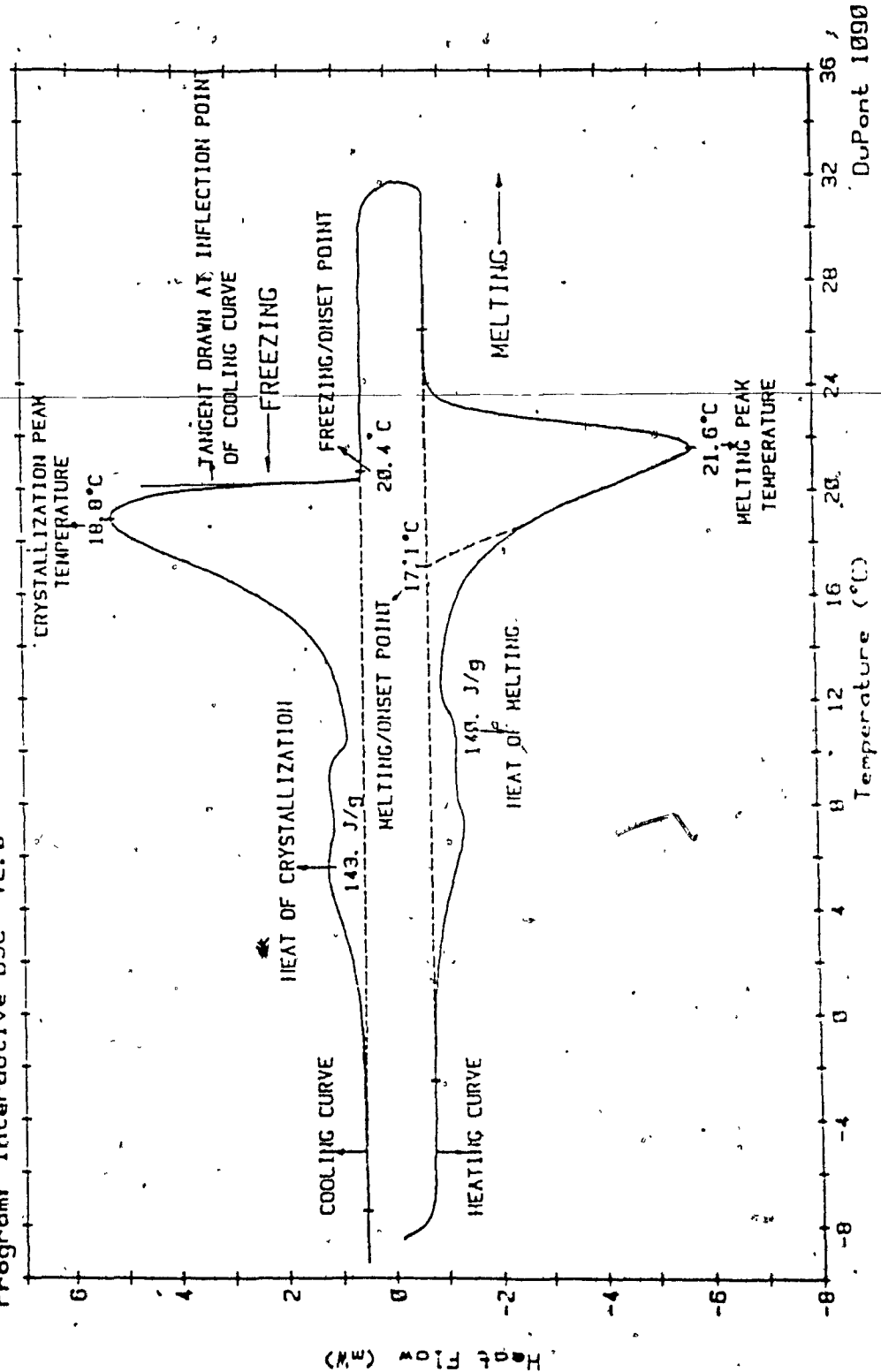


Figure 3.3 DSC Analysis of Butyl Stearate

(a) Melting Point

The initial melting point or onset temperature on the heating curve is the calculated temperature at the intersection of the base line with the tangent to the inflection point in the curve of heat flow versus temperature.

(b) Freezing Point

The initial freezing point or onset temperature on the cooling curve may be shifted if an initial crystal is slow to form. In the absence of supercooling, the freezing point is calculated as the temperature at the intersection of the base line and the tangent to the inflection point in the curve of heat flow versus temperature. In case the sample supercools and the temperature rises by more than 0.25°C upon crystallization, then the initial freezing point is taken as the highest temperature observed. In both the onset temperature calculations, a least square fitting method is used to draw the tangent. The region of interest on the curve is examined until the inflection point is found. The tangent line is now drawn at this inflection point and is further projected to intersect the base line. One eight points are used for the fit.

(c) Melting Peak Temperature

This parameter is defined as the temperature of the point which is located farthest from the base line in the heating curve. Since its location depends on the rate of heating, most runs are taken at

the same rate, i.e. 2°C/min for initial tests and 0.2°C/min for final tests.

(d) Crystallization Peak Temperature

This parameter is defined as the temperature of the point which is located farthest from the base line in the freezing curve.

(e) Heat of Melting and Freezing

The heats of melting and freezing are calculated from the integrated area over time for the heat flow associated with melting or crystallization based on the following formula [29]:

$$\Delta H = \frac{k}{m} \times \int_{t_i}^{t_2} \times \frac{\Delta \dot{Q}}{f(T)} dt$$

where:

ΔH = heat of transition

m = mass of the specimen

$\Delta \dot{Q}$ = heat of flux

t = time

$f(T)$ = temperature dependent heat transfer function

k = DSC constant (obtained by calibration)

The calibration constant k , is slightly dependent on temperature in a non-linear way. It is linearized electronically by the Thermal analyzer to become constant over the short temperature range of these experiments. The calculated heats of transition are given in J/g.

3.5.1 Thermal Analysis Procedure

The instrument is first calibrated by scanning pure indium samples having melting point of 156.6°C and latent heat of melting of 28.4 J/g . The temperature repeatability was 0.3°C and the repeatability of latent heat as $\pm 1\%$ for a scanning rate of 2°C/min , and $\pm 2.5\%$ for a scanning rate of 0.2°C/min due to increased electronic noise.

Samples of 2 to 7 mg for PCM, 6 to 7 mg for vermiculite, 15 to 20 mg for activated charcoal and about 30 mg for gypsum were weighed in aluminum pans on a Sartorius 4501 microbalance (with an accuracy of $\pm 0.005 \text{ mg}$).

These samples were scanned at a heating or cooling rate of 2.0 or 0.2°C/min in a nitrogen atmosphere. The rate at which data were sampled was 0.4 sec/point for a 2.0°C/min heating or cooling and 2.4 sec/point for a 0.2°C/min heating or cooling rate. The controlled inert atmosphere is provided by a nitrogen cylinder equipped with a pressure regulator and a gas flowmeter as shown in Figure 3.4.

3.5.2 1090 DuPont Thermal Analyzer

The 1090 DuPont Thermal analyzer is the basic control unit for the DSC system already described in the preceding paragraphs. It is a compact unit comprising of a digital temperature programmer, a printer/plotter, disk memory and the data analyzer. When associated with the DSC module, it controls the heating rate and measures actual sample temperatures as well as stores data. The stored data can be

recalled, analyzed and plotted on graphs. Software programs are available for data analysis and calibration. The equipment is shown in Figure 3.5.

3.6 THERMAL ANALYSIS RESULTS

Thermal analysis were performed on gypsum, vermiculite and activated charcoal specimens impregnated with Butyl Stearate (PCM) @ 28%, 200% and 40% respectively.

3.6.1 Butyl Stearate on Gypsum

From heat flow diagram (Figure 3.6), following results are derived:

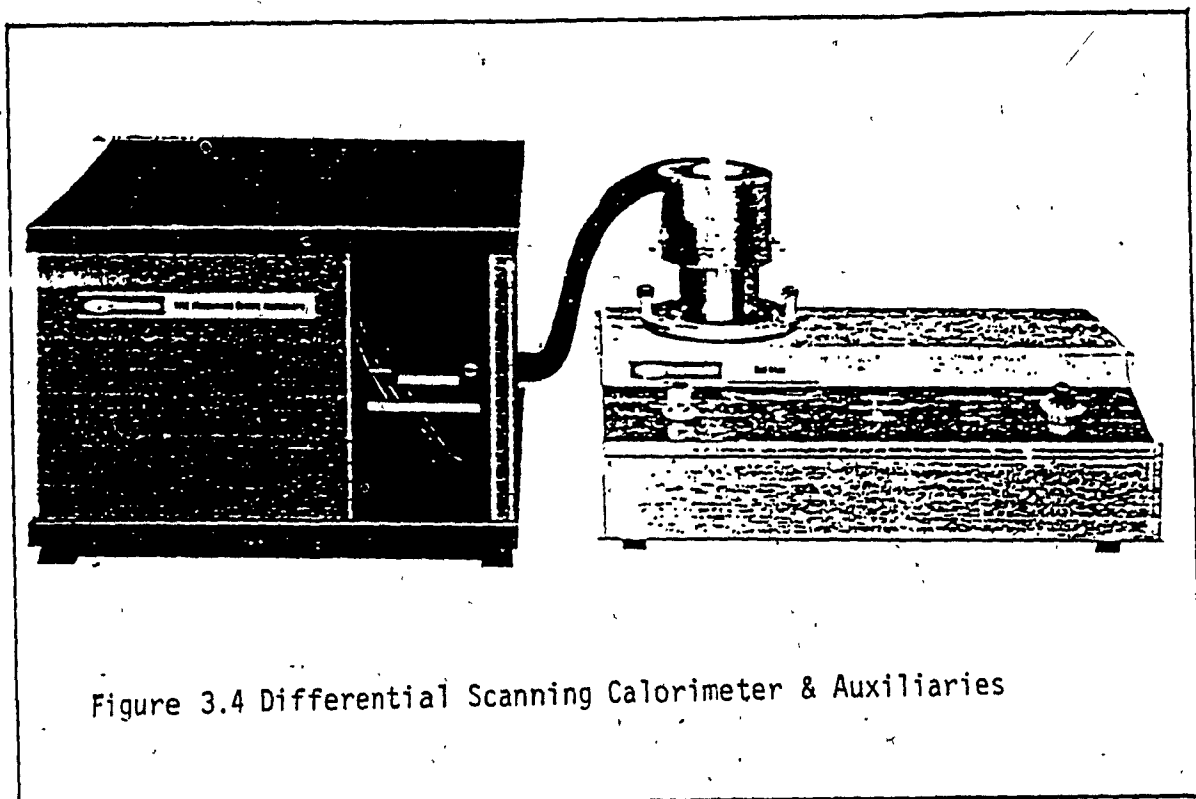
- 1) Latent heat of crystallization = 42.0 J/g
- 2) Latent heat of melting = 41.1 J/g
- 3) Crystallization peak temperature = 18.1°C
- 4) Melting peak temperature = 22.5°C

This shows that there is no loss of Butyl stearate from material and that no chemical reaction took place between the fatty acid and gypsum.

The tests were repeated on the same specimen after three months which showed no change or loss of PCM in the material.

3.6.2 Butyl Stearate on Activated Charcoal

The following results were obtained from the heat flow diagram of activated charcoal impregnated with butyl stearate (Figure 3.7).



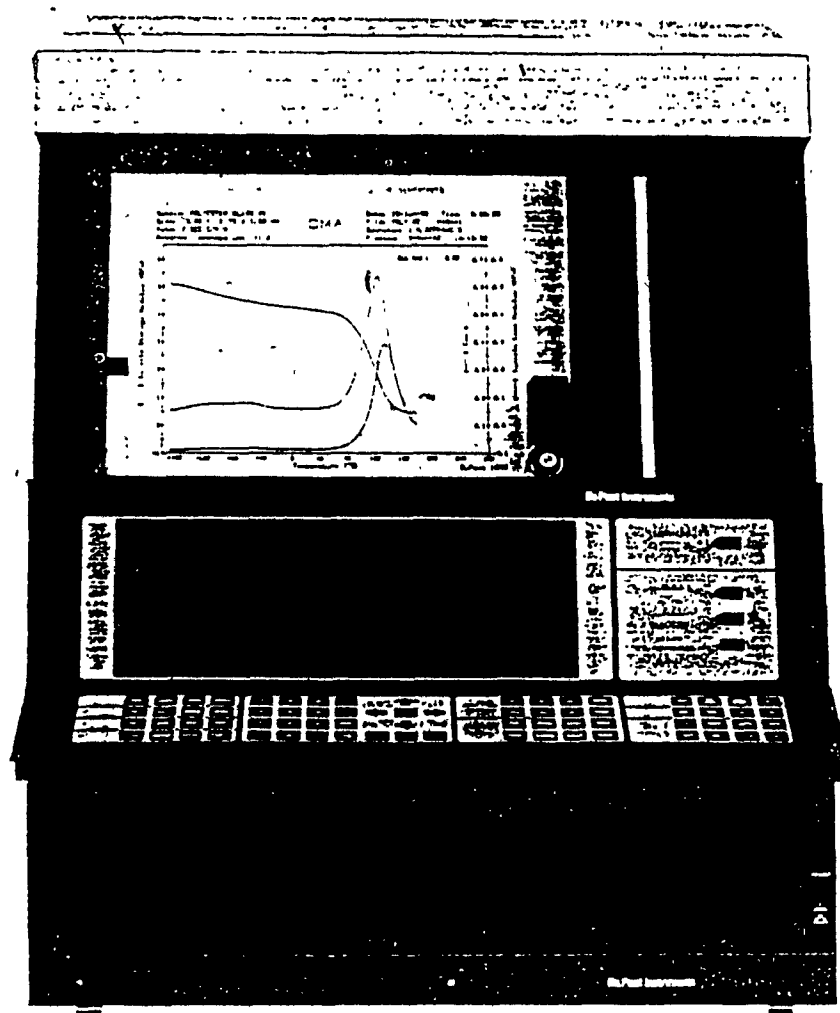


Figure 3.5 Thermal Analyzer - Computer/Printer

Date: 17-Aug-87 Time: 10:17:18

Sample: BU:ST.ON PLASTER OF PAR

Size: 32.667MG

Rate: 20C/MIN

Program: 'Interactive DSC V2.0'

DSC

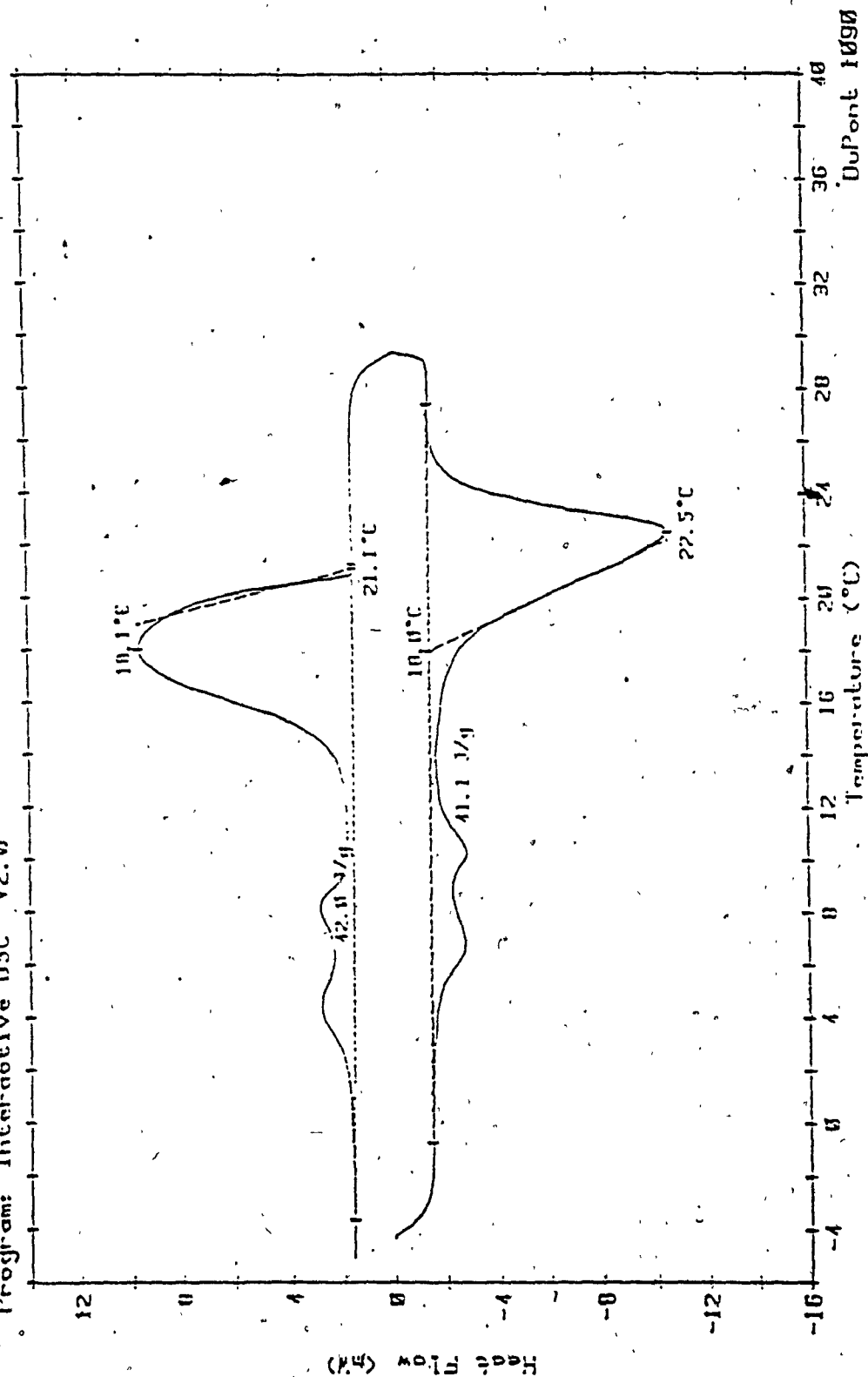


Figure 3.6 DSC Analysis Bu ST on Gypsum

Date: 8-Aug-07 Time: 11:19:20

Sample: RU ST.01 ACT.CH.11/VAC.2 @ 28%

Size: 10.600MG

Rate: 20/MIN

Program: Interactive DSC V2.0

DSC

Plotted: 6-Aug-07 12:13:33

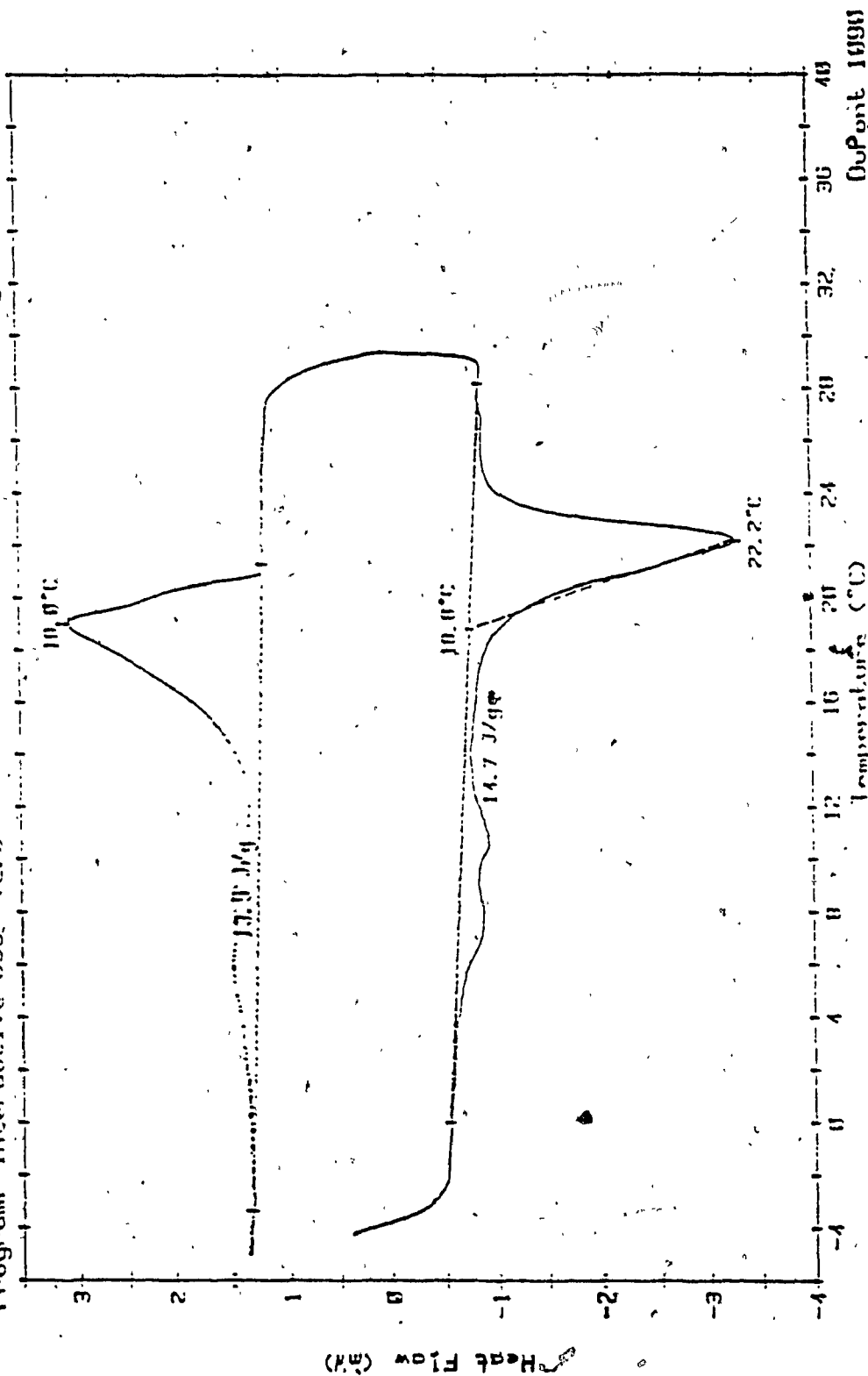


Figure 3.7 DSC Analysis Ru St on Activated Charcoal

- 1) Latent heat of crystallization = 13.5 J/g
- 2) Latent heat of melting = 14.7 J/g
- 3) Crystallization peak temperature = 19.0°C
- 4) Melting peak temperature = 22.2°C

If there were no loss of the PCM in the material, the latent heat of the impregnated activated charcoal should have been:

$$\frac{0.4}{1.4} * 140 = 40 \text{ J/g}$$

The results show that activated charcoal is not capable of discharging the expected heat flow.

3.6.3 Butyl stearate on Vermiculite

Vermiculite specimen impregnated at 200% Butyl Stearate were tested and following results obtained (Figure 3.8):

- 1) Latent heat of crystallization = 101 J/g
- 2) Latent heat of melting = 103 J/g
- 3) Crystallization peak temperature = 17.6°C
- 4) Melting peak temperature = 23.0°C

The results indicate that there was no loss of PCM from the material and is chemically non-reactive with it.

Sample: DU. ST. ON VILCULITE V1 #2 © 2008 Date: 7-Aug-87 Time: 10:44:13

DSC

Size: 8.75MMG

Rate: 20C/MIN

Program: Interactive DSC V2.0

Plotted: 7-Aug-87 11:39:59

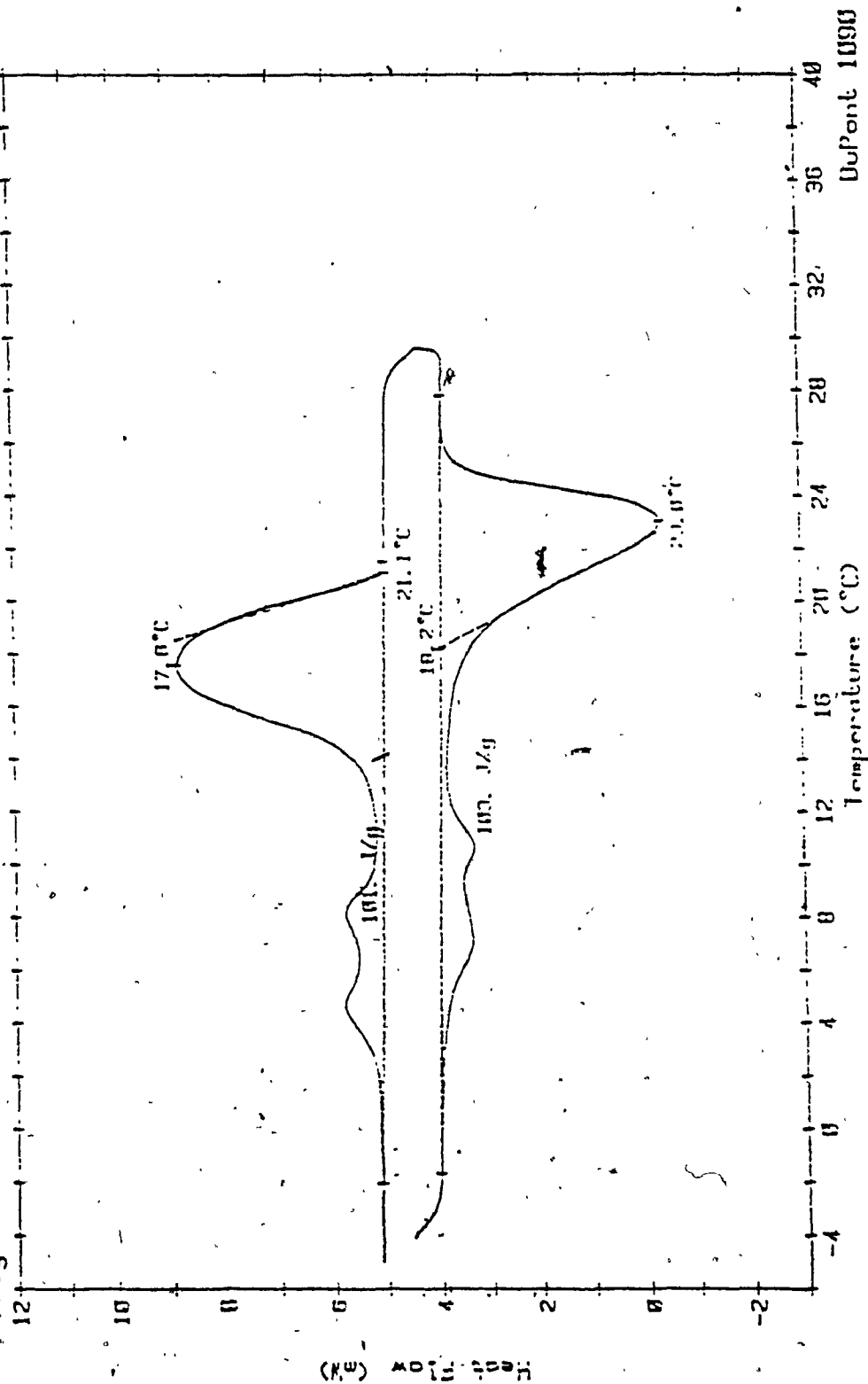


Figure 3.8 DSC Analysis Du ST on Vermiculite

CHAPTER 4

THE COMPOSITE

In the previous chapters preliminary research of literature and materials was discussed. The methods of absorption and thermal analysis of the materials, their absorption capacities for the PCM and retention thereof was also explained at length.

At this stage of the research work certain materials were indeed available which had sufficient absorption capacities and could be incorporated as possible constituents for our proposed composite.

4.1 POLYMER CONCRETE

Polymer concrete composites are being developed in many countries and new applications being probed. Three main categories of polymer concrete are currently in use, these are [30]:

- 1) Polymer Concrete (PC) prepared by mixing a resin with aggregates
- 2) Polymer Impregnated Concrete (PIC) prepared by impregnating normal concrete with a monomer which is polymerized in situ.
- 3) Polymer-Portland Cement Concrete (PPCC) prepared by adding a resin to portland cement during mixing stage; the mix being polymerized in situ.

The properties of these categories of polymer concrete are different from each other and add to many possibilities of cements and plastics.

4.2 POLYMER CONCRETE COMPOSITE

Experiments were performed to prepare polymer concrete composites from a polyester resin used as a binder together with different grades of mineral loadings as aggregates and fillers. The mineral loadings comprised of (Figure 4.1):

- coarse aggregates like expanded shale, volcanic rock, activated charcoal and gypsum all impregnated with PCM
- fillers like calcium carbonate, silica, Ottawa sand and celite-commercial name of a silicate filler

Different grades of polyester resins supplied by Mia Chemicals were used as binders.

Considering requirements of thermal storage it was considered necessary that sufficient quantity of PCM must be encapsulated within the composite. Accordingly a composite with 20% PCM required 50 to 80% of the aggregate materials and fillers. At the same time enough quantity of resin 15 to 20% was required to prepare a consistent and homogeneous mix.

Specimen composites were prepared with different mix compositions of aggregates, fillers and resin. It was however, observed that even after curing for several hours the specimen did not dry and PCM leaked out.

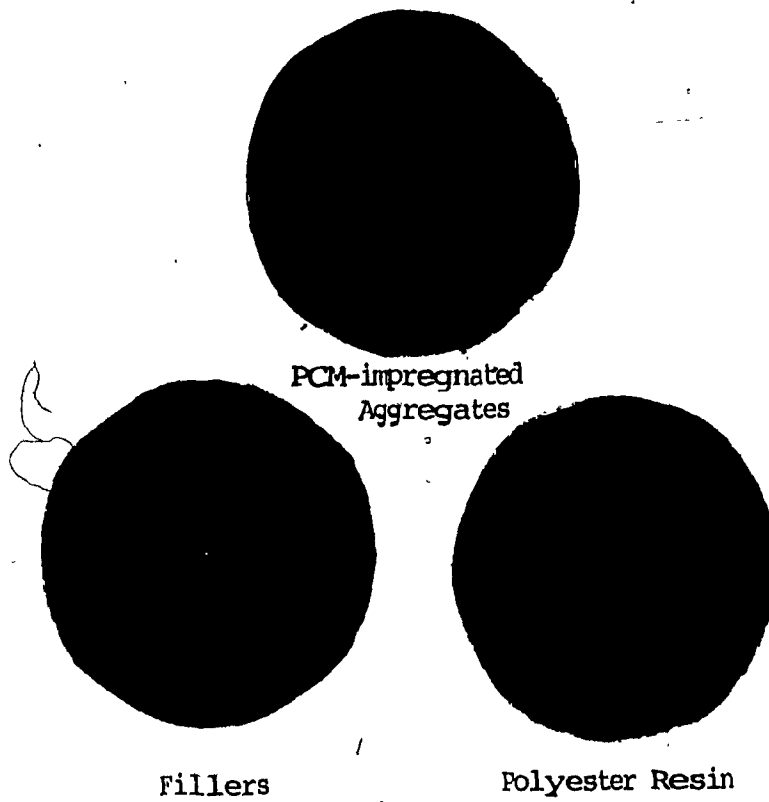


Figure 4.1 Polymer Concrete Composite Constituents.

Polyester resin as we know is a solution of polyester in styrene, which forms almost 40% of the content, having molecular weight of 104 has a tendency to replace butyl stearate (molecular weight 340) in the aggregate.

After considering the results of the specimen composites, it was considered that this method of encapsulation of PCM in a polymer concrete composite was neither feasible nor economical.

4.3 GYPSUM CONCRETES

Concrete mixes were prepared with coarse aggregates such as expanded shale and crushed stone, and fillers like wood sawdust, vermiculite, sand and ordinary Portland cement grade 10 as in a normal concrete. Gypsum powder was used as the starting material for all the mix compositions, with different water: gypsum ratios. The use of gypsum powder in the mix has two major functions viz; act as a binder material and being the principal absorbant of PCM.

Specimen tiles were prepared from various mix compositions, and absorption tests performed on the specimens to find out their capacity to absorb the PCM. The results tabulated in the following paragraphs of this chapter are the average results, from five tests for each specimen.

Compressive strength of the specimens were performed according to ASTM Standards C 39, C 192, C 317 and C 472.

Thermal analysis of the specimens were performed to find out transition temperatures and heats of fusion and crystallization. The analysis also helped ascertain any chemical reaction or otherwise between the component materials and the PCM.

The results of possible chemical reaction were also confirmed through infrared spectra.

Thermal conductivity tests of different specimens were carried out with a view to find out ways to improve the thermal conductivity of the composite. Detailed experimental procedure of the tests prepared are described in the later pages of this chapter.

4.3.1 Gypsum-Sand-Aggregate

In the first stage concrete mixes were prepared using gypsum powder, sand and coarse aggregate. Different mix compositions were experimented and best results for absorption of PCM obtained when the gypsum content in the mix was 50% (Table 4-1).

Figure 4.2 represents the absorption capacity of the specimens with varying water: gypsum ratios. The absorption increased from 10.85% for a water: gypsum ratio of 0.4 to 27% for a ratio of 0.8 in the mix composition marked G1. Compressive strength results (Table 4) show that the specimens with this composition had compressive strength of 6.06 MPa, based on the average results from five specimens.

TABLE 4-1

Results of absorption Tests of PCM in the specimens with
different water: gypsum ratios

Specimen No. G-1
Mix Composition:

Gypsum : 50%
Sand : 20%
Coarse Aggregate : 30%

Specimen No.	Water: Gypsum Ratio in the mix	Absorption of PCM wt %
G-1.1	0.4	10.85 *
G-1.2	0.5	14.5 *
G-1.3	0.6	19.0 *
G-1.4	0.7	22.1 *
G-1.5	0.8	27.0 *

* indicates average result from five specimen

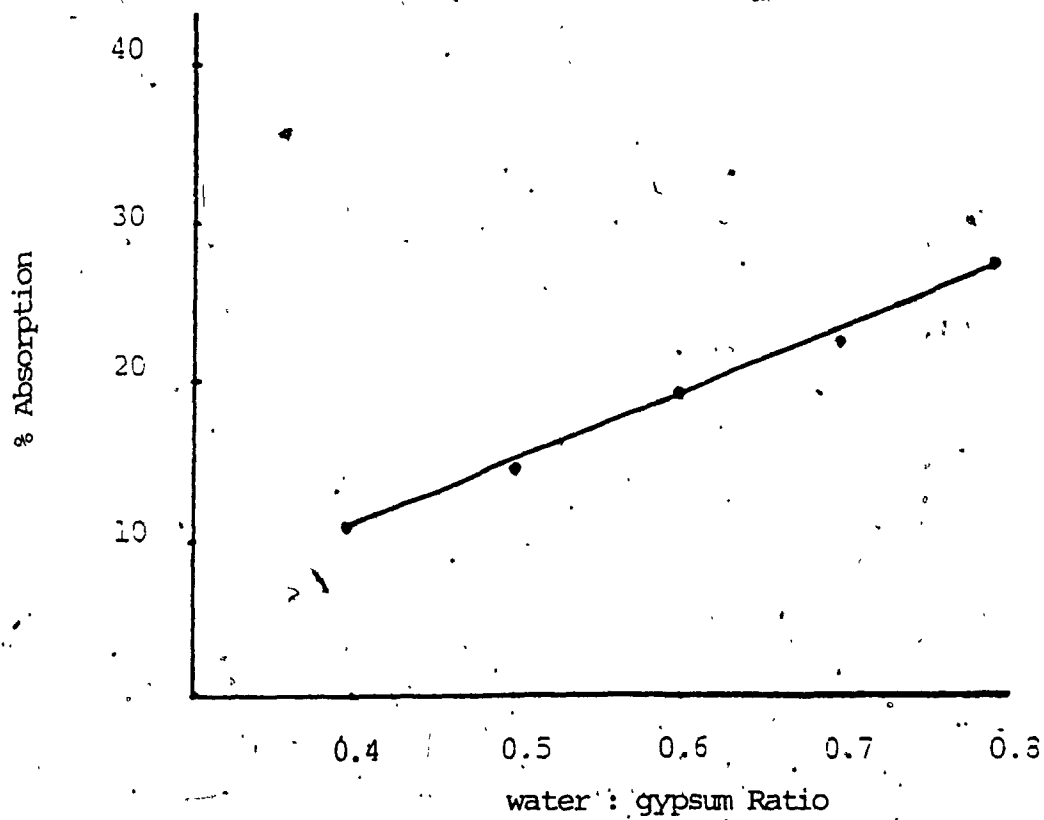


Figure 4.2 Absorption of PCM in Gypsum Concrete Specimens prepared with different water : gypsum ratios

4.3.2 Introduction of Wood Saw-dust

Wood-saw dust was introduced in the gypsum concrete mix in the next stage to see the effects, if any, on the absorption capacity as well as its compressive strength.

Table 4-2 shows results of absorption of different mix compositions with 5% saw dust in each mix. The absorption capacity of specimens showed steady rise (Figure 4.3) from 12.5% @ 30% gypsum to 21.41% @ 50% gypsum content in the mix.

Results of absorption for different water:gypsum ratios in specimen marked G-6 are shown in Table 4-3 and graphically represented in Figure 4.4. The absorption of the specimen increased from 15% to 34.8% for the same mix composition for water:gypsum ratios from 0.4 to 0.8.

Compressive strength for the mix composition G-6 is 2.76 MPa, the result being average of five specimens.

TABLE 4-2

Results of absorption tests for different mix compositions on
introduction of wood saw-dust in the mix

Specimen No.	Mix Composition	Absorption of PCM wt %
G-2	Gypsum : 30% Sand : 15% Saw dust : 5% Coarse aggregate : 50%	12.5 *
G-3	Gypsum : 35% Sand : 15% Saw dust : 5% Coarse aggregate : 45%	14.0 *
G-4	Gypsum : 40% Sand : 15% Saw dust : 5% Coarse aggregate : 40%	15.2 *
G-5	Gypsum : 45% Sand : 15% Saw dust : 5% Coarse aggregate : 35%	18.0
G-6	Gypsum : 50% Sand : 15% Saw dust : 5% Coarse aggregate : 30%	21.4 *

Water: Gypsum ratio of 0.6 was maintained for all the specimen

* indicates average result from five specimens

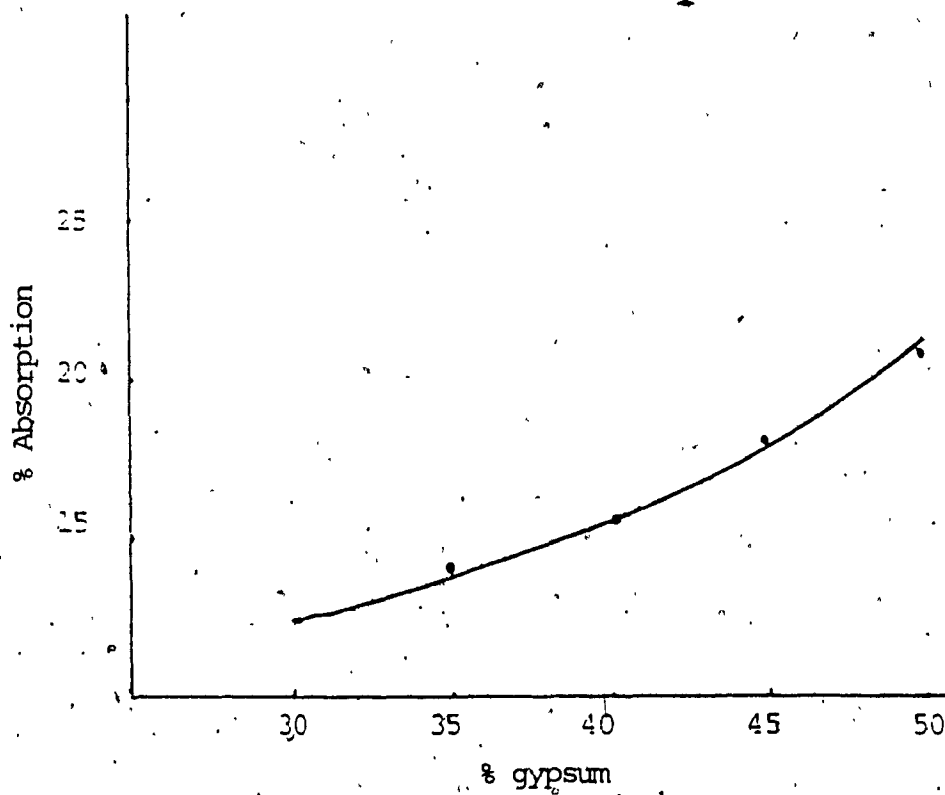


Figure 4.3 Absorption of PCM in Specimen Composites with 5 % sawdust and different quantities of gypsum in the mix

TABLE 4-3

Results of Absorption of PCM in the specimen No. G-6 with
different water:gypsum ratios

Specimen No. G-6
Mix Composition:

Gypsum : 50%
Sand : 15%
Saw dust : 5%
Coarse aggregate : 30%

Specimen No.	Water: Gypsum Ratio in the mix	Absorption of PCM* wt. %
G-6.1	0.4	15.0 *
G-6.2	0.5	18.1 *
G-6.3	0.6	21.4 *
G-6.4	0.7	28.2 *
G-6.5	0.8	34.8 *

* indicates average result from 5 specimen

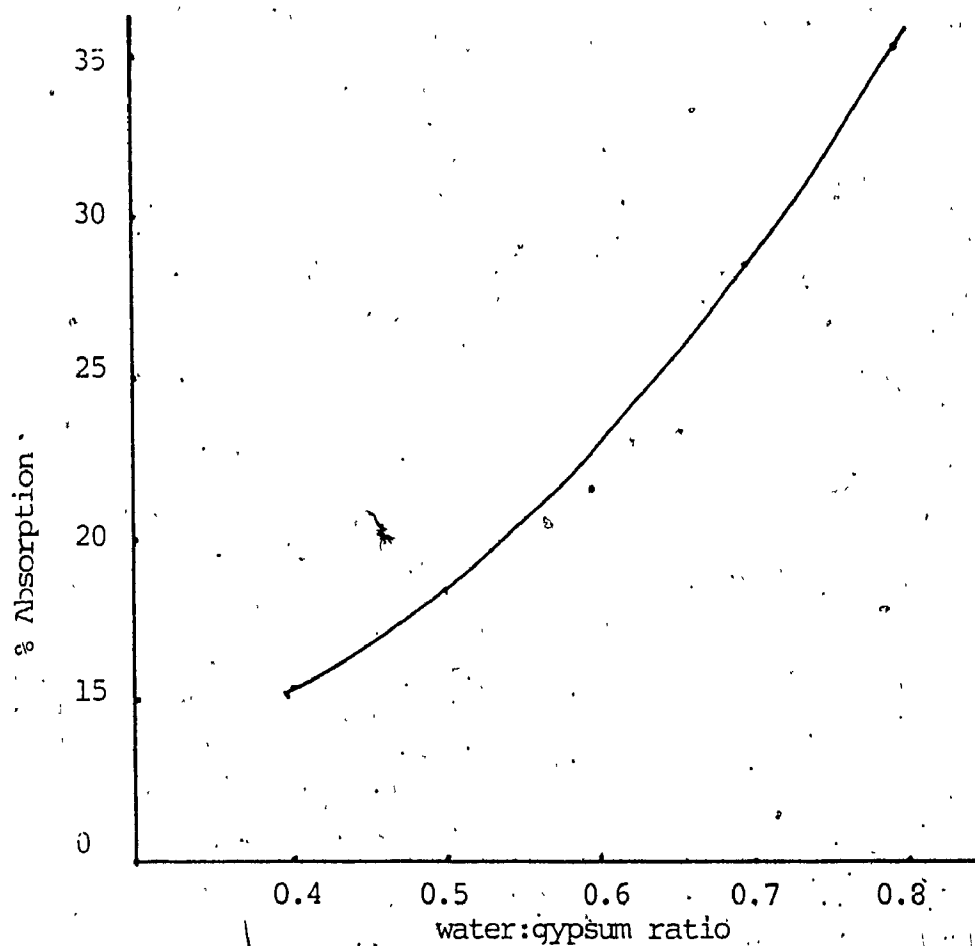


Figure 4.4 Absorption of PCM in specimens with 50 % gypsum
5 % sawdust and different water : gypsum ratios in the mix

TABLE 4-4

Compressive strength test results of specimen Nos. G-1 and G-6

Specimen No.	Compressive Strength MPa	Remarks
Mix Composition: G-1		
G-1.1	6.12	specimens No. G-1.1 to G-1.5 were tested at 28 days
G-1.2	6.24	
G-1.3	5.92	
G-1.4	6.1	
G-1.5	5.95	
Average Compressive Strength		: 6.06 MPa
Standard deviation (Appendix B)		: 0.12 MPa
Probable % error of mean (Appendix B)		: 1%
Mix Composition: G-6		
G-6.1	2.84	The specimens were tested at 28 days curing Water: gypsum ratio = 0.6
G-6.2	2.90	
G-6.3	2.60	
G-6.4	2.68	
G-6.5	2.80	
Average Compressive Strength		: 2.76 MPa
Standard deviation (Appendix B)		: 0.14 MPa
Probable % error of mean (Appendix B)		: 2.2%

4.3.3 Introduction of Portland Cement

The specimen prepared for various tests thus far had only gypsum powder as the bonding agent for the constituents of the composite mixes. The results of specimen G-1 and G-6 exhibit fairly low compressive strengths for these mix compositions (Table 4-4). In the next stage of the research, ordinary Portland cement was introduced for better bond between the constituents of the mix.

Table 4-5 shows absorption of two specimen mix compositions after introduction of cement @ 10%. Absorption of the mix with different water: gypsum/cement ratios of specimen G-7 are shown in Table 4-6. It is observed that the absorption varies between 14.5 to 30.3% for water:gypsum/cement ratios of 0.4 to 0.8 (Figure 4.5).

It is also observed that the introduction of portland cement in the mix had only a minor negative affect on the absorption (Figure 4.6). A decrease of 0.5% to 3.5% resulted for water:gypsum, or gypsum/cement ratios in the mixes ranging between 0.4 to 0.8.

Compressive strength results show (Table 4-7) an improvement for the mix composition G-7 over those of G-6.

TABLE 4-5

Absorption results of PCM in the specimen on introduction of
Portland Cement in the mix

Specimen No.	Mix Composition	Absorption of PCM wt %
G-7	Gypsum : 50% Saw dust : 5% Sand : 10% Cement : 10% Coarse aggregate : 25% Water:gypsum/cement ratio : 0.6	20.5 *
G-7.1	Gypsum : 40% Saw dust : 5% Sand : 10% Cement : 10% Coarse aggregate : 35% Water:gypsum/cement ratio : 0.6	16.8 *

* indicates average result from 5 specimens

TABLE 4-6

Absorption results of PCM in the specimen No. G-7 prepared
with different water:gypsum/cement ratios in the mix

Specimen No. G-7
Mix Composition:

Gypsum : 50%
Sand : 10%
Cement : 10%
Saw dust : 5%
Coarse aggregate : 25%

Specimen No.	Water: Gypsum/Cement Ratio in the mix	Absorption of PCM wt %
G-7.1	0.4	14.5 *
G-7.2	0.5	17.8 *
G-7.3	0.6	20.5 *
G-7.4	0.7	27.0 *
G-7.5	0.8	30.3 *

* indicates average result from 5 specimens

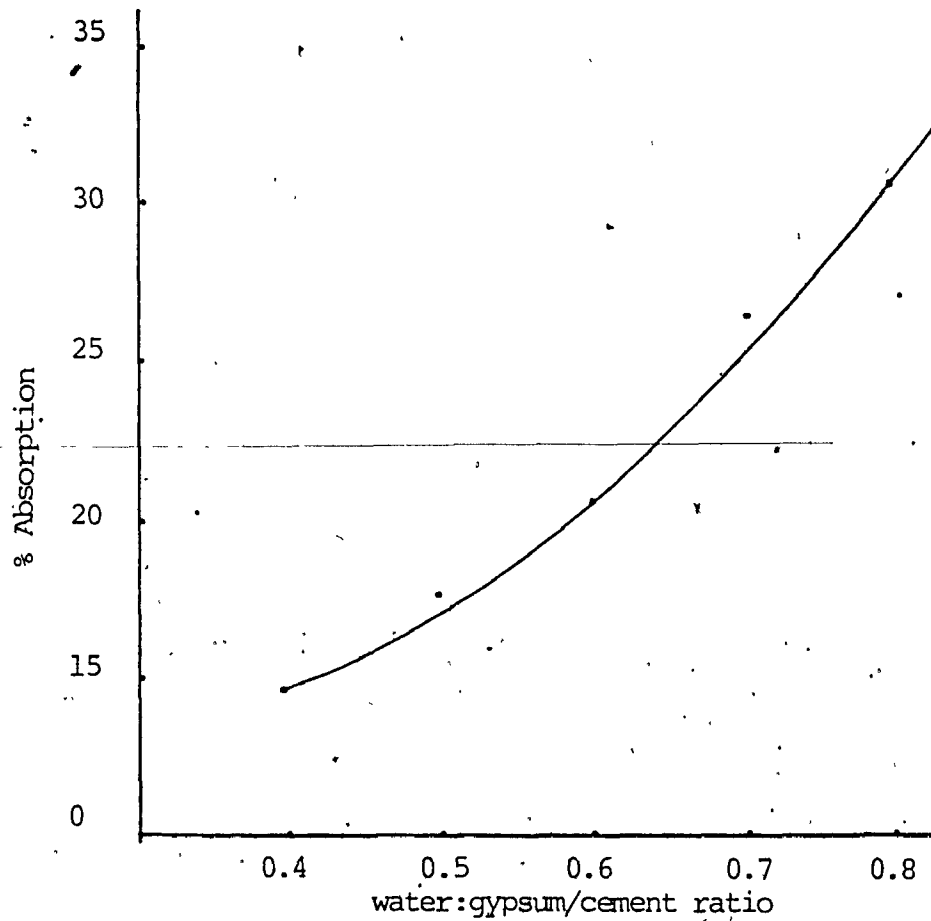


Figure 4.5 Absorption of PCM in specimens with 50 % gypsum
5 % sawdust and 10 % Portland cement and different ratios of
water : gypsum/cement in the mix

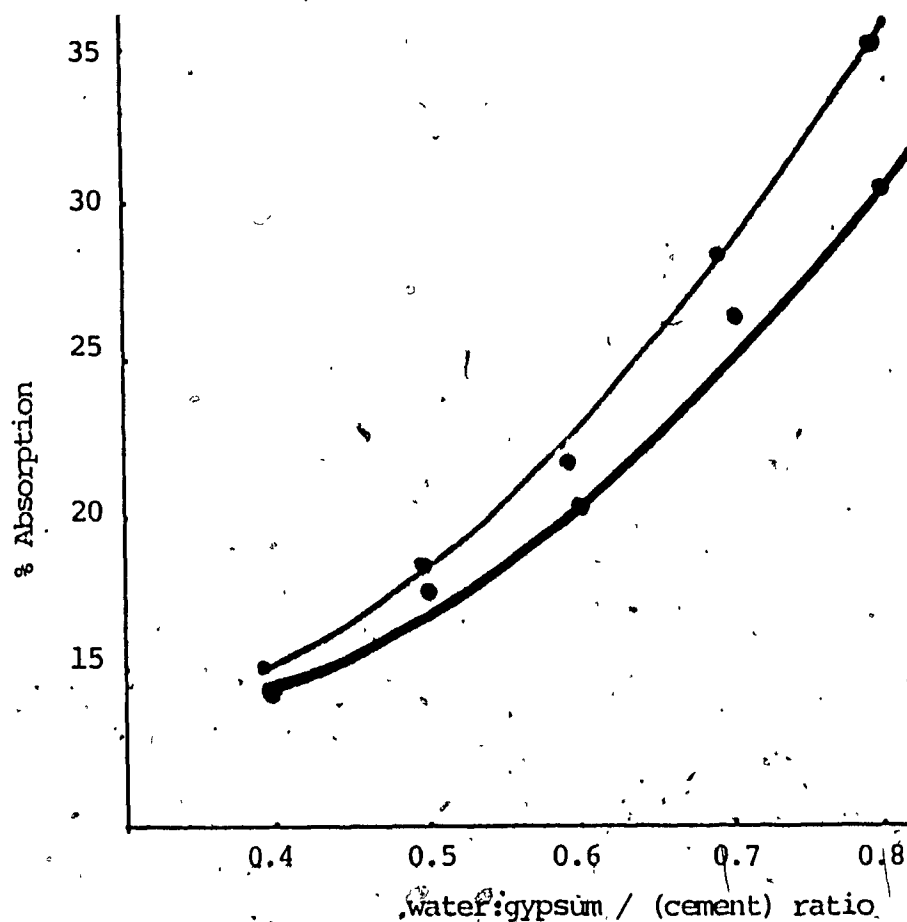


Figure 4.6 Comparative results of absorption of PCM in specimens with and without Portland cement in the mix

LEGEND

Specimen without Portland Cement

Specimens with Portland Cement

TABLE 4-7

Compressive Strength Results for Mix No. G-7

Specimen No.	Compressive Strength	Remarks
Mix Composition: G-7, with water: gypsum/cement ratio of 0.6		
G-7.1	2.9	
G-7.2	2.8	
G-7.3	2.98	The specimens were tested at 28 days curing
G-7.4	1.98	G-7.4 discarded
G-7.5	2.84	
Average Compressive Strength from 4 specimens : 2.88 MPa		
Standard deviation (Appendix B) : 0.062 MPa		
Probable % error of mean (Appendix B) : 1%		

4.3.4 Introduction of Expanded Vermiculite

Preliminary experiments showed that expanded vermiculite has an absorption capacity of over 300%. In order to improve absorption capacity of our composite with lesser amounts of gypsum powder, expanded vermiculite was now introduced to replace wood sawdust.

The specimens showed marked improvement in absorbing PCM even on reducing the gypsum content from 50% to 25%. The results show (Table 4-8) that on addition of 5% vermiculite, the absorption of various specimens was between 31.8% @ 40% gypsum to 27% @ 25% gypsum content. Figure 4.7 is a graphical representation of the absorption of PCM in mixes with varying quantities of gypsum and 5% of vermiculite.

A comparison of the absorption results of the mixes with saw dust and vermiculite is shown in Figure 4.8. In a mix with 35% gypsum and 5% saw dust the absorption was 12.5% whereas the same mix with 5% vermiculite resulted in 28.5% absorption of the PCM. Compression tests were performed on the following specimens from mix composition G-11:

- 1) 5 specimen cylinders after 7 days curing
- 2) 5 specimen cylinders after 28 days curing
- 3) 5 specimen cylinders after 28 days of curing were impregnated with Butyl Stearate (PCM) @ 15%. The specimens were then coated with a film of polyester resin, 2T 035 a product of Mia Chemicals, Montreal.

TABLE 4-8

Absorption of PCM in specimen composites on introduction
of Expanded Vermiculite in the mix

Specimen No.	Mix Composition	Absorption of PCM wt %
G-8	Gypsum : 40% Vermiculite : 5% Sand : 10% Cement : 10% Coarse aggregate : 35%	31.8 *
G-9	Gypsum : 35% Vermiculite : 5% Sand : 10% Cement : 10% Coarse aggregate : 40%	28.5 *
G-10	Gypsum : 30% Vermiculite : 5% Sand : 10% Cement : 10% Coarse aggregate : 45%	27.4 *
G-11	Gypsum : 25% Vermiculite : 5% Sand : 10% Cement : 10% Coarse aggregate : 50%	26.8 *

Water: Gypsum/Cement ratio was maintained at 0.6

* indicates average result from 5 specimens

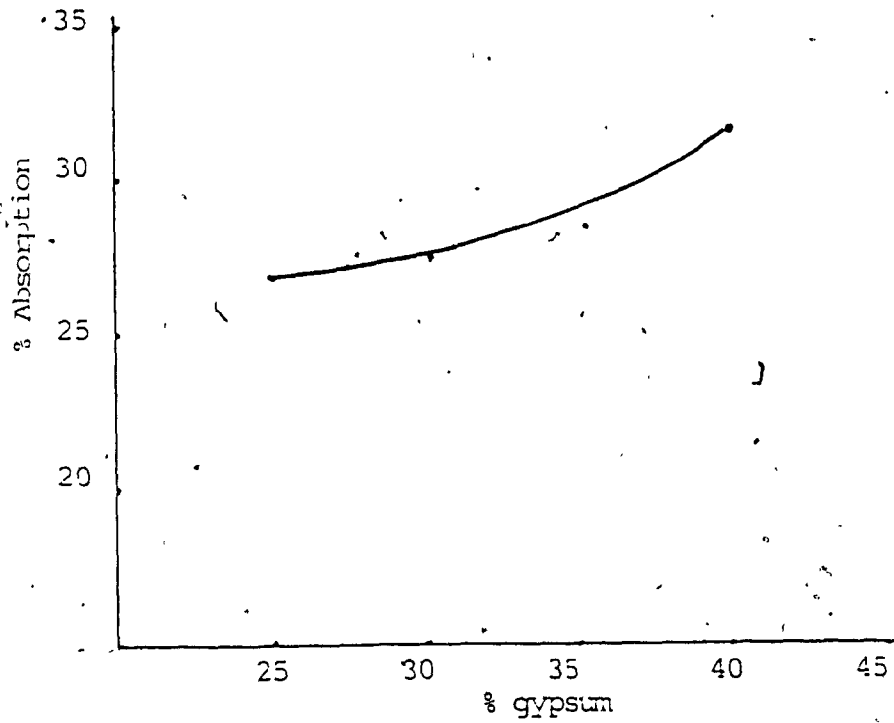


Figure 4.7 Absorption of PCM in specimens on introduction of vermiculite in the mix

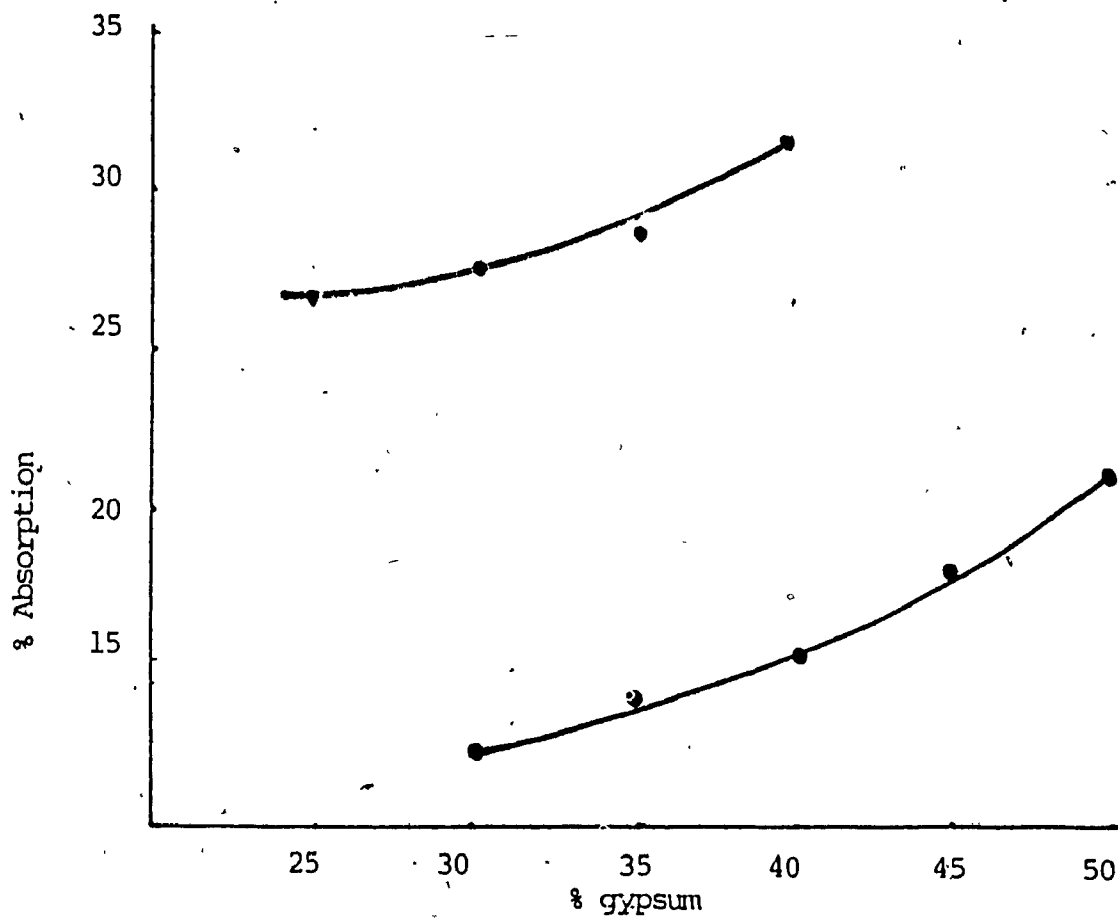


Figure 4.8 Comparative results of absorption of PCM in specimens with sawdust or vermiculite in the mix

LEGEND

Specimens with sawdust



Specimens with vermiculite



The results show (Table 4-9) that the compressive strength increased from an average of 2.38 MPa at 7 days to 3.57 MPa at 28 days. However, the compressive strength for the PCM impregnated specimens dropped to 3.08 MPa, a loss of 12.8%.

Further experiments were performed to prepare specimens with lower quantities of vermiculite to see the effects, if any, on the absorption capacities as well as the compressive strengths of the composite so prepared.

It was observed that on lowering the quantity of vermiculite from 5% as in specimen No. G-11 to 3% in specimen No. G-12, the absorption was greatly reduced from 26.8% to 15.0%. Further reduction of vermiculite by 0.5% showed small changes, being 14.15% for 2.5% vermiculite and 13.8% for a mix with 2.0% of vermiculite content (Table 4.10, Figure 4.9).

Compressive strength of specimens from G-12 mix with 3% vermiculite showed considerable improvement over those of G-11.

At 28 days curing the average compressive strength of five specimens was 7.88 MPa and that of PCM impregnated and coated with polyester resin film 5.35 MPa (Table 4-11).

With 2.5% vermiculite content in the specimens, the compressive strength results showed further improvement. At 28 days, average compressive strength of five specimens was 8.8 MPa and that of PCM impregnated and coated with polyester resin film as 6.46 MPa as shown in Table 4-12.

TABLE 4-9

Compressive Strength Results of Mix Composition G-11

Specimen No.	Compressive Strength MPa	Remarks
Mix Composition: G-11		
G-11.1	2.26	Specimen Nos. G-11.1 to G-11.5 were tested at 7 day curing
G-11.2	2.17	
G-11.3	2.24	
G-11.4	2.26	
G-11.5	2.98	
Average Compressive Strength of G-11.1 to G-11.4 : 2.23 MPa		
Standard deviation (Appendix B) : 0.05 MPa		
Probable % error of mean (Appendix B) : 1.3%		
G-11.6	4.05	Specimen Nos. G-11.6 to G-11.10 were tested at 28 day curing
G-11.7	3.30	
G-11.8	3.59	
G-11.9	3.50	
G-11.10	3.41	
Average compressive strength of G-11.6 to G-11.10.: 3.57 MPa		
Standard deviation (Appendix B) : 0.28 MPa		
Probable % error of mean (Appendix B) : 3.6%		
G-11.11	3.05	Specimen Nos. G-11 to G-11.15 were impregnated with PCM @ 15% and coated with polyester resin film
G-11.12	3.11	
G-11.13	3.17	
G-11.14	2.88	
G-11.15	3.20	
Average compressive strength of G-11.11 to 11.15 : 3.08 MPa		
Standard deviation (Appendix B) : 0.122 MPa		
Probable % error of mean (Appendix B) : 1.8%		

TABLE 4-10

Absorption of PCM in specimen composites on lowering
Vermiculite content in the mix

Specimen No.	Mix Composition	Absorption of PCM wt %
G-12	Gypsum : 25% Vermiculite : 3% Sand : 12% Cement : 10% Coarse aggregate : 50%	15.0 *
G-13	Gypsum : 25% Vermiculite : 2.5% Sand : 12.5% Cement : 10% Coarse aggregate : 50%	14.15 *
G-14	Gypsum : 25% Vermiculite : 2% Sand : 13% Cement : 10% Coarse aggregate : 50%	13.8 *

Water: Gypsum/Cement ratio in all the specimens was 0.60

* indicates average result from 5 specimens

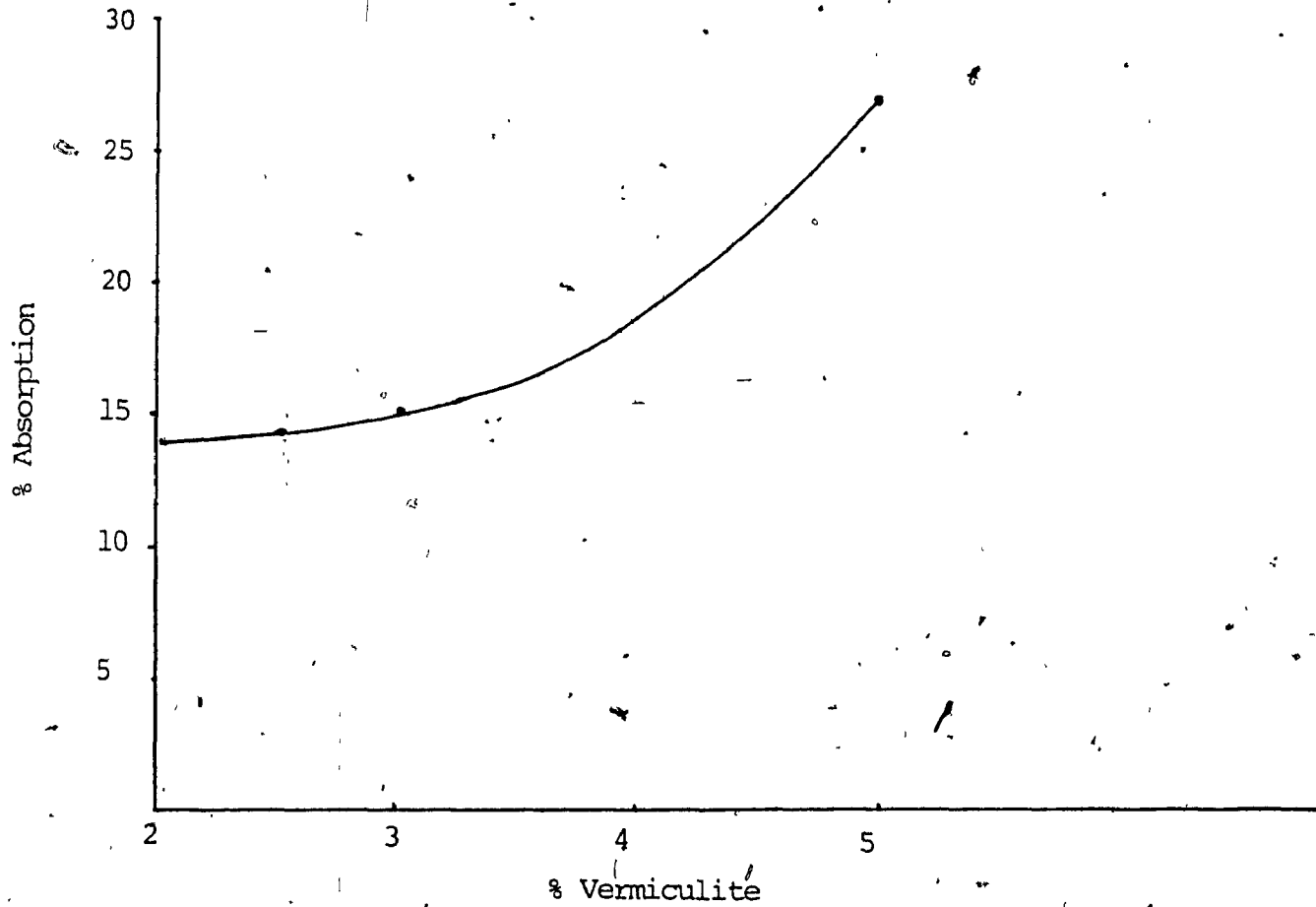


Figure 4.9 Absorption of PCM in specimens on lowering vermiculite content in the mix

TABLE 4-11

Compressive Strength Results of Mix Composition G-12

Specimen No.	Compressive Strength MPa	Remarks
Mix Composition: G-12		
G-12.1	7.4	Specimen Nos. G-12.1 to G-12.5 were tested at 28 day curing
G-12.2	8.4	
G-12.3	7.2	
G-12.4	7.6	
G-12.5	8.1	
Average Compressive Strength of G-12.1 to G-12.5 : 7.74 MPa		
Standard deviation (Appendix B) : 0.46 MPa		
Probable % error of mean (Appendix B) : 2.6%		
G-12.6	5.33	Specimen Nos. G-12.6 to G-12.10 were tested after impregnation with PCM @ 15% and coating with polyester resin film
G-12.7	5.40	
G-12.8	5.10	
G-12.9	5.60	
G-12.10	5.29	
Average compressive strength of G-12.6 to G-12.10 : 5.35 MPa		
Standard deviation (Appendix B) : 0.18 MPa		
Probable % error of mean (Appendix B) : 1.5%		

TABLE 4-12
Compressive Strength Results of Mix Composition G-14

Specimen No.	Compressive Strength MPa	Remarks
Mix Composition: G-14		
G-14.1	8.64	Specimen Nos. G-14.1 to G-14.5 were tested at 28 day curing
G-14.2	8.83	
G-14.3	8.65	
G-14.4	9.10	
G-14.5	6.48	
Average Compressive Strength of G-14.1 to G-14.4 : 8.8 MPa		
Standard deviation (Appendix B) : 0.21 MPa		
Probable % error of mean (Appendix B) : 1.2%		
G-14.6	6.04	Specimen Nos. G-14.6 to G-14.10 were tested after impregnation with PCM @ 15% and coating with polyester resin film
G-14.7	6.30	
G-14.8	7.03	
G-14.9	6.14	
G-14.10	6.80	
Average compressive strength of G-14.6 to G-14.10 : 6.46 MPa		
Standard deviation (Appendix B) : 0.41 MPa		
Probable % error of mean (Appendix B) : 2.8%		

4.4 DSC ANALYSIS

The method, techniques, apparatus used and the purpose of the thermal analysis of the specimens by means of Differential Scanning Calorimeter have been described in the earlier pages of this thesis.

During the preliminary research on aggregates, thermal analysis were performed on each individual material. After having successfully encapsulated the PCM within a composite, it was necessary to analyze the composite to see the effects, if any, on the constituents.

Specimen tiles from four different mix compositions comprising of gypsum, vermiculite, sand, cement and coarse aggregates were prepared. These specimens were impregnated with Butyl Stearate at different percentages of absorption before being subjected to thermal analysis.

4.4.1 Thermal Analysis Results

- 1) Specimen No. G-17 with 23% Butyl Stearate (PCM), Figure 4.10:

Latent Heat of Crystallization : 43.5 J/g

Latent Heat of Melting : 43.7 J/g

Crystallization Peak Temperature : 17.2°C

Melting Peak Temperature : 22.6°C

There was no loss of PCM from the composite

No chemical reaction resulted between PCM and composite materials.

Sample: G-17/23XDU. STEARATE Date: 19-Oct-07 Time: 14:51:56

DSC

Size: 17.636MC

Rate: 20/MIN

Program: Interactive DSC V2.0

Plotted: 19-Oct-07 15:44:04

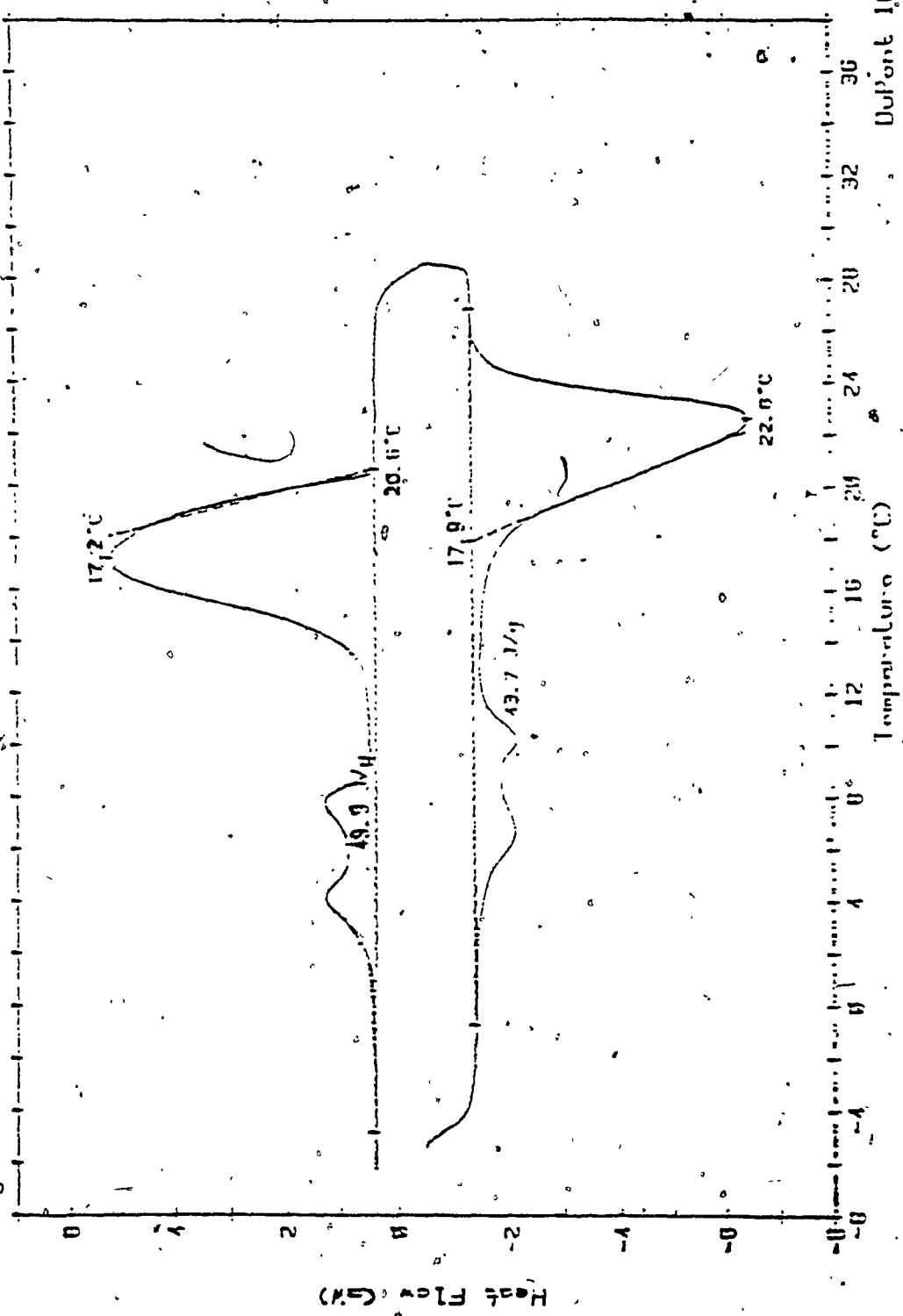


Figure 4.10 DSC Analysis of specimen composite G-17 impregnated @ 23 % Bu St

2) Specimen No. G-18 with 28.2% Butyl Stearate (PCM) Figure 4.11.

Latent Heat of Crystallization	: 57.5 J/g
Latent Heat of Melting	: 57.1 J/g
Crystallization Peak Temperature	: 17.1°C
Melting Peak Temperature	: 22.9°C

The analysis prove that no loss of PCM occurred from the composite and that there was no chemical reaction between the composite constituents.

3) Specimen No. G-21 with 19.5% Butyl Stearate (PCM), Figure 4.12.

Latent Heat of Crystallization	: 37.3 J/g
Latent Heat of Melting	: 37.3 J/g
Crystallization Peak Temperature	: 17.6°C
Melting Peak Temperature	: 22.3°C

The same specimen was again analyzed after three months and no change in the results noticed. There was no loss of PCM from the specimen composite and no chemical reaction resulted between Butyl Stearate and composite constituents.

4.5 INFRARED SPECTROSCOPY

When a radiation strikes a layer of a chemical substance, it is only partially transmitted. The remainder is reflected or absorbed in varying degrees depending upon the substance, and the frequency of radiation absorption which may occur if the energy of the incident

Sample: G-18/28.2%BU. STEARATE
 Size: 21.971MG
 Rate: 2C/MIN
 Program: Interactive DSC V2.0
 Date: 6-Nov-87 Time: 9:42:56
 Plotted: 6-Nov-87 10:39:22

DSC

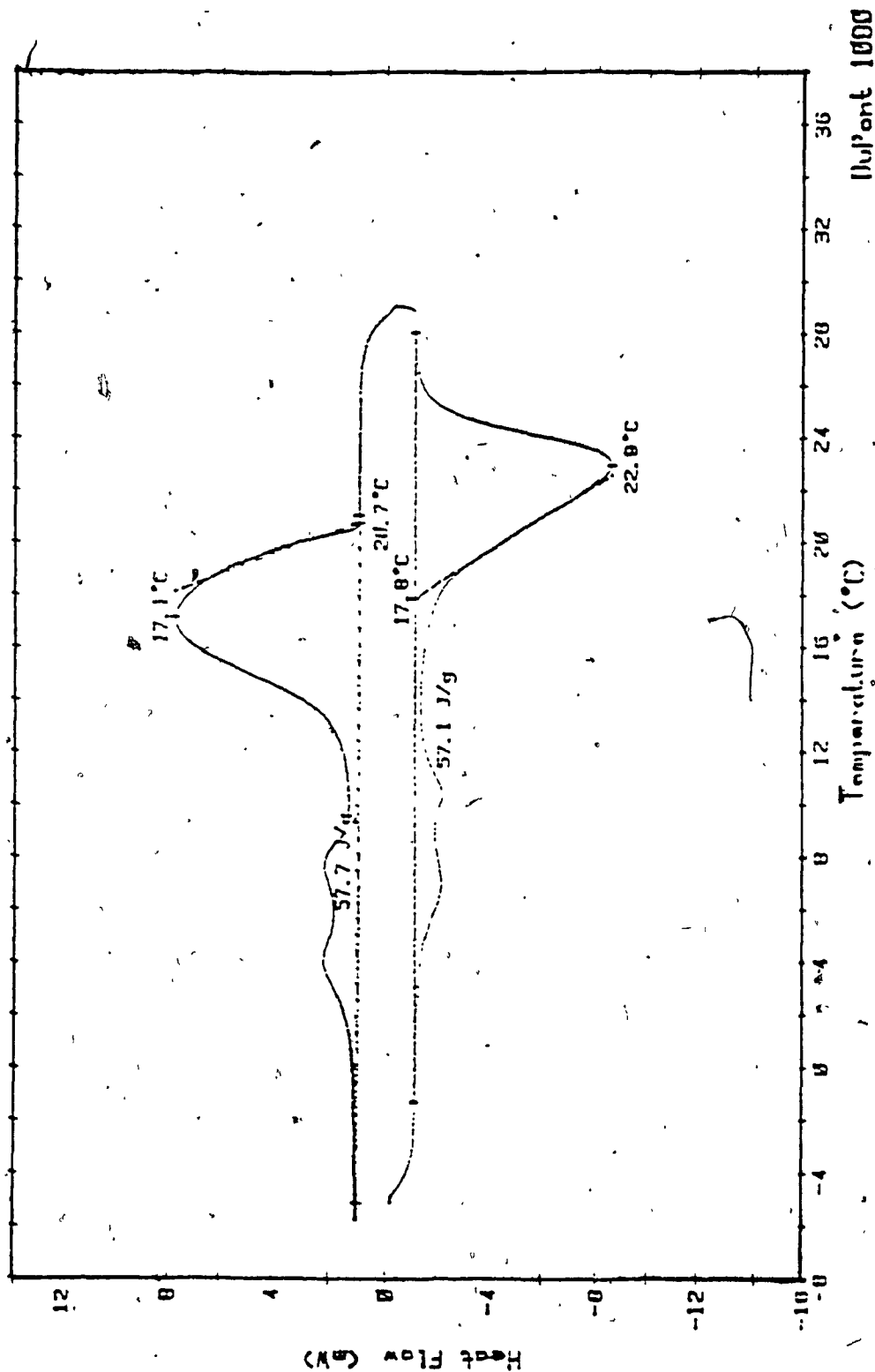


Figure 4.11 DSC Analysis of specimen composite G-18 impregnated @ 28.2 % Bu St

Sample: G-21 I 18.5XDU. STEARATE

Size: 24.729MG

Rate: 2C/MIN

Program: Interactive DSC V2.0

Date: 10-04-07

Time: 10:04:55

DSC

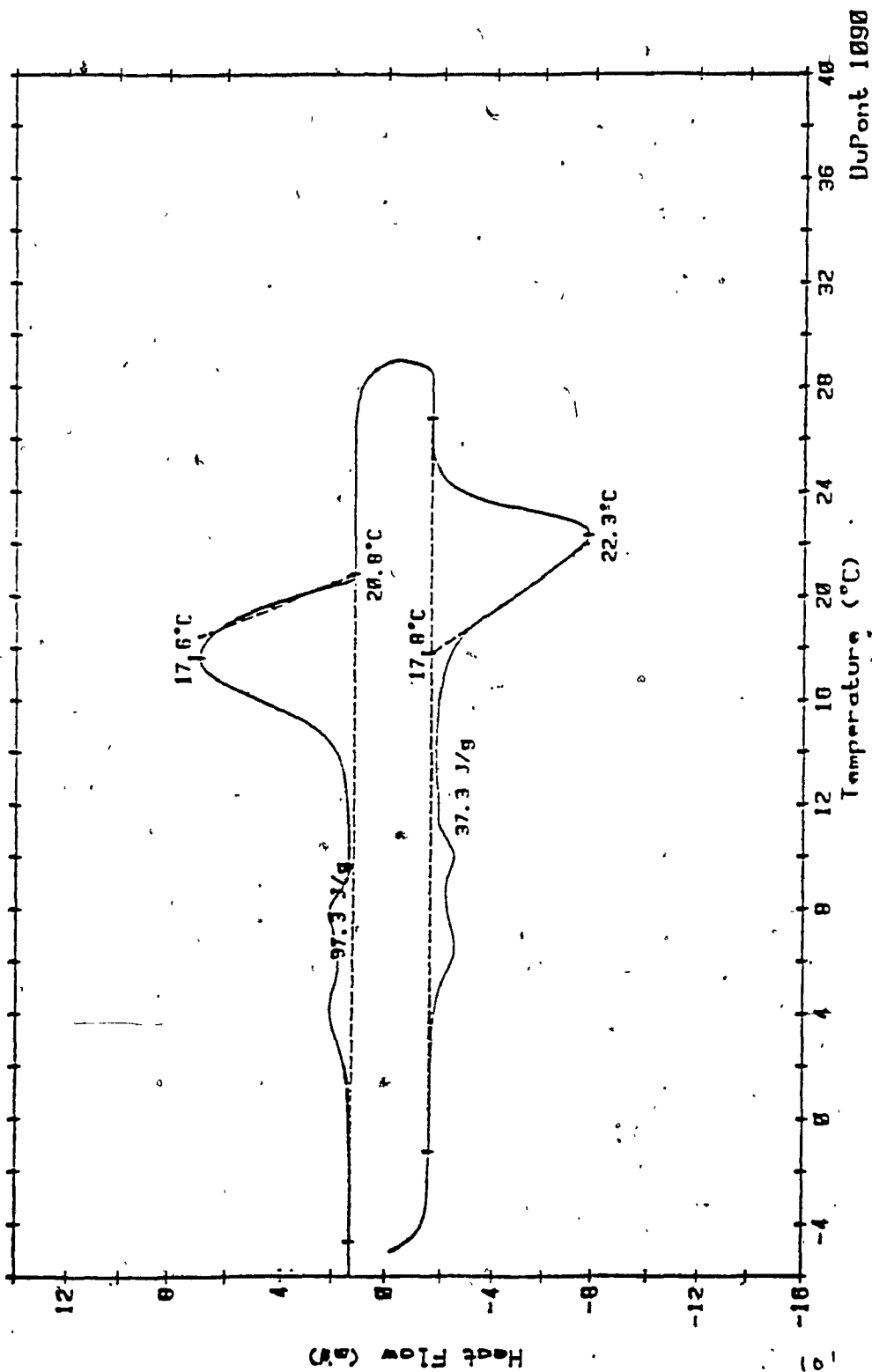


Figure 4.12 DSC Analysis of specimen composite G-21 imprecipitated @ 19.5 % Du SE

protons coincides with an energy change within the substance contacted.

The basic components of an infrared spectrometer are shown below:

SOURCE---SAMPLE---MONOCHROMATOR---DETECTOR---RECORDER

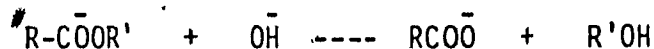
Infrared energy is provided to the system by a source rich in infrared radiation.

The function of monochromator is to disperse or sort into its component frequencies the radiation provided by the source and transmitted by the sample. The function is accomplished by dispersion elements such as prism and gratings. When spectra are recorded the dispersion element rotates slowly and very precisely, so as to present very narrow band of radiation increasing or decreasing energy to the detector. The energy of infrared radiation is very low and therefore, requires extremely sensitive means of detection, usually thermocouples.

4.5.1 Infrared Analysis of Specimen

The infrared analysis was done in order to verify and reconfirm if there may have been any interaction between Butyl Stearate, the PCM, and the components of the specimen.

The presence of Calcium Hydroxide which is formed during the cement hydration may produce hydrolyzation of the ester according to the following reaction:



If that reaction took place, the characteristic infrared absorption peak of saturated aliphatic esters from 1740 cm^{-1} will be totally or partially replaced by the characteristic peak of carboxylate ion RCOO^- at 1560 cm^{-1} .

4.5.2 Test Procedure

Each specimen was prepared by dispersing 15 mg of the solid sample after 24 hour drying at 100°C in 100 mg of potassium bromide and sintering 300 mg of this mixture in a disc. The spectra were investigated with an infrared spectrometer Beckman Model 4240.

4.5.3 Test Results

The infrared spectra of specimen No. G-19 impregnated with Butyl Stearate @ 25.7% was run after one month of impregnation. Spectrum in Figure 4.13 shows that the characteristic bond of ester i.e; C=O group is at 1740 cm^{-1} and there is no absorption band at 1560 cm^{-1} .

The same specimen was analyzed after another six month period. The spectrum in Figure 4.14 presents the same characteristic band as in the first case.

It is therefore concluded that Butyl Stearate used in this research work as a phase change material is not affected by the presence of Calcium Hydroxide resulting from the cement hydration.

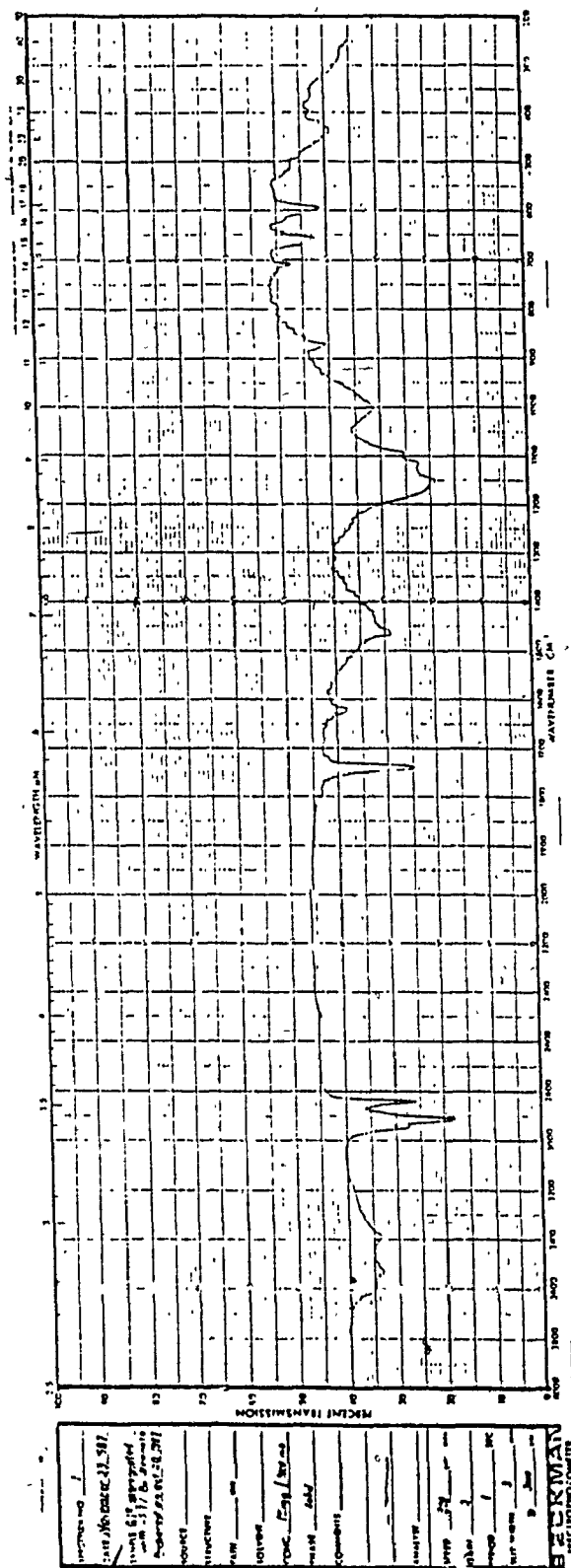


Figure 4.13 Infrared Spectrum of a PCM-impregnated specimen

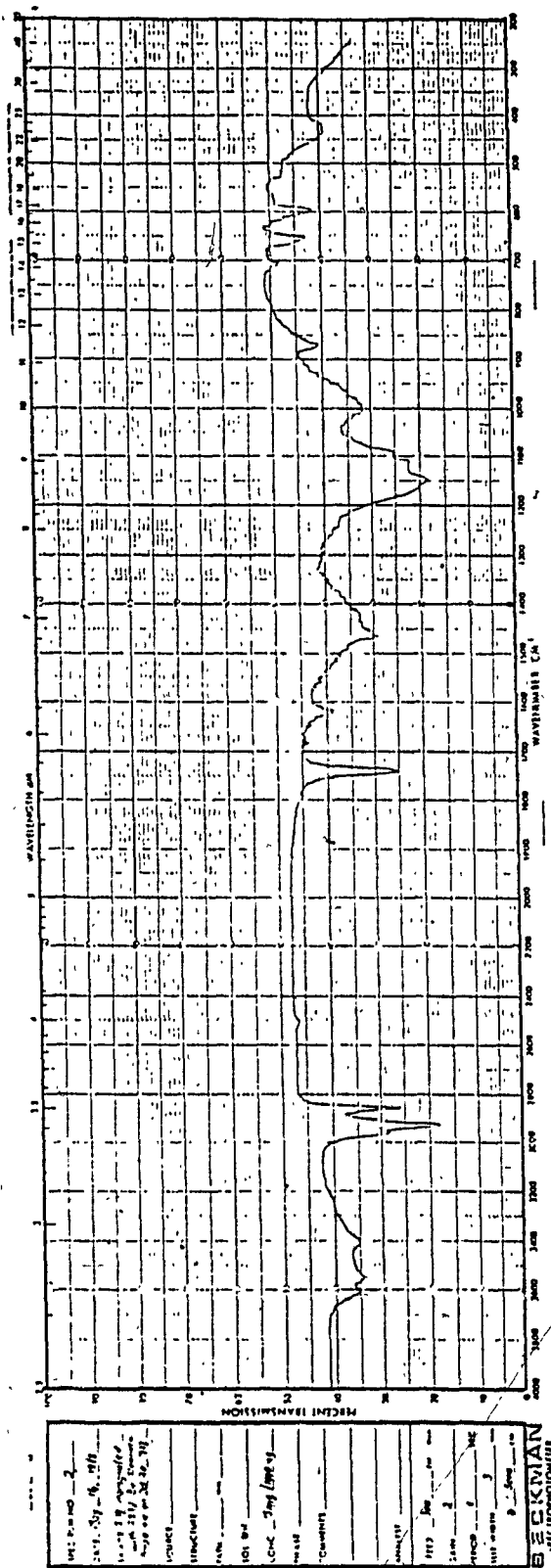


Figure 4.14 Infrared Spectrum of the PCM-impregnated specimen repeated after 6 months

4.6 THERMAL CONDUCTIVITY

The composites encapsulating the phase change material were coated with polyester resin in order to completely seal off all the sides. This eliminated any possibility of leakage of the PCM from the composite.

Polyester resins traditionally exhibit very low thermal conductivity. This property of the material has adverse effect on our composite as it would prevent heat transfer to and from the composite. Heat transfer is a very important factor to allow crystallization and melting of the PCM inside the resin-bound composite. It was therefore vitally important to improve the thermal conductivity of the resin.

At present no resins are readily available in the market with thermal properties required for such applications. Research work is continuing to develop conductive polymers ripe for commercialization. The industry hopes of displacing copper as a primary electric conductor and putting automobiles on the road powered by the plastic batteries [31].

Carbon black was considered as a possible filler to improve thermal conductivity of the resin. Carbon materials are often added to polymers to obtain composite materials with improved mechanical and electrical properties, but there are few reports on improving thermal conductivity by adding carbon materials. Infact some reports suggest

that the thermal conductivity of polymers filled with carbon black could not be appreciably improved.

Carbon black has another disadvantage in that it would impart black color to the composite which may not be desirable from aesthetic considerations.

Metal fillers are known for their good thermal properties, it was therefore considered to attempt improvement of thermal conductivity by adding metal powder in the resin.

A number of specimen tiles were prepared with varying quantities of Aluminum powder and tests performed. Table 4-13 shows the amount of resin and Aluminum powder required for resin bound composite tiles 20 cm x 20 cm x 1.25 cm size.

The results show that 1.0 to 1.13% of resin and 0.22 to 0.57 % of Aluminum powder of the total weight of the tiles was required to bound the composite.

4.6.1 Thermal Conductivity Measurement

The facility for measuring thermal conductivity was designed by Centre for Building Studies of Concordia University. It provides a wide range of flexibility in the monitoring rate and in the manner of recording and analysing results. The arrangement of equipment and recording thermal conductivity is shown in Figure 4.15. It comprises of the following equipment:

TABLE 4-13

Resin and Al powder requirements for coating specimen tiles

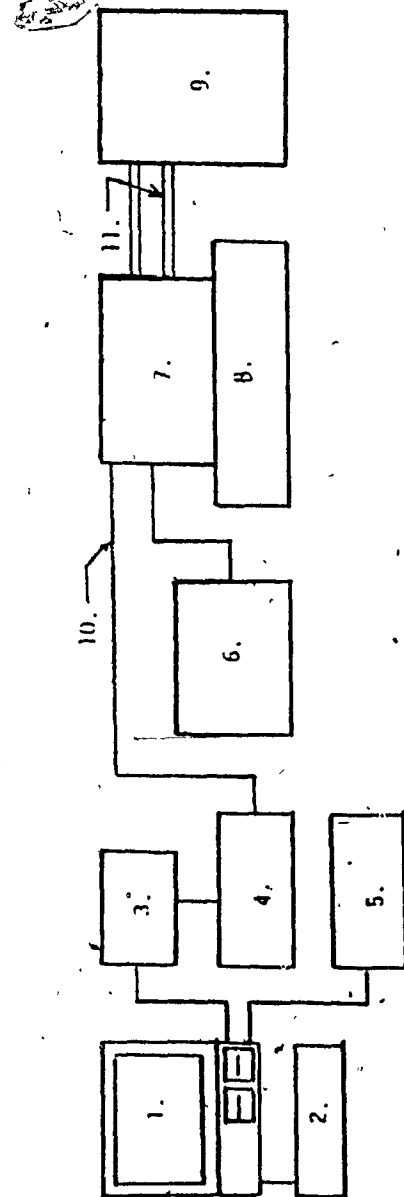
Specimen No.	Wt. of specimen (W1) g	PCM in the specimen %	Wt. of resin bound specimen (W2) g	Resin in the specimen (W2-W1) g		Al in resin %	Al in the specimen %
1 }	935.0	-	-	-	-	-	-
2							
3 }	1058	15	-	-	-	-	-
4							
6 }	1050.0	15	1062.0	12		-	-
7							
11 }	1052.0	15	1074.0	12	1.12	20	0.22
12							
8 }	1047.0	15	1060.0	13	1.22	30	0.36
10							
13 }	1039.3	15	1051.0	11.7	1.12	40	0.45
14							
23 }	1069.0	15	1080.0	10.8	1.00	50	0.55
24							
19 }	1063.8	15	1074.0	10.2	0.95	60	0.57
20							

Thermal conductivity instrument	--	Dynatech model TCFGM-N
Regulated Power supply	---	Lambda model LK 342A
Coolant Circulator	--	Lambda model RS
Switch Controller	--	Fluke 2205A
Multimeter	--	Fluke 8840A
IBM PC with monitor, keyboard, and GPIB printer	--	Epson spectrum model LX 80

The test were performed according to ASTM Standards C-177 on a number of specimen tiles. The specimens included the following categories of tiles.

- 1) Plain tiles comprising of gypsum, sand, cement, expanded vermiculite and coarse aggregate.
- 2) Tiles of above mentioned materials impregnated with PCM @ 15%
- 3) PCM impregnated tiles bound by metal-filled resin. Aluminum powder in different percentages was used as metallic filler in the polyester resin.

The results of the tests are shown in Table 4-14. These results prove that thermal conductivity of resin-bound composites can be improved with addition of metal fillers to the resin.



- | | |
|---|--|
| 1. - IBM PC AND SCREEN | 7. - THERMAL CONDUCTIVITY TEST CABINET |
| 2. - IBM KEYBOARD | 8. - DYNATECH GUARDED HEAT PLATE THERMAL CONDUCTIVITY INSTRUMENT MODEL TCFGM-114 |
| 3. - FLUKE MULTIMETER MODEL 100A | 9. - LAMBDA COOLANT CIRCULATOR MODEL RCS |
| 4. - FLUKE SWITCH CONTROLLER MODEL 220CA | 10. - THERMOCOMPTE SENSOR LEADS |
| 5. - EPSON SPECIMIM PRINTER MODEL 1300 | 11. - COOLANT-PIPES |
| 6. - LAMBDA REGULATED POWER SUPPLY MODEL 347A | |

Figure 4.15 Arrangement of equipment for Thermal Conductivity measurement

The graphical representation of the results in Figure 4.16 shows that by addition of aluminum powder to the resin, the thermal conductivity increased from 2.61182 Btu-in/ft², hr, °F or 0.37662 w/m °C for a composite which contained no metal filler in the resin to 3.24034 Btu-in/ft²,hr,°F or 0.46726 w/m°C for a composite bound by a 60% aluminum powder filled resin.

4.6.1.1 Lignin-filled Polyester Resin

Lignin which is the principal source of woody structures is a low cost material. Lignins are currently highly under utilized. Unmodified lignins are used as binders, fillers and resin extenders and have the potential of becoming a major source of polymer-based products [32]. Kraft lignin used in this research work is a by-product of the forest products industry.

Lignin powder being rich in carbon, was introduced in the polyester resin for coating PCM impregnated tiles. Thermal conductivity tests (Appendix C) show that with 10% lignin in the resin the K-factor was 0.45991 W/m°C, the value being higher than the result achieved with 50% aluminum in resin. Addition of higher amounts of lignin tended to lower the K-factor.

4.7 COMPOSITE THERMAL STORAGE CAPACITY

Heat capacity of a material is the amount of heat required to raise its temperature. It is generally provided as specific heat capacity where heat capacity data is normalized to mass and temperature range. Thus, the units of specific heat capacity are J/Kgx°K or

TABLE 4-14

Thermal conductivity results of Specimen tiles
coated with Al-filled polyester resin

Specimen No.		Aluminum in resin %	K-factor		R-value	
			W/m°C	Btu-in/ft, hr, °F	W/m°C	Btu-in/ft, hr, °F
A-1&2	*	-	0.332	2.305	0.039	0.225
A-3&4	**	-	0.438	3.037	0.029	0.165
A-6&7	***	-	0.376	2.611	0.036	0.205
A-11&12	^	20	0.378	2.627	0.034	0.198
A-8&10	^	30	0.390	2.704	0.033	0.191
A-13&14	^	40	0.425	2.947	0.030	0.175
A-23&24	^	50	0.437	3.031	0.030	0.173
A-19&20	^	60	0.467	3.240	0.028	0.159

* Plain tile with no PCM or resin

** Tiles impregnated @ 15% PCM

*** Resin-bound tiles impregnated @ 15% PCM

^ Aluminum powder added to resin for coating the tiles impregnated with PCM @ 15%

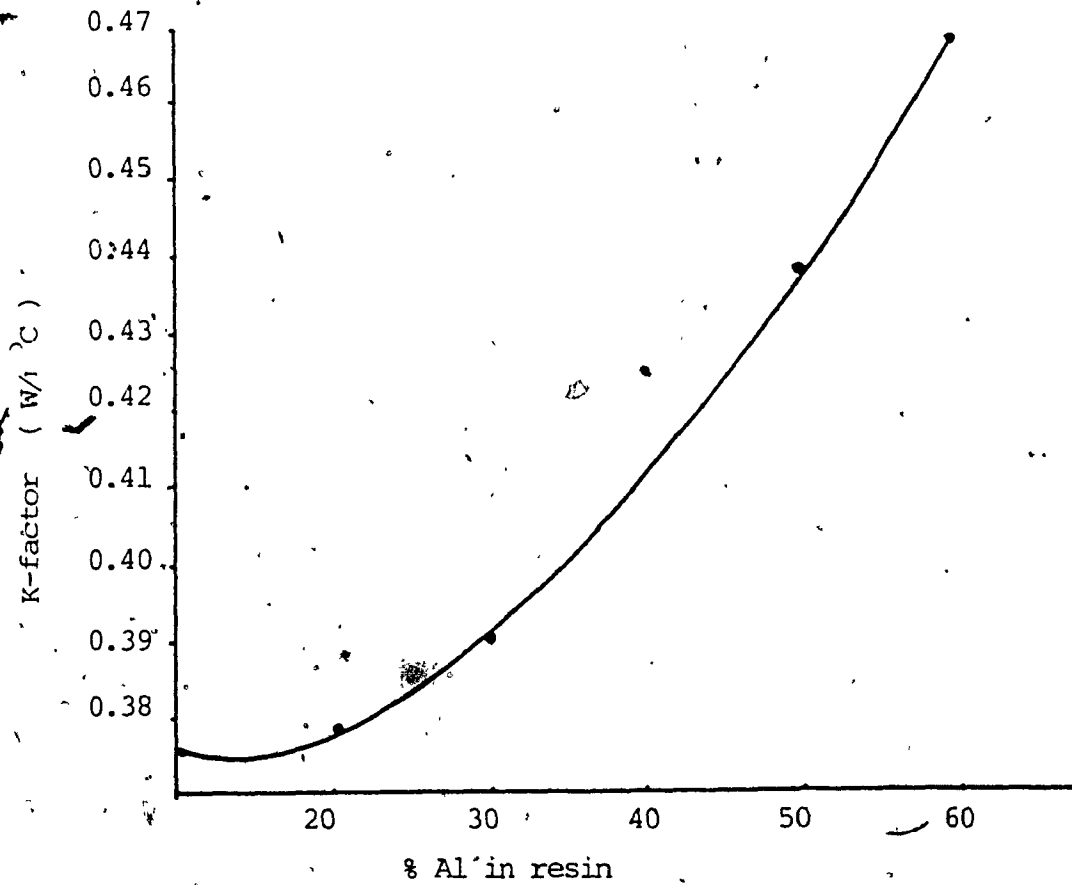


Figure 4.16 Thermal Conductivity of specimen tiles coated with polyester resin filled with different amounts of Aluminum

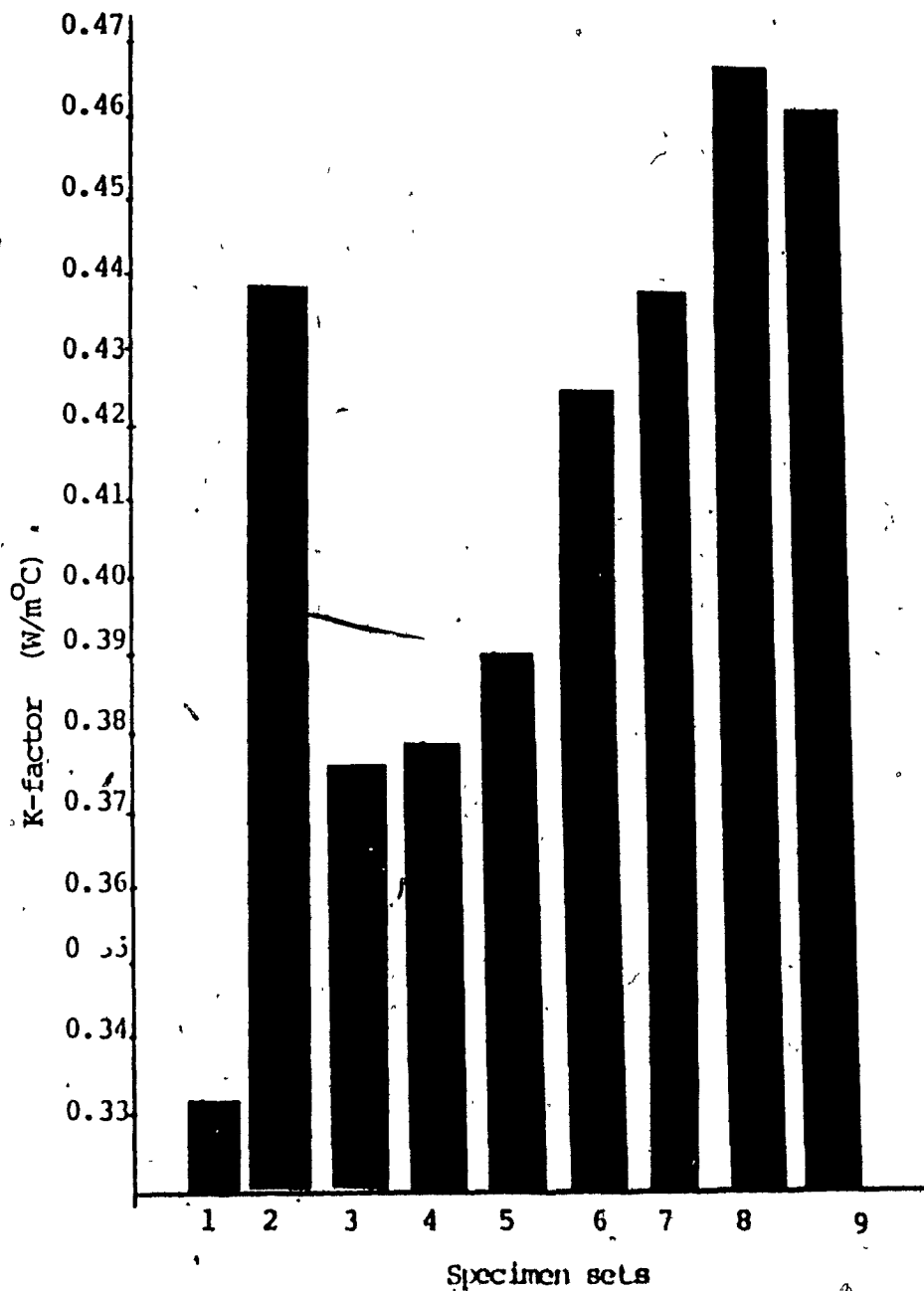


Figure 4.17 Thermal Conductivity of specimen tiles

LEGEND:

- SET 1 : Plain Tile
- SET 2 : Tile impregnated with PCM @ 15 %
- SET 3 : PCM impregnated tiles coated with Polyester resin
- SET 4 : PCM impregnated tiles coated with 20% Al-filled resin
- SET 5 : PCM impregnated tiles coated with 30% Al-filled resin
- SET 6 : PCM impregnated tiles coated with 40% Al-filled resin
- SET 7 : PCM impregnated tiles coated with 50% Al-filled resin
- SET 8 : PCM impregnated tiles coated with 60% Al-filled resin
- SET 9 : PCM impregnated tiles coated with 10% Lignin-filled resin

Cal/gx°C. The quantity of heat storage in the composite for a temperature swing equivalent to the transition range of the PCM which is, $\pm 4^{\circ}\text{C}$ is the sum of the sensible heat of the composite materials and the latent heat of the PCM encapsulated within the composite. Specific heat capacity can be determined by using Du Pont Thermal Analysis Differential Scanning Calorimetry system. This technique provides a rapid accurate and precise measurement of specific heat capacity of solid materials as well as liquids. The specific heat measurements can also be used in the evaluation of other thermodynamic properties of the materials. DSC provides a direct measurement of the differential heat flow between the sample and an inert reference which can be related directly to its specific heat capacity.

4.7.1 Test Procedure

The measurements are made by heating a test specimen at a known and fixed rate. Once dynamic heating equilibrium of the specimen is obtained, the heat flow is recorded as a function of temperature. This heat flow, normalized to specimen mass and heating rate, is directly proportional to the specimen's specific heat capacity. In practice two thermal experiments are required for each measurement. In the first, a baseline run is performed on the empty sample pan and lid. In the second run, the test specimen is enclosed in the pan and lid. The specific heat capacity is derived from the difference between the resulting two curves.

Before starting the actual tests, heat flow calibration of the apparatus is required. This was obtained by running baseline and experimental traces for sapphire used as a calibration material (Figure 4.18). This material is readily available and its specific heat capacity is known to five figures.

Sample pans and lids are first cleaned by washing in dichloromethane and then dried in a DSC cell at 400°C for 10 minutes to remove any volatiles which otherwise might evolve during the experimental measurement.

Test specimens are now loaded into the DSC cell at room temperature and the cell is heated or cooled to a temperature 50°C below the temperature at which data is required. The cell is allowed to equilibrate at this temperature for 5 minutes. A temperature program of 20°C/minute is then initiated from that equilibrium temperature to 5°C above the highest temperature at which specific heat capacity information is desired. Thermal curve is recorded in the instrument's disk memory. (Figure 4.19).

4.7.2 Calculations [33]

Specific heat capacity of the specimen is calculated by measuring the Y-axis displacement between the specimen and blank curves at the desired temperature, and substituting into the following equation:

$$C_p = \frac{Y (60 \text{ E.m.u.})}{m \cdot \Delta T} \quad (4.1)$$

Date: 7-Jun-88 Time: 11:55:17

Sample: SAPHIRE
Size: 61.141MG
Rate: 20C/MIN
Program: Interactive DSC V2.0

DSC

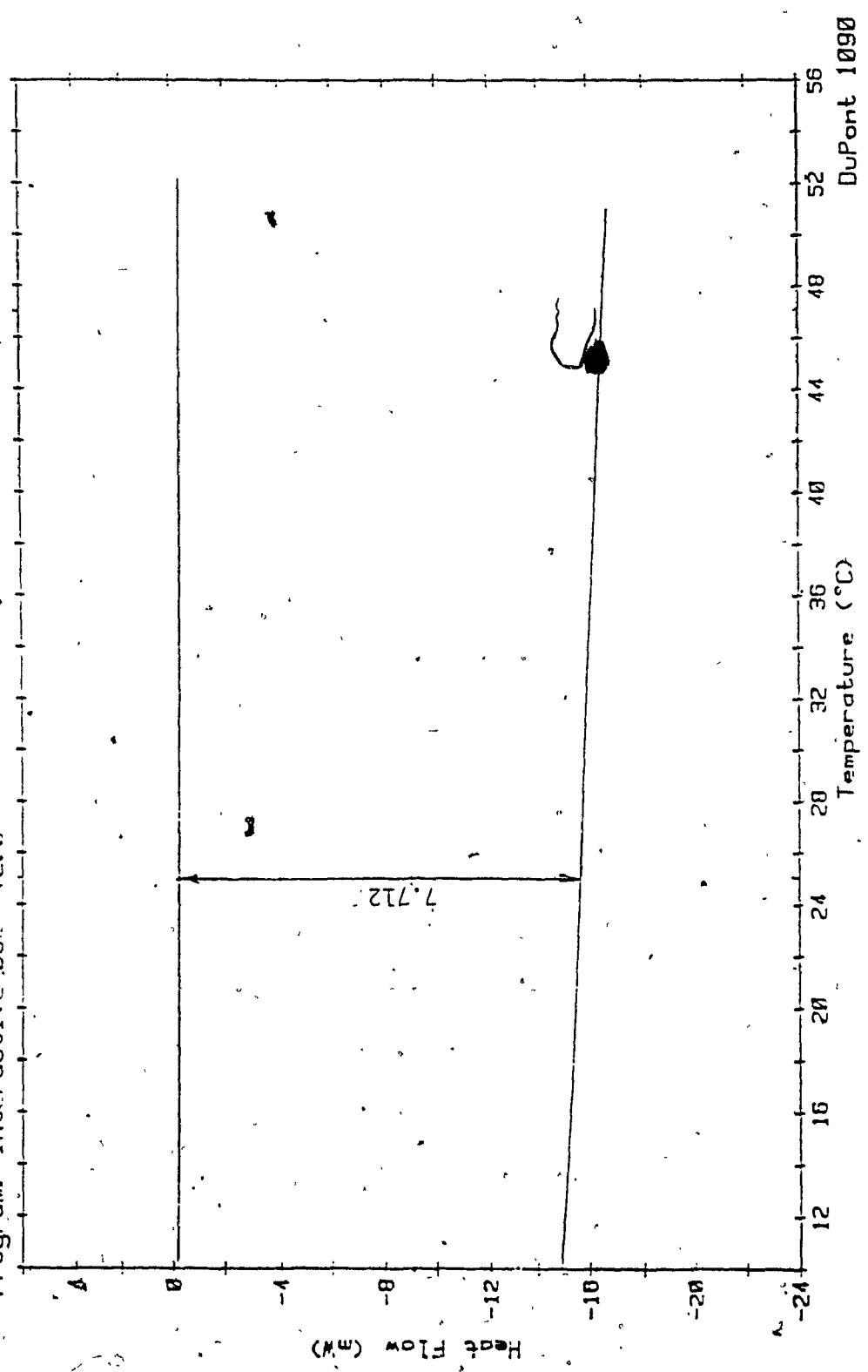


Figure 4.18 Specific Heat Capacity of Saphire - Calibration

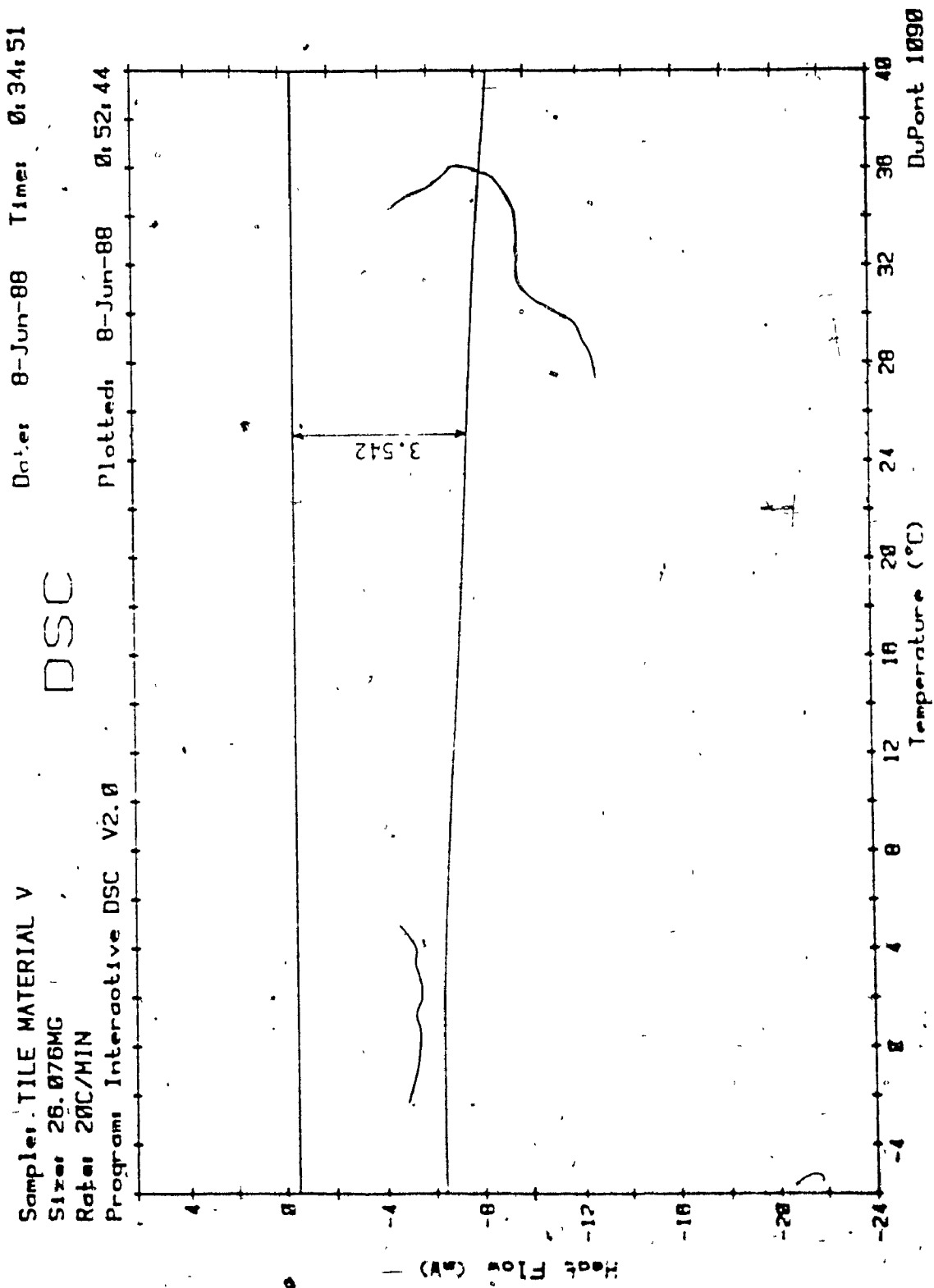


Figure 4.10 Specific Heat Capacity of specimen tile

where,

C_p = specific heat capacity (J/g°C)

E = DSC cell calibration coefficient at the desired temperature

H_r = heating rate (°C/min)

Y = Y-axis displacement between the sample and blank (cm)

Δq = Y-axis range (mW/cm)

m = sample mass (mg)

4.7.2.1 Calibration Coefficient of DSC cell with Sapphire

Specific heat capacity of sapphire at 25°C (C_p) = 0.775 J/g°C

Heating rate (H_r) = 20°C/min

Sample mass (m) = 61.141 mg

Y-axis displacement between sample and blank

(Y), from Figure 4.16 = 7.712 cm

substituting in equation 4.1,

$$E = \frac{0.775 \times 20 \times 61.141}{60 \times 2 \times 7.712}$$

calculating, E , the DSC cell calibration coefficient at 25°C is = 1.024

4.7.2.2 Specific Heat Capacity of the Composite

H_r = 20

m = 26.076 mg

E = 1.024 (from equation 2)

$$Y @ 25^{\circ}\text{C} = 3.542 \text{ (from Figure 4.17)}$$

substituting in equation 4.1,

$$C_p = \frac{1.024 \times 60 \times 3.542 \times 2}{26.076 \times 20}$$

$$= 0.835 \text{ J/g}^{\circ}\text{C}$$

4.7.2.3 Heat Storage Calculations for the Specimen Tile

Size of the tile	= 20 x 20 cm or 0.04 m ²
Weight of specimen tile	= 0.80 kg or 20 kg/m ²
C _p for the tile	= 0.835 J/g [°] C (from eq. 3) = 835 J/kg [°] C
Temperature swing (T)	= 4 [°] C

Let, Q₁ = sensible heat of tile

Q₂ = total latent heat of PCM @ 25% in a tile

Q₃ = total latent of PCM @ 15% in tile

Q = quantity of heat stored by 1 m² of tile

Sensible heat of the tile, Q₁ = weight of the tile (kg/m²) x
specific heat capacity of tile x T = 20 x 835 x 4

or Q₁ = 66,800 J/kg or 66.8 KJ/kg

Latent heat of PCM encapsulated in the tile, Q₂ or Q₃ = weight of
PCM in the tile/m² x Latent Heat of PCM.

Latent Heat of PCM (Butyl Stearate) = 140 J/g or 140,000 J/kg.

For specimen tile in which 25 wt. % of PCM is encapsulated,
weight of PCM/m² of tile = 5 kg.

Therefore,

$$Q_2 = 5 \times 140,000 = 700,000 \text{ J/m}^2 \text{ or } 700 \text{ KJ/m}^2$$

Q = The quantity of heat stored by 1 sq m of tile with

25% PCM for a temperature swing of 4°C = Q₁ + Q₂

$$= 66.8 + 700$$

$$= 766.8 \text{ KJ/m}^2$$

For specimen tile of same specification with 15 wt.% PCM, weight
of PCM/m² of tile = 3 kg

$$Q_3 = 3 \times 140,000$$

$$= 420,000 \text{ J/m}^2 \text{ or } 420 \text{ KJ/m}^2$$

Q = The quantity of heat stored by 1 sq m of tile with

15% PCM for a temperature swing of 4°C = Q₁ + Q₃

$$= 66.8 + 420$$

$$= 486.8 \text{ KJ/m}^2$$

Previous work on the subject in which gypsum wallboard was
impregnated @ 25% using the same PCM showed heat capacity of 350
KJ/m² [1]. The results show that the composite tile produced in this
research work behaves better from the energy storage point of view
than the gypsum wall board with the same amounts of PCM.

CHAPTER 5

COST ANALYSIS

It was previously considered that the cost of storage of latent heat has a difficulty in competing with low electrical energy tariffs [34]. During the present research work low cost materials and simple techniques of preparation of the composite were adopted. The results indicate that it is now possible to encapsulate PCM in low cost composites.

5.1 COST OF MATERIALS

The prices of the materials listed in the following lines were obtained from a general market survey and do not necessarily represent the exact cost of the materials when purchased in bulk quantities. The prices of some of the materials like gypsum powder and vermiculite are those of the super markets which are highly exaggerated.

- 1) Coarse aggregate 6-8 mm size : \$ 7.75/ton or \$ 0.003/kg
- 2) Gypsum (Plaster of Paris) : \$ 1.00/kg
- 3) Portland cement : \$ 5.45/30kg or \$ 0.18/kg
- 4) Sand : \$ 2.25/30kg or \$ 0.075/kg
- 5) Expanded vermiculite : \$ 0.60/kg
- 6) Butyl Stearate (PCM) : \$ 1.10/kg
- 7) Polyester resin : \$ 2.00/kg
- 8) Aluminum powder : \$ 10.00/kg

5.2 MIX COMPOSITION USED FOR COST ANALYSIS

Gypsum	: 25%
Sand	: 10%
Cement	: 10%
Expanded vermiculite	: 5%
Coarse aggregate	: 50%

5.3 SPECIFICATION OF SPECIMEN TILE

Size	: 20 cm x 20 cm x 1.25 cm
Weight of dry tile (W1)	: 0.80 kg
The tile was impregnated with PCM @ 25%	
Weight of tile after impregnation (W2)	: 1.00 kg
Weight of PCM in the tile (W2-W1)	: 0.20 kg

The PCM impregnated tile was coated with Polyester resin filled with 50% Aluminum powder

Weight of Polyester coated tile (W3)	: 1.015 kg
Weight of Polyester resin & Al powder	: 0.015 kg
Weight of Polyester resin resin	: 0.010 kg
Weight of Al powder	: 0.005 kg

5.4 THE COST OF TILE

The cost of the specimen tile size 20 cm x 20 cm x 1.25 cm works out as \$0.60 or \$15.00 per sq. meter.

The cost analysis of the specimen tile shown in Table 5-1 does not represent the ultimate true cost of such tiles when manufactured

TABLE 5-1

Cost Analysis of a Specimen Tile

Material	Weight % of material in the mix	Wt. of material in kg	Unit Price specimen \$/kg	Total Cost tile \$
Weight of Plain tile:		0.80		
Coarse aggregate	50	0.40	0.008	0.032
Gypsum	25	0.20	1.00	0.200
Sand	10	0.08	0.075	0.006
Cement	10	0.08	0.18	0.015
Vermiculite	5	0.04	0.60	0.025
Final weight of tile:		1.015		
PCM (Butyl Stearate)		0.20	1.10	0.220
Polyester resin 2T 035		0.01	2.00	0.020
Aluminum powder		0.005	10.00	0.050
			(approx.)	0.60
TOTAL COST: \$ 0.60				

on mass scale. The cost worked out above is based on the cost of materials alone and does not cater for the following:

- cost of equipment used and space facility
- cost of energy consumption,
- man-hours utilized in preparation of the tile
- over-head expenses.

CHAPTER 6

CONCLUSIONS

The primary objective of this research work was to encapsulate an organic phase change material in a composite for the purpose of storage of thermal energy. This research work is completely different from all the previous works on the subject because of the fact that phase change materials were previously being stored in readily available existing products such as gypsum wallboard and plexy glass/poroplastic wax sheets.

In the present research work a different approach was devised for preparing a new kind of composite from abundantly available low cost materials for encapsulating an organic phase change material.

6.1 CONCLUSIONS CONCERNING THE ABSORPTION CAPABILITIES OF MATERIALS

In the preliminary stages of the research, more than ten different types of aggregate and filler materials were investigated for absorption capacities of the PCM and their capability to retain it without loss. Materials like expanded shale, volcanic rock, crushed stone, activated charcoal, clay, wood sawdust gave promising results of absorption of PCM. The absorption capacities of these materials ranged between 10-40 %. Gypsum and expanded vermiculite showed even better results of absorption and thermal characteristics, and were subsequently selected as the principal constituents of the composite. These two materials are capable of absorbing PCM @ 50 and 300 % respectively. Thermal analysis showed that the PCM had no chemical reaction with these materials and full latent heat could be utilized.

6.2 CONCLUSIONS CONCERNING PREPARATION OF THE COMPOSITE

More than 50 mix compositions were used for preparing trial mixes from the selected aggregate and filler materials in various combinations. During the preparation of the specimens, quantities of certain materials like coarse aggregate, sand and portland cement were kept constant while changing the quantities of the absorbant materials step by step in a logical ascending or descending order.

The specimens were tested at every stage for absorption of PCM, compressive strength as well as the behaviour of PCM once encapsulated inside the composite. From the experimental data contained in this thesis, it is concluded that 25 to 50 % content of calcined gypsum in combination with other materials like coarse aggregate, portland cement, sand and 2 to 5 % vermiculite is capable of storing as much as 30 weight percent of PCM.

6.3 CONCLUSIONS CONCERNING THERMAL ASPECTS OF THE COMPOSITE

The test results from DSC and Infrared analysis show that the composite is capable of retaining the entire quantity of the encapsulated PCM without loss or chemical reaction. The composite is thus able to store and release full latent heat of the PCM. From the experimental results it has also been shown that the thermal storage capacity of such composites ranges between 480 - 766 KJ/m² which is by far much higher than that of PCM-impregnated gypsum wallboard used in previous research work at the Centre for Building Studies, Concordia University.

6.4 CONCLUSIONS CONCERNING COST OF THE COMPOSITE

It has always been considered that the cost of storage of latent heat is very high because the materials used for such storage were expensive. In this research work however, low cost materials were used for production of a thermal storage mass.

From the cost analysis contained in this thesis, it is concluded that the use of low cost materials in preparation of the composite resulted in low cost, easy to prepare composite. The cost of the composite hand made at the laboratory scale formed in shape of $\frac{1}{4}$ " thick tiles is \$15.00 /m² which will further reduce when manufactured on large scale.

In this research work a new kind of composite with abilities of built-in energy has been successfully prepared for use in buildings. The composite has many possibilities of applications such as floor, wall and ceiling tiles.

6.5 RECOMMENDATIONS FOR FURTHER STUDIES

On the basis of the work presented in this thesis, it is recommended that the following aspects be considered for further research on the subject:

- i) To investigate possible application of the composite on outside of the buildings.
- ii) To investigate durability of the composite in terms of physical, mechanical and chemical aspects.

- iii) Study fire hazardness of the composite and improvement in this regard by means of adding fire retardant agents.
- iv) Possibilities of use of other materials like rubber waste (from used tires) and fibrous materials in preparation of the composite.
- v) Use of other types of resins and conductive materials.
- vi) Physical testing in a model for investigating actual energy saving costs.
- vii) The following tests are recommended by the ASTM and Canadian General Standards Board when the composite will be used for floor tiles:
 - Abrasion resistance
 - Bond strength of tiles to portland cement
 - Breaking strength
 - Electrical resistance
 - Thermal shock resistance
- viii) Study the different possibilities to install the composite tiles in ceilings, walls and floors.

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APPENDIX A

MIA Chemicals - Division of Fiberglas Canada Inc.
131 Hymus Blvd., Pointe Claire

PRODUCT INFORMATION

MIAPOL 2T035 POLYESTER RESIN

Miapol 2T035 is a medium reactive unsaturated polyester resin in styrene. It is not formulated, i.e., it contains no accelerators, fillers or other additives.

USES:

With proper modification, Miapol 2T035 can be used for many applications, such as the following:

Castings

Coatings and Glass-Fibre-reinforced laminates produced by all conventional methods including matched metal die molding, continuous laminating, pultruding, etc.

It is recommended that, in the case of translucent sheet or panels, a commercial light stabilizer be added to the resin, in order to achieve maximum light stability. The low initial styrene content may be increased in accordance with end-use requirements.

SPECIFICATIONS OF MIAPOL 2T035 AS SUPPLIED:

Viscosity @ 25°C., poises	4 - 6
Specific Gravity @ 25°C.	1.1515
Monomer Content	34%-38%
Styrene Compatibility	infinite

CURING:

2T035 Can be cured with all commonly known systems, such as metal salts/hydroperoxides, tertiary amines/peroxides, heat/peroxides, etc. If a tack free surface is required in the case of open-mold laminating, about 0.1 to 0.2% of paraffin wax dissolved in styrene should be added.

TYPICAL GEL CHARACTERISTICS OF MIAPOL 2T035

(at 21°C. with 0.25% Cobalt 12 & 1% Miacat 60)

Minutes	15-20
S.P.I. Geltime, minutes	5-7
S.P.I. Peak Exotherm	165-170°C/8'-10'

TYPICAL CURED CASTING PROPERTIES OF 2T035

Heat Distortion	60°C-65°C
Barcol Hardness	45
% Water Absorption	0.17
Flexural Strength	8.14×10^7 n/m ² (11,800 psi)
Flexural Modulus	4.14×10^9 n/m ² (6.0×10^5 psi)
Tensile Strength	6.62×10^7 n/m ² (9600 psi)
Tensile Modulus	3.99×10^9 n/m ² (5.8×10^5 psi)

STORAGE AND HANDLING

Miapol resins should be stored in a cool place away from sources of heat and out of direct sunlight. If properly stored, (at 20°C or less), Miapol 2T035 will have a minimum shelf life of four months. Note that resin stored for a longer period of time will tend to be slower curing.

Polyesters resins should be used in well-ventilated areas. Since styrene monomer is a highly flammable and volatile liquid, it is essential that appropriate precautions be taken: smoking; open flames or heaters must not be permitted in the area. Good housekeeping must be maintained at all times.

APPENDIX B

Test Data on Thermal Conductivity Measurement (ASTM C177 Test Method)

Tests Performed by Mr. N. Low

Report No. CBS-090-Khan.001

Date: March 14, 1988

Customer: Mr. Khan
Centre for Building Studies,
Concordia University
Montreal Canada

Material: Gypsum Concrete Tiles dried at ambient temperature

Sample id: Specimen # 1 bottom and specimen # 2 top
No. 1 and No. 2 set

Original sample thickness .016175 m
Thickness of top specimen .01315 m
Thickness of bottom specimen .0132 m
Weight of sample .935 kg

Room conditions: Temperature: 22°C
Humidity: 40% R.H.
Coolant temperature: 22°C

Elapsed time 0 min.

TC 1	19.80444	CH19 Volts	2.01000
TC 2	19.80444	CH20 Amps	0.28100
TC 3	20.50674	K-Factor =	0.66375
TC 4	20.53180	R-Value =	0.01985
TC 5	20.50674	DT top =	0.62701
TC 6	20.47743	DT bot =	0.71482
TC 7	19.87550	Mean temp. =	20.17022
TC 8	19.85465		

Elapsed time 15 min.

TC 1	19.97250	CH19 Volts	2.05500
TC 2	19.99334	CH20 Amps	0.28720
TC 3	20.97489	K-Factor =	0.48922
TC 4	20.99568	R-Value =	0.02693
TC 5	20.97065	DT top =	0.89997
TC 6	20.92484	DT bot =	1.00236
TC 7	20.04778	Mean temp. =	20.49093
TC 8	20.04778		

Elapsed time 30 min.

TC 1 20.15031
TC 2 20.15031
TC 3 21.30225
TC 4 21.30225
TC 5 21.27724
TC 6 21.27724
TC 7 20.25063

CH19 Volts 2.04900
CH20 Amps 0.28630
K-Factor = 0.42708
R-Value = 0.03085
DT top = 1.01408
DT bot = 1.15194
Mean temp. = 20.74824

Elapsed time 45 min.

TC 1 20.32516
TC 2 20.34598
TC 3 21.55150
TC 4 21.57648
TC 5 21.55150
TC 6 21.52551
TC 7 20.40036
TC 8 20.45049

CH19 Volts 2.04400
CH20 Amps 0.28480
K-Factor = 0.39332
R-Value = 0.03350
DT top = 1.11358
DT bot = 1.22842
Mean temp. = 20.96600

Elapsed time 60 min.

TC 1 20.40735
TC 2 20.42916
TC 3 21.72907
TC 4 21.75829
TC 5 21.75828
TC 6 21.70833
TC 7 20.55770
TC 8 20.55770

CH19 Volts 2.04500
CH20 Amps 2.28570
K-Factor = 0.36830
R-Value = 0.03577
DT top = 1.17560
DT bot = 1.32532
Mean temp. = 21.11311

Elapsed time 75 min.

TC 1 20.45221
TC 2 20.50233
TC 3 21.83213
TC 4 21.85714
TC 5 21.83218
TC 6 21.85714
TC 7 20.63185

CH19 Volts 2.04200
CH20 Amps 0.28550
K-Factor = 0.35630
R-Value = 0.03698
DT top = 1.21281
DT bot = 1.36739
Mean temp. = 21.19961

Elapsed time 90 min.

TC 1 20.53544
TC 2 20.56049
TC 3 21.91084
TC 4 21.93580
TC 5 21.93580
TC 6 21.91084
TC 7 20.66069
TC 8 20.71078

CH19 Volts 2.04200
CH20 Amps 2.28550
K-Factor = 0.35182
R-Value = 0.03745
DT top = 1.23759
DT bot = 1.37536
Mean temp. = 21.27009

Elapsed time 105 min.

TC 1 20.55062
TC 2 20.57142
TC 3 21.94668
TC 4 21.97588
TC 5 21.99659
TC 6 21.97164
TC 7 20.72596
TC 8 20.72596

CH19 Volts 2.04200
CH20 Amps 0.28550
K-Factor = 0.34581
R-Value = 0.03810
DT top = 1.25816
DT bot = 1.40026
Mean temp. = 21.30810

Elapsed time 120 min.

TC 1 20.53227
TC 2 20.55733
TC 3 21.98256
TC 4 21.98256
TC 5 21.98680
TC 6 21.95761
TC 7 20.68258
TC 8 20.73266

CH19 Volts 2.04300
CH20 Amps 0.28460
K-Factor = 0.34048
R-Value = 0.03870
DT top = 1.26459
DT bot = 1.43776
Mean temp. = 21.30180

Elapsed time 135 min.

TC 1 20.51446
TC 2 20.56032
TC 3 21.96058
TC 4 21.96483
TC 5 21.98978
TC 6 21.96483
TC 7 20.68982
TC 8 20.71486

CH19 Volts 2.04200
CH20 Amps 0.28550
K-Factor = 0.34045
R-Value = 0.03870
DT top = 1.27496
DT bot = 1.42531
Mean temp. = 21.29494

Elapsed time 150 min.

TC 1 20.47012
TC 2 20.52024
TC 3 21.94562
TC 4 21.94138
TC 5 21.97057
TC 6 21.94562
TC 7 20.69559
TC 8 20.64550

CH19 Volts 2.04200
CH20 Amps 0.28530
K-Factor = 0.33578
R-Value = 0.03924
DT top = 1.28755
DT bot = 1.44832
Mean temp. = 21.26683

Elapsed time 165 min.

TC 1 20.41351
TC 2 20.45937
TC 3 21.88500
TC 4 21.91420

CH19 Volts 2.04200
CH20 Amps 0.28550
K-Factor = 0.33419
R-Value = 0.03942

TC 5 21.91420
TC 6 21.88924
TC 7 20.61397
TC 8 20.61397

DT top = 1.28776
DT bot = 1.46316
Mean temp. = 21.21293

Elapsed time 180 min.

TC 1 20.40756
TC 2 20.43262
TC 3 21.88756
TC 4 21.91252
TC 5 21.91252
TC 6 21.88756
TC 7 20.61228
TC 8 20.58723

CH19 Volts 2.04300
CH20 Amps 0.28540
K-Factor = 0.33071
R-Value = 0.03984
DT top 1.30029
DT bot = 1.47995
Mean temp. = 21.20498

Elapsed time 195 min.

TC 1 20.37293
TC 2 20.42296
TC 3 21.37369
TC 4 21.85298
TC 5 21.87794
TC 6 21.87794
TC 7 20.57757
TC 8 20.57757

CH19 Volts 2.04200
CH20 Amps 0.28530
K-Factor = 0.33215
R-Value = 1.03967
DT top = 1.30037
DT bot = 1.46544
Mean temp. = 21.17918

Elapsed time 210 min.

TC 1 20.32001
TC 2 20.37441
TC 3 21.82534
TC 4 21.82109
TC 5 21.37102
TC 6 21.87102
TC 7 20.59568
TC 8 20.52051

CH19 Volts 2.04200
CH20 Amps 0.28540
K-Factor = 0.32951
R-Value = 0.03998
DT top = 1.31292
DT bot = 1.47600
Mean temp. = 21.14988

Sample has reached steady state in automatic termination mode.

Average values at end of test:

K-factor = 0.33247 W/m°C
= 2.30560 Btu-in/ft²,hr, °F

R-value based on thermocouple separation:

R-value = 0.03963 m²·C/W
= 0.22503 ft²,hr,°F/Btu

Test Data on Thermal Conductivity Measurement (ASTM C177 Test Method)

Report No. CBS-090-Khan.002

Date: March 14, 1988

Customer: Mr. Khan
Centre for Building Studies
Concordia University
Montreal Canada

* Material: Gypsum Concrete Tiles incorporated with PCM

Sample id: Specimen 3 bottom and specimen 4 top

Original sample thickness .01575 m
Thickness of top specimen .0127 m
Thickness of bottom specimen .0128 m
Weight of sample 1.058 kg

Room conditions: Temperature: 22°C
Humidity: 40% R.H.
Coolant temperature: 22°C

Elapsed time 0 min.

TC 1	20.02116	CH19 Volts	2.06200
TC 2	20.07134	CH20 Amps	0.28810
TC 3	20.99840	K-Factor =	0.50615
TC 4	20.99840	R-Value =	0.02519
TC 5	21.02342	DT top =	0.83914
TC 6	21.07346	DT bot =	0.95214
TC 7	20.22184	Mean temp. =	20.57560
TC 8	20.19676		

Elapsed time 15 min.

TC 1	20.02971	CH19 Volts	2.06000
TC 2	20.10497	CH20 Amps	0.28820
TC 3	21.05270	K-Factor =	0.47020
TC 4	21.05270	R-Value =	0.02712
TC 5	21.13201	DT top =	0.94138
TC 6	21.13201	DT bot =	0.98536
TC 7	20.23038	Mean temp. =	20.61066
TC 8	20.15087		

Elapsed time 30 min.

TC 1 20.05533
TC 2 20.10551
TC 3 21.05323
TC 4 21.05523
TC 5 21.10327
TC 6 21.13254
TC 7 20.17649
TC 8 20.13059

CH19 Volts 2.06100
CH20 Amps 0.28800
K-Factor = 0.46753
R-Value = 0.02727
DT top = 0.96437
DT bot = 0.97281
Mean temp. = 20.60128

Elapsed time 45 min.

TC 1 20.06495
TC 2 20.09004
TC 3 21.06708
TC 4 21.06708
TC 5 21.14213
TC 6 21.14213
TC 7 20.16529
TC 8 20.11513

CH19 Volts 2.05800
CH20 Amps 0.28800
K-Factor = 0.45410
R-Value = 0.02808
DT top = 1.00192
DT bot = 1.98959
Mean temp. = 20.60673

Elapsed time 60 min.

TC 1 20.01477
TC 2 20.06495
TC 3 21.09210
TC 4 21.09636
TC 5 21.09636
TC 6 21.14213
TC 7 20.21545
TC 8 20.09004

CH19 Volts 2.06000
CH20 Amps 0.28800
K-Factor = 0.44252
R-Value = 0.02831
DT top = 0.99151
DT bot = 1.05437
Mean temp. = 20.60778

Elapsed time 75 min.

TC 1 19.97313
TC 2 19.99822
TC 3 21.05059
TC 4 21.02557
TC 5 21.10062
TC 6 21.12138
TC 7 20.12367
TC 8 20.04841

CH19 Volts 2.06000
CH20 Amps 0.28790
K-Factor = 0.43564
R-Value = 0.02927
DT top = 1.02496
DT bot = 1.05240
Mean temp. = 20.55520

Elapsed time 90 min.

TC 1 19.96567
TC 2 20.01586
TC 3 21.04315
TC 4 21.07242
TC 5 21.07242
TC 6 21.12245
TC 7 20.12048
TC 8 20.04522

CH19 Volts 2.06000
CH20 Amps 0.28750
K-Factor = 0.43416
R-Value = 0.02937
DT top = 1.01459
DT bot = 1.06702
Mean temp. = 1.06702

Elapsed time 105 min.

TC 1 19.98812
TC 2 20.01322
TC 3 21.04052
TC 4 21.04052
TC 5 21.06553
TC 6 21.09055
TC 7 20.11357
TC 8 20.03831

CH19 Volts 2.05900
CH20 Amps 0.28750
K-Factor = 0.44237
R-Value = 0.02882
DT top = 1.00210
DT bot = 1.03984
Mean temp. = 20.54879

Elapsed time 120 min.

TC 1 19.95876
TC 2 19.97958
TC 3 21.00697
TC 4 21.01123
TC 5 21.08629
TC 6 21.11131
TC 7 20.13011
TC 8 20.03404

CH19 Volts 2.06000
CH20 Amps 0.28800
K-Factor = 0.44017
R-Value = 0.02897
DT top = 1.01672
DT bot = 1.03994
Mean temp. = 20.53978

Elapsed time 135 min.

TC 1 19.90856
TC 2 19.93366
TC 3 20.96118
TC 4 20.98621
TC 5 21.03625
TC 6 21.03625
TC 7 20.05912
TC 8 19.95876

CH19 Volts 2.05900
CH20 Amps 0.28790
K-Factor = 0.43489
R-Value = 0.02932
DT top = 1.02731
DT bot = 1.05259
Mean temp. = 20.48500

Elapsed time 150 min.

TC 1 19.89683
TC 2 19.92193
TC 3 20.94523
TC 4 20.94949
TC 5 20.99528
TC 6 21.02456
TC 7 20.02231
TC 8 19.94703

CH19 Volts 2.06000
CH20 Amps 0.28790
K-Factor = 0.43861
R-Value = 0.02907
DT top = 1.02525
DT bot = 1.03798
Mean temp. = 20.46283

Sample has reached steady state in automatic termination mode.

Average values at end of test:

K-factor = $0.43804 \text{ W/m}^2\text{C}$
= $3.03773 \text{ Btu-in/ft}^2\text{,hr,}^{\circ}\text{F}$

R-value based on thermocouple separation:

R-value = $0.02911 \text{ m}^2\text{C/W}$
= $0.16528 \text{ ft}^2\text{,hr,}^{\circ}\text{F/Btu}$

2

Test Data on Thermal Conductivity Measurement (ASTM C177 Test Method)

Report No. CBS-090-Khan.003

Date: March 14, 1988

Customer: Mr. Khan
Centre for Building Studies
Concordia University
Montreal Canada

Material: Gypsum Concrete Tiles incorporated with PCM and
surface coated with polyester resin

Sample id: Specimen 6 bottom and specimen 7 top

Original sample thickness .01665 m
Thickness of top specimen .0137 m
Thickness of bottom specimen .0136 m
Weight of sample 1.062 kg

Room conditions: Temperature: 22°C
Humidity: 40% R.H.
Coolant temperature: 22°C

Elapsed time 0 min.

TC 1	19.55975	CH19 Volts	2.05800
TC 2	19.60572	CH20 Amps	0.28770
TC 3	20.43801	K-Factor =	0.65213
TC 4	20.41294	R-Value =	0.02093
TC 5	20.43801	DT top =	0.63964
TC 6	20.46307	DT bot =	0.84274
TC 7	19.86111	Mean temp. =	20.06741
TC 8	19.76068		

Elapsed time 15 min.

TC 1	19.56031	CH19 Volts	2.05700
TC 2	19.61055	CH20 Amps	0.28770
TC 3	20.66406	K-Factor =	0.45609
TC 4	20.66405	R-Value =	0.02993
TC 5	20.68909	DT top =	1.04083
TC 6	20.71414	DT bot =	1.07862
TC 7	19.71102	Mean temp. =	20.15297
TC 8	19.61055		

Elapsed time 30 min.

TC 1 19.71213
TC 2 19.73724
TC 3 20.84044
TC 4 20.81540
TC 5 20.91553
TC 6 20.91553
TC 7 19.84195
TC 8 19.73724

CH19 Volts 2.05700
CH20 Amps 0.28770
K-Factor = 0.43859
R-Value = 0.43859
DT top = 1.10091
DT bot = 1.10324
Mean temp. = 20.30817

Elapsed time 45 min.

TC 1 19.73780
TC 2 19.75863
TC 3 20.93685
TC 4 20.93685
TC 5 21.03695
TC 6 21.03695
TC 7 19.90926
TC 8 19.78374

CH19 Volts 2.05800
CH20 Amps 0.28760
K-Factor = 0.40640
R-Value = 0.03359
DT top = 1.19045
DT bot = 1.18864
Mean temp. = 20.39213

Elapsed time 60 min.

TC 1 19.72013
TC 2 19.77463
TC 3 20.99858
TC 4 20.97356
TC 5 21.04863
TC 6 21.10292
TC 7 19.92525
TC 8 20.03404

CH19 Volts 2.05900
CH20 Amps 0.39215
K-Factor = 0.39215
R-Value = 0.03481
DT top = 1.22798
DT bot = 1.23870
Mean temp. = 20.41425

Elapsed time 75 min.

TC 1 19.77463
TC 2 19.79973
TC 3 21.02787
TC 4 21.02787
TC 5 21.07791
TC 6 21.12794
TC 7 19.90015
TC 8 19.79973

CH19 Volts 2.05800
CH20 Amps 0.28770
K-Factor = 0.38787
R-Value = 0.03519
DT top = 1.25298
DT bot = 1.24069
Mean temp. = 20.44198

Elapsed time 90 min.

TC 1 19.83395
TC 2 19.83395
TC 3 21.08699
TC 4 21.06197
TC 5 21.13702
TC 6 21.16203
TC 7 19.95518
TC 8 19.85906

CH19 Volts 2.05800
CH20 Amps 0.28740
K-Factor = 0.38913
R-Value = 0.03508
DT top = 1.24241
DT bot = 1.24052
Mean temp. = 20.49127

Elapsed time 105 min.

TC 1 19.83024
TC 2 19.85962
TC 3 21.10830
TC 4 21.10830
TC 5 21.18334
TC 6 21.23335
TC 7 20.00593
TC 8 19.88044

CH19 Volts 2.05800
CH20 Amps 0.28760
K-Factor = 0.38238
R-Value = 0.03570
DT top = 1.26516
DT bot = 1.26337
Mean temp. = 20.52619

Elapsed time 120 min

TC 1 19.78318
TC 2 19.83339
TC 3 21.11145
TC 4 21.11145
TC 5 21.16147
TC 6 21.21149
TC 7 19.98399
TC 8 19.85850

CH19 Volts 2.06000
CH20 Amps 0.28770
K-Factor = 0.37692
R-Value = 0.03621
DT top = 1.26524
DT bot = 1.30316
Mean temp. = 20.50638

Elapsed time 135 min.

TC 1 19.80401
TC 2 19.82484
TC 3 21.13220
TC 4 21.08217
TC 5 21.14721
TC 6 21.20723
TC 7 19.97972
TC 8 19.85422

CH19 Volts 2.05800
CH20 Amps 0.28770
K-Factor = 0.37809
R-Value = 0.03610
DT top = 1.26525
DT bot = 1.29276
Mean temp. = 20.50520

Elapsed time 150 min.

TC 1	19.83395	CH19 Volts	2.05800
TC 2	19.85478	CH20 Amps	0.28750
TC 3	21.13276	K-Factor =	0.37818
TC 4	21.10774	R-Value =	0.03609
TC 5	21.18704	DT top =	1.27988
TC 6	21.18704	DT bot =	1.27588
TC 7	19.95518	Mean temp. =	20.51989
TC 8	19.87988		

Elapsed time 165 min.

TC 1	19.85162	CH19 Volts	2.05800
TC 2	19.87672	CH20 Amps	0.28760
TC 3	21.15462	K-Factor =	0.37648
TC 4	21.12961	R-Value =	0.03626
TC 5	21.22963	DT top =	1.29027
TC 6	21.22965	DT bot =	1.27794
TC 7	19.95202	Mean temp. =	20.53133
TC 8	19.87672		

Elapsed time 180 min.

TC 1	19.82168	CH19 Volts	2.05900
TC 2	19.87189	CH20 Amps	0.28770
TC 3	21.14980	K-Factor =	0.37346
TC 4	21.12479	R-Value =	0.03655
TC 5	21.19982	DT top =	1.30062
TC 6	21.24558	DT bot =	1.29051
TC 7	19.99738	Mean temp. =	20.53222
TC 8	19.84679		

Sample has reached steady state in automatic termination mode.

Average values at end of test:

K factor = 0.37662 W/m°C
= 2.61182 Btu-in/ft²,hr,°F

R-Value based on thermocouple separation:

R-value = 0.03624 m²·C/W
= 0.20581 ft²,hr,°F/Btu

Test Data on Thermal Conductivity Measurement (ASTM C177 Test Method)

Report No. CBS-090-Khan.006

Date: March 14, 1988

Customer: Mr. Khan
Centre for Building Studies
Concordia University
Montreal Canada

Material: Gypsum Concrete Tiles incorporated with PCM
surfaces coated with metal-filled polyester resin

Sample id: Specimen-11 bottom and specimen 12 top

Original sample thickness .01625 m
Thickness of top specimen .0133 m
Thickness of bottom specimen .0132 m
Weight of sample 1.074 kg

Room conditions: Temperature: 22°C
Humidity: 40% R.H.
Coolant temperature: 22°C

Elapsed time 0 min.

TC 1	20.16885	CH19 Volts	2.09700
TC 2	20.16885	CH20 Amps	0.29310
TC 3	21.02060	K-Factor =	0.56388
TC 4	21.04562	R-Value =	0.02350
TC 5	21.09565	DT top =	0.86413
TC 6	21.07064	DT bot =	0.86425
TC 7	20.21901	Mean temp. =	20.62603
TC 8	20.21901		

Elapsed time 15 min.

TC 1	20.29518	CH19 Volts	2.09800
TC 2	20.32026	CH20 Amps	0.29310
TC 3	21.34667	K-Factor =	0.46367
TC 4	21.39667	R-Value =	0.02858
TC 5	21.40091	DT top =	1.03887
TC 6	21.35092	DT bot =	1.06395
TC 7	20.32451	Mean temp. =	20.84809
TC 8	20.34958		

Elapsed time 30 min.

TC 1	20.43946	CH19 Volts	2.09900
TC 2	20.44371	CH20 Amps	0.29330
TC 3	21.59471	K-Factor *	0.42874
TC 4	21.56548	R-Value *	0.03090
TC 5	21.64467	DT top *	1.13838
TC 6	21.59471	DT bot *	1.13851
TC 7	20.44371	Mean temp. *	21.03067
TC 8	20.51889		

Elapsed time 45 min.

TC 1	20.55160	CH19 Volts	2.09800
TC 2	20.55160	CH20 Amps	0.29330
TC 3	21.72722	K-Factor *	0.41065
TC 4	21.75219	R-Value *	0.03227
TC 5	21.80213	DT top *	1.18798
TC 6	21.75643	DT bot *	1.18811
TC 7	20.55160	Mean temp. *	21.16547
TC 8	20.63101		

Elapsed time 60 min.

TC 1	20.65200	CH19 Volts	2.09800
TC 2	20.65200	CH20 Amps	0.29320
TC 3	21.88147	K-Factor *	0.39771
TC 4	21.90642	R-Value *	0.03332
TC 5	21.92714	DT top *	1.21043
TC 6	21.88147	DT bot *	1.24194
TC 7	20.68131	Mean temp. *	21.28602
TC 8	20.70635		

Elapsed time 75 min.

TC 1	20.74374	CH19 Volts	2.09700
TC 2	20.72369	CH20 Amps	0.29330
TC 3	21.99858	K-Factor *	0.39442
TC 4	21.97363	R-Value *	0.03359
TC 5	22.02353	DT top *	1.22263
TC 6	21.99858	DT bot *	1.24989
TC 7	20.77378	Mean temp. *	21.38045
TC 8	20.80307		

Elapsed time 90 min.

TC 1 20.82054
TC 2 20.82054
TC 3 22.07013
TC 4 22.07438
TC 5 22.09933
TC 6 22.07438
TC 7 20.82480
TC 8 20.89990

CH19 Volts 2.09800
CH20 Amps 0.29320
K-Factor = 0.39389
R-Value = 0.03364
DT top = 1.22450
DT bot = 1.25172
Mean temp. = 21.46050

Elapsed time 105 min.

TC 1 20.83386
TC 2 20.86316
TC 3 22.11261
TC 4 22.11261
TC 5 22.16249
TC 6 22.13755
TC 7 20.88819
TC 8 20.93825

CH19 Volts 2.09800
CH20 Amps 0.29320
K-Factor = 0.39000
R-Value = 0.03397
DT top = 1.23680
DT bot = 1.26409
Mean temp. = 21.50609

Elapsed time 120 min.

TC 1 20.85955
TC 2 20.85955
TC 3 22.18383
TC 4 22.18383
TC 5 22.23371
TC 6 22.18808
TC 7 20.88884
TC 8 20.93890

CH19 Volts 2.09800
CH20 Amps 0.29320
K-Factor = 0.37209
R-Value = 0.03561
DT top = 1.29703
DT bot = 1.32429
Mean temp. = 21.54204

Elapsed time 135 min.

TC 1 20.86827
TC 2 20.89330
TC 3 22.16758
TC 4 22.16758
TC 5 22.24240
TC 6 22.19253
TC 7 20.91833
TC 8 20.94336

CH19 Volts 2.09700
CH20 Amps 0.29310
K-Factor = 0.37872
R-Value = 0.03499
DT top = 1.28662
DT bot = 1.28680
Mean temp. = 21.54917

Elapsed time 150 min.

TC 1 20.86001
TC 2 20.88504
TC 3 22.18430
TC 4 22.15936
TC 5 22.20924
TC 6 22.18430
TC 7 20.93510
TC 8 20.93937

CH19 Volts 2.09800
CH20 Amps 0.29330
K-Factor = 0.38130
R-Value = 0.03475
DT top = 1.25953
DT bot = 1.29930
Mean temp. = 21.54459

Elapsed time 165 min.

TC 1 20.83475
TC 2 20.85978
TC 3 22.15913
TC 4 22.15913
TC 5 22.21326
TC 6 22.18833
TC 7 20.88908
TC 8 20.93914

CH19 Volts 2.09700
CH20 Amps 0.29310
K-Factor = 0.37504
R-Value = 0.03533
DT top = 1.28668
DT bot = 1.31186
Mean temp. = 21.53033

Elapsed time 180 min

TC 1 20.84681
TC 2 20.84254
TC 3 22.12126
TC 4 22.12126
TC 5 22.17114
TC 6 22.14620
TC 7 20.87184
TC 8 20.89687

CH19 Volts 2.09600
CH20 Amps 0.29320
K-Factor = 0.38201
R-Value = 0.03469
DT top = 1.27432
DT bot = 1.27658
Mean temp. = 21.50224

Elapsed time 195 min.

TC 1 20.79176
TC 2 20.84183
TC 3 22.11630
TC 4 22.11630
TC 5 22.16618
TC 6 22.14124
TC 7 20.86886
TC 8 20.87114

CH19 Volts 2.09800
CH20 Amps 0.29330
K-Factor = 0.37756
R-Value = 0.03509
DT top = 1.26471
DT bot = 1.29950
Mean temp. = 21.48895

Elapsed time 210 min.

TC 1	20.77400	CH19 Volts	2.09700
TC 2	20.79904	CH20 Amps	0.29310
TC 3	22.09861	K-Factor =	0.37860
TC 4	22.09861	R-Value =	0.03500
TC 5	22.14850	DT top =	1.26192
TC 6	22.09861	DT bot =	1.31209
TC 7	20.84911	Mean temp. =	21.46758
TC 8	20.87415		

Elapsed time 225 min.

TC 1	20.73918	CH19 Volts	2.09800
TC 2	20.76850	CH20 Amps	0.29330
TC 3	22.03896	K-Factor =	0.38087
TC 4	22.04323	R-Value =	0.03479
TC 5	22.11381	DT top =	1.27456
TC 6	22.06818	DT bot =	1.28725
TC 7	20.81857	Mean temp. =	21.42559
TC 8	20.81430		

Sample has reached steady state in automatic termination mode.

Average values at end of test:

K-factor = $0.37882 \text{ W/m}^{\circ}\text{C}$
= $2.62702 \text{ Btu-in/ft}^2\text{,hr,}^{\circ}\text{F}$

R-Value based on thermocouple separation:

R-value = $0.03498 \text{ m}^2\text{.}^{\circ}\text{C/W}$
= $0.19862 \text{ ft}^2\text{,hr,}^{\circ}\text{F/Btu}$

Test Data on Thermal Conductivity Measurement (ASTM C177 Test Method)

Report No. CBS-090-Khan.005

Date: March 14, 1988

Customer: Mr. Khan
Centre for Building Studies
Concordia University
Montreal Canada

Material: Gypsum Concrete Tiles incorporated with PCM
and surface coated with metal-filled polyester resin

Sample id: Specimen 8 bottom and specimen 10 top

Original sample thickness .01615 m
Thickness of top specimen .013 m
Thickness of bottom specimen .0133 m
Weight of sample 1.06 kg

Room conditions: Temperature: 22°C
Humidity: 40% R.H.
Coolant temperature: 22°C

Elapsed time 0 min.

TC 1 19.49597
TC 2 19.52110
TC 3 20.54981
TC 4 20.54981
TC 5 20.62496
TC 6 20.62496
TC 7 19.89780
TC 8 19.72205

CH19 Volts 2.06000
CH20 Amps 0.28790
K-Factor = 0.50342
R-Value = 9.02612
DT top = 0.81503
DT bot = 0.04127
Mean temp. = 20.12331

Elapsed time 15 min.

TC 1 19.44029
TC 2 19.49055
TC 3 20.59451
TC 4 20.62383
TC 5 20.69470
TC 6 20.64460
TC 7 19.66641
TC 8 19.54080

CH19 Volts 2.05900
CH20 Amps 0.28780
K-Factor = 0.42212
R-Value = 0.03115
DT top = 1.06605
DT bot = 1.14375
Mean temp. = 20.08696

Elapsed time 30 min.

TC 1 19.53652
TC 2 19.58676
TC 3 20.66538
TC 4 20.66538
TC 5 20.74051
TC 6 20.71547
TC 7 19.69152
TC 8 19.58676

CH19 Volts 2.05900
CH20 Amps 0.28780
K-Factor = 0.42530
R-Value = 0.03092
DT top = 1.08885
DT bot = 1.10374
Mean temp. = 20.14854

Elapsed time 45 min.

TC 1 19.58248
TC 2 19.63273
TC 3 20.73624
TC 4 20.76128
TC 5 20.83640
TC 6 20.78632
TC 7 19.78341
TC 8 19.60761

CH19 Volts 2.05900
CH20 Amps 0.28790
K-Factor = 0.41332
R-Value = 0.03182
DT top = 1.11585
DT bot = 1.14116
Mean temp. = 20.21581

Elapsed time 60 min.

TC 1 19.58935
TC 2 19.58935
TC 3 20.76813
TC 4 20.79317
TC 5 20.86827
TC 6 20.79317
TC 7 19.76516
TC 8 19.61447

CH19 Volts 2.05900
CH20 Amps 0.28770
K-Factor = 0.39977
R-Value = 0.03289
DT top = 1.14090
DT bot = 1.19130
Mean temp. = 20.22263

Elapsed time 75 min.

TC 1 19.59734
TC 2 19.64758
TC 3 20.80113
TC 4 20.80113
TC 5 20.87624
TC 6 20.82617
TC 7 19.77315
TC 8 19.64758

CH19 Volts 2.06000
CH20 Amps 0.28790
K-Factor = 0.40241
R-Value = 0.03268
DT top = 1.14084
DT bot = 1.17867
Mean temp. = 20.24629

Elapsed time 90 min.

TC 1 19.58338
TC 2 19.65874
TC 3 20.81225
TC 4 20.83729
TC 5 20.91238
TC 6 20.86232
TC 7 19.80941
TC 8 19.63362

CH19 Volts 2.05900
CH20 Amps 0.28760
K-Factor = 0.39330
R-Value = 0.03343
DT top = 1.16584
DT bot = 1.20371
Mean temp. = 20.26367

Elapsed time 105 min

TC 1 19.62022
TC 2 19.61594
TC 3 20.81967
TC 4 20.79890
TC 5 20.87400
TC 6 20.87400
TC 7 19.79174
TC 8 19.66618

CH19 Volts 2.06000
CH20 Amps 0.28790
K-Factor = 0.40209
R-Value = 0.03270
DT top = 1.13039
DT bot = 1.19120
Mean temp. = 20.25392

Elapsed time 120 min

TC 1 19.64050
TC 2 19.64050
TC 3 20.86918
TC 4 20.86918
TC 5 20.91924
TC 6 20.91924
TC 7 19.81629
TC 8 19.66562

CH19 Volts 2.06000
CH20 Amps 0.28790
K-Factor = 0.38781
R-Value = 0.03391
DT top = 1.17829
DT bot = 1.22868
Mean temp. = 20.29247

Elapsed time 135 min.

TC 1 19.60999
TC 2 19.65595
TC 3 20.86381
TC 4 20.85955
TC 5 20.90961
TC 6 20.88458
TC 7 19.80662
TC 8 19.65595

CH19 Volts 2.05900
CH20 Amps 0.28790
K-Factor = 0.38966
R-Value = 0.03375
DT top = 1.16580
DT bot = 1.22870
Mean temp. = 20.28076

Elapsed time 150 min.

TC 1	19.63456	CH19 Volts	2.06000
TC 2	19.68479	CH20 Amps	0.28780
TC 3	20.86326	K-Factor =	0.39172
TC 4	20.86326	R-Value =	0.03357
TC 5	20.96337	DT top =	1.17822
TC 6	20.91332	DT bot =	1.20358
TC 7	19.83545	Mean temp. =	20.30535
TC 8	19.68479		

Elapsed time 165 min.

TC 1	19.61635	CH19 Volts	2.05800
TC 2	19.67086	CH20 Amps	0.28780
TC 3	20.84511	K-Factor =	0.38969
TC 4	20.89517	R-Value =	0.03374
TC 5	20.94523	DT top =	1.16573
TC 6	20.89517	DT bot =	1.22654
TC 7	19.84235	Mean temp. =	20.29710
TC 8	19.66658		

Elapsed time 180 min.

TC 1	19.64947	CH19 Volts	2.05900
TC 2	19.67886	CH20 Amps	0.28780
TC 3	20.87812	K-Factor =	0.39122
TC 4	20.88238	R-Value =	0.03361
TC 5	20.93244	DT top =	1.16787
TC 6	20.90315	DT bot =	1.21608
TC 7	19.80014	Mean temp. =	20.30303
TC 8	19.69970		

Sample has reached steady state in automatic termination mode.

Average values at end of test:

K-factor = 0.39002 W/m°C
 = 2.70470 Btu-in/ft²,hr,°F

R-Value based on thermocouple separation:

R-value = 0.03372 m²°C/W
 = 0.19146 ft²,hr,°F/Btu

Test Data on Thermal Conductivity Measurement. (ASTM C177 Test Method)

Report No. CBS-090-Khan.007

Date: March 14, 1988

Customer: Mr. Khan
Centre for Building Studies
Concordia University
Montreal Canada

Material: Gypsum Concrete Tiles incorporated with PCM
and surface coated with metal-filled polyester resin

Sample id: Specimen # 13 bottom and specimen # 14 top

Original sample thickness .0161 m
Thickness of top specimen .01305 m
Thickness of bottom specimen .01315 m
Weight of sample 1.051 kg

Room conditions: Temperature: 22°C
Humidity: 40% R.H.
Coolant temperature: 22°C

Elapsed time 0 min.

TC 1	20.69924	CH19 Volts	2.09800
TC 2	20.72428	CH20 Amps	0.29330
TC 3	21.79948	K-Factor =	0.38188
TC 4	21.80375	R-Value =	0.03430
TC 5	21.85368	DT top =	0.22550
TC 6	21.87437	DT bot =	0.30092
TC 7	21.04968	Mean temp. =	21.13087
TC 8	20.92456		

Elapsed time 15 min.

TC 1	20.24410	CH19 Volts	2.09800
TC 2	20.42410	CH20 Amps	0.29330
TC 3	21.72502	K-Factor =	0.38188
TC 4	21.72502	R-Value =	0.03430
TC 5	21.79993	DT top =	1.22550
TC 6	21.79993	DT bot =	1.30092
TC 7	20.67464	Mean temp. =	21.13087
TC 8	20.47422		

Elapsed time 30 min.

TC 1 20.33289
TC 2 20.33289
TC 3 21.55920
TC 4 21.55493
TC 5 21.60490
TC 6 21.62988
TC 7 20.50834
TC 8 20.37874

CH19 Volts 2.09800
CH20 Amps 0.29340
K-Factor = 0.40245
R-Value = 0.03255
DT top = 1.17385
DT bot = 1.22417
Mean temp. = 20.98772

Elapsed time 45 min.

TC 1 20.22824
TC 2 20.27839
TC 3 21.47990
TC 4 21.47990
TC 5 21.55486
TC 6 21.55486
TC 7 20.47464
TC 8 20.25332

CH19 Volts 2.10000
CH20 Amps 0.29340
K-Factor = 0.39959
R-Value = 0.03278
DT top = 1.19088
DT bot = 1.22658
Mean temp. = 20.91301

Elapsed time 60 min.

TC 1 20.18296
TC 2 20.23311
TC 3 21.40978
TC 4 21.38479
TC 5 21.43477
TC 6 21.43477
TC 7 20.38354
TC 8 20.20804

CH19 Volts 2.09900
CH20 Amps 0.29340
K-Factor = 0.41471
R-Value = 0.03159
DT top = 1.13898
DT bot = 1.18925
Mean temp. = 20.83397

Elapsed time 75 min.

TC 1 20.15605
TC 2 20.18113
TC 3 21.36224
TC 4 21.35797
TC 5 21.40796
TC 6 21.40796
TC 7 20.33158
TC 8 20.20621

CH19 Volts 2.09900
CH20 Amps 0.29330
K-Factor = 0.41416
R-Value = 0.03163
DT top = 1.13906
DT bot = 1.19151
Mean temp. = 20.80139

Elapsed time 90 min.

TC 1 20.14568
TC 2 20.17076
TC 3 21.34763
TC 4 21.34336
TC 5 21.41835
TC 6 21.41835
TC 7 20.36707
TC 8 20.19156

CH19 Volts 2.09900
CH20 Amps 0.29330
K-Factor = 0.41491
R-Value = 0.03157
DT top = 1.13904
DT bot = 1.18728
Mean temp. = 20.80035

Elapsed time 105 min.

TC 1 20.11391
TC 2 20.13900
TC 3 21.31597
TC 4 21.29097
TC 5 21.39097
TC 6 21.36597
TC 7 20.31454
TC 8 20.16408

CH19 Volts 2.09800
CH20 Amps 0.29330
K-Factor = 0.41652
R-Value = 0.03145
DT top = 1.13916
DT bot = 1.17702
Mean temp. = 20.76193

Elapsed time 120 min.

TC 1 20.14209
TC 2 20.16717
TC 3 21.31905
TC 4 21.31905
TC 5 21.34405
TC 6 21.34405
TC 7 20.26748
TC 8 20.16717

CH19 Volts 2.09900
CH20 Amps 0.29330
K-Factor = 0.42127
R-Value = 0.03110
DT top = 1.12672
DT bot = 1.16442
Mean temp. = 20.75876

Elapsed time 135 min.

TC 1 20.16289
TC 2 20.18797
TC 3 21.31478
TC 4 21.33979
TC 5 21.36478
TC 6 21.36478
TC 7 20.31335
TC 8 20.21305

CH19 Volts 2.09800
CH20 Amps 0.29320
K-Factor = 0.42798
R-Value = 0.03061
DT top = 1.10158
DT bot = 1.15185
Mean temp. = 20.78267

Elapsed time 150 min.

TC 1	20.14149	CH19 Volts	2.09900
TC 2	20.19165	CH20 Amps	0.29330
TC 3	21.31846	K-Factor =	0.42557
TC 4	21.34346	R-Value =	0.03078
TC 5	21.36846	DT top =	1.10372
TC 6	21.36846	DT bot =	1.16438
TC 7	20.34210	Mean temp. =	20.78268
TC 8	20.18738		

Elapsed time 165 min.

TC 1	20.12319	CH19 Volts	2.09900
TC 2	20.17336	CH20 Amps	0.29330
TC 3	21.32522	K-Factor =	0.42127
TC 4	21.35022	R-Value =	0.03110
TC 5	21.35022	DT top =	1.12671
TC 6	21.35022	DT bot =	1.16444
TC 7	20.27367	Mean temp. =	20.75868
TC 8	20.17336		

Elapsed time 180 min.

TC 1	20.12689	CH19 Volts	2.10000
TC 2	20.17705	CH20 Amps	0.29330
TC 3	21.30390	K-Factor =	0.42891
TC 4	21.30390	R-Value =	0.03054
TC 5	21.32890	DT top =	1.09956
TC 6	21.32463	DT bot =	1.15193
TC 7	20.27736	Mean temp. =	20.75246
TC 8	20.17705		

Sample has reached steady state in automatic termination mode.

Average values at end of test:

K-factor = 0.42500 W/m°C
= 2.94731 Btu-in/ft²,hr,°F

R-Value based on thermocouple separation:

R-value = 0.03082 m²·C/W
= 0.17503 ft²,hr,°F/Btu

Test Data on Thermal Conductivity Measurement (ASTM C177 Test Method)

Report No. CBS-090-Khan.014

Date: March 14, 1988

Customer: Mr. Khan
Centre for Building Studies
Concordia University
Montreal, Canada

Material: Gypsum Concrete Tiles incorporated with PCM
and surface coated with metal-filled polyester resin

Sample id: Specimen # 23 bottom and specimen # 24 top

Original sample thickness .017325
Thickness of top specimen .0132 m
Thickness of bottom specimen .01345 m
Weight of sample 1.08 kg

Room conditions: Temperature: 22°C
Humidity: 40% R.H.
Coolant temperature: 22°C

Elapsed time 0 min.

TC 1	18.68525	CH19 Volts	2.17500
TC 2	18.73562	CH20 Amps	0.30400
TC 3	19.82108	K-Factor =	0.49018
TC 4	19.84191	R-Value =	0.02718
TC 5	19.86701	DT top =	1.03062
TC 6	19.91721	DT bot =	1.12106
TC 7	18.96218	Mean temp. =	19.32388
TC 8	18.76080		

Elapsed time 15 min.

TC 1	18.31529	CH19 Volts	2.17400
TC 2	18.34050	CH20 Amps	0.30390
TC 3	19.74946	K-Factor =	0.37731
TC 4	19.74946	R-Value =	0.03532
TC 5	19.79968	DT top =	1.37092
TC 6	19.82479	DT bot =	1.42157
TC 7	18.51692	Mean temp. =	19.08273
TC 8	18.36571		

Elapsed time 30 min.

TC 1	18.25626
TC 2	18.30239
TC 3	19.66127
TC 4	19.66127
TC 5	19.68639
TC 6	19.73662
TC 7	18.52923
TC 8	18.32760

CH19 Volts	2.17500
CH20 Amps	0.30400
K-Factor =	0.39574
R-Value =	0.03367
DT top =	1.28309
DT bot =	1.38195
Mean temp. =	19.02013

Elapsed time 45 min.

TC 1	18.21327
TC 2	18.23849
TC 3	19.54737
TC 4	19.54309
TC 5	19.57249
TC 6	19.62273
TC 7	18.44017
TC 8	18.28892

CH19 Volts	2.17500
CH20 Amps	0.30400
K-Factor =	0.41319
R-Value =	0.03225
DT top =	1.23307
DT bot =	1.31935
Mean temp. =	18.93332

Elapsed time 60 min.

TC 1	18.20095
TC 2	18.22617
TC 3	19.50569
TC 4	19.50569
TC 5	19.53081
TC 6	19.55594
TC 7	18.42786
TC 8	18.29752

CH19 Volts	2.17600
CH20 Amps	0.30400
K-Factor =	0.42673
R-Value =	0.03123
DT top =	1.18069
DT bot =	1.29213
Mean temp. =	18.90633

Elapsed time 75 min.

TC 1	18.16655
TC 2	18.21699
TC 3	19.47142
TC 4	19.47570
TC 5	19.52167
TC 6	19.55108
TC 7	18.41439
TC 8	18.21699

CH19 Volts	2.17600
CH20 Amps	0.30400
K-Factor =	0.42159
R-Value =	0.03161
DT top =	1.22068
DT bot =	1.28178
Mean temp. =	18.87935

Elapsed time 90 min.

TC 1	18.14935
TC 2	18.17457
TC 3	19.42915
TC 4	19.43343
TC 5	19.45856
TC 6	19.50882
TC 7	18.40150
TC 8	18.24593

CH19 Volts	2.17400
CH20 Amps	0.30390
K-Factor =	0.43383
R-Value =	0.03071
DT top =	1.15998
DT bot =	1.26932
Mean temp. =	18.85017

Elapsed time 105 min.

TC 1	18.17085
TC 2	18.19607
TC 3	19.40459
TC 4	19.43400
TC 5	19.45485
TC 6	19.48426
TC 7	18.35166
TC 8	18.25081

CH19 Volts	2.17400
CH20 Amps	0.30390
K-Factor =	0.43380
R-Value =	0.03040
DT top =	1.16833
DT bot =	1.23583
Mean temp. =	18.84339

Elapsed time 120 min.

TC 1	18.12843
TC 2	18.15365
TC 3	19.41258
TC 4	19.40830
TC 5	19.46285
TC 6	19.48797
TC 7	18.40579
TC 8	18.22501

CH19 Volts	2.17500
CH20 Amps	0.30390
K-Factor =	0.43401
R-Value =	0.03070
DT top =	1.16001
DT bot =	1.26940
Mean temp. =	18.83557

Elapsed time 135 min.

TC 1	18.14075
TC 2	18.16598
TC 3	19.39973
TC 4	19.37459
TC 5	19.42486
TC 6	19.47512
TC 7	18.34249
TC 8	18.21642

CH19 Volts	2.17400
CH20 Amps	0.30400
K-Factor =	0.43841
R-Value =	0.03039
DT top =	1.17054
DT bot =	1.23379
Mean temp. =	18.81749

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Elapsed time 150 min.

TC 1 18.14563
TC 2 18.17085
TC 3 19.40459
TC 4 19.40459
TC 5 19.42972
TC 6 19.45485
TC 7 18.34736
TC 8 18.24651

CH19 Volts 2.17500
CH20 Amps 0.30400
K-Factor = 0.44099
R-Value = 0.03022
DT top = 1.14535
DT bot = 1.24635
Mean temp. = 18.82551

Sample has reached steady state in automatic termination mode.

Average values at end of test:

K-factor = 0.43711 W/m°C
= 3.03126 Btu-in/ft²,hr,°F

R-Value based on thermocouple separation:

R-value = 0.03048 m²°C/W
= 0.17311 ft²,hr,°F/Btu

Test Data on Thermal Conductivity Measurement (ASTM C177 Test Method)

Report No. CBS-090-Khan.012

Date: March 14, 1988

Customer: Mr. Khan
Centre for Building Studies
Concordia University
Montreal Canada

Material: Gypsum Concrete Tiles incorporated with PCM
and surface coated with metal-filled polyester resin

Sample id: Specimen # 19 bottom and specimen # 20 top

Original sample thickness .016125 m
Thickness of top specimen .0133 m
Thickness of bottom specimen .01295 m
Weight of sample 1.074 kg

Room conditions: Temperature: 22°C
Humidity: 42% R.H.
Coolant temperature: 20°C

Elapsed time 0 min.

TC 1	18.67275	CH19 Volts	2.17500
TC 2	18.74400	CH20 Amps	0.30400
TC 3	19.97576	K-Factor =	0.46088
TC 4	19.97576	R-Value =	0.02848
TC 5	20.07612	DT top =	0.98186
TC 6	20.10549	DT bot =	1.26739
TC 7	19.14668	Mean temp. =	19.47097
TC 8	19.07121		

Elapsed time 15 min.

TC 1	18.44659	CH19 Volts	2.17500
TC 2	18.49699	CH20 Amps	0.30400
TC 3	19.88024	K-Factor =	0.38422
TC 4	19.87596	R-Value =	0.03416
TC 5	19.95125	DT top =	1.29480
TC 6	19.95553	DT bot =	1.40631
TC 7	18.69423	Mean temp. =	19.24047
TC 8	18.62296		

Elapsed time 30 min.

TC 1	18.43487
TC 2	18.46008
TC 3	19.71793
TC 4	19.74304
TC 5	19.79326
TC 6	19.74304
TC 7	18.58606
TC 8	18.51048

CH19 Volts	2.17500
CH20 Amps	0.30400
K-Factor =	0.41473
R-Value =	0.03165
DT top =	1.21988
DT bot =	1.28301
Mean temp. =	19.12359

Elapsed time 45 min.

TC 1	18.33716
TC 2	18.38758
TC 3	19.62057
TC 4	19.62057
TC 5	19.67080
TC 6	19.67080
TC 7	18.51359
TC 8	18.38758

CH19 Volts	2.17500
CH20 Amps	0.30410
K-Factor =	0.41902
R-Value =	0.03132
DT top =	1.22022
DT bot =	1.25819
Mean temp. =	19.02608

Elapsed time 60 min.

TC 1	18.29045
TC 2	18.34087
TC 3	19.52377
TC 4	19.52377
TC 5	19.54890
TC 6	19.54890
TC 7	18.44170
TC 8	18.34087

CH19 Volts	2.17600
CH20 Amps	0.30410
K-Factor =	0.43915
R-Value =	0.02989
DT top =	1.15761
DT bot =	1.20811
Mean temp. =	18.94490

Elapsed time 75 min.

TC 1	18.16655
TC 2	18.21699
TC 3	19.47142
TC 4	19.47570
TC 5	19.52167
TC 6	19.55108
TC 7	18.41439
TC 8	18.21699

CH19 Volts	2.17600
CH20 Amps	0.30410
K-Factor =	0.44471
R-Value =	0.02951
DT top =	1.15556
DT bot =	1.18093
Mean temp. =	18.90868

Elapsed time 90 min.

TC 1 18.25351
TC 2 18.27433
TC 3 19.43670
TC 4 19.43670
TC 5 19.51209
TC 6 19.48268
TC 7 18.40048
TC 8 18.32916

CH19 Volts 2.17700
CH20 Amps 0.30410
K-Factor = 0.45089
R-Value = 0.02911
DT top = 1.13257
DT bot = 1.17273
Mean temp. = 18.89072

Elapsed time 105 min.

TC 1 18.19760
TC 2 18.24803
TC 3 19.38097
TC 4 19.40610
TC 5 19.43124
TC 6 19.43124
TC 7 18.37409
TC 8 18.24803

CH19 Volts 2.17500
CH20 Amps 0.30410
K-Factor = 0.45328
R-Value = 0.02896
DT top = 1.12018
DT bot = 1.17072
Mean temp. = 18.83966

Elapsed time 120 min.

TC 1 18.18899
TC 2 18.21421
TC 3 19.37239
TC 4 19.34725
TC 5 19.42266
TC 6 19.39753
TC 7 18.34028
TC 8 18.21421

CH19 Volts 2.17500
CH20 Amps 0.30410
K-Factor = 0.45331
R-Value = 0.02895
DT top = 1.13285
DT bot = 1.15822
Mean temp. = 18.81219

Elapsed time 135 min.

TC 1 18.19388
TC 2 18.21480
TC 3 19.32270
TC 4 19.34784
TC 5 19.39812
TC 6 19.37298
TC 7 18.29045
TC 8 18.26524

CH19 Volts 2.17500
CH20 Amps 0.30400
K-Factor = 0.46378
R-Value = 0.02830
DT top = 1.10771
DT bot = 1.13093
Mean temp. = 18.80075

Elapsed time 150 min.

TC 1 18.16436
TC 2 18.23572
TC 3 19.31842
TC 4 19.37298
TC 5 19.39383
TC 6 19.37869
TC 7 18.36178
TC 8 18.23572

CH19 Volts 2.17500
CH20 Amps 0.30400
K-Factor = 0.46585
R-Value = 0.02817
DT top = 1.08251
DT bot = 1.14566
Mean temp. = 18.80644

Elapsed time 165 min.

TC 1 18.12564
TC 2 18.17609
TC 3 19.28411
TC 4 19.30925
TC 5 19.35953
TC 6 19.35953
TC 7 18.27696
TC 8 18.20131

CH19 Volts 2.17300
CH20 Amps 0.30390
K-Factor = 0.45756
R-Value = 0.02868
DT top = 1.12040
DT bot = 1.14582
Mean temp. = 18.76155

Elapsed time 180 min.

TC 1 18.15947
TC 2 18.18469
TC 3 19.29269
TC 4 19.29269
TC 5 19.36911
TC 6 19.31783
TC 7 18.28556
TC 8 18.20991

CH19 Volts 2.17500
CH20 Amps 0.30400
K-Factor = 0.46855
R-Value = 0.02801
DT top = 1.09523
DT bot = 1.12061
Mean temp. = 18.76387

Elapsed time 195 min.

TC 1 18.18098
TC 2 18.20620
TC 3 19.28899
TC 4 19.31413
TC 5 19.38954
TC 6 19.33927
TC 7 18.30706
TC 8 18.23142

CH19 Volts 2.17600
CH20 Amps 0.30400
K-Factor = 0.47150
R-Value = 0.02784
DT top = 1.09517
DT bot = 1.10797
Mean temp. = 18.78220

Elapsed time 210 min.

TC 1 18.13366
TC 2 18.15888
TC 3 19.29210
TC 4 19.31724
TC 5 19.36752
TC 6 19.34238
TC 7 18.31019
TC 8 18.18410

CH19 Volts 2.17600
CH20 Amps 0.30420
K-Factor = 0.45858
R-Value = 0.02862
DT top = 1.10781
DT bot = 1.15840
Mean temp. = 18.76326

Elapsed time 225 min.

TC 1 18.15028
TC 2 18.17550
TC 3 19.28352
TC 4 19.28352
TC 5 19.35895
TC 6 19.30867
TC 7 18.25116
TC 8 18.20072

CH19 Volts 2.17400
CH20 Amps 0.30410
K-Factor = 0.46586
R-Value = 0.02817
DT top = 1.10787
DT bot = 1.12064
Mean temp. = 18.75154

Elapsed time 240 min.

TC 1 18.15517
TC 2 18.18039
TC 3 19.26325
TC 4 19.28840
TC 5 19.33868
TC 6 19.31354
TC 7 18.28126
TC 8 18.18039

CH19 Volts 2.17500
CH20 Amps 0.30410
K-Factor = 0.47140
R-Value = 0.02784
DT top = 1.09529
DT bot = 1.10805
Mean temp. = 18.75013

Elapsed time 255 min.

TC 1 18.14657
TC 2 18.16748
TC 3 19.30068
TC 4 19.30068
TC 5 19.37610
TC 6 19.35096
TC 7 18.31879
TC 8 18.19271

CH19 Volts 2.17600
CH20 Amps 0.30410
K-Factor = 0.46147
R-Value = 0.02844
DT top = 1.10778
DT bot = 1.14365
Mean temp. = 18.78924

Elapsed time 270 min.

TC 1 18.12877
TC 2 18.17922
TC 3 19.26209
TC 4 19.26209
TC 5 19.33751
TC 6 19.33751
TC 7 18.28009
TC 8 18.15399

CH19 Volts 2.17600
CH20 Amps 0.30400
K-Factor = 0.46619
R-Value = 0.02815
DT top = 1.12047
DT bot = 1.10809
Mean temp. = 18.74266

Elapsed time 285 min.

TC 1 18.10785
TC 2 18.18352
TC 3 19.24123
TC 4 19.26637
TC 5 19.31666
TC 6 19.29152
TC 7 18.25917
TC 8 18.13307

CH19 Volts 2.17500
CH20 Amps 0.30400
K-Factor = 0.46857
R-Value = 0.02801
DT top = 1.10797
DT bot = 1.10812
Mean temp. = 18.72492

Elapsed time 300 min.

TC 1 18.14657
TC 2 18.17179
TC 3 19.27900
TC 4 19.25468
TC 5 19.33011
TC 6 19.30496
TC 7 18.27268
TC 8 18.17179

CH19 Volts 2.17500
CH20 Amps 0.30390
K-Factor = 0.47107
R-Value = 0.02786
DT top = 1.09531
DT bot = 1.10807
Mean temp. = 18.74155

Elapsed time 315 min.

TC 1 18.11645
TC 2 18.14167
TC 3 19.27495
TC 4 19.27495
TC 5 19.32523
TC 6 19.32523
TC 7 18.29299
TC 8 18.16690

CH19 Volts 2.17600
CH20 Amps 0.30410
K-Factor = 0.46355
R-Value = 0.02831
DT top = 1.09529
DT bot = 1.14589
Mean temp. = 18.73980

Elapsed time 330 min.

TC 1	18.12877	CH19 Volts	2.17600
TC 2	18.14969	CH20 Amps	0.30390
TC 3	19.23265	K-Factor =	0.46692
TC 4	19.25780	R-Value =	0.02811
TC 5	19.33322	DT top =	1.11837
TC 6	19.30808	DT bot =	1.10599
TC 7	18.25487	Mean temp. =	18.72685
TC 8	18.14969		

Sample has reached steady state in automatic termination mode.

Average values at end of test:

K-factor = $0.46726 \text{ W/m}^2\text{C}$
= $3.24034 \text{ Btu-in/ft}^2\text{,hr,}^\circ\text{F}$

R-Value based on thermocouple separation:

R-value = $0.02809 \text{ m}^2\text{C/W}$
= $0.15951 \text{ ft}^2\text{,hr,}^\circ\text{F/Btu}$

Test Data on Thermal Conductivity Measurement (ASTM C177 Test Method)

Report No. CBS-090-Khan.015

Date: July 12, 1988

Customer: Mr. Khan
Centre for Building Studies
Concordia University

Material: Gypsum Concrete Tiles
both surfaces coated with lignin material @ 10%

Sample id: Specimen # 1 bottom and specimen # 2 top
Nos. 1+2 set

Original sample thickness .0169 m
Thickness of top specimen .014 m
Thickness of bottom specimen .0138 m
Weight of sample 1.11 kg

Room conditions: Temperature: 22°C
Humidity: 54% R.H.
Coolant temperature: 22°C

Elapsed time 0 min.

TC 1	18.62172	CH19 Volts	2.11300
TC 2	18.59225	CH20 Amps	0.29570
TC 3	19.04542	K-Factor =	1.23834
TC 4	19.04542	R-Value =	0.01122
TC 5	19.15031	DT top =	0.40057
TC 6	19.09574	DT bot =	0.43844
TC 7	18.74765	Mean temp. =	18.87447
TC 8	18.69728		

Elapsed time 15 min.

TC 1	19.15458	CH19 Volts	2.11500
TC 2	19.17973	CH20 Amps	0.29570
TC 3	19.35574	K-Factor =	2.66889
TC 4	19.38088	R-Value =	0.00521
TC 5	19.45628	DT top =	0.18854
TC 6	19.43115	DT bot =	0.20115
TC 7	19.28032	Mean temp. =	19.30859
TC 8	19.23003		

Elapsed time 30 min.

TC 1 19.46907
TC 2 19.44394
TC 3 19.82072
TC 4 19.82072
TC 5 19.87093
TC 6 19.84583
TC 7 19.59470
TC 8 19.51933

CH19 Volts 2.11600
CH20 Amps 0.29570
K-Factor = 1.56267
R-Value = 0.00890
DT top = 0.30136
DT bot = 0.36422
Mean temp. = 19.67315

Elapsed time 45 min.

TC 1 19.78709
TC 2 19.78709
TC 3 20.33904
TC 4 20.33904
TC 5 20.38918
TC 6 20.33904
TC 7 19.91261
TC 8 19.83731

CH19 Volts 2.11600
CH20 Amps 0.29570
K-Factor = 0.99927
R-Value = 0.01391
DT top = 0.48915
DT bot = 0.55195
Mean temp. = 20.09130

Elapsed time 60 min.

TC 1 20.07169
TC 2 20.09678
TC 3 20.77346
TC 4 20.79850
TC 5 20.84857
TC 6 20.82353
TC 7 20.19711
TC 8 20.12186

CH19 Volts 2.11300
CH20 Amps 0.29570
K-Factor = 0.01844
R-Value = 0.67657
DT top = 0.70175
DT bot = 0.70175
Mean temp. = 20.46644

Elapsed time 75 min.

TC 1 20.20136
TC 2 20.25151
TC 3 21.10306
TC 4 21.10306
TC 5 21.15309
TC 6 21.12808
TC 7 20.40193
TC 8 20.30166

CH19 Volts 2.11600
CH20 Amps 0.29570
K-Factor = 0.62471
R-Value = 0.02225
DT top = 0.78878
DT bot = 0.87662
Mean temp. = 20.70547

Elapsed time 90 min.

TC 1	20.34330	CH19 Volts	2.11200
TC 2	20.36411	CH20 Amps	0.29570
TC 3	21.31965	K-Factor =	0.55559
TC 4	21.34465	R-Value =	0.02502
TC 5	21.36541	DT top =	0.89067
TC 6	21.34465	DT bot =	0.97845
TC 7	20.53954	Mean temp. =	20.87631
TC 8	20.38918		

Elapsed time 105 min.

TC 1	20.45206	CH19 Volts	2.11600
TC 2	20.47712	CH20 Amps	0.29570
TC 3	21.47810	K-Factor =	0.53308
TC 4	21.50309	R-Value =	0.02608
TC 5	21.52808	DT top =	0.92569
TC 6	21.52808	DT bot =	1.02600
TC 7	20.65249	Mean temp. =	21.02141
TC 8	20.55229		

Elapsed time 120 min.

TC 1	20.49368	CH19 Volts	2.11700
TC 2	20.51874	CH20 Amps	0.29570
TC 3	21.54882	K-Factor =	0.50693
TC 4	21.59455	R-Value =	0.02742
TC 5	21.64451	DT top =	0.98803
TC 6	21.61953	DT bot =	1.06548
TC 7	20.69409	Mean temp. =	21.08848
TC 8	20.59390		

Elapsed time 135 min.

TC 1	20.56459	CH19 Volts	2.11600
TC 2	20.58965	CH20 Amps	0.29570
TC 3	21.64027	K-Factor =	0.50474
TC 4	21.66525	R-Value =	0.02754
TC 5	21.71520	DT top =	0.98575
TC 6	21.66525	DT bot =	1.07564
TC 7	20.76921	Mean temp. =	21.15615
TC 8	20.63975		

Elapsed time 150 min.

TC 1 20.57309
TC 2 20.60240
TC 3 21.67796
TC 4 21.72791
TC 5 21.77362
TC 6 21.72367
TC 7 20.77346
TC 8 20.67754

CH19 Volts 2.11500
CH20 Amps 0.29570
K-Factor = 0.48635
R-Value = 0.02858
DT top = 1.02314
DT bot = 1.11519
Mean temp. = 21.19121

Elapsed time 165 min.

TC 1 20.58540
TC 2 20.58540
TC 3 21.73594
TC 4 21.74017
TC 5 21.79011
TC 6 21.76091
TC 7 20.78576
TC 8 20.68559

CH19 Volts 2.11600
CH20 Amps 0.29570
K-Factor = 0.47453
R-Value = 0.02929
DT top = 1.03984
DT bot = 1.15266
Mean temp. = 21.20866

Elapsed time 180 min.

TC 1 20.56459
TC 2 20.63975
TC 3 21.74017
TC 4 21.76514
TC 5 21.81508
TC 6 21.79011
TC 7 20.81504
TC 8 20.68984

CH19 Volts 2.11500
CH20 Amps 0.29580
K-Factor = 0.47273
R-Value = 0.02940
DT top = 1.05016
DT bot = 1.15049
Mean temp. = 21.22747

Elapsed time 195 min.

TC 1 20.56035
TC 2 20.61045
TC 3 21.73594
TC 4 21.76091
TC 5 21.81085
TC 6 21.78588
TC 7 20.78576
TC 8 20.68559

CH19 Volts 2.11400
CH20 Amps 0.29570
K-Factor = 0.46702
R-Value = 0.02976
DT top = 1.06269
DT bot = 1.16303
Mean temp. = 21.21696

Elapsed time 210 min.

TC 1 20.55185
TC 2 20.60195
TC 3 21.75244
TC 4 21.77741
TC 5 21.82734
TC 6 21.77741
TC 7 20.80230
TC 8 20.67710

CH19 Volts 2.11600
CH20 Amps 0.29570
K-Factor = 0.46224
R-Value = 0.03007
DT top = 1.06268
DT bot = 1.18802
Mean temp. = 21.22098

Elapsed time 225 min.

TC 1 20.58540
TC 2 20.58540
TC 3 21.76091
TC 4 21.78588
TC 5 21.83581
TC 6 21.81085
TC 7 20.83583
TC 8 20.71063

CH19 Volts 2.11600
CH20 Amps 0.29570
K-Factor = 0.46483
R-Value = 0.02990
DT top = 1.05009
DT bot = 1.18799
Mean temp. = 21.23884

Elapsed time 240 min.

TC 1 20.58115
TC 2 20.63125
TC 3 21.75244
TC 4 21.75668
TC 5 21.80661
TC 6 21.78164
TC 7 20.80655
TC 8 20.68135

CH19 Volts 2.11400
CH20 Amps 0.29560
K-Factor = 0.47264
R-Value = 0.02941
DT top = 1.05018
DT bot = 1.14835
Mean temp. = 21.22471

Elapsed time 255 min.

TC 1 20.57690
TC 2 20.60195
TC 3 21.75244
TC 4 21.77741
TC 5 21.85231
TC 6 21.82734
TC 7 20.82734
TC 8 20.70214

CH19 Volts 2.11600
CH20 Amps 0.29550
K-Factor = 0.46199
R-Value = 0.03009
DT top = 1.07508
DT bot = 1.17550
Mean temp. = 21.23973

Elapsed time 270 min.

TC 1 20.55185
TC 2 20.57690
TC 3 21.75244
TC 4 21.75244
TC 5 21.82734
TC 6 21.77741
TC 7 20.80230
TC 8 20.65205

CH19 Volts 2.11500
CH20 Amps 0.29570
K-Factor = 0.45948
R-Value = 0.03025
DT top = 1.07520
DT bot = 1.18806
Mean temp. = 21.21159

Elapsed time 285 min.

TC 1 20.56840
TC 2 20.58921
TC 3 21.74397
TC 4 21.76894
TC 5 21.81888
TC 6 21.76894
TC 7 20.76877
TC 8 20.66860

CH19 Volts 2.11600
CH20 Amps 0.29570
K-Factor = 0.46183
R-Value = 0.03010
DT top = 1.07522
DT bot = 1.17765
Mean temp. = 21.21196

Elapsed time 300 min.

TC 1 20.54335
TC 2 20.59345
TC 3 21.76894
TC 4 21.79391
TC 5 21.81888
TC 6 21.79391
TC 7 20.81885
TC 8 20.66860

CH19 Volts 2.11600
CH20 Amps 0.29570
K-Factor = 0.45713
R-Value = 0.03041
DT top = 1.06267
DT bot = 1.21302
Mean temp. = 21.22499

Elapsed time 315 min.

TC 1 20.57690
TC 2 20.57690
TC 3 21.75244
TC 4 21.77741
TC 5 21.82734
TC 6 21.80238
TC 7 20.77726
TC 8 20.70214

CH19 Volts 2.11400
CH20 Amps 0.29560
K-Factor = 0.45912
R-Value = 0.03028
DT top = 1.07516
DT bot = 1.18802
Mean temp. = 21.22410

Sample has reached steady state in automatic termination mode.

Average values at end of test:

K-factor = 0.45991 W/m²°C
= 3.18939 Btu-in/ft²,hr,°F

R-Value based on thermocouple separation:

R-value = 0.03022 m²°C/W
= 0.17162 ft²,hr,°F/Btu

Test Data on Thermal Conductivity Measurement (ASTM C177 Test Method)

Report No. CBS-090-Khan.016

Date: July 12, 1988

Customer: Mr. Khan
Centre for Building Studies
Concordia University

Material: Gypsum Concrete Tiles
both surfaces coated with lignin material @ 20%

Sample id: Specimen # 3 bottom and specimen # 4 top
Nos. 3+4 set

Original sample thickness .0169 m
Thickness of top specimen .0139 m
Thickness of bottom specimen .0139 m
Weight of sample 1.118 kg

Room conditions: Temperature: 22°C
Humidity: 54% R.H.
Coolant temperature: 22°C

Elapsed time 0 min.

TC 1	19.36809	CH19 Volts	2.11600
TC 2	19.36809	CH20 Amps	0.29560
TC 3	19.61938	K-Factor =	2.74538
TC 4	19.74495	R-Value =	0.00506
TC 5	19.64449	DT top =	0.06492
TC 6	19.71984	DT bot =	0.31407
TC 7	19.64449	Mean temp. =	19.58742
TC 8	19.59000		

Elapsed time 10 min.

TC 1	19.35148	CH19 Volts	2.11600
TC 2	19.37662	CH20 Amps	0.29560
TC 3	19.42689	K-Factor =	6.28698
TC 4	19.42689	R-Value =	0.00221
TC 5	19.50654	DT top =	0.10266
TC 6	19.47715	DT bot =	0.06284
TC 7	19.40175	Mean temp. =	19.41799
TC 8	19.37662		

Elapsed time 20 min.

TC 1	19.46863
TC 2	19.49376
TC 3	19.59425
TC 4	19.62364
TC 5	19.69899
TC 6	19.66961
TC 7	19.54401
TC 8	19.46863

CH19 Volts	2.11600
CH20 Amps	0.29560
K-Factor =	3.40321
R-Value =	0.00408
DT top =	0.17798
DT bot =	0.12775
Mean temp. =	19.57019

Elapsed time 30 min.

TC 1	19.62790
TC 2	19.62790
TC 3	19.87900
TC 4	19.87900
TC 5	19.95430
TC 6	19.90410
TC 7	19.67813
TC 8	19.60278

CH19 Volts	2.11600
CH20 Amps	0.29560
K-Factor =	1.92737
R-Value =	0.00721
DT top =	0.28874
DT bot =	0.25110
Mean temp. =	19.76914

Elapsed time 40 min.

TC 1	19.74921
TC 2	19.79943
TC 3	20.17584
TC 4	20.20092
TC 5	20.25107
TC 6	20.22599
TC 7	19.87474
TC 8	19.77432

CH19 Volts	2.11600
CH20 Amps	0.29570
K-Factor =	1.25697
R-Value =	0.01106
DT top =	0.41400
DT bot =	0.41405
Mean temp. =	20.00644

Elapsed time 50 min.

TC 1	19.89984
TC 2	19.92069
TC 3	20.49748
TC 4	20.50173
TC 5	20.55185
TC 6	20.52679
TC 7	20.00023
TC 8	19.92494

CH19 Volts	2.11500
CH20 Amps	0.29560
K-Factor =	0.89187
R-Value =	0.01559
DT top =	0.57673
DT bot =	0.58935
Mean temp. =	20.22794

Elapsed time 60 min.

TC 1 20.07975
TC 2 20.10484
TC 3 20.80655
TC 4 20.83159
TC 5 20.83159
TC 6 20.85662
TC 7 20.18009
TC 8 20.10484

CH19 Volts 2.11700
CH20 Amps 0.29570
K-Factor = 0.72902
R-Value = 0.01907
DT top = 0.70164
DT bot = 0.72677
Mean temp. = 20.47448

Elapsed time 70 min.

TC 1 20.14225
TC 2 20.16733
TC 3 21.04410
TC 4 21.04410
TC 5 21.09413
TC 6 21.09413
TC 7 20.29271
TC 8 20.17158

CH19 Volts 2.11400
CH20 Amps 0.29560
K-Factor = 0.59356
R-Value = 0.02342
DT top = 0.86198
DT bot = 0.88931
Mean temp. = 20.63129

Elapsed time 80 min.

TC 1 20.25532
TC 2 20.28040
TC 3 21.23192
TC 4 21.25268
TC 5 21.25692
TC 6 21.25692
TC 7 20.38068
TC 8 20.28040

CH19 Volts 2.11500
CH20 Amps 0.29560
K-Factor = 0.54713
R-Value = 0.02541
DT top = 0.92639
DT bot = 0.97444
Mean temp. = 20.77441

Elapsed time 90 min.

TC 1 20.29271
TC 2 20.31778
TC 3 21.39420
TC 4 21.39420
TC 5 21.41920
TC 6 21.41920
TC 7 20.49324
TC 8 20.39299

CH19 Volts 2.11500
CH20 Amps 0.29550
K-Factor = 0.50345
R-Value = 0.02761
DT top = 0.97609
DT bot = 1.08895
Mean temp. = 20.89044

Elapsed time 100 min.

TC 1 20.34711
TC 2 20.39299
TC 3 21.49417
TC 4 21.52340
TC 5 21.54414
TC 6 21.54414
TC 7 20.54335
TC 8 20.44312

CH19 Volts 2.11400
CH20 Amps 0.29560
K-Factor = 0.47474
R-Value = 0.02928
DT top = 0.05091
DT bot = 0.13874
Mean temp. = 20.97905

Elapsed time 110 min.

TC 1 20.41805
TC 2 20.44312
TC 3 21.59411
TC 4 21.64407
TC 5 21.64407
TC 6 21.67328
TC 7 20.61851
TC 8 20.51829

CH19 Volts 2.11600
CH20 Amps 0.29580
K-Factor = 0.45691
R-Value = 0.03042
DT top = 0.09028
DT bot = 1.18851
Mean temp. = 21.06919

Elapsed time 120 min.

TC 1 20.46393
TC 2 20.46393
TC 3 21.66481
TC 4 21.68979
TC 5 21.71053
TC 6 21.73973
TC 7 20.61426
TC 8 20.53910

CH19 Volts 2.11600
CH20 Amps 0.29570
K-Factor = 0.44069
R-Value = 0.03154
DT top = 1.14845
DT bot = 1.21337
Mean temp. = 21.11076

Elapsed time 130 min.

TC 1 20.46818
TC 2 20.49324
TC 3 21.69402
TC 4 21.74397
TC 5 21.76894
TC 6 21.76894
TC 7 20.66860
TC 8 20.54335

CH19 Volts 2.11500
CH20 Amps 0.29560
K-Factor = 0.43311
R-Value = 0.03209
DT top = 1.16296
DT bot = 1.23829
Mean temp. = 21.14366

Elapsed time 140 min.

TC 1 20.48049
TC 2 20.53060
TC 3 21.78121
TC 4 21.80617
TC 5 21.83114
TC 6 21.83114
TC 7 20.70595
TC 8 20.58071

CH19 Volts 2.11600
CH20 Amps 0.29560
K-Factor = 0.42024
R-Value = 0.03308
DT top = 1.18781
DT bot = 1.28815
Mean temp. = 21.19343

Elapsed time 150 min.

TC 1 20.48899
TC 2 20.51404
TC 3 21.81464
TC 4 21.83961
TC 5 21.83537
TC 6 21.86457
TC 7 20.68940
TC 8 20.61426

CH19 Volts 2.11500
CH20 Amps 0.29570
K-Factor = 0.41222
R-Value = 0.03372
DT top = 1.19814
DT bot = 1.32561
Mean temp. = 21.20761

Elapsed time 160 min.

TC 1 20.50555
TC 2 20.55566
TC 3 21.85610
TC 4 21.88106
TC 5 21.88106
TC 6 21.88106
TC 7 20.75603
TC 8 20.60576

CH19 Volts 2.11600
CH20 Amps 0.29570
K-Factor = 0.41008
R-Value = 0.03390
DT top = 1.20017
DT bot = 1.33798
Mean temp. = 21.24029

Elapsed time 170 min.

TC 1 20.52635
TC 2 20.55141
TC 3 21.85187
TC 4 21.87683
TC 5 21.87683
TC 6 21.90179
TC 7 20.72674
TC 8 20.62656

CH19 Volts 2.11600
CH20 Amps 0.29560
K-Factor = 0.40994
R-Value = 0.03391
DT top = 1.21266
DT bot = 1.32547
Mean temp. = 21.24230

Elapsed time 180 min.

TC 1 20.50555
TC 2 20.55566
TC 3 21.88106
TC 4 21.90603
TC 5 21.90603
TC 6 21.93099
TC 7 20.78107
TC 8 20.73081

CH19 Volts 2.11500
CH20 Amps 0.29570
K-Factor = 0.40394
R-Value = 0.03441
DT top = 1.21256
DT bot = 1.36294
Mean temp. = 21.26215

Elapsed time 190 min.

TC 1 20.51785
TC 2 20.54291
TC 3 21.89333
TC 4 21.91828
TC 5 21.91328
TC 6 21.94324
TC 7 20.74329
TC 8 20.64311

CH19 Volts 2.11500
CH20 Amps 0.29540
K-Factor = 0.39774
R-Value = 0.03495
DT top = 1.23756
DT bot = 1.37542
Mean temp. = 21.26504

Elapsed time 200 min.

TC 1 20.53060
TC 2 20.55141
TC 3 21.90179
TC 4 21.95171
TC 5 21.95594
TC 6 21.95171
TC 7 20.75178
TC 8 20.68091

CH19 Volts 2.11600
CH20 Amps 0.29570
K-Factor = 0.39678
R-Value = 0.03503
DT top = 1.23748
DT bot = 1.38574
Mean temp. = 21.28448

Elapsed time 210 min.

TC 1 20.51785
TC 2 20.56796
TC 3 21.91828
TC 4 21.94324
TC 5 21.96320
TC 6 21.96820
TC 7 20.76833
TC 8 20.66816

CH19 Volts 2.11600
CH20 Amps 0.29560
K-Factor = 0.39445
R-Value = 0.03524
DT top = 1.14995
DT bot = 1.38786
Mean temp. = 21.29003

Elapsed time 220 min.

TC 1 20.52210
TC 2 20.54716
TC 3 21.92252
TC 4 21.92252
TC 5 21.92252
TC 6 21.94748
TC 7 20.74754
TC 8 20.67241

CH19 Volts 2.11600
CH20 Amps 0.29570
K-Factor = 0.39834
R-Value = 0.03489
DT top = 1.22503
DT bot = 1.38789
Mean temp. = 21.27553

Elapsed time 230 min.

TC 1 20.54716
TC 2 20.59301
TC 3 21.91828
TC 4 21.96320
TC 5 21.97243
TC 6 21.99315
TC 7 20.79762
TC 8 20.66816

CH19 Volts 2.11500
CH20 Amps 0.29530
K-Factor = 0.39608
R-Value = 0.03509
DT top = 1.24990
DT bot = 1.37316
Mean temp. = 21.30725

Sample has reached steady state in automatic termination mode.

Average values at end of test:

K-factor = 0.39663 W/m°C
= 2.75089 Btu-in/ft²,hr,°F

R-Value based on thermocouple separation:

R-value = 0.03504 m²°C/W
= 0.19898 ft²,hr,°F/Btu

Test Data on Thermal Conductivity Measurement (ASTM C177 Test Method)

Report No. CBS-090-Khan.017

Date: July 12, 1988

Customer: Mr. Khan
Centre for Building Studies
Concordia University

Material: Gypsum Concrete Tiles,
both surfaces coated with lignin material @ 30%

Sample id: Specimen # 5 bottom and specimen # 6 top
Nos. 5+6 set

Original sample thickness .01675 m
Thickness of top specimen .0137 m
Thickness of bottom specimen .0138 m
Weight of sample 1.12 kg

Room conditions: Temperature: 22°C
Humidity: 54% R.H.
Coolant temperature: 22°C

Elapsed time 0 min.

TC 1 19.26282
TC 2 19.26282
TC 3 20.34241
TC 4 20.26720
TC 5 20.11672
TC 6 20.04146
TC 7 % 1.033087E+23
TC 8 19.86153

CH19 Volts 2.11600
CH20 Amps 0.29570
K-Factor = -0.00000
R-Value = %6.92342E+25
DT top = %5.165437E+27
DT bot = 1.04198
Mean temp. = %1.2913593+27

TEST ABORTED

Average values at end of test:

K-factor = 0.39563 W/m°C
= 2.75089 Btu-in/ft²,hr,°F

R-value based on thermocouple separation:

R-value = 0.03466 m²·C/W
= 0.19683 ft²,hr·F/Btu

R-value based on original sample thickness:

R-value = 0.04223 m²·C/W
= 0.23978 ft²,hr,°F/Btu

Test Data on Thermal Conductivity Measurement (ASTM C177 Test Method)

Report No. CBS-090-Khan.018

Date: July 13, 1988

Customer: Mr. Khan
Centre for Building Studies
Concordia University

Material: Gypsum Concrete Tiles
both surfaces coated with lignion fill polyester resin @ 40%

Sample id: Specimen # 7 bottom and specimen # 8 top
Nos. 7+8 set

Original sample thickness .017 m
Thickness of top specimen .0139 m
Thickness of bottom specimen .0141 m
Weight of sample 1.125 kg

Room conditions: Temperature: 22°C
Humidity: 54% R.H.
Coolant temperature: 22°C

Elapsed time 0 min.

TC 1 19.41704
TC 2 19.39191
TC 3 20.09501
TC 4 20.09501
TC 5 20.27047
TC 6 20.22042
TC 7 19.84406
TC 8 19.81896

CH19 Volts 2.11500
CH20 Amps 0.29570
K-Factor = 0.95032
R-Value = 0.01473
DT top = 0.41399
DT bot = 0.69054
Mean temp. = 19.89412

Elapsed time 15 min.

TC 1 19.45070
TC 2 19.45070
TC 3 19.85257
TC 4 19.87768
TC 5 19.90278
TC 6 19.87768
TC 7 19.55121
TC 8 19.45070

CH19 Volts 2.11600
CH20 Amps 0.29560
K-Factor = 1.39415
R-Value = 0.01073
DT top = 0.38927
DT bot = 0.41443
Mean temp. = 19.67675

Elapsed time 20 min.

TC 1 19.68915
TC 2 19.68915
TC 3 20.09076
TC 4 20.09076
TC 5 20.09076
TC 6 20.06567
TC 7 19.61379
TC 8 19.53843

CH19 Volts 2.11600
CH20 Amps 0.29570
K-Factor = 1.14904
R-Value = 0.01208
DT top = 0.50210
DT bot = 0.40161
Mean temp. = 19.85856

Elapsed time 30 min.

TC 1 19.86916
TC 2 19.89426
TC 3 20.39592
TC 4 20.39592
TC 5 20.42098
TC 6 20.39592
TC 7 19.81896
TC 8 19.69341

CH19 Volts 2.11600
CH20 Amps 0.29560
K-Factor = 0.89760
R-Value = 0.01560
DT top = 0.65227
DT bot = 0.51421
Mean temp. = 20.11057

Elapsed time 40 min.

TC 1 20.00698
TC 2 20.03207
TC 3 20.70883
TC 4 20.68384
TC 5 20.73817
TC 6 20.73817
TC 7 19.98189
TC 8 19.88575

CH19 Volts 2.11600
CH20 Amps 0.29580
K-Factor = 0.70753
R-Value = 0.01979
DT top = 0.80435
DT bot = 0.67683
Mean temp. = 20.34697

Elapsed time 50 min.

TC 1 20.08225
TC 2 20.13242
TC 3 20.93420
TC 4 20.93420
TC 5 21.00927
TC 6 20.98849
TC 7 20.10734
TC 8 20.00698

CH19 Volts 2.11600
CH20 Amps 0.29570
K-Factor = 0.59244
R-Value = 0.02363
DT top = 0.94172
DT bot = 0.82686
Mean temp. = 20.52440

Elapsed time 60 min.

TC 1 20.18259
TC 2 20.30371
TC 3 21.15938
TC 4 21.15514
TC 5 21.23440
TC 6 21.23440
TC 7 20.23274
TC 8 20.13242

CH19 Volts 2.11600
CH20 Amps 0.29570
K-Factor = 0.52357
R-Value = 0.02674
DT top = 1.05182
DT bot = 0.94959
Mean temp. = 20.69548

Elapsed time 70 min.

TC 1 20.27864
TC 2 20.30371
TC 3 21.30518
TC 4 21.30518
TC 5 21.40517
TC 6 21.38017
TC 7 20.30371
TC 8 20.20341

CH19 Volts 2.11400
CH20 Amps 0.29550
K-Factor = 0.48587
R-Value = 0.02881
DT top = 0.13911
DT bot = 1.01400
Mean temp. = 21.81065

Elapsed time 80 min.

TC 1 20.36235
TC 2 20.38742
TC 3 21.48862
TC 4 21.48862
TC 5 21.58856
TC 6 21.58856
TC 7 20.43330
TC 8 20.31221

CH19 Volts 2.11500
CH20 Amps 0.29580
K-Factor = 0.44979
R-Value = 0.03113
DT top = 1.21580
DT bot = 1.11373
Mean temp. = 21.95621

Elapsed time 90 min.

TC 1 20.37892
TC 2 20.40398
TC 3 21.55511
TC 4 21.58009
TC 5 21.65503
TC 6 21.65003
TC 7 20.45411
TC 8 20.35385

CH19 Volts 2.11600
CH20 Amps 0.29580
K-Factor = 0.43194
R-Value = 0.03241
DT top = 1.25105
DT bot = 1.17614
Mean temp. = 21.00452

Elapsed time 100 min.

TC 1 20.43330
TC 2 20.45836
TC 3 21.65926
TC 4 21.65926
TC 5 21.75916
TC 6 21.75916
TC 7 20.48342
TC 8 20.40823

CH19 Volts 2.11600
CH20 Amps 0.29560
K-Factor = 0.41461
R-Value = 0.03377
DT top = 1.31333
DT bot = 1.21344
Mean temp. = 21.07752

Elapsed time 110 min.

TC 1 20.45411
TC 2 20.47917
TC 3 21.72995
TC 4 21.75493
TC 5 21.82983
TC 6 21.82983
TC 7 20.55434
TC 8 20.42480

CH19 Volts 2.11400
CH20 Amps 0.29570
K-Factor = 0.40026
R-Value = 0.03498
DT top = 1.34026
DT bot = 1.27580
Mean temp. = 21.13212

Elapsed time 120 min.

TC 1 20.47917
TC 2 20.47917
TC 3 21.78413
TC 4 21.77990
TC 5 21.87975
TC 6 21.82983
TC 7 20.52929
TC 8 20.42905

CH19 Volts 2.11500
CH20 Amps 0.29570
K-Factor = 0.39111
R-Value = 0.03580
DT top = 1.37562
DT bot = 1.30284
Mean temp. = 21.14879

Elapsed time 130 min.

TC 1 20.47492
TC 2 20.52929
TC 3 21.82559
TC 4 21.82559
TC 5 21.92544
TC 6 21.95040
TC 7 20.60020
TC 8 20.44986

CH19 Volts 2.11500
CH20 Amps 0.29570
K-Factor = 0.38282
R-Value = 0.03657
DT top = 1.41289
DT bot = 1.32349
Mean temp. = 21.19766

Elapsed time 140 min.

TC 1 20.50423
TC 2 20.52503
TC 3 21.85479
TC 4 21.85479
TC 5 21.95463
TC 6 21.92968
TC 7 20.57939
TC 8 20.47917

CH19 Volts 2.11600
CH20 Amps 0.29570
K-Factor = 0.38070
R-Value = 0.03677
DT top = 1.41287
DT bot = 1.34016
Mean temp. = 21.21022

Elapsed time 150 min.

TC 1 20.53778
TC 2 20.55859
TC 3 21.86326
TC 4 21.88822
TC 5 21.00877
TC 6 21.98382
TC 7 20.63799
TC 8 20.51273

CH19 Volts 2.11600
CH20 Amps 0.29570
K-Factor = 0.38131
R-Value = 0.03672
DT top = 1.42094
DT bot = 1.32755
Mean temp. = 21.24889

Elapsed time 160 min.

TC 1 20.53354
TC 2 20.55434
TC 3 21.88399
TC 4 21.88399
TC 5 22.00877
TC 6 21.98382
TC 7 20.60445
TC 8 20.50848

CH19 Volts 2.11500
CH20 Amps 0.29570
K-Factor = 0.37682
R-Value = 0.03715
DT top = 1.43983
DT bot = 1.34005
Mean temp. = 21.24517

Elapsed time 170 min.

TC 1 20.54203
TC 2 20.56709
TC 3 21.89245
TC 4 21.94237
TC 5 22.04219
TC 6 22.01723
TC 7 20.64224
TC 8 20.51698

CH19 Volts 2.11500
CH20 Amps 0.29570
K-Factor = 0.37240
R-Value = 0.03759
DT top = 1.45010
DT bot = 1.36285
Mean temp. = 21.27032

Elapsed time 180 min.

TC 1	20.52929
TC 2	20.55859
TC 3	21.92968
TC 4	21.93391
TC 5	22.05868
TC 6	22.03373
TC 7	20.60869
TC 8	20.48342

CH19 Volts	2.11400
CH20 Amps	0.29550
K-Factor =	0.36229
R-Value =	0.03864
DT top =	1.50015
DT bot =	1.38785
Mean temp. =	21.26700

Elapsed time 190 min.

TC 1	20.56284
TC 2	20.58789
TC 3	21.96309
TC 4	21.93814
TC 5	22.06713
TC 6	22.04219
TC 7	20.63799
TC 8	20.51273

CH19 Volts	2.11500
CH20 Amps	0.29580
K-Factor =	0.36708
R-Value =	0.03814
DT top =	1.47930
DT bot =	1.37525
Mean temp. =	21.28900

Elapsed time 200 min.

TC 1	20.56284
TC 2	20.58789
TC 3	21.96309
TC 4	21.96309
TC 5	22.08785
TC 6	22.06290
TC 7	20.63799
TC 8	20.53778

CH19 Volts	2.11600
CH20 Amps	0.29570
K-Factor =	0.36450
R-Value =	0.03841
DT top =	1.48749
DT bot =	1.38773
Mean temp. =	21.30043

Elapsed time 210 min.

TC 1	20.54203
TC 2	20.61719
TC 3	21.94237
TC 4	21.93814
TC 5	22.06713
TC 6	22.04219
TC 7	20.64224
TC 8	20.51698

CH19 Volts	2.11500
CH20 Amps	0.29570
K-Factor =	0.36939
R-Value =	0.03790
DT top =	1.47505
DT bot =	1.36065
Mean temp. =	21.28853