National Library of Canada
Bibliothèque nationale du Canada

Canadian Theses Service
Service des thèses canadiennes

Ottawa, Canada
K1A 0N4

NOTICE

The quality of this microform is heavily dependent upon the quality of the original thesis submitted for microfilming. Every effort has been made to ensure the highest quality of reproduction possible.

If pages are missing, contact the university which granted the degree.

Some pages may have indistinct print especially if the original pages were typed with a poor typewriter ribbon or if the university sent us an inferior photocopy.

Reproduction in full or in part of this microform is governed by the Canadian Copyright Act, R.S.C. 1970, c. C-30, and subsequent amendments.

AVIS

La qualité de cette microforme dépend grandement de la qualité de la thèse soumise au microfilmage. Nous avons tout fait pour assurer une qualité supérieure de reproduction.

S'il manque des pages, veuillez communiquer avec l'université qui a conféré le grade.

La qualité d'impression de certaines pages peut laisser à désirer, surtout si les pages originales ont été dactylographiées à l'aide d'un ruban usé ou si l'université nous a fait parvenir une photocopie de qualité inférieure.

La reproduction, même partielle, de cette microforme est soumise à la Loi canadienne sur le droit d'auteur, SRC 1970, c. C-30, et ses amendements subséquents.

NL-339 (r. 88/04) c

Canada

LATENT HEAT STORAGE IN CONCRETE

Douglas W. Hawes

A Thesis

in the

Centre for Building Studies

Faculty of Engineering

Presented in Partial Fulfilment of the Requirements
for the degree of Doctor of Philosophy at
Concordia University
Montreal, Quebec, Canada

January 1991

National Library of Canada
Canadian Theses Service

Bibliothèque nationale du Canada
Service des thèses canadiennes

Ottawa, Canada
K1A 0N4

ISBN 0-315-64740-X

CONCORDIA UNIVERSITY
Division of Graduate Studies

This is to certify that the thesis prepared

By: Mr. Douglas W. Hawes

Entitled: Latent Heat Storage in Concrete

and submitted in partial fulfillment of the requirements for the degree of

Doctor of Philosophy (BUILDING STUDIES)

complies with the regulations of the University and meets the accepted standards with respect to originality and quality.

Signed by the final examining committee:

M E Szabo
Chair, Dean of Graduate Studies
Dr. M.E. Szabo

External Examiner
Dr. P.C. Aitcin

External to Program
Dr. Z. Zielinski

Examiner
Dr. R. Guy

F. Haghighat
Examiner
Dr. F. Haghighat

Feldman
Thesis Supervisor
Dr. D. Feldman

Approved by
Director, Center for Building Studies

March 19 1991

Dean of Faculty of Engineering
and Computer Science

ABSTRACT

LATENT HEAT STORAGE IN CONCRETE

DOUGLAS W. HAWES
CONCORDIA UNIVERSITY, 1990

The development of improved means of thermal storage is an aspect of energy conservation which has lagged other advances in this field. The intent of the present work is to address this need. To that end, concrete building materials were selected as ideal candidates for improvement in respect to their thermal storage capability. This was achieved by the incorporation of organic phase change materials (PCM's) in the concrete. These PCM's absorb or release the latent heat of fusion at a selected temperature and thereby greatly enhance the heat storage capacity of the impregnated concrete over a small temperature range.

Relevant properties of the constituent materials, means of their combination, stability and conditions of operation were studied for the purpose of optimizing their thermal storage performance and reducing the cost of PCM concrete. Various manufacturing procedures were also developed.

Two types of PCM's were found to be satisfactory.

In addition, several other promising candidates were studied with the intention of future development. Various PCM's were used to impregnate different types of concrete to optimize performance.

Modification of the concretes were performed to enhance their compatibility with the PCM's. Four types of aggregate were studied, three of which are also found to be suitable for pre-impregnation.

The energy storing concretes developed in this research have a very wide range of use in the storage of waste heat, heat from solar collectors or off-peak, low cost heat. In addition, they can also be used to improve the performance of burners and chillers through reduction of operating frequency by thermal storage. Their application is cost effective in areas with an appropriate diurnal temperature swing and, as fuel costs rise, they may be applied in colder regions as well.

Original aspects of energy storage developed in this work comprise:

(i) new concrete modules with organic PCM's including fatty esters, fatty alcohols and C22 - C24 paraffins
(ii) the application of lightweight aggregates such as pumice, expanded shale and expanded slag as PCM carriers for direct incorporation in concrete
(iii) various techniques for direct incorporation of PCM's without carriers
(iv) the use of pozzolans to modify concrete to permit use of alkali sensitive PCM's
(v) development of theoretical considerations of PCM diffusion in concrete and the determination of absorption characteristics
(vi) development of technique for defining absorption constants
(vii) the use of PCM's as protective substances in concrete

(viii) development of means to use walls, floors and ceilings for enhanced thermal storage

ACKNOWLEDGEMENTS

The author wishes to express his sincere gratitude to his supervisor, Dr. Dorel Feldman, for his constant guidance, help and encouragement throughout the entire course of this research.

Special appreciation is also due to Mrs. Dorina Banu for her invaluable assistance with laboratory procedures and for her technical support.

I am grateful to many of the faculty at the Centre for Building Studies for their counsel and to Mrs. Nancy Kamal, Mr. Hans Obermier. Mr. Joseph Hrib, Mr. Joseph Zilka, Mr. Norman Low and Mr. R. Patterson for their help with various aspects of the work.

I am also very grateful to Mrs. Gloria Miller for typing this thesis and for her help in arranging its presentation.

This work is dedicated to my wife

Louise L. Hawes

for her constant love, support and patience

TABLE OF CONTENTS

Page

LIST OF FIGURES

LIST OF FIGURES (Cont'd)

LIST OF FIGURES (Cont'd)

LIST OF TABLES

LIST OF TABLES (Cont'd)

LIST OF ABBREVIATIONS

ABL	autoclaved concrete block
AC	air cured
BS	butyl stearate
CBS	Centre for Building Studies
CH*	calcium hydroxide
CHS*	calcium silicate hydrate ($C_3S_2H_3$)
C_2S*	dicalcium silicate
C_3AH_6*	tricalcium aluminohexahydrate
C_3S*	tricalcium silicate
$C_5S_6H_5$*	tobermorite
DD	dodecanol
dd	degree day
DS	dimethyl sulfoxide
DSC	differential scanning calorimetry
EA	entrained air
EXS	expanded shale (aggregate)
EXSL	expanded slag (aggregate)
FA	fly ash
H*	water
HDPE	high density polytethylene
HVAC	heating, ventilating and air conditioning
LA	low alkali (cement)
OPC	ordinary Portland cement
PAR	paraffin
PCM	phase change material
PEG	polyethylene glycol
PI	pre-impregnated
PUM	pumice concrete block
REG	regular concrete block
RH	relative humidity
S*	silica
SC	steam cured
SF	silica fume
TD	tetradecanol
WC	water cured
w/c	water/cement (ratio)
WT	weight
*	conventional concrete notation

CHAPTER 1

OBJECTIVE

The objective of this research comprises the development of latent heat storage in concrete with particular reference to masonry applications.

In particular, it is intended that these building products have the following characteristics:

(a) Be capable of absorbing and releasing appropriate amounts of thermal energy within a designated range of temperatures.

(b) Be appropriate for any application where conventional or lightweight concrete products are now used in buildings for walls, ceilings, floors and roofs.

(c) Be suitable for installation by tradesmen with ordinary skills in conventional structures.

(d) Be suitable for manufacture in conventional production facilities.

(e) Have an installed cost such that the differential between them and conventional concrete products would be economically justified by the energy savings obtained by their use.

CHAPTER 2

INTRODUCTION

2.1 RATIONALE

The necessity for preserving our fossil fuel resources has long been recognized but it is only within the past two decades that there have been widely perceived economic incentives to take effective action to that end. More recently, apprehension concerning atmospheric contamination resulting from the combustion of fossil fuel for power generation has provided additional stimulus to find a solution to this problem. In addition, the hazards of being dependent upon nuclear energy and difficulties with importing fuel have also become serious enough to accelerate research in the conservation of energy and in the development of practical and cost effective means of using renewable energy.

In the building field, more advanced building design, more effective HVAC controls, better insulation, new developments in the design of windows and doors, improved methods of ensuring air tightness and vapour sealing as well as more efficient burners, chillers and heat exchangers represent some of the advances which have been made to increase the conservation of building energy.

However, there is one sphere of activity relating to alternative energy use where the scale of development has been markedly less than those in other areas. This field of investigation is the development of an appropriate and economical means of thermal storage in buildings. The need for this research is related to the fact that a space heating system must incorporate some form of thermal storage for it to make effective use of virtually any form of thermal energy for space heating. In like manner, thermal storage is also required in space cooling applications for the absorption of excess thermal energy during the day so that it may be subsequently released to the cool night air.

2.2 HISTORICAL AND GENERAL DESCRIPTION

The necessity for incorporating a storage element into a space conditioning system has been recognized since the earliest concepts of thermal energy management were developed tens of thousands of years ago. Originally, naturally occurring materials such as rock and earth were used as sensible heat reservoirs and these were followed by brick and concrete. Over a long period, these materials were gradually incorporated into building structures and thermal installations (e.g. ovens and regenerators) to serve that purpose.

In the fifth century B.C. this aspect of architecture was sufficiently advanced to be considered an important feature of town planning. The town of New Olynthus, which was built in northern Greece at this time, was specifically arranged so as to take maximum advantage of solar radiation for the purposes of heating and lighting. The streets were laid out in such a manner as to provide each house with a southern exposure. The houses themselves incorporated thick adobe walls for thermal storage and covered porches which admitted sun to the houses in the winter but shaded them from direct solar radiation in summer. The ancient Greek concept of beauty was enhanced in these houses, according to Xenophon, because, as well as being aesthetically pleasing, they also provided a comfortable ambience for living. The city of Priene, founded in the fourth century B.C. in southwest Turkey, is another example of urban planning which was clearly influenced by a good understanding of these principles (Perlin, 1985).

Water, with a latent heat of melting of 335 J/g, has long been used as a thermal storage material but, except for very special circumstances where ice, snow and permafrost can be used, it is not usually considered a building material and is mentioned here only for the sake of completeness.

An important aspect of the temperature modulating system is the movement of the thermal exchange medium over the heat exchange surfaces of whatever thermal storage medium is used. Both early and contemporary structures using thermal storage incorporate various means of natural circulation. It is only within comparatively recent history that mechanically assisted thermal storage and recovery was achieved. It will also be noted that the thermal storage function of building materials can apply to a wide temperature range, depending upon the heat source and mode of application.

2.3 THE IMPORTANCE OF THERMAL STORAGE

Thermal storage allows heat to be stored and then to be released as required. Its development is important for the following reasons:

(a) It makes feasible the use of low cost energy which would otherwise be wasted because its supply frequently exceeds or is asychronous with thermal demand. This type of energy may be derived from the following sources:

(i) passive and/or active solar heating

(ii) warm infiltrated air

(iii) heat generated by occupants, particularly where large numbers are found as in classrooms, public rooms, theatres, restaurants and so forth

(iv) heat produced from lighting, cooking, appliances, heat-emitting equipment or exothermic processes.

(b) Energy may sometimes be purchased at lower cost during off-peak periods for storage and discharge at times when full rates would otherwise be charged.

(c) In addition to time-shifting energy consumption, thermal storage can also effect a diminution of the demand peak which will be reflected in a reduction in energy costs, smaller equipment sizing and more efficient operation.

(d) Excess heat may also be absorbed during the day to moderate the temperature in a building. In this case, the heat is stored for subsequent transfer to cool night air which is circulated over the heat storage surfaces then discharged to the exterior. Thus, using the outside air at night (or whenever the temperature falls to the requisite level) enables a thermal storage system to replace or supplement the function of an air conditioning system.

(e) Reduction of furnace cycling may be achieved by the use of thermal storage. In this application, control of the burner is arranged so that ignition does not occur until the stored heat is depleted, i.e. the thermostat is set to cause the burner to ignite at a temperature below the freezing point of the PCM. The burner then continues to burn until the PCM is completely melted, i.e. until the room air temperature is a few degrees above the melting point. This arrangement will prolong the duration of both the firing and off cycles. It will be recalled that the optimum efficiency of combustion is not attained until appropriate conditions are reached in the combustion chamber and that the warm-up period required for this process takes a finite amount of time. It follows then that the greater the ratio of firing time to warm-up time, the higher will be the average efficiency. Therefore, if the duration of both the firing and off cycles is prolonged by storage and release of heat in the building and if the furnace can be selected so that its optimum performance range corresponds more closely to the average heating load, rather than to the peak load, a considerable saving can be realized. Research has shown that combustion efficiency can be improved between 11%

and 54% by reducing short cycle operation (Michal, 1979; Berlad, 1979). In Canada it is estimated that the average would be approximately 30% because of the cold climate.

(f) In a manner analogous to the foregoing, the efficiencies of heat pumps and chillers can be expected to have higher coefficients of performance where their operating schedules incorporate the long on and off cycles made possible by thermal storage (Michal, 1979; Berlad, 1979).

(g) A wide thermostat dead band, plus the thermal inertia of PCM storage effectively lengthen the intermediate seasons which are characterized by only light heating and cooling demands. The effective outdoor temperature balance point for heating is lowered, while that for cooling is raised, as compared with those for a normal thermostat setting at the centre of the comfort zone. This decreases the seasonal heating and cooling loads considerably, whatever the sources of heating and cooling energy.

The principal building elements used for sensible heat storage are masonry walls, floors and ceilings. The form of the units and the manner in which they may be arranged can be chosen to suit their application.

2.4 APPLICATIONS

2.4.1 Temperature Ranges

There are five principal temperature ranges for thermal storage:

(a) hydronic heating: 75-90°C
(b) hot water heating: 60-75°C
(c) hot air heating: 35-60°C
(d) space heating: 17-25°C
(e) cold storage: 5-20°C

The present work is concerned with applications (c) and (d).

Application (c) would be considered where air in this temperature range could be supplied at low cost. This grade of stored heat could be used directly for some process such as drying which requires heat at this temperature or it could be mixed with cooler air and used for space conditioning. Sources of heat for storage in this range include solar collectors as well as the exhaust heat from any exothermic process.

Applications in the range (d) are the most common since it is within the human comfort zone and it also covers the temperatures at which most waste heat is available for storage in a building.

Whereas quite feasible, the remaining applications are beyond the scope of the present work.

2.4.2 Modes of Operation

Conventional space conditioning systems usually comprise several subsystems which include equipment to effect the transmission and exchange of heat from place to place and from one medium to another. These systems are costly to install and operate. On the other hand, in a building which is constructed of energy storing concrete products, the functions of heat reservoir, thermal conduit, heat exchanger and building element may be combined. If such heat storage building elements are installed throughout a building they can be used in two ways.

(a) Heat exchange via interior walls

Concrete blocks are manufactured with a variety of surfaces ranging from the strictly functional to those which are also aesthetically pleasing, so the opportunities for using these products are quite extensive. Then, if bare blocks comprise the interior surfaces of a building, heat exchange can take place throughout the enclosure at these surfaces. In this case, the operation of an air distribution system to effect the collection and distribution of air for heating and cooling may not be required during certain periods of the intermediate seasons. This desirable situation exists for a number of reasons. To begin with, the effective depth of thermal storage material is comparatively shallow so that the conductive path to and from storage is relatively short. Then, since the surface area is so large, convective as well as radiative couplings serve as effective means of heat exchange with the room air (Neeper, 1984). Finally, owing to the fact that heat storing concrete products can be installed throughout an entire building, the desired heat storage may be distributed evenly over the area to be thermally conditioned. In this case it should be observed that due provision must be made for adequate circulation of air throughout the conditioned space, especially where an internal source or loss of heat is concentrated, e.g. a south facing window or frequently used external doorway.

(b) Heat exchange via the cores

An alternative to the foregoing mode of operation is to use PCM hollow concrete block for thermal storage by collecting hot or cold air and passing it through the cores of the blocks where thermal exchange occurs at the internal surfaces. This function can be realized by an appropriate arrangement of headers at the top and bottom of the walls through which the air can pass to the exchange surfaces.

While it would be possible, under certain circumstances, for such a system to function by allowing natural convection to achieve the requisite circulation, it will normally require a fan powered collection and distribution system to feed air to and receive it from the headers at the top and bottom of the walls. There are a number of arrangements suitable for this purpose, some of which comprise the use of lintel blocks through which air can pass to the interior spaces from the distribution system and conversely. It follows that such a system could be very easily adapted for use with an external source of hot air whose heat energy could be stored for later use or to employ cool air to lower the temperature of the blocks and allow them to function as a heat sink from which unwanted heat could later be dumped. Examples of such sources are solar collectors or hot exhaust air from which heat could be extracted and stored or, conversely, cool night air (Lee, 1984; NCMA-TEK, 1981).

(c) Combined operations

Various combinations of the two foregoing modes could be used to meet the requirements of a particular situation.

2.5 LATENT HEAT STORAGE

Until quite recently, thermal storage in building materials depended upon their sensible heat characteristics. This form of heat storage was usually only practical where a large structural mass was available. Moreover, it had several decided drawbacks. In many instances, the payback period of high mass thermal storage was too long because of construction cost. The second shortcoming was related to the fact that, in order to provide adequate thermal storage in winter, the required mass was very large. Moreover, under certain circumstances, the accumulated heat in such a mass could render a building very uncomfortable, if not uninhabitable, until it cooled down (Lof, 1978).

Then, in the 1940's, research in the field of latent heat storage began in earnest with the use of materials which change their state within the comfort zone. When melting or freezing, these materials respectively absorb or release heat in the process and are known as phase change materials (PCM's). Moreover, some are able to perform this function within a small temperature range and thus avoid the uncomfortable temperature variations which are characteristic of sensible heat storage in the building mass. Therefore, if a PCM with the appropriate characteristics can be effectively incorporated in a suitable building element, the heat storage capacity so introduced can contribute to both energy conservation and thermal comfort.

As mentioned above, if ordinary concrete is used for heat storage in the sensible form, the amount of thermal storage required for comfort in the winter when using passive solar energy as the principal source, can give rise to overheating in summer. This may occur after a succession of hot, sunny days and warm nights when the temperature does not fall sufficiently to cool the concrete mass. However, if PCM is used for a significant portion of the thermal storage required, then the problem of cooling the thermal storage mass down to the comfort zone (i.e. the PCM freezing temperature) is reduced to manageable proportions. This is because the specific heat stored in liquid PCM will only be approximately 3% of that of concrete of equivalent thermal capacity. The relative effects of sensible and latent heat storage may be approximated by comparing the specific heat of concrete (0.88 J/g) through a small (6°C) temperature rise, which is equal to about 5.3 J/g, with the latent heat of PCM which has a heat storage value in the range of 140-200 J/g.

2.6 PRIOR RESEARCH IN RESPECT TO PCM'S AND THEIR INCORPORATION

Phase change materials are divided into two principal categories: inorganic and organic. These materials will be considered separately as follows.

2.6.1 PCM Categories

(a) Inorganic PCM's

Most of the early work in latent heat storage was carried out using inorganic materials. Prominent researchers in this field include M. Telkes, H.G. Lorsch, J. Schröder, K. Gawron, G. Lane and D. Chahroudi (Telkes, 1975; Lorsch, 1975; Schröder, 1977; Lane, 1976; Chahroudi, 1975).

Of the inorganic PCM's, one of the most interesting groups are the salt hydrates (in which the salt is bound to water). These behave in a more complex way than organic compounds because hydration/dehydration occurs. At a temperature below the hydration point, the anhydrate becomes hydrated and crystallizes with the evolution of heat. Upon heating, the crystal dissolves in its water of hydration, thereby absorbing heat (Hariri, 1988).

Table 1 shows some well known salt hydrates which were considered potentially useful since they have transition temperatures appropriate to heating and cooling buildings (Abhat, 1983). One of the materials in this group which showed early promise was Na_2 $S04 \cdot 10$ H_20 (Glauber's Salt) and it was extensively studied (Altman, 1972). In addition to its use in space heating, this material was

TABLE 1
THERMAL PROPERTIES OF SOME SALT HYDRATES

MATERIAL	MELTING POINT °C	HEAT OF FUSION		DENSITY g/cm³	SPECIFIC HEAT J/g.K	THERMAL CONDUCT -IVITY W/m.K
		J/g	J/cm³			
H_2O[1]	0	333	306	0.917 (0 °C) 0.998 (20°C)	2.09 (S)[2] 4.18 (L)[2]	2.2 (S)[2] 0.6 (20°C)
$KF\cdot4H_2O$	18.5	231	336	1.455 (18°C) 1.447 (20°C)	1.84 (S) 2.39 (L)	-
$CaCl_2\cdot6H_2O$	29.7	171	256	1.710 (25°C) 1.496 (L)	1.45 (S)	-
$Na_2SO_4\cdot10H_2O$	32.4	254	377	1.485 (S)	1.93 (S)	0.544
$Na_2HPO_4\cdot12H_2O$	35.0	281	405	1.520 (S) 1.442 (L)	1.70 (S) 1.95 (L)	0.514 (32°C) 0.476 (49°C)
$Zn(NO_3)_2\cdot6H_2O$	36.4	147	304	2.065 (14°C)	1.34 (S) 2.26 (L)	-
$Na_2S_2O_3\cdot5H_2O$	48.0	201	322	1.73 (S) 1.67 (L)	1.46 (S) 2.39 (L)	-
$Ba(OH)_2\cdot8H_2O$	78.0	267	581	2.180 (S)	1.17 (S)	-
$MgCl_2\cdot6H_2O$	116.0	165	239	1.57 (20°C) 1.442(78°C)	1.72 (S) 2.82 (L)	-

[1] DATA FOR H_2O IS INCLUDED FOR THE SAKE OF COMPARISON
[2] S - SOLID; L - LIQUID

also considered useful for air conditioning applications. Other PCM's listed in this table also have some useful characteristics.

Some of the principal advantages of the salt hydrates are:

(i) they change state within useful temperature ranges
(ii) they have relatively high latent heats per unit volume

(iii) there is no flammability hazard

(iv) they are relatively inexpensive

Unfortunately, these materials are corrosive and require special containment as well as space for the containers. The extra cost of these facilities offsets the cost advantage of the PCM's themselves (Feldman, 1985; Heine, 1981). However, the major reasons why inorganic PCM's are not suitable for use in building materials are their tendencies to supercool and to melt incongruently (Lorsch, 1975). For example, $Na_2 SO_4 \cdot 1OH_2O$ melts to a saturated aqueous phase and a solid phase of anhydrous sodium sulphate. The solid phase then settles out and this results in an incomplete conversion to the decahydrate on cooling below the transition temperature. In consequence of this, the latent heat exchanged is correspondingly decreased. Unless prevented, this phenomenon is irreversible. Thickening agents to prevent settling and nucleating agents to prevent supercooling were tried but, so far, these results have not proven satisfactory.

Some work has been carried out in respect to the binary, tertiary and higher order eutectics of salt hydrates but much work remains to be done in this area (Lorsch, 1975).

Whereas inorganic PCM's may have an application in some types of building thermal storage (Ervin, 1975), they were not considered suitable for incorporation in concrete.

(b) Organic PCMS

The value of organic materials as heat storage materials has been known for a long time but it was only within the last two decades that general interest has been shown in respect to their incorporation in building materials (Lane, 1976; Hale, 1971).

Organic PCM's offer a number of important advantages:

(i) there is a wide selection from which to choose
(ii) the components melt congruently and do not become segregated
(iii) many do not have a supercooling problem
(iv) they are chemically stable
(v) they can be incorporated in the building material without containment
(vi) because of (v) the overall cost is competitive with inorganic PCM's

The principal disadvantages of organic PCM's are:

(i) low thermal conductivity
(ii) high volume changes during phase change
(iii) flammability

The foregoing advantageous and disadvantageous characteristics are discussed in detail later in the text.

Table 2 lists some of the organic materials currently under consideration as

PCM's for thermal storage applications in buildings (van Galen, 1986).

At the Centre for Building Studies (CBS) research in the field of organic PCM's has been ongoing for over eleven years. This research has been largely concentrated on the incorporation of PCM's in various building products. During that time a wide range of building materials has been studied in respect to their suitability as matrices for many types of PCM's (Feldman, 1984; Feldman,1985; Feldman, 1987). These materials include:

(i) poly(vinyl chloride)
(ii) poly(vinyl alcohol)
(iii) poly(vinyl acetate)
(iv) vinyl acetate-vinyl chloride copolymer
(v) cement
(vi) high density polyethylene
(vii) ceramic tiles
(viii) gypsum

The PCM's studied in this work and selected for incorporation in the building materials comprise a broad selection of substances (Feldman, 1986; Hawes, 1989; Hawes, 1990).

(i) fatty acids
(ii) fatty esters
(iii) fatty alcohols

TABLE 2
THERMAL PROPERTIES OF SOME ORGANIC MATERIALS

			TRANSITION		SPECIFIC HEATS	
MATERIAL	MELTING RANGE (°C)	SOLIDIFICATION RANGE (°C)	TEMPERATURE RANGE (°C)	LATENT HEAT J/g	$C_{p,sol}$ J/g.K	$C_{p,liq}$ J/g.K
Octadecane (99% pure)	27-32	24-29	27-32	253	1.81	1.95
Eicosane (technically pure)	30.41	25-37	9-15 15-30 30-41	25 19 138	2.06	1.80
N-Eicosane (99% pure)	34-41	30-36	34-41	245	1.72	2.12
Commercial wax	35-47	30-45	10-25 25-35 35-47	26 12 147	1.83	2.03
Shell paraffin wax 52/54	45-57	40-52	20-40 40-47	45 152	2.04	2.06
Shell paraffin wax 60/63	52-64	49-60	40-52 52-64	53 148	1.94	1.77
Shell microcrystalline wax 60/63	30-69	20-63	30-69	130	1.90	1.77
Palmatine acid	55-63	52-60	55-63	193	2.20	1.70
Stearic acid	55-71	52-64	55-71	191	2.07	1.90
Acetamide*	55-74	36-41	55-74	198	1.98	2.81
Biphenyl*	66-73	63-60	66-73	117	–	–
Naphthalene*	77-87	67-64	77-87	140	–	–
Shell microcrystalline wax 85/88	65-95	65-89	65-95	179	1.89	1.8
Pentaglycerine*	82-88	63-68	82-88	154	1.76	2.78
Succinic Anhydride*	115-119	100-101	115-119	167	2.07	3.32
Benzoic acid*	120-125	112-120	120-125	130	1.90	2.26
Low Density Polyethylene	100-110	–	100-110	94	–	–
High Density Polyethylene	125-136	116-127	125-136	200	2.68	2.81

* Supercooling

(iv) alkanes

(v) polyglycols

These studies indicated that, if carefully selected and correctly applied, various combinations of building materials and PCM's have the potential for greatly enhancing the beneficial effects of thermal storage in a building product. This benefit can either take the form of providing greater thermal storage capacity for the same mass or the same thermal storage capacity for a smaller mass.

2.6.2 Prior Work in Means of PCM Incorporation

The means of incorporating PCM's in the concrete is an important aspect which will be discussed in detail later. Previous work in this area involved the use of paraffin blends with melting points at or near the human comfort zone. Since this temperature range is close to ambient conditions encountered during mixing and curing, high density polyethylene (HDPE) was used as the carrier for the wax to provide a hard pellet suitable for mixing. However, to render the HDPE suitable for this purpose it was necessary to prepare this material by subjecting it to gamma radiation in a nitrogen atmosphere or by electron beam radiation in air. Vulcanized rubber pellets were also used as a carrier (Salyer, 1986). The present work concerns the development of other means of PCM incorporation, both direct and indirect which are suitable for low cost, high volume production.

CHAPTER 3

RESEARCH METHODOLOGY

To achieve the desired objectives it was necessary to examine the characteristics of many PCM's, various types of concrete and several other materials; to test and observe the performance of a number of combinations of these substances under a variety of conditions and thence to develop stable forms of PCM concrete which would function effectively to provide latent heat storage.

To this end, the work was divided into a progressive series of tasks. These are listed below and each is discussed in the relevant section of the text.

3.1 PREPARATORY RESEARCH

(a) Selection of concrete as a PCM matrix material

(b) Selection of concrete blocks as a research medium

(c) Selection of PCM's

(d) Selection of means of incorporating PCM in concrete

(e) Flammability aspects

3.2 TEST PROCEDURES FOR PCM CONCRETE SPECIMENS

(a) Concrete preparation, measurement and immersion

(b) Differential scanning calorimetry (DSC) analysis

(c) PCM absorption tests

(d) Water absorption tests

(e) Thermal conductivity tests

(f) Temperature cycling test

(g) Flexural strength tests

(h) Chemical analyses

(i) Fire tests

3.3 CHARACTERIZATION OF PCM CONCRETE

(a) Experimental procedure data tabulation

(b) Study of means of PCM incorporation

(c) Evaluation of thermal properties

(d) Optimization of concrete - PCM compatibility

(e) Effect of temperature on PCM absorption

(f) Dilution of PCM as a means to increase absorption

(g) Effects of duration and frequency of immersion

(h) Effect of PCM on moisture absorption

(i) Effect of curing

(j) Thermal conductivity

(k) Effect of temperature cycling

(l) Flexural strength

(m) Fire resistance

(n) Absorption of PCM's in concrete

(o) Stability

3.4 ECONOMIC IMPACT

(a) Costs

(b) Benefits

(c) Conclusions

3.5 GENERAL CONCLUSIONS

(a) Outcome of the research

(b) Contributions to the technology

(c) Recommendations for further work

CHAPTER 4

PREPARATORY RESEARCH

4.1 SELECTION OF CONCRETE AS A PCM MATRIX MATERIAL

4.1.1 General Considerations

The great range of available properties and the broad scope of its applications make concrete an ideal building medium. Moreover, the ready availability of its constituents, their relatively low cost and the ongoing refinements in all aspects of its preparation and placement have led to and sustained its great popularity as a construction material. In addition to its functional and economic advantages, concrete enjoys the user confidence generated by a technology which is based upon study, experimentation and practical experience with a series of materials which evolved from those used in such early structures as the Pyramid of Cheops which was built about 3000 B.C. (Mindess, 1981).

4.1.2 Portland Cement

The cement now used in concrete is Portland cement and its main components are as shown in Table 3, together with their proportions in each of the five ASTM and CSA types of concrete. In addition to these, there are also some special purpose cements.

TABLE 3
COMPOSITION AND PROPERTIES OF PORTLAND CEMENT TYPES

CHEMICAL COMPONENT	SHORTHAND NOTATION	ASTM TYPES: ROMAN NUMERALS CSA NOS.: ARABIC NUMERALS PROPORTIONS IN %				
		I 10	II 20	III 30	IV 40	V 50
TRICALCIUM SILICATE (3CaO•SiO$_2$)	C$_3$S	50	45	60	25	40
DICALCIUM SILICATE (2CaO•SiO$_2$)	C$_2$S	25	30	15	50	40
TRICALCIUM ALUMINATE (3CaO•Al$_2$O$_3$)	C$_3$A	12	7	10	5	4
TETRACALCIUM ALUMINOFERRITE 4CaO•Al$_2$O$_3$•Fe$_2$O$_3$)	C$_4$ AF	8	12	8	12	10
CALCIUM SUFATE DIHYDRATE (CaSO$_4$•2H$_2$O)	CSH$_2$	5	5	5	4	4
FINENESS (BLAINE, m^2/kg)	-	350	350	450	300	350
COMPRESSIVE STRENGTH (1 day, MPa)	-	7	6	14	3	6
HEAT OF HYDRATION (7 days, J/g)	-	330	250	500	210	250

When mixed with water, the principal product of hydration is a calcium silicate hydrate (CSH) which usually contains small amounts of Al, Fe, Mg and other ions. CSH is a poorly crystalline material which forms extremely small particles (less than 1 µm) in any dimension and whose composition will vary with the type of cement used. The second major hydration product is calcium hydroxide $Ca(OH)_2$ which is formed from the lime released. The selection of PCM's for incorporation in concrete must take account of the action which the products of hydration may have upon the PCM and conversely. Particular care must be excercised in respect to potential attack by $Ca(OH)_2$.

The structure of hydrated cement comprises the hydrates of the various compounds which is referred to as the gel, crystals of $Ca(OH)_2$, some minor components, unhydrated cement and voids referred to as capillary pores whose size varies between 10 and 0.01 µm. Within the gel there also exist interstitial voids called gel pores which range in size from 10 to < 0.5 nm. During the hydration process the volume of capillary pores decreases while that of gel pores increases (Mindess, 1981).

Total gel volume may be determined as follows:

$$V_g = 0.68\,\alpha \text{ cm}^3\text{/g of original cement.} \qquad \text{(eq. 1)}$$

where V_g = gel volume $\text{cm}^3\text{/g}$

α = fraction of cement which has hydrated

Gel porosity is calculated as follows:

$$P_g = \frac{W_g}{V_g} = 0.26$$ (constant for all normally hydrated cements) (eq. 2)

where:

P_g = gel porosity (fraction)

W_g = water volume cm^3/g

Capillary porosity is found by the following relationship:

$$P_c = \frac{w}{c} - 0.36\,\alpha$$ (eq. 3)

where: P_c = capillary porosity (fraction)

w/c = water/cement ratio (by weight)

All pores are important in the absorption of PCM. Whereas the pores can be affected by temperature and loss of moisture, it will be seen that the dimensions and number of capillary pores can also be determined by the w/c ratio. However, as shown in Table 4, the amount of water in cement also has an important bearing on the strength of concrete so the selection of w/c must be governed by all aspects of the application (Mindess, 1981).

TABLE 4
RELATIONSHIP BETWEEN w/c RATIO AND COMPRESSIVE STRENGTH OF CONCRETE

28 DAY COMPRESSIVE STRENGTH MPa	w/c	
	NON-AIR-ENTRAINED CONCRETE	AIR-ENTRAINED CONCRETE
45	0.37	-
40	0.42	-
35	0.47	0.39
30	0.54	0.45
25	0.61	0.52
20	0.69	0.60
15	0.80	0.71

4.1.3 Aggregates

Aggregates occupy 60-80% of the concrete volume and hence have an important influence on its properties, mix proportions and cost. They comprise a very wide range of materials and characteristics which, like cement, must be appropriately chosen for their application. Aggregates must be clean, hard, strong and free of coatings which could affect hydration and the strength of the aggregate - cement paste bond. They must also be selected so as to avoid any undesirable alkali-aggregate reaction between them and the cement paste. Finally, aggregates intended for use in PCM concrete must also be considered with respect to their porosity and any propensity to react with the PCM.

Aggregates are divided into three principal categories:

(a) high density materials such as barite, magnetite, iron, steel et al;

(b) normal density substance such as sand, gravel, crushed stone and air cooled blast furnace slag;

(c) low density aggregates which are separated into two categories:

  (i) those such as expanded shale, clay, slate and slag which are used to produce structural low-density concrete having a density in the 1350 to 1850 kg/m^3 range

  (ii) the lower density types such as pumice, scoria, perlite, vermiculite and diatomite which are used in the manufacture of insulating concretes in the 250 to 1450 kg/m^3 range.

Concretes with aggregates in category (a) are special purpose types which were not included in the present work. Those with aggregates in category (b) were included because of their widespread use and those in category (c) were also examined because of their high absorptivity.

4.1.4 Curing

Concrete must be properly cured if its optimum properties are to be developed. The three principal parameters which govern effective curing are adequate moisture for hydration, appropriate conditions of temperature and the time required to attain adequate strength before formwork is removed. Special situations of mass, type of concrete or environment may require appropriate variations of some of the values given below.

(a) Effect of Moisture

The object of curing is to keep the concrete as nearly saturated as possible until the spaces which were originally filled with water have been filled to the desired extent by the products of hydration. Since the curing process requires water, it is important to ensure that it is present in sufficient amounts. This can be achieved by adding water to the surface of the concrete by fine sprays or wetted fabric and/or by preventing the loss of water through evaporation by some form of sealant (Neville, 1981).

In this connection it should be noted that theoretically there is enough water in concrete to ensure complete hydration without additional water if the w/c ratio is 0.42 or greater. However, in practice there is always a loss of water by evaporation and absorption by aggregates, formwork or subgrade and this must be reduced by appropriate measures. If the internal relative humidity drops below about 80% hydration will stop and strength development will be arrested (Mindess, 1981).

(b) Effect of Temperature

It is important that the temperature of curing concrete remain within the limits which allow a uniform distribution of the hydration products. The temperature of the concrete at 100% RH should not be allowed to rise above about 23°C during the first 28 days. During this time, an ideal process would be to allow the temperature to rise from 13°C to 23°C on the 28th day(Neville, 1981). Steam curing is carried out at higher temperatures and is described in Sections 4.2.3 and 6.9.

(c) Effect of Time

Although the hydration process continues indefinitely, the time normally used to allow ordinary concrete to develop its design strength is 28 days. However, this period can be accelerated or retarded by appropriate additives which result in a loss or gain in ultimate strength.

4.2 SELECTION OF CONCRETE BLOCKS AS PRINCIPAL RESEARCH MEDIUM

4.2.1 Rationale

Although it is intended that the incorporation of PCM be used in all appropriate concrete installations, the concrete products considered most suitable for the present stage of research are concrete blocks. The reasons for this choice are as follows:

(a) They are widely used in a great variety of structures.

(b) They are versatile in application and comprise many shapes.

(c) The heat exchange surface area is large enough to permit storage of significant amounts of heat through a temperature range within the comfort zone. High temperature storage can also be used, either for direct application (e.g. drying) or for mixing for use in building heating.

(d) The heat exchange depth is short.

(e) Heat can be exchanged at faces or core surfaces or any combination thereof.

(f) Manufacturing quality control can be easily achieved.

(g) Blocks can be laid in stack or running bond to provide continuous air passage through the hollow cores.

(h) Test structures can be easily constructed.

(i) Research results on blocks can be readily extrapolated to provide data on the thermal performance of hollow core slabs and panels.

(j) Concrete has good absorptivity and emissivity characteristics.

It should be noted that, while concrete blocks were the preferred medium for this stage of research, some work was also carried out in respect to the incorporation of PCM in ordinary concrete.

4.2.2 SELECTION OF CONCRETE BLOCK TYPES

There are several types of concrete block produced in North America but the most commonly used comprise some variation of the following types:

(a) Regular (Type 1/No. 10) cement with limestone aggregate and sand which is steam cured at atmospheric pressure.

(b) Lightweight concrete using expanded slag aggregate and fines which is cured with steam under high pressure.

(c) Lightweight concrete using expanded shale aggregate and fines which is steam cured at atmospheric pressure.

(d) Lightweight concrete using Grecian pumice aggregate and fines which is steam cured at atmospheric pressure.

Some PCM's such as paraffin are not affected by inclusion in concrete. However, the alkaline nature of most concretes can make them unsuitable for use with other PCM's, particularly fatty acids, some fatty esters and some fatty alcohols. So, in the latter cases, it is necessary to ensure that they are incorporated in a compatible type of concrete.

4.2.3 Curing of Concrete Blocks

The curing of concrete blocks significantly affects their compatibility with PCM and it falls into two principal categories.

(a) Blocks which are cured under high pressure steam, i.e. autoclaving. This process requires a pressure vessel in which the blocks are cured at about 180°C and the resulting reaction is:

H_2O

$(3\ CaO\bullet SiO_2 + 2\ CaO\bullet SiO_2) + 4\ SiO_2$

Portland cement + silica water

$3\ CaO\bullet 2SiO_2\bullet 3H_2O + \quad 2\ Ca(OH)_2 \quad + 4SiO_2 \quad \rightarrow$

calcium silicate hydrate + calcium hydroxide + silica

$CSH \quad \rightarrow$

poorly crystallized, low-lime gel

$5\ CaO\bullet 6\ SiO_2\bullet 5H_2O$ (eq. 4)

Tobermorite

The presence of silica promotes the formation of poorly crystallized CSH, but one which has less lime than that formed in normal hydration. (Hence it is not written as $C_3S_2H_3$). This low-lime gel converts to another crystalline hydrate, called tobermorite, on continued heating. This change is not accompanied by a very large change in density, and hence the initial strength is maintained during the complete autoclave cycle. It will be noted that silica must be present in sufficient quantity to effect this reaction. Steam curing produces a strong, stable concrete in which the products of hydration are coarse and microcrystalline and have low shrinkage.

At these high temperatures calcium sulfoaluminate hydrates are not formed. Both the sulfate and aluminate apparently enter into the CSH and tobermorite structures. Alumina is said to increase the rate of crystallization of tobermorite. C_3AH_6 is occasionally observed but is only a minor component (Mindess, 1981; Neville, 1981; Taylor, 1977).

(b) Blocks which are cured by heating with steam under atmospheric conditions at about 80°C. This method produces a different reaction from (a), i.e.:

$$\underset{\text{Portland cement}}{(3\,CaO{\bullet}SiO_2 + 2\,CaO{\bullet}SiO_2)} + \underset{\text{water}}{H_2O} \longrightarrow$$

$$\underset{\text{calcium silicate hydrate}}{3\,CaO{\bullet}2\,SiO_2{\bullet}3\,H_2O} \quad \underset{\text{calcium hydroxide}}{+\,2\,Ca(OH)_2} \qquad \text{(eq. 5)}$$

From this it will be seen that autoclaved concrete block (ABL) is relatively free of $Ca(OH)_2$ and is, therefore, a promising material for use with PCM's. On the other hand, as seen from equation 5, concrete products which were cured at low pressure contain $Ca(OH)_2$ and this means that they will have a higher alkalinity than the autoclaved products. However, in view of their very common use in the building industry, it was decided to investigate the suitability of a number of types of concrete blocks which have been steam cured at atmospheric pressure, including regular concrete block (REG), pumice concrete (PUM), lightweight concrete using expanded shale aggregate (EXS) and expanded slag aggregate (EXSL) well as ordinary Portland cement concrete (OPC) together with modified forms of some of these concrete types.

4.2.4 Concrete Block Cement

The most common type of cement used in concrete block and indeed, in most concrete work of any kind, is Type I (No. 10) Portland cement. Therefore, all of the present work was carried out using this kind of cement. However, as noted in the previous section, the alkalinity of concrete results in a reaction with certain types of PCM's, so a low alkaline Type I (No. 10) cement was used where it was desired to reduce this effect as much as possible.

4.2.5 Modification of Concrete

It is intended that PCM incorporation interfere as little as possible with existing concrete construction and block manufacturing techniques. However, it was deemed necessary to consider various ways of modifying the concrete as a means of improving the stability of those PCM's which are affected by the alkaline products of hydration. To this end, the use of pozzolans such as silica fume (SiO_2) and fly ash (principally SiO_2, Al_2O_3, CaO and Fe_2O_3) were selected for incorporation in conjunction with conventional additives such as an air entraining agent and a superplasticiser.

Several forms of modifying concrete characteristics by the manner of curing were also selected as appropriate. These were:

(a) steam curing at atmospheric pressure

(b) water curing

(c) air curing

(d) combinations of (a), (b) and (c)

In addition, autoclaved concrete, regular concrete and pumice concrete blocks were obtained from concrete block manufacturers.

4.3 SELECTION OF PCM'S

There are a great number of heat storage materials available on the market, so that some plan of discrimination was required to effect an appropriate choice for the purpose intended.

The selection process was divided into two principal elements: choice of type and screening of candidates within that type. The first element indicated the broad category of PCM's most suitable for consideration and the second established a set of criteria against which the characteristics of the candidates were compared.

4.3.1 Choice of Type of Phase Change

Phase changes which occur within a relatively constant temperature range are divided into the following types:

(a) solid-liquid

(b) solid-solid

(c) liquid-liquid

(d) liquid-gas

(e) solid-gas

Only category (a) was selected for the present work because it alone comprised materials which offered the combination of appropriate volumetric change, heat of transformation, ease of containment and temperature range required for the application intended.

4.3.2 PCM Characteristic Selection Criteria

Choosing a suitable PCM involved subjecting each candidate to a rather lengthy set of criteria. In addition to the conventional requirements for a practical heat storage material (Telkes, 1975; Schröder, 1977; Lorsch, 1975; Lane et al, 1976; Feldman, 1986; Feldman, 1985; Feldman, 1987; Lane 1976; Lane 1979; van Galen, 1986; Hale, 1971; Beilsteins, 1958) it was also necessary to consider the additional characteristics requisite to its incorporation in concrete (Heine, 1981; Neville, 1981; Taylor, 1977). The qualification criteria are discussed below.

4.3.2.1 Thermodynamic considerations

(a) Latent heat of fusion

When a solid is heated, very little of the applied energy is used to expand the material. Instead, most of the heat goes into increasing the vibrational energy of the atoms and molecules, while the temperature and the sensible heat increase.

When the mean amplitude of the vibrations has reached the point where it equals the inter-atomic (or inter-molecular) spacing, these particles begin to free themselves from the crystal lattice and the atomic or molecular structure of the substance changes. Much of the applied energy then goes into freeing the remainder of the particles from the lattice. During this process, the temperature rises very little until all of the atoms or molecules have become free and the substance has been transformed into a liquid. The energy used to effect this change of state is referred to as the latent heat of fusion. When a completely liquid state has been attained, further application of heat causes a resumption of the increase in temperature of the substance in its liquid state.

When heat is removed, the process is reversed with the exception that the liquid may remain in a liquid state below the freezing point (supercooling) until crystalline growth is eventually initiated by some nucleus and solidification occurs. It should be noted that various structural forms are possible within certain solids (polymorphism), although a single solid form is preferred for most of the present research (Van Vlack, 1964; Marshall, 1958).

It should be noted that, although a change of state theoretically occurs at constant temperature, in fact, a small temperature difference (4-6°C) is required around the melting and freezing points to produce the exchange of heat needed to effect the change of state throughout the impregnated concrete. Even this small temperature difference will involve a significant change in the sensible heat of both concrete and PCM. This additional heat must then be added to the latent heat to arrive at the total heat storage capacity of impregnated concrete.

The PCM selected should have the highest possible latent heat per dollar invested, since the greater the latent heat, the less the amount of PCM required to meet the thermal storage capacity and heat transfer rate required. However, this transfer of heat must be achieved in a manner consistent with the other requisite characteristics discussed here. As a result, a satisfactory value for this very important characteristic is normally found only after examination of many candidates. A reasonable range for the latent heat of fusion was established as 130-200 J/g.

(b) Heat transfer properties

The thermal performance of a storage system is dependent on the heat transfer properties of the PCM and its container, as well as those of any other elements required for the heat storage system (Abhat, 1983). These properties are governed principally by the effects of conductivity, diffusivity, configuration and position of the system elements. In contrast to central thermal storage systems, the problem of heat transfer in a PCM concrete system is greatly reduced by the fact that PCM impregnated concrete combines the functions of reservoir and heat exchanger. To a varying degree, it can also form part of the air distribution and collection system. As a result, considerations relating to the characteristics of many items of equipment such as thermal reservoirs, heat exchangers and their space requirements which normally comprise the total heating system, do not apply in this case.

The inner structure of concrete encloses a large percentage of void space which can be occupied (up to approximately 10% of the weight of the concrete) by the PCM's used in this project. PCM in the liquid state is prevented from running back out of the voids and capillaries in the concrete by surface tension and other means of retention to be discussed later.

If a mass of solid PCM is subjected to a small temperature difference, the melting or freezing plane advances very slowly. This is because the large latent heat ensures conditions which are approximately isothermal near the melting or freezing plane. The small temperature difference, therefore, results in only a low thermal current. Moreover, during the freezing process, heat transfer to the outside face of a PCM mass is impeded because the PCM material between the freezing plane and the outside is solid so that convective heat transfer cannot occur (Feldman, 1985). As opposed to the foregoing case, which relates only to PCM by itself, in impregnated concrete the structure of the concrete serves as a heat conductor which provides a thermal short circuit between the liquid PCM and the face(s) of the concrete where heat exchange occurs. This allows the solidification process to occur simultaneously at different depths of the PCM. This process augments the effective heat transfer area and thus increases the rate of heat release, when required, as in the case of a small temperature difference between the air and the concrete. It follows that the conductivity and thermal diffusivity of both the concrete and the PCM must be considered together.

When the cycle reverses and the PCM begins to melt, there is virtually no convective heat transfer in the PCM itself because it is divided into small, thin masses in the voids of the concrete. However, here again, thermal transfer is aided by the concrete structure, so that the entire mass of solid PCM can be melted simultaneously.

Another important aspect of the heat transfer process is the geometry of impregnated concrete block. Since the thickness of concrete at the faces is only about 40 mm, the thermal exchange process is facilitated because of the relatively short distance through which the heat must travel to and from the face of the material where transfer occurs. It should be recalled that thermal exchange can occur at either or both external faces and/or the internal faces of the cores. In addition, concrete block has a high surface-to-volume ratio which is conducive to effective heat transfer.

Since impregnated concrete block can be installed in or adjacent to any space to be heated or cooled, the ducting will usually be limited to connections to the block headers. Circulation fans will usually be required but in those climates where natural ventilation can occur due to significant diurnal temperature variations, it is possible that even these modest auxiliaries may not be required.

It should be noted here that where external walls are used for thermal storage in a cold climate, the outer face will be insulated and, in many cases, one or both sides may be covered with wallboard or other covering so that heat exchange will be confined to the inner (core) faces of the block. It is also feasible to combine PCM concrete as a central storage system with PCM wallboard as local thermal storage (Feldman, 1987).

(c) Transition temperature

The phase transition temperature range must be appropriate and the melting process should be complete at its upper limit. In the case of passive heating, temperatures in the region of 20°C were selected so that heat would be released and absorbed in the 16-25°C range, noting that a small temperature difference is required for heat transfer. The most critical factor in the selection of temperatures for this application is usually that temperature in the freezing curve which denotes the point by which most (the significant portion) of thermal energy has been released in the freezing process.

It should be noted that if a thermostat is mounted 1.5m above the floor, the temperature in the region of one's ankles will usually be lower than that of the thermostat setting due to air stratification. However, if heat release occurs over the entire height of the wall or from the floor, as in the case of PCM impregnated concrete walls and floors, then the vertical temperature difference will be less. In this event, a melting range which has a bottom limit of about 17°C could provide comfort at the ankles equivalent to the situation for a conventional heater with the thermostat set at 20°C. It will be seen that a 3°C difference in thermostat setting will, in itself, result in a considerable energy saving.

The initial melting and freezing temperatures should be within 4°C of each other to prevent excursions outside the comfort zone and these characteristics should not change over the life of the material.

An alternative to operating the thermal storage system within the human comfort temperature range is to store the heat at a higher (intermediate) temperature and then mix the air discharge from storage with cooler air in the conventional manner. This manner of operation applies to the utilization of air received directly from a solar collector (50-60°C) or other intermediate temperature source and permits the use of inexpensive and stable PCM's which are not applicable to heat storage directly at the lower temperatures.

(d) Phase equilibrium

As the material or compound comprising the PCM changes from one phase to the other, it is desirable that equilibrium be maintained in both phases. That is, the composition of the PCM in liquid form should be identical with that in the solid form under all conditions of operation. This implies that the melting of the components be congruent and that they do not segregate during this process. While incongruent melting does not constitute a problem when only one substance is involved, difficulties can arise when the PCM comprises two or more ingredients. In the latter case, separation during melting may occur by precipitation of denser components in such a manner as to impede or prevent their recombination during freezing. When the distribution of the material is changed in this manner its storage capacity may be altered drastically.

(e) Vapour pressure

Vapour pressure is a factor to be considered in the containment of a PCM when ambient conditions are such as to produce a vapour phase of any of its components. In order to have a low vapour pressure at its operating temperature, the PCM used must have a boiling point that is about 200°C higher than the operating range.

4.3.2.2 Physical Properties

(a) Appearance

The PCM must remain within the building material in both states and not cause unacceptable changes in colour or surface condition, e.g. oiliness or crystalline formation. Retention of liquid PCM in the pores of the building material is achieved by surface tension and other mechanisms to be discussed later.

(b) Volumetric change

It is most important to ensure that the volumetric changes associated with the phase change of the PCM are such as not to cause damage to the container or medium through which it is dispersed. For this reason, the PCM's selected were those which contracted on freezing. Therefore, if the concrete is impregnated by immersing it in liquid PCM, the volumetric change is not expected to cause a problem at any ambient condition below the immersion temperature. As the PCM solidifies, it will leave minute air pockets in the spaces occupied by the liquid and, should localized melting in adjacent areas subsequently cause these air spaces to become filled, further heating will only cause the excess liquid to be expelled into other voids since the PCM never occupies all the available air spaces in the concrete.

If, on the other hand, the PCM is introduced in solid form, since it forms only a small percentage of the concrete volume (5-10%), when it melts the excess liquid will be driven into adjacent voids as described above. If encapsulation is used, due consideration must be given to both the encapsulant and the concrete structure to accommodate the expansive effect on melting.

(c) Density

When considering PCM candidates of approximately equal cost and thermal characteristics, it is usually desirable to select the material within the greatest density so that the heat storage per unit volume will be maximized.

4.3.2.3 Kinetic considerations

(a) Avoidance of supercooling

As previously mentioned, some materials remain in the liquid state when their temperature drops below the freezing point. When this occurs, the latent heat is not released at the desired temperature and the prime function of the PCM is negated. If the degree of supercooling is low, it may be acceptable, providing the temperature at which crystallization actually occurs is not below the minimum temperature desired for the conditioned space. It follows that supercooling is a characteristic to be avoided or, when its occurrence is unavoidable, it must be treated with due care. Since organic compounds display little tendency to supercool (Lane, 1983) most are suitable PCM candidates in this respect, although those with an extended freezing curve should be avoided.

(b) Crystallization rate

When a substance solidifies, the process begins with the formation of tiny crystallite nuclei on which the rest of the solid forms. For some PCM's, notably the salt hydrates, this process must frequently be artificially induced with additives to produce satisfactory results and this adds to the cost and reduces the latent heat per unit mass. However, more important than the rate of nucleation is the rate of crystal growth, since a high rate of growth does not require such a high concentration of nuclei in order to affect solidification at a satisfactory rate (Garg, 1985). The rate of crystallization is controlled by the kinetics of incorporation of the molecules in the crystal lattice and by the rate of heat transfer (Lane, 1983). Therefore, it follows that both of these processes must proceed at a speed which will ensure the exchange of heat within an acceptable period of time for effective temperature conditioning.

4.3.2.4 Consideration of stability and compatibility

In some thermal storage systems it is possible to renew the PCM and in such instances, a low cost material with a moderately long life can be acceptable under certain circumstances. On the other hand, where the PCM is incorporated in a building material, one must ensure that it has a life expectancy comparable to that of the building itself. This means that chemical reactions such as hydrolysis, oxidation and thermal decomposition must be limited to an extremely low rate.

The PCM must not inhibit any of the reactions which normally occur at any stage of the mixing, placing and curing of concrete. It must have a reasonable pH and it must also be inert in respect to the materials with which it may come in contact. These include various building products, wiring, piping, fasteners, system components, paints and other wall coverings, adhesives, drapery, appliances, furniture, cleaning materials and insulation (on outer faces).

4.3.2.5 Considerations of toxicity, flammability and nuisance

The PCM in concrete must be non-toxic and such that injury cannot result from skin contact, ingestion or inspiration of it or any compound it may form in the concrete.

The incorporation of a PCM into a concrete building material must not constitute a fire or fume hazard, so it should be non-flammable or at least, fire resistant. The danger of explosion must be non-existent, whether caused by heat, shock or spontaneous reaction.

There are certain nuisance factors to be avoided when selecting a PCM. These include, particularly, the use of materials which may cause allergic reactions or result in an unpleasant odour.

4.3.2.6 Economic considerations

Since it is probable that the use of heat storing building materials will increase, it is important that the supply of PCM's used for that purpose be sufficiently abundant so as not to result in a shortage which will cause manufacturing difficulties and an escalation in price.

The materials for the PCM's selected should be such that they are readily available. Preferably, they should be obtained from renewable sources and/or be a by-product.

The principal factors relating to the total cost of thermal storage (Feldman, 1987) are:

(i) thermal storage material
(ii) processing
(iii) containment
(iv) maintenance of containers
(v) storage space

(vi) heat exchanger for heat absorption and discharge

(vii) heat collection and distribution facilities

It will be seen that a PCM which can be incorporated directly into the concrete eliminates considerations (iii), (iv) and (v). Item (vi) is obtained without cost since the large surface area of concrete enables it to function as an effective convective and radiative heat exchanger, although it is expected to function chiefly in the convective mode. Item (vii) will vary in accordance with the mode of operation since concrete blocks can either function directly as absorbers and emitters of heat in situ or can serve purely in a thermal storage role with air being fed to and from them via the open cores from headers at floor and ceiling. In the latter mode, some form of air mover will usually be required and, if a single unit serves the whole building, a distribution and collection system will also be required. It will be noted that heat may be collected entirely within the building or it may include that from an external source such as a solar collector or exothermic process.

This leaves items (i) and (ii) to consider and it follows that the cost of the PCM and its incorporation plus the cost of any auxiliary equipment must be competitive with any other form of HVAC system by virtue of the energy saved. The term cost in this sense implies installed and operating expense over the life of the building.

4.3.3 Choice of PCM Candidates

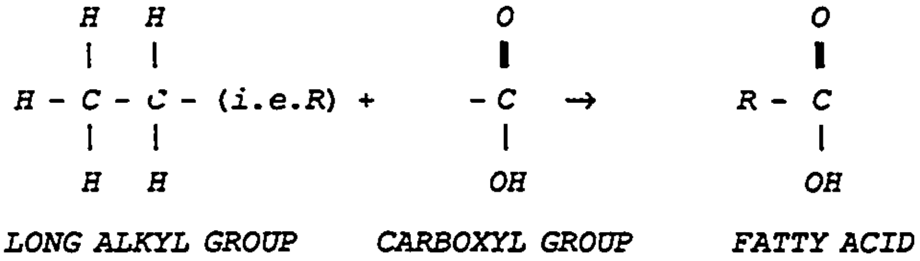
On the basis of the foregoing criteria, from study of the referenced literature and on the basis of previous work (Feldman, 1987) the principal PCM candidates chosen for study were narrowed down to the following:

(a) Butyl stearate(BS): CH_3-$(CH_2)_{16}$-$COO(CH_2)_3$-CH_3
(b) 1-Dodecanol(DD): CH_3-$(CH_2)_{11}$-OH
(c) Polyethylene Glycol(PEG): $H(OCH_2$-$CH_2)_n$-OH - Carbowax 600
(d) 1-Tetradecanol(TD): CH_3-$(CH_2)_{13}$-OH - EPAL 14 Alcohol
(e) Paraffin (PAR): CH_3-$(CH_2)_n$-CH_3
(f) Dimethyl Sulfoxide (DS): $(CH_3)_2$ SO

4.3.3.1 Characteristics of selected PCM's

(a) Butyl stearate (BS) (butyl octadecanoate)

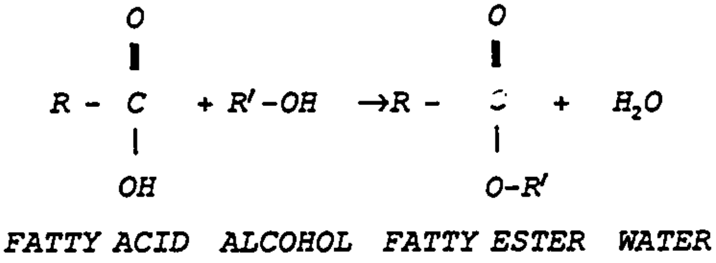
Fatty acids are a very useful group of organic PCM's and have been used successfully in inert building materials such as gypsum (Feldman, 1986; Feldman, 1987). They include capric acid, lauric acid and palmitic acid as well as various mixtures thereof. Fatty acids are a family of organic compounds comprising a carboxyl group which combines with an alkyl group as follows:



$$H-\overset{\displaystyle H}{\underset{\displaystyle H}{\overset{|}{\underset{|}{C}}}}-\overset{\displaystyle H}{\underset{\displaystyle H}{\overset{|}{\underset{|}{C}}}}-(i.e.R)\;+\;-\overset{\displaystyle O}{\overset{\|}{\underset{\displaystyle OH}{\underset{|}{C}}}}\;\rightarrow\;R-\overset{\displaystyle O}{\overset{\|}{\underset{\displaystyle OH}{\underset{|}{C}}}}$$

(eq. 6)

Another typical fatty acid is stearic acid: CH_3-$(CH_2)_{16}$-COOH which is principally derived from meat processing waste. However, it is not practical to place a fatty acid in direct contact with most concretes because the consequent acid-alkali reactions result in a modification of the PCM. For this reason, when selecting PCM candidates from this group for incorporation in concrete, it was decided to replace a fatty acid with a fatty ester which is less reactive with concrete. A fatty ester is produced by reacting a fatty acid with alcohol in a reactor as follows:



$$R-\overset{\displaystyle O}{\overset{\|}{\underset{\displaystyle OH}{\underset{|}{C}}}}\;+\;R'-OH\;\rightarrow R-\overset{\displaystyle O}{\overset{\|}{\underset{\displaystyle O-R'}{\underset{|}{C}}}}\;+\;H_2O$$

(eq. 7)

For example, the conversion of stearic acid into the ester butyl stearate (BS), one of the principal PCM's used in this work, is as follows:

CH_3-$(CH_2)_{16}$-$COOH+CH_3$-$(CH_2)_3$-$OH = CH_3(CH_2)_{16}$-$COO(CH_2)_3$-CH_3+H_2O (eq. 8)

STEARIC ACID + BUTYL ALCOHOL = BUTYL STEARATE + WATER

Butyl stearate (BS) was chosen as a PCM principally because of its relatively low cost, ready availability, low melting point, reasonable latent heat value, low flammability and stability. It is soluble in alcohol and ether but insoluble in water. Closely allied to this ester is propyl palmitate which could be used as an alternative PCM of this type if necessary. It is also soluble in alcohol and ether but insoluble in water.

Some of the relevant characteristics of butyl stearate are:

melting point: 19°C
latent heat: 140 J/g
viscosity: 0.0028 Ns/m^2 at 80°C
molecular weight: 340.57
density: 0.855 - 0.860 g/cm^3 (25/25°C)
boiling point: 222°C
flash point: 160°C (ASTM D92)
auto ignition temp.: 355°C
cost: $1.34 (Cdn)/kg, Oct. 1990

(b) Dodecanol (DD) (lauryl alcohol)

Dodecanol, CH_3-$(CH_2)_{11}$-OH, is a fatty alcohol which, like BS, is soluble in alcohol and ether but not soluble in water. It is derived from renewable sources, being found as a glyceride in vegetable fats such as coconut and laurel oils. It is also synthesized by a process in which ethylene, an aluminum powder catalyst, oxygen and water are combined to produce even carbon number primary alcohols.

Dodecanol (DD) was selected as a PCM because it is a common substance which is easily available at moderate cost, has a high latent heat and was likely to be chemically stable in concrete because of its low reactivity with mature concrete products. Some of the relevant characteristics of dodecanol are:

melting point: 24-27°C
latent heat: 200 J/g
viscosity: 0.0029 Ns/m^2 at 80°C
molecular weight: 186.33
density: 0.820 g/cm^3
boiling point: 255°C
cost: $1.82 (Cdn)/kg, Oct. 1990

(c) Polyethylene glycol (PEG)

Polyethylene Glycol, $HOCH_2$-CH_2(-O-CH_2-CH_2-)$_n$OH, was chosen from a family of colorless, water soluble liquids having molecular weights in the 200 to 6000 range. PEG is soluble in aromatic hydrocarbons and many organic solvents.

The PEG selected from this group has an acceptable latent heat, a moderate cost and is readily available.

Some of the relevant characteristics of PEG 600 are:

melting point: 20°C
latent heat: 130 J/g
viscosity: 0.0992 Ns/m^2 @ 30°C

molecular weight: 600
density: 1.12 g/cm^3 @ 25°C
flash point: 232°C (ASTM D92)
cost: $1.96 (Cdn)/kg, Oct. 1990

(d) Tetradecanol (TD) (myristyl alcohol)

Tetradecanol CH_3-$(CH_2)_{12}$-CH_2-OH is a fatty alcohol which is soluble in ether and alcohol but is insoluble in water. It is used as a chemical intermediate, plasticiser and perfume fixative.

melting point: 38°C
latent heat: 205 J/g
viscosity: 0.0105 Ns/m^2
molecular weight: 214.4
density: 0.822 g/cm^3 @ 38°C
flash point: 140.5°C (ASTM D92)
cost: $2.27 (Cdn)/kg, Oct. 1990

(e) Paraffin (PAR)

Paraffin, CH_3-$(CH_2)_n$-CH_3, is a macrocrystalline wax derived from petroleum and is a by-product of the oil refining process and consists principally of normal alkanes. It is produced in large quantities and is readily available throughout the world. As well as having the desired thermal characteristics, paraffin is also suitable as a PCM because of its stability, low cost and ready availability. It is particularly useful for thermal storage applications around the intermediate range

(50-60°C) where low cost heat is available within these temperature limits from sources such as solar collectors or exothermic processes.

Some of the relevant characteristics of PAR are:

melting point: 61°C

latent heat: 200 J/g

viscosity: 0.0053 Ns/m^2 at 80°C

molecular weight: 400

density: 0.915 g/cm^3 @ 25°C, 0.778 g/cm^3 @ 80°C, 0.769 g/cm^3 @ 100°C

flash point: 232°C (ASTM D92)

cost: $0.88 (Cdn)/kg, Oct. 1990

(f) <u>Dimethyl sulfoxide (DS)</u>

Dimethyl sulfoxide $(CH_3)_2$ SO is an ether which is soluble in water, alcohol and ether. It is in general use as an industrial solvent and as a laboratory medium for chemical reactions. It is also an analgesic and anti-inflammatory agent.

melting point: 17.2°C

latent heat: 166 J/g

viscosity: 0.00198 Ns/m^2 at 25°C

molecular weight: 78

density: 1.10 g/cm^3 at 20°

flash point: 95°C (ASTM D92)

cost: $1.50 (Cdn)/kg, Oct. 1990

4.4 SELECTION OF MEANS OF INCORPORATING PCM IN CONCRETE

In the course of this research three principal means of introducing PCM in concrete were examined. They are as follows:

4.4.1 Direct Incorporation

This process involves incorporation of the PCM directly into the concrete mix. It is potentially a practical and possibly the least expensive method but its successful application depends upon four critical factors.

(i) The introduction of PCM to the mix must not interfere with the hydration process.

(ii) The presence of PCM in the mix must not affect the strength of the paste-aggregate bond in the concrete.

(iii) There must not be any significant reaction between the PCM and either the components of the mix or the products of hydration.

(iv) The production process must not entail the use of temperatures significantly higher than the range of intended operation for the PCM concrete.

While direct incorporation is not the principal means of producing PCM-concrete studied in this work it is, nevertheless, a potentially useful one, so several procedures were selected for investigation. These comprised:

(i) The introduction of varying amounts of TD in powder form.

(ii) The introduction of PAR in the form of small cylinders.

(iii) The pre-impregnation of expanded shale and pumice aggregate with BS, DD and PEG.

It will be noted that, in its liquid state, PCM is retained in the voids and capillaries by surface tension, viscosity and hydrogen bonding which will be discussed later so that it is not necessary to encapsulate it for reasons of retention in the material. It will be recalled that surface tension and viscosity are affected by temperature and that, as a result, the amount of material retained is also thereby affected.

4.4.2 Immersion

This technique involves dipping blocks in liquid PCM. It is the method which has been used in the preparation of most of the specimens now under study. The process is quite flexible and could range from an automated continuous production line to a simple and relatively inexpensive batch process. Study has indicated that, whereas this procedure may be more expensive than a successful direct incorporation method, the unit cost differential between the two methods is probably not significant because the production quantities are so large. In addition to being suitable for an in-line production process, the immersion process also has the added advantage of being suitable for use with ordinary blocks from stock to meet market demand.

This procedure, being simple and more suitable for laboratory scale experimentation, was selected as the principal means of incorporating PCM's during this research. In addition, the results of incorporation by other methods were examined and compared in some cases.

4.4.3 Encapsulation

This procedure is a variation of the direct incorporation process in which the PCM is fed into the mix in encapsulated form. The choice of encapsulant is critical since it must have the following properties:

(a) it must not react with the chemicals in either the PCM or the concrete
(b) it must have reasonably good heat transfer properties
(c) it must withstand the rigours of manufacturing, transport, construction and use
(d) it must be in a form convenient for incorporation into the concrete mix

There are two principal means of incorporation:
microencapsulation and macroencapsulation.

(a) Microencapsulation

This is a process whereby small, spherical or rod shaped particles are enclosed in a thin, high molecular weight polymeric film. This can be achieved through emulsion polymerization followed by membrane formation around each microdroplet by interfacial polymerization. The coated particles can then be incorporated in any matrix which is compatible with the encapsulating film. It follows that the film must be compatible with both the PCM and the matrix. It must also be flexible enough to accommodate volume changes in the PCM and strong enough to withstand the mechanical stress of manufacturing, installation and service (Baxter, 1977; Chang 1984).

(b) Macroencapsulation

This procedure comprises the inclusion of PCM in some form of package such as tubes, pouches, panels or other receptacle. These containers can serve directly as heat exchangers or they can be incorporated in a building product. As in the case of microencapsulation, care must be exercised in respect to compatibility of film and PCM as well as film and matrix. Since the capsules are larger than in the case of microencapsulation, the weight ratio of PCM to encapsulant is probably greater in this case. Whereas this means that the material cost of capsules is likely to be less, this advantage will be offset by the cost of filling them. So, unless a large scale production process is costed in detail, it is not possible to state definitely at the present time which of the two processes is the less expensive. The thicker film required in macroencapsulation will slow down the heat transfer process but will be more suitable for use in concrete mixing.

4.5 FLAMMABILITY ASPECTS

The flammability of all materials used in buildings is an important consideration, particularly in respect to safety and structural integrity. For this reason, the flammability of PCM used, its weight proportion to the concrete and the application of the impregnated building product are factors which will affect whether or not a fire retardant is required. In the event that one is found to be necessary, it must be carefully selected to meet the following requirements:

(i) be effective with the particular PCM used for the control of fire spread as well as limiting toxic fume and smoke generation;

(ii) remain effective throughout the life of the PCM;

(iii) have zero or very low toxicity;

(iv) be compatible with both PCM and concrete;

(v) be available at low or moderate cost.

It should be noted that some well known fire retardants such as inorganic salts are effective, cheap and non-toxic but they have a relatively short service life. In addition, whereas many fire retardants can effectively control flame spread, this function is unfortunately accompanied by an increase in smoke generation which is, in itself, a serious hazard.

Fire tests of impregnated concrete must be conducted at an approved fire testing facility in any event. These tests will determine the fire resistance and also the flammability of the product. They will also ascertain whether or not a fire retardant is necessary and provide some indication of the requisite degree of retardation. If required, an appropriate fire retardant will then be selected and incorporated so that the product can be given a final approval test.

At this time fume tests must also be conducted to determine the amount and the type of fume generated during a fire and hence the degree of hazard inherent in the product.

For the present research, study of the flammability aspects of various PCM concrete combinations was confined to use of the equipment described in section 5.9.

CHAPTER 5

TEST PROCEDURES FOR PCM CONCRETE SPECIMENS

5.1 CONCRETE PREPARATION, MEASUREMENT AND IMMERSION

Concrete for the test specimens was either cut from commercially available concrete block or was prepared and cured in the laboratory. The test specimens were cut with a minimum thickness of approximately 33 mm which is about the average thickness of the wall of a concrete block. The length and width varied with the test requirements. Mixing for small amounts of concrete was done in a Bakeslee Bench Model Mixer while that for larger amounts was carried out in a Bakeslee Model B-20 Mixer.

In order to obtain uniform results, immediately prior to immersion the specimens were dried and preheated to the requisite temperature in a circulating oven. Preheating temperatures varied and are described later. The oven used was a Fisher Isotemp Oven Model 350. This oven was also used for curing concrete by sealing the fresh concrete in plastic to prevent moisture loss.

The specimens were weighed before and after immersion and appropriate intervals up to the completion of research. Weighing was performed on an Ohaus Dial-O-Gram Balance (2610 g). This balance was also used to weigh small quantities of mix ingredients while larger quantities were weighed on an Ohaus Heavy Duty Solution Balance (20 Kg).

Immersion of the specimens was performed in a stainless steel vessel containing the required PCM which was heated to the required temperature in a Lab-line Imperial III Constant Temperature Bath. The PCM temperature and the immersion times are given later.

5.2 DIFFERENTIAL SCANNING CALORIMETRY (DSC) ANALYSIS

Thermal characteristics of the specimens were measured on a Du Pont 910 Differential Scanning Calorimeter. Each test required approximately 2 mg of material which was obtained from 5-10 g samples which were taken from the specimens then pulverized and thoroughly mixed. The results of these analyses are printed in graphical form. A typical example is given in Figure 1 which shows the results of a DSC analysis of BS. It will be noted that the latent heat in Joules per gram (J/g) for PCM is about 130 for PEG, 140 for BS, 166 for DS and 200 for DD, TD and PAR. This may be compared with the sensible heat of concrete through a temperature rise of 6°C which is only about 5.3 J/g. The addition of 3.5% by weight of DD to concrete block will raise its thermal storage capacity through the 6°C centred on the melting point of DD from 1.15 MJ/m^2 to 2.67 MJ/m^2, a gain of 133%.

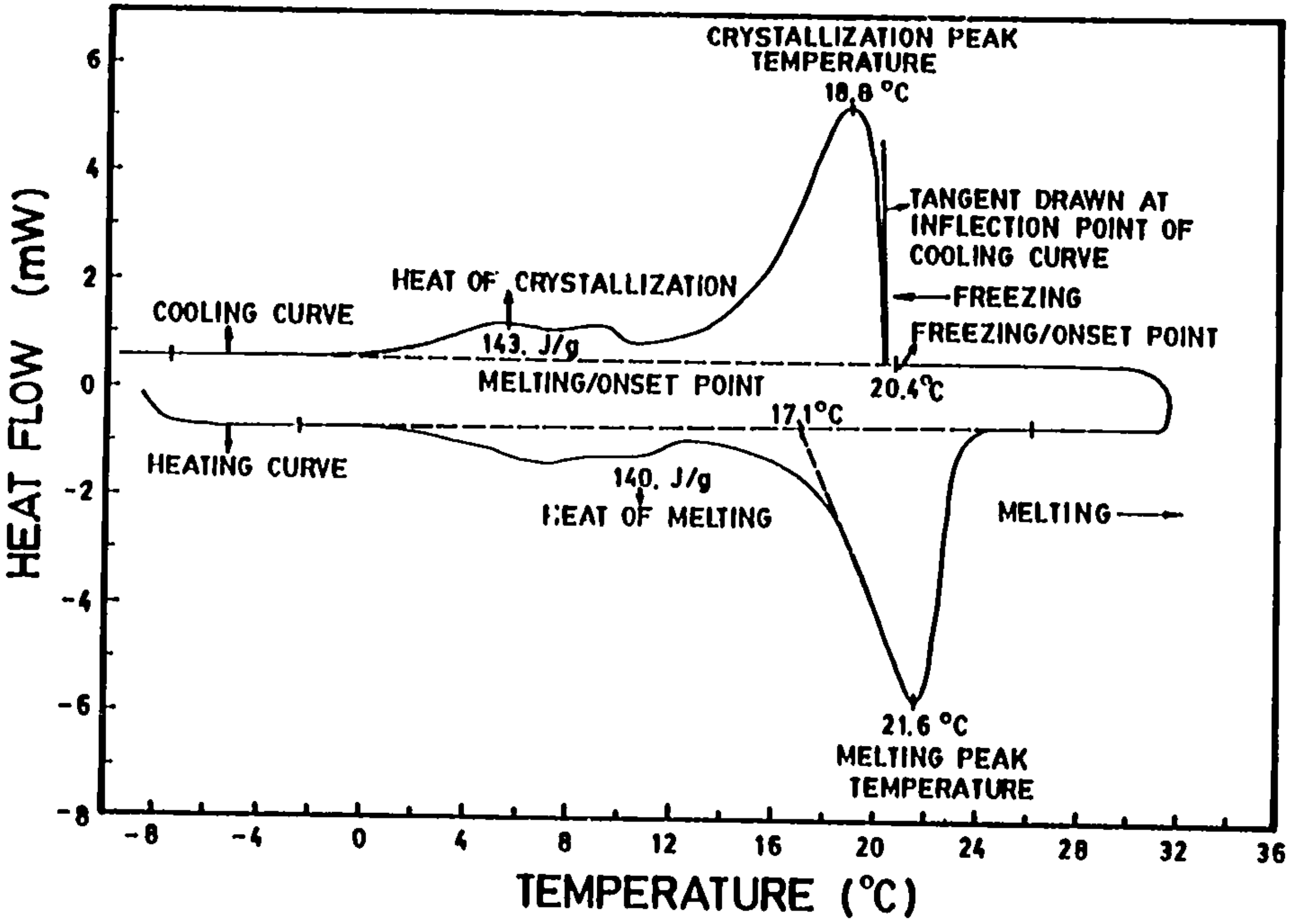


FIGURE 1 - DSC ANALYSIS OF BUTYL STEARATE

The following thermal characteristics are analyzed:

(i) melting point

(ii) latent heat of melting

(iii) freezing point

(iv) latent heat of crystallization

(v) melting curve characteristic

(vi) cooling curve characteristic

In addition to the foregoing data, successive DSC tests of the same sample provide a good indication of PCM stability in concrete. A principal cause of instability is reaction of the PCM with different compounds of concrete and, when this occurs, some or all of the PCM will be altered and this will be reflected in a change of thermal characteristics, including a deterioration of latent heats or phase transition temperatures. Other causes of deterioration include excessive heating, chemical contamination and physical damage.

Figures 2, 3 and 4 are representative of values obtained when various PCM's are incorporated in concrete and the impregnated concrete was analyzed.

These tests were carried out periodically throughout the duration of the work.

The rate of heating and cooling used throughout these tests was 2°C/min. This rate was based upon previous work which was found to be satisfactory. As

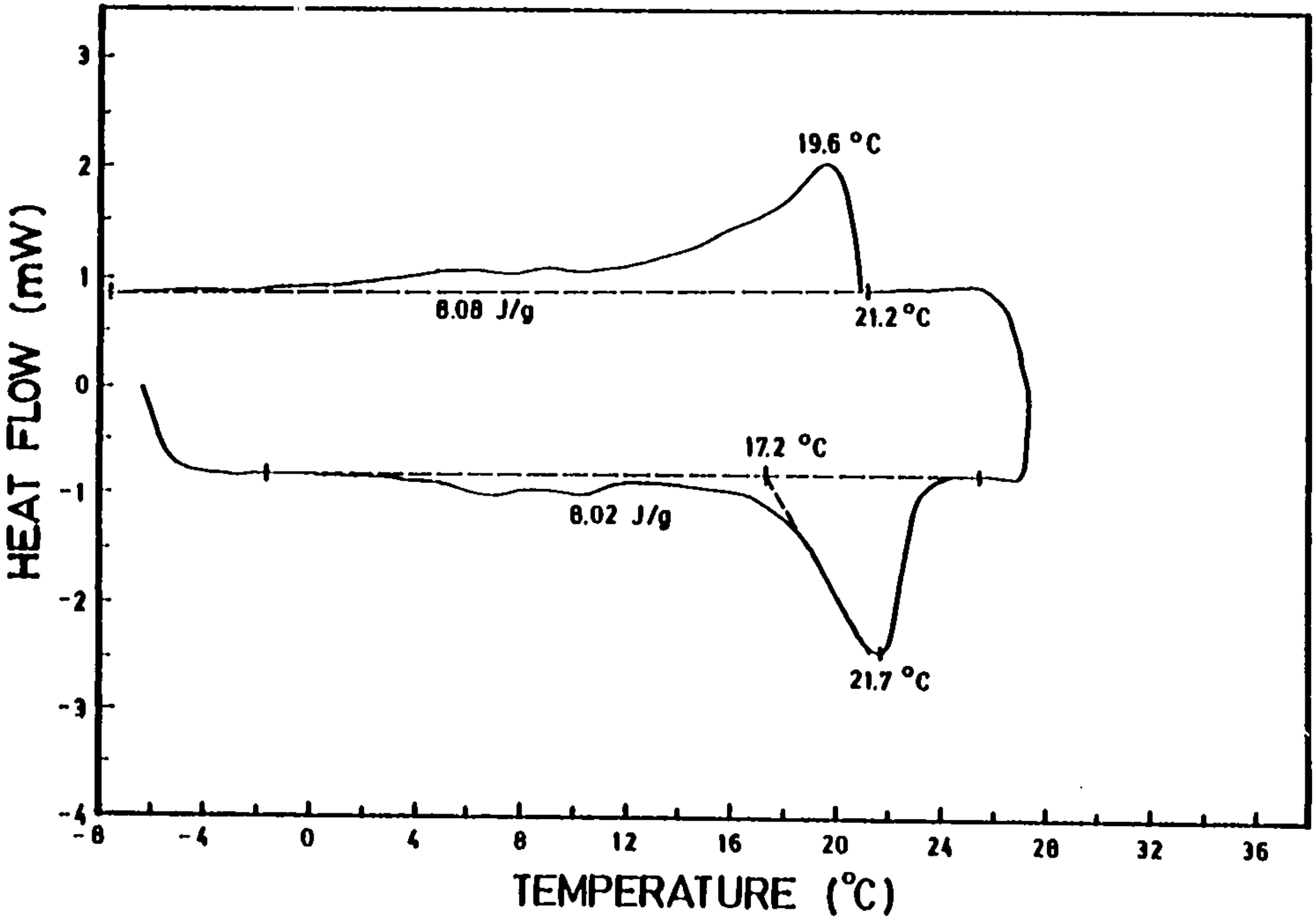


FIGURE 2 - DSC ANALYSIS OF BUTYL STEARATE IN AUTOCLAVED BLOCK

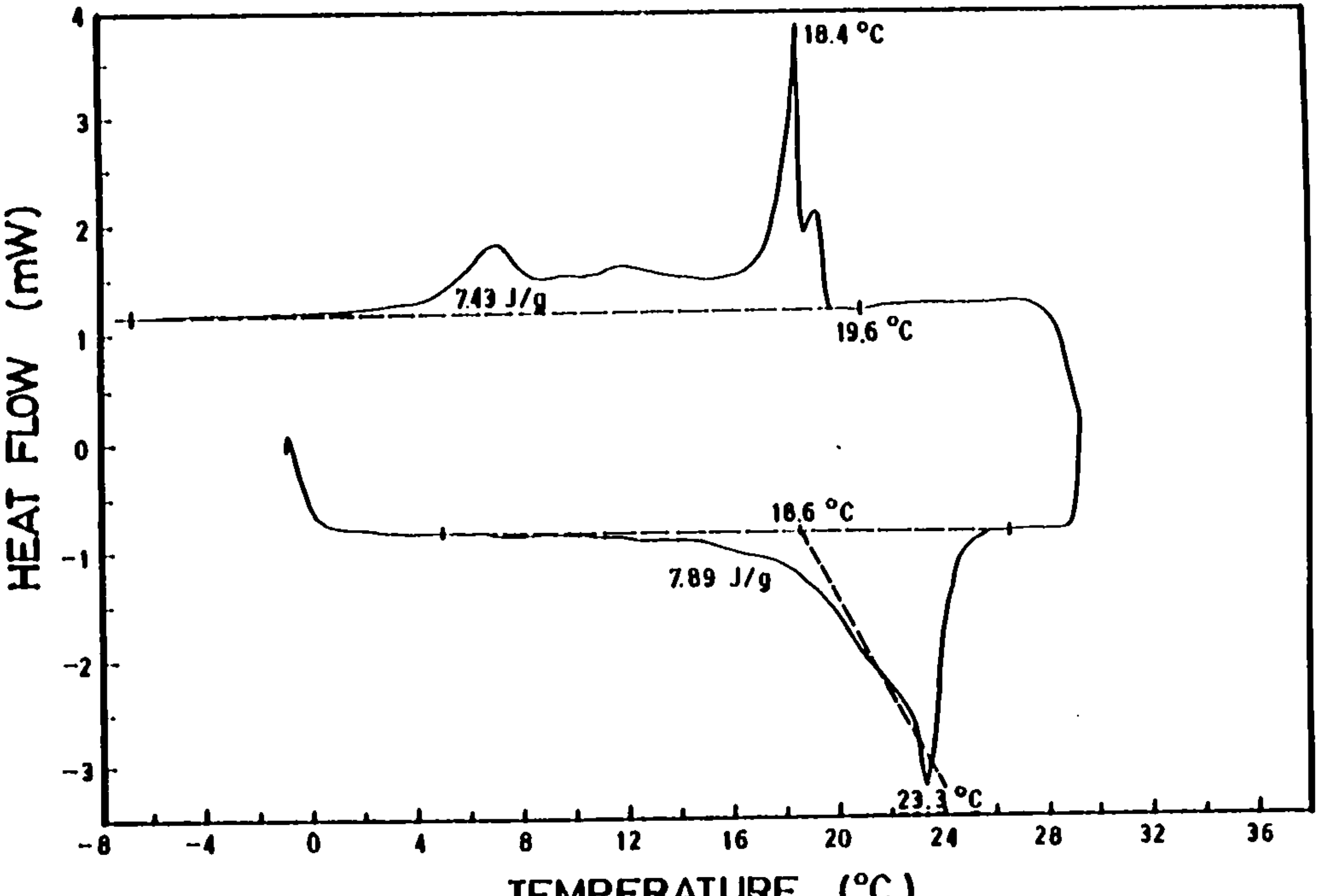


FIGURE 3 - DSC ANALYSIS OF DODECANOL IN AUTOCLAVED BLOCK

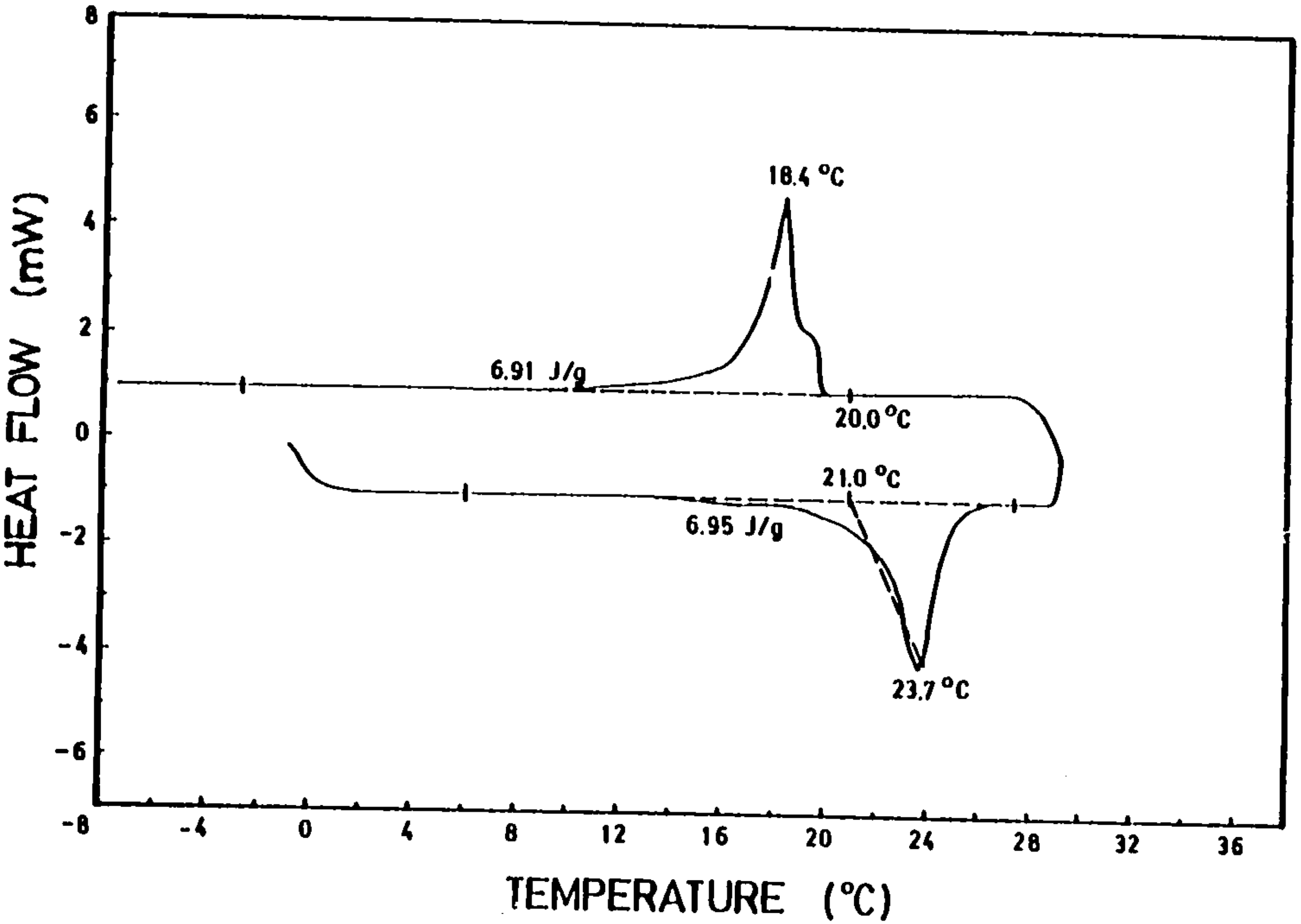


FIGURE 4 - DSC ANALYSIS OF DODECANOL IN REGULAR CONCRETE BLOCK

a check, some comparative tests were carried out at a rate of 0.2°C/min. but no advantage was found in conducting the analyses at a slower rate. The apparatus is shown in Figure 5. Also shown is a Sartorius Microbalance Model 4501 which was used to weigh the DSC specimens.

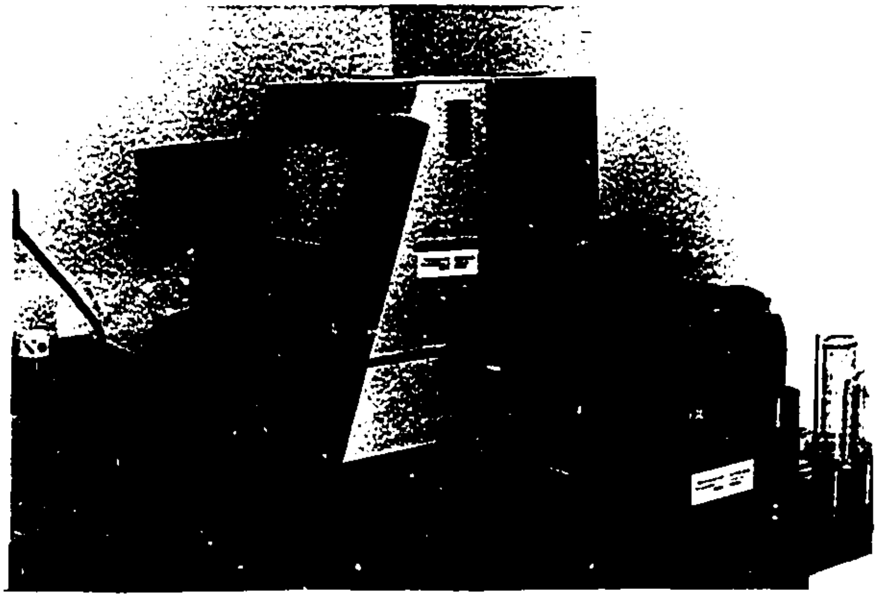
5.3 PCM ABSORPTION TESTS

Adequate absorptivity is one of the principal requisites of concrete to be used with PCM so this characteristic was measured in each instance. The weight of PCM absorbed was determined gravimetrically. In the case of multiple immersion, weighing was performed immediately before and immediately after each immersion. In addition, the samples were weighed periodically to ascertain if any weight difference had occurred due to loss of PCM, absorption or loss of moisture or for any other reason. A series of absorption tests were conducted wherein the variation of certain parameters were studied to observe their effect upon the absorption of PCM. In addition, a technique was developed for the definition of absorption constants to be applied to each combination of concrete and PCM.

5.4 WATER ABSORPTION TESTS

Tests are performed to measure the water absorption of several types of unimpregnated and impregnated concrete using various PCM's. Specimens were first weighed, then immersed in water at room temperature for 24 hours, removed from the bath, drained and then weighed again. By comparing the difference in

DIFFERENTIAL SCANNING CALORIMETER AND AUXILIARIES



THERMAL ANALYSER (COMPUTER/PRINTER) AND DYNAMIC MECHANICAL ANALYSER

FIGURE 5 - EQUIPMENT FOR MEASURING THERMAL CHARACTERISTICS

the amount of water absorbed between impregnated and plain concrete the effect of PCM on water absorption was determined.

5.5 THERMAL CONDUCTIVITY TESTS

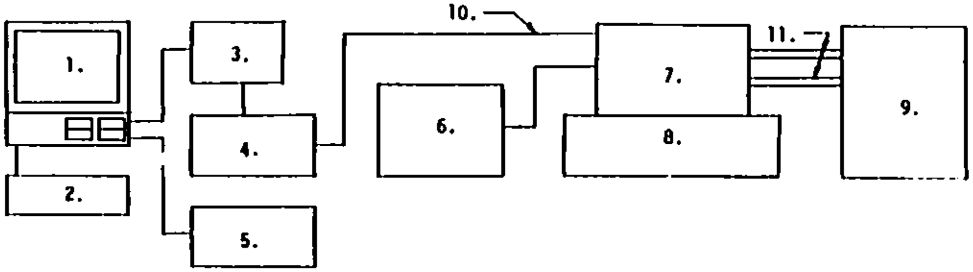
A series of tests were performed to measure the thermal conductivity of various PCM and concrete combinations and to compare them with each other and with unimpregnated concrete of each type. The guarded hot plate technique was used and the equipment is shown in Figure 6.

5.6 TEMPERATURE CYCLING TEST

For this test specimens were placed in a controlled environment chamber and cycled through approximately 500 six-hour temperature cycles, each ranging between -25°C and + 33°C. This facility, designed and built by Controlled Environments Inc. has a temperature accuracy of ± 2°C. It is shown in Figure 7.

5.7 FLEXURAL STRENGTH TESTS

A representative number of strength tests were conducted with both unimpregnated and impregnated specimens for comparison. These tests were conducted on an Instron Model 1125 Universal Testing Instrument. This apparatus comprises a loading frame and console which is used for carrying out tension, compression and reverse stress tests. This apparatus is shown in Figure 7.



1. - IBM PC AND SCREEN
2. - IBM KEYBOARD
3. - FLUKE MULTIMETER MODEL 8840A
4. - FLUKE SWITCH CONTROLLER MODEL 2205A
5. - EPSON SPECTRUM PRINTER MODEL LX80
6. - LAMBDA REGULATED POWER SUPPLY MODEL 342A
7. - THERMAL CONDUCTIVITY TEST CABINET
8. - DYNATECH GUARDED HEAT PLATE THERMAL CONDUCTIVITY INSTRUMENT MODEL TCFGM-N4
9. - LAMBDA COOLANT CIRCULATOR MODEL RCS
10.- THERMOCOUPLE SENSOR LEADS
11.- COOLANT PIPES

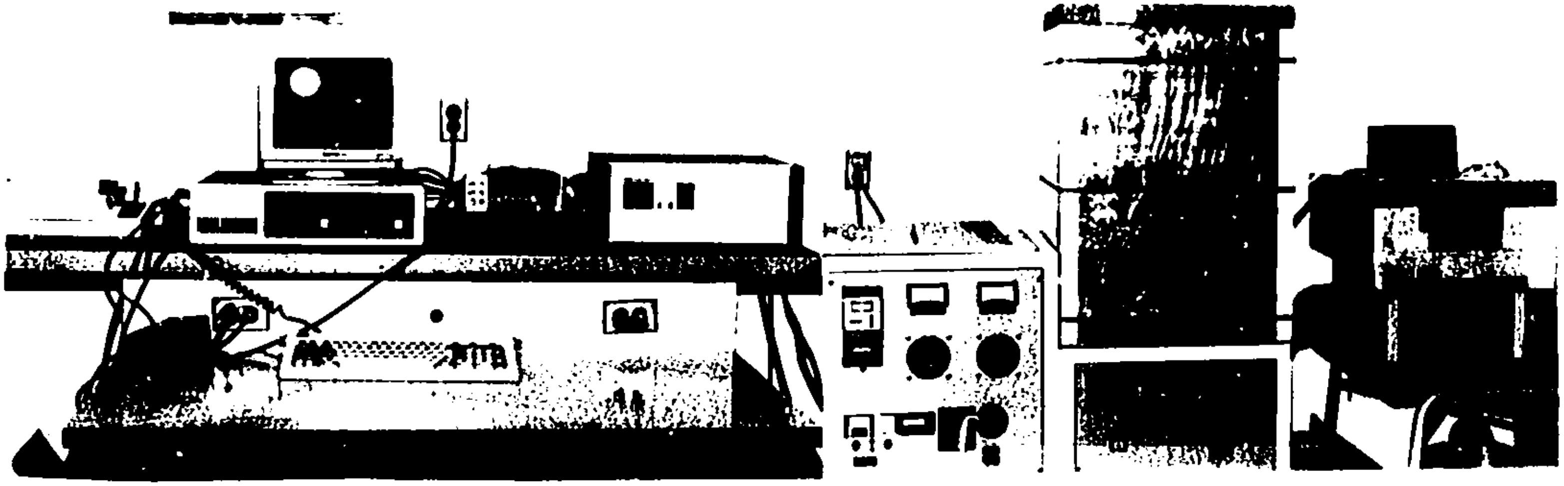


FIGURE 6 - THERMAL CONDUCTIVITY MEASUREMENT APPARATUS

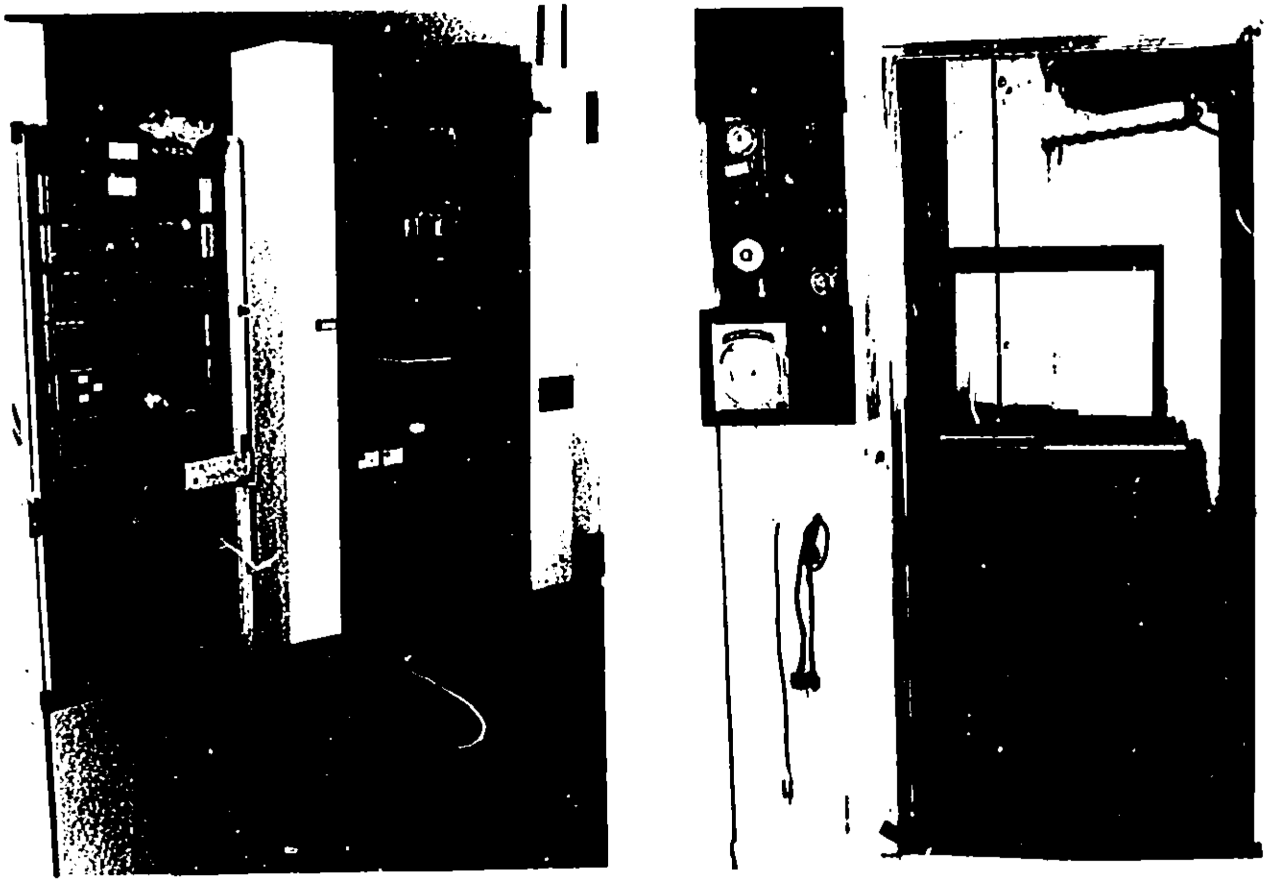


FIGURE 7 - INSTRON UNIVERSAL TESTING INSTRUMENT AND CONTROLLED ENVIRONMENT CHAMBER

5.8 CHEMICAL ANALYSES

Representative specimens were periodically analyzed to determine the effectiveness of measures to control alkalinity in the concrete and also as a check of PCM stability. These are described later.

5.9 FIRE TESTS

These tests were conducted in the CBS laboratories. They comprised directing a 700°C (± 10°C) flame for 10 minutes at a specimen impregnated with PCM.

The test and the apparatus used, which is shown in Figure 8, was designed to approximate the flame resistance and flame spread tests conducted at the National Research Council Institute for Research in Construction or other comparable fire testing facility and is based upon the ASTM 60 cm tunnel (ASTM, D3806).

Subsequent to the present stage of development it will be necessary to confirm the results of the above test with a full scale fire rating and fume measurement test.

5.10 EQUIPMENT LIST

Blakeslee Concrete Mixer-Bench Model

Blakeslee Model B-20 Concrete Mixer

Ohaus Heavy Duty Solution Balance (20 kg)

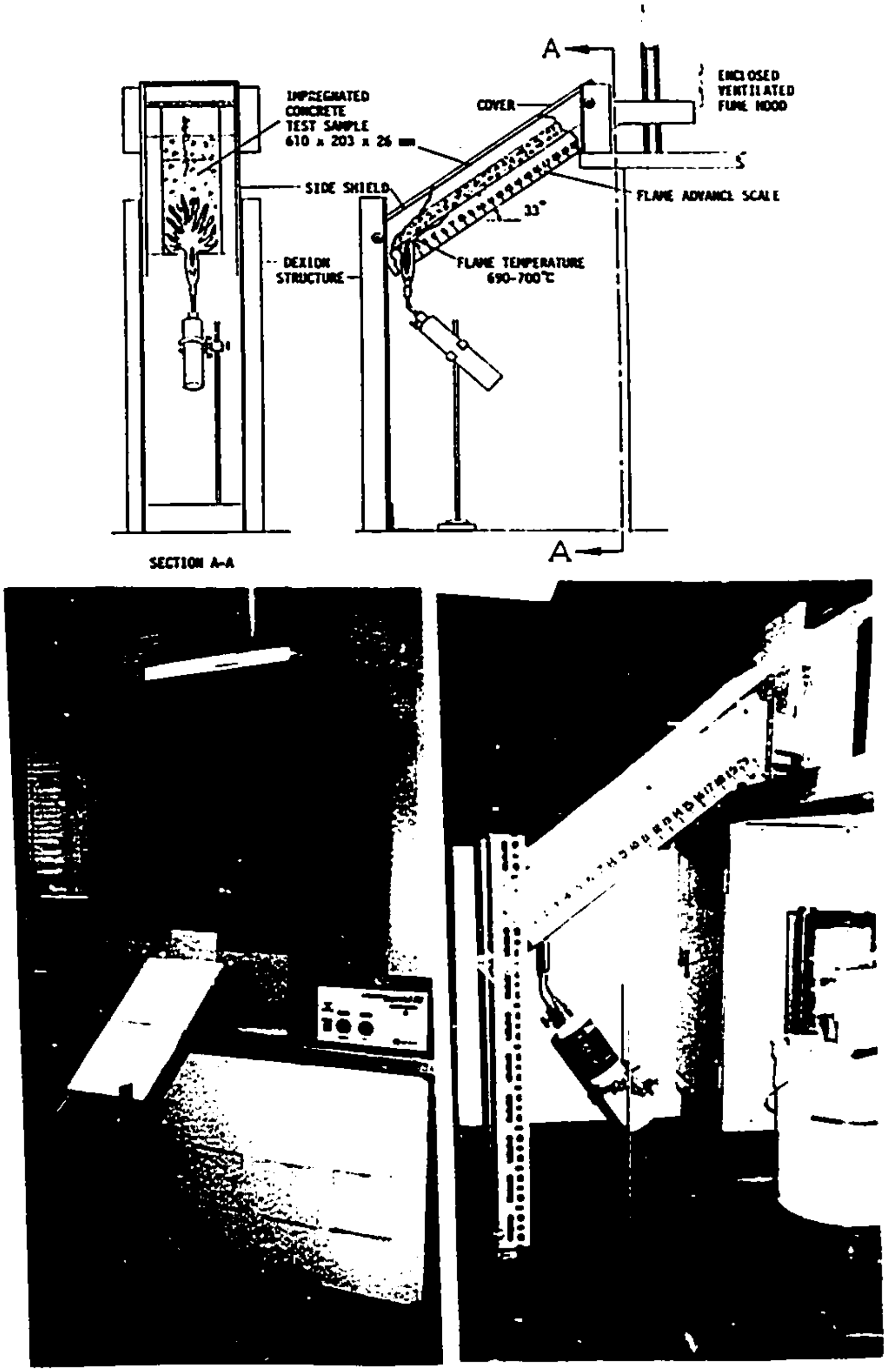


FIGURE 8 - FLAME SPREAD MEASUREMENT APPARATUS AND FUME HOOD

Ohaus Dial-O-Gram Balance (0 - 2610 g)

Fisher Isotemp Oven Model 350

Lab-line Imperial III Water Bath

Du Pont 910 Differential Scanning Calorimeter

Sartorius Model 4501 Microbalance

Thermal Conductivity Instrument Dynatech Model TCFGM-N4 with IBM-PC, printer and auxiliaries

Temperature cycling chamber manufactured by Controlled Environments with a variable frequency cycle, temperature range from - 30°C to 40°C and an accuracy of ± 2°C

Instron Model 1125 Universal Testing Instrument

CBS Flame Spread Measurement Apparatus

Fisher Surface Tensiomat

Ubbelohde Type Viscometer (Certif No. B828)

Olympus BH Microscope (50 X Magnification)

Doric Trendicator 400A Type T/°C with Doric Multipoint Selector 405A, with copper-constantan type thermocouples for temperature indication (used in preliminary work)

CHAPTER 6

CHARACTERIZATION OF PCM CONCRETE

6.1 EXPERIMENTAL PROCEDURE DATA TABULATION

The data obtained from a series of procedures involving the incorporation of several PCM's in different types of concrete under various conditions are tabulated in Appendix A, Tables A1 to A51. The results of this work are set forth in diagrams, photos and text and are analyzed in the following sections.

6.2. STUDY OF MEANS OF PCM INCORPORATION

It will be recalled that the three principal means of PCM incorporation are:

(a) direct incorporation

(b) immersion

(c) encapsulation

Although all three methods were studied, emphasis was placed on the immersion process for reasons of flexibility, simplicity and suitability for laboratory scale procedures.

6.2.1 Direct Incorporation

While direct incorporation is not the principal means of incorporation studied in this work, it is certainly an important method, so three ways of using this procedure were investigated and these are discussed below. To avoid interference with the hydration process, two of the PCM's used (TD, PAR) were introduced directly into the concrete mix in solid form which, therefore, required no carrier. The melting temperature of these PCM's was above that normally encountered in mixing, placing and curing some types of concrete. They would be appropriate for heating applications with a flat plate solar collector or other heat source which operates above the human comfort temperature. The desired air temperature would then be simply attained by conventional mixing techniques to provide a wide range of temperature modulation. The details are as follows.

(a) Direct incorporation of powdered PCM

TD was finely ground and the resulting powder was introduced at the end of the dry mixing sequence. Three PCM proportions were used: 5%, 7.5% and 10% of total dry concrete weight. Specimens of all three proportions are well formed and have a smooth, pleasing appearance. The plasticity of the mix improved with the increase in PCM content and this will undoubtedly be of benefit in forming concrete products.

(b) Direct incorporation of small solid particles

PAR was formed into 3 mm diameter cylinders approximately 4 mm long which were introduced in the same manner and in the same proportions as for TD. The PAR specimens were also well formed with an even, attractive finish. The improvement in plasticity of the mix over a conventional concrete was again noted, although it was slightly less marked than in the case of the addition of TD powder.

(c) Direct incorporation of pre-impregnated aggregate

It was also found that if compatible PCM's were used to impregnate expanded shale, expanded slag and pumice aggregate, direct incorporation could be achieved, although further work is required to refine this technique. It was noted that the incorporation of PCM in a porous carrier did not seriously inhibit a reaction between the absorbed PCM and the hydration products in the concrete so that care must be exercised in selecting a PCM which is compatible with both the aggregate and the concrete.

The direct incorporation methods investigated were found to be practical, easy to control and are procedures which would easily lend themselves to a wide variety of concrete pouring techniques as well as to the production of concrete products. It could also be used for pargetting where the applied layer is thick enough to be effective.

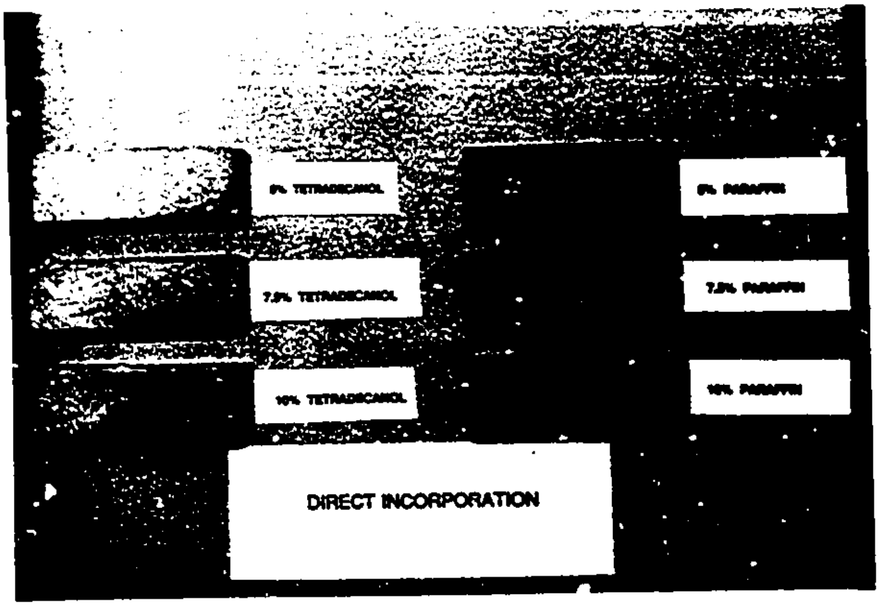
There are, however, two important caveats to be observed in respect to direct incorporation. In the case of procedures (a) and (b) it should be noted that PCM's used in these procedures must be intended for applications where the phase change is required at a temperature higher than that prevailing during the mixing and setting of the concrete so that the PCM remains in the solid state during these processes and does not, therefore, interfere with hydration nor destroy the paste-aggregate bond. The second caution applies to all three procedures where the subsequent application of high temperature curing could result in PCM loss through vaporization, and under certain circumstances, could also constitute an explosion hazard during processing.

Specimens of directly incorporated PCM's are shown in Figure 9.

6.2.2 Immersion

The main area of investigation comprised the use of the immersion process because, at this stage of development, it remains the most flexible one since it can be applied to a wide range of PCM transition temperatures. It was also found to be easy to control and susceptible to a wide variation of process conditions such as temperature of PCM introduction, temperature of concrete, time of immersion and number of immersions. These technical variations are discussed below.

In addition to the foregoing advantages, this method can be used to impregnate ordinary concrete products, either as part of the continuous production process or as a batch process which can be applied to concrete products drawn from stock at any time. Moreover, since the facilities required for immersion are relatively simple and not necessarily related to the basic product process, they can be set up at any convenient place in, adjacent to or remote from the concrete block plant. It follows, therefore, that immersion can be carried out at distribution centres where a wide variety of impregnated concrete products can be supplied from ordinary product inventories as and when required. In addition, this process



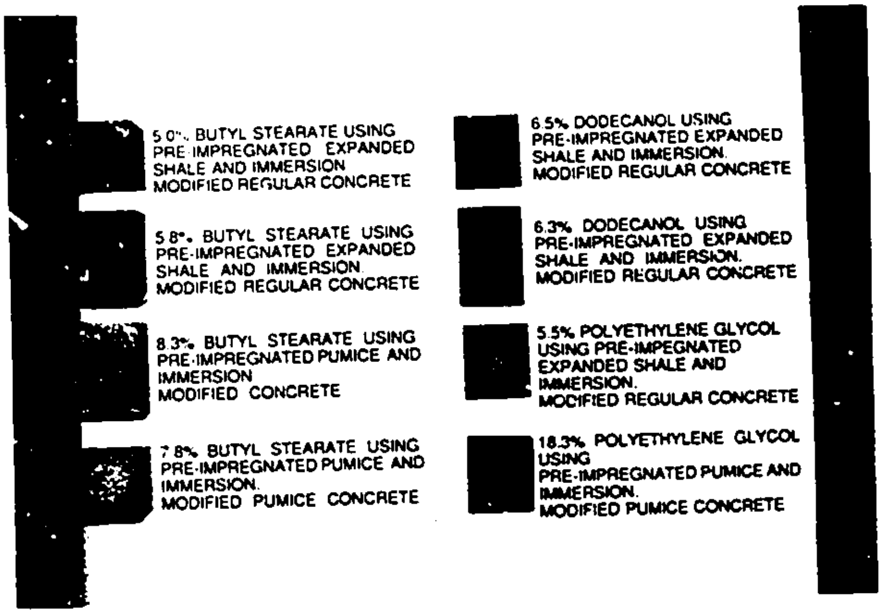


FIGURE 9 - VARIOUS PCM CONCRETE SPECIMENS

is particularly suited to a developing market until the demand for types and quantities of each item is established because the impregnated product can be produced at source using whatever immersion technique is most appropriate.

The principal limitation of this technique is that it cannot be applied to poured concrete structures.

6.2.3 Encapsulation

This process comprises the envelopment of PCM within a capsule of various materials, forms and sizes prior to incorporation so that it may be introduced to the mix in a convenient manner.

(a) Microencapsulation

Microencapsulation of the quantity of PCM necessary for effective latent heat storage in concrete was studied and deemed to be beyond the scope of the present work because it was considered unlikely to be cost effective at the present stage of development. However, it is possible that further study and development could render the process economically feasible.

(b) Macroencapsulation

Whereas it was felt that this procedure was also likely to be too costly at present, it was considered possible that a large market for PCM concrete could justify further research into a process which could become a useful method of direct incorporation. To that end, a limited study was carried out using capsules

5 mm in diameter and 15 mm long. It was found that the body and cap of the capsule had a tendency to separate in the mixing process. Freezing the capsule did little to alleviate the difficulty because some PCM's melted before mixing was complete. Nevertheless, this is not seen as a serious problem since a sealed, injection filled capsule could be used in full scale production. However, two problems of a more serious nature were encountered. The first was the fact that the low density capsules were apt to float to the top so that an even dispersion was not achieved. Since this was not found to be the case in the direct incorporation tests, it appears that there is a critical maximum size for encapsulated PCM. The second serious problem affecting the use of capsules of this size was the fact that they could be easily damaged when at or near the surface of the concrete. When pierced, the PCM can run out and not only cease to be effective but also cause staining of the adjacent surface. For these reasons, further work in this direction was discontinued since it was unlikely to become productive at this stage.

6.2.4 Conclusions

(a) Direct incorporation was proven to be feasible with materials such as pure TD and PAR in varying forms and proportions. In addition, direct incorporation was also found to be possible by using porous aggregates impregnated with compatible PCM's. In large scale production, the impregnation procedure is potentially the most economical and practical. However, the PCM's must be chosen to conform to the requirements of both the intended production process and product application.

(b) The immersion process proved to be simple, flexible and well suited to experimental investigation. It is also the process whereby any concrete product may be converted to PCM concrete. It cannot be used with cast-in-place concrete.

(c) Microencapsulation in likely to remain an uneconomical procedure. Macroencapsulation (5-10 mm), although more economical than microencapsulation, is still too costly. However, if a radically new approach to inexpensive means of encapsulation of concrete products were developed, the latter process might become practical and economical.

6.3 EVALUATION OF THERMAL PROPERTIES OF PCM CONCRETE

6.3.1 Experimental Results

Table 5 and Figures 10 to 15 illustrate the thermal performance of some specimens from the early stages of the work which were measured over a period of approximately one year.

The specimens in Table 5 were tested over a period of one year and comprise combinations of conventional, unmodified concrete block and PCM's which were considered likely to be stable from prior investigation. These

Table 5 - THERMAL PERFORMANCE OF IMPREGNATED CONCRETE

Specimen No.	Figure No.	Concrete	PCM	Melting Pt. °C	Freezing Pt. °C	Average Latent Heat J/g	Age days	% PCM by wt.
1	6	ABL	BS	16.1	15.8	3.35	364	3.7
17	7	REG	DD	18.6	19.2	3.27	364	2.5
31	8	ABL	BS	16.0	16.3	4.70	370	4.4
33	9	ABL	DD	15.1	17.0	4.52	370	2.8
37	10	REG	BS	16.8	20.7	3.80	370	2.3
39	11	REG	DD	17.8	17.4	3.75	370	2.5

specimens are for thermal storage in or near the human comfort zone. The impregnated concrete in this group can be used in several ways. It can be applied in a storage rôle wherein the air to be heated or cooled is passed through the cores in a block wall or it can be used to absorb or release heat at the outer surface as in walls, ceilings and floors or it can combine these functions. Later work included paraffin as a PCM which is intended for use solely in those applications where heated air in the 55-65°C range is available from solar collectors or an exothermic process. Also added later was TD with a transition temperature in the 35 - 38°C range. The discharged air from these types of thermal storage can be used directly in a processing function or can be mixed with cooler air for human comfort conditioning.

A number of points are worthy of note in Figures 10 to 15. An ideal curve will be characterised by being sharply defined at the transition points, having a

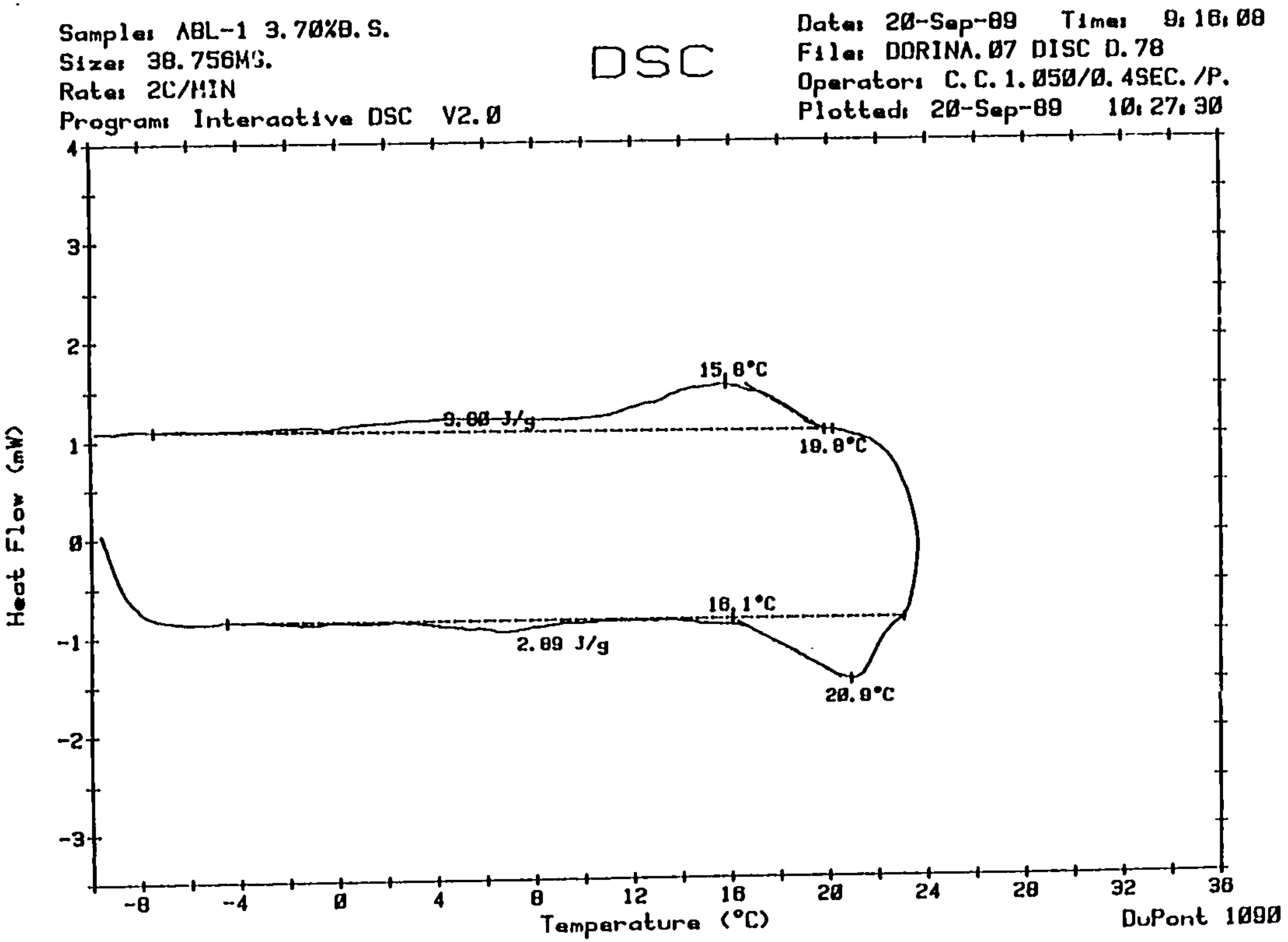


FIGURE 10 - DSC ANALYSIS OF BUTYL STEARATE IN AUTOCLAVED BLOCK

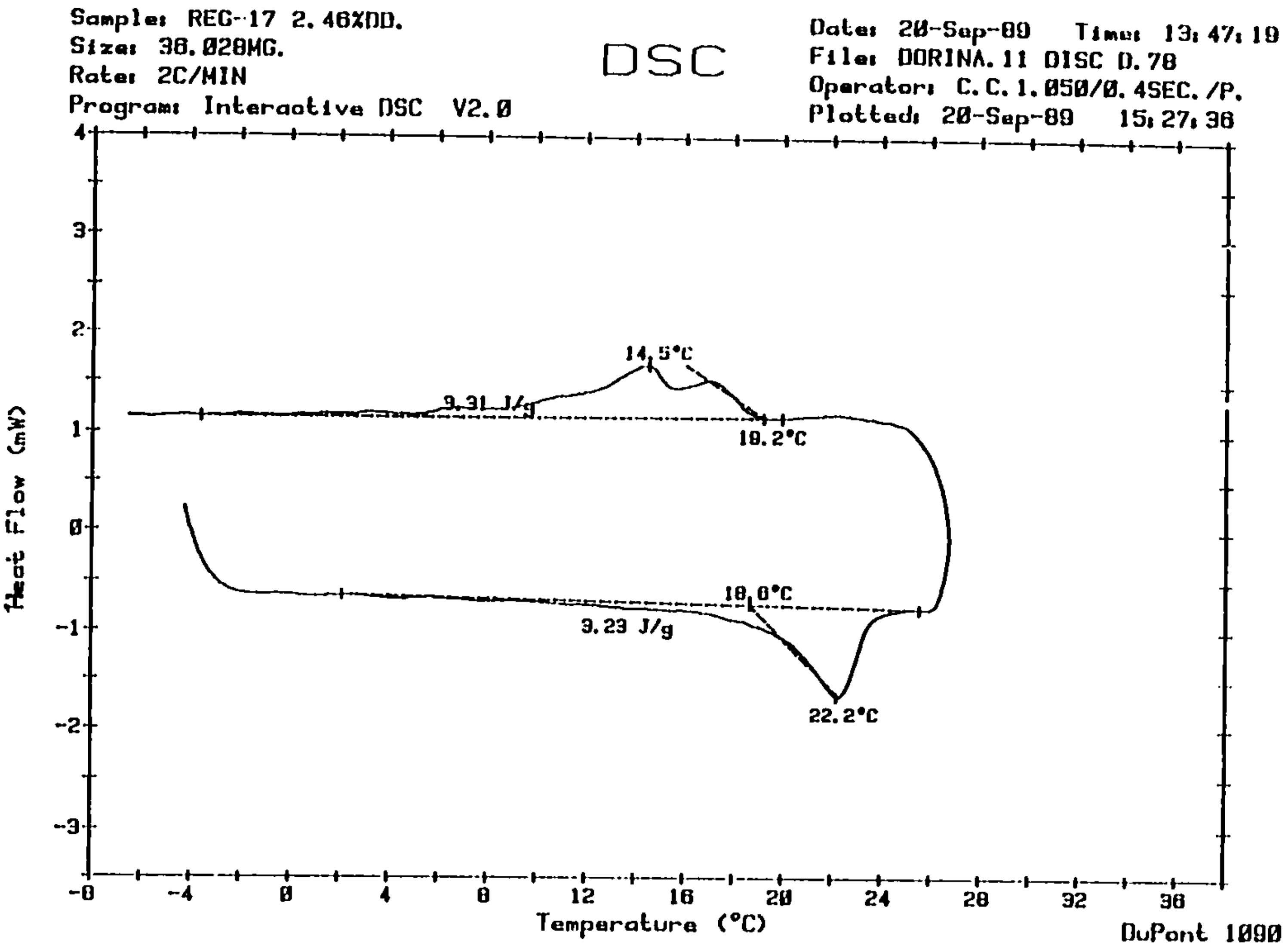


FIGURE 11 - DSC ANALYSIS OF DODECANOL IN REGULAR CONCRETE BLOCK

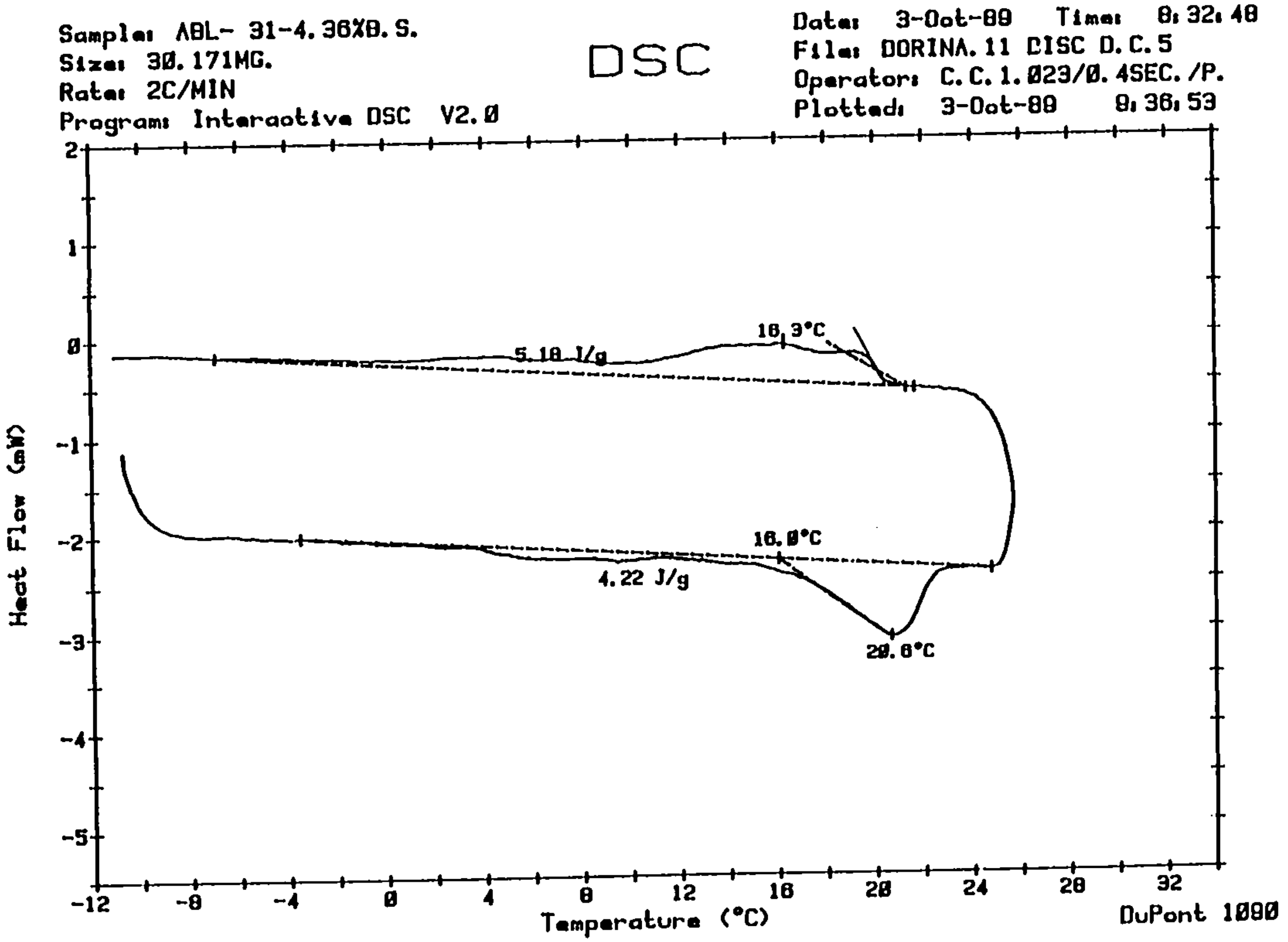


FIGURE 12 - DSC ANALYSIS OF BUTYL STEARATE IN AUTOCLAVED BLOCK

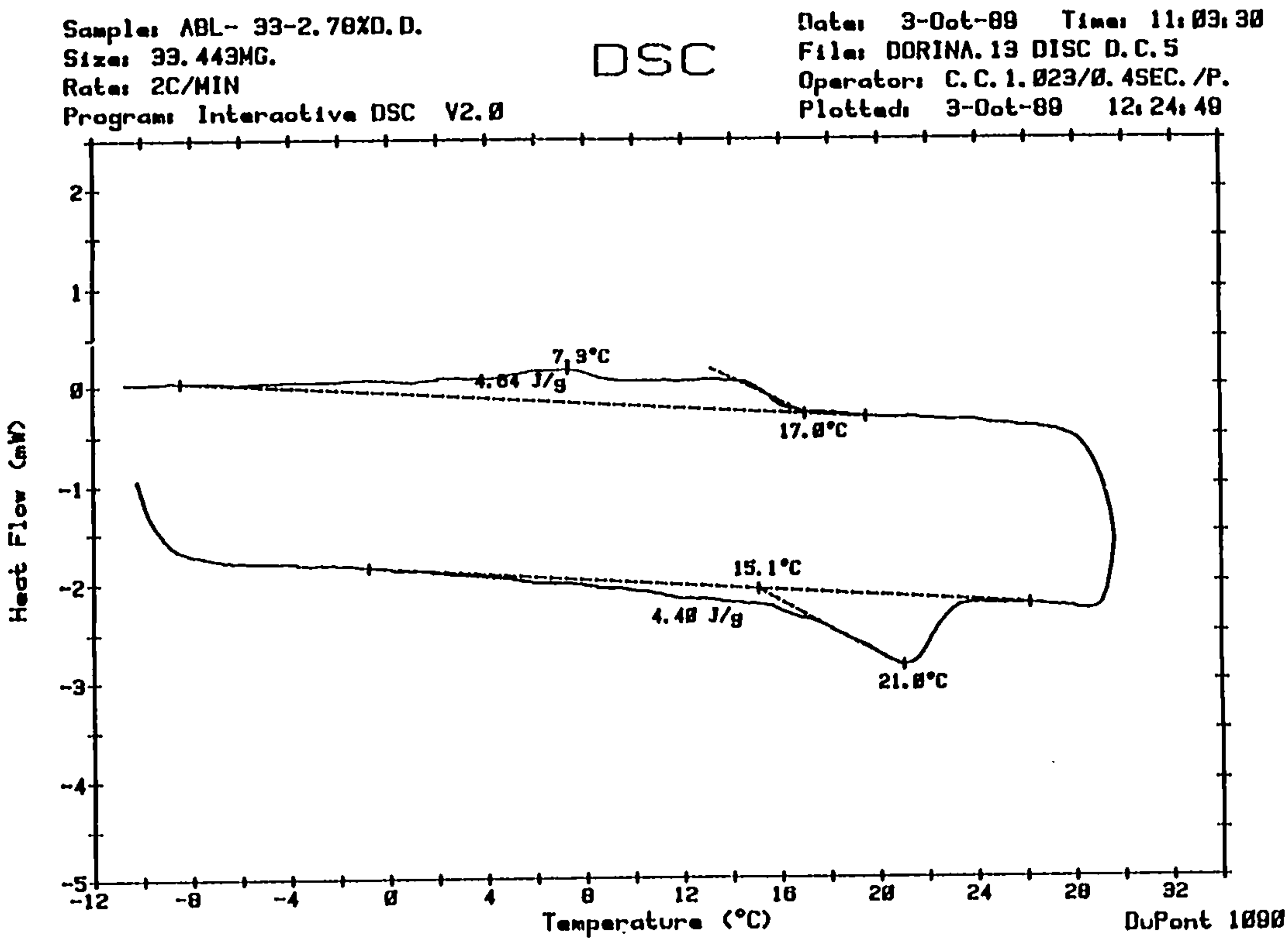


FIGURE 13 - DSC ANALYSIS OF DODECANOL IN AUTOCLAVED BLOCK

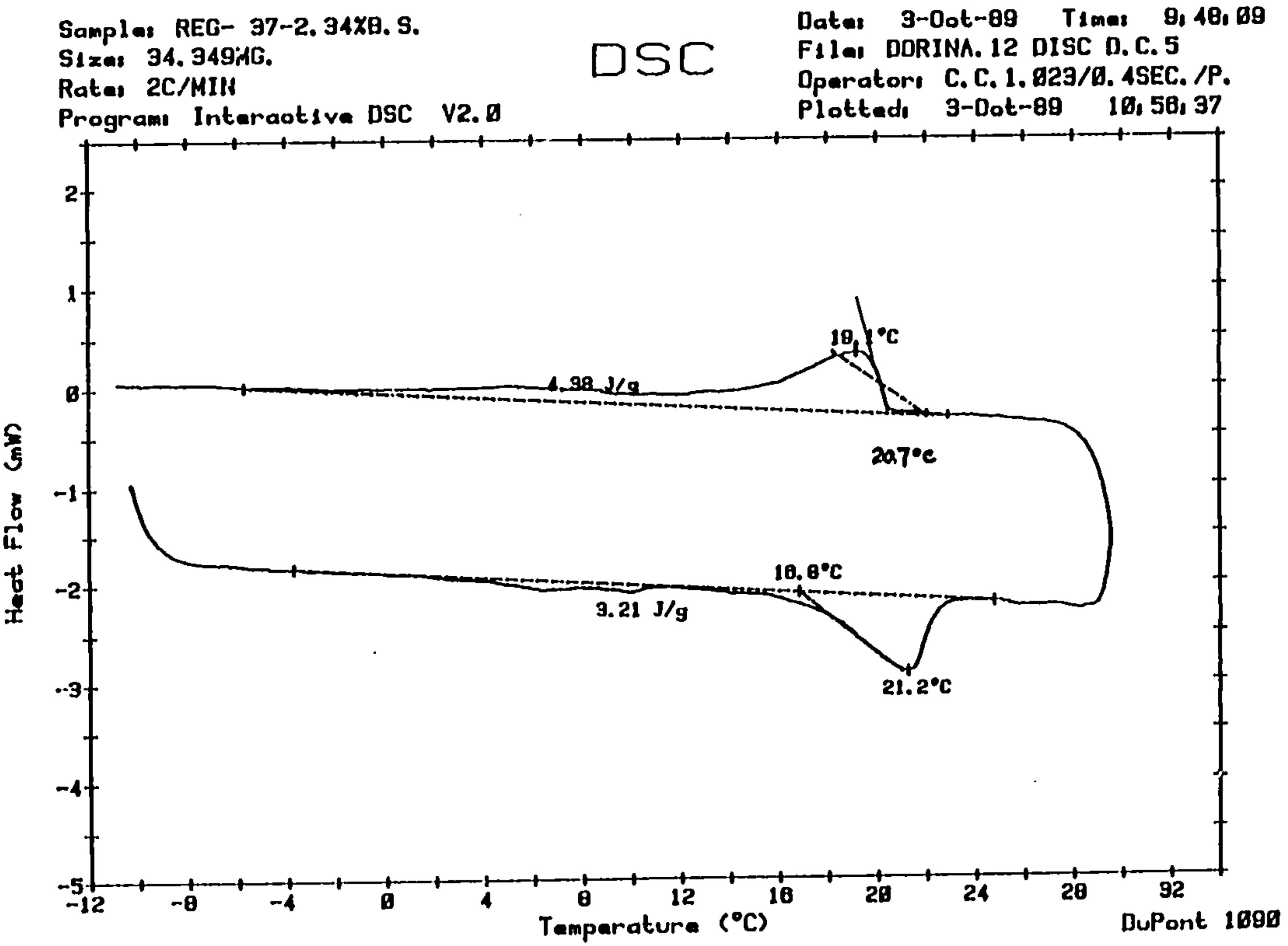


FIGURE 14 - DSC ANALYSIS OF BUTYL STEARATE IN REGULAR CONCRETE BLOCK

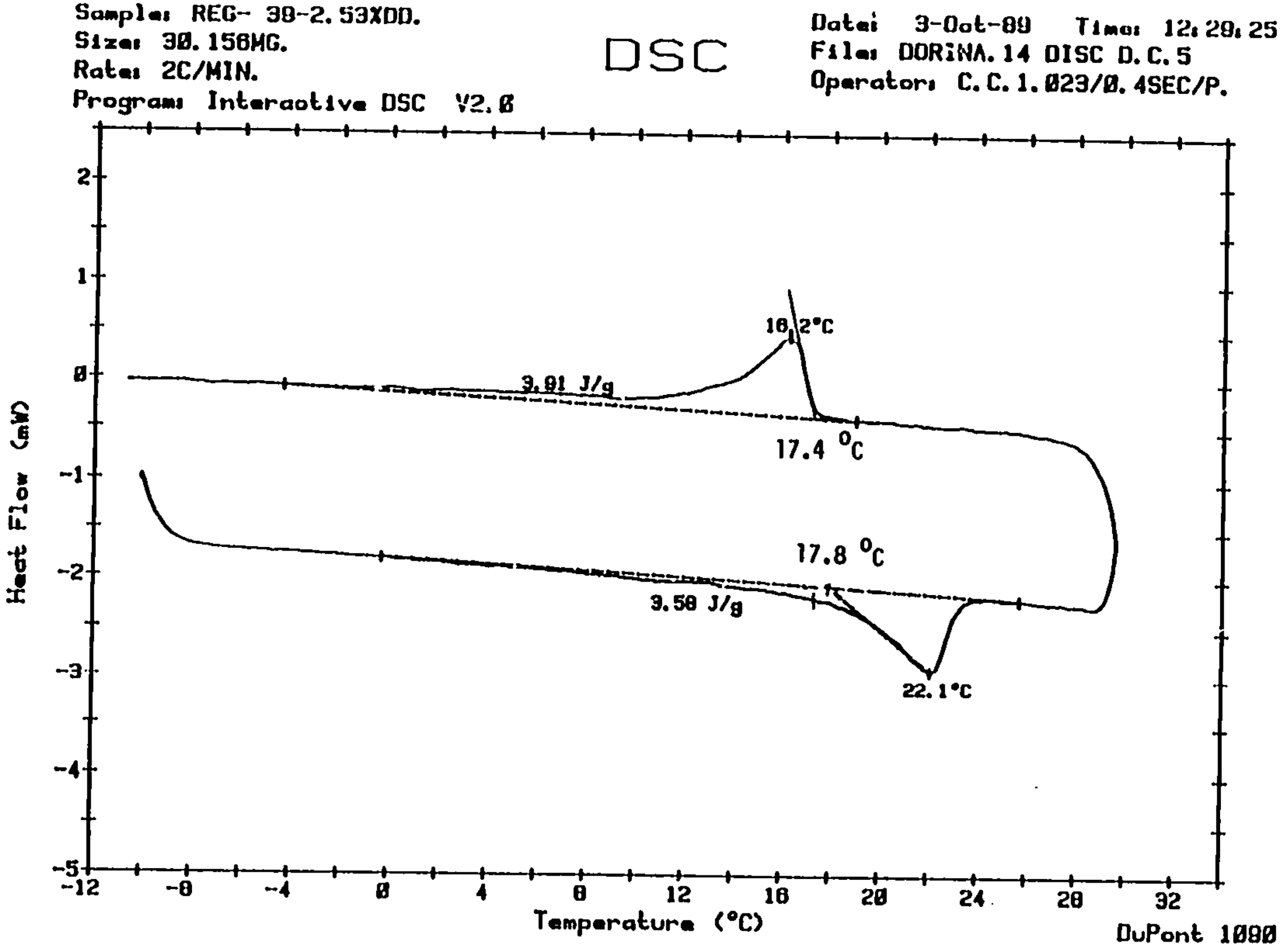


FIGURE 15 - DSC ANALYSIS OF DODECANOL IN REGULAR CONCRETE BLOCK

regular shape, a narrow operating temperature range and, preferably, a latent heat of at least 5 J/g.

The latent heat values are determined by the latent heat of the PCM (preferably not less than 140 J/g), by the amount of PCM absorbed in the concrete and by the characteristics of both the PCM and the concrete structure. The latent heat values found in specimens 1, 17, 31, 33, 37 and 39 are representative of values obtained in the early stages of this work and, while adequate for the application intended, are at the lower end of the scale. In addition, the freezing curves in ABL showed a tendency to extend beyond the desired lower temperature. For this reason, studies were conducted with the view to improving absorption and thermal characteristics.

6.3.2 Conclusions

Study of the experimental results showed that the ideal thermal properties of PCM concrete comprise a latent heat of about 5 J/g, sharply defined transition points within a desired temperature range and a thermal characteristic stability over the service life of the product. Experimentation with various PCM and concrete combinations at this stage indicated the necessity of conducting further research into means of increasing the amounts of PCM absorbed by the concrete and into other processes for improving the thermal characteristics of PCM concrete.

6.4 OPTIMIZATION OF CONCRETE-PCM COMPATIBILITY

6.4.1 Determination of Alkalinity

One of the earliest tests conducted was that used to determine alkalinity in mature specimens of concrete block. This test included all the concrete block types shown in section 4.2.3 except OPC. In addition, it comprised two non-autoclaved specimens: expanded slag (aggregate) block (EXSL) and expanded shale (aggregate) block (EXS). The results of this test are shown in Table 6.

TABLE 6 - COMPARATIVE ALKALINITY OF CONCRETE TYPES

TYPE	pH
ABL	7.0
REG	8.5
PUM	9.5/10.0
EXSL	8.5/9.0
EXS	6.5

Alkalinities in Table 6 were determined as the pH of water in which specimens were immersed for 28 days. The weight of water and concrete were approximately equal. While this is not an absolute indication of alkalinity, it does provide a convenient comparative guide.

From the results of these preliminary tests it was apparent that the concretes with the lower alkalinities were more suitable for use with BS, DD and TD on account of their susceptibility to alkaline attack. Subsequent observation confirmed this to be the case. All concretes in this group were considered suitable for use with PAR since it is inert in an alkaline medium. Another PCM, polyethylene glycol (PEG), was also used in the early stages of the work but it proved to deteriorate when combined with the types of concrete employed so its use was discontinued for the time being. It was also decided to limit work with EXS at present because of lower market demand for this type of block.

As a result of this and similar investigations it was concluded that PCM-concrete compatibility could be improved by modification of the concrete to render it less aggressive with some PCM's. Research in this direction was then undertaken and is covered in section 6.4.2.

It should be noted that whereas alkalinity testing provides a reasonable indication of probable compatibility, the desired stability of PCM in concrete can best be determined by measuring its heat storage performance at successive time intervals after immersion by means of DSC analysis.

Figures 16 and 17 show the stability of the first six specimens listed in Table 5 when analyzed at various intervals after immersion for a period of approximately one year. From these results it will be seen that BS can be quite stable in autoclaved block and, if immersed after a curing period of 8 days, in regular block as well. DD appears to undergo a deterioration in the early stages of impregnation and then to become quite stable in both autoclaved block and regular concrete block, particularly when immersed in the latter 8 days after mixing. In the case of regular block, the improvement in stability when specimens were immersed 8 days

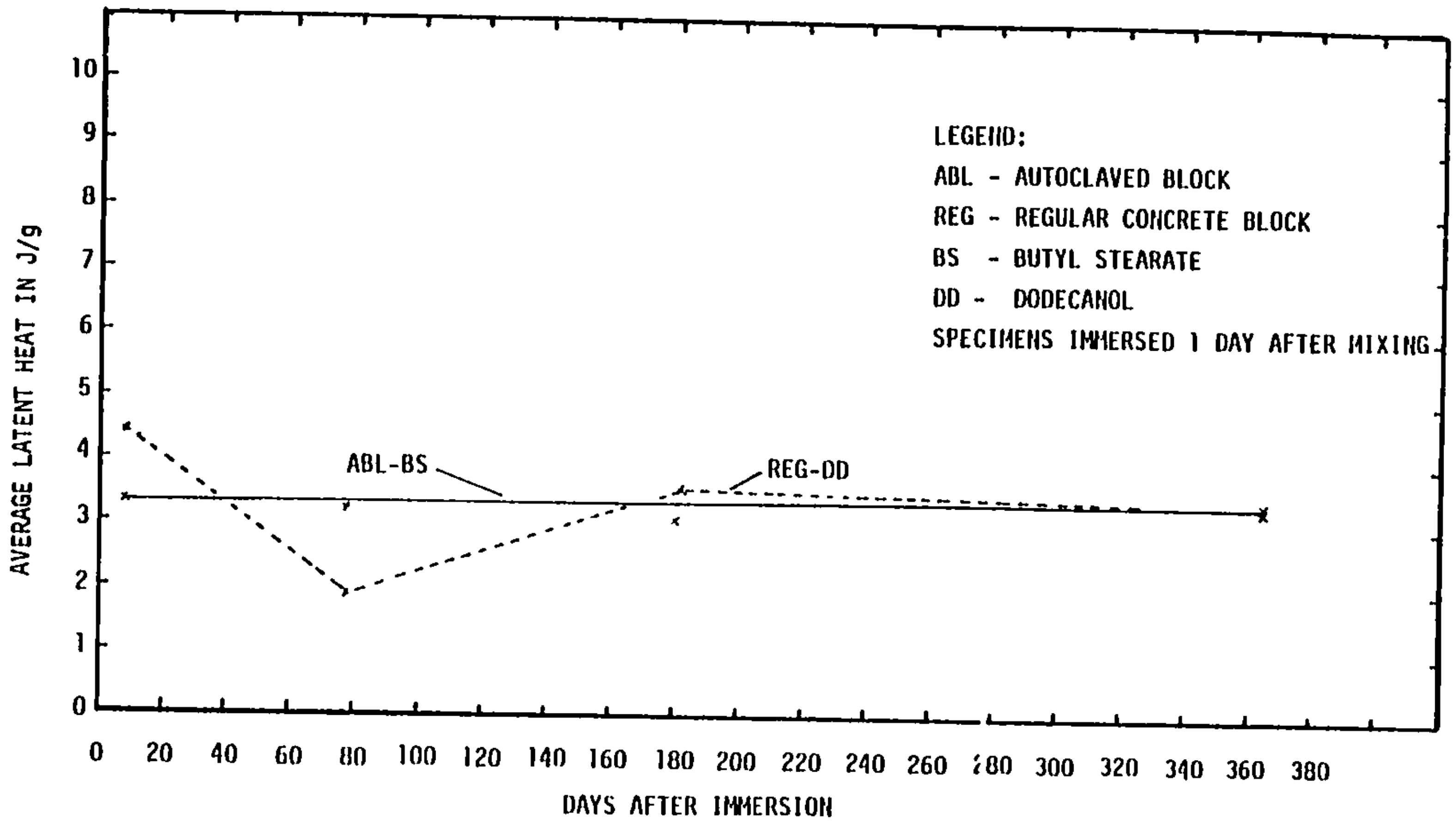


FIGURE 16 - STABILITY OF PCM IN CONCRETE SPECIMENS IMMERSED ONE DAY AFTER MIXING

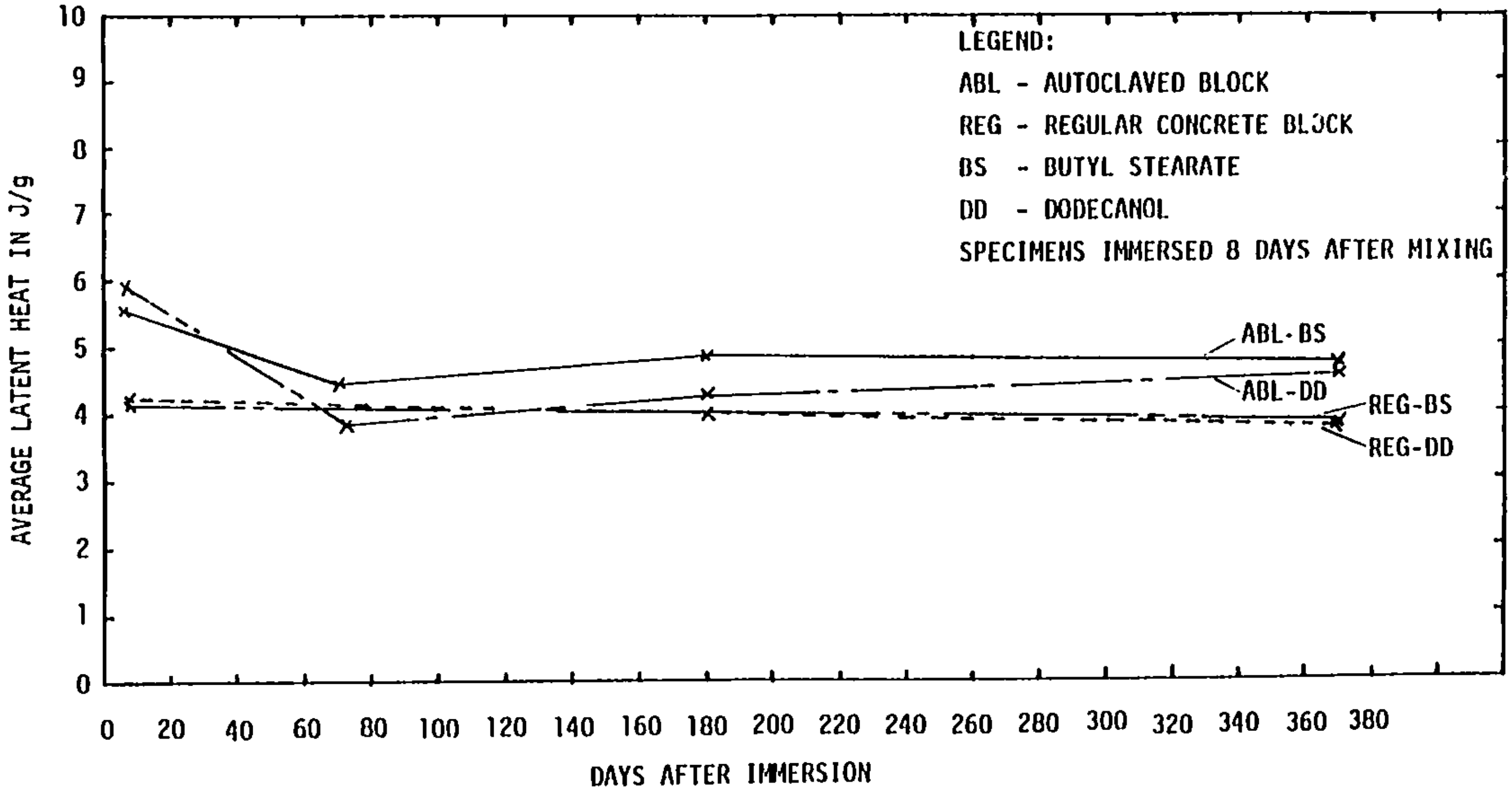


FIGURE 17 - STABILITY OF PCM IN CONCRETE SPECIMENS IMMERSED EIGHT DAYS AFTER MIXING

after mixing, rather than 1 day after mixing, is likely due to the fact that some of the $Ca(OH)_2$ in the concrete has reacted with CO_2 in the atmosphere to form $CaCO_3$ so that less remains to form an undesirable reaction with the PCM.

It should be noted that early experimentation with the method of preparing samples for the DSC resulted in somewhat erratic results for the samples tested 70-80 days after immersion. As mentioned earlier, PEG (not shown here) did not appear to be a satisfactory candidate for use with concrete in the forms tested up to that time. Pumice concrete (not shown with BS and DD) is ideal for use with PCM from the point of view of absorptance but its high alkalinity makes it unsuitable for use in an unmodified form with any of the PCM's used in this test. It was later used successfully with PAR and, in modified form, with BS, DD and TD.

The study of a number of procedures and conditions relating to the manufacture of PCM concrete was then undertaken with the objective of improving its performance.

6.4.2 Optimization of Concrete-PCM Compatibility by the Use of Pozzolans

The first in the following series of investigations into means of improving the performance of PCM concrete was the study of the use of pozzolans in the mix as a means of enhancing the concrete-PCM compatibility.

Pozzolans such as fly ash, silica fume and slag may be defined as siliceous or siliceous and aluminous concrete additives which, in themselves, possess little or no cementitious value but which will, in finely divided form and in the presence of moisture, chemically react with $Ca(OH)_2$ at ambient temperature to form compounds possessing cementitious properties (ASTM, C595).

Fly ash is produced as a waste product in the combustion of pulverized coal while silica fume is a by-product from the manufacture of metallic silicon or ferrosilicon alloys. These waste materials are not fully utilized at present.

The valuable effect of pozzolans on the workability, strength and durability of concrete is well known. In concrete based on pure Portland cements, the weak and easily soluble $Ca(OH)_2$ can be as much as 20-25% by weight of the cement paste while the rest of the paste consists of hydrated calcium silicate which forms the binding agent. When pozzolanic materials such as fly ash and silica fume are used, the $Ca(OH)_2$ is transformed into less soluble calcium silicate hydrate (CSH) and the strength and durability of the concrete is thereby improved to a considerable degree. In addition, the detrimental effects of reaction with $Ca(OH)_2$ are reduced when PCM's which are sensitive to this attack are used. It should be noted that the pH of concrete containing reinforcing steel must be maintained high enough for the passivation of the metal. Further work remains to establish a balance between this requirement and the use of reactive PCM's in reinforced concrete (Sellevold, 1983).

It was found that the addition of silica fume and fly ash increased the impermeability of the concrete and, therefore, decreased its ability to absorb PCM. In an effort to offset this effect, an air entraining agent was used and, since the pozzolans are hygroscopic, a water reducing agent (lignosulfonate) was also required (Sellevold, 1983). Whereas the use of an air entraining agent did reduce the concrete density, it did not significantly affect PCM absorption because the air voids so created are small and discrete as opposed to the more continuous cracks, fissures and pores found in other types of concrete. From this it follows that, when using these pozzolans with PCM, care must be exercised in mixing to ensure adequate absorptivity through the use of absorbent aggregate or other means.

Table 7 shows the comparative absorptivity of various concretes with and without the inclusion of silica fume in the concrete mix. From this it will be seen that the effect on absorption was quite serious. To overcome this difficulty, various means of improving the PCM absorption were investigated and tested. This is described later in the text.

TABLE 7
Comparative Absorptivity of Concrete With and Without Silica Fume

PCM	Concrete Type	PCM Absorbed as a Percentage of Weight of Concrete	
		With Silica Fume	Without Silica Fume
DD	REG	1.2	2.7
DD	PUM	1.6	3.9
BS	REG	1.7	2.7
BS	PUM	2.9	4.4
PEG	REG	1.6	3.7
PEG	PUM	2.7	3.8

(a)

Formulation for Concretes in Table 7(a), Weights are in %

Component	Regular Concrete (REG)	Pumice Concrete (PUM)
Cement (low alkali)	11.1	20.9
Sand	61.8	
Aggregate and fines	16.6	62.8
Silica Fume	1.3	2.7
Water	9.2	13.7

(b)

6.4.3 Conclusions

Concretes with comparatively low alkalinity were found to be best for use with PCM's which are alkaline sensitive. Therefore, it was decided to increase the number of concretes suitable for use with these PCM's by modifying some of the more alkaline ones to reduce their alkalinity. It was then found that pozzolans achieved this objective very effectively. Pozzolans are economical substitutes for cement which reduce the alkalinity of the concrete and thereby enhance the stability of the impregnated PCM while retaining the properties of the concrete. Since pozzolans make concrete more impervious, it was found necessary to take appropriate measures to ensure that it remains sufficiently porous to absorb the requisite amount of PCM.

6.5 EFFECT OF TEMPERATURE ON PCM ABSORPTION

6.5.1 Effect of Concrete Temperature on Absorptivity

The effect of varying the concrete temperature at the time of immersion was examined for several types of concrete and various PCM's in respect to the amount of PCM absorbed in each case. During these tests the PCM temperature remained constant at 80°C while the temperature of the concrete specimens at immersion was increased from 20°C to 160°C. The latter temperature was selected because it is approximately the temperature of concrete products shortly after discharge from an autoclave so that, if immersion were carried out at this point in the manufacturing process, it would not be necessary to reheat the product. For this test, each concrete specimen was given a single immersion because reheating impregnated specimens to 50 - 130°C above their operating temperature would likely result in loss of PCM. It will be recalled that the PCM temperature remained constant (80°C) so that all the temperatures discussed in this section refer to the concrete temperature at immersion. Each immersion was for 4 hours.

The results of this experiment are shown in Figure 18.

In the case of autoclaved block impregnated with polyethylene glycol (ABL-PEG) several distinct stages were observed. Between 20°C and 80°C the percentage of specimen weight due to absorbed PCM increases slowly from 7.89% to 8.28% then it rises sharply to 100°C where it reaches a value of 9.62% then, up to 140°C, it again rises slowly to 9.86%. Finally, at 160°C, it again rises significantly to 11.33% for an overall gain in PCM content of 44% (i.e. from a content of 7.89% at 80°C to 11.33% at 160°C). The word gain used subsequently in this section will refer to an increase in PCM content after the first immersion.

For autoclaved block impregnated with paraffin (ABL-PAR) the rise from 6.89% PCM content at 20°C to 7.33% at 80°C was, as in the previous case, only 0.4%. However, from this point the PCM weight drops to 7.07% at 100°C and only recovers to 7.14% at 120°C. Then, between this temperature and 140°C where the content of PCM is 8.13%, there is a sharp rise. Between 140°C and 160°C the increase in weight to 8.26% is very modest. The entire gain in PCM content was relatively low in this case, being only 20% (6.89% to 8.26%). The drop in PCM content between 80°C and about 125°C is a phenomenon which occurs at slightly

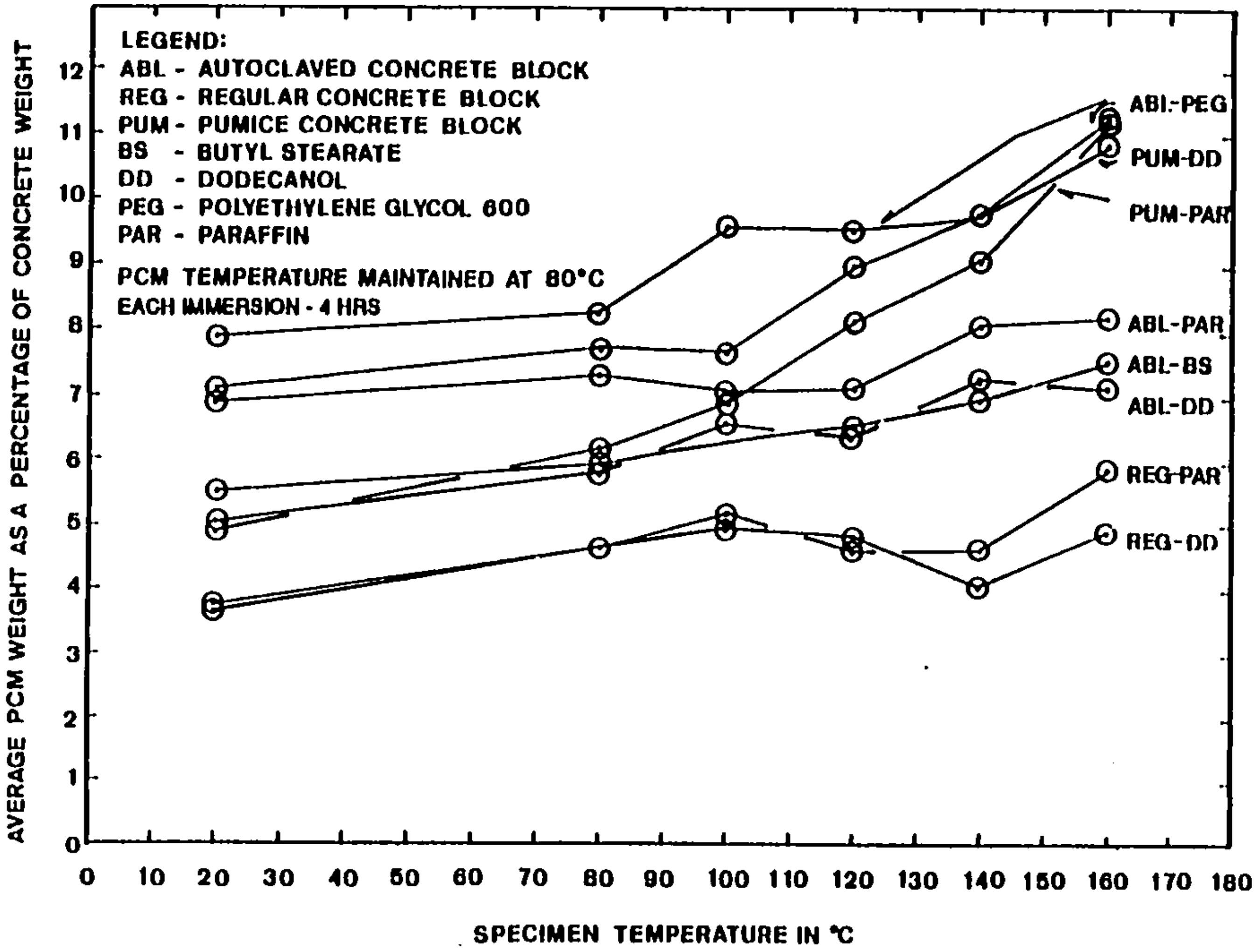


FIGURE 18 - THE EFFECT OF CONCRETE TEMPERATURE AT IMMERSION ON ABSORPTIVITY

higher temperature ranges in three more cases in this series and also in another test series where the temperature of the concrete remained constant while that of the PCM was varied. Therefore, since it is an occurrence worthy of note, common to both test series, it will be analyzed subsequently as a separate topic in section 6.5.3.

Autoclaved block impregnated with butyl stearate (ABL-BS) demonstrates a steady increase of PCM content without loss and with very little variation between 20°C (5.56%) and 160°C (7.57%) for an overall gain of 36%.

In the case of autoclaved block impregnated with dodecanol (ABL-DD), the increase of absorbed PCM between 20°C (5.01%) and 80°C (5.85%) is a modest one. Then, from the latter point to 100°C it rises sharply to 6.60%. From this point to about 130°C there is a loss which, as previously mentioned, will be explained later. Finally, from this point to 140°C there is again a sharp rise in the amount of PCM absorbed to 7.33%. The slight drop to 7.14% at 160°C may be a manifestation of the weight drop phenomenon to be discussed later but is more likely to be the result of some unperceived variation in the specimens. The total gain in PCM content is 43% (5.01% - 7.14%). For pumice concrete impregnated with dodecanol (PUM-DD), the increase in PCM content between 20°C (7.04%) and 100°C (7.66%) is quite small. From the latter point to 160% it rises sharply and steadily to 10.91% for an overall gain of PCM content of 55% (7.04% - 10.91%).

In the case of pumice concrete impregnated with paraffin (PUM-PAR) the increase in PCM content rises at a slightly increasing rate from a value of 4.92% at 20°C to 11.22% at 160°C for an overall gain in PCM content of 128%.

For regular concrete impregnated with paraffin (REG-PAR) and with dodecanol (REG-DD) the growth is gradual to the 100°C point and then falls off in the manner characteristic of the reduction of PCM content with varying temperature which will be discussed later. In the case of REG-PAR, the PCM content at about 150°C again rises to equal the 100°C level and it eventually reaches a maximum PCM content of 5.91% at 160°C for an overall gain of 61% (3.67% - 5.91%). For REG-DD, the maximum PCM content (5.21%) is reached at 100°C. Increasing the temperature from this point results first in a loss, then it recovers (approximately) the 100°C value again at 160°C for an overall PCM content gain of 33% (3.70% - 4.91%).

From this it will be seen that in the cases of ABL-PEG, ABL-PAR, ABL-BS, PUM-DD, PUM-PAR and REG-PAR raising the temperature of the concrete at immersion from 20°C to 160°C can markedly increase its absorptivity if it is deemed necessary to have a higher PCM content than that available at a lower temperature. In the case of ABL-PAR, however, if a PCM content of about 7.3% is considered sufficient, a concrete temperature of 80°C is adequate because a value 7.3% is not attained again until a temperature of about 125° is reached. Similarly, in the case of REG-PAR the value of 4.64% attained at 80°C is not again attained until a temperature of about 150°C is reached. In the case of ABL-DD there is no point in going above 140°C and the value at 100°C (6.6%) should be considered, if possible. In the case of REG-DD there is no point in raising the concrete temperature above 100°C.

Since the temperature of concrete products shortly after autoclaving is about 160°C and after steam curing is about 80°C, full advantage should be taken of this condition in arranging immersion facilities to avoid the necessity for reheating.

6.5.1.1 Conclusions

In all cases, the absorption of PCM was found to increase with the concrete temperature up to 80°C. Above that temperature, the increase in PCM absorption was observed to vary, so that careful consideration must be given to immersion at temperatures above this point simply to increase the amount of absorption. However, in the case of ABL, since the block will be discharged from the autoclave at a higher temperature in any event, some advantage may be taken of this condition by immersing the block at or close to the discharge temperature, but the gain in absorption will vary from one PCM to another.

6.5.2 Effect of PCM Temperature on Absorptivity

The effect of varying the PCM temperature during immersion was examined for several types of concrete and various PCM's in relation to the amount of PCM absorbed in each case. For this test series, the temperature of the concrete specimen at immersion was kept at 20°C and for each combination of concrete and PCM the same specimen was used throughout. The temperature of the PCM was changed progressively from 80°C to 100°C to 120°C to 100°C to 80°C to 100°C and repeated at 100°C. It will be recalled that the temperature of the concrete at immersion remained constant (20°C) so that all temperatures discussed in this section refer to PCM temperature. Each immersion was for 4 hours.

The results of this test series are shown in Figure 19.

Under the conditions of this test series, the ABL-PEG, PUM-DD, PUM-PAR, ABL-BS and ABL-DD specimens were observed to be at, or close to, saturation in respect to the amount of PCM absorbed after the fifth immersion (second immersion at 80°C). Beyond this point, the subsequent immersions at 100°C had a negative effect because raising the temperature above that at the point of maximum saturation (second immersion at 80 °C) merely allowed more material to drain from the specimens when they were removed from the bath. This is due to the fact that the PCM viscosity was decreased and the pore structure was slightly more open than at the fully saturated point. A further immersion again at 100°C produced a very small increase in the case of ABL-PEG and PUM-PAR but merely increased the loss slightly in the other cases mentioned above.

The optimum content for ABL-PAR, REG-PAR and REG-DD was obtained at 120°C (third immersion) and dropping the temperature of the next immersion to 100°C caused a significant drop in content where it remained approximately constant up to the fifth immersion (second at 80°C). In all cases, raising the temperature from 80°C (fifth immersion) to 100°C for the sixth immersion had a negative effect in that the PCM content dropped. In the cases of REG-DD and REG-PAR, the seventh immersion at 100°C simply continued the negative effect

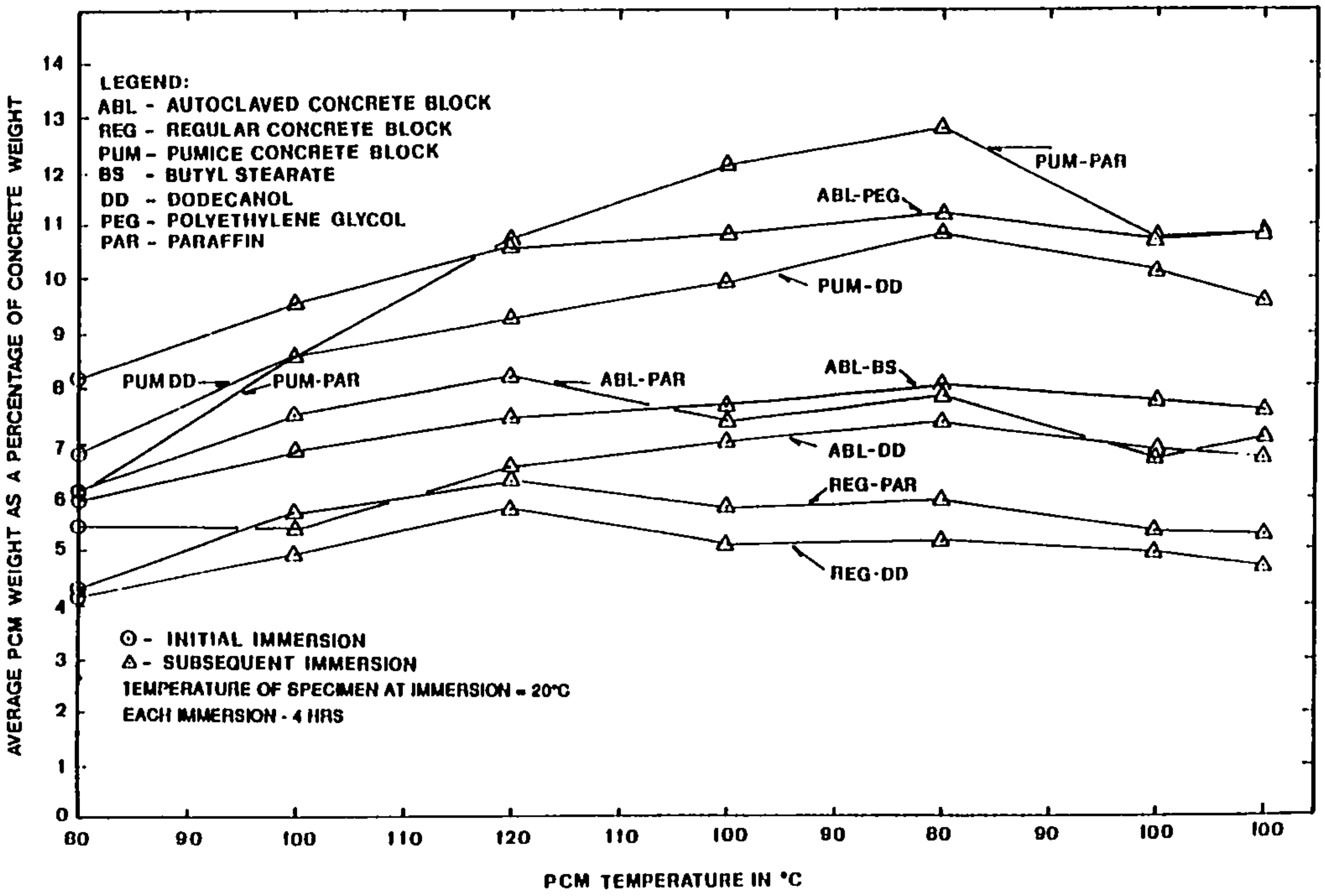


FIGURE 19 - THE EFFECT OF PCM TEMPERATURE ON ABSORPTIVITY

while in the case of ABL-PAR it had a slightly positive effect.

The anomalies of the reduction of PCM content with an increase in temperature will be discussed later.

6.5.2.1 Conclusions

It was found that raising the temperature of the PCM will increase the PCM content of the concrete up to a point which varies with the combination of concrete and PCM used as well as with the number of immersions. In some cases, raising the PCM temperature above 120°C can have a negative effect. It is, therefore, necessary to consider the PCM content required for each combination and to plan the appropriate immersion procedure for optimum absorption.

6.5.3 Reduction of PCM content with Varying Temperature and the Effect of PCM Polarity

The phenomenon of PCM loss with increasing temperature was noted in the previous two sections. In Figure 18 this behaviour is demonstrated in particular by ABL-PAR at 100°C and 120°C, by ABL-DD at 120°C and by REG-PAR and REG-DD at 120°C and 140°C. In Figure 19 a PCM loss with increased temperature eventually occurs in all cases, but principally after the sixth immersion as the temperature of the saturated specimens was raised from 80°C to 100°C. The mechanisms are different in each case and will, therefore, be discussed separately.

The effect of raising the temperature of the concrete at immersion while maintaining the PCM temperature at 80°C is shown in Figure 18. In this case, individual specimens were used for each immersion and were heated to the required temperature in an oven. It will be recalled that water in small capillaries (5-50 nm) exerts hydrostatic tension so that its removal through drying will result in a compressive stress on the capillary walls, thereby causing a contraction of the system (Mehta, 1986). This contractive effect appears not only to reflect the loss of moisture but also to cause a reduction in capillary size which impedes the absorption of liquid PCM.

In Figure 18 the result of enlargement of the concrete voids due to thermal expansion is observed up to about 100°C at which point the aforementioned contractive effect in the pores becomes noticeable and a change of slope may be seen in many of the weight gain curves. In some cases, the upward trend is actually reversed and a downward trend continues until a point is reached where the effect of thermal expansion at that temperature is sufficient to offset the compressive effect so that absorption of liquid PCM may again increase as the immersion temperature is raised.

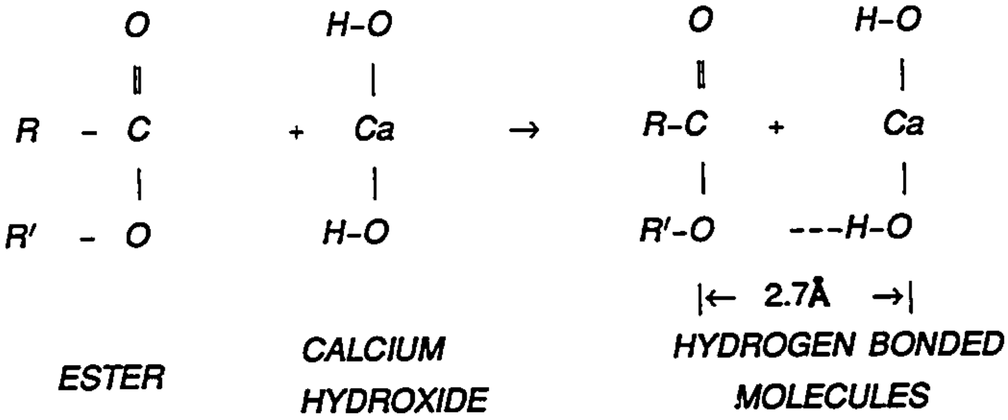
It will also be noted that the compressive effect becomes less noticeable as the structure of the concrete becomes progressively more open in going from regular to autoclaved to pumice concrete.

In the case of Figure 19 the prevailing conditions are different from those in Figure 18. Each of the specimens in Figure 19 was progressively immersed at the temperatures shown, whereas those in Figure 18 comprise separate specimens for each immersion. Two separate aspects of the curves in Figure 19 will be considered. The first aspect covers the results to the optimum saturation point. In this group of specimens the evaporation of water at 100°C is impeded because of the presence of PCM in the concrete (i.e. the specimens were raised to this temperature in the bath). As a result, the compressive effect is not as apparent as in the case of the specimens in Figure 18, where evaporation was allowed to occur in the oven prior to immersion in the PCM. Therefore, in Figure 19 it will be seen that the effect of thermal expansion is the dominant one up to about 120°C. Then, when the temperature of immersion is lowered below this point, contraction occurs and a break in the curves is perceived and, in some cases, the slope is even reversed.

In the case of REG it will be seen that the absorption of PCM in a dense structure is more susceptible to the effect of thermal expansion and contraction as demonstrated by the reduction of PCM absorbed as the temperature of immersion is dropped from 120°C to 100°C.

Where the structure is more open, as in the case of ABL and PUM, there is less tendency for the PCM to be expelled. A notable exception to the latter condition is the case of ABL-PAR where the PCM content is reduced as the temperature of immersion is lowered from 120°C to 100°C even in a relatively open structure. This occurs because PAR is not a polar substance, while the other PCM's in ABL (BS, DD) are polar materials and, as such, they are subject to hydrogen bonding with the hydrates in the concrete. This bonding which is described below, renders them less likely to be expelled from the structure than a non-polar PCM such as PAR.

Hydrogen is unique among the elements in that its valence electron is the only electron in the atom. When hydrogen is bonded to a highly electro-negative atom such as oxygen, which exerts a strong attraction for the bonding electron pair, the effect is very much like that of a bare proton at the end of the bond. This proton then has an attraction for the unshared electrons of an atom in another molecule as shown below. This attractive interaction is termed the hydrogen bond.



$$\begin{array}{ccccccc} & O & & H-O & & O & H-O \\ & \| & & | & & \| & | \\ R & - C & + & Ca & \rightarrow & R-C \quad + & Ca \\ & | & & | & & | & | \\ R' & - O & & H-O & & R'-O & ---H-O \\ & & & & & \multicolumn{2}{c}{|\leftarrow 2.7\text{Å} \rightarrow|} \end{array}$$

(Eq. 9)

As shown, the bond is conditioned by a distance of 2.7Å between the oxygen atoms and has an energy of 4-8 cal/g. The bond energy is large enough that it is not easily broken by molecular collisions at room temperature, however, at higher temperatures it may be disrupted more easily as a result of high energy collision (Brown, 1963).

When the temperature of immersion is reduced from 100°C to 80°C it appears that the structure is still sufficiently open to absorb more PCM and substantiates results obtained in the multiple immersion tests in which the PCM temperature was maintained at 80°C.

The second aspect to be considered is that following the fifth immersion where another mechanism may be seen to operate. Under the conditions of this test, the specimens have reached an optimum point in the case of PUM-PAR, PUM-DD, ABL-PEG, ABL-BS and ABL-DD and further immersions at 100°C merely result in loss of PCM, likely due to drainage on removal from the bath. This would occur because, at the higher temperature, the PCM viscosity would be reduced and the pore structure would be more open as previously discussed. This could argue the merit of a high immersion temperature and a lower extraction temperature. However, since such a procedure would lead to complications in the production process for a small increase in PCM content, it will not be pursued at this time. In the case of the remaining three specimens in this group, the drainage loss at this point is irrelevant since, in practice, they would not be immersed beyond their optimum point.

6.5.3.1 Conclusions

As the temperature was increased it became apparent that both the expansive and contractive effects must be considered for each type of PCM-concrete combination in order to optimize absorption. In addition, it was found that the temperature of the bath at the time of removal of the product must not be such as to unduly lower the PCM viscosity and thereby cause excessive drainage from the concrete. Hydrogen bonding is considered to be a factor in the retention of polar PCM's in the concrete.

6.6 DILUTION OF PCM AS A MEANS TO INCREASE ABSORPTION

The purpose of this aspect of the work was to investigate the feasibility of adding a diluent to a PCM as a means of decreasing its viscosity at the temperature of absorption and hence increasing the amount of PCM absorbed by the concrete.

The types of concrete block material studied were regular, autoclaved and pumice and the PCM's used were as follows:

(a) dodecanol
    dodecanol plus 5% ethanol
    dodecanol plus 10% ethanol

The results of these tests are shown in Figure 20.

(b) paraffin

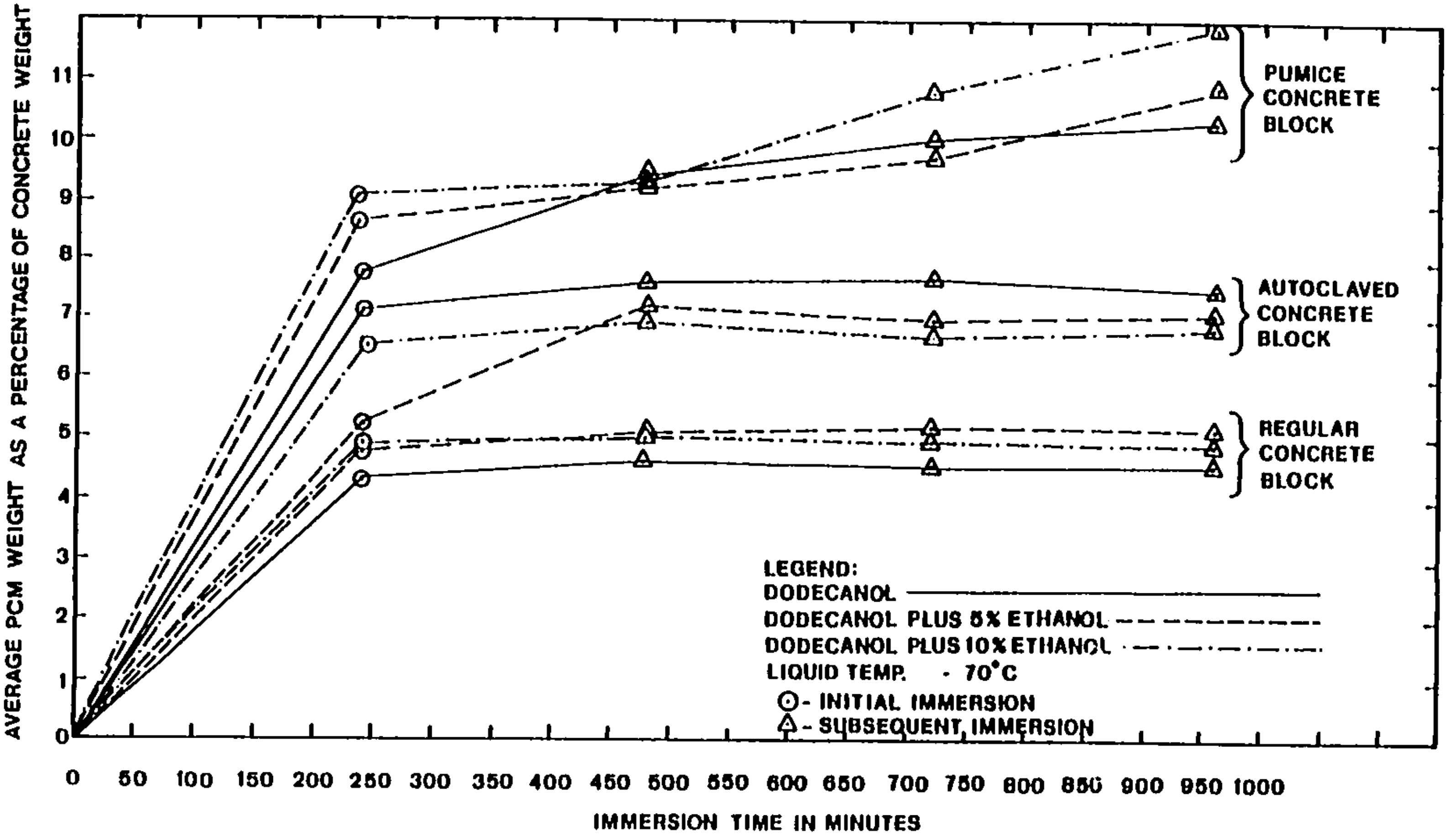


FIGURE 20 - THE EFFECT OF ETHANOL AS A THINNER TO INCREASE ABSORPTION OF DODECANOL

paraffin plus 5% turpentine

paraffin plus 10% turpentine

The results of these tests are shown in Figure 21.

The proportions of PCM and diluent were monitored at each immersion because of the volatility of the diluents. Whenever necessary, the original proportionality was restored. Whereas there was a slight tendency for the diluents to evaporate, it was never by an amount significant enough to affect the outcome of the test. Moreover, it was found that this loss could be largely controlled by covering the vessels more carefully to prevent evaporation.

Each specimen was given four successive immersions of 240 minutes each. The dodecanol and its diluents were maintained at 70°C while the paraffin and its diluents were maintained at 90°C.

An exception to the abovementioned PCM temperatures was made in the case of the initial immersion of pumice concrete where the paraffin temperature was 120°C for the first immersion only. It will be noted that the PCM content was less after the second immersion than after the first. This was because the second immersion was carried out at 30°C lower than the first and thermal contraction of the concrete, caused by the drop in temperature, resulted in the expulsion of some PCM at the lower temperature when it was still in the liquid state. This effect was previously discussed.

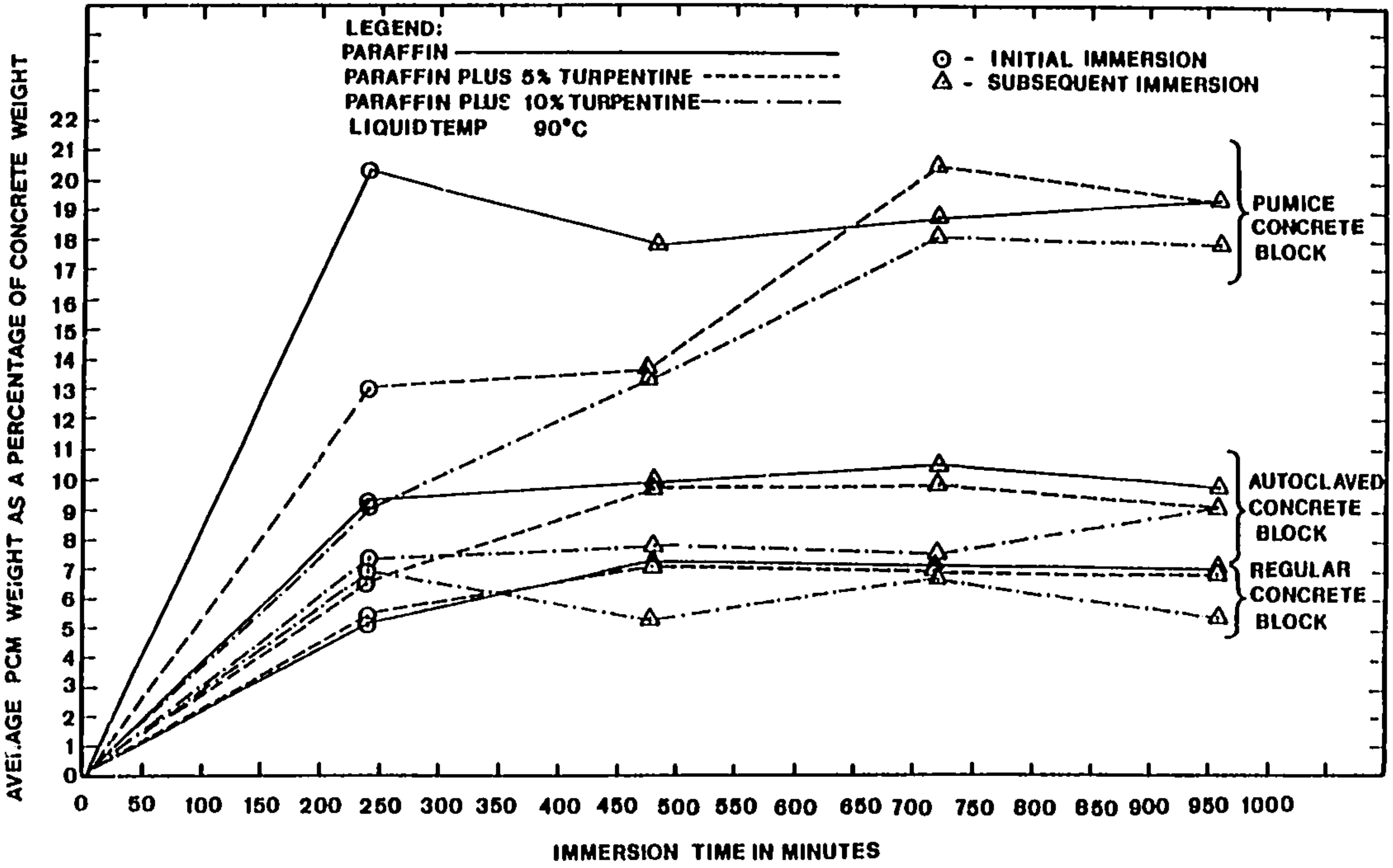


FIGURE 21 - THE EFFECT OF TURPENTINE AS A THINNER TO INCREASE ABSORPTION OF PARAFFIN

In the case of regular concrete it will be seen from Figure 20 that the absorption of the diluted PCM is slightly greater than for the undiluted PCM. This is probably due to the fact that more of the less viscous material was able to pass into the gel of this type of concrete. It may be seen that 5% diluent was sufficient to cause the greater absorption and that the addition of another 5% merely reduced the weight of the PCM material absorbed. It should be noted that the PCM has had its latent heat capacity reduced 5-10% by the dilution process and, since the increase in the amount of PCM absorbed due to dilution is of the same order of magnitude, there does not appear to be any advantage in using ethanol as a diluent with dodecanol.

The increased absorption of diluted PCM by pumice concrete is caused by the less viscous material passing into the porous aggregate as well as into the gel pores. As before, the gain in the amount of PCM absorbed is approximately offset by the reduction in latent heat available because of dilution of the PCM

In the case of autoclaved block, the gel structure is slightly more porous than that of regular concrete but the aggregate is not as absorbent as that of pumice concrete. The effect is that the volume of liquid absorbed is not significantly affected by dilution of dodecanol with ethanol. However, the denser the liquid, the greater will be the weight absorbed for a given volume, which accounts for the fact that the undiluted PCM, which has the highest density, shows the greatest weight gain of the three liquids.

It will be noted that the more porous the structure, the greater the number of immersions required before saturation is reached. In the case of regular block, a single immersion under the proper conditions was sufficient to establish the optimum degree of absorption while two immersions were required for autoclaved block. However, even four immersions did not produce a saturation level in the pumice block. From this it will be seen that the number of immersions for maximum absorption will vary with the type of aggregate.

The specimens were re-examined after 30 days and it was found that, in the case of dodecanol with ethanol, there was a weight loss. In the case of regular concrete this was approximately equal to the weight of the diluent while in the case of autoclaved and pumice concrete the loss was about twice as great. Therefore, the net effect in the latter two cases was a considerable loss of diluted PCM through leakage from the more open structures of autoclaved and pumice concrete. It is most likely that some of the loss was due to evaporation of ethanol. This form of loss had not occurred with the undiluted PCM.

In the test series with paraffin and turpentine (Figure 21) it was found that the use of the latter actually produced a negative effect in that this thinner did not cause a significant difference in the amount of liquid absorbed. As a result, the undiluted PCM showed a slightly greater weight gain than the solutions containing turpentine. The point of interest here is that this occurred despite the fact that the density of turpentine (0.86) is higher than that of liquid paraffin (0.78) and is probably due to excessive drainage at the time of removal due to the lower viscosity. It should be noted here that while the density of solid paraffin is 0.91, shrinkage occurs during solidification so that the net weight gain is dependent upon the amount of paraffin absorbed in the liquid state, at which time its density is lower.

Re-examination of these specimens after 30 days did not disclose any significant weight difference from the value obtained immediately after immersion as in the case of dodecanol and ethanol.

6.6.1 Conclusions

The thinners used in this study did not prove to be an effective means of increasing the thermal storage effectiveness of PCM concrete and, in some cases, even had the opposite effect to that desired. However, this procedure did show that, in the case of dodecanol and ethanol, thinning the liquid did increase absorption slightly, as expected, and that this principle may possibly find application to more viscous PCM's or to permit reduction of the immersion temperature, providing that the net viscosity was not reduced to the point where it resulted in excessive drainage during removal from the bath or in subsequent slow leakage.

It follows that, for equivalent latent heat per unit volume at the temperature of impregnation, the PCM with the lowest viscosity at that temperature will result in the greatest amount of heat storage per unit volume of concrete, providing that this viscosity does not induce excessive drainage or subsequent leakage from the particular type of concrete used.

6.7 EFFECTS OF DURATION AND FREQUENCY OF IMMERSION

Immersion should, ideally, be accomplished as quickly as possible, particularly if it is an element of a high volume production process. On the other hand, the amount of PCM absorbed must be sufficient for the application. To meet both of these requirements it is necessary to develop an immersion technique for each combination of concrete and PCM. Therefore, once the absorptivity has been optimized as previously discussed, the remaining factors to be determined are those of the duration and frequency of immersion.

Figure 22 shows the effect of successive immersions at varying time intervals of specimens of regular aggregate concrete with silica fume and fly ash in various PCM's. The PCM temperature was maintained at 80°C. In all cases, the specimens achieved 60% of the maximum attained (at the fourth immersion) at the end the first 30 minute immersion, 75-77% at the end of the second 30 minute immersion and increased only moderately to 83-92% by the end of the 60 minute third immersion. From this it will be seen that, in this case, if the desired weight of PCM is 4.5%, only one 30 minute immersion will be required for PEG, three immersions (approximately 90 minutes) for BS and four immersions and 440 minutes for DD.

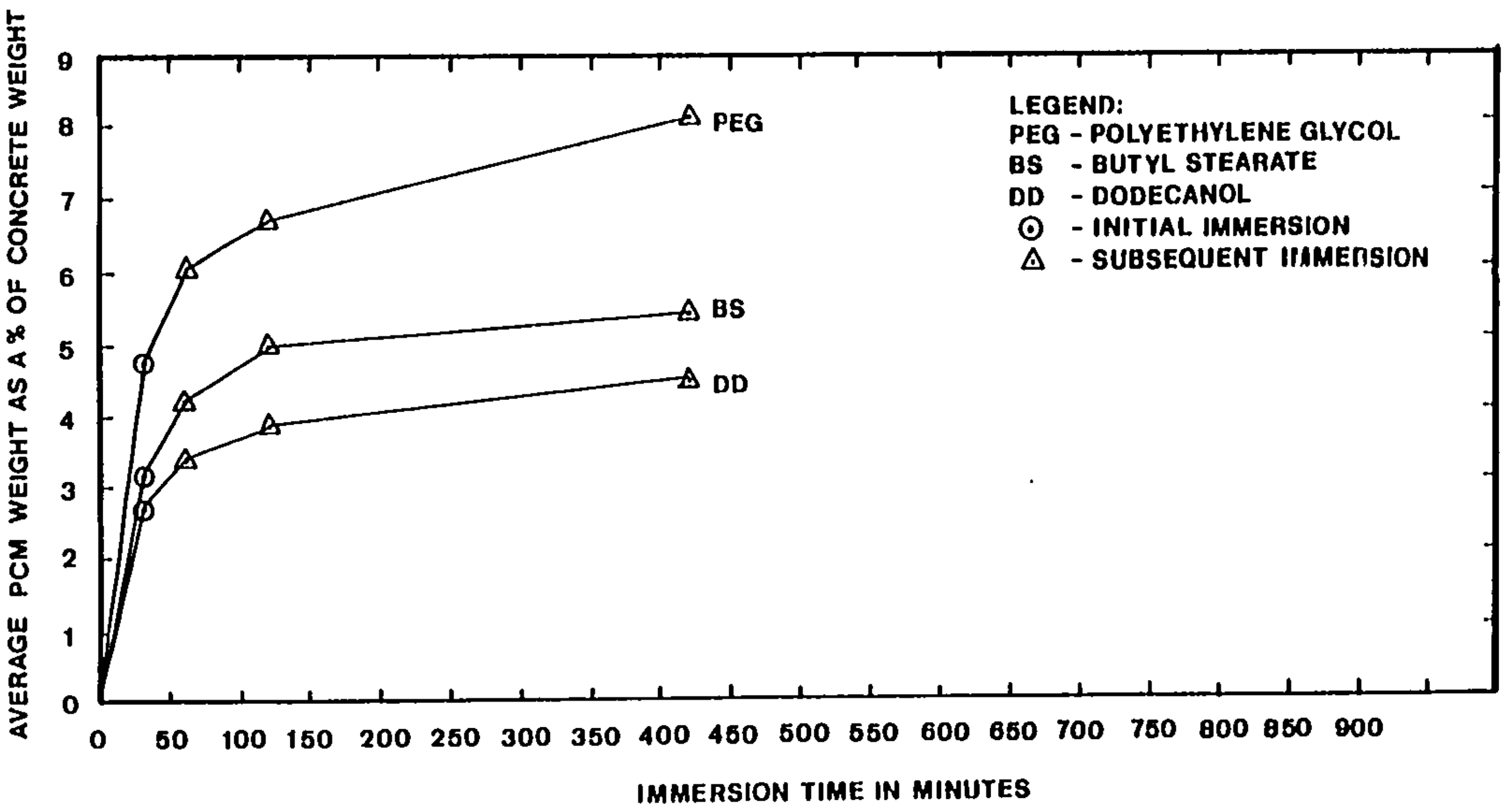


FIGURE 22 - IMMERSION CHARACTERISTICS OF VARIOUS PCM'S IN REGULAR CONCRETE

Figure 23 shows the result of successive immersions at varying time intervals of pumice aggregate concrete with silica fume and fly ash in four PCM's maintained at 80°C. The presence of silica fume and fly ash in this concrete rendered it much less absorbent than ordinary pumice concrete and it will be seen that the absorption of PEG, BS and DD was approximately the same at the 350 minute point as in Figure 22 and that further immersion time accomplished relatively little. As before, the process would be cut off at the point where the required percentage of PCM had been absorbed.

Figures 24 and 25 compare the effects of long and short immersions and the number of immersions required. In the case of PUM-PAR (Figure 24), a single immersion of 20 minutes produced an absorption of 7.31% while a second immersion of a further 390 minutes increased the amount absorbed to 10.14% and a further immersion showed this value to be the maximum attainable under these circumstances. The PCM temperatures were 90°C, 110°C, 130°C. At the present stage of this work it appears that 7.31% PCM by weight is satisfactory so, in this case, a single 20 minute immersion would be sufficient.

In the case of REG-PAR (Figure 24), a single immersion of 20 minutes produced about 50% of the maximum absorption attainable and since this would most likely be insufficient, a further immersion would be required. A single 240 minute immersion of another specimen produced a satisfactory percentage. On the other hand, the second 270 minute immersion of the first specimen fell a little below the 5% desirable minimum. A second immersion of the first specimen and

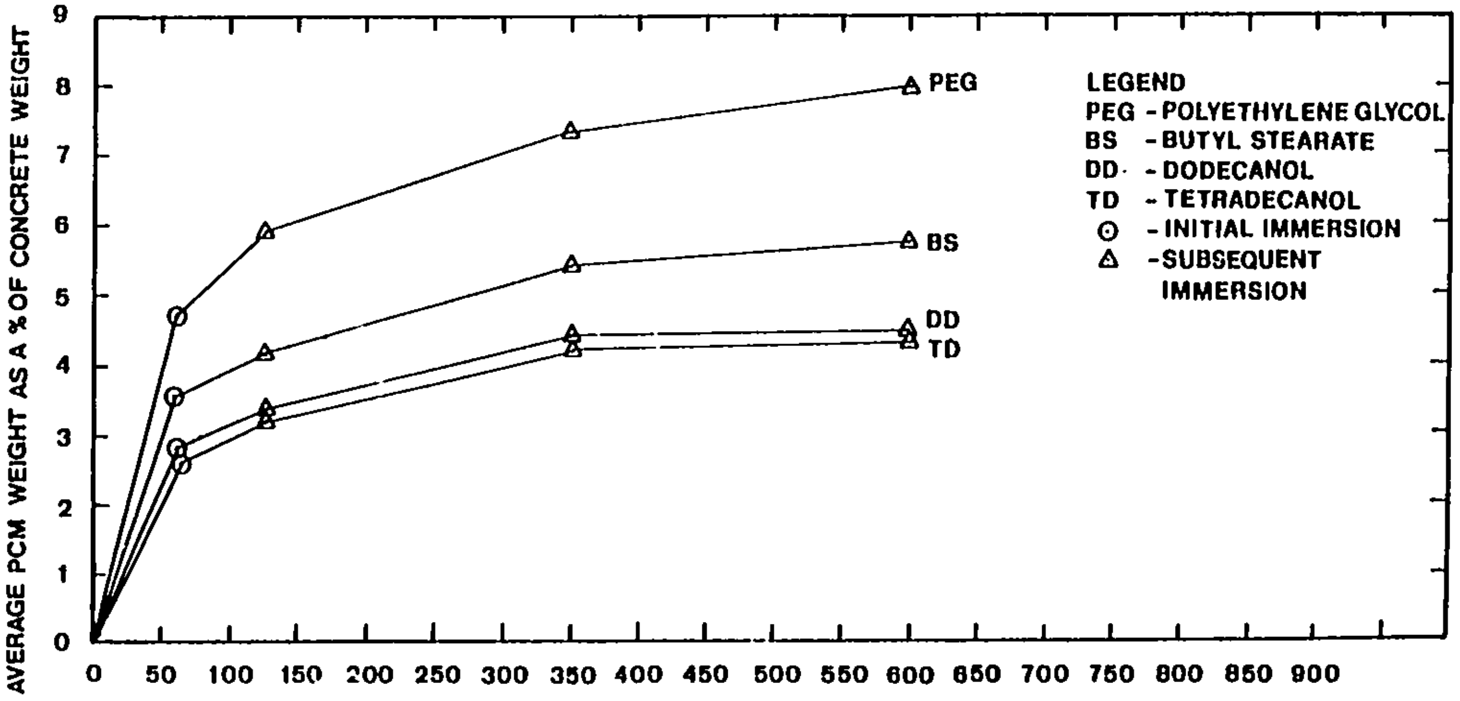


FIGURE 23 - IMMERSION CHARACTERISTICS OF VARIOUS PCM'S IN PUMICE CONCRETE

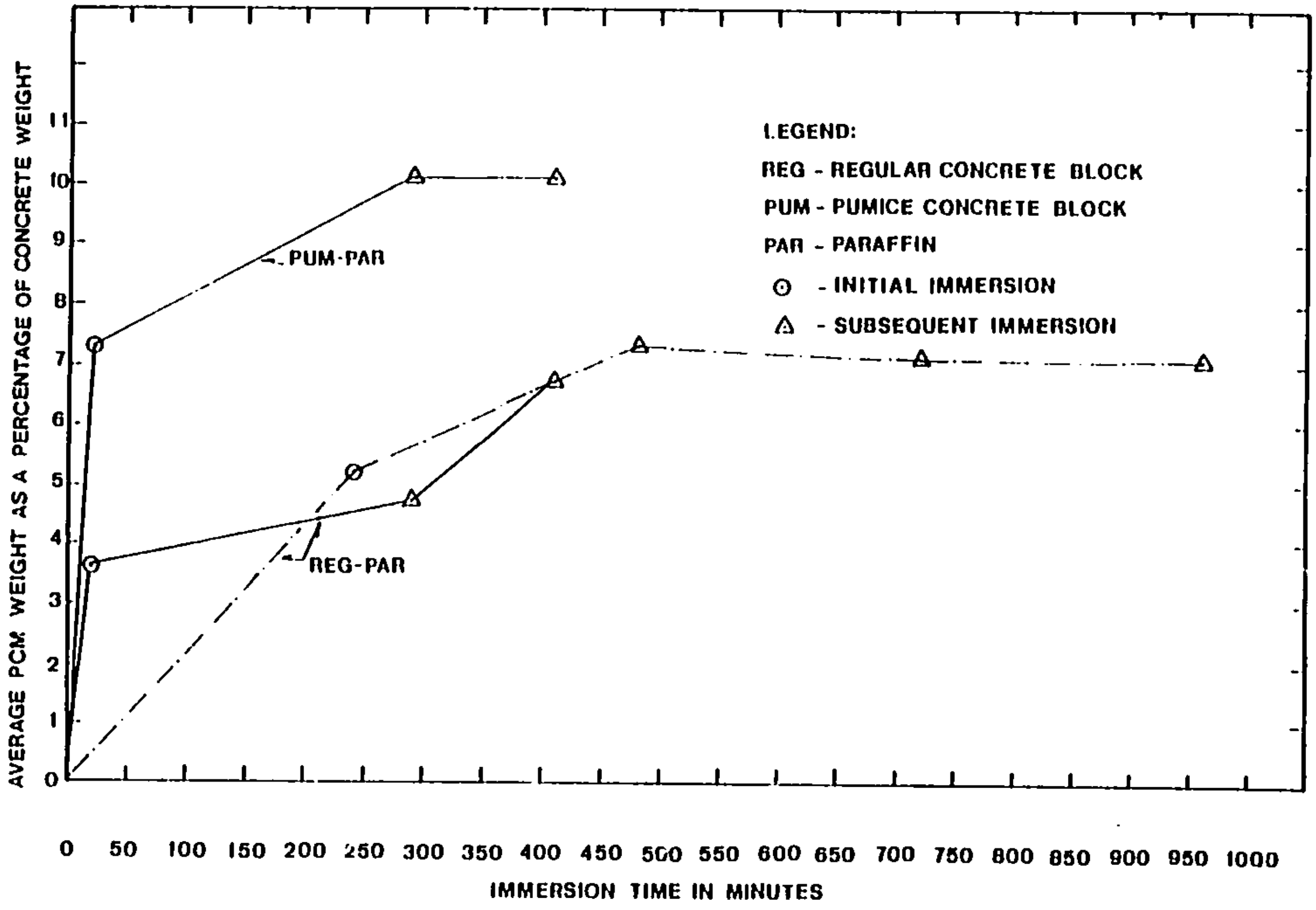


FIGURE 24 - COMPARISON OF NUMBER AND DURATION OF IMMERSIONS REQUIRED FOR VARIOUS PCM-CONCRETE COMBINATIONS

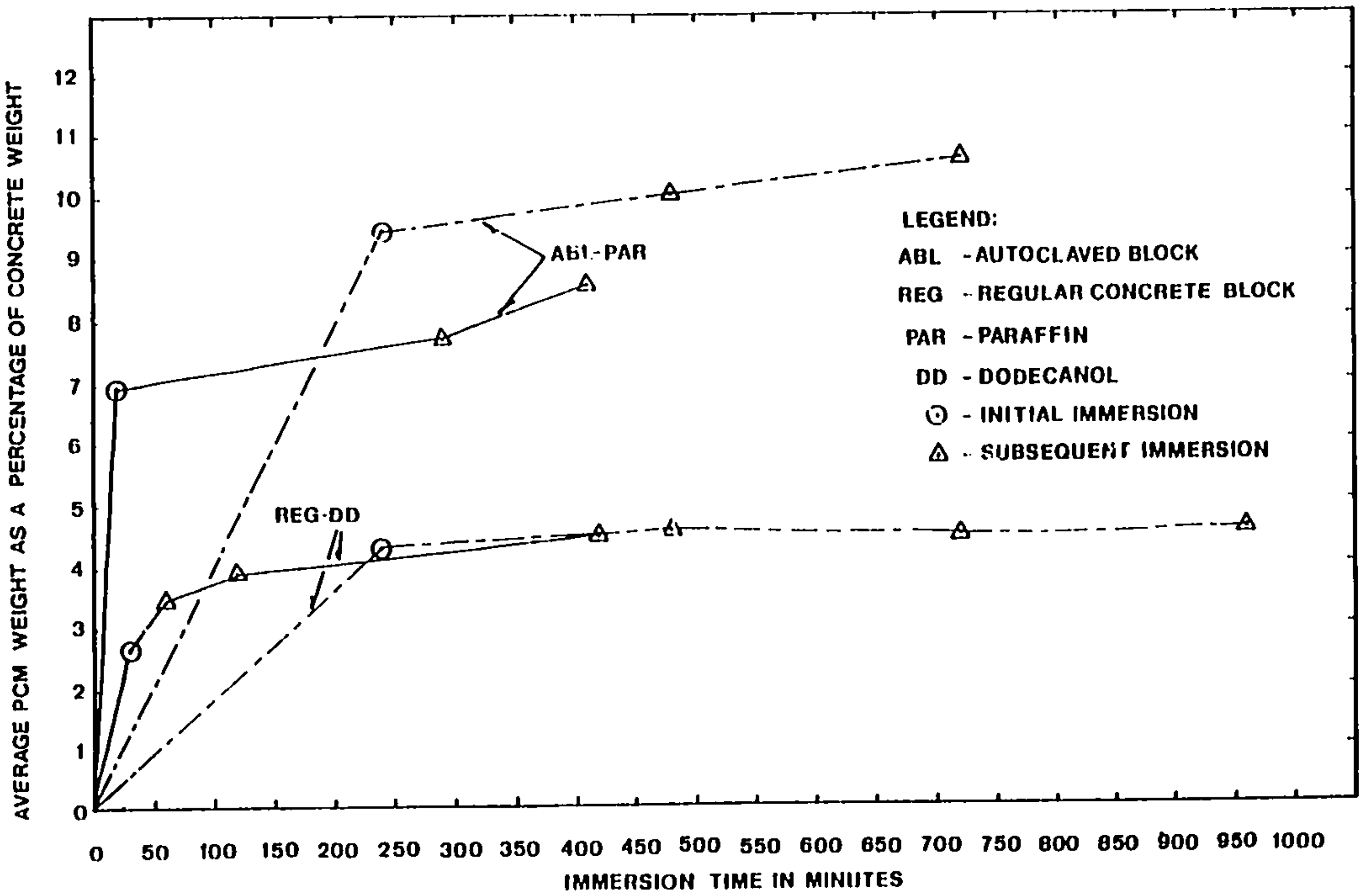


FIGURE 25 - COMPARSION OF NUMBER AND DURATION OF IMMERSIONS REQUIRED FOR VARIOUS PCM-CONCRETE COMBINATIONS

a third immersion of the second specimen attained values of approximately 7% which is about the maximum which one may expect of a specimen of this density. From this it would appear that two 240 minutes immersions would produce optimum results. Immersion temperatures were as above. Protracted immersion was shown to have no value in this case.

In the case of ABL-PAR (Figure 25), an immersion of the first specimen for 20 minutes accomplished 74% of the absorption attained by the second specimen in a 240 minute immersion. It follows that if a maximum of 7% PCM is required then a single 20 minute immersion is sufficient; if 9.5% then a single 240 minute immersion is needed and, if 10%, then two immersions, each of 240 minutes, will be necessary.

A better comparison may be seen in the case of REG-DD (Figure 25) where a series of short term immersions are shown to achieve approximately the same degree of absorption as a single 240 minute immersion and exactly the same at 420 minutes. This pair of curves is an improvement on the foregoing tests in that the difference between the long and short term curves is better defined so that an exact determination of choice is possible. They represent a procedure which could be used in production to decide the type of immersion required for each combination of concrete and PCM. However, the results of this work led to consideration of an alternative method for determining the degree of absorption required and this will be discussed in section 6.14.

6.7.1 Conclusions

At a given immersion temperature, for a specific type of concrete, it was found that the duration and frequency of immersions necessary to effect absorption of the required amount of PCM will vary with the PCM and, up to a point, with the number of immersions. Therefore, to achieve the desired absorption, these factors must be chosen appropriately and tested to develop dependable production procedures. To assist in this process, consideration was then given to the development of a more precise procedure for absorption prediction and this was carried out as discussed in section 6.14.

6.8 EFFECT OF PCM IMPREGNATION ON MOISTURE ABSORPTION

A number of specimens were immersed in water at 20°C for 24 hours to measure comparative absorption. Several types of concrete were tested and in each case an unimpregnated specimen was compared with specimens which had been impregnated with various appropriate PCM's. The results are shown in Figure 26 and Table 8.

In the case of regular concrete, the percentage weight of water absorbed by the paraffin impregnated specimen is exceedingly small (0.02%) while absorbed percentage values for those impregnated with BS, PEG and DD are 0.81, 2.15 and 2.70 respectively. When considered as a percentage of the weight of moisture absorbed by the unimpregnated specimen, the values are 0.51, 20.61, 54.71 and 68.70 for PAR, BS, PEG and DD respectively. Paraffin is particularly effective

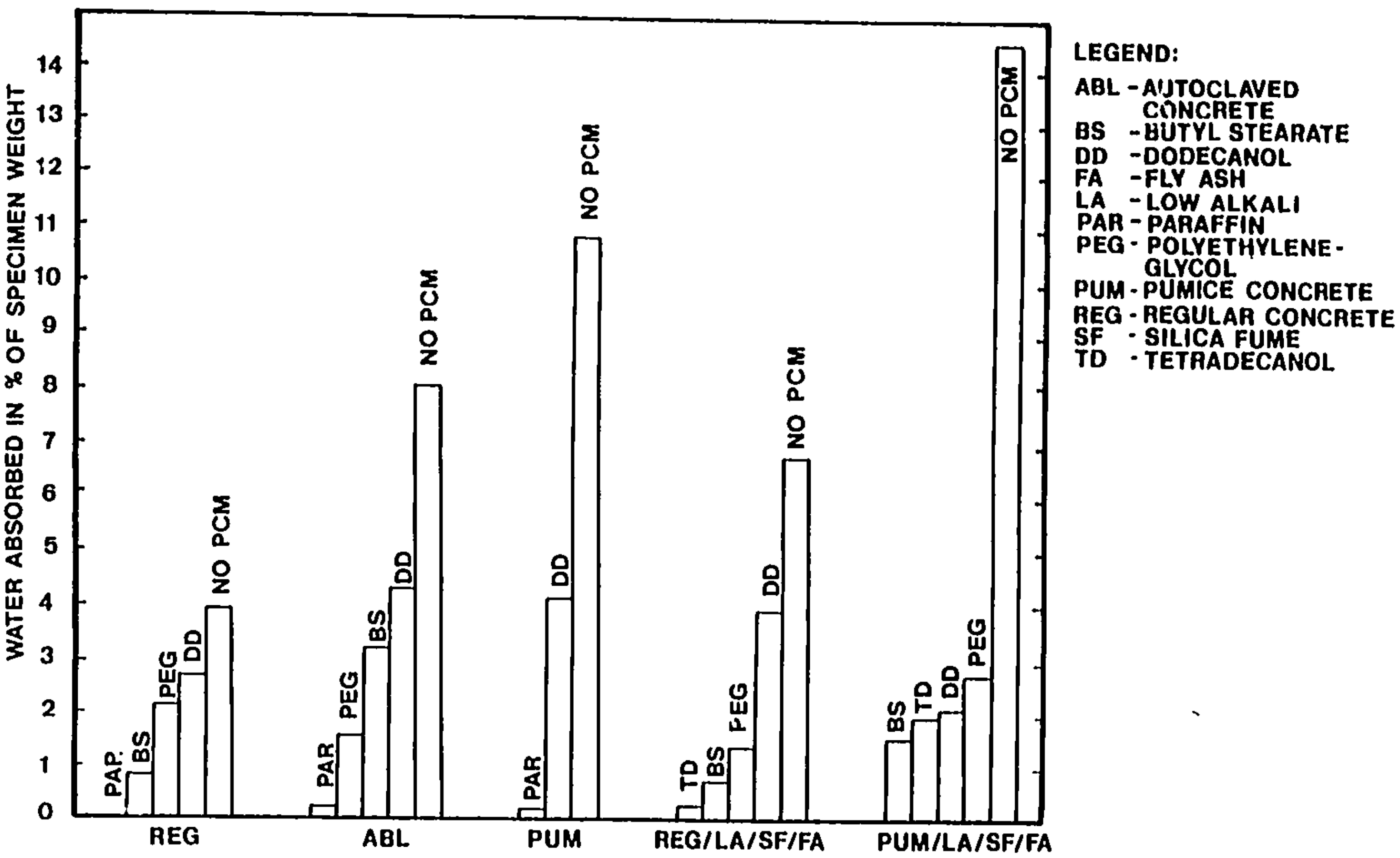


FIGURE 26 - COMPARATIVE MOISTURE ABSORPTION

TABLE 8 SHEET 1
COMPARATIVE MOISTURE ABSORPTION TEST

IMMERSION TIME: 24 hrs; WATER TEMP. 20°C
SC = STEAM CURED; AC = AIR CURED

SPEC NO.	CONCRETE	PCM	POURING TO IMMERSION INTERVAL DAYS & CURE	% PCM BY WT	WT. IN g	WT. OUT g	ABSORBED MOISTURE AS % WT. OF SPECIMEN	ABSORBED MOISTURE AS % WT. OF MOISTURE IN UNIMPREGNATED SPECIMEN
38	REG	BS	8	3.82	217.30	219.11	0.83	21.10
361	REG	DD	303	5.06	157.50	161.75	2.70	68.70
42	REG	PEG	8	5.25	208.90	213.40	2.15	54.71
370	REG	PAR	303	7.17	180.82	180.85	0.02	0.51
420	ABL	BS	330	7.90	143.09	147.73	3.24	40.25
364	ABL	DD	303	7.85	145.39	151.64	4.30	53.42
422	ABL	PEG	330	11.91	149.23	151.60	1.59	19.75
373	ABL	PAR	303	10.21	129.39	129.71	0.25	3.11
368	PUM	DD	303	12.01	106.64	111.06	4.14	38.16
376	PUM	PAR	303	19.81	116.25	116.53	0.25	
425	PUM	PAR	360	9.60	71.52	71.62	0.14	
MEAN	PUM	PAR	-	-	--	--	0.20	1.84
247	REG/LA/ SF/FA	BS	SC/AC 31	5.53	129.80	130.74	0.72	10.60
249	REG/LA/ SF/FA	DD	SC/AC 31	4.63	133.09	138.31	3.92	57.73
253	REG/LA/ SF/FA	PEG	SC/AC 31	7.85	141.50	143.45	1.38	20.32
254	REG/LA/ SF/FA	TD	SC/AC 34	3.18	152.24	152.68	0.29	4.27

TABLE 8 SHEET 2
COMPARATIVE MOISTURE ABSORPTION TEST
IMMERSION TIME: 24 hrs; WATER TEMP. 20°C
SC = STEAM CURED; AC = AIR CURED

SPEC No	CONCRETE	PCM	POURING TO IMMERSION INTERVAL DAYS & CURE	% PCM BY WT	WT. IN g	WT. OUT g	ABSORBED MOISTURE AS % WT OF SPECIMEN	ABSORBED MOISTURE AS % WT. OF MOISTURE IN UNIMPREGNATED SPECIMEN
313	PUM/LA/SF/FA	BS	SC/AC 34	6.45	109.75	111.45	1.55	10.64
315	PUM/LA/SF/FA	DD	SC/AC 34	4.41	108.34	110.61	2.10	14.41
319	PUM/LA/SF/FA	PEG	SC/AC 34	8.23	110.69	113.75	2.76	18.94
323	PUM/LA/SF/FA	TD	SC/AC 34	5.07	110.43	112.60	1.97	13.52
500	REG				187.34	195.00	4.09	
501	REG				207.11	214.90	3.76	
MEAN	REG						3.93	
502	ABL				186.00	200.74	7.92	
503	ABL				225.60	244.05	8.18	
MEAN	ABL						8.05	
504	PUM				115.19	128.05	11.16	
505	PUM				106.39	117.60	10.54	
MEAN	PUM						10.85	
506	REG/LA/SF/FA				137.74	146.84	6.61	
507	REG/LA/SF/FA				125.01	133.71	6.96	
MEAN	REG/LA/SF/FA						6.79	
508	PUM/LA/SF/FA				101.66	116.45	14.55	
509	PUM/LA/SF/FA				104.02	119.20	14.59	
MEAN	PUM/LA/SF/FA						14.57	

because, as a non-polar, hydrophobic substance, it is not subject to hydrogen bonding and is, therefore, free to fill even the smaller pores because of its mobility.

Autoclaved block has a more absorbent structure and consequently the values are a little higher although, in this case, it will be recalled that the density of ABL is approximately 80% that of REG so the relative increase when compared with REG should also be considered in that light. The absorbed percentage of moisture was found to be 0.25, 1.59, 3.24 and 4.30 for ABL specimens impregnated respectively with PAR, PEG, BS and DD. The values for weight of moisture absorbed by the various impregnated specimens when considered as a percentage of that absorbed by the unimpregnated specimen are 3.11, 19.75, 40.25 and 53.42 for PAR, PEG, BS and DD respectively.

For pumice concrete, the percentage weight of moisture absorbed was 0.2% for the paraffin impregnated specimen and 4.14% for that impregnated with DD. Again, the relatively light weight for pumice concrete should be considered when comparing actual weights of moisture, since the density of pumice concrete is in the order of 60% of regular concrete. For the impregnated specimens, the values for the weight of moisture absorbed expressed as a percentage of that absorbed by the unimpregnated specimens are 1.84 for PAR and 38.16 for DD.

Regular concrete with low alkali cement, silica fume and fly ash (REG/LA/SF/FA) has somewhat different characteristics from the REG sample because of the presence of the pozzolans (silica fume and fly ash) which tend to reduce absorption. However, in this case the presence of more than the usual amount of air entrainment actually resulted in slightly greater absorption. The percentage weight of water absorbed was 0.29, 0.72, 1.38 and 3.92 for the specimens impregnated with TD, BS, PEG and DD respectively. When considered as a percentage of the weight of moisture absorbed by the unimpregnated specimen, the values are 4.27, 10.60, 20.32 and 57.73 for the TD, BS, PEG and DD specimens respectively.

In the case of pumice concrete which contains low alkali cement, silica fume and fly ash the impregnated specimens show relatively low absorptance with percentages of moisture of 1.55, 1.97, 2.10 and 2.76 being found in the BS, TD, DD and PEG specimens respectively. In the same order, these specimens have values of 10.64, 13.52, 14.41 and 18.94 expressed as percentage of moisture in the unimpregnated specimen.

The freeze-thaw resistance of concrete depends on a number of characteristics and conditions among which the permeability and porosity are two of the most important (Neville, 1981; Illston, 1979). As a result, the effective reduction of these properties by the impregnant will correspondingly improve the freeze-thaw resistance of impregnated concrete. Similarly, PCM impregnated concrete can also provide greater resistance to attack by other liquids which can be destructive.

6.8.1 Conclusions

It was found that, in all cases, the impregnated specimens were markedly less water absorbent than the unimpregnated specimens. PAR was particularly effective in this respect while BS and TD also performed very well. As a result, PCM concrete has greater freeze-thaw resistance than ordinary concrete as well as having improved resistance to attack by harmful liquids.

6.9 EFFECT OF CURING CONCRETE FOR PCM APPLICATIONS

6.9.1 Types of Curing

The manner of curing concrete was investigated because it has a marked effect upon its strength, alkalinity, absorptivity and other characteristics (Neville, 1981; Mehta, 1986). The effect of curing on absorptivity is of particular interest in this research. The types of concrete block and the various curing methods used are described below.

(a) Steam cured REG comprising limestone, limestone dust, sand, cement and water

In this case the formed blocks were either obtained directly from a manufacturer or were prepared in the CBS building materials laboratory. In the latter event, some modifications to the mix were usually made to obtain a particular effect such as lower alkalinity. The period between mixing and impregnation varied from one day to more than a year. The standard form of this type of concrete block is normally allowed to set at ambient temperatures for about 3 hours, then an hourly temperature gradient of 22 to 33°C is maintained between

1 and 6 hours and the block is steam cured for 5 to 21 hours in the 38-93°C range (i.e. moist curing). After this it is allowed to cool over a period of several hours. The entire cycle is usually completed in less than 24 hours (Neville, 1981; Mehta, 1986). The times, temperatures and rates of change must be held within limits consistent with the desired product characteristics but will vary within those bounds from one manufacturer to another.

(b) ABL made with expanded slag aggregate, fines, cement and water

This type of block was obtained only from a manufacturer since it was not possible to prepare autoclaved specimens in the laboratory. Whereas production techniques will vary from one plant to another, a typical procedure is to have the fresh concrete product remain at ambient temperature and pressure for about 3 hours and then place it in a pressure vessel (autoclave) where the pressure is gradually increased over a period of about 3 hours to a maximum pressure of approximately 1 MPa (182°C). It then remains at these conditions for between 5 and 8 hours after which the pressure is released over a period of 20 to 30 minutes. This rapid release accelerates drying and thus reduces subsequent shrinkage. The block is then decreased to ambient temperature over a 10-12 hour period (Neville, 1981; ACI Manual, 1980). As before, the intervals between mixing and immersion in PCM varied from one day to more than a year.

As stated in Section 4.2.3, there is a big difference in the type of hydrated cement paste produced by the high pressure process (ABL) and that in the low (atmospheric) pressure process (REG) because of the type of binder formed in each. The finely ground silica used in the former process reacts with the $Ca(OH)_2$ released on hydration to form $CaOSiO_2\,nH_20$. This results in a microcrystalline structure in which there is much less free $Ca(OH_2)$ than in the low pressure process so that there is less opportunity for reaction with a PCM.

(c) Steam cured PUM made with pumice aggregate, fines, cement and water

In this case the product was either obtained directly from the manufacturer or prepared with pumice aggregate in the CBS laboratory. This type of concrete is a lightweight (1400 kg/m^3) material and is more alkaline than either of the foregoing types. Pumice aggregate is a light coloured, volcanic glass which is very porous and, as a result, pumice concrete is much more absorbent than the concretes using conventional aggregate or even expanded slag or shale. Manufacture of pumice concrete block normally employs the low pressure (atmospheric) steam curing process.

(d) Modified concretes

In addition to the foregoing conventional types of block, modified concrete blocks were also prepared. These included regular concrete as well as concrete using pumice, expanded slag and expanded shale aggregates in which low alkali cement was used and where portions of the cement were replaced with pozzolans such as silica fume and fly ash. These specimens were all prepared and steam cured in the laboratory. Steam curing was followed by air or water curing.

(e) Steam curing in the laboratory

Most of the concrete block specimens prepared in the CBS laboratory used a curing technique which simulated the conventional commercial steam curing process. In this procedure, freshly poured concrete specimens in their molds were placed in polyethylene bags which were tightly sealed to prevent the loss of moisture. As the temperature was increased, conditions in the bag with the entrapped moisture approximated the conventional steam curing process very closely. The bagged specimens were placed in an oven at 20°C and the temperature was raised by 2.5°C every 15 minutes up to maximum of 75°C. This temperature was then maintained for 12 hours, after which it was reduced by about 2.5°C every 15 minutes over a period of 5 hours until a temperature of 25°C was attained. At this point, the oven was switched off and the door was opened to allow the temperature of the specimens to drop the remaining 5°C to room temperature (Levitt, 1982). Following this, the specimens were demolded and then water cured and/or air cured for a designated period.

(f) OPC

The OPC specimens used in this work were either cured in water or in a moist enclosure for 30 days. In all other respects the specimens used were conventional structural concrete.

(g) Air and water curing

In the case of concrete blocks obtained from the manufacturers, all curing after steam curing or autoclaving occurred in ambient air. In the case of steam cured specimens prepared in the laboratory, two subsequent procedures were used. After steam curing some specimens were air cured under plastic to retard moisture loss for 30 days or until required. The remainder of the specimens were immersed in water for a period of about 30 days then air cured until required. Exceptions to the foregoing are found in the case of OPC concrete specimens which had either been only air cured or were water cured for about 30 days then air cured till required. The abbreviations used are:

AC - air cured

SC - steam cured

WC - water cured

6.9.2 Comparative Absorptivity

The comparative effects of different types of curing on absorptivity may be seen in Figure 27 and Table 9.

It will be seen that, for regular concrete, the absorptance is lowest for water curing and slightly more for air curing and markedly greater for steam curing in all cases. For EXS, the foregoing pattern is followed with BS while with DD and PEG the water cured and air cured positions are reversed but the value for steam curing is greater than the others for all three PCM's. In the case of pumice concrete, the air cured concrete is less absorbent than the water cured which is, in turn, less absorbent than the steam cured concrete, except with DD where the water cured pumice is slightly more absorbent than the steam cured. The

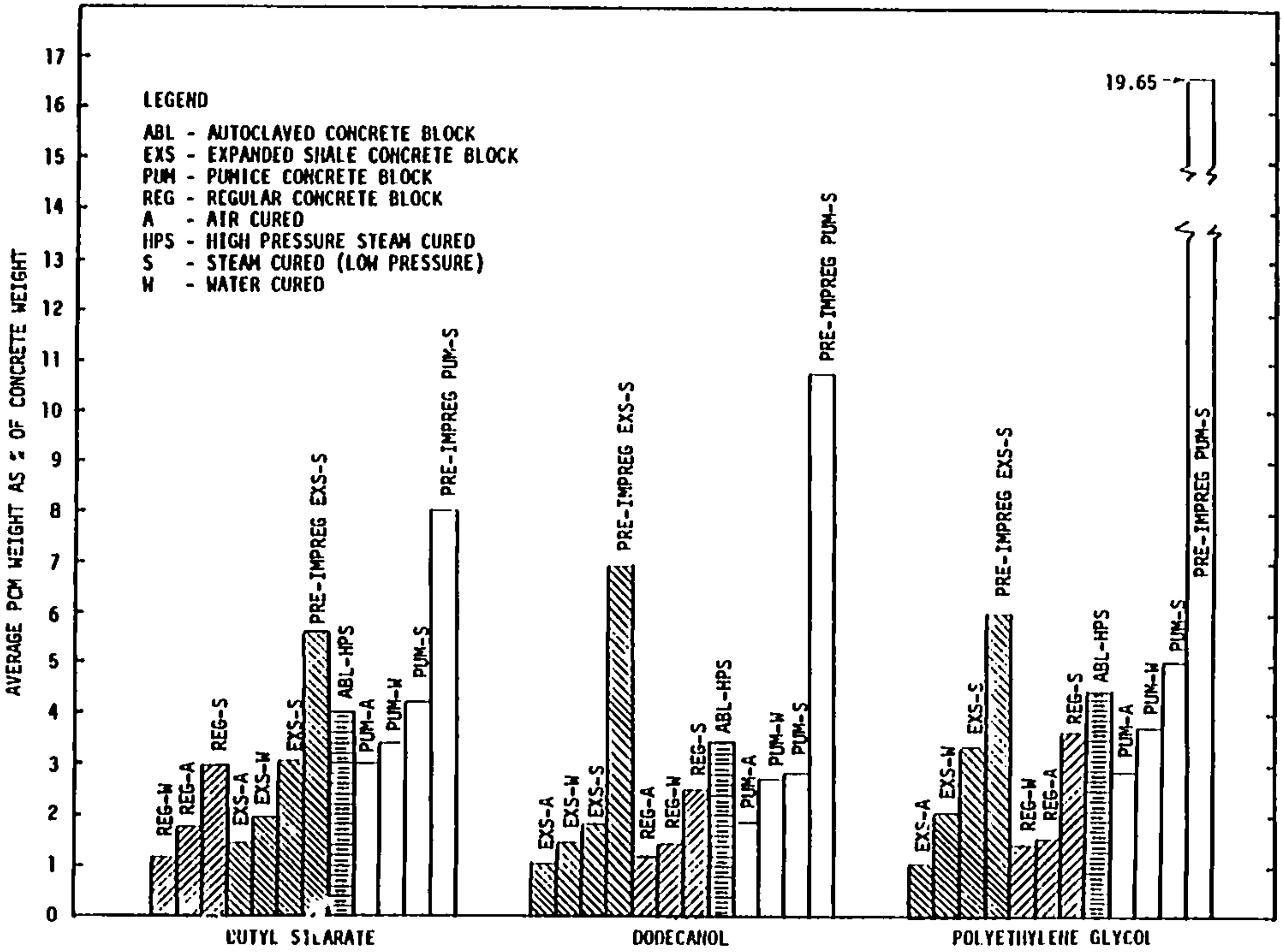


FIGURE 27 - THE EFFECT OF CURING ON ABSORPTIVITY

TABLE 9 SHEET 1

EFFECT OF CURING ON ABSORPTIVITY
PCM AND CONCRETE TEMP.: 80°C; IMMERSION TIME: 12 MIN.

PCM	CONCRETE	CURE	MEAN PCM WT. AS % CONC. WT*	STANDARD DEVIATION	COEFFICIENT OF VARIATION %
BS	REG	WATER	1.14	0.38	33.3
BS	EXS	AIR	1.43	0.25	17.5
BS	REG	AIR	1.74	0.15	8.6
BS	EXS	WATER	1.92	0.29	15.1
BS	REG	STEAM	2.97	0.73	24.6
BS	PUM	AIR	3.00	0.45	15.0
BS	EXS	STEAM	3.03	0.33	10.9
BS	PUM	WATER	3.40	0.24	7.1
BS	ABL	H.P.STEAM	4.00	0.73	18.3
BS	PUM	STEAM	4.22	0.38	9.0
BS	PRE-IMPREG EXS	STEAM	5.60	0.40	7.1
BS	PRE-IMPREG PUM	STEAM	8.00	0.21	2.6

* MEAN OF FIVE VALUES

TABLE 9 SHEET 2

EFFECT OF CURING ON ABSORPTIVITY
PCM AND CONCRETE TEMP.: 80°C; IMMERSION TIME: 12 MIN.

PCM	CONCRETE	CURE	MEAN PCM WT. AS % CONC. WT*	STANDARD DEVIATION	COEFFICIENT OF VARIATION %
DD	EXS	AIR	1.03	0.21	20.4
DD	REG	AIR	1.20	0.10	8.3
DD	REG	WATER	1.42	0.27	19.0
DD	EXS	WATER	1.45	0.26	17.9
DD	EXS	STEAM	1.82	0.33	18.1
DD	PUM	AIR	1.86	0.35	18.8
DD	REG	STEAM	2.50	0.58	23.2
DD	PUM	WATER	2.70	0.36	13.3
DD	PUM	STEAM	2.81	0.98	34.9
DD	ABL	H.P. STEAM	3.43	1.12	32.6
DD	PRE-IMPREG EXS	STEAM	6.90	0.30	4.3
DD	PRE-IMPREG PUM	STEAM	10.74	0.97	9.0

* MEAN OF FIVE VALUES

DATE TABLE 9 SHEET 3

EFFECT OF CURING ON ABSORPTIVITY
PCM AND CONCRETE TEMP.: 80°C; IMMERSION TIME: 12 MIN.

PCM	CONCRETE	CURE	MEAN PCM WT. AS % CONC. WT*	STANDARD DEVIATION	COEFFICIENT OF VARIATION %
PEG	EXS	AIR	1.05	0.22	20.9
PEG	REG	WATER	1.42	0.27	19.0
PEG	REG	AIR	1.55	0.09	5.8
PEG	EXS	WATER	2.09	0.26	12.4
PEG	PUM	AIR	2.89	0.30	10.4
PEG	EXS	STEAM	3.38	0.38	11.2
PEG	REG	STEAM	3.65	1.12	30.7
PEG	PUM	WATER	3.76	0.78	20.7
PEG	ABL	H.P. STEAM	4.48	0.78	17.5
PEG	PUM	STEAM	5.08	1.69	33.3
PEG	PRE-IMPREG EXS	STEAM	6.00	0.8	13.3
PEG	PRE-IMPREG PUM	STEAM	19.65	1.16	5.9

* MEAN OF FIVE VALUES

variations in the absoptivity are likely due to the fact that air curing allows the following reaction to occur:

$$Ca(OH)_2 \text{ [in concrete]} + CO_2 \text{ [in air]} \rightarrow CaCO_3 + H_2O \qquad \text{(Eq. 10)}$$

This reaction also occurs in water but much more slowly. As a result, the void structure (and hence the absorptivity) caused by the formation of $CaC0_3$ will vary between that produced by air curing and that by water curing. The amount of PCM absorbed will also be affected by the difference in the basic structure of each type of concrete. In addition, absorptivity will be influenced by the polarity of the PCM's used. The latter effect will be discussed later.

Specimens of pre-impregnated expanded shale and pre-impregnated pumice were also examined and it will be seen that this is an effective means of augmenting the normal absorption procedure. It does, however, involve an extra operation because, in addition to the normal PCM absorption technique, the aggregate must be impregnated before it is added to the mix.

6.9.3 Conclusions

Several types of non-autoclaved concrete which had been cured in various ways were tested for PCM absorptance and it was found that steam cured products were the best overall choice. This result is fortunate from the point of view of PCM concrete since many concrete products suitable for PCM incorporation are steam cured.

Of the steam cured products, autoclaved block is in a class by itself since it is produced by a high pressure curing process. Among the single operation specimens (i.e. all except the pre-impregnated ones) the ABL specimens showed the highest overall absorptivity.

6.10 THERMAL CONDUCTIVITY OF PCM CONCRETE

Eight pairs of 190x190x28 mm specimens were tested for conductivity. The specimens impregnated with BS and DD were tested with the PCM in the liquid state while the specimens impregnated with PAR were tested in the solid state.

Two types of concrete were used, regular and autoclaved. For each type of concrete, test pairs were prepared without PCM, with BS, with DD and with PAR. The results are shown in Table 10.

In the case of regular concrete, the R-values for the impregnated specimens ranged from equal to 18% greater than that for the unimpregnated specimens. This can be explained by the fact that the structure of regular concrete is relatively dense with most of the PCM content held in voids between which conduction is limited to that provided by small capillaries and pores.

TABLE 10
THERMAL CONDUCTIVITY TESTS
SPECIMENS: 190X190X28 mm; BS & DD TESTED IN LIQUID STATE, PAR IN SOLID STATE; A=BOTTOM SPEC., B=TOP SPEC.

SPEC	CONCRETE TYPE	PCM	INITIAL WT.	FINAL WT.	GAIN		AVERAGE THICKNESS	K-FACTOR	R-VALUE
			g	g	g	%	mm	W/m°C	m² °C/W
564A	REG	None	-	-	-	-	27.2	0.9227	0.033
564B	REG	None	-	-	-	-	27.8		
565A	REG	BS	2231.40	2311.02	79.62	3.57	28.9	0.7978	0.039
565B	REG	BS	2172.80	2246.15	73.35	3.38	28.0		
566A	REG	DD	2091.52	2177.90	86.38	4.13	27.6	0.9303	0.033
566B	REG	DD	2112.70	2208.42	95.72	4.53	27.8		
567A	REG	PAR	2250.00	2360.00	110.00	4.89	28.4	0.8384	0.037
567B	REG	PAR	2260.00	2370.20	110.20	4.88	28.2		
568A	ABL	None	-	-	-	-	26.6	0.4098	0.072
568B	ABL	None	-	-	-	-	26.8		
569A	ABL	BS	1748.55	1840.68	92.13	5.27	26.8	0.5111	0.059
569B	ABL	BS	1748.55	1842.40	93.95	5.37	27.5		
570A	ABL	DD	1726.61	1832.64	106.03	6.14	26.8	0.5329	0.050
570B	ABL	DD	1686.81	1803.38	116.57	6.91	26.8		
571A	ABL	PAR	1721.52	1862.00	140.48	8.16	26.9	0.5491	0.054
571B	ABL	PAR	1759.65	1909.60	149.95	8.52	26.9		

The PCM in the voids then represents the principal variable in respect to conductivity. It has been found that the amount of heat conducted through some liquids in an isolated void of generally spherical shape can be less than that transferred by radiation across the same void when it is filled with air (Low, 1990). As a result, the R-value of regular concrete impregnated with PCM can be greater than that of the unimpregnated concrete.

ABL, on the other hand, has a more open structure where the voids can constitute a series of relatively continuous thermal paths which, although irregular, parallel those of the concrete matrix itself. When these are filled with PCM, this network offers a better conducting path than in the unimpregnated case where thermal radiation must take place via a series of irregular shapes rather than via the more regular one encountered in REG. As a result, heat transfer by radiation is less effective than by conduction through the PCM so that the R-values in the impregnated specimens varied between 17% and 30% lower than the unimpregnated specimens.

Although the conductivity of PCM's in the liquid state is different from that in the solid condition, this difference does not appear to be significant when it is dispersed throughout the concrete matrix which constitutes the principal conducting medium.

6.10.1 Conclusions

The R-value of REG concrete impregnated with PCM was found to be equal to or greater than that for unimpregnated REG concrete while the R-value for ABL PCM concrete was observed to be less than that for unimpregnated ABL concrete. These differences are not considered large enough to be significant in respect to heat loss because exterior blocks will likely be insulated in any event. The conductivity of impregnated blocks must be incorporated into the calculations of the thermal charge-discharge cycle.

6.11 EFFECT OF TEMPERATURE CYCLING ON PCM CONCRETE

Table 11 shows the results of subjecting 57 specimens of impregnated concrete to a freeze-thaw cycling test in which the cycle frequency was 6 hours and the temperatures alternated between 33°C and -25°C for a total of 560 cycles. It will be noted that freeze-thaw in this instance refers to the freezing and melting of PCM as well as that of moisture.

In the case of ABL-BS the test appears to have had no effect on the specimens other than a slight darkening which one expects with some impregnated concrete combinations because of the oleaginous nature of the PCM's.

The ABL-DD combination in two cases showed no change at all while in two others a very slight dust was deposited on the surface of the specimen and on the material on which it was supported. The weight change due to this loss was not

TABLE 11 SHEET 1 - TEMPERATURE CYCLING TEST
TEMPERATURE RANGE - 25°C + 33°C
CYCLING FREQUENCY 6 HOURS; NO. OF CYCLES 560

SPEC No.	CONCRETE	PCM	INTERVAL BETWEEN POURING & IMMERSION DAYS	% PCM BY WT.	WT. IN g	WT. OUT g	LOSS % OF WT.	REMARKS
2	ABL	BS	1	3.38	226.50	227.61	-	APP. OK
2.2	ABL	DD	1	4.02	157.42	158.41	-	APP. OK
6	ABL	PEG	1	5.33	217.59	218.80	-	APP. DK
14	REG	BS	1	3.06	216.60	217.54		APP. OK
11	REG	DD	1	3.15	212.10	212.60		APP. OK DUSTY DEPOSIT
16	REG	PEG	1	3.44	222.28	223.89		APP. DK
32	ABL	BS	8	4.68	174.09	174.75		SLIGHTLY DK
34	ABL	DD	8	5.50	225.42	226.55		APP. OK
35	ABL	PEG	8	4.48	117.29	178.20		VERY SLIGHTLY DK
38	REG	BS	8	3.82	217.40	217.79		VERY SLIGHTLY DK
40	REG	DD	8	3.38	212.63	211.10	0.72	SLIGHT CRUMBLING
42	REG	PEG	8	5.25	205.63	206.70		APP. OK
46	ABL	BS	30	2.31	178.32	179.01		SLIGHTLY DARK
44	ABL	DD	30	4.45	93.61	93.30	0.33	APP. OK DUSTY DEPOSIT
48	ABL	PEG	30	3.51	190.70	192.95		VERY SLIGHTLY DK
52	REG	BS	30	3.11	201.89	202.22		VERY SLIGHTLY DK
50	REG	DD	30	2.13	165.51	167.25		APP. OK VERY SLIGHT DUST
51	REG	PEG	30	3.13	183.19	184.49		SLIGHTLY DK

APP. = Appearance
DK = Dark

TABLE 11 SHEET 2 - TEMPERATURE CYCLING TEST
TEMPERATURE RANGE - 25°C + 33°C
CYCLING FREQUENCY 6 HOURS; NO. OF CYCLES 560

SPEC NO.	CONCRETE	PCM	INTERVAL BETWEEN POURING & IMMERSION DAYS	% PCM BY WT.	WT. IN. g	WT. OUT g	LOSS % OF WT.	REMARKS
75	ABL	BS	65	4.55	179.23	179.60		SLIGHTLY DK
77	ABL	DD	65	2.29	197.51	199.10		APP. OK
79	ABL	PEG	65	5.03	178.02	178.24		SLIGHT DUST SLIGHTLY DK DUSTY DEPOSIT
69	REG	BS	65	2.24	193.92	194.24		APP OK
70	REG	DD	65	1.98	187.00	188.91		APP OK
72	REG	PEG	65	1.75	196.47	197.29		SLIGHTLY DK
143	PRE-IMP EXS/LA/SF	BS	SC+AC 41	5.7	187.00	187.79		APP OK
147	PRE-IMP EXS/LA/SF	DD	SC+AC 41	6.9	188.10	191.50		APP OK
149	PRE-IMP EXS/LA/SF	PEG	SC+AC 41	6.3	189.85	193.27		APP OK
152	PRE-IMP PUM/LA/SF	BS	SC+AC 40	12.72	150.35	150.35		APP OK
156	PRE-IMP PUM/LA/SF	DD	SC+AC 40	11.1	148.84	146.24	1.75	DUSTY DEPOSIT (ORIGINAL MIX WAS VERY POROUS)
158	PRE-IMP PUM/LA/SF	PEG	SC+AC 40	20.0	154.05	157.55		SLIGHTLY DK
198	PUM/LA/SF	BS	WC35+AC66	4.62	64.07	64.16		APP OK
200	PUM/LA/SF	DD	WC35+AC66	2.97	64.16	64.38		APP OK

TABLE 11 SHEET 3 - TEMPERATURE CYCLING TEST
TEMPERATURE RANGE - 25°C + 33°C
CYCLING FREQUENCY 6 HOURS; NO. OF CYCLES 560

SPEC NO.	CONCRETE	PCM	INTERVAL BETWEEN POURING & IMMERSION DAYS	% PCM BY WT.	WT. IN. g	WT. OUT g	LOSS % OF WT.	REMARKS
202	PUM/LA/SF	PEG	WC35+AC66	4.90	50.51	51.31		APP OK
204	REG/LA/SF	BS	SC+AC 91	2.98	143.35	143.69		APP OK
206	REG/LA/SF	DD	SC+AC 91	4.62	70.87	70.64	0.32	APP OK
208	REG/LA/SF	PEG	SC+AC 91	5.88	75.32	75.92		APP OK
210	EXS/LA/SF	BS	SC+AC 91	3.19	109.00	110.21		APP OK
212	EXS/LA/SF	DD	SC+AC 91	1.71	72.91	74.15		APP OK
214	EXS/LA/SF	PEG	SC+AC 91	3.74	66.68	67.80		APP OK
216	PUM/LA/SF	BS	SC+AC 91	4.13	88.48	89.38		APP OK
218	PUM/LA/SF	DD	SC+AC 91	3.63	47.88	47.80	0.17	APP OK
220	PUM/LA/SF	PEG	SC+AC 91	4.61	53.40	54.07		APP OK
222	PRE-IMP EXS/LA/SF	BS	SC+AC 92	5.79	186.63	187.38		APP OK
224	PRE-IMP EXS/LA/SF	DD	SC+AC 92	6.32	206.23	211.70		APP OK
226	PRE-IMP EXS/LA/SF	PEG	SC+AC 92	4.72	184.40	190.50		APP OK

TABLE 11 SHEET 4 - TEMPERATURE CYCLING TEST
TEMPERATURE RANGE - 25°C + 33°C
CYCLING FREQUENCY 6 HOURS; NO. OF CYCLES 560

SPEC NO.	CONCRETE	PCM	INTERVAL BETWEEN POURING & IMMERSION DAYS	% PCM BY WT.	WT. IN. g	WT. OUT g	LOSS % OF WT.	REMARKS
234	REG	PAR	230	7.14	306.38	305.50	0.29	APP OK
237	ABL	PAR	230	8.95	195.24	195.76		APP OK
241	PUM	PAR	230	11.75	150.15	151.10		APP OK
244	OPC	PAR	230	2.82	346.86	348.17		APP OK
337	REG/LA/SF/FA	BS	SC+AC 35	3.56	160.08	159.34	0.46	DARK
340	REG/LA/SF/FA	DD	SC+AC 35	2.82	158.60	158.54	0.04	APP OK SLIGHT DUSTING
343	REG/LA/SF/FA	PEG	SC+AC 35	4.10	163.80	164.70		APP OK
347	REG/LA/SF/FA	TD	SC+AC 35	3.18	152.33	152.10	0.15	APP OK VERY SLIGHT DUSTING
349	REG/LA/SF/FA	BS	SC+WC 29	2.35	161.80	161.28	0.32	DARK
351	REG/LA/SF/FA	DD	SC+WC 29	2.01	158.63	158.70		APP OK VERY SLIGHT DUSTING
356	REG/LA/SF/FA	PEG	SC+WC 29	3.46	161.04	161.72		APP OK
359	REG/LA/SF/FA	TD	SC+WC 29	2.64	160.30	159.72	0.36	APP OK VERY SLIGHT DUSTING

detectable in one case and was 0.33% in the other. Since a slight efflorescence is occasionally observed in the case of DD, it is probable that melting and freezing will cause it to be deposited, together with loose, surface particulate matter which has been absorbed by the efflorescence. The dusting effect of DD will be discussed later.

The ABL-PAR combination showed no change after cycling.

ABL-PEG combinations were found to be stable but, in one instance, some dusting was observed. However, the weight loss was not detectable.

In the case of REG-BS, no change was observed in four specimens other than a slight darkening in two of them which is characteristic of some impregnated concretes.

As in the case of ABL-DD, the REG-DD combination showed some deposition of dust in three of the four specimens tested, although this was measurable only in one case (0.72% loss). The reason for this deposition is as for ABL-DD and will be discussed later.

No change was observed for the REG-PEG combinations other than a slight darkening found in some impregnated concretes.

No change was found in the REG-PAR other than a very small weight loss (0.29%) probably due to drainage of excessive PCM.

In the case of pumice concrete, no change was detected in the PUM-PAR combination.

All of the foregoing tests were conducted using standard commercial specimens of concrete block. The dusting which occurs with DD in most cases appears to be similar to but actually less severe than the results produced by the freeze-thaw effect in the unimpregnated materials. Therefore, impregnation of these materials with PCM's appears to have a beneficial effect in this respect.

For the modified concrete types prepared in the laboratory the following effects were observed.

Pre-impregnated EXS/LA/SF steam cured specimens impregnated with BS, DD and PEG showed no change.

The pre-impregnated PUM/LA/SF steam cured specimen impregnated with BS showed no change while that impregnated with DD showed a significant deposit. The only change observed when using PEG with this type of concrete was a slight darkening.

The PUM/LA/SF specimens which were water cured and impregnated with BS,DD and PEG showed no effect.

REG/LA/SF steam cured specimens impregnated with BS and PEG showed no effect while a slight loss (0.32%) was observed as a result of DD effloresence.

EXS/LA/SF steam cured specimens impregnated with BS, DD and PEG showed no effect.

PUM/LA/SF steam cured specimens impregnated with BS and PEG showed no effect, while a very slight loss (0.17%) was observed in the case of DD.

REG/LA/SF/FA steam cured specimens impregnated with BS and PEG showed no effect other than darkening and a slight loss (0.46%) in the case of BS. The specimens impregnated with DD and TD showed negligible dusting and the weight loss was only 0.04% and 0.15% respectively.

The only loss in the REG/LA/SF/FA specimens which were steam cured followed by water curing then impregnated with BS, DD, PEG and TD was observed in the case of TD which was very slight (0.36%).

No change was observed in the case of OPC impregnated with PAR.

6.11.1 Conclusions

As a result of these tests it was found that, under the conditions observed, the only significant effects produced by the temperature cycling on impregnated specimens were those relating to DD and this was less than that subsequently observed in the case of unimpregnated specimens. These results were as expected because, as seen in section 6.8, the impregnated specimens were shown to be markedly less moisture absorbent than the unimpregnated ones and hence less subject to freeze thaw damage. Except in the case of a very porous test mix the loss of PCM was observed to be negligible.

6.12 FLEXURAL STRENGTH OF PCM CONCRETE

Figure 28 and Table 12 show that there is no significant difference in strength between plain concrete and that impregnated with PCM in the liquid state. This satisfactory performance is possibly due to the fact that, in the case of absorbed PCM, the cement gel is not dilated (Neville, 1981) as well as the absence of disjoining pressure (Mehta, 1986).

It will be noted that the presence of PAR increases the flexural strength of concrete by about 50% when the PCM is the solid state. This is mentioned as a matter of interest only since a practical application for this condition has not yet been found.

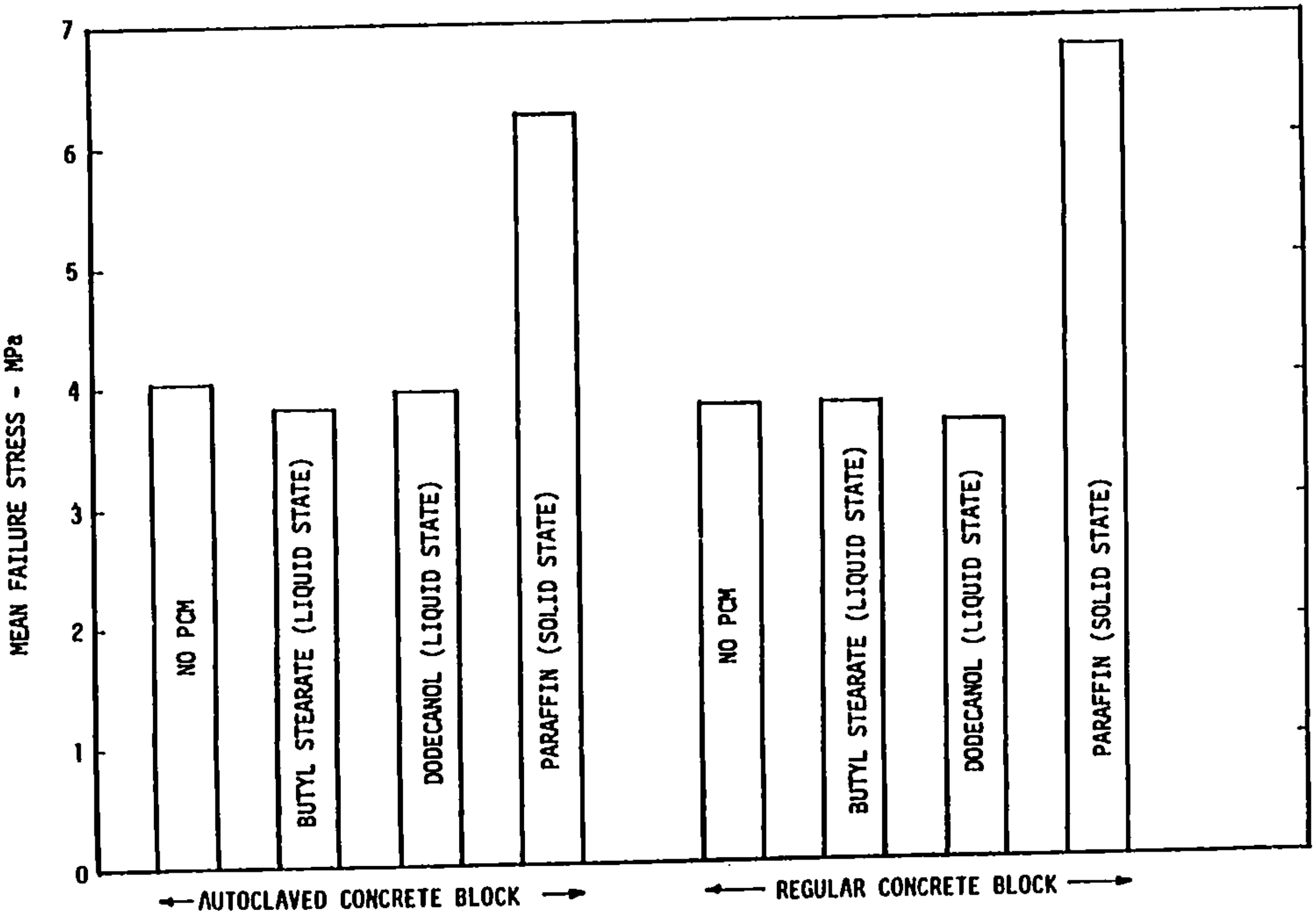


FIGURE 28 - COMPARATIVE FLEXURAL STRENGTH OF PLAIN AND IMPREGNATED CONCRETE

TABLE 12 SHEET 1
FLEXURAL STRENGTH TESTS
IMMERSION TIME: 300 MIN AT 90°C PLUS 960 MIN AT 90°C → 20 °C
CONCRETE TEMPERATURE AT IMMERSION 100°C
SPECIMENS TESTED WITH PCM IN LIQUID STATE

SPECIMEN NO.	CONCRETE TYPE	PCM	INITIAL WT	FINAL WT	GAIN		LOAD WEIGHT	MEAN LOAD	MEAN FAILURE STRESS
			g	g	g	%	Kg	N	N/mm^2
540	ABL	PAR	469.65	504.60	34.95	7.44	178	1923	6.29
541	ABL	PAR	489.07	526.05	36.98	7.56	166		
542	ABL	PAR	518.22	556.24	38.02	7.34	208		
543	ABL	PAR	477.84	513.50	35.66	7.46	215		
544	ABL	PAR	479.97	516.69	36.72	7.65	200		
545	ABL	PAR	512.25	549.72	37.47	7.31	210		
546	REG	PAR	544.76	591.90	47.14	8.65	210	2065	6.75
547	REG	PAR	551.78	596.49	44.71	8.10	215		
548	REG	PAR	567.20	613.16	45.96	8.10	222		
549	REG	PAR	560.76	602.84	42.08	7.50	220		
550	REG	PAR	572.13	616.79	44.66	7.80	218		
551	REG	PAR	565.19	610.11	44.92	7.95	178		

TABLE 12 SHEET 2
FLEXURAL STRENGTH TESTS
IMMERSION TIME: 300 MIN AT 80°C PLUS 960 MIN AT 80°C → 20 °C
CONCRETE TEMPERATURE AT IMMERSION 100°C
SPECIMENS TESTED WITH PCM IN LIQUID STATE

SPECIMEN N0.	CONCRETE TYPE	PCM	INITIAL WT	FINAL WT	GAIN		LOAD WEIGHT	MEAN LOAD	MEAN FAILURE STRESS
			g	g	g	%	Kg	N	N/mm²
528	ABL	DD	485.62	517.41	31.79	6.54	126	1207	3.95
529	ABL	DD	473.23	504.54	31.31	6.61	115		
530	ABL	DD	486.50	518.69	32.19	6.61	126		
531	ABL	DD	465.45	496.95	31.50	6.76	-		
532	ABL	DD	511.80	546.65	34.85	6.81	125		
533	ABL	DD	503.63	536.63	33.00	6.55	122		
534	REG	DD	600.40	628.29	27.89	4.64	124	1118	3.66
535	REG	DD	595.75	623.35	27.60	4.63	129		
536	REG	DD	593.56	621.10	27.54	4.64	108		
537	REG	DD	577.73	606.89	29.16	5.04	104		
538	REG	DD	577.44	606.00	28.56	4.94	103		
539	REG	DD	582.22	609.48	27.26	4.68	114		

TABLE 12 SHEET 3
FLEXURAL STRENGTH TESTS
IMMERSION TIME: 300 MIN AT 80°C PLUS 960 MIN AT 80°C → 20 °C
CONCRETE TEMPERATURE AT IMMERSION 100°C
SPECIMENS TESTED WITH PCM IN LIQUID STATE

SPECIMEN NO.	CONCRETE TYPE	PCM	INITIAL WT	FINAL WT	GAIN		LOAD WEIGHT	MEAN LOAD	MEAN FAILURE STRESS
			g	g	g	%	Kg	N	N/mm^2
510	ABL	BS	490.83	530.70	39.87	8.12	135	1167	3.82
511	ABL	BS	495.70	534.65	39.15	7.90	117		
512	ABL	BS	457.49	494.40	36.91	8.07	-		
513	ABL	BS	460.01	496.30	36.29	7.89	116		
514	ABL	BS	473.31	512.20	38.89	8.22	114		
515	ABL	BS	466.07	503.15	37.08	7.95	109		
516	REG	BS	598.17	628.30	30.13	5.04	128	1172	3.83
517	REG	BS	580.73	611.12	30.39	5.23	110		
518	REG	BS	605.09	634.58	29.49	4.87	124		
519	REG	BS	603.70	637.80	34.10	5.65	119		
520	REG	BS	544.91	573.10	28.19	5.17	107		
521	REG	BS	600.70	630.96	30.26	5.04	129		

TABLE 12 - SHEET 4
FLEXURAL STRENGTH TESTS
CONTROL SPECIMEN

SPECIMEN NO	CONCRETE TYPE	SPECIMEN WEIGHT g	LOAD WEIGHT Kg	MEAN LOAD N	MEAN FAILURE STRESS N/mm^2
552	ABL	505.79	108	1236	4.04
553	ABL	491.74	115		
554	ABL	493.93	132		
555	ABL	511.80	145		
556	ABL	481.49	128		
557	ABL	484.39	130		
558	REG	575.01	123	1167	3.82
559	REG	587.78	124		
560	REG	573.90	117		
561	REG	586.34	106		
562	REG	600.09	126		
562	REG	577.64	120		

6.12.1 Conclusions

It was found that there is no significant difference in the strength of plain or impregnated concrete when PCM is in the liquid state. PCM in the solid state will increase the strength of the concrete by about 50% in the case of PAR.

6.13 FIRE RESISTANCE OF PCM CONCRETE

6.13.1 Flame Spread

Table 13 and Figure 29 show the results produced when three 200 mm x 200 mm x 30 mm specimens were placed in the fire testing apparatus described in section 5.9 and Figure 8 where one side of the lowest specimen was subject to a directly impinging 700°C (± 10°C) flame for ten minutes. The three specimens used in each test were placed end-to-end and held at the edges to present an area open to the flame which was sloped at approximately 33° to the horizontal to allow convection to assist the spread of flame.

In no case did the flame travel more than 100 mm from the point of application, i.e. the maximum dimension of the burned area was 200 mm, so that burning was only visible on the lowest specimen in each test.

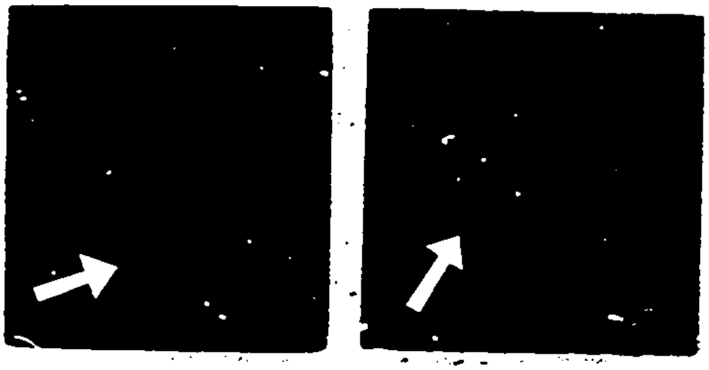
6.13.2 Effects of Burning

In the case of ABL-BS, 8.3% of the weight of PCM was lost. The general area affected by the flame was lighter in colour than the surrounding material and had an oval shape with axes 100 mm and 200 mm in length. There was no after-burning when the torch flame was removed. The visible fume discharge was negligible.

For the REG-BS combination, PCM loss was negligible. The axes of the white, oval burned area measured 60 mm x 100 mm and there was no after-burning. Visible fume discharge was negligible.

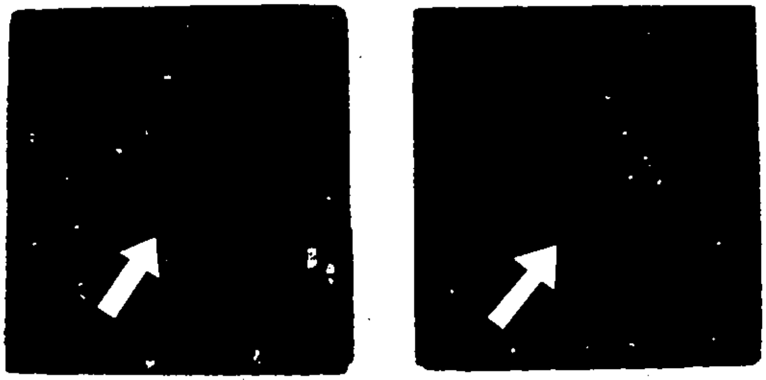
TABLE 13 - FIRE TESTS
SPECIMENS SUBJECTED TO 700°C ± 10°C FLAME FOR TEN MINUTES
TORCH TIP TO SPECIMEN: 100 mm; TORCH FLAME LENGTH: 120 mm

SPECIMEN NO.	CONCRETE TYPE	PCM	INITIAL WT. g	FINAL WT. g	GAIN		CONDITIONS AFTER TEST		AFTER-BURNING	VISIBLE FUME DISCHARGE
					g	% OF WT. OF CONCRETE	% OF PCM LOST	BURNED AREA		
522 A	ABL	BS	2657.0	2798.0	231.0	9.00	-	-	-	-
522 B	ABL	BS	2469.3	2694.0	224.7	9.10	-	-	-	-
522 C	ABL	BS	2553.6	2734.9	181.3	7.10	8.3	White oval spot 100x200mm	NONE	NEG.
523 A	REG	BS	2941.0	3107.5	166.5	5.66	NEG.	White oval spot 60x100mm	NONE	NEG.
523 B	REG	BS	2964.0	3143.2	179.2	6.05	-	-	-	-
523 C	REG	BS	2733.0	2862.9	129.9	4.75	-	-	-	-
524 A	ABL	DD	2469.7	2635.1	165.4	6.70	18.1	White oval spot 100x150mm	NONE	Slight. Stops after flame removal
524 B	ABL	DD	2358.9	2535.0	176.1	7.46	17.0	-	-	
524 C	ABL	DD	2236.0	2450.8	214.8	9.60	13.9	-	-	-
525 A	REG	DD	2931.6	3086.5	154.9	5.28	6.4	White oval spot 100x120mm	NONE	Moderate. Stops after flame removal
525 B	REG	DD	2996.8	3165.5	168.7	5.63	-	-	-	
525 C	REG	DD	2996.0	3165.0	169.0	5.64	-	-	-	-
526 A	ABL	PAR	2537.0	2723.6	186.6	7.36	5.3	Brown oval spot 50x80mm	-	Moderate. Stops after flame removal
526 B	ABL	PAR	2402.8	2610.0	207.2	8.62	-	-	-	
526 C	ABL	PAR	2390.5	2567.6	177.1	7.41	-	-	-	-
527 A	REG	PAR	2870.0	3010.0	140.0	4.88	7.1	Brown oval spot 30x40mm	NONE	Very slight. Stops after flame removal
527 B	REG	PAR	2740.0	2890.0	150.0	5.47	-	-	-	-
527 C	REG	PAR	2930.0	3080.0	150.0	5.12	-	-	-	-



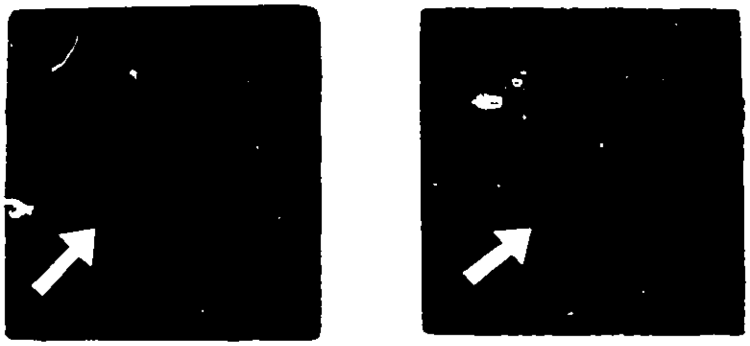
REGULAR BLOCK - BUTYL STEARATE

AUTOCLAVED BLOCK - BUTYL STEARATE



REGULAR BLOCK - DODECANOL

AUTOCLAVED BLOCK - DODECANOL



REGULAR BLOCK - PARAFFIN

AUTOCLAVED BLOCK - PARAFFIN

FIGURE 29 - FLAME SPREAD TESTS

In the case of ABL-DD, the loss in weight of PCM in the specimen touched by the flame was 18.1%. Of all the flame tests, this was the only instance in which loss of PCM (17.0% and 13.9%) also occurred in the two adjacent specimens. This was possibly due to volatilization but is more probably attributable to drainage caused by a combination of lower PCM viscosity at the high temperature, the relatively open structure of ABL and the fact that the hydrogen bonding is destroyed at higher temperatures. In the specimen on which the flame impinged there was a white, oval area 100 mm x 150 mm. There was no after-burning. The visible fume discharge was slight and stopped when the flame was removed.

In the case of REG-DD, the PCM weight loss was 6.4%. The axes of the whitish, burned, oval area were 100 mm and 120 mm. There was no after burning. There was a visible fume discharge of moderate density which stopped when the flame was removed. Although the PCM was DD, in this case there was no measurable weight loss in the adjacent specimens. In all probability, this was due to the greater surface tension in the smaller diameters of the pore structure of REG when compared to ABL.

For the ABL-PAR combination, the loss in weight of PCM was 5.3%. The burned area had a brownish colour. It was quite small and oval in shape with axes of 50 mm and 80 mm. There was no after-burning. The visible fume discharge was moderate in intensity and stopped as soon as the flame was removed.

In the case of REG-PAR, the PCM weight loss was 7.1%. The burned area was brown and oval in shape with axes of only 30 mm and 40 mm in length. There was no after-burning. The fume discharge was very slight and stopped when the flame was removed.

6.13.3 General Observations

It should be noted that only the visible portion of fume discharge was observed. Prior to placing a PCM concrete product on the market it will be necessary to measure and analyse the fume discharge when subjected to the temperatures encountered in a burning building. These tests must be carried out in an approved fire-testing establishment with the necessary fume measurement facilities.

The addition of flammable material to concrete must, inevitably, lead to some combustion under appropriate circumstances. However, it will be seen that the low proportion of combustible to non-combustible in PCM block (about 5% in most cases) did not give rise to a self-sustaining flame in the foregoing tests. In addition, the edge of the torch flame was about 40 mm from the centre of flame application and the spread of flame beyond this point was limited to approximately 80 mm.

The area of flame application was affected more or less in a manner which one would find in ordinary concrete which had been heated to 700°C for 10 minutes. Moreover, it is probable that some amelioration may actually have been effected by the absorption of heat required to melt and vaporize the PCM. Although very slight cracking was noted in some cases, no crumbling or obvious physical deterioration was observed and all specimens remained intact.

No indication of burning was observed on the side opposite to that to which the flame was applied.

After a few weeks, the PCM migrated back into the areas from which it had been driven by the flame. The whitish areas disappeared in most cases, leaving only a small brown residue at the centre of the point of flame application as shown in Figure 29.

It was not deemed necessary at this stage of the development to add a fire retardant. This decision was made because of the apparently low rate of flame spread and evidently satisfactory degree of fire resistance. Furthermore, it was desired to avoid fume generation problems which could arise from the addition of some fire retardants.

The foregoing work gives a reasonable indication of how PCM concrete block might perform under fire conditions similar to those used in these tests. However, it must be repeated that full scale testing must be carried out at an approved fire testing establishment. At such a facility it will be possible to conduct flame spread and fire resistance on a large scale and to perform fume measurement tests as well. This will lead to the evaluation of the final product design. Then, if any modifications have been found necessary, the product may be re-tested and an approved fire rating can be given.

Since concrete using lightweight aggregate such as expanded slag or pumice is ideal for use with PCM's, it should be noted that the unimpregnated fire resistance of these concretes is approximately 32% greater than that of concrete using calcareous aggregate and 42% greater than concrete made with silicious material (Neville, 1981).

6.13.4 Conclusions

Fire resistance of PCM concrete is good and the flame spread is minimal, Fume discharge was observed visually and ranged from negligible to moderate. However, fire spread, fire resistance and fume generation must be measured and rated at a full scale fire testing facility before a PCM concrete product can be placed on the market.

6.14 ABSORPTION OF PCM'S IN CONCRETE

6.14.1 Summary of Factors

It was seen that many factors affect the absorptivity of each concrete - PCM combination. Since this is one of the most critical aspects of the incorporation of PCM, some of the most significant factors are briefly reviewed here.

(a) Concrete structure

The size and form of the gel and capillary pores as well as other openings such as voids and fissures in the matrix will affect the volume of the space necessary for the storage and flow of PCM. In addition, the diameter of the capillaries will determine the effect of surface tension. The porosity of the aggregate also contributes to the absorptivity of the concrete. The latter effect can be significant in the case of porous aggregates such as pumice, expanded shale and expanded slag.

(b) Temperature

Temperature acts in various ways to affect the absorption of PCM in concrete. It will be recalled that the rise of liquid in a capillary is expressed by the following formula (Hutcheon, 1983).

$$h - \frac{2\gamma}{g\rho r} \qquad \text{(eq. 11)}$$

where h = height of liquid retained in the capillary

γ = interfacial tension between liquid and air

ρ = density

r = radius of the capillary

g = gravitational constant

A temperature rise in the concrete will increase the radius of the capillaries. It will also decrease both the interfacial tension and the density of the liquid but will decrease the former more than the latter so that the net result can be a reduction in the amount of liquid retained in the capillaries. Therefore, it follows that, while it is necessary to raise the temperature of the concrete and the PCM to a point where conditions are satisfactory for impregnation, it should not be higher than necessary, so that retention of PCM in the capillaries will be as high as possible when the concrete is removed from the bath. The effect of cooling the liquid before removal of the concrete from the bath was not considered necessary at this time because of the added cost of production which it would entail.

It should also be noted that the temperature of the concrete will gradually approach that of the PCM bath if the liquid mass is significantly greater than that of the concrete.

(c) Viscosity

The viscosity of the PCM during absorption varies inversely with its temperature and it must be low enough at the immersion temperature to achieve effective penetration into the concrete and high enough to prevent excessive drainage from the product when it is removed from the bath. It will be noted that the viscosity at the upper limit of its installed environment must be such as to allow surface tension to prevent migration of the PCM to the outer surface of the concrete where it can be lost and cause undesirable surface effects. The effects of viscosity are discussed later in this section.

(d) Time of immersion

The absorption process is exponentially related to the time of immersion as will be discussed later in this section. The effect of immersion time and the number of immersions necessary was discussed in section 6.7.

(e) Area of absorption

The amount of liquid absorbed by a solid is directly related to its surface area. It is also affected by the size and shape of the absorbing solid as discussed later in this section.

(f) Liquid pressure

The depth of the liquid in the bath constitutes a head pressure which drives the PCM into the concrete. In the current research the very small depths employed have exerted negligible pressures. However, this factor will be important if the head pressure becomes significant.

(g) Moisture removal

Various models of the concrete microstructure exist but common to most is the conclusion that both van der Waals' force and the stronger ionic and covalent bonding play very important rôles in the binding which exists between the gel particles. In addition, water in various forms exists in this structure:

(i) bulk water in the capillary pores

(ii) absorbed water on and between surfaces in the micropores

(iii) water in solutions of different minerals.

The loss of this water from the capillary pores can induce compressive stress due to surface tension effects while loss of water from between the layers and from the surfaces changes the bonding potential (Mindess, 1981). From this it will be seen that the removal of water from the concrete structure through drying, together with the physical effects on the concrete of the drying temperature, can cause changes in the concrete structure which will affect its reaction with a PCM in addition to the purely volumetric considerations involved. It follows that the introduction of the PCM into the concrete also affects it in a manner analogous to that of the introduction of water.

(h) Polarity

Some PCM's such as DD are polar substances and are, therefore, subject to hydrogen bonding with polar materials in the concrete. This bonding can restrict the amount of material absorbed because it offers an impediment to flow. The degree of polarity varies; for example, BS is less polar than DD and some PCM's such as PAR are not polar at all. The effect of hydrogen bonding is discussed later in this section.

(i) Age

The volume of gel pores (dia 15-20Å) increases as concrete ages and that of the larger diameter capillary pores (~1.3µm) decreases so that porosity decreases with age. This will vary with the type of concrete and with the water-cement ratio (Neville, 1981).

6.14.2 Technique for the Determination of Constants for the Absorption of PCM in Concrete

The specific absorptivity of a given building material for a given PCM is a characteristic of great importance in respect to PCM impregnation. An understanding of this property is required for all forms of impregnation but it has particular relevance to the immersion process where it affects not only the dispersion of PCM throughout the material but also the duration of immersion and the amount of PCM absorbed.

It follows then that absorption constants which would relate the amount of a given PCM absorbed per unit area by a given type of concrete in a given time under standard conditions of temperature and pressure would be very useful in the manufacturing process.

(a) Flow of PCM in concrete

Both liquid and vapour flow are possible through the interconnected pore system of concrete. Liquid-like flow can be expected along thick sorbed films and the smaller capillaries that have been filled by merged films while both film and vapour flow may occur in the larger unfilled pores and capillaries.

The migration of liquid in sorbed films and capillaries will be determined by the head pressure (e.g. that produced by surface tension or external pressure) and that of vapour by the vapour pressure gradient. Under isothermal conditions these different flows will reinforce one another while under a temperature gradient they may differ in direction and magnitude (Hutcheon, 1983).

In addition, the diffusion of one substance in another is governed by four effects.

(i) ordinary diffusion resulting from a concentration gradient

(ii) thermal diffusion resulting from a thermal gradient

(iii) pressure diffusion resulting from a pressure gradient (e.g. surface tension head pressure)

(iv) forced diffusion because of unequal forces on the two substances

Where more than one substance (e.g. PCM and moisture) is being diffused in another (concrete) the different characteristics of the three materials make the resolution of diffusion very complicated, indeed (Bird, 1960). These flows are described by the following equations.

(i) Permeability for liquid flow in concrete may be expressed by Darcy's Law in the following form (Neville, 1981):

$$\frac{dM}{dt} = \frac{A\,k\,hp}{x} \qquad \text{(eq. 12)}$$

M = mass of liquid in kg

t = time of flow in s

A = cross sectional area through which flow occurs in m^2

h = hydraulic head in m

x = length of flow path in m

k = coefficient of liquid permeability in m/s

ρ = density in kg/m^3

(ii) Permeability for vapour transmission may be similarly expressed by an analogous formula (Hutcheon, 1983):

$$\frac{dM}{dt} = -\mu A \frac{dp}{dx} \qquad \text{(eq. 13)}$$

where M = mass of vapour transmitted in kg

p = vapour pressure in Pa

μ = permeability in ng/smPa

(iii) Diffusion may be described by the following form of Fick's Law:

$$\frac{dM}{dt} = -D\,A \frac{dc}{dx} \qquad \text{(eq. 14)}$$

where M = mass flow in kg

D = diffusivity coefficient in m^2/s

c = liquid concentration in kg/m^3

x = direction of diffusion (unidirectional in this case) in m.

This equation accounts for the fact that the flux goes to zero as the specimen becomes homogeneous (Shewmon, 1963).

In view of the fact that the flows described above are not constant with time, a modified form of Washburn's equation (Spooner, 1983) offers a rational means of combining them.

$$M = A\,K\,t^{x} \qquad \text{(eq. 15)}$$

where M = mass of absorbed PCM in kg

A = area of contact between PCM and concrete in m^2

K = constant for the PCM-concrete combination in kg/m^2s^x

t = time in s

x = exponent appropriate to the conditions and materials used

(b) Determination of absorption constants

Equation 15 becomes practical only if appropriate values of K and the exponent of time can be determined. These may be determined as follows.

The mass of liquid absorbed by the pores in the concrete during surface contact with liquid (PCM) may be expressed as:

$$M = d\,\rho\,a \qquad \text{(eq. 16)}$$

where M = mass of absorbed liquid (PCM) in kg

d = depth of the meniscus (depth of penetration) in m

ρ = density of the liquid kg/m^3

a = total cross section of the filled pores in m^2

(i.e. the effective area of the absorbed material)

Then, combining equations (15) and (16)

$$d\rho a = AKt^{x} \qquad \text{(eq. 17)}$$

and by rearranging eq. 17:

$$K = \frac{d\rho a}{t^{x}A} \qquad \text{(eq. 18)}$$

It will be seen that, for a given set of conditions and materials, the constant (K) incorporates the relationship between the effective pore area (a) and the contact surface (A), the depth of PCM penetration (d), the density of the liquid (ρ) and the time of contact (t). It follows that the exponent (x) of the time factor (t) must be appropriate to the relevant materials and conditions of immersion.

If values for K and the exponent of t could be established, then, knowing the area (A) through which the material will be absorbed, it would be possible to calculate the time required to absorb the desired mass of PCM (M) under the given conditions from equation 15.

To confirm this, research was carried out in respect to the absorption of BS, DD and PAR in both REG and ABL concrete. Standard conditions for absorption were set at 80°C for both concrete and PCM at ambient atmospheric pressure. To establish the desired values equation 15 was rearranged as:

$$K = M/At^{x} \qquad \text{(eq. 19)}$$

To begin with, values for M and A were established by measurement. It was also known from a study of Washburn's work with moisture in concrete (Spooner, 1983) that the values of the exponents of t for PCM's would likely fall within the range 0.1 to 1.0.

Under the aforementioned standard conditions, provisional values of K were determined for each combination of PCM and concrete through a series of absorption times ranging from 60 to 360 seconds by successively applying approximately twelve different time exponents within the abovementioned scale of values. Then, since the appropriate value of K in each case would be that which remained virtually constant throughout the range of immersion times, it follows that the time exponent which produced the greatest degree of constancy was also the applicable value.

The results of this experiment are shown in Tables 14 to 19 and are summarized in Table 20.

From Table 20 it may be seen that the foregoing procedure resulted in very little variation in the values of K determined over the range of times selected.

TABLE 14
DETERMINATION OF ABSORPTION CHARACTERISTICS OF REG-BS PCM AND CONCRETE 80°C AT IMMERSION

SPEC. NO.	CONCRETE WT. kg.	IMPREG WT. kg.	PCM WT.(M) kg.	IMMERSION TIME (t) s	ABSORPT. AREA(A) m^2	CONSTANT K			PENETRATION	
						$M/At^{0.5}$	ARITH. MEAN	COEFF. OF VARIATION %	mm	ARITH. MEAN
600	0.13330	0.13521	0.00191	60	0.001553	0.542	0.529	6.4	13.3	11.6
601	0.13175	0.13340	0.00165	60	0.001505	0.483			9.5	
602	0.12302	0.12500	0.00198	60	0.001550	0.563			12.1	
603	0.14469	0.14684	0.00215	100	0.001661	0.515	0.534	4.7	13.0	13.1
604	0.13030	0.13230	0.00200	100	0.001538	0.518			13.0	
605	0.12975	0.13220	0.00245	100	0.001711	0.570			13.4	
606	0.14089	0.14334	0.00245	160	0.001608	0.552	0.556	1.6	14.5	15.1
607	0.12780	0.13080	0.00300	160	0.001913	0.568			14.1	
608	0.12348	0.12636	0.00288	160	0.001906	0.548			16.6	
609	0.14350	0.14603	0.00253	240	0.001648	0.513	0.502	2.2	14.9	14.6
610	0.14375	0.14627	0.00252	240	0.001728	0.487			14.6	
611	0.15325	0.15579	0.00254	240	0.001680	0.505			14.5	
612	0.12510	0.12781	0.00271	360	0.001525	0.518	0.551	1.4	19.0	17.7
613	0.13243	0.13527	0.00284	360	0.001556	0.562			17.4	
614	0.11920	0.12183	0.00263	360	0.001490	0.544			16.8	

TABLE 15
DETERMINATION OF ABSORPTION CHARACTERISTICS OF ABL-BS PCM AND CONCRETE 80°C AT IMMERSION

SPEC. No.	CONCRETE WT. Kg.	IMPREG WT. kg.	PCM WT.(M) kg.	IMMERSION TIME (t) s	ABSORPT. AREA(A) m^2	CONSTANT K			PENETRATION	
						$M/At^{0.5}$	ARITH. MEAN	COEFF. OF VARIATION %	mm	ARITH. MEAN
615	0.11894	0.12127	0.00233	60	0.001576	0.433	0.418	2.8	16.5	16.1
616	0.11745	0.11965	0.00220	60	0.001589	0.405			15.3	
617	0.11528	0.11759	0.00222	60	0.001567	0.415			16.5	
618	0.10578	0.10843	0.00265	100	0.001594	0.418	0.450	5.6	17.1	18.8
619	0.11625	0.11906	0.00281	100	0.001472	0.480			18.6	
620	0.12025	0.12302	0.00277	100	0.001542	0.451			20.6	
621	0.10336	0.10660	0.00324	160	0.001519	0.465	0.460	4.5	20.9	21.1
622	0.11415	0.11730	0.00315	160	0.001618	0.425			21.0	
623	0.10359	0.10721	0.00362	160	0.001613	0.490			21.5	
624	0.09766	0.10134	0.00368	240	0.001503	0.473	0.461	7.8	23.5	23.1
625	0.11188	0.11560	0.00372	240	0.001447	0.497			24.4	
626	0.11007	0.11352	0.00345	240	0.001619	0.412			21.4	
627	0.11050	0.11494	0.00444	360	0.001636	0.464	0.464	0.8	26.3	25.5
628	0.11052	0.11451	0.00399	360	0.001486	0.459			25.1	
629	0.0953	0.09903	0.00373	360	0.001362	0.468			25.2	

TABLE 16
DETERMINATION OF ABSORPTION CHARACTERISTICS OF REG-DD PCM AND CONCRETE 80°C AT IMMERSION

SPEC. NO.	CONCRETE WT. Kg.	IMPREG WT. Kg.	PCM WT.(M) Kg.	IMMERSION TIME (t) s	ABSORPT. AREA(A) m^2	CONSTANT K			PENETRATION	
						$M/At^{0.1}$	ARITH. MEAN	COEFF. OF VARIATION %	mm	ARITH. MEAN
636	0.16021	0.16161	0.00140	60	0.001786	0.521	0.550	6.5	7.7	9.0
637	0.12473	0.12610	0.00137	60	0.001517	0.600			11.0	
638	0.11404	0.11516	0.00112	60	0.001408	0.529			8.2	
639	0.13725	0.13870	0.00145	100	0.001677	0.546	0.516	12.3	10.0	9.2
640	0.15093	0.15193	0.00153	100	0.001690	0.575			9.3	
641	0.14131	0.14240	0.00109	100	0.001606	0.428			8.2	
642	0.15040	0.15190	0.00150	160	0.001788	0.505	0.554	17.0	10.6	11.3
643	0.14179	0.14370	0.00191	160	0.001676	0.686			11.4	
644	0.13552	0.13680	0.00128	160	0.001633	0.472			11.6	
645	0.14519	0.14693	0.00174	240	0.001751	0.574	0.568	3.9	12.0	12.6
646	0.14720	0.14899	0.00179	240	0.001748	0.592			12.2	
647	0.14204	0.14354	0.00150	240	0.001610	0.539			13.7	
648	0.11841	0.11996	0.00155	360	0.001453	0.592	0.526	8.9	13.8	13.3
649	0.15810	0.15974	0.00164	360	0.001814	0.502			13.5	
650	0.15623	0.15780	0.00157	360	0.001798	0.485			12.5	

TABLE 17
DETERMINATION OF ABSORPTION CHARACTERISTICS OF ABL-DD PCM AND CONCRETE 80°C AT IMMERSION

SPEC. NO.	CONCRETE WT. Kg.	IMPREG WT. Kg.	PCM WT.(M) Kg.	IMMERSION TIME(t) s	ABSORPT. AREA(A) m^2	CONSTANT K			PENETRATION	
						$M/At^{.2}$	ARITH. MEAN	COEFF. OF VARIATION %	mm	ARITH. MEAN
651	0.10955	0.11204	0.00249	60	0.001658	0.662	0.633	3.4	13.5	14.2
652	0.13115	0.13349	0.00234	60	0.001685	0.612			15.0	
653	0.10681	0.10900	0.00219	60	0.001547	0.624			14.0	
654	0.10175	0.10435	0.00260	100	0.001410	0.734	0.614	13.9	16.1	15.9
655	0.10120	0.10332	0.00212	100	0.001530	0.552			15.0	
656	0.12229	0.12470	0.00241	100	0.001730	0.555			16.5	
657	0.13886	0.14149	0.00263	160	0.001798	0.530	0.602	11.9	16.7	18.2
658	0.12130	0.12374	0.00244	160	0.001537	0.575			19.0	
659	0.11817	0.12141	0.00324	160	0.001678	0.700			19.0	
660	0.11612	0.11891	0.00279	240	0.001514	0.616	0.588	3.8	18.3	18.7
661	0.11094	0.11384	0.00290	240	0.001654	0.586			18.9	
662	0.11369	0.11644	0.00275	240	0.001634	0.562			19.0	
663	0.17384	0.17812	0.00428	360	0.001938	0.681	0.596	10.1	18.9	19.8
664	0.10020	0.10281	0.00261	360	0.001460	0.551			20.1	
665	0.12426	0.12734	0.00308	360	0.001707	0.556			20.3	

TABLE 18
DETERMINATION OF ABSORPTION CHARACTERISTICS OF REG-PAR PCM AND CONCRETE 80°C AT IMMERSION

SPEC. NO.	CONCRETE WT. Kg.	IMPREG WT. Kg.	PCM WT.(M) Kg.	IMMERSION TIME(t) s	ABSORPT. AREA(A) m^2	CONSTANT K			PENETRATION	
						M/At**	ARITH. MEAN	COEFF. OF VARIATION %	mm	ARITH. MEAN
672	0.14724	0.14784	0.00060	60	0.001618	0.0140	0.0157	11.6	6.7	7.2
673	0.17055	0.17120	0.00065	60	0.001659	0.0148			8.0	
674	0.14773	0.14850	0.00077	60	0.001597	0.0182			7.0	
675	0.15851	0.15950	0.00099	100	0.001591	0.0158	0.0163	6.5	7.9	8.9
676	0.16030	0.16144	0.00114	100	0.001610	0.0178			9.5	
677	0.15249	0.15346	0.00097	100	0.001573	0.0155			9.4	
678	0.15209	0.15359	0.00150	160	0.001585	0.0163	0.0181	9.1	10.8	10.7
679	0.13873	0.14058	0.00185	160	0.001574	0.0203			10.4	
680	0.13719	0.13883	0.00164	160	0.001598	0.0177			10.8	
681	0.13324	0.13541	0.00217	240	0.001642	0.0165	0.0166	4.7	14.1	14,4
682	0.14023	0.14260	0.00237	240	0.001682	0.0176			14.5	
683	0.14251	0.14462	0.00211	240	0.001672	0.0157			14.7	
684	0.14639	0.14916	0.00277	360	0.001749	0.0143	0.0143	0.6	17.0	17.1
685	0.13965	0.14222	0.00257	360	0.001633	0.0142			17.1	
686	0.14752	0.15010	0.00258	360	0.001614	0.0144			17.3	

TABLE 19
DETERMINATION OF ABSORPTION CHARACTERISTICS OF ABL-PAR PCM AND CONCRETE 80°C AT IMMERSION

SPEC. NO.	CONCRETE WT. Kg.	IMPREG WT. Kg.	PCM WT.(M) Kg.	IMMERSION TIME(t) s	ABSORPT. AREA(A)	CONSTANT K			PENETRATION	
						$M/At^{0.5}$	ARITH. MEAN	COEFF. OF VARIATION %	mm	ARITH. MEAM
687	0.11565	0.11779	0.00214	60	0.001671	0.375	0.380	6.2	15.2	15.0
688	0.14779	0.14980	0.00201	60	0.001662	0.354			15.5	
689	0.15184	0.15420	0.00236	60	0.001682	0.411			14.2	
690	0.10230	0.10461	0.00231	100	0.001465	0.396	0.388	9.3	18.2	17.4
691	0.12520	0.12750	0.00230	100	0.001696	0.341			16.1	
692	0.10375	0.10615	0.00240	100	0.001410	0.428			17.9	
693	0.10355	0.10581	0.00226	160	0.001426	0.346	0.391	8.1	18.5	19.0
694	0.10710	0.10961	0.00251	160	0.001550	0.416			18.5	
695	0.09868	0.10140	0.00272	160	0.001443	0.411			20.0	
696	0.12760	0.13095	0.00335	240	0.001701	0.380	0.367	2.8	20.3	20.3
697	0.11601	0.11895	0.00294	240	0.001546	0.367			20.3	
698	0.11320	0.11604	0.00284	240	0.001550	0.354			20.4	
699	0.11038	0.11345	0.00307	360	0.001416	0.371	0.378	1.3	21.6	21.8
700	0.09685	0.09999	0.00314	360	0.001409	0.381			20.0	
701	0.11120	0.11494	0.00374	360	0.001676	0.382			23.9	

TABLE 20
VALUES FOR CONSTANT K AND EXPONENT OF TIME (t)
ABSORPTION TIMES: 60 TO 360 SECONDS

CONCRETE & PCM COMBINATION	Constant K		EXPONENT OF TIME FACTOR (t)
	ARITH. MEAN*	COEFFICIENT OF VARIATION %	
REG-BS	0.534	3.6	0.2
ABL-BS	0.451	3.8	0.3
REG-DD	0.543	3.5	0.1
ABL-DD	0.607	2.3	0.2
REG-PAR	0.0162	3.1	0.8
ABL-PAR	0.381	2.2	0.3

* Mean of five values

(c) Discussion of procedure for determination of absorption constants

Single face absorption in an upward direction through a horizontal liquid-solid interface was the technique selected for the development of a means of determining absorption constants. The reasons for this choice are as follows.

(i) The process of absorption can be easily observed and the penetration determined very quickly.

(ii) In a full size block the area of absorption remains relatively constant during immersion. However, when a laboratory size specimen is completely immersed, the effective area through which the liquid is absorbed is constantly diminishing as the advancing front of absorbed material is shared with fronts from adjacent faces until, at the centre, the area becomes a point or a line. On the other hand, the area of absorption through a single face of a rectangular specimen remains relatively constant.

(iii) The exact conditions of absorption can be duplicated for successive observations.

It should be noted that the single face absorption technique was adopted merely for experimental convenience and for reasons of observation. In practice, under any given set of conditions complete immersion will result in establishing the required constants.

Single face absorption would be used in production when it is desired to impregnate only one face of the block. However, the complete immersion technique would be used more frequently. As previously stated, this procedure would be quite suitable with large masses such as concrete blocks. Variations in hydraulic head resulting from the depth of the immersion tank could produce some variation in the rate of absorption. This would depend upon the depth of the bath and/or the application of any other pressure. These effects would have to be measured and accounted for when designing the facilities and establishing the variation which would thereby be produced in the constants.

It was noted that the molding and de-molding process produced a trowelling effect upon the surface which diminished the absorptivity when compared with that of a cut surface.

Since most of the PCM is absorbed in the first few minutes of contact, an upper limit of 360 seconds was used for practical reasons because of the large number of tests required. This limit can, of course, be increased where a longer immersion time is deemed appropriate.

Penetration depths were measured instantly after contact with the liquid was stopped. Whereas the mass of absorbed liquid remained the same, the migration of liquid into the concrete continued in some instances after removal of contact with the liquid. The extent of this continued movement was usually quite small (0-5 mm) and varied with the materials used. The degree of further migration was also observed to change very slightly in some materials with the position of the specimen, that is, whether the flow was vertically upwards or downwards. The depth of PCM penetration is of interest because it will affect the rate of heat transfer in and out of the material. This was discussed in a previous work (Feldman, 1987).

The age of the concrete will affect its absorptivity. This was observed during the early stages of this work (Hawes, 1989). All the specimens used in the development of the technique for determination of absorption constants were mature specimens of the same age.

It should be pointed out that the purpose of the foregoing work was to develop and prove a procedure for establishing absorption constants for PCM in concrete. However, it is not intended to limit or fix these values since they must be established for each combination of materials used and the conditions of their absorption.

Exponents given were rounded off to one significant figure but this can be further refined for a standard product where operating conditions are rigidly controlled and a large number of specimens may be measured to obtain greater accuracy, if required.

6.14.2.1 Conclusions

An equation was developed which relates the mass of absorbed PCM to the time of immersion and the surface area through which it is absorbed. It was also found that, for a given set of processing conditions (e.g. type of PCM, type of concrete, temperature and pressure), it is possible to arrive at a set of absorption constants. Then, through the application of the appropriate constants in this equation, one can predetermine the amount of PCM (and hence the latent heat storage capacity of the product) which will be absorbed in a given time. This was tested and found to be practical.

6.14.3 The Effects of PCM Viscosity, Concrete Structure and Hydrogen Bonding on PCM Penetration and Filled Void Fraction

The nature of the work involved and the results of the foregoing tests also offered an opportunity to observe the effects of viscosity and hydrogen bonding on PCM penetration and the filled void fraction.

6.14.3.1 PCM penetration

From Tables 14 to 19 the single face penetrations at 360s are :

REG - BS: 17.7 mm
REG - DD: 13.3 mm
REG - PAR: 17.1 mm

ABL - BS: 25.5 mm
ABL - DD: 19.8 mm
ABL - PAR: 21.8 mm

The viscosities of the PCM's at 80°C are:

BS: 0.0028 Ns/m^2
DD: 0.0029 Ns/m^2
PAR: 0.0053 Ns/m^2

Comparing the penetration in REG-BS with that of REG-PAR it will be seen that the lower viscosity of BS has allowed somewhat greater penetration. Similarly, in the case of ABL-BS and ABL-PAR the penetration of BS is slightly greater than that of PAR for the same reason. It is noted, moreover, that the more open structure of ABL permits deeper penetration for both PCM's.

In the case of REG-DD, despite a viscosity comparable to that of BS, the penetration is markedly lower than the other two PCM's in REG. The reason for this is that the polarity of

DD [CH_3-$(CH_2)_{11}$-OH] is much higher than that of

BS [CH_3-$(CH_2)_{16}$-COO$(CH_2)_3$-CH_3] while

PAR [CH_3-$(CH_2)_n$-CH_3] is not a polar material

From this it will be seen that hydrogen bonding can occur very easily between DD and the silica hydrates in the concrete. Moreover, the degree of bonding is much greater in regular concrete than in autoclaved concrete because the former contains much more $Ca(OH)_2$ than the latter, as discussed in Section 4.2.3. It was also noted that hydrogen bonding retarded the speed of penetration, particularly in the case of REG-DD and, to a lesser degree, with ABL-DD.

One would expect to see a greater difference in penetration between BS and PAR in both REG and ABL because the viscosity of PAR under the conditions of the test is nearly twice as great as that of BS. However, the penetration difference is not very great, despite the difference in viscosity, and this is due to the fact that hydrogen bonding has also occurred to retard penetration in the case of BS, although to a lesser degree than with DD.

6.14.3.2 Conclusions

It was found, as one might expect, that penetration of PCM's in a given concrete at a given temperature is increased by a lower viscosity and retarded by a more dense concrete structure. Hydrogen bonding depends on the polarity of the PCM and the amount of available $Ca(OH)_2$ in the concrete. Its action retards penetration but does not limit it, as will be seen in the next section.

6.14.3.3 Filled void fraction

From Tables 21, 22 and 23 the filled void fractions in the concrete impregnated with PCM after 2 hours are:

REG-BS: 0.117 REG-DD: 0.130 REG-PAR: 0.109
ABL-BS: 0.158 ABL-DD: 0.164 ABL-PAR: 0.157

These specimens were immersed for a period of 2 hours which was sufficiently long for the effect of retardation of absorption by hydrogen bonding to be negligible in respect to filling the voids with PCM.

During the course of this work it was observed that if concrete is immersed in PCM long enough, a small absorption-desorption cycle can occur so that the amount of PCM in immersed specimens may fluctuate slightly. In the case of DD it will be seen that the PCM content is higher than the other two PCM's and that this condition is more marked in the case of REG than for ABL. The reason for this is that the hydrogen bonding which retards the absorption process can also act to retain polar PCM's in the concrete by slowing down the effect of desorption in the cycling process mentioned above. In addition, it may also provide an attractive force into otherwise unfilled small pores. As before, the bonding effect

TABLE 21
FILLED VOID FRACTION REG-BS AND ABL-BS PCM AND CONCRETE AT IMMERSION: 60°C

1	2	3	4	5	6	7	8	9	10	11
								EFFECTIVE VOID FRACTION		
SPEC. NO.	TYPE	CONC. ONLY WT. IN AIR g	IMMERSE TIME s	IMPREG. SPEC. WT IN PCM g(GROSS)	CAGE WT. IN PCM g(TARE)	IMPREG. SPEC. WT. IN PCM g(NET)	IMPREG. SPEC. WT. IN AIR g	$\frac{8-3}{8-7}$	ARITH. MEAN FOR SAME TYPE AND TIME	COEFF. OF VARIATION %
630	REG-BS	170.30	360	122.18	12.23	109.95	174.51	0.065		
		170.30	1800	123.52	12.23	111.29	176.14	0.090		
		170.30	3600	124.19	12.23	111.96	176.80	0.100		
		170.30	7200	124.72	12.23	112.67	177.43	0.110		
631	REG-BS	174.48	360	124.72	12.23	112.49	179.70	0.077	0.078	13.6
		174.48	1800	125.81	12.23	113.58	181.16	0.099	0.100	8.6
		174.48	3600	126.72	12.23	114.49	182.08	0.112	0.109	6.8
		174.48	7200	127.20	12.23	114.97	182.60	0.120	0.117	4.5
632	REG-BS	152.40	360	111.40	12.23	99.17	157.70	0.091		
		152.40	1800	112.31	12.23	100.08	158.91	0.111		
		152.40	3600	112.73	12.23	100.50	159.29	0.117		
		152.40	7200	113.20	12.23	100.97	159.58	0.122		
633	ABL-BS	139.00	360	96.70	12.23	84.47	148.65	0.150		
		139.00	1800	97.53	12.23	85.30	149.06	0.158		
		139.00	3600	97.10	12.23	84.87	149.80	0.166		
		139.00	7200	97.10	12.23	84.87	149.30	0.160		
634	ABL-BS	177.45	360	119.95	12.23	107.72	189.71	0.150	0.146	3.6
		177.45	1800	120.30	12.23	108.07	190.35	0.157	0.156	1.7
		177.45	3600	120.20	12.23	108.07	190.70	0.160	0.160	3.3
		177.45	7200	120.20	12.23	108.07	190.70	0.160	0.158	1.5
635	ABL-BS	169.72	360	114.35	12.23	102.12	180.62	0.139		
		169.72	1800	114.74	12.23	102.51	181.75	0.152		
		169.72	3600	115.20	12.23	102.97	181.82	0.153		
		169.72	7200	115.52	12.23	103.29	181.86	0.155		

TABLE 22
FILLED VOID FRACTION REG-DD AND ABL-DD PCM AND CONCRETE AT IMMERSION: 80°C

1	2	3	4	5	6	7	8	9	10	11
								EFFECTIVE VOID FRACTION		
SPEC NO.	TYPE	CONC. ONLY WT. IN AIR g	IMMERSE TIME s	IMPREG. SPEC. WT IN PCM g(GROSS)	CAGE WT. IN PCM g(TARE)	IMPREG. SPEC. WT. IN PCM g(NET)	IMPREG. SPEC. WT. IN AIR g	$\frac{8-3}{8-7}$	ARITH. MEAN FOR SAME TYPE AND TIME	COEFF. OF VARIATION %
666	REG-DD	150.37	360	110.46	12.00	98.46	155.81	0.095		
		150.37	1800	111.60	12.00	99.60	156.99	0.115		
		150.37	3600	112.12	12.00	100.12	157.42	0.123		
		150.37	7200	112.44	12.00	100.44	157.49	0.125		
667	REG-DD	144.49	360	107.26	12.00	95.26	151.10	0.118	0.102	10.4
		144.49	1800	108.34	12.00	96.34	152.10	0.136	0.120	9.2
		144.49	3600	108.63	12.00	96.63	152.32	0.141	0.129	6.7
		144.49	7200	108.81	12.00	96.81	152.32	0.141	0.130	5.8
668	REG-DD	153.26	360	112.79	12.00	100.79	158.70	0.094		
		153.26	1800	113.70	12.00	101.70	159.65	0.110		
		153.26	3600	114.30	12.00	102.30	160.35	0.122		
		153.26	7200	114.74	12.00	102.74	160.50	0.125		
669	ABL-DD	101.95	360	75.13	12.00	63.13	109.31	0.159		
		101.95	1800	75.81	12.00	63.81	109.50	0.165		
		101.95	3600	75.94	12.00	63.94	109.52	0.166		
		101.95	7200	75.96	12.00	63.96	109.52	0.166		
670	ABL-DD	113.41	360	81.97	12.00	69.97	121.09	0.150	0.148	6.4
		113.41	1800	82.51	12.00	70.51	121.41	0.157	0.159	2.7
		113.41	3600	82.60	12.00	70.60	121.80	0.164	0.162	2.7
		113.41	7200	82.92	12.00	70.92	121.80	0.165	0.164	1.3
671	ABL-DD	115.95	360	83.15	12.00	71.15	123.00	0.136		
		115.95	1800	84.25	12.00	72.25	123.94	0.155		
		115.95	3600	84.32	12.00	72.32	124.02	0.156		
		115.95	7200	84.81	12.00	72.81	124.20	0.161		

TABLE 23
FILLED VOID FRACTION REG-PAR AND ABL-PAR PCM AND CONCRETE AT IMMERSION: 80°C

1	2	3	4	5	6	7	8	9	10	11
								EFFECTIVE VOID FRACTION		
SPEC NO.	TYPE	CONC. ONLY WT. IN AIR g	IMMERSE TIME s	IMPREG. SPEC. WT IN PCM g(GROSS)	CAGE WT. IN PCM g(TARE)	IMPREG. SPEC. WT. IN PCM g(NET)	IMPREG. SPEC. WT. IN AIR g	$\frac{8-3}{8-7}$	ARITH. MEAN FOR SAME TYPE AND TIME	COEFF. OF VARIATION %
702	REG-PAR	148.36	360	110.70	11.95	98.75	153.60	0.098		
		148.36	1800	111.92	11.95	99.97	154.24	0.108		
		148.36	3600	112.24	11.95	100.29	154.32	0.110		
		148.36	7200	112.40	11.95	100.45	154.60	0.115		
703	REG-PAR	150.61	360	111.99	11.95	100.04	155.50	0.088	0.088	7.4
		150.61	1800	113.60	11.95	101.65	156.40	0.106	0.103	6.5
		150.61	3600	114.10	11.95	102.15	156.41	0.107	0.105	4.9
		150.61	7200	114.35	11.95	102.40	156.56	0.110	0.109	4.9
704	REG-PAR	152.75	360	113.30	11.95	101.35	157.19	0.080		
		152.75	1800	114.22	11.95	102.27	158.02	0.095		
		152.75	3600	114.48	11.95	102.53	158.19	0.098		
		152.75	7200	114.72	11.95	102.77	158.40	0.102		
705	ABL-PAR	145.60	360	103.30	11.95	91.35	154.88	0.148		
		145.60	1800	103.74	11.95	91.79	155.84	0.160		
		145.60	3600	103.97	11.95	92.02	155.90	0.161		
		145.60	7200	103.97	11.95	92.02	155.90	0.161		
706	ABL-PAR	145.94	360	104.14	11.95	92.19	154.03	0.131	0.140	4.8
		145.94	1800	104.40	11.95	92.45	155.10	0.146	0.155	4.3
		145.94	3600	104.41	11.95	92.46	155.13	0.147	0.156	4.2
		145.94	7200	104.41	11.95	92.46	155.13	0.147	0.157	4.5
707	ABL-PAR	141.53	360	100.70	11.95	88.75	150.34	0.143		
		141.53	1800	100.79	11.95	88.84	151.60	0.160		
		141.53	3600	100.96	11.95	89.01	151.61	0.161		
		141.53	7200	101.00	11.95	89.05	151.74	0.163		

is stronger in the case of DD than BS and does not apply in the case of PAR. In a long immersion such as this, the effect of viscosity becomes less marked.

6.14.3.4 Conclusions

Three anticipated phenomena were confirmed:

(i) The void volume was found to be greater in ABL than in REG

(ii) The voids were filled more effectively and more quickly in ABL than in REG

(iii) If sufficient time is allowed for immersion, viscosity will not be an important factor

In addition, it was also established that hydrogen bonding can cause the filled void fraction to increase.

6.15 STABILITY OF PCM CONCRETE

The stability of several PCM concrete combinations were examined for periods up to 692 days. The thermal characteristics of these specimens are shown in Table 24 and are examined in detail in the following discussion. The relative DSC analyses are found in Appendix B, Figures A1 to A23.

The effects of modifying the concrete and using an improved immersion technique may be seen in the later results shown in Table 24 (specimen nos. 209 and up). In some cases the increase in latent heat values were as much as 196% of the values of the earlier specimens. In addition, modifying the concrete by means of pozzolans has rendered feasible the use of more highly alkaline concretes such as PUM with more alkaline sensitive PCM's such as BS.

TABLE 24

THERMAL CHARACTERISTICS OF IMPREGNATED SPECIMENS

SPECIMEN No.	TYPE OF CONCRETE	PCM			AVERAGE LATENT HEAT OF IMPREGNATED CONCRETE J/g	AGE DAYS
		NATURE	MELTING POINT °C	FREEZING POINT °C		
1	ABL	BS	16.6	20.9	3.5	590
31	ABL	BS	15.2	19.3	5.7	692
37	REG	BS	16.9	20.7	4.2	588
168	REG	BS	15.4	19.9	3.2	373
248	REG	BS	15.4	20.4	5.5	391
24	PUM	BS	17.3	21.4	4.2	364
153	PUM	BS	15.9	22.2	6.0	423
179	PUM	BS	16.2	20.3	3.6	373
191	EXS	BS	17.0	21.4	3.0	372
209	EXS	BS	14.9	18.3	5.5	475
7	ABL	DD	10.8	16.5	3.1	653
39	REG	DD	9.2	6.4	2.4	692
250	REG	DD	5.0	9.6	4.7	432
27	PUM	DD	18.0	19.4	3.3	364
229	PUM	DD	14.9	12.0	12.7	377
346	REG	TD	26.2	32.0	5.7	406
358	REG	TD	31.6	35.7	6.4	403
321	PUM	TD	32.2	35.7	12.5	404
333	PUM	TD	32.0	26.8	7.0	403
233	REG	PAR	52.4	60.2	11.9	428
236	ABL	PAR	53.2	60.6	18.9	421
239	PUM	PAR	52.9	60.8	22.7	407
242	OPC	PAR	51.7	60.4	7.6	407

6.15.1 Stability of Butyl Stearate in Concrete

Great attention was paid to ensuring the stability of BS. As a saturated fatty ester it is chemically stable but, in alkaline conditions, it can hydrolize according to the following reaction:

$$RCOOR_1+H_20 \rightarrow RCOOH+R_1OH \qquad \text{(eq. 20)}$$

and it was important to ensure that this did not occur to a significant degree.

Figure 30 shows the stability of BS in ABL over an extended period which indicates a satisfactory performance for this service. In the present work, ABL was left unmodified because it was deemed to be a satisfactory medium. The slight diminution in latent heat in the case of specimen 31 was not deemed to be serious since the most recent test (day 692) showed a latent heat value approximately equal to the initial value. All curves shown in Figures 30 to 33 inclusive and 35 to 39 inclusive were generated by the least squares method.

Figure 31 illustrates the performance of BS-REG. Specimen 37 demonstrates that BS remains stable in REG over a long period. It was prepared in the early stages of the work when the stability of this PCM was unknown. Therefore, modification of the concrete was tried using low alkali cement and silica fume and the results of this are represented by specimen 168 where it will be seen that, although the specimen is stable, the greater density of the modified concrete resulted in less absorption of the PCM so that a further modification was required. This is shown in specimen 248 where a combination of low alkali cement, silica

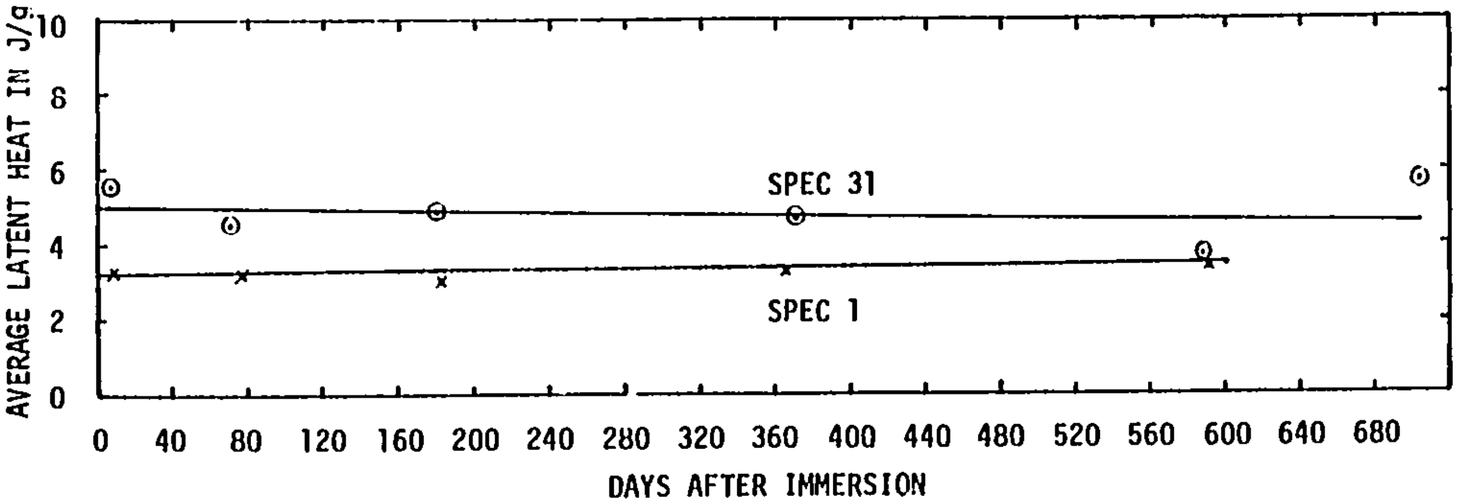


FIGURE 30 - THE STABILITY OF BUTYL STEARATE IN AUTOCLAVED CONCRETE BLOCK

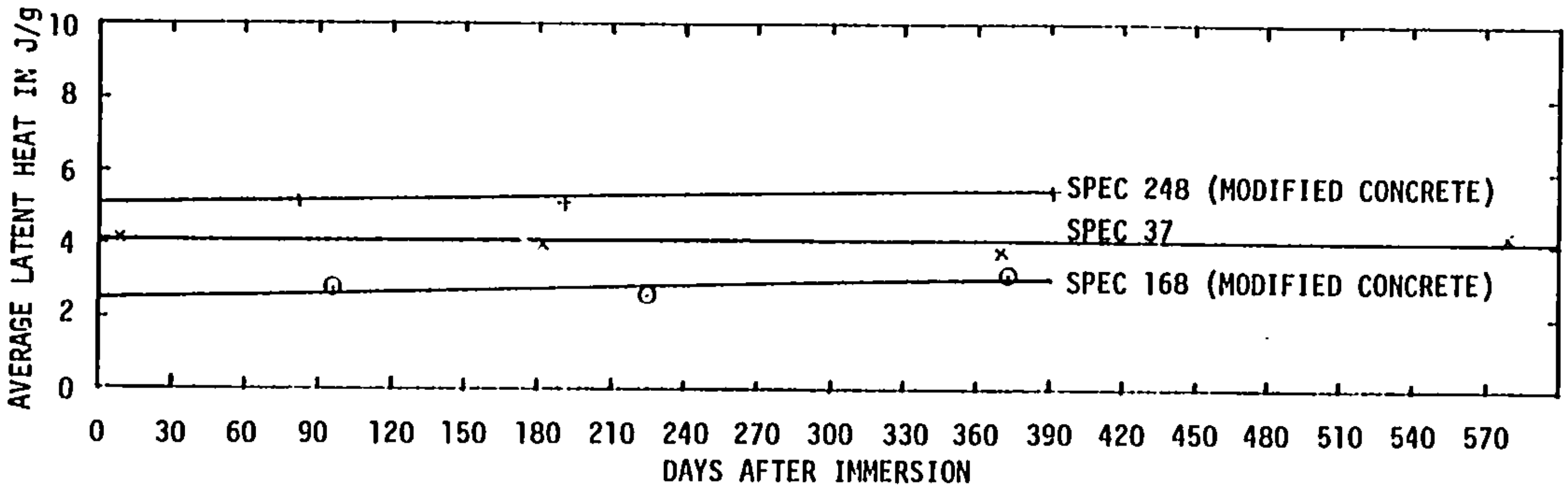


FIGURE 31 - THE STABILITY OF BUTYL STEARATE IN REGULAR CONCRETE BLOCK

fume and fly ash was used in a mix which was less dense than that of specimen 168.

In many respects, pumice is an ideal medium for the absorption of PCM because of its porous structure. Unfortunately, it is relatively alkaline, with the result that PCM's such as BS and DD suffer destructive reactions in unmodified pumice. This is shown in Figure 32 by specimen 24. To offset this, silica fume was incorporated in the mix of specimen 179 and, while the result was stable, the reduced porosity produced a corresponding diminution in the absorption of the PCM. To increase the PCM content in this case, an alternative technique was used. The pumice aggregate was pre-impregnated with BS and was then incorporated into the mix, together with the low alkali cement and silica fume, to reduce the alkalinity. The hardened concrete was then immersed in PCM with the result shown in specimen 153.

In Figure 33, expanded shale was used as the aggregate. Earlier experiments had shown that unmodified concrete with expanded shale aggregate (ordinary light weight concrete) was not a good medium for alkali sensitive PCM's. Therefore, modified concrete was used in later experiments. In this case, low alkali cement and silica fume was incorporated in the concrete and both the specimens shown demonstrated good stability. Since both specimens were steam cured in this instance, the difference in absorptivity was attributed to differences in the composition of the mix.

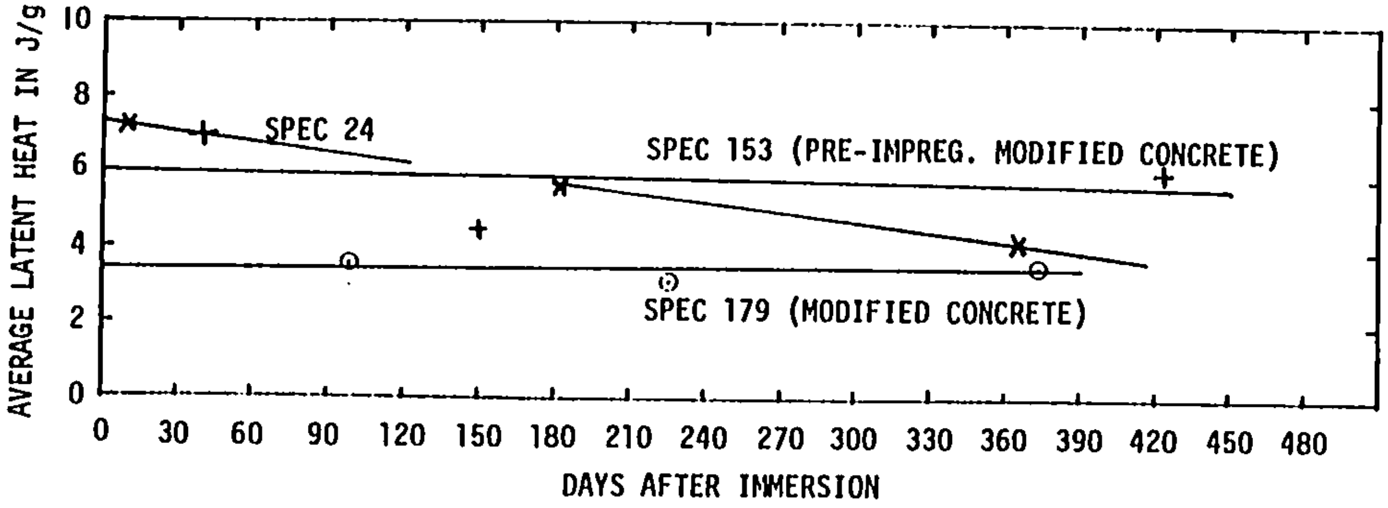


FIGURE 32 - THE STABILITY OF BUTYL STEARATE IN PUMICE CONCRETE BLOCK

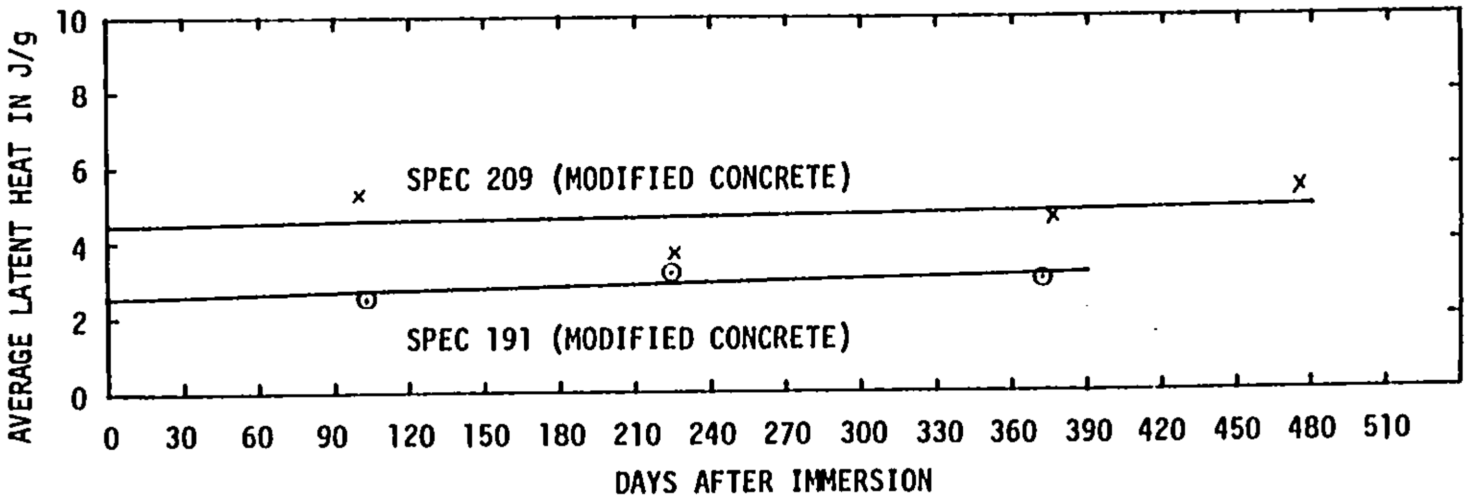


FIGURE 33 - THE STABILITY OF BUTYL STEARATE IN EXPANDED SHALE CONCRETE BLOCK

6.15.2 Stability of Dodecanol in Concrete

Figure 34 demonstrates the stability of DD in ABL. It will be seen that, after a significant initial loss of latent heat, the performance remained stable for an extended period. Since there were no facilities for producing autoclaved concrete in the CBS laboratory, it was not possible to modify ABL and observe the effect during these tests. However, it is reasonable to assume that the most likely reason for this loss of latent heat is that some of the DD migrated into smaller pores of ABL where increased surface tension would cause it to remain liquid far below the normal freezing point (Hamik, 1980) so that the heat of fusion would not be released. It is probable that hydrogen bonding is also a factor in the retention of PCM in the smaller pores.

Figure 35 represents the behaviour of DD in REG. Specimen 39 shows the steady loss of latent heat due to the instability of DD in unmodified concrete. This deterioration was noticed early in the research so steps were taken to effect an improvement by modifying REG by the addition of low alkali cement, silica fume and fly ash. The results of this modification are shown in specimen 250 which demonstrates a stable performance.

Figure 36 represents the performance of DD in PUM. In the initial experiment, DD was incorporated in unmodified PUM with the result that a steady deterioration of the PCM took place because of its instability in alkaline PUM concrete (curve

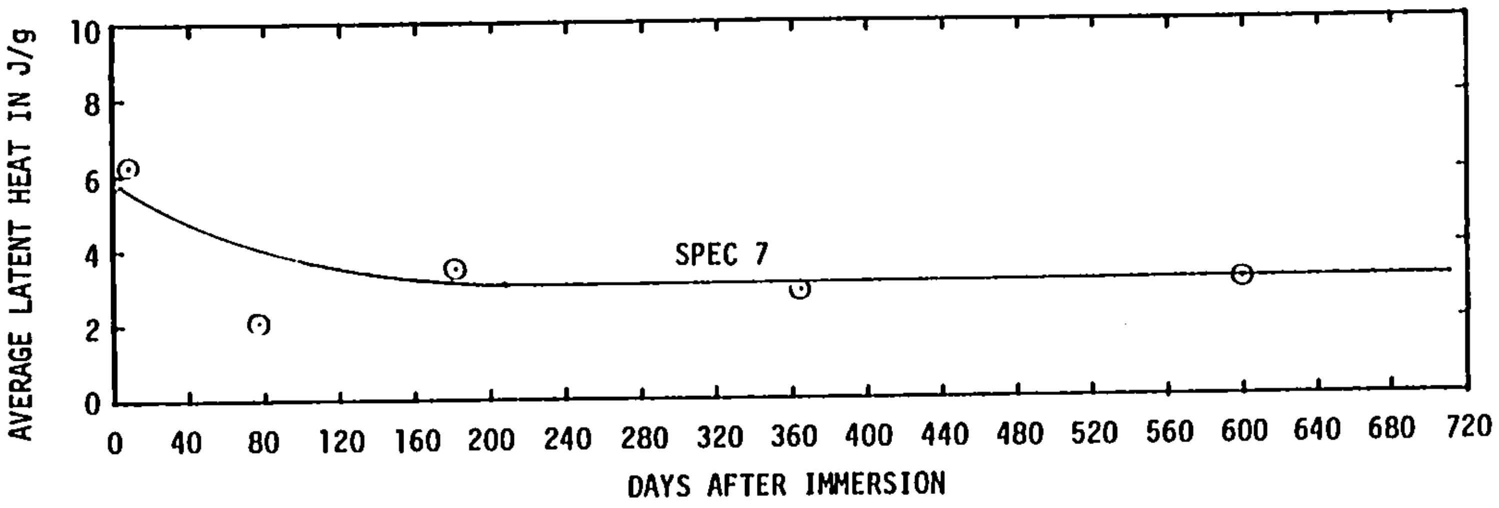


FIGURE 34 - THE STABILITY OF DODECANOL IN AUTOCLAVED CONCRETE BLOCK

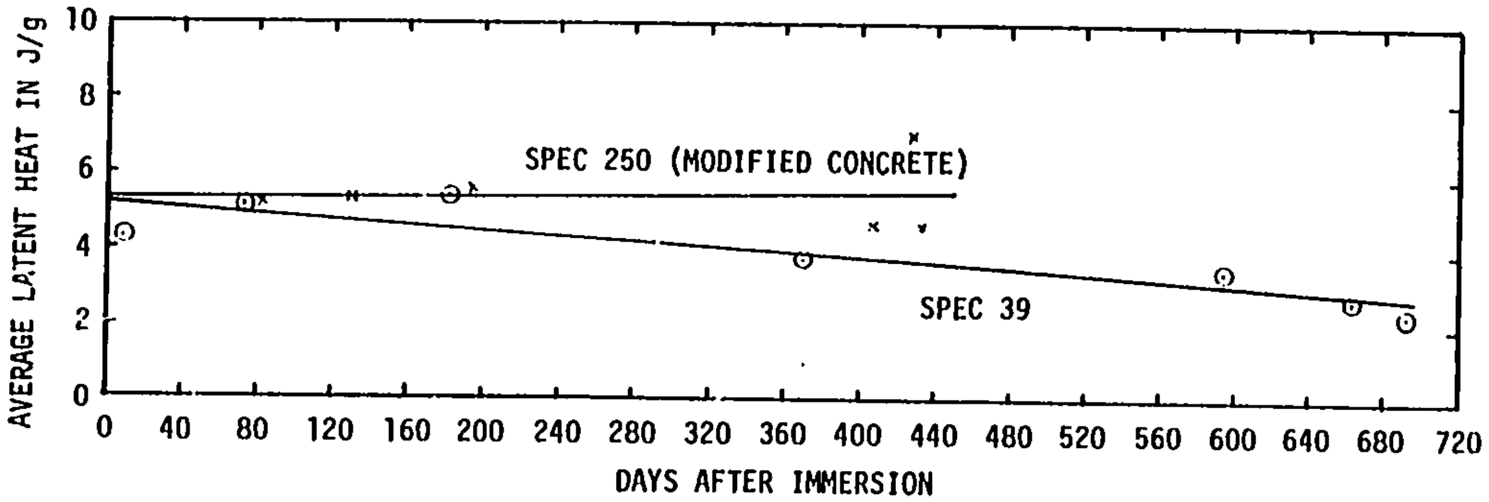


FIGURE 35 - THE STABILITY OF DODECANOL IN REGULAR CONCRETE BLOCK

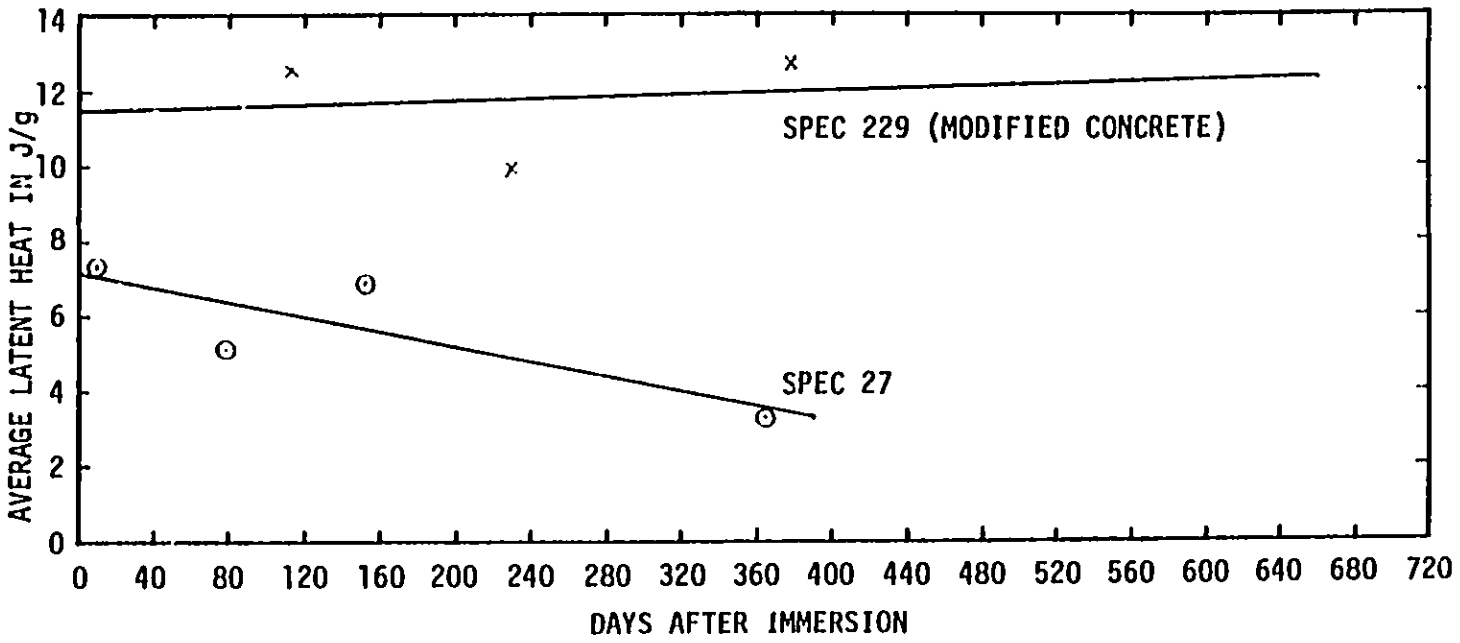


FIGURE 36 - THE STABILITY OF DODECANOL IN PUMICE

for specimen 27). Again, this trend was observed at an early date so the PUM concrete was modified by the use of low alkali cement and silica fume. This proved to be effective in bringing the stability of DD to a satisfactory level as shown in specimen 229.

6.15.3 Stability of Tetradecanol in Concrete

The experiments conducted in respect to the stability of Tetradecanol (TD) in concrete were carried out after some experience had been gained with the behaviour of DD in concrete. Since they are both fatty alcohols and since the performance of DD in modified concrete was satisfactory, while that in unmodified concrete was not, it was deemed appropriate to use only modified concrete with TD.

Figure 37 illustrates the performance of TD in modified REG. Both specimens were steam cured but the after-curing is the case of specimen 346 was in air while that for specimen 358 was in water. Both specimens have stable latent heat values but a 10°C shift was noted in the freezing point of specimen 346 and this is examined in section 6.15.5.

In Figure 38 the results of impregnating modified PUM with TD are shown. The negative slope of specimen 333 in likely due to the fact that, although both specimens were initially steam cured, the after-curing in the case of specimen 333 was in water while that of specimen 321 was in air. Since PUM is more reactive to DD and TD than REG, it is likely that the after-curing in water may have

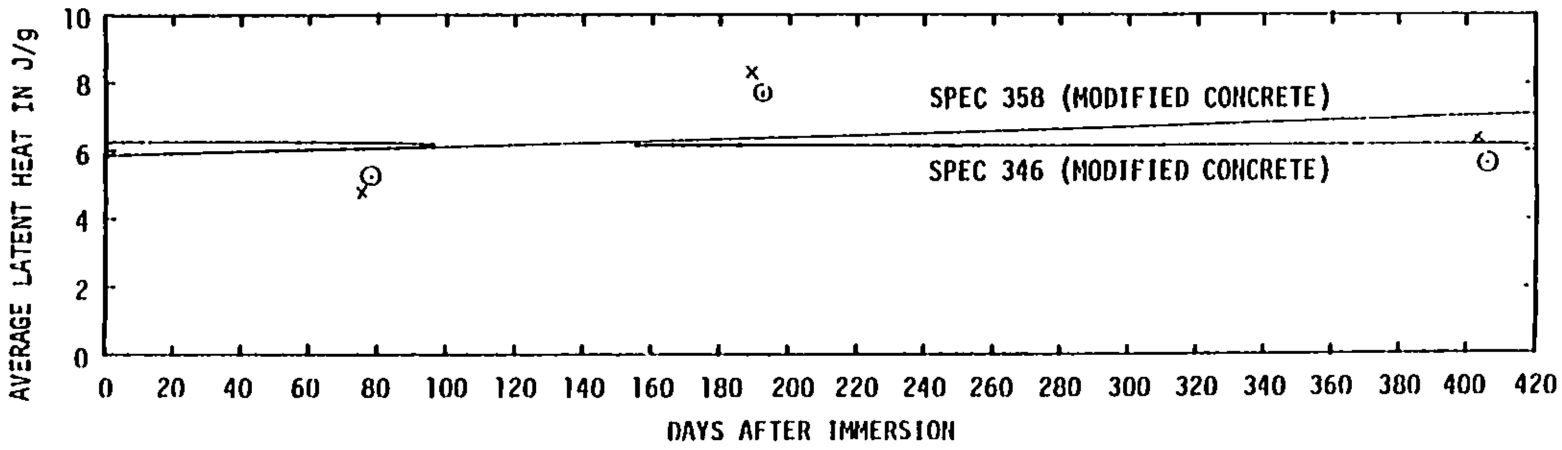


FIGURE 37 - THE STABILITY OF TETRADECANOL IN REGULAR CONCRETE BLOCK

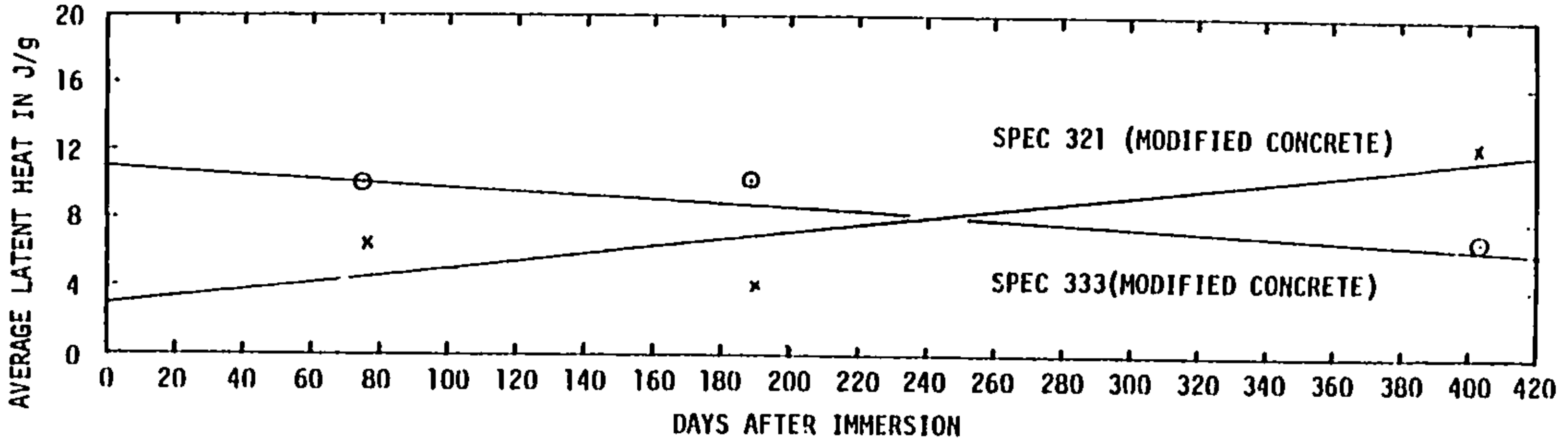


FIGURE 38 - THE STABILITY OF TETRADECANOL IN PUMICE CONCRETE BLOCK

interfered with the continuing formation of Ca CO_3 to the degree that it left the PUM mix more reactive than that of specimen 321. As a result, the latent heat in this case was significantly diminished while that of specimen 321 demonstrated a satisfactory stability.

6.15.4 Stability of Paraffin in Concrete

Figure 39 shows the performance of PAR in various types of unmodified concrete. As one would expect from a non-reactive substance such as paraffin, the latent heats are very stable. It will be seen that there is no necessity to modify any of the concretes used.

PAR is a PCM which is very easily absorbed because its viscosity can be reduced to a satisfactory level by moderate heating (e.g. the viscosity of the type used was 0.0053 Ns/m^2 at 80°C). In addition, it is a non-polar substance so that hydrogen bonding with the hydrates in the concrete is not a problem.

The different latent heats reflect the absorptivity of the different materials which have progressively more open structures from OPC to PUM. While the larger values of latent heat are of interest, at this stage of the research it is not expected that the greater amounts of absorbed PCM which they represent will often be required.

The paraffin studied in this work has been confined to those paraffins melting in the 55°C - 60°C range because they can be easily impregnated using either the

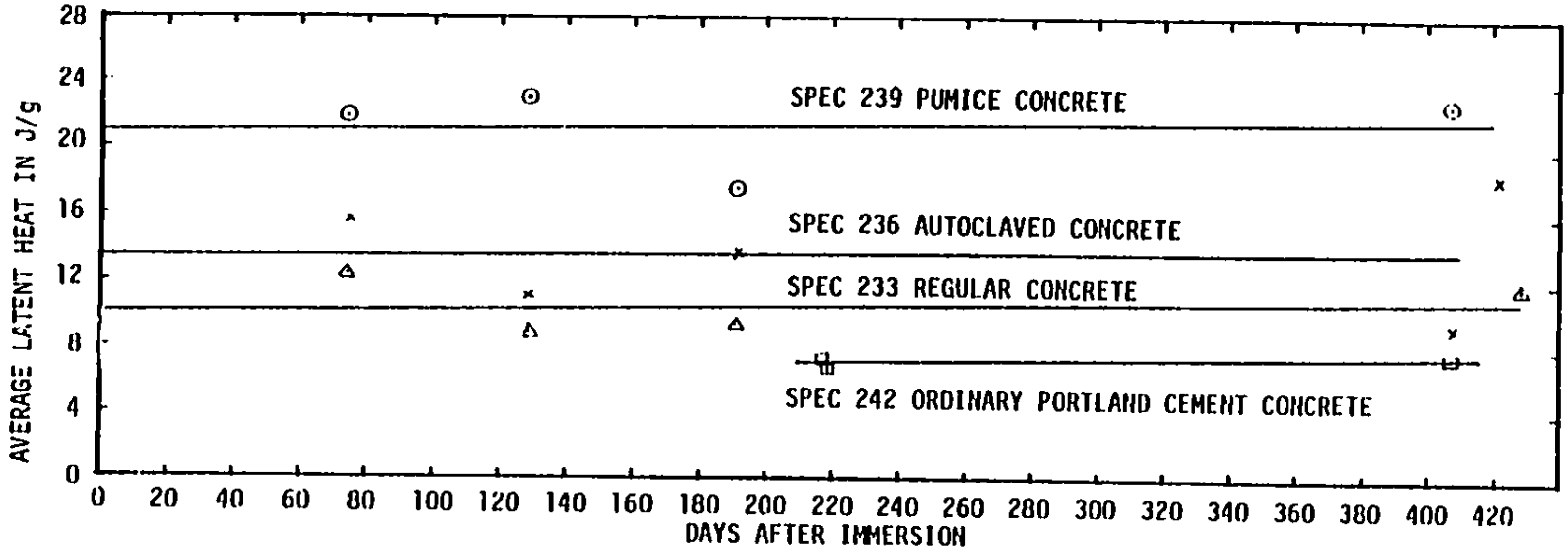


FIGURE 39 - THE STABILITY OF PARAFFIN IN VARIOUS TYPES OF CONCRETE

direct or indirect method and because information about their behaviour was desired. It follows logically from this study that paraffins melting in the human comfort temperature range can also be used for thermal storage and that, for the present, immersion offers the most practical method of impregnation of PAR in the lower temperature range.

6.15.5 Phase Transition Temperature Shift

No problems of any significance were observed in respect to the transition temperatures of the aforementioned specimens of BS and PAR as these specimens aged.

However, this stability was not found to the same extent in the specimens impregnated with the fatty acid alcohols. In the case of all of the aforementioned DD specimens it was observed that the transition temperatures became progressively lower with age (about 2 years). On the other hand, about half of the specimens impregnated with TD showed a downward shift only in their freezing points while their melting points remained relatively unchanged. This is explained below.

In specimen 7 (ABL-DD), Figure 34, for example, the freezing point dropped from about 20°C to 11°C while the melting point drop was from 18°C to 16°C. In the case of specimen 39 (REG-DD), Figure 35, the freezing point drop was from 19°C to 6°C and that of the melting point was from 20°C to 9°C. In the case of specimen 250 (REG-DD), Figure 35, the freezing point drop was from 20°C to

10°C and that of the melting point from 20°C to 5°C. For specimen 229 (PUM-DD), Figure 36, a 6°C drop in the freezing point was noted but the melting point remained stable.

This phenomenon was also observed in the case of specimen 333 (PUM-TD), Figure 38, where the freezing point dropped from 37°C to 27°C but the melting point was not affected. In the case of specimen 346 (REG-TD), Figure 37, the freezing point drop was from 36°C to 26°C while, again, the melting point was relatively unaffected.

As the PCM migrates into the smaller pores, surface tension will cause the freezing point to drop (Harnik, 1980). As a result, although heat will be released on freezing, this will not occur until increasingly lower freezing temperatures have been attained. Conversely, as the temperature rises above this freezing point, latent heat will begin to be absorbed by the PCM in the smaller pores at a lower temperature than that by the PCM in pores with a larger diameter. It follows that the temperature range over which the liquid-solid transition occurs will reflect the range of pore sizes in which the PCM is distributed.

In addition, both DD and TD exhibit polymorphism and have two distinct crystallization points, so that even a slight drop in the freezing temperature caused by the above effect could cause a shift downwards in the transition temperature and result in a domination of crystallization temperature by the lower point. This dominance by the lower point does not necessarily occur on melting, which explains the lack of downward shift in melting transition temperature in some cases.

Both DD and TD are the most highly polar of the PCM's used and, as discussed in sections 6.5.3 and 6.14.3, migration of PCM is influenced by this effect. Therefore, it is possible that, as the PCM contracts on freezing, hydrogen bonding may cause retention of material in the smaller pores to a greater extent than with other PCM's. Further modification of the concrete is indicated towards the improvement of the performance of DD and TD in this respect.

The range of pore sizes is, therefore, a parameter which must be considered. Ideally, the smaller pores would constitute a relatively small percentage of the total into which the PCM is absorbed but this will vary with each combination of PCM and concrete. Should the absorption into the smaller pores have a significant effect upon heat storage performance, then consideration should be given to changing the combination of materials, modifying the concrete or simply using more PCM.

In some cases the transition temperature not only shifts downward but the characteristic peaked curve also becomes flattened and can extend well below the useful range, indicating that the PCM has migrated into a wider range of smaller pores. Further investigation is required in this area to study the effect of controlling this process by further modification of the concrete and by pre-impregnation with an appropriate liquid filler so that the PCM will remain in those pores where the transition temperature is not greatly affected. It will be seen that improvements in this area will not only ameliorate the problems of transition temperature shift and extension of the transition range in the fatty acid alcohols but it could lead to a means of optimizing the thermal performance of all impregnants.

6.15.6 Deferred PCM Candidates

As previously mentioned, work on PEG was discontinued for the time being. Later in the work it was found that DS was also a material which would require a degree of modification which was beyond the scope of the present research. It is intended that work on these and other candidates requiring further modification of the concrete or modification of the PCM itself will be continued at a later date.

6.15.7 Confirmation of Method for Determination of PCM Stability in Concrete

Table 25 shows the comparative results of two distinct tests for PCM content in concrete after 400 days. In the chemical tests the PCM samples were extracted with methanol, the extract was filtered and the filtrate was then evaporated. The residue was then reported as the appropriate PCM. In the samples measured by DSC the amount of residual PCM was determined from the measured latent heat divided by the latent heat per unit weight of the appropriate PCM. It will be seen that, in most cases, there is reasonably close agreement between the two methods of measurement and this serves to confirm the validity of using the DSC method

TABLE 25
TESTS OF PCM CONTENT IN CONCRETE AFTER 400 DAYS

					% PCM AFTER 400 DAYS	
SPECIMEN NO.	CONCRETE	PCM	ORIGINAL % PCM BY WEIGHT	INTERVAL BETWEEN MIXING AND IMMERSION IN PCM DAYS	MEASURED BY CHEM. ANALYSIS	MEASURED BY DSC
1	ABL	BS	3.70	1	2.11	2.39
7	ABL	DD	3.19	1	1.17	1.44
5	ABL	PEG	5.07	1	3.99	2.15
9	REG	BS	3.00	1	1.27	1.01
17	REG	DD	2.46	1	0.13	1.64
31	ABL	BS	4.36	8	2.69	3.35
33	ABL	DD	2.78	8	1.67	2.26
37	REG	BS	2.34	8	2.12	2.69
39	REG	DD	2.53	8	1.57	1.87
43	ABL	BS	4.45	30	2.89	2.46
44	ABL	DD	4.79	30	1.49	1.63
49	REG	BS	2.54	30	2.04	1.97
53	REG	DD	3.32	30	0.09	1.30

as a means of determining the amount of PCM in a concrete sample with a reasonable degree of accuracy.

Losses of PCM from the specimens may be due to reaction with the hydration products of the impregnated concrete or drainage from the concrete specimen. By intention, these losses are as small as possible. However, even if they were negligible, perfect agreement between original and measured PCM content is not probable because it is likely that some PCM will be permanently retained in the gel pores even after preparation for analysis. In addition, some losses occur during the preparation process, principally during crushing.

6.15.8 Conclusions

The use of modified concrete was found to increase the stability of PCM's, particularly in the more alkaline concretes. This procedure, together with the development of improved means of PCM incorporation techniques, resulted in a greater range of stable PCM concrete with good thermal performance. BS was found to be stable in ABL and REG as well as in modified REG, PUM and EXS. DD suffered some initial loss in ABL then remained stable. DD and TD maintained stable latent heat values in modified REG and PUM but their phase transition temperatures showed a tendency to drift downwards and this will require rectification. PAR was found to remain stable in ABL, REG, PUM and OPC. Stability was measured by DSC analysis and confirmed by chemical analysis of selected specimens.

CHAPTER 7

ECONOMIC IMPACT

7.1 COST OF PCM CONCRETE THERMAL STORAGE

It is estimated that the average two storey residence could have about 2000 (190 mm x 190 mm x 390 mm) hollow concrete blocks in the external walls which would be suitable for thermal storage. If internal masonry walls were also used for this purpose, the total figure would be approximately 3800 blocks. A row house would attain about 90% of this value. The foregoing values comprise about 60% of the total wall area, since the remaining 40% would be rendered impractical for this purpose because of window and door openings and other building features. These blocks would sit on a conventional perimeter foundation for the external walls and rest on their own footings for the internal walls. Other arrangements are also possible. There are 12.5 blocks per m^2 of wall area.

From Figure 40 it is seen that 2.0 MJ/m^2 is a conservative estimate of the thermal storage capacity of PCM impregnated concrete block. This comprises both the latent heat and the sensible heat through a 6°C temperature change. Then, with 3800 blocks, 12.5 blocks per m^2, a thermal storage value of 2.0 MJ/m^2 and a heat recovery efficiency of 66%, the thermal storage capacity would be approximately 402 MJ. This may be compared with the average daily space

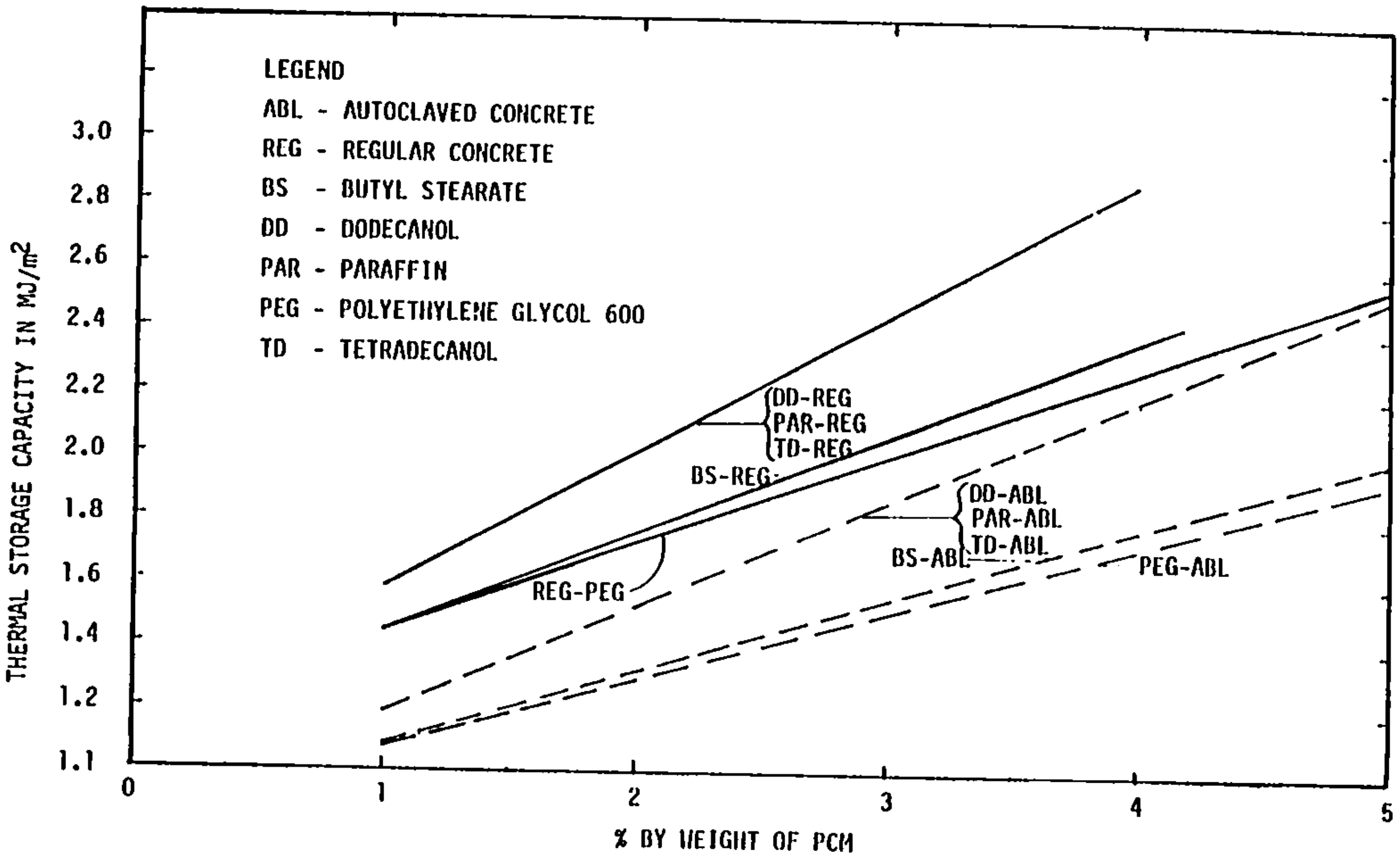


FIGURE 40 - THERMAL STORAGE CAPACITY AS A FUNCTION OF WEIGHT PERCENTAGE OF PCM IN CONCRETE

heating requirements for Canada shown in Table 26 and will be found to equal or exceed the requirements in 115 of the 126 cases mentioned.

For thermal storage to be cost effective, the additional capital cost which it entails should be recovered through energy savings within a reasonable period. Some major cost elements are estimated as follows in 1990 dollars:

(a) PCM: 2000 to 4000
(b) Cost of impregnation: 1200 to 1800
(c) Extra cost of masonry construction: 0 to several thousand
(d) From the above, deduct the difference between fossil fuel heating system and electric (backup) heater: ~ 1500

As a large market develops for PCM it is expected that the cost will drop significantly so that it is unlikely that (a) above will exceed 3000.

The additional cost for the incorporation of PCM for a concrete block building of any type is estimated to be \$16/m^2 and this includes commercial industrial and institutional buildings which can be ideal candidates for PCM thermal storage.

7.2 BENEFITS OF PCM CONCRETE THERMAL STORAGE

The benefits to be derived from a thermal storage system will be determined principally by the cost of energy, the installed and operating cost of the system as well as the efficacity of the installation in a given environment. Among the

TABLE 26
AVERAGE DAILY SPACE HEATING REQUIREMENT - IN MJ

CITY	JAN	FEB	MAR	APRIL	MAY	JUN	JULY	AUG	SEPT	OCT	NOV	DEC	MAX
VANCOUVER	208	181	165	125	78	-	-	-	52	108	162	191	208
EDMONTON	466	397	333	200	107	-	-	-	111	181	317	419	466
CALGARY	402	341	297	198	115	-	-	-	101	168	279	386	402
REGINA	485	428	348	198	96	-	-	-	87	173	311	417	485
SASKATOON	503	440	359	198	95	-	-	-	94	177	320	433	503
WINNIPEG	503	388	354	197	96	-	-	-	80	161	304	432	503
TORONTO	334	325	256	160	82	-	-	-	46	119	198	290	334
OTTAWA	390	371	284	168	76	-	-	-	57	133	227	347	390
MONTREAL	380	354	277	166	72	-	-	-	52	126	216	336	380
QUEBEC	406	389	304	200	99	-	-	-	76	153	246	365	406
FREDERICTON	367	356	276	188	100	-	-	-	69	142	224	330	367
HALIFAX	324	325	265	198	120	-	-	-	59	127	197	282	325
CHARLOTTETOWN	339	344	285	217	129	-	-	-	63	133	205	298	344
ST. JOHN'S	290	297	266	216	158	-	-	-	79	141	192	256	297

Basis of Calculation: Heated area 225 m^2; heating req'ts 0.06 MJ/m^2 . dd;
house construction to 1980 Bldg. Code (or better);
dd below 18°C avg. 1951-1980. (Feldman, 1987; Canadian Climate, 1982)

principal factors affecting the latter aspect are the sources of energy and applications of thermal storage as discussed in section 2.3.

In parts of the U.S. and in other regions of the world where the diurnal temperature cycle rises above and falls below the thermal comfort zone throughout a major part of the year, PCM concrete can now offer an attractive economic alternative to heating and cooling systems or to the installation of mass concrete (or equivalent) required to effect the same degree of thermal storage necessary for temperature regulation in buildings. In addition to providing inexpensive thermal storage, PCM thermal storage systems do not occupy valuable space and are relatively maintenance free.

At the present time, for PCM concrete block to be cost effective in most Canadian houses, a source of low cost heat would be required such as appropriately designed passive solar facilities, Trombe wall or active solar collection system. Alternatively, heat obtained as a waste product from some exothermic process could furnish the required thermal energy to be stored and released as required.

Commercial and industrial applications can be easier to justify where the energy required for space conditioning is largely consumed during working hours and can be replenished over the remaining hours of the day either from natural sources or by-product energy.

Fossil fuel reserves are diminishing, their cost of extraction is increasing, the market price fluctuates in a manner which contributes significantly to instability in the national economy and the hazards associated with their transport and consumption are becoming increasingly unacceptable. Nuclear power has an uncertain future for reasons of ultimate environmental safety and it may not be possible to depend on it indefinitely as an energy source for space heating either (Hawes, 1990). In addition, it appears that energy rationing will become an increasingly important factor in this process. For example, California has recently enacted legislation which requires homeowners to install solar units to meet at least 50% of their hot water requirements. As a result, when used appropriately, PCM concrete can become increasingly competitive as a building material.

Although the foregoing observations have largely been confined to concrete block, it follows that a wide variety of other concrete products may be similarly treated. In particular, this applies to hollow core panels and slabs so that floor and ceiling areas can be used for latent thermal storage as well.

7.2.1 Conclusions

Through the use of PCM concrete it is quite possible to provide thermal storage capacity in a house which is equal to most daily space heating requirements, even in Canada. The extra cost of such an installation will be approximately $5000 and will be cost effective whenever the diurnal temperature rises above and falls below the human comfort zone for a significant part of the year. In most parts of Canada it would require a low cost energy source (e.g. a solar array) to provide a satisfactory return on investment. Commercial applications can be justified where low cost exhaust heat is available. The trends in energy cost and availability increasingly favour the use of PCM concrete.

CHAPTER 8

GENERAL CONCLUSIONS

8.1 OUTCOME OF THE RESEARCH

This research has realized its objectives and demonstrated that PCM concrete shows considerable promise as a cost effective and practical means of thermal storage in buildings. While it is now ready for use, it is still in an early stage of development and further work is expected to extend its range of application.

Although suitable in Canada under appropriate circumstances, the principal application of latent heat storage in concrete at present will be found in those climates with a significant diurnal temperature swing such as that found in large areas of the U.S. However, when fossil fuel prices rise significantly, as they inevitably must or when the use of high grade energy is restricted, then, as a practical means of thermal storage, PCM concrete will find a wide range of application in Canada as well.

8.2. CONTRIBUTIONS TO THE TECHNOLOGY

As a result of this work, the original concepts listed below were established and patent applications have been made in respect to this research.

(a) PCM concrete was developed in several practical forms which render possible economic advantages to be derived from energy storage at reasonable cost through use of walls, floors and ceilings for enhanced thermal storage without the necessity for massive construction or the installation of heat storage reservoirs. This permits the use of low cost energy from a wide variety of sources which can result in:

(i) reduction of energy consumption for HVAC

(ii) reduction of HVAC equipment size

(iii) more economical operation of burners and chillers.

The energy savings in any particular building will vary with type, occupancy and location but can range upwards from about 30%.

(b) It was demonstrated that thermal storage capacity of several types of concrete block can be greatly enhanced when it is impregnated with a fatty ester such as BS as the PCM.

(c) It was proven that C-22 and C-24 paraffins can function very well as PCM's in many types of concrete and can be used with a heat source in the 50°C - 60°C range (e.g. with solar collectors).

(d) It was shown that TD can be used for latent heat storage in modified concretes where it is desired to store heat in the 30°C - 40°C range.

Further work is required to control the phase transition temperature shift on freezing.

(e) It was found that DD can be used for latent heat storage in modified concretes in the human comfort temperature range. Further work is indicated to control the shift in both transition temperatures.

(f) It was shown that all of the abovementioned PCM's can be incorporated in concrete by immersion; in addition, TD and PAR in prepared, solid forms can also be incorporated directly into the concrete mix.

(g) A technique was developed whereby PCM's which are liquid at ambient temperatures can be incorporated directly into the concrete mix without the use of carriers. This was achieved by pre-impregnating porous aggregates such as expanded shale, expanded slag and pumice with PCM prior to mixing.

(h) Techniques were developed whereby concretes whose hydration products react with some PCM's to destroy all or part of their latent heat capacity can be modified by the use of pozzolans so that the thermal storage values remain stable.

(i) Theoretical considerations of PCM diffusion in concrete were developed together with the determination of absorption characteristics.

(j) A technique was developed for the definition of absorption constants for particular combinations of concrete and PCM (or any fluid).

(k) It was shown that PCM's can be used to improve the durability and to impart other desirable characteristics to concrete so that it is less water absorbent and hence has greater protection from freeze-thaw damage and attack by harmful liquids.

(l) The effects of incorporated PCM's on various physical and chemical properties of concrete were determined.

8.3 RECOMMENDATIONS FOR FURTHER WORK

As in most research projects, the work undertaken here has not only resulted in enlightenment in a number of areas but it has also disclosed some aspects of latent heat storage in concrete which, although beyond the scope of the present work, are nevertheless worthy of further investigation as the necessary personnel, time, facilities and money become available for this purpose. They comprise the following projects:

(a) Carry out full scale fire and fume tests at a recognized fire testing facility.

(b) Conduct research in the modification of PCM's to extend their applications and improve their thermal characteristics.

(c) Extend the work already done with pozzolans to further examine their rôle in safely reducing the effects of PCM-alkaline reaction.

(d) Carry out full scale thermal performance testing of PCM concrete by means of a small test structure.

(e) Continue with further development of direct incorporation techniques.

(f) Extend the use of PCM concrete into other applications.

(g) Determine optimum pH for steel reinforced PCM concrete.

(h) Study the means of optimizing the combined use of PCM concrete and solar arrays.

(i) Conduct a comprehensive economic study for the use of PCM concrete which will be related to the projected cost of energy.

REFERENCES:

Abhat, A., Low Temperature Latent Heat Thermal Energy Storage: Heat Storage Materials, Solar Energy, Vol. 30, No. 4, 1983, p. 313-332.

ACI Manual of Concrete Practice, Part 5, American Concrete Institute, Detroit, 1980, sects. 516, 517.

Altman, M., Yeh, H. and Lorsch, H.G., "Final Report NSF/RANN/SE/ G127976", University of Pennsylvania, 1972.

ASTM C595 - American Society for Testing Materials.

ASTM D3806 - American Society for Testing Materials.

Baxter, G., "Microencapsulation Technology and Modern Business Forms", TAPPI Vol. 60 No. 5, 1977.

Beilsteins Handbuch der Organischen Chemie, Springer-Verlag, Berlin 1958.

Berlad, A.L., "Thermal Energy Storage for Buildings", Transactions of International Assembly on Energy Storage, Dubrovnik, Yugoslavia, 1979, p. 307-313.

Bird, R.B., Stewart, W.E. and Lightfoot, E.N., "Transport Phenomena", John Wiley & Sons, New York, 1960, p. 496.

Brown, T.L., "General Chemistry", Chas. E. Meville Books Inc., Columbus, OH, 1963, p. 126.

"Canadian Climate Normals - Degree Days 1951 - 1980", Environment Canada (Ref. QC 985 C33 + V.4 SEL) 1982.

Chang, T.M.S., "Artificial Cells in Medicine and Biotechnology", Applied Biochemistry and Biotechnology, Vol., 10, 1984.

Charoudi, D., "Suspension Media for Heat Storage Materials", Proceedings of the Workshop on Solar Energy Subsystems for the Heating and Cooling of Buildings, Charlottesville, Vriginia, ASHRAE, 1975.

Ervin, G., "Solar Heat Storage Based on Inorganic Chemical Reactions", Proceedings of the Workshop on Solar Energy Storage Subsystems for the Heating and Cooling of Buildings, Charlottesville, Virginia, ASHRAE, 1975, pp. 17-23.

Feldman, D., Shapiro, M.M., Fazio, P. and Sayegh, S., "The Compressive Strength of Cement Blocks Permeated with Organic Phase Change Material", Energy and Buildings, 1984.

Feldman, D., Shapiro, M.M., Fazio, P., "A Heat Storage Module with a Polymer Structural Matrix", Polymer Engineering and Science, Vol. 25, No. 7, 1985, p. 406-411.

Feldman, D., Shapiro, M. and Banu, D., "Organic Phase Change Matrials for Thermal Energy Storage", Solar Energy Materials, Elsevier Science Publishers, B.V., Amsterdam, 1986.

Feldman, D., Shapiro, M.M., Fazio, P., Hawes, D.W. and Banu, D., "Energy Storing Wallboard (Phase I)", Report of Contract File No. 23216-6-6090/01-ST, Renewable Energy Branch, Energy Mines and Resources Canada, Ottawa, 1987.

Garg, H.P., Mullick, S.C., Bhargava, A.K., "Solar Thermal Energy Storage", D. Reidel Publishing Company, Dordrecht, Holland, 1985.

Hale, D.V.., Hover, M.J., O'Neill, M.J., Phase Change Materials Handbook, Lockheed Missiles and Space Company, Huntsville, Alabama, 1971.

Hawes, D.W., Banu, D. and Feldman, D., "Latent Heat Storage in Concrete", Solar Energy Materials, 19, 1989, pp. 335-348.

Hawes, D.W., Banu, D., Feldman, D., "Latent Heat Storage in Concrete, II", Solar Energy Materials, 21, 1990, pp. 61-80.

Hariri, A.S., Ward, I.C., "A Review of Thermal Storage Systems Used in Building Applications", Building and Environment, Vol. 23, No. 1, pp. 1-10, Great Britain, 1988.

Harnik, A.B., Meier, V. and Rosli, A., "Combined Influence of Freezing and Deicing Salt on Concrete - Physical Aspects, Durability of Building Materials and Components", ASTM STP 691, P.J. Sereda and G.G. Litvan, eds., ASTM, 1980, pp. 476-483.

Heine, D., "The Chemical Compatibility of Construction Materials with Latent Heat Storage Materials", International Conference on Energy Storage, Brighton, U.K., BRHA Fluid Engineering, 1981.

Hutcheon, N.B. and Handegord, G.O.P., "Building Science for A Cold Climate", John Wiley & Sons, Toronto, 1983, pp. 67-78.

Illston, J.M., Dinwoodie, J.M., Smith, A.A., "Concrete, Timber and Metals", Van Nostrand Reinhold, New York, 1979, pp. 554,6.

Lane, G.A., et al, "Isothermal Solar Heat Storage Materials", National Science Foundation and the Energy Research and Development Administration, Contract No. NSF - C906, Washington, D.C., 1976.

Lane, G.A., et al, "Heat of Fusion Systems for Solar Energy Storage", Proceedings of the Workshop on Solar Energy Storage Subsystems for the Heating and Cooling of Buildings, Charlottesville, Virginia, 1979, p. 43-59.

Lane, G.A., "Solar Heat Storage: Latent Heat Materials, Vol. 1: Background and Scientific Principles", CRC Press, Inc., Boca Raton, Florida, 1983.

Lee, T.G., "Heat Storage and Passive Discharge in Structural Masonry Wall: The Calgary Chinese Alliance Church", Sun World, Vol. 8, No. 2, 1984.

Levitt, M.. "Precast Concrete Materials. Manufacture, Properties and Usage", Applied Science Publishers, London, 1982, pp. 151-154.

Lof, G.O.G., 'A Problem with Passive", Solar Age, 3 (No. 9), Sept. 1978.

Lorsch, H.G., Kaufman, K.W. and Denton, J.C., "Thermal Energy Storage for Solar Heating and Off-peak Air Conditioning", Energy Conversion Vol. 15, pp. 1-8, Pergammon Press, U.K., 1975.

Low, N.W., Private Communication, Concordia University, 1990.

Marshall, J.S., Pounder, E.L., "Physics" MacMillan, New York, 1958, p. 347.

Mehta, P.K., "Concrete, Structure, Properties and Materials", Prentice-Hall Inc., N.J., 1986, pp. 32-90.

Michal, C.J., Lewis, D.C., "Natural Thermal Storage: An Overview of Performance Expectations and Design Techniques Using the M_e Factor", Proceedings of Conference on Solar Energy Storage Options, Vol. I, Trinity University, San Antonio, Texas, 1979, p. 379-389.

Mindess, S. and Young, J.F., "Concrete", Prentice-Hall, New Jersey, 1981.

Neeper, D.A., McFarland, R.D., Hedstrom, J.C., Lazarus, G.S., "Potential Performance Benefits of Advanced Components and Materials Research", Proceedings of the Passive and Hybrid Solar Energy Update, U.S. Department of Energy, DOE/CONF-8409118, Dist. Category U.C.-59C, 1984, p. 20-26.

Neville, A.M., "Properties of Concrete", Pitman Publishing Limited, London, 1981.

Perlin, J., "Ancient Greek Solar Architecture: Lessons for Today's Architects", Intersol 85, Proceedings of Ninth Biennial Congress of I.S.E.S., Pergammon Press, Montreal, June, 1985.

Salyer, I., Sircar, A., Chartoff, R., and Miller, E., "Advanced Phase Change Materials for Passive Solar Applications", U.S. Dept. of Energy Contract DOE/CE/30755-TI, March 1986.

Schröder, J., and Gawron, K., "Properties of Some Salt Hydrates for Latent Heat Storage", International Journal of Energy Research, John Wiley, Vol. 1, 1977, pp. 351-363.

Sellevold, E.J., and Radjy, F.F., "Condensed Silica Fume (Microsilica) in Concrete: Water Demand and Strength Development", Fly Ash, Silica Fume, Slag and other Mineral by-products in Concrete, Vol., I, American Concrete Institute Publication No. SP769, 1983, pp. 677-698.

NCMA-TEK 120, "Second Generation Passive Solar Systems Using Concrete Masonry", National Concrete Masonry Association, Herndon, Virginia, 1981.

Shewmon, P.G., "Diffusion in Solids", McGraw-Hill, New York, 1963, p. 2.

Spooner, D.C., "The Practical Relevance of Mechanisms of Water and Water Vapour Transport in Porous Building Materials", Autoclaved Aerated Concrete, Moisture and Properties, ed. Wittmann, F.H., Elsevier Scientific Publishing Co., Amsterdam, 1983, pp. 33.

Taylor, W.H., "Concrete Technology and Practice", 4th Ed., McGraw-Hill, 1977.

Telkes, M., "Thermal Storage for Solar Heating and Cooling", Proceedings of the Workshop on Solar Energy Storage Subsystems for the Heating and Cooling of Buildings, Charlottesville, Virginia, ASHRA, 1975, pp. 17-23.

Van Galen, E., Van Den Brink, G.J., Energy Storage in Phase Change Materials for solar Applications, International Journal of Ambient Energy, Vol. 7, No. 1, Ambient Press Limited, Loughborough, U.K., 1986, pp. 31-46.

Van Vlack, L.H., "Elements of Materials Science", Addison-Wesley Publishing Company, Don Mills 1964, p. 7.

APPENDIX A

TABLES A1 - A51

TABLE A1 - PCM IMPREGNATION PROCEDURE - 21/9/88
AUTOCLAVED BLOCK-MIXED 20/9/88

SPECIMEN NO.	CONCRETE TYPE	PCM	INIT. WT. g	FINAL WT. g	GAIN		IMMERSION TIME MIN.	IMMERSION TEMP. °C	CONCRETE TEMP. °C
					g	%			
1	ABL	BS	223.68	231.95	8.27	3.70	12	78-82	80
2	"	BS	225.47	233.10	7.63	3.38			
3	"	DD	171.45	174.58	3.13	1.83			
4	"	DD	225.91	232.10	6.19	2.74			
5	"	PEG	218.72	229.80	11.08	5.07			
6	"	PEG	229.39	241.61	12.22	5.33			
7	"	DD	220.06	227.09	7.03	3.19			
21	"	BS	180.52	186.71	7.19	3.98			
22	"	DD	170.44	177.29	6.85	4.02			
23	"	PEG	174.84	182.90	8.06	4.61			

Average PCM in ABL - % of Concrete Weight

BS - 3.69
DD - 2.95
PEG - 5.00

TABLE A2 - PCM IMPREGNATION PROCEDURE - 21/9/88
REGULAR BLOCK - MIXED 20/9/88

SPECIMEN NO.	CONCRETE TYPE	PCM	INIT. WT. g	FINAL WT. g	GAIN		IMMERSION TIME MIN.	IMMERSION TEMP. °C	CONCRETE TEMP. °C
					g	%			
8	REG	BS	202.16	206.91	4.75	2.35	12	78-82	80
9	REG	BS	197.09	203.01	5.92	3.00			
10	REG	DD	204.80	208.80	4.0	1.95			
11	REG	DD	209.03	215.61	6.58	3.15			
12	REG	PEG	199.89	203.79	3.90	1.95			
13	REG	PEG	206.81	216.95	10.14	4.90			
14	REG	BS	212.40	218.89	6.49	3.06			
15	REG	DD	197.41	200.41	3.0	1.52			
16	REG	PEG	215.30	222.70	7.40	3.44			
17	REG	DD	197.89	202.75	4.86	2.46			
18	REG	BS	202.75	207.26	4.51	2.22			
19	REG	DD	215.07	220.04	4.97	2.31			
20	REG	PEG	187.60	198.24	10.64	5.67			

Average PCM in REG - % of Concrete Weight

BS - 2.66
DD - 2.28
PEG - 3.99

TABLE A3 - PCM IMPREGNATION PROCEDURE - 21/9/88
PUMICE BLOCK - MIXED MORE THAN 60 DAYS

SPECIMEN NO.	CONCRETE TYPE	PCM	INIT. WT. g	FINAL WT. g	GAIN		IMMERSION TIME MIN.	IMMERSION TEMP. °C	CONCRETE TEMP. °C
					g	%			
24	PUMICE	BS	142.40	148.60	6.20	4.35	12	78-82	80
25	PUMICE	BS	143.85	150.24	6.39	4.44			
26	PUMICE	DD	144.31	150.34	6.03	4.18			
27	PUMICE	DD	142.50	147.77	5.27	3.70			
28	PUMICE	PEG	139.89	148.69	11.80	8.62			
29	PUMICE	PEG	138.55	148.14	9.59	6.92			
30	PUMICE	PEG	139.14	149.90	10.76	7.73			

Average PCM in PUM - % of Concrete Weight

BS - 4.40
DD - 3.94
PEG - 7.76

TABLE A4 - PCM IMPREGNATION PROCEDURE - 28/9/88
AUTOCLAVED BLOCK - MIXED 20/9/88

SPECIMEN NO.	CONCRETE TYPE	PCM	INIT. WT. g	FINAL WT. g	GAIN g	GAIN %	IMMERSION TIME MIN.	IMMERSION TEMP. °C	CONCRETE TEMP. °C
31	ABL	BS	178.64	186.43	7.79	4.36	12	78-82	80
32	ABL	BS	167.86	175.71	7.85	4.68			
33	ABL	DD	177.10	182.02	4.92	2.78			
34	ABL	DD	218.34	230.34	12.00	5.50			
35	ABL	PEG	169.45	177.04	7.59	4.48			
36	ABL	PEG	165.37	175.00	9.63	5.82			

Average PCM in ABL - % of Concrete Weight

BS - 4.52
DD - 4.14
PEG - 5.15

TABLE A5 - PCM IMPREGNATION PROCEDURE - 28/9/88
REGULAR BLOCK - MIXED 20/9/88

SPECIMEN NO.	CONCRETE TYPE	PCM	INIT. WT. g	FINAL WT. g	GAIN		IMMERSION TIME MIN.	IMMERSION TEMP. °C	CONCRETE TEMP. °C
					g	%			
37	REG	BS	196.31	200.91	4.60	2.34	12	78-82	80
38	REG	BS	210.60	218.64	8.04	3.82			
39	REG	DD	209.63	214.94	5.31	2.53			
40	REG	DD	206.50	213.49	6.99	3.38			
41	REG	PEG	186.58	193.40	6.82	3.56			
42	REG	PEG	199.62	210.10	10.48	5.25			

Average PCM in REG - % of Concrete Weight

BS - 3.08
DD - 2.95
PEG - 4.46

TABLE A6 - PCM IMPREGNATION PROCEDURE - 20/10/88
AUTOCLAVED AND REGULAR BLOCK - MIXED 20/9/88

SPECIMEN NO.	CONCRETE TYPE	PCM	INIT. WT. g	FINAL WT. g	GAIN		IMMERSION TIME MIN.	IMMERSION TEMP. °C	CONCRETE TEMP. °C
					g	%			
43	ABL	BS	169.50	177.05	7.55	4.45	12	80-82	80
44	ABL	DD	124.20	130.15	5.95	4.79			
45	ABL	PEG	167.40	174.20	6.80	4.00			
46	ABL	BS	172.60	176.0	4.0	2.31			
47	ABL	DD	124.00	129.45	5.45	4.40			
48	ABL	PEG	183.60	190.05	6.45	3.51			
49	REG	BS	167.25	171.50	4.25	2.54			
50	REG	DD	164.40	167.90	3.50	2.13			
51	REG	PEG	177.05	182.60	5.55	3.13			
52	REG	BS	195.80	201.89	6.09	3.11			
53	REG	DD	183.90	190.00	6.1	3.32			
54	REG	PEG	183.75	190.70	6.95	3.78			

Average PCM in ABL - % of Concrete Weight

BS - 3.38
DD - 4.60
PEG - 3.79

Average PCM in REG - % of Concrete Weight

BS - 2.54
DD - 3.03
PEG - 3.46

TABLE A7 - IMPREGNATION PROCEDURE - 21/11/88
REGULAR AND PUMICE BLOCK (CONCORDIA MIX) - MIXED 14/11/88

SPECIMEN TYPE	CONCRETE TYPE	PCM	INIT. WT. g	FINAL WT. g	GAIN		IMMERSION TIME MIN.	IMMERSION TEMP. °C	CONCRETE TEMP. °C
					g	%			
55	REGC	BS	97.60	100.11	2.51	2.57	12	80	80
56	REGC	BS	158.80	161.34	2.54	1.60			
57	REGC	DD	104.26	106.60	2.34	2.24			
58	REGC	DD	165.12	167.15	2.03	1.23			
59	REGC	PEG	102.60	104.85	2.25	2.19			
60	REGC	PEG	105.84	108.55	2.71	2.56			
61	PUMC	BS	93.50	97.33	3.83	4.10			
62	PUMC	BS	130.23	133.24	3.01	2.31			
63	PUMC	DD	126.75	130.40	3.65	2.88			
64	PUMC	DD	121.66	125.31	3.65	3.00			
65	PUMC	PEG	119.61	124.10	4.49	3.75			
66	PUMC	PEG	124.71	129.42	4.71	3.78			
67	REGC	BS	157.39	160.20	2.81	1.79	1080		

Average PCM in REGC - % of Concrete Weight

BS - 2.10
DD - 1.74
PEG - 2.38

Average PCM in PUMC - % of Concrete Weight (Specs. 61 - 66 only)

BS - 3.84
DD - 3.65
PEG - 4.60

TABLE A8 - IMPREGNATION PROCEDURE - 24/11/88
REGULAR AND AUTOCLAVED BLOCK - MIXED 20/9/88

SPECIMEN No.	CONCRETE TYPE	PCM	INIT. WT. g	FINAL WT. g	GAIN		IMMERSION TIME MIN.	IMMERSION TEMP. °C	CONCRETE TEMP. °C
					g	%			
68	REG	BS	189.50	193.96	4.46	2.35	12	80	80
69	REG	BS	188.46	192.68	4.22	2.24			
70	REG	DD	184.16	187.80	3.64	1.98			
71	REG	DD	168.27	173.80	5.53	3.29			
72	REG	PEG	189.29	195.55	3.32	1.75			
73	REG	PEG	182.50	189.42	5.92	3.79			
74	REG	BS	215.11	225.05	9.94	4.62			
75	ABL	BS	172.66	180.52	7.86	4.55			
76	ABL	DD	173.64	178.45	4.81	2.77			
77	ABL	DD	195.66	200.15	4.49	2.29			
78	ABL	PEG	172.85	180.55	7.70	4.45			
79	ABL	PEG	169.41	177.93	8.52	5.03			

Average PCM in ABL - % of Concrete Weight

BS - 4.59
DD - 2.53
PEG - 4.74

Average PCM in REG - % of Concrete Block

BS - 2.30
DD - 2.64
PEG - 2.77

TABLE A9 - IMPREGNATION PROCEDURE - 14/3/88
REGULAR AGGREGATE, LOW ALKALI TYPE 10 CEMENT AND SILICA FUME, CONCRETE MIXED 23/1/89, AIR CURED 43 DAYS

SPECIMEN No.	PCM	INIT. WT. g	FINAL WT. g	GAIN		IMMERSION TIME MIN.	IMMERSION TEMP. °C	CONCRETE TEMP. °C
				g	%			
80	BS	253.79	257.84	4.05	1.60	12	80	80
81	BS	260.62	265.05	4.43	1.70			
82	PEG	259.64	264.02	4.38	1.69			
83	DD	237.20	239.68	2.48	1.05			
84	DD	255.71	258.85	3.14	1.23			
85	PEG	261.80	265.92	4.12	1.57			
86	BS	305.80	313.20	7.40	2.42			

TABLE A10 - PCM PROCEDURE - 14/3/88
EXPANDED SHALE AGGREGATE, LOW ALKALI TYPE 10 CEMENT
AND SILICA FUME, CONCRETE MIXED 23/1/89, AIR CURED 43 DAYS

SPECIMEN No.	PCM	INIT. WT. g	FINAL WT. g	GAIN		IMMERSION TIME MIN.	IMMERSION TEMP. °C	CONCRETE TEMP. °C
				g	%			
87	BS	187.80	190.60	2.80	1.49	12	80	80
88	BS	117.17	119.22	2.05	1.75			
89	DD	180.29	182.20	1.91	1.06			
90	DD	112.71	114.24	1.53	1.36			
91	PEG	227.23	230.37	3.14	1.38			
92	PEG	119.90	122.56	2.66	2.22			
93	DD	245.06	247.80	2.74	1.12			

TABLE A11 - PCM IMPREGNATION PROCEDURE - 14/3/88
PUMICE AGGREGATE, LOW ALKALI TYPE 10 CEMENT AND SILICA FUME, CONCRETE MIXED 23/1/89, AIR CURED 43 DAYS

SPECIMEN No.	PCM	INIT. WT. g	FINAL WT. g	GAIN		IMMERSION TIME MIN.	IMMERSION TEMP. °C	CONCRETE TEMP. °C
				g	%			
94	BS	151.27	154.51	3.24	2.14	12	80	80
95	BS	57.81	59.74	1.93	3.34			
96	DD	172.05	174.29	2.24	1.30			
97	DD	53.72	54.90	1.18	2.20			
98	PEG	167.12	171.30	4.18	2.50			
99	PEG	60.96	62.96	2.00	3.28			
100	BS	184.85	191.11	6.26	3.39			

TABLE A12 - PCM IMPREGNATION PROCEDURE - 14/3/88 PUMICE AGGREGATE, LOW ALKALI TYPE 10 CEMENT AND SILICA FUME, CONCRETE MIXED 23/1/89, IMMERSED IN WATER 24/1/89, REMOVED 28/2/89 THEN AIR CURED 14 DAYS

SPECIMEN No.	PCM	INIT. WT. g	FINAL WT. g	GAIN		IMMERSION TIME MIN.	IMMERSION TEMP. °C	CONCRETE TEMP. °C
				g	%			
101	BS	286.14	290.45	4.31	1.51	12	80	80
102	BS	92.13	99.64	7.51	8.15			
103	DD	265.25	267.94	2.69	1.01			
104	DD	147.11	149.70	2.59	1.76			
105	PEG	255.41	259.00	3.59	1.41			
106	PEG	100.50	102.76	2.26	2.25			
107	SPARE	323.10	-	-	-	↓	↓	↓

TABLE A13 - PCM IMPREGNATION PROCEDURE - 14/3/88, EXPANDED SHALE AGGREGATE, LOW ALKALI TYPE 10 CEMENT AND SILICA FUME, CONCRETE MIXED 23/1/89, IMMERSED IN WATER 24/1/89, REMOVED 28/2/89 THEN AIR CURED 14 DAYS

SPECIMEN No.	PCM	INIT. WT. g	FINAL WT. g	GAIN		IMMERSION TIME MIN.	IMMERSION TEMP. °C	CONCRETE TEMP. °C
				g	%			
108	BS	208.75	212.20	3.45	1.65	12	80	80
109	BS	112.40	114.26	1.86	1.65	↓	↓	↓
110	DD	192.60	195.10	2.50	1.30	↓	↓	↓
111	DD	112.75	114.40	1.65	1.46	↓	↓	↓
112	PEG	208.25	212.01	3.76	1.81	↓	↓	↓
113	PEG	113.80	115.95	2.15	1.89	↓	↓	↓
114	DD	234.75	237.42	2.67	1.14	↓	↓	↓

TABLE A14 - PCM IMPREGNATION PROCEDURE - 14/3/88, PUMICE AGGREGATE, LOW ALKALI TYPE 10 CEMENT AND SILICA FUME, CONCRETE MIXED 23/1/89, IMMERSED IN WATER 24/1/89, REMOVED 28/2/89 THEN AIR CURED 14 DAYS

SPECIMEN No.	PCM	INIT. WT. g	FINAL WT. g	GAIN		IMMERSION TIME MIN.	IMMERSION TEMP. °C	CONCRETE TEMP. °C
				g	%			
115	BS	146.70	151.31	4.61	3.14	12	80	80
116	BS	38.00	40.09	2.09	5.50			
117	DD	177.90	181.80	3.90	2.19			
118	DD	42.20	43.97	1.77	4.19			
119	PEG	153.67	158.22	4.55	2.96			
120	PEG	54.39	56.62	2.23	4.10			
121	PEG	202.04	207.72	5.68	2.81			

TABLE A15 - PCM IMPREGNATION PROCEDURE - 14/3/88, REGULAR AGGREGATE, LOW ALKALI TYPE 10 CEMENT AND SILICA FUME, CONCRETE MIXED 1/2/89, STEAM CURED 1/2/89 - 2/2/89 THEN AIR CURED 40 DAYS

SPECIMEN No.	PCM	INIT. WT. g	FINAL WT. g	GAIN		IMMERSION TIME MIN.	IMMERSION TEMP. °C	CONCRETE TEMP. °C
				g	%			
122	BS	201.64	208.00	6.36	3.15	12	80	80
123	BS	133.88	139.84	5.96	4.45			
124	DD	205.10	209.10	4.00	1.95			
125	DD	132.60	135.54	2.94	2.22			
126	PEG	204.23	209.65	5.42	2.65			
127	PEG	136.32	141.00	4.68	3.43			
128	BS	283.31	290.88	7.57	2.67			

TABLE A16 - PCM IMPREGNATION PROCEDURE - 14/3/88
EXPANED SHALE AGGREGATE, LOW ALKALI TYPE 10 CEMENT AND SILICA FUME, CONCRETE MIXED 1/2/89, STEAM CURED 1/2/89 - TO 2/2/89 THEN AIR CURED 40 DAYS

SPECIMEN No.	PCM	INIT. WT. g	FINAL WT. g	GAIN		IMMERSION TIME MIN.	IMMERSION TEMP. °C	CONCRETE TEMP. °C
				g	%			
129	BS	217.31	222.87	5.56	2.56	12	80	80
130	BS	104.90	108.34	3.54	3.38			
131	DD	182.85	186.29	3.44	1.88			
132	DD	106.05	108.50	2.45	2.31			
133	PEG	184.25	189.45	5.20	2.82			
134	PEG	107.39	111.41	4.02	3.74			
135	BS	226.70	232.84	6.14	2.71			

TABLE A17 - PCM IMPREGNATION PROCEDURE - 14/3/88
PUMICE AGGREGATE, LOW ALKALI TYPE 10 CEMENT AND SILICA FUME, CONCRETE MIXED 1/2/89, STEAM CURED 1/2/89 - 2/2/89 THEN AIR CURED 40 DAYS

SPECIMEN No.	PCM	INIT. WT. g	FINAL WT. g	GAIN		IMMERSION TIME MIN.	IMMERSION TEMP. °C	CONCRETE TEMP. °C
				g	%			
136	BS	147.95	153.41	5.46	3.69	12	80	80
137	BS	91.00	94.51	3.51	3.86	↓	↓	↓
138	DD	154.83	157.55	2.72	1.76			
139	DD	90.06	92.62	2.56	2.84			
140	PEG	139.40	143.83	4.43	3.18			
141	PEG	87.51	90.50	2.99	3.42			
142	DD	190.85	193.56	2.71	1.42			

TABLE A18 - IMPREGNATION PROCEDURE - 14/3/89
PRE-IMPREGNATED EXPANDED SHALE AGGREGATE, LOW ALKALI TYPE 10 CEMENT
AND SILICA FUME, CONCRETE MIXED 31/1/89, STEAM CURED 31/1/89 - 1/2/89
THEN AIR CURED 41 DAYS

SPECIMEN No.	PCM	PCM ADDED TO AGG. g (APP)	PCM ADDED TO IMPREG. SPEC.			TOTAL WT. PCM g (APP)	% PCM IN SPEC. g (APP)	IMMERSION TIME (Agg. & Spec) MIN.	IMMERSION TEMP. °C	CONCRETE TEMP. °C
			INITIAL WT. g	FINAL WT. g	GAIN g					
143	BS	8.36	189.61	192.26	2.65	11.01	5.8	15	80	80
144	BS	8.93	202.60	205.50	2.90	11.83	5.8			
145	BS	9.71	220.44	221.96	1.52	11.23	5.0			
146	DD	11.06	193.16	195.38	2.22	13.30	6.8			
147	DD	10.81	188.45	190.90	2.45	13.26	6.9			
148	DD	12.10	210.93	212.74	1.81	13.91	6.5			
149	PEG	7.89	189.30	193.65	4.35	12.24	6.3			
150	PEG	8.13	195.15	199.25	4.10	12.23	6.1			
151	PEG	8.99	215.73	218.70	2.97	11.96	5.5			

TABLE A19 - PCM IMPREGNATION PROCEDURE - 14/3/89
PRE-IMPREGNATED PUMICE AGGREGATE, LOW ALKALI TYPE 10 CEMENT AND SILICA FUME, CONCRETE MIXED 1/2/89, STEAM CURED 1/1/89 - 2/2/89 THEN AIR CURED 40 DAYS

SPECIMEN No.	PCM	PCM ADDED TO AGG. g (APP)	PCM ADDED TO IMPREG. SPEC.			TOTAL WT. PCM g (APP)	% PCM IN SPEC. q (APP)	IMMERSION TIME (Agg. & Spec) MIN.	IMMERSION TEMP. °C	CONCRETE TEMP. °C
			INITIAL WT. g	FINAL WT. g	GAIN g					
152	BS	11.84	158.84	159.72	0.88	12.72	8.0	15	80	80
153	BS	11.85	158.91	159.80	0.89	12.74	8.0			
154	BS	13.31	178.47	179.04	0.57	13.88	7.8			
155	DD	12.76	156.90	162.60	5.70	18.46	11.4			
156	DD	12.10	148.76	153.71	4.95	17.05	11.1			
157	DD	13.15	161.70	167.25	5.55	18.70	11.2			
158	PEG	25.38	149.84	155.55	5.71	31.09	20.0			
159	PEG	25.37	149.82	155.65	5.83	31.20	20.0			
160	PEG	32.25	190.41	193.50	3.09	35.34	18.3			

NOTE: Marked Efflorescence on 155,156 and 157.

TABLE A20 - PCM IMPREGNATION PROCEDURE - 14/3/88

ORDINARY PORTLAND CEMENT CONCRETE (STD TYPE 10 CEMENT)
MIXED 5/5/88 - WATER CURED (28 DAYS)

SPECIMEN No.	PCM	INIT. WT. g	FINAL WT. g	GAIN		IMMERSION TIME MIN.	IMMERSION TEMP. °C	CONCRETE TEMP. °C
				g	%			
161	BS	140.12	141.80	1.68	1.20	12	80	80
162	DD	255.23	257.25	2.02	0.79	12	80	80
163	PEG	93.55	94.89	1.34	1.43	12	80	80

(a)

ORDINARY PORTLAND CEMENT CONCRETE (STD TYPE 10 CEMENT)
MIXED 5/5/88 - MOIST CURED (28 DAYS)

SPECIMEN No.	PCM	INIT. WT. g	FINAL WT. g	GAIN		IMMERSION TIME MIN.	IMMERSION TEMP. °C	CONCRETE TEMP. °C
				g	%			
164	BS	170.34	173.06	2.72	1.60	12	80	80
165	DD	284.50	287.26	2.76	0.97	12	80	80
166	PEG	92.11	94.20	2.09	2.27	12	80	80

(b)

TABLE A21 - PCM IMPREGNATION PROCEDURE - 3/5/89
REGULAR AGGREGATE, LOW ALKALI TYPE 10 CEMENT AND SILICA FUME, CONCRETE MIXED 23/1/89, AIR CURED 100 DAYS

SPECIMEN No.	PCM	INIT. WT. g	FINAL WT. g	GAIN		IMMERSION TIME MIN.	IMMERSION TEMP. °C	CONCRETE TEMP. °C
				g	%			
167	BS	225.85	229.60	3.75	1.66	12	80	80
168	BS	182.00	185.65	3.65	2.00	↓	↓	↓
169	DD	264.65	267.75	3.10	1.17			
170	DD	174.23	176.55	2.32	1.33			
171	PEG	236.73	240.20	3.47	1.47			
172	PEG	185.31	188.08	2.77	1.49			

TABLE A22 - PCM IMPREGNATION PROCEDURE - 3/5/89
EXPANDED SHALE AGGREGATE, LOW ALKALI TYPE 10 CEMENT AND SILICA FUME, CONCRETE MIXED 23/1/89, AIR CURED 100 DAYS

SPECIMEN No.	PCM	INIT. WT. g	FINAL WT. g	GAIN		IMMERSION TIME MIN.	IMMERSION TEMP. °C	CONCRETE TEMP. °C
				g	%			
173	BS	205.01	207.15	2.14	1.04	12	80	80
174	BS	106.59	108.14	1.55	1.45	↓	↓	↓
175	DD	219.03	220.85	1.82	0.83	↓	↓	↓
176	DD	107.71	108.66	0.95	0.88	↓	↓	↓
177	PEG	191.40	193.29	1.89	0.99	↓	↓	↓
178	PEG	115.00	116.50	1.50	1.30	↓	↓	↓

TABLE A23 - PCM IMPREGNATION PROCEDURE - 3/5/89
PUMICE AGGREGATE, LOW ALKALI TYPE 10 CEMENT AND SILICA FUME, CONCRETE MIXED 23/1/89, AIR CURED 100 DAYS

SPECIMEN No.	PCM	INIT. WT. g	FINAL WT. g	GAIN		IMMERSION TIME MIN.	IMMERSION TEMP. °C	CONCRETE TEMP. °C
				g	%			
179	BS	100.66	103.66	3.00	2.98	12	90	80
180	BS	77.11	79.54	2.43	3.15			
181	DD	89.79	91.70	1.91	2.13			
182	DD	83.15	84.65	1.50	1.80			
183	PEG	79.65	82.10	2.45	3.08			
184	PEG	98.14	100.80	2.66	2.71			

TABLE A24 - PCM IMPREGNATION PROCEDURE - 4/5/89
REGULAR AGGREGATE, LOW ALKALI TYPE 10 CEMENT AND SILICA FUME,
CONCRETE MIXED 23/1/89, IMMERSED IN WATER 24/1/89,
REMOVED 28/2/89 THEN AIR CURED 65 DAYS

SPECIMEN No.	PCM	INIT. WT. g	FINAL WT. g	GAIN		IMMERSION TIME MIN.	IMMERSION TEMP. °C	CONCRETE TEMP. °C
				g	%			
185	BS	98.89	102.00	3.11	3.14	12	80	80
186	BS	146.68	147.80	1.12	0.76	↓	↓	↓
187	DD	96.65	98.12	1.47	1.52			
188	DD	150.84	152.95	2.11	1.40			
189	PEG	154.39	156.76	2.37	1.54			
190	PEG	85.21	86.79	1.58	1.85			

TABLE A25 - PCM IMPREGNATION PROCEDURE - 4/5/89
EXPANDED SHALE AGGREGATE, LOW ALKALI TYPE 10 CEMENT AND SILICA FUME, CONCRETE MIXED 23/1/89, IMMERSED IN WATER 24/1/89, REMOVED 28/2/89 THEN AIR CURED 66 DAYS

SPECIMEN No.	PCM	INIT. WT. g	FINAL WT. g	GAIN		IMMERSION TIME MIN.	IMMERSION TEMP. °C	CONCRETE TEMP. °C
				g	%			
191	BS	119.75	122.15	2.40	2.00	12	80	80
192	BS	80.40	82.30	1.90	2.36	↓	↓	↓
193	DD	118.57	120.50	1.93	1.63	↓	↓	↓
194	DD	76.40	77.74	1.34	1.75	↓	↓	↓
195	PEG	116.98	119.56	2.58	2.21	↓	↓	↓
196	PEG	74.46	76.30	1.84	2.47	↓	↓	↓

TABLE A25 - PCM IMPREGNATION PROCEDURE - 4/5/89
PUMICE AGGREGATE, LOW ALKALI TYPE 10 CEMENT AND SILICA FUME,
CONCRETE MIXED 23/1/89, IMMERSED IN WATER 24/1/89,
REMOVED 28/2/89 THEN AIR CURED 66 DAYS

SPECIMEN No.	PCM	INIT. WT. g	FINAL WT. g	GAIN		IMMERSION TIME MIN.	IMMERSION TEMP. °C	CONCRETE TEMP. °C
				g	%			
197	BS	96.61	100.12	3.51	3.63	12	80	80
198	BS	61.21	64.04	2.83	4.62			
199	DD	90.10	92.75	2.65	2.94			
200	DD	62.93	64.80	1.87	2.97			
201	PEG	73.99	76.99	3.00	4.05			
202	PEG	48.16	50.52	2.36	4.90			

TABLE A27 - PCM IMPREGNATION PROCEDURE - 4/5/89
REGULAR AGGREGATE, LOW ALKALI TYPE 10 CEMENT AND SILICA FUME,
CONCRETE MIXED 1/2/89, STEAM CURED 1/2/89 - 2/2/89
THEN AIR CURED 91 DAYS

SPECIMEN No.	PCM	INIT. WT. g	FINAL WT. g	GAIN		IMMERSION TIME MIN.	IMMERSION TEMP. °C	CONCRETE TEMP. °C
				g	%			
203	BS	126.08	131.63	5.55	4.40	12	80	80
204	BS	138.78	142.91	4.13	2.98	↓	↓	↓
205	DD	115.41	118.64	3.23	2.80	↓	↓	↓
206	DD	67.92	71.06	3.14	4.62	↓	↓	↓
207	PEG	130.82	136.19	5.37	4.10	↓	↓	↓
208	PEG	70.87	75.04	4.17	5.88	↓	↓	↓

TABLE A28 - PCM IMPREGNATION PROCEDURE - 4/5/89 EXPANDED SHALE AGGREGATE, LOW ALKALI TYPE 10 CEMENT AND SILICA FUME, CONCRETE MIXED 1/2/89, STEAM CURED 1/2/89 - 2/2/89 THEN AIR CURED 91 DAYS

SPECIMEN No.	PCM	INIT. WT. g	FINAL WT. g	GAIN		IMMERSION TIME MIN.	IMMERSION TEMP. °C	CONCRETE TEMP. °C
				g	%			
209	BS	115.30	119.10	3.80	3.30	12	80	80
210	BS	105.40	108.76	3.36	3.19	↓	↓	↓
211	DD	100.46	101.87	1.41	1.40	↓	↓	↓
212	DD	71.20	72.42	1.22	1.71	↓	↓	↓
213	PEG	104.39	107.75	3.36	3.22	↓	↓	↓
214	PEG	63.32	65.69	2.37	3.74	↓	↓	↓

TABLE A29 - PCM IMPREGNATION PROCEDURE - 4/5/89
PUMICE AGGREGATE, LOW ALKALI TYPE 10 CEMENT AND SILICA FUME, CONCRETE MIXED 1/2/89, STEAM CURED 1/2/89 - 2/2/89 THEN AIR CURED 91 DAYS

SPECIMEN No.	PCM	INIT. WT. g	FINAL WT. g	GAIN		IMMERSION TIME MIN.	IMMERSION TEMP. °C	CONCRETE TEMP. °C
				g	%			
215	BS	90.25	94.62	4.37	4.84	12	80	80
216	BS	84.82	98.32	3.50	4.13			
217	DD	92.35	95.10	2.75	2.98			
218	DD	46.30	47.98	1.68	3.63			
219	PEG	96.08	100.55	4.47	4.65			
220	PEG	50.71	53.05	2.34	4.61			

TABLE A30 - PCM IMPREGNATION PROCEDURE - 4/5/89
PRE-IMPREGNATED EXPANDED SHALE AGGREGATE, LOW ALKALI TYPE 10 CEMENT AND SILICA FUME, CONCRETE MIXED 31/2/89, STEAM CURED 31/1/89 - 1/2/89 THEN AIR CURED FOR 40 DAYS

SPECIMEN No.	PCM	PCM ADDED TO AGG. g (APP)	PCM ADDED TO IMPREG. SPEC.			TOTAL WT. PCM g (APP)	% PCM IN SPEC. g (APP)	IMMERSION TIME (Agg. & Spec) MIN.	IMMERSION TEMP. °C	CONCRETE TEMP. °C
			INITIAL WT. g	FINAL WT. g	GAIN g					
221	BS	8.91	202.45	203.55	1.10	10.01	4.94	15	80	80
222	BS	8.18	185.93	188.52	2.59	10.77	5.79	↓	↓	↓
223	DD	11.80	205.60	208.06	2.46	14.26	6.94	↓	↓	↓
224	DD	12.35	215.11	216.35	1.24	13.59	6.32	↓	↓	↓
225	PEG	7.96	190.97	196.42	5.45	13.41	7.02	↓	↓	↓
226	PEG	7.87	188.74	189.78	1.04	8.91	4.72	↓	↓	↓

TABLE A31 - PCM IMPREGNATION PROCEDURE - 4/5/89
PRE-IMPREGNATED PUMICE AGGREGATE, LOW ALKALI TYPE 10 CEMENT AND
SILICA FUME, CONCRETE MIXED 1/2/89, STEAM CURED 1/2/89 - 2/2/89
THEN AIR CURED FOR 91 DAYS

SPECIMEN No.	PCM	PCM ADDED TO AGG. g (APP)	PCM ADDED TO IMPREG. SPEC.			TOTAL WT. PCM g (APP)	% PCM IN SPEC. g (APP)	IMMERSION TIME (Agg. & Spec) MIN.	IMMERSION TEMP. °C	CONCRETE TEMP. °C
			INITIAL WT. g	FINAL WT. g	GAIN g					
227	BS	12.10	162.35	162.68	0.33	12.43	7.66	15	80	80
228	BS	11.10	148.95	150.15	1.20	12.30	8.26	↓	↓	↓
229	DD	12.29	151.11	152.14	1.03	13.32	8.81	↓	↓	↓
230	DD	11.63	143.09	147.45	4.36	15.99	11.17	↓	↓	↓
231	PEG	25.43	150.10	152.45	2.35	27.78	18.51	↓	↓	↓
232	PEG	24.65	145.50	152.10	6.60	31.25	21.48	↓	↓	↓

TABLE A31-S SHEET 1
% BS IN SPECIMENS - SUMMARY OF TABLE A9 TO A31
CONSERVATIVE VALUES ONLY (LARGER SPECIMENS)

REG (WC)(AC) : 1.14 - TABLES A12 & A24

EXS (AC) : 1.27 - TABLES A10 & A22

REG (AC : 1.74 - TABLES A9 & A21

EXS (WC)(AC) : 1.83 - TABLES A13 & A25

PUM (AC) : 2.92 - TABLES A11 & A23

EXS (SC)(AC) : 2.94 - TABLES A16 & A28

REG (SC)(AC) : 3.30 - TABLES A15 & A27

PUM (WC)(AC) : 3.39 - TABLES A14 & A26

PUM (SC)(AC) : 4.13 - TABLES A17 & A29

PRE - IMMPREG. EXS (SC)(AC) : 5.25 - TABLES A18 & A30
PRE - IMMPREG. PUM (SC)(AC) : 7.82 - TABLES A19 & A31

TABLE A31-S SHEET 2
% DD IN SPECIMENS - SUMMARY OF TABLE A9 TO A31
CONSERVATIVE VALUES ONLY (LARGER SPECIMENS)

EXS (AC) : 0.96 - TABLES A10 & A22

REG (AC) : 1.19 - TABLES A9 & A21

REG (WC)(AC) : 1.21 - TABLES A12 & A24

EXS (WC)(AC) : 1.47 - TABLES A12 & A25

PUM (AC) : 1.72 - TABLES A11 & A23

EXS (SC)(AC) : 1.64 - TABLES A16 & A28

PUM (SC)(AC) : 2.25 - TABLES A17 & A29

REG (SC)(AC) : 2.41 - TABLES A15 & A27

PUM (WC)(AC) : 2.58 - TABLES A14 & A26

PRE - IMMPREG. EXS (SC)(AC) : 6.53 - TABLES A18 & A30
PRE - IMMPREG. PUM (SC)(AC) : 10.6 - TABLES A19 & A31

TABLE A31-S SHEET 3
% PEG IN SPECIMENS - SUMMARY OF TABLE A9 TO A31
CONSERVATIVE VALUES ONLY (LARGER SPECIMENS)

EXS (AC) : 1.19 - TABLES A10 & A22

REG (WC)(AC) : 1.48 - TABLES A12 & A24

REG (AC) : 1.56 - TABLES A9 & A21

EXS (WC)(AC) : 2.01 - TABLES A13 & A25

PUM (AC) : 2.76 - TABLES A11 & A23

EXS (SC)(AC) : 3.02 - TABLES A16 & A28

REG (SC)(AC) : 3.35 - TABLES A15 & A27

PUM (WC)(AC) : 3.43 - TABLES A14 & A26

PUM (SC)(AC) : 3.91 - TABLES A17 & A29

PRE - IMMPREG. EXS (SC)(AC) : 6.26 - TABLES A18 & A30
PRE - IMMPREG. PUM (SC)(AC) : 18.41 - TABLES A19 & A31

TABLE A32 SHEET 1

PCM IMPREGNATION PROCEDURE: 10/5/89 - 12/6/89, PCM: PAR (UNICERE 62)
CONCRETE: MATURE SPECIMENS, MINIMUM AGE 8 MONTHS
IMMERSION DATA TIMES: 1st - 20 MIN. AT 90°C, 2ND - SPECIMENS 233-238: 270 MIN. AT 80°C,
SPECIMENS 239 - 245: 120 MIN. AT 110°C, 3RD - 120 MIN. AT 130-140°C

SPECIMEN NO.	CONCRETE	INIT. WT. g	1st IMMERSION			2ND IMMERSION			3RD IMMERSION			TOTAL GAIN	
			FINAL WEIGHT	GAIN		FINAL WEIGHT	GAIN		FINAL WEIGHT	GAIN		g	%*
			g	g	%	g	g	%	g	g	%		
233	REG	321.53	333.19	11.66	3.63	336.80	3.61	1.08	342.85	6.05	1.80	21.32	6.63
234	REG	285.46	297.29	11.83	4.14	300.21	2.92	0.98	305.84	5.63	1.88	20.38	7.14
235	REG	296.40	305.40	9.00	3.04	309.09	3.69	1.21	315.16	6.07	1.96	18.76	6.33
236	ABL	229.32	245.50	16.18	7.06	246.98	1.48	0.60	248.90	1.92	0.78	19.58	8.54
237	ABL	178.89	191.80	12.91	7.22	193.10	1.30	0.68	194.90	1.80	0.93	16.01	8.95
238	ABL	183.05	195.30	12.25	6.69	196.95	1.65	0.84	197.99	1.04	0.53	13.94	8.16
239	PUM	130.81	141.14	10.33	7.90	144.29	3.15	2.23	144.61	0.32	0.22	13.80	10.55
240	PUM	84.19	89.29	5.10	6.06	91.29	2.00	2.24	91.02	-	-	7.10	8.43
241	PUM	133.54	144.18	10.64	7.97	149.23	5.05	3.50	149.23	-	-	15.69	11.75
242	OPC(3%EA)	359.68	364.11	4.43	1.23	368.89	4.78	1.31	368.90	-	-	9.21	2.56
243	OPC(3%EA)	323.99	327.65	3.66	1.13	329.30	1.65	0.50	329.52	0.22	0.07	5.53	1.71
244 **	OPC(3%EA)	336.30	340.80	4.50	1.34	345.28	4.48	1.31	345.79	0.51	0.15	9.49	2.82
245	REG	140.61	146.29	5.68	4.04	150.51	4.22	2.88	150.82	0.31	0.22	10.21	7.26

* BASED ON INITIAL WEIGHT
** WITH 5% ETHANOL WETTING AGENT ON 1ST IMMERSION

TABLE A32 - SHEET 2
AVERAGES FOR TABLE A32 - SHEET 1 PCM:PAR

SPECIMEN No.	CONCRETE	INITIAL WT. 9	INCREASE OVER INITIAL WEIGHT %			
			1st IMMERSION 20 MIN.	2nd IMMERSION 270 MIN.	3rd IMMERSION 120 MIN.	
233	REG	321.53	3.63	4.75	6.63	
234	REG	285.46	4.14	5.17	7.14	
235	REG	296.40	3.04	4.28	6.33	
AVG 233-235	REG	----	3.60	4.73	6.70	

SPECIMEN No.	PCM	INITIAL WT. 9	INCREASE OVER INITIAL WEIGHT %			
			1st IMMERSION 20 MIN.	2nd IMMERSION 270 MIN.	3rd IMMERSION 120 MIN.	
236	ABL	229.32	7.06	7.70	8.54	
237	ABL	178.89	7.22	7.94	8.95	
238	ABL	183.05	6.69	7.59	8.16	
AVG 236-238	ABL	----	6.99	7.74	8.55	

SPECIMEN No.	PCM	INITIAL WT. 9	INCREASE OVER INITIAL WEIGHT %			
			1st IMMERSION 20 MIN.	2nd IMMERSION 270 MIN	3rd IMMERSION 120 MIN.	
239	PUM	130.81	7.90	10.3	10.55	
240	PUM	84.19	6.06	8.43	8.11	
241	PUM	133.54	7.97	11.7	11.75	
AVG 239-241	PUM	----	7.31	10.14	10.14	

TABLE A32 - SHEET 3- AVERAGES FOR TABLE A32 - SHEET 1 PCM:PAR

SPECIMEN No.	PCM	INITIAL WT. 9	INCREASE OVER INITIAL WEIGHT %			
			1st immersion 20 min.	2nd immersion 270 min	3rd immersion 120 min	4th immersion
242	OPC	359.68	1.23	2.56	2.56	
243	OPC	323.99	1.13	1.64	1.71	
244	OPC	336.30	1.34	2.67	2.82	
AVG 242-244	OPC	----	1.23	2.29	2.36	

TABLE A33 SHEET 1

PCM IMPREGNATION PROCEDURE 23/5/89 - 8/6/89, REG. AGGREGATE, LOW ALKALI TYPE 10 CEMENT WITH SILICA FUME AND FLY ASH, CONCRETE MIXED 17/4/89, STEAM CURED 17/4/39 - 18/4/89, AIR CURED 18/4/89 -18/5/89, 22.5% ENTRAINED AIR,
IMMERSION TIMES: 1st - 30 MIN., 2nd - 30 MIN., 3rd - 60 MIN, 4th - 300 MIN, PCM TEMP. 80°C, SPECIMEN TEMP. 20°C

SPECIMEN NO.	PCM	INIT. WT. g	1st IMMERSION			2ND IMMERSION			3RD IMMERSION			4TH IMMERSION			TOTAL GAIN	
			FINAL WEIGHT g	GAIN		FINAL WEIGHT g	GAIN		FINAL WEIGHT g	GAIN		FINAL WEIGHT g	GAIN		g	%*
				g	%		g	%		g	%		g	%		
246	BS	131.57	135.82	4.25	3.23	137.11	1.29	0.95	138.00	0.89	0.65	138.65	0.65	0.47	7.08	5.38
247	BS	127.17	131.14	3.97	3.12	132.45	1.31	1.00	133.50	1.05	0.79	134.20	0.70	0.52	7.03	5.53
248	BS	127.50	131.66	4.16	3.26	132.90	1.24	0.94	133.91	1.01	0.76	134.31	0.40	0.30	6.81	5.34
249	DD	129.25	132.31	3.06	2.37	133.52	1.21	0.91	134.25	0.73	0.55	135.24	0.99	0.74	5.99	4.63
250	DD	129.50	133.09	3.59	2.77	133.90	0.81	0.61	134.47	0.57	0.43	134.84	0.37	0.28	5.34	4.12
251	DD	126.71	130.46	3.75	2.96	131.33	0.92	0.71	132.00	0.62	0.47	132.65	0.65	0.49	5.94	4.69
252	PEG	129.19	135.83	6.64	5.14	137.30	1.47	1.08	138.20	0.90	0.66	139.64	1.44	1.04	10.45	8.09
253	PEG	133.57	138.57	5.00	3.74	140.60	2.03	1.46	141.95	1.35	0.96	144.05	2.10	1.48	10.48	7.85
254	PEG	130.20	137.64	7.44	5.71	138.75	1.11	0.81	139.25	0.50	0.36	141.04	1.79	1.29	10.84	8.33

* BASED ON INITIAL WEIGHT

TABLE A33 SHEET 2
AVERAGES FOR TABLE A33 SHEET 1
REG/LA/SF/FA/SC/AC, 22.5% EA

SPECIMEN No.	PCM	INITIAL WT. 9	INCREASE OVER INITIAL WEIGHT %			
			1st IMMERSION 30 MIN.	2nd IMMERSION 30 MIN.	3rd IMMERSION 60 MIN.	4th IMMERSION 300 MIN.
246	BS	131.57	3.23	4.21	4.89	5.38
247	BS	127.17	3.21	4.15	4.98	5.53
248	BS	127.50	3.26	4.24	5.03	5.34
AVG 246-248	BS	———	3.20	4.20	4.97	5.42

SPECIMEN No.	PCM	INITIAL WT. 9	INCREASE OVER INITIAL WEIGHT %			
			1st IMMERSION 30 MIN.	2nd IMMERSION 30 MIN.	3rd IMMERSION 60 MIN.	4th IMMERSION 300 MIN.
249	DD	129.25	2.37	3.30	3.87	4.63
250	DD	129.50	2.77	3.39	3.67	4.12
251	DD	126.71	2.96	3.69	4.17	4.69
AVG 249-251	DD	———	2.70	3.46	3.90	4.48

SPECIMEN No.	PCM	INITIAL WT. 9	INCREASE OVER INITIAL WEIGHT %			
			1st IMMERSION 30 MIN.	2nd IMMERSION 30 MIN.	3rd IMMERSION 60 MIN.	4th IMMERSION 300 MIN.
252	PEG	129.19	5.14	6.28	6.97	8.09
253	PEG	133.57	3.74	5.26	6.27	7.85
254	PEG	130.20	5.71	6.57	6.95	8.33
AVG 252-254	PEG	———	4.86	6.04	6.73	8.09

TABLE A34 SHEET 1

PCM IMPREGNATION PROCEDURE 23/5/89 - 12/6/89, REG. AGGREGATE, LOW ALKALI TYPE 10 CEMENT WITH SILICA FUME AND FLY ASH,
CONCRETE MIXED 17/4/89, STEAM CURED 17/4/89 - 18/4/89, WATER CURED 18/4/89 -18/5/89, 22.5% ENTRAINED AIR,
IMMERSION TIMES: 1st - 30 MIN., 2nd - 180 MIN., 3rd - 60 MIN., 4th - 300 MIN, PCM TEMP. 80°C, SPECIMEN TEMP. 20°C

SPECIMEN NO.	PCM	INIT. WT. g	1st IMMERSION			2ND IMMERSION			3RD IMMERSION			4TH IMMERSION			TOTAL GAIN	
			FINAL WEIGHT g	GAIN		FINAL WEIGHT g	GAIN		FINAL WEIGHT g	GAIN		FINAL WEIGHT g	GAIN		g	%*
				g	%		g	%		g	%		g	%		
255	BS	132.94	136.04	3.10	2.33	137.10	1.06	0.78	137.20	0.10	0.07	137.35	0.15	0.11	4.41	3.32
256	BS	130.45	133.50	3.05	2.34	134.70	1.20	0.90	134.80	0.10	0.07	135.08	0.28	0.21	4.63	3.55
257	BS	132.70	135.65	2.95	2.22	136.55	0.90	0.66	136.55	-	-	136.80	0.25	0.18	4.10	3.09
258	DD	131.90	134.16	2.26	1.71	135.50	1.34	1.00	135.90	0.40	0.30	136.01	0.11	0.08	4.11	3.12
259	DD	133.12	135.45	2.33	1.75	136.75	1.30	0.96	137.10	0.35	0.26	137.31	0.21	0.15	4.19	3.15
260	DD	134.34	136.59	2.25	1.67	137.81	1.22	0.89	138.20	0.39	0.28	138.36	0.16	0.12	4.02	2.99
261	PEG	128.29	133.10	4.81	3.75	135.10	2.00	1.50	135.52	0.42	0.31	136.62	1.10	0.09	8.33	6.49
262	PEG	131.45	135.50	4.05	3.08	137.30	1.80	1.33	137.80	0.50	0.36	138.70	0.90	0.65	7.25	5.52
263	PEG	131.40	135.82	4.42	3.36	137.76	1.94	1.43	137.92	0.16	0.12	139.00	1.08	0.78	7.60	5.78

* BASED ON INITIAL WEIGHT

TABLE A34 SHEET 2
AVERAGES FOR TABLE A34 SHEET 1
REG/LA/SF/FA/SC/WC, 22.5% EA

SPECIMEN No.	PCM	INITIAL WT. 9	INCREASE OVER INITIAL WEIGHT %			
			1st IMMERSION 30 MIN.	2nd IMMERSION 180 MIN	3rd IMMERSION 60 MIN.	4th IMMERSION 300 MIN.
255	BS	132.94	2.33	3.13	3.20	3.32
256	BS	130.45	2.34	3.26	3.33	3.55
257	BS	132.70	2.22	2.90	2.90	3.09
AVG 255-257	BS	——	2.30	3.09	3.14	3.32

SPECIMEN No.	PCM	INITIAL WT. 9	INCREASE OVER INITIAL WEIGHT %			
			1st IMMERSION 30 MIN.	2nd IMMERSION 180 MIN	3rd IMMERSION 60 MIN.	4th IMMERSION 300 MIN.
258	DD	131.90	1.71	2.73	3.03	3.12
259	DD	133.12	1.75	2.73	2.99	3.15
260	DD	134.34	1.67	2.58	2.87	2.99
AVG 258-260	DD	——	1.71	2.68	2.96	3.09

SPECIMEN No.	PCM	INITIAL WT. 9	INCREASE OVER INITIAL WEIGHT %			
			1st IMMERSION 30 MIN.	2nd IMMERSION 180 MIN.	3rd IMMERSION 60 MIN.	4th IMMERSION 300 MIN.
261	PEG	128.29	3.75	5.31	5.64	6.49
262	PEG	131.45	3.08	4.45	4.33	5.52
263	PEG	131.40	3.36	4.84	4.96	5.78
AVG 251-263	PEG	——	3.40	4.97	5.14	5.93

TABLE A35 SHEET 1

PCM IMPREGNATION PROCEDURE 29/5/89 - 13/6/89, REG. AGGREGATE, LOW ALKALI TYPE 10 CEMENT WITH SILICA FUME AND FLY ASH, CONCRETE MIXED 18/4/89, STEAM CURED 18/4/89 - 19/4/89, AIR CURED 19/4/89 -29/5/89, 4.5% ENTRAINED AIR, IMMERSION TIMES: 1st - 30 MIN., 2nd - 30 MIN., 3rd - 60 MIN, 4th - 300 MIN, PCM TEMP. 80°C, SPECIMEN TEMP. 20°C

SPECIMEN NO.	PCM	INIT. WT. g	1st IMMERSION			2ND IMMERSION			3RD IMMERSION			4TH IMMERSION			TOTAL GAIN	
			FINAL WEIGHT g	GAIN g	GAIN %	FINAL WEIGHT g	GAIN g	GAIN %	FINAL WEIGHT g	GAIN g	GAIN %	FINAL WEIGHT g	GAIN g	GAIN %	g	%*
264	BS	165.33	168.65	3.32	2.01	169.25	0.60	0.36	169.60	0.35	0.21	170.05	0.45	0.27	4.72	2.85
265	BS	169.05	172.49	3.44	2.03	173.00	0.51	0.30	173.00	-	-	173.40	0.40	0.23	4.35	2.5[illegible]
266	BS	163.76	166.85	3.09	1.89	167.54	0.69	0.41	167.54	-	-	168.09	0.55	0.33	4.33	2.64
267	DD	161.44	163.88	2.44	1.51	164.40	0.52	0.32	164.40	-	-	164.96	0.56	0.34	3.52	2.18
268	DD	166.50	169.50	2.55	1.53	169.60	0.55	0.33	169.75	0.15	0.09	170.40	0.65	0.38	3.90	2.34
269	DD	155.84	158.31	2.47	1.58	158.72	0.41	0.26	158.72	-	-	159.23	0.51	0.32	3.39	2.18
270	PEG	165.05	169.13	4.08	2.47	170.34	1.21	0.72	170.75	0.41	0.24	171.65	0.90	0.53	6.60	4.00
271	PEG	158.98	163.77	4.79	3.01	164.62	0.85	0.52	165.00	0.38	0.23	165.51	0.51	0.31	6.53	4.11
272	PEG	159.43	163.40	3.97	2.49	164.20	0.80	0.49	164.60	0.40	0.24	165.34	0.74	0.45	5.91	3.71
273	TD	162.00	164.50	2.50	1.54	164.96	0.46	0.28	165.13	0.17	0.10	165.30	0.17	0.10	3.30	2.04
274	TD	162.60	165.13	2.53	1.56	165.46	0.33	0.20	165.60	0.14	0.08	165.94	0.34	0.21	3.34	2.05
275	TD	164.71	167.21	2.50	1.52	167.79	0.58	0.35	167.85	0.06	0.04	168.30	0.45	0.27	3.59	2.18

* BASED ON INITIAL WEIGHT

TABLE A35 SHEET 2
AVERAGES FOR TABLE A35 SHEET 1
REG/LA/SF/FA/SC/AC, 4.5% EA

SPECIMEN No.	PCM	INITIAL WT. 9	INCREASE OVER INITIAL WEIGHT %			
			1st IMMERSION 30 MIN.	2nd IMMERSION 30 MIN.	3rd IMMERSION 60 MIN.	4th IMMERSION 300 MIN.
264	BS	165.33	2.01	2.37	2.58	2.85
265	BS	169.05	2.03	2.34	2.34	2.57
266	BS	163.76	1.89	2.31	2.31	2.64
AVG 264-266	BS	———	1.98	2.34	2.41	2.69

SPECIMEN No.	PCM	INITIAL WT. 9	INCREASE OVER INITIAL WEIGHT %			
			1st IMMERSION 30 MIN.	2nd IMMERSION 30 MIN.	3rd IMMERSION 60 MIN.	4th IMMERSION 300 MIN.
267	DD	161.44	1.51	1.83	1.83	2.18
268	DD	166.50	1.53	1.86	1.95	2.34
269	DD	155.84	1.58	1.85	1.85	2.18
AVG 267-269	DD	———	1.54	1.85	1.88	2.23

SPECIMEN No.	PCM	INITIAL WT. 9	INCREASE OVER INITIAL WEIGHT %			
			1st IMMERSION 30 MIN.	2nd IMMERSION 20 MIN.	3rd IMMERSION 60 MIN.	4th IMMERSION 300 MIN.
270	PEG	165.05	2.47	3.21	3.45	4.00
271	PEG	158.98	3.01	3.55	3.79	4.11
272	PEG	159.43	2.49	2.99	3.24	3.71
AVG 270-272	PEG	———	2.49	3.25	3.49	3.94

.../2

TABLE A35 SHEET 3
AVERAGES FOR TABLE A35 SHEET 1
REG/LA/SF/FA/SC/AC, 4.5% EA

SPECIMEN No.	PCM	INITIAL WT. g	INCREASE OVER INITIAL WEIGHT %			
			1st IMMERSION 30 MIN.	2nd IMMERSION 30 MIN.	3rd IMMERSION 60 MIN.	4th IMMERSION 300 MIN.
273	TD	162.00	1.54	1.83	1.93	2.04
274	TD	162.60	1.56	1.76	1.84	2.05
275	TD	164.71	1.52	1.87	1.91	2.18
AVG 273-275	TD	——	1.54	1.82	1.89	2.09

TABLE A36 SHEET 1

PCM IMPREGNATION PROCEDURE 29/5/89 - 14/6/89; REG. AGGREGATE, LOW ALKALI TYPE 10 CEMENT WITH SILICA FUME AND FLY ASH, CONCRETE MIXED 18/4/89, STEAM CURED 18/4/89 - 19/4/89, WATER CURED 19/4/89 -19/5/89, 4.5% ENTRAINED AIR, IMMERSION TIMES: 1st - 30 MIN., 2nd - 30 MIN., 3rd - 60 MIN, 4th - 300 MIN, PCM TEMP. 80°C, SPECIMEN TEMP. 20°C

SPECIMEN NO.	PCM	INIT. WT. g	1st IMMERSION			2ND IMMERSION			3RD IMMERSION			4TH IMMERSION			TOTAL GAIN	
			FINAL WEIGHT	GAIN		FINAL WEIGHT	GAIN		FINAL WEIGHT	GAIN		FINAL WEIGHT	GAIN		g	%*
			g	g	%	g	g	%	g	g	%	g	g	%		
276	BS	163.10	164.83	1.73	1.06	165.20	0.37	0.22	165.42	0.22	0.13	165.50	0.08	0.05	2.40	1.47
277	BS	164.81	166.55	1.74	1.06	166.80	0.25	0.15	166.90	0.10	0.06	167.21	0.31	0.19	2.40	1.46
278	BS	171.01	172.89	1.88	1.10	173.18	0.29	0.17	173.30	0.12	0.07	173.51	0.21	0.12	2.50	1.46
279	DD	162.28	163.97	1.69	1.04	164.24	0.27	0.16	164.35	0.11	0.07	164.45	0.10	0.06	2.17	1.34
280	DD	174.85	176.46	1.61	0.92	176.81	0.35	0.20	177.15	0.34	0.19	177.38	0.23	0.13	2.53	1.45
281	DD	163.33	164.95	1.62	0.99	165.20	0.25	0.15	165.20	-	-	165.50	0.30	0.18	2.17	1.33
282	PEG	187.25	190.25	3.00	1.60	191.03	0.78	0.41	191.53	0.50	0.26	193.04	1.51	0.79	5.79	3.09
283	PEG	180.50	183.05	2.55	1.41	183.80	0.75	0.41	184.15	0.35	0.19	185.40	1.25	0.68	4.90	2.71
284	PEG	170.11	172.40	2.29	1.35	173.00	0.60	0.35	173.30	0.30	0.17	174.45	1.15	0.66	4.34	2.55
285	TD	162.00	163.41	1.41	0.87	163.70	0.29	0.18	163.82	0.12	0.07	164.14	0.32	0.20	2.14	1.32
286	TD	165.61	167.20	1.59	0.96	167.50	0.30	0.18	167.61	0.11	0.07	167.90	0.29	0.17	2.17	1.31
287	TD	171.90	173.59	1.69	0.98	173.81	0.22	0.13	173.96	0.15	0.09	174.30	0.34	0.20	2.40	1.40

* BASED ON INITIAL WEIGHT

TABLE A36 SHEET 2
AVERAGES FOR TABLE A36 SHEET 1
REG/LA/SF/FA/SC/WC, 4.5% EA

SPECIMEN No.	PCM	INITIAL WT. 9	INCREASE OVER INITIAL WEIGHT %			
			1st IMMERSION 30 MIN.	2nd IMMERSION 30 MIN.	3rd IMMERSION 60 MIN.	4th IMMERSION 300 MIN.
276	BS	163.10	1.06	1.29	1.42	1.47
277	BS	164.81	1.06	1.21	1.27	1.46
278	BS	171.01	1.10	1.27	1.34	1.46
AVG 276-278	BS	———	1.07	1.26	1.34	1.46

SPECIMEN No.	PCM	INITIAL WT. 9	INCREASE OVER INITIAL WEIGHT %			
			1st IMMERSION 30 MIN.	2nd IMMERSION 30 MIN.	3rd IMMERSION 60 MIN.	4th IMMERSION 300 MIN.
279	DD	162.28	1.04	1.21	1.28	1.34
280	DD	174.85	0.92	1.12	1.32	1.45
281	DD	163.33	0.99	1.14	1.14	1.33
AVG 279-281	DD	———	0.98	1.16	1.25	1.37

SPECIMEN No.	PCM	INITIAL WT. 9	INCREASE OVER INITIAL WEIGHT %			
			1st IMMERSION 30 MIN.	2nd IMMERSION 20 MIN.	3rd IMMERSION 60 MIN.	4th IMMERSION 300 MIN.
282	PEG	187.25	1.60	2.02	2.29	3.09
283	PEG	180.50	1.41	1.83	2.02	2.71
284	PEG	170.11	1.35	1.69	1.88	2.55
AVG 282-284	PEG	———	1.45	1.85	2.06	2.78

TABLE A36 SHEET 3
AVERAGES FOR TABLE A36 SHEET 2
REG/LA/SF/FA/SC/MC, 4.5% EA

SPECIMEN No.	PCM	INITIAL WT. g	INCREASE OVER INITIAL WEIGHT %			
			1st IMMERSION 30 MIN.	2nd IMMERSION 30 MIN.	3rd IMMERSION 60 MIN.	4th IMMERSION 300 MIN.
285	TD	162.00	0.87	1.05	1.12	1.32
283	TD	165.61	0.96	1.14	1.21	1.31
284	TD	171.90	0.98	1.11	1.20	1.40
AVG 285-297	TD	——	0.94	1.10	1.18	1.34

TABLE A37 SHEET 1

PCM IMPREGNATION PROCEDURE: 31/5/89 - 15/6/89, PUMICE AGGREGATE, LOW ALKALI TYPE 10 CEMENT WITH SILICA FUME AND FLY ASH, CONCRETE MIXED 25/4/89, STEAM CURED 25/4/89 - 26/4/89, AIR CURED 26/4/89 - 31/5/89, 28.5% ENTRAINED AIR, IMMERSION TIMES: 1ST - 60 MIN., 2ND - 60 MIN., 3RD - 240 MIN.**, 4TH - 240 MIN.**, PCM TEMP. - 80°C, SPECIMEN TEMP. - 20°C

SPECIMEN NO.	PCM	INIT. WT. g	1st IMMERSION			2ND IMMERSION			3RD IMMERSION			4TH IMMERSION			TOTAL GAIN	
			FINAL WEIGHT	GAIN		FINAL WEIGHT	GAIN		FINAL WEIGHT	GAIN		FINAL WEIGHT	GAIN		g	%*
			g	g	%	g	g	%	g	g	%	g	g	%		
288	BS	94.12	96.00	1.88	2.00	96.50	0.50	0.52	98.12	1.62	1.68	98.12	-	-	4.00	4.25
289	BS	93.76	95.80	2.04	2.18	96.25	0.45	0.47	98.00	1.75	1.82	98.00	-	-	4.24	4.52
290	BS	97.74	99.60	1.86	1.90	100.12	0.52	0.52	101.75	1.63	1.63	101.75	-	-	4.01	4.10
291	DD	96.86	98.72	1.86	1.92	99.00	0.28	0.28	100.35	1.35	1.36	100.35	-	-	3.49	3.60
292	DD	94.44	96.00	1.56	1.65	96.35	0.35	0.36	97.32	0.97	1.00	97.32	-	-	2.88	3.05
293	DD	96.41	98.02	1.61	1.67	98.40	0.38	0.39	99.55	1.15	1.17	99.55	-	-	3.14	3.26
294	PEG	93.89	96.25	2.36	2.51	97.00	0.75	0.80	98.55	1.55	1.60	98.55	-	-	4.66	4.96
295	PEG	97.22	99.71	2.49	2.56	100.52	0.81	0.81	102.22	1.70	1.69	102.22	-	-	5.00	5.14
296	PEG	102.26	104.78	2.52	2.46	105.38	0.60	0.57	106.70	1.32	1.25	106.70	-	-	4.44	4.34
297	TD	95.31	96.99	1.68	1.76	97.48	0.49	0.51	98.50	1.02	1.05	98.50	-	-	3.19	3.35
298	TD	92.58	94.24	1.66	1.79	94.60	0.36	0.38	95.58	0.98	1.04	95.58	-	-	3.00	3.24
299	TD	98.55	100.70	2.15	2.18	100.95	0.25	0.25	102.13	1.18	1.17	102.13	-	-	3.58	3.63

* BASED ON THE INITIAL WEIGHT
** PLUS OVERNIGHT SOAK IN COOLING PCM

TABLE A37 SHEET 2
AVERAGES FOR TABLE A37 SHEET 1
PUM/LA/SF/FA/SC/AC, 28.5% EA

SPECIMEN No.	PCM	INITIAL WT. 9	INCREASE OVER INITIAL WEIGHT %			
			1st IMMERSION 60 MIN.	2nd IMMERSION 60 MIN.	3rd IMMERSION 240 MIN.	4th IMMERSION 240 MIN.
288	BS	94.12	2.00	2.53	4.25	4.25
289	BS	93.76	2.18	2.66	4.52	4.52
290	BS	97.74	1.90	2.43	4.10	4.10
AVG 288-290	BS	———	2.03	2.54	4.29	4.29

SPECIMEN No.	PCM	INITIAL WT. 9	INCREASE OVER INITIAL WEIGHT %			
			1st IMMERSION 60 MIN.	2nd IMMERSION 60 MIN.	3rd IMMERSION 240 MIN.	4th IMMERSION 240 MIN.
291	DD	96.86	1.92	2.21	3.60	3.60
292	DD	94.44	1.65	2.02	3.05	3.05
293	DD	96.41	1.67	2.06	3.26	3.26
AVG 291-293	DD	———	1.75	2.10	3.30	3.30

SPECIMEN No.	PCM	INITIAL WT. 9	INCREASE OVER INITIAL WEIGHT %			
			1st IMMERSION 60 MIN.	2nd IMMERSION 60 MIN.	3rd IMMERSION 240 MIN.	4th IMMERSION 240 MIN.
294	PEG	93.89	2.51	3.31	4.96	4.96
295	PEG	97.22	2.56	3.39	5.14	5.14
296	PEG	102.26	2.46	3.05	4.34	4.34
AVG 294-296	PEG	———	2.51	3.25	4.81	4.81

TABLE A37 SHEET 3
AVERAGES FOR TABLE A37 SHEET 1
PUM/LA/SF/FA/SC/AC, 28.5% EA

SPECIMEN No.	PCM	INITIAL WT. 9	INCREASE OVER INITIAL WEIGHT %			
			1st IMMERSION 60 MIN.	2nd IMMERSION 60 MIN.	3rd IMMERSION 240 MIN.	4th IMMERSION 240 MIN.
297	TD	95.31	1.76	2.28	3.35	3.35
298	TD	92.58	1.79	2.18	3.24	3.24
299	TD	98.55	2.18	2.43	3.63	3.63
AVG 297-299	TD	——	1.91	2.30	3.41	3.41

TABLE A38 SHEET 1

PCM IMPREGNATION PROCEDURE: 31/5/89 - 19/6/89, PUMICE AGGREGATE, LOW ALKALI TYPE 10 CEMENT WITH SILICA FUME AND FLY ASH, CONCRETE MIXED 25/4/89, STEAM CURED 25/4/89 - 26/4/89, WATER CURED 26/4/89 - 26/5/89, 28.5% ENTRAINED AIR, IMMERSION TIMES: 1ST - 60 MIN., 2ND - 60 MIN., 3RD - 240 MIN.**, 4TH - 240 MIN.**, PCM. TEMP. 80°C, SPECIMEN TEMP. 20°C

SPECIMEN NO.	PCM	INIT. WT. g	1st IMMERSION			2ND IMMERSION			3RD IMMERSION			4TH IMMERSION			TOTAL GAIN	
			FINAL WEIGHT g	GAIN g	GAIN %	FINAL WEIGHT g	GAIN g	GAIN %	FINAL WEIGHT g	GAIN g	GAIN %	FINAL WEIGHT g	GAIN g	GAIN %	g	%*
300	BS	98.31	100.35	2.04	2.08	101.00	0.65	0.65	101.70	0.70	0.69	102.10	0.40	0.39	3.79	3.86
301	BS	100.07	102.10	2.03	2.03	103.00	0.90	0.88	103.70	0.70	0.68	104.10	0.40	0.39	4.03	4.03
302	BS	96.59	98.16	1.57	1.63	98.90	0.74	0.75	99.75	0.85	0.85	100.06	0.31	-	3.47	3.59
303	DD	99.21	100.73	1.52	1.53	101.40	0.67	0.67	101.40	-	-	101.40	-	-	2.19	2.21
304	DD	97.88	99.15	1.27	1.30	99.82	0.67	0.68	100.05	0.23	0.23	100.05	-	-	2.17	2.22
305	DD	98.31	99.65	1.34	1.36	100.58	0.93	0.93	100.58	-	-	100.58	-	-	2.27	2.31
306	PEG	93.34	95.39	2.05	2.20	96.65	1.26	1.32	97.24	0.59	0.61	97.40	-	-	3.90	4.18
307	PEG	94.58	96.50	1.92	2.03	97.70	1.20	1.24	98.10	0.40	0.41	93.10	-	-	3.52	3.72
308	PEG	92.51	94.70	2.19	2.37	95.90	1.20	1.27	96.30	0.40	0.42	96.40	0.10		3.79	4.10
309	TD	98.80	100.12	1.32	1.37	100.70	0.58	0.58	100.70	-	-	100.70	-	-	1.90	1.92
310	TD	92.90	94.21	1.31	1.41	94.80	0.59	0.63	95.20	0.40	0.42	95.20	-	-	2.30	2.48
311	TD	98.78	100.10	1.32	1.34	100.92	0.82	0.82	100.92	-	-	100.92	-	-	2.14	2.17

* BASED ON THE INITIAL WEIGHT

** PLUS OVERNIGHT SOAK IN COOLING PCM

TABLE A38 SHEET 2
AVERAGES FOR TABLE A38 SHEET 1
PUM/LA/SF/SF/FA/SC/MC, 28.5% EA

SPECIMEN No.	PCM	INITIAL WT. g	INCREASE OVER INITIAL WEIGHT %			
			1st IMMERSION 60 MIN.	2nd IMMERSION 60 MIN.	3rd IMMERSION 240 MIN.	4th IMMERSION 240 MIN.
300	BS	98.31	2.08	2.74	3.45	3.86
301	BS	100.07	2.03	2.93	3.63	4.03
302	BS	96.59	1.63	2.39	3.27	3.59
AVG 300-302	BS	———	1.91	2.69	3.45	3.83

SPECIMEN No.	PCM	INITIAL WT. g	INCREASE OVER INITIAL WEIGHT %			
			1st IMMERSION 60 MIN.	2nd IMMERSION 60 MIN.	3rd IMMERSION 240 MIN.	4th IMMERSION 240 MIN.
303	DD	99.21	1.53	2.21	2.21	2.21
304	DD	97.89	1.30	1.98	2.22	2.22
305	DD	98.31	1.36	2.31	2.31	2.31
AVG 203-305	DD	———	1.40	2.17	2.25	2.25

SPECIMEN No.	PCM	INITIAL WT. g	INCREASE OVER INITIAL WEIGHT %			
			1st IMMERSION 60 MIN.	2nd IMMERSION 60 MIN.	3rd IMMERSION 240 MIN.	4th IMMERSION 240 MIN.
306	PEG	93.34	2.20	3.55	4.18	4.18
307	PEG	94.58	2.03	3.29	3.72	3.72
308	PEG	92.51	2.37	3.66	4.10	4.10
AVG 306-308	PEG	———	2.20	3.50	4.00	4.00

TABLE A38 SHEET 3
AVERAGES FOR TABLE A38 SHEET 1
PUM/LA/SF/FA/SC/WC, 28.5% EA

SPECIMEN No.	PCM	INITIAL WT. g	INCREASE OVER INITIAL WEIGHT %			
			1st IMMERSION 60 MIN.	2nd IMMERSION 60 MIN.	3rd IMMERSION 240 MIN.	4th IMMERSION 240 MIN.
309 310 311	TD TD TD	98.80 92.90 98.78	1.37 1.41 1.34	1.92 2.04 2.17	1.92 2.48 2.17	1.92 2.48 2.17
AVG 309-311	TD	———	1.37	2.04	2.19	2.19

TABLE A39 SHEET 1

PCM IMPREGNATION PROCEDURE: 1/6/89 - 14/6/89, PUMICE AGGREGATE, LOW ALKALI TYPE 10 CEMENT WITH
SILICA FUME AND FLY ASH, CONCRETE MIXED 24/4/89, STEAM CURED 24/4/89 - 25/4/89, AIR CURED 25/4/89 - 1/6/89,
14.2% ENTRAINED AIR, IMMERSION TIMES: 1ST - 60 MIN., 2ND - 60 MIN., 3RD - 240 MIN.**,
4TH - 240 MIN.**, PCM. TEMP. 80°C, SPECIMEN TEMP. 20°C

SPECIMEN NO.	PCM	INIT. WT. g	1st IMMERSION			2ND IMMERSION			3RD IMMERSION			4TH IMMERSION			TOTAL GAIN	
			FINAL WEIGHT g	GAIN g	GAIN %	FINAL WEIGHT g	GAIN g	GAIN %	FINAL WEIGHT g	GAIN g	GAIN %	FINAL WEIGHT g	GAIN g	GAIN %	g	%*
312	BS	108.50	112.74	4.24	3.91	113.10	0.36	0.32	114.67	1.57	1.39	115.14	0.47	0.41	6.64	5.89
313	BS	106.90	111.05	4.15	3.88	111.90	0.85	0.77	113.34	1.44	1.29	113.80	0.46	0.41	6.90	6.45
314	BS	108.19	111.40	3.21	2.97	112.05	0.65	0.58	113.25	1.20	1.07	113.50	0.25	0.22	5.31	4.91
315	DD	109.04	111.99	2.95	2.71	112.55	0.56	0.50	113.75	1.20	1.07	113.85	0.10	0.09	4.81	4.41
316	DD	110.16	113.50	3.34	3.03	114.04	0.54	0.48	115.15	1.11	0.97	115.25	0.10	0.09	5.09	4.62
317	DD	103.00	105.95	2.95	2.86	106.46	0.51	0.48	107.50	1.04	0.98	107.60	0.10	0.09	4.60	4.47
318	PEG	108.41	113.23	4.82	4.45	114.48	1.25	1.10	116.00	1.52	1.33	116.65	0.65	0.56	8.24	7.60
319	PEG	107.84	113.05	5.21	4.83	114.36	1.31	1.16	116.09	1.75	1.73	116.69	0.60	0.52	8.87	8.23
320	PEG	107.20	112.45	5.25	4.90	113.71	1.26	1.12	115.01	1.30	1.14	115.73	0.72	0.63	8.53	7.96
321	TD	105.96	108.84	2.88	2.72	109.44	0.60	0.55	110.50	1.06	0.97	110.55	0.05	0.05	4.59	4.33
322	TD	109.50	112.10	2.60	2.37	112.65	0.55	0.49	113.73	1.08	0.96	113.76	0.03	0.03	4.26	3.89
323	TD	107.74	111.16	3.42	3.17	111.80	0.64	0.58	112.96	1.16	1.04	113.20	0.24	0.21	5.46	5.07

* BASED ON THE INITIAL WEIGHT
** PLUS OVERNIGHT SOAK IN COOLING PCM

Note: beneficial effects of 5 hours heat soak prior to first immersion

TABLE A39 SHEET 2
AVERAGES FOR TABLE A39 SHEET 1
PUM/LA/SF/FA/SC/AC, 14.2% EA

SPECIMEN No.	PCM	INITIAL WT. g	INCREASE OVER INITIAL WEIGHT %			
			1st IMMERSION 60 MIN.	2nd IMMERSION 60 MIN.	3rd IMMERSION 240 MIN.	4th IMMERSION 240 MIN.
312	BS	108.50	3.91	4.24	5.69	5.89
313	BS	106.90	3.88	4.58	6.02	6.45
314	BS	108.19	2.97	3.57	4.68	4.91
AVG	BS	——	3.59	4.16	5.46	5.75

SPECIMEN No.	PCM	INITIAL WT. g	INCREASE OVER INITIAL WEIGHT %			
			1st IMMERSION 60 MIN.	2nd IMMERSION 60 MIN.	3rd IMMERSION 240 MIN.	4th IMMERSION 240 MIN.
315	DD	109.04	2.71	3.22	4.32	4.41
316	DD	110.16	3.03	3.52	4.53	4.62
317	DD	103.00	2.86	3.36	4.37	4.47
AVG	DD	——	2.87	3.37	4.41	4.50

SPECIMEN No.	PCM	INITIAL WT. g	INCREASE OVER INITIAL WEIGHT %			
			1st IMMERSION 60 MIN.	2nd IMMERSION 60 MIN.	3rd IMMERSION 240 MIN.	4th IMMERSION 240 MIN.
318	PEG	108.41	4.45	5.60	7.00	7.60
319	PEG	107.84	4.83	6.04	7.65	8.23
320	PEG	107.20	4.90	6.07	7.29	7.96
AVG	PEG	——	4.73	5.90	7.31	7.93

SPECIMEN No.	PCM	INITIAL WT. g	INCREASE OVER INITIAL WEIGHT %			
			1st IMMERSION 60 MIN.	2nd IMMERSION 60 MIN.	3rd IMMERSION 240 MIN.	4th IMMERSION 240 MIN.
321	TD	105.96	2.72	3.28	4.28	4.33
322	TD	109.50	2.37	2.88	3.86	3.89
323	TD	107.74	3.17	3.77	4.84	5.07
AVG	TD	——	2.75	3.31	4.33	4.43

TABLE A40 SHEET 1

PCM IMPREGNATION PROCEDURE: 1/6/89 - 15/6/89, PUMICE AGGREGATE, LOW ALKALI TYPE 10 CEMENT WITH SILICA FUME AND FLY ASH, CONCRETE MIXED 24/4/89, STEAM CURED 24/4/89 - 25/4/89, WATER CURED 25/4/89 - 26/5/89, 14.2% ENTRAINED AIR, IMMERSION TIMES: 1ST - 60 MIN., 2ND - 120 MIN., 3RD - 240 MIN.**, 4TH - 240 MIN.**, PCM. TEMP. 80°C, SPECIMEN TEMP. 20°C

SPECIMEN NO.	PCM	INIT. WT. g	1st IMMERSION			2ND IMMERSION			3RD IMMERSION			4TH IMMERSION			TOTAL GAIN	
			FINAL WEIGHT	GAIN		FINAL WEIGHT	GAIN		FINAL WEIGHT	GAIN		FINAL WEIGHT	GAIN		g	%*
			g	g	%	g	g	%	g	g	%	g	g	%		
324	BS	114.44	117.91	3.47	3.03	118.40	0.49	0.42	119.79	1.39	1.17	120.05	0.26	0.22	5.61	4.90
325	BS	107.82	111.65	3.83	3.55	112.27	0.62	0.56	113.53	1.26	1.12	113.87	0.34	0.30	6.05	5.61
326	BS	109.10	112.10	3.00	2.75	112.40	0.30	0.28	113.52	1.12	1.00	113.76	0.24	0.21	4.66	4.27
327	DD	112.41	115.25	2.84	2.53	115.65	0.40	0.35	116.70	1.05	0.91	116.70	-	-	4.29	3.82
328	DD	112.65	115.27	2.62	2.33	115.54	0.27	0.23	116.36	0.82	0.71	116.49	0.13	0.11	3.84	3.41
329	DD	110.95	113.91	2.96	2.67	114.00	0.09	0.08	114.95	0.95	0.83	114.95	-	-	4.00	3.61
330	PEG	108.79	113.74	4.95	4.55	114.70	0.96	0.84	115.84	1.14	0.99	116.20	0.36	0.31	7.41	6.81
331	PEG	106.00	111.26	5.26	4.96	112.25	0.99	0.89	113.39	1.14	1.02	113.71	0.32	0.28	7.71	7.27
332	PEG	107.39	112.70	5.31	4.94	113.54	0.84	0.75	114.74	1.20	1.06	114.85	0.11	0.10	7.46	6.95
333	TD	111.00	113.90	2.90	2.61	114.30	0.40	0.35	115.30	1.00	0.90	115.30	-	-	4.30	3.87
334	TD	109.19	111.74	2.55	2.34	112.24	0.50	0.45	113.00	0.76	0.69	113.00	-	-	3.81	3.49
335	TD	105.29	108.40	3.11	2.95	108.65	0.25	0.23	109.87	1.22	1.09	109.87	-	-	4.58	4.35

* BASED ON THE INITIAL WEIGHT
** PLUS OVERNIGHT SOAK IN COOLING PCM

TABLE A40 SHEET 2
AVERAGES FOR TABLE A40 SHEET 1
PUM/LA/SF/FA/SC/WC, 14.2% EA

SPECIMEN No.	PCM	INITIAL WT. 9	INCREASE OVER INITIAL WEIGHT %			
			1st IMMERSION 60 MIN.	2nd IMMERSION 120 MIN.	3rd IMMERSION 240 MIN.	4th IMMERSION 240 MIN.
324	BS	114.44	3.03	3.46	4.67	4.90
325	BS	107.82	3.55	4.13	5.29	5.61
326	BS	109.10	2.75	3.02	4.05	4.27
AVG 324-326	BS	———	3.11	3.54	4.67	4.93

SPECIMEN No.	PCM	INITIAL WT. 9	INCREASE OVER INITIAL WEIGHT %			
			1st IMMERSION 60 MIN.	2nd IMMERSION 120 MIN.	3rd IMMERSION 240 MIN.	4th IMMERSION 240 MIN.
327	DD	112.41	2.53	2.88	3.82	3.82
328	DD	112.65	2.33	2.57	3.29	3.41
329	DD	110.95	2.67	2.75	3.61	3.61
AVG 327-329	DD	———	2.51	2.73	3.57	3.61

SPECIMEN No.	PCM	INITIAL WT. 9	INCREASE OVER INITIAL WEIGHT %			
			1st IMMERSION 60 MIN.	2nd IMMERSION 120 MIN.	3rd IMMERSION 240 MIN.	4th IMMERSION 240 MIN.
330	PEG	108.79	4.55	5.43	6.48	6.81
331	PEG	106.00	4.96	5.89	6.97	7.27
332	PEG	107.39	4.94	5.73	6.84	6.95
AVG 330-332	PEG	———	4.82	5.68	6.76	7.01

TABLE A40 SHEET 3
AVERAGES FOR TABLE A40 SHEET 1
PUM/LA/SF/FA/SC/HC, 14.2% EA

SPECIMEN No.	PCM	INITIAL WT. g	INCREASE OVER INITIAL WEIGHT %			
			1st IMMERSION 60 MIN.	2nd IMMERSION 120 MIN.	3rd IMMERSION 240 MIN.	4th IMMERSION 240 MIN.
333 334 335	TD TD TD	111.00 109.19 105.29	2.61 2.34 2.95	2.97 2.79 3.19	3.87 3.49 4.35	3.87 3.49 4.35
AVG	BS	——	2.63	2.98	3.90	3.90

TABLE A41 SHEET 1

PCM IMPREGNATION PROCEDURE: 5/6/89 - 12/6/89, REG. AGGREGATE, LOW ALKALI TYPE 10 CEMENT WITH SILICA FUME AND FLY ASH, CONCRETE MIXED 1/5/89, STEAM CURED 1/5/89 - 2/5/89, AIR CURED 2/5/89 - 5/6/89, 11% ENTRAINED AIR, IMMERSION TIMES: 1ST - 120 MIN., 2ND - 180 MIN., 3RD - 240 MIN., 4TH - 240 MIN.**, PCM. TEMP. 80°C, SPECIMEN TEMP. 20°C

SPECIMEN NO.	PCM	INIT. WT. g	1st IMMERSION			2ND IMMERSION			3RD IMMERSION			4TH IMMERSION			TOTAL GAIN	
			FINAL WEIGHT g	GAIN		FINAL WEIGHT g	GAIN		FINAL WEIGHT g	IN		FINAL WEIGHT g	GAIN		g	%*
				g	%		g	%		g	%		g	%		
336	BS	147.90	150.84	2.94	1.99	151.58	0.74	0.49	152.69	1.11	0.73	153.05	0.36	0.24	5.15	3.48
337	BS	156.76	159.75	2.99	1.91	160.61	0.86	0.54	161.91	1.30	0.81	162.34	0.43	0.27	5.58	3.56
338	BS	154.12	156.40	2.28	1.48	157.00	0.60	0.38	158.19	1.19	0.76	158.64	0.45	0.28	4.52	2.93
339	DD	157.82	160.20	2.38	1.51	161.10	0.90	0.56	161.77	0.67	0.42	162.26	0.49	0.30	4.44	2.81
340	DD	157.59	159.95	2.36	1.50	161.01	1.06	0.66	161.70	0.69	0.43	162.04	0.34	0.21	4.45	2.82
341	DD	154.66	157.08	2.42	1.56	157.71	0.63	0.40	158.30	0.59	0.37	158.61	0.31	0.20	3.95	2.55
342	PEG	152.51	156.00	3.49	2.29	157.25	1.25	0.80	158.50	0.75	0.48	158.81	0.30	0.20	5.80	3.80
343	PEG	160.37	163.71	3.34	2.08	165.40	1.69	1.03	166.74	1.34	0.81	166.95	0.21	0.13	6.58	4.10
344	PEG	152.91	156.48	3.57	2.33	157.80	1.32	0.84	158.80	1.00	0.63	159.00	0.20	0.13	6.09	3.98
345	TD	153.63	155.90	2.25	1.46	156.65	0.75	0.48	157.40	0.75	0.48	157.80	0.40	0.25	4.15	2.70
346	TD	151.98	154.39	2.41	1.59	155.10	0.71	0.46	156.20	1.10	0.71	155.39	0.19	0.12	4.41	2.90
347	TD	148.21	150.80	2.59	1.75	151.53	0.73	0.48	152.38	0.85	0.56	152.93	0.55	0.36	4.72	3.18

* BASED ON THE INITIAL WEIGHT
** PLUS OVERNIGHT SOAK IN COOLING PCM

TABLE A41 SHEET 2
AVERAGES FOR TABLE A41 SHEET 1
REG/LA/SF/FA/SC/AC, 11% EA

SPECIMEN No.	PCM	INITIAL WT. 9	INCREASE OVER INITIAL WEIGHT %			
			1st IMMERSION 120 MIN.	2nd IMMERSION 180 MIN.	3rd IMMERSION 240 MIN.	4th IMMERSION 240 MIN.
336 337 338	BS BS BS	147.90 156.76 154.12	1.99 1.91 1.48	2.49 2.46 1.87	3.24 3.29 2.64	3.48 3.56 2.93
AVG 336-338	BS	———	1.79	2.27	3.06	3.32

SPECIMEN No.	PCM	INITIAL WT. 9	INCREASE OVER INITIAL WEIGHT %			
			1st IMMERSION 120 MIN.	2nd IMMERSION 180 MIN.	3rd IMMERSION 240 MIN.	4th IMMERSION 240 MIN.
339 340 341	DD DD DD	157.82 157.59 154.66	1.51 1.50 1.56	2.08 2.17 1.97	2.50 2.61 2.35	2.81 2.82 2.55
AVG 339-341	DD	———	1.52	2.07	2.49	2.73

SPECIMEN No.	PCM	INITIAL WT. 9	INCREASE OVER INITIAL WEIGHT %			
			1st IMMERSION 120 MIN.	2nd IMMERSION 180 MIN.	3rd IMMERSION 240 MIN.	4th IMMERSION 240 MIN.
342 343 344	PEG PEG PEG	152.51 160.37 152.91	2.29 2.08 2.33	3.11 3.14 3.20	3.93 3.97 3.85	3.80 4.10 3.98
AVG 342-344	PEG	———	2.23	3.15	3.92	3.96

TABLE A41 SHEET 3
AVERAGE FOR TABLE A41 SHEET 1
REG/LA/SF/FA/SC/AC, 11% EA

SPECIMEN No.	PCM	INITIAL WT. 9	INCREASE OVER INITIAL WEIGHT %			
			1st IMMERSION 120 MIN.	2nd IMMERSION 180 MIN.	3rd IMMERSION 240 MIN.	4th IMMERSION 240 MIN.
345 346 347	TD TD TD	153.65 151.98 148.21	1.46 1.59 1.75	1.95 2.05 2.24	2.44 2.78 2.81	2.70 2.90 3.18
AVG 345-347	TD	———	1.60	2.08	2.68	2.93

TABLE A42 SHEET 1
PCM IMPREGNATION PROCEDURE: 5/6/89 - 15/6/89, REG. AGGREGATE, LOW ALKALI TYPE 10 CEMENT WITH
SILICA FUME AND FLY ASH, CONCRETE MIXED 1/5/89, STEAM CURED 1/5/89 - 2/5/89,
WATER CURED 2/5/89 - 31/5/89, 11% ENTRAINED AIR, IMMERSION
TIMES: 1ST - 120 MIN., 2ND - 300 MIN.**, 3RD - 240 MIN.***, 4TH - 300 MIN.**, PCM. TEMP. 80°C, SPECIMEN TEMP. 20°C

SPECIMEN NO.	PCM	INIT. WT. g	1st IMMERSION			2ND IMMERSION			3RD IMMERSION			4TH IMMERSION			TOTAL GAIN	
			FINAL WEIGHT	GAIN		FINAL WEIGHT	GAIN		FINAL WEIGHT	IN		FINAL WEIGHT	GAIN		g	%*
			g	g	%	g	g	%	g	g	%	g	g	%		
348	BS	155.29	156.90	1.61	1.04	157.60	0.70	0.45	158.81	1.21	0.77	158.91	0.10	0.06	3.62	2.33
349	BS	159.74	161.35	1.61	1.01	161.90	0.55	0.34	163.50	1.60	0.99	163.50	--	--	3.76	2.35
350	BS	168.75	170.29	1.54	0.91	170.75	0.46	0.27	172.30	1.55	0.91	172.30	--	--	3.55	2.10
351	DD	159.00	160.30	1.30	0.82	160.88	0.58	0.36	162.20	1.32	0.82	162.20	--	--	3.20	2.01
352	DD	163.51	164.75	1.24	0.76	165.15	0.40	0.24	166.45	1.30	0.78	166.45	--	--	2.94	1.80
353	DD	166.60	168.00	1.40	0.84	168.55	0.55	0.38	169.85	1.30	0.77	169.85	--	--	3.25	1.95
354	PEG	153.41	155.54	2.13	1.39	156.79	1.25	0.80	157.72	0.93	0.59	157.92	0.20	0.13	4.51	2.94
355	PEG	164.21	166.52	2.31	1.41	168.13	1.61	0.97	169.12	0.99	0.59	169.32	0.20	0.12	5.11	3.11
356	PEG	158.50	161.14	2.64	1.67	162.60	1.46	0.91	163.90	1.30	0.80	163.98	0.08	0.05	5.48	3.46
357	TD	161.49	162.90	1.41	0.87	163.45	0.55	0.34	164.62	1.17	0.72	164.62	--	--	3.13	1.94
358	TD	161.32	162.80	1.48	0.92	163.47	0.67	0.41	164.80	1.33	0.81	164.80	--	--	3.48	2.16
359	TD	158.25	160.04	1.79	1.13	160.69	0.56	0.35	162.15	1.55	0.97	162.15	--	--	3.90	2.46

* BASED ON THE INITIAL WEIGHT
** SPECIMENS PREHEATED TO 45°C; *** PLUS OVERNIGHT SOAK IN COOLING PCM

TABLE A42 SHEET 2
AVERAGES FOR TABLE A42 SHEET 1
REG/LA/SF/FA/WC/AC, 11% EA

SPECIMEN No.	PCM	INITIAL WT. 9	INCREASE OVER INITIAL WEIGHT %			
			1st IMMERSION 120 MIN.	2nd IMMERSION 300 MIN.	3rd IMMERSION 240 MIN.	4th IMMERSION 300 MIN.
348 349 350	BS BS BS	155.29 159.74 168.75	1.04 1.01 0.91	1.49 1.35 1.19	2.27 2.35 2.10	2.33 2.35 2.10
AVG 348-350	BS	——	0.99	1.34	2.24	2.26

SPECIMEN No.	PCM	INITIAL WT. 9	INCREASE OVER INITIAL WEIGHT %			
			1st IMMERSION 120 MIN.	2nd IMMERSION 300 MIN.	3rd IMMERSION 240 MIN.	4th IMMERSION 240 MIN.
351 352 353	DD DD DD	159.00 163.51 166.60	0.82 0.76 0.84	1.18 1.00 1.17	2.01 1.79 1.95	2.01 1.80 1.95
AVG 351-353	DD	——	0.81	1.12	1.92	1.92

SPECIMEN No.	PCM	INITIAL WT. 9	INCREASE OVER INITIAL WEIGHT %			
			1st IMMERSION 120 MIN.	2nd IMMERSION 300 MIN.	3rd IMMERSION 240 MIN.	4th IMMERSION 300 MIN.
354 355 356	PEG PEG PEG	153.41 164.21 158.50	1.39 1.41 1.67	2.20 2.39 2.59	2.81 2.99 3.41	2.94 3.11 3.46
AVG 354-356	PEG	——	1.49	2.39	3.07	3.17

TABLE A42 SHEET 3
AVERAGES FOR TABLE A42 SHEET 1
REG/LA/SF/FA/SC/AC, 11% EA

SPECIMEN No.	PCM	INITIAL WT. 9	INCREASE OVER INITIAL WEIGHT %			
			1st IMMERSION 120 MIN.	2nd IMMERSION 180 MIN.	3rd IMMERSION 240 MIN.	4th IMMERSION 240 MIN.
357 358 356	TD TD TD	161.49 161.32 158.25	0.87 0.92 1.13	1.21 1.33 1.48	1.94 2.15 2.46	1.94 2.16 2.46
AVG 357-359	TD	———	0.97	1.34	2.18	2.19

TABLE A43 SHEET 1
PCM IMPREGNATION PROCEDURE: 11/7/89 - 20/7/89, PCM: DD
IMMERSION TIMES: 1st - 240 MIN., 2nd - 240 MIN., 3rd - 240 MIN., 4th - 240 MIN.
PCM TEMP. 70°C, SPECIMEN TEMP. 20°C

SPECIMEN NO.	CON-CRETE	INIT. WT. g	1st IMMERSION			2ND IMMERSION			3RD IMMERSION			4TH IMMERSION			TOTAL GAIN	
			FINAL WEIGHT	GAIN		FINAL WEIGHT	GAIN		FINAL WEIGHT	GAIN		FINAL WEIGHT	GAIN		g	%*
			g	g	%	g	g	%	g	g	%	g	g	%		
360	REG	154.90	161.15	6.25	4.03	161.90	0.75	0.47	161.65	(0.25)	(0.15)	161.75	0.10	0.062	6.85	4.42
361	REG	152.10	159.60	7.50	4.93	159.75	0.15	0.094	159.62	(0.13)	(0.081)	159.80	0.18	0.11	7.70	5.06
362	REG	142.00	147.75	5.75	4.05	148.05	0.30	0.20	147.95	(0.10)	(0.068)	147.95	-	-	5.95	4.19
363	ABL	127.09	136.15	9.06	7.13	136.35	0.20	0.15	136.69	0.34	0.25	136.65	(0.04)	(0.029)	9.56	7.52
364	ABL	138.90	149.15	10.25	7.38	150.04	0.89	0.60	150.20	0.16	0.11	149.80	(0.40)	(0.27)	10.90	7.85
365	ABL	132.71	141.65	8.94	6.74	142.78	1.13	0.80	142.55	(0.23)	(0.16)	142.20	(0.35)	(0.25)	9.49	7.15
366	PUM	98.00	104.62	6.62	6.76	105.92	1.30	1.24	106.20	0.28	0.26	106.60	0.40	0.38	8.60	8.78
367	PUM	102.42	110.03	7.61	7.43	111.75	1.72	1.56	112.62	0.87	0.78	112.80	0.18	0.16	10.38	10.13
368	PUM	97.89	106.95	9.06	9.26	108.75	1.80	1.68	109.30	0.55	0.51	109.65	0.35	0.32	11.76	12.01

* BASED ON INITIAL WEIGHT

TABLE A43 SHEET 2
AVERAGES FOR TABLE A43 SHEET 1
PCM:DD

SPECIMEN No.	PCM	INITIAL WT. 9	INCREASE OVER INITIAL WEIGHT %			
			1st IMMERSION 240 MIN.	2nd IMMERSION 240 MIN.	3rd IMMERSION 240 MIN.	4th IMMERSION 300 MIN.
360	REG	154.90	4.03	4.52	4.36	4.42
361	REG	152.10	4.93	5.03	4.94	5.06
362	REG	142.00	4.05	4.26	4.19	4.19
AVG 360-362	REG	———	4.34	4.60	4.50	4.56

SPECIMEN No.	PCM	INITIAL WT. 9	INCREASE OVER INITIAL WEIGHT %			
			1st IMMERSION 240 MIN.	2nd IMMERSION 240 MIN.	3rd IMMERSION 240 MIN.	4th IMMERSION 240 MIN.
363	ABL	127.09	7.13	7.29	7.55	7.52
364	ABL	138.90	7.38	8.02	8.14	7.85
365	ABL	132.71	6.74	7.59	7.41	7.15
AVG 363-365	ABL	———	7.08	7.63	7.70	7.51

SPECIMEN No.	PCM	INITIAL WT. 9	INCREASE OVER INITIAL WEIGHT %			
			1st IMMERSION 240 MIN.	2nd IMMERSION 240 MIN.	3rd IMMERSION 240 MIN.	4th IMMERSION 240 MIN.
366	PUM	98.00	6.76	8.08	8.37	8.78
367	PUM	102.42	7.43	9.11	9.96	10.13
368	PUM	97.89	9.26	11.09	11.66	12.01
AVG 366-368	PUM	———	7.82	9.43	10.0	10.31

TABLE A44 SHEET 1
PCM IMPREGNATION PROCEDURE: 11/7/89 - 20/7/89, PCM: PAR,
IMMERSION TIMES: 1st - 240 MIN., 2nd - 240 MIN., 3rd - 240 MIN., 4th - 240 MIN.,
PCM TEMP. 90°C (PEAK AT IMMERSION 125°C) SPECIMEN TEMP. 20°C

SPECIMEN NO.	CON-CRETE	INIT. WT. g	1st IMMERSION			2ND IMMERSION			3RD IMMERSION			4TH IMMERSION			TOTAL GAIN	
			FINAL WEIGHT	GAIN		FINAL WEIGHT	GAIN		FINAL WEIGHT	GAIN		FINAL WEIGHT	GAIN			
			g	g	%	g	g	%	g	g	%	g	g	%	g	%*
369	REG	147.94	155.95	8.01	5.41	158.75	2.80	1.80	158.85	0.10	0.063	158.50	(0.35)	(0.22)	10.56	7.14
370	REG	168.54	177.41	8.87	5.26	181.30	3.89	2.19	180.55	(0.75)	(0.41)	180.62	0.07	0.039	12.08	7.17
371	REG	182.10	191.09	8.99	4.94	195.12	4.03	2.11	194.48	(0.64)	(0.33)	194.70	0.22	0.11	12.60	6.92
372	ABL	154.55	168.89	14.25	9.22	170.55	1.75	1.04	170.90	0.35	0.21	169.58	(1.32)	(0.77)	15.03	9.73
373	ABL	117.09	128.67	11.58	9.89	129.15	0.48	0.37	129.90	0.75	0.58	129.05	(0.85)	(0.65)	11.96	10.21
374	ABL	118.52	129.50	10.98	9.26	129.65	0.15	0.12	130.65	1.00	0.77	129.80	(0.85)	(0.65)	11.28	9.52
375	PUN	96.55	116.29	19.74	** 20.44	114.00	[2.29]	(1.97)	115.20	1.20	1.05	115.3	0.10	0.09	18.75	19.42
376	PUN	96.90	117.40	20.50	** 21.16	114.01	(3.39)	(2.89)	115.45	1.44	1.26	116.10	0.65	0.56	19.20	19.81
377	PUN	107.55	128.45	20.9	** 19.43	126.55	(1.90)	(1.48)	126.80	0.25	0.20	127.50	0.70	0.55	19.95	18.55

** UNICERE TEMP. 120°
* BASED ON INITIAL WEIGHT

TABLE A44 SHEET 2
AVERAGES FOR TABLE A44 SHEET 1
PCM: PAR

SPECIMEN No.	PCM	INITIAL WT. 9	INCREASE OVER INITIAL WEIGHT %			
			1st IMMERSION 240 MIN.	2nd IMMERSION 240 MIN.	3rd IMMERSION 240 MIN.	4th IMMERSION 300 MIN.
369	REG	147.94	5.41	7.31	7.37	7.14
370	REG	168.54	5.26	7.57	7.13	7.17
371	REG	182.10	4.94	7.15	6.80	6.92
AVG 369-371	REG	———	5.20	7.34	7.10	7.08

SPECIMEN No.	PCM	INITIAL WT. 9	INCREASE OVER INITIAL WEIGHT %			
			1st IMMERSION 240 MIN.	2nd IMMERSION 240 MIN.	3rd IMMERSION 240 MIN.	4th IMMERSION 240 MIN.
372	ABL	154.55	9.22	10.35	10.58	9.73
373	ABL	117.09	9.89	10.30	10.94	10.21
374	ABL	118.52	9.26	9.39	10.23	9.52
AVG 372-374	ABL	———	9.46	10.01	10.58	9.82

SPECIMEN No.	PCM	INITIAL WT. 9	INCREASE OVER INITIAL WEIGHT %			
			1st IMMERSION 240 MIN.	2nd IMMERSION 240 MIN.	3rd IMMERSION 240 MIN.	4th IMMERSION 240 MIN.
375	PUM	95.55	20.44	18.07	19.32	19.42
376	PUM	96.90	21.16	17.66	19.14	19.81
377	PUM	107.55	19.43	17.67	17.90	18.55
AVG 375-377	PUM	———	20.34	17.80	18.79	19.26

TABLE A45 SHEET 1
PCM IMPREGNATION PROCEDURE: 20/7/89 - 31/7/89, PCM: DD + 5% ETHANOL
IMMERSION TIMES: 1st - 240 MIN., 2nd - 240 MIN., 3rd - 240 MIN., 4th - 240 MIN.,
PCM TEMP. 70°C SPECIMEN TEMP. 20°C

SPECIMEN NO.	CON-CRETE	INIT. WT. g	1st IMMERSION			2ND IMMERSION			3RD IMMERSION			4TH IMMERSION			TOTAL GAIN	
			FINAL WEIGHT	GAIN		FINAL WEIGHT	GAIN		FINAL WEIGHT	GAIN		FINAL WEIGHT	GAIN			
			g	g	%	g	g	%	g	g	%	g	g	%	g	%*
378	REG	139.75	145.72	5.97	4.27	146.30	0.58	0.40	146.45	0.15	0.10	146.45	-	-	6.70	4.79
379	REG	137.30	144.20	6.90	5.03	144.55	0.35	0.24	144.70	0.15	0.10	144.70	-	-	7.40	5.39
380	REG	146.95	154.18	7.23	4.92	154.65	0.47	0.30	154.65	-	-	154.65	-	-	7.70	5.24
381	ABL	110.70	116.40	5.70	5.15	118.00	1.60	1.37	118.20	0.20	0.17	118.30	0.10	0.085	7.60	6.87
382	ABL	115.89	122.20	6.31	5.44	124.95	2.75	2.25	124.25	(0.70)	(0.56)	124.65	0.40	0.32	8.76	7.56
383	ABL	120.76	126.90	6.41	5.08	129.55	2.65	2.09	129.00	(0.55)	(0.42)	129.25	0.25	0.19	8.49	7.03
385	PUN	92.58	100.00	7.42	8.01	100.65	0.65	0.65	100.65	-	-	101.78	1.13	1.12	9.20	9.94
386	PUN	96.80	105.95	9.15	9.45	106.45	0.50	0.47	107.05	0.60	0.56	108.20	1.15	1.07	11.40	11.78

* BASED ON INITIAL WEIGHT

TABLE A45 SHEET 2
AVERAGES FOR TABLE A45 SHEET 1
PCM: PAR WITH 5% ETHANOL

SPECIMEN No.	PCM	INITIAL WT. 9	INCREASE OVER INITIAL WEIGHT %			
			1st IMMERSION 240 MIN.	2nd IMMERSION 240 MIN.	3rd IMMERSION 240 MIN.	4th IMMERSION 300 MIN.
378	REG	139.75	4.27	4.69	4.79	4.79
379	REG	137.30	5.03	5.28	5.39	5.39
380	REG	146.95	4.92	5.24	5.24	5.24
AVG 378-380	REG	———	4.74	5.07	5.14	5.14

SPECIMEN No.	PCM	INITIAL WT. 9	INCREASE OVER INITIAL WEIGHT %			
			1st IMMERSION 240 MIN.	2nd IMMERSION 240 MIN.	3rd IMMERSION 240 MIN.	4th IMMERSION 240 MIN.
381	ABL	110.70	5.15	6.59	6.78	6.87
382	ABL	115.89	5.44	7.82	7.21	7.56
383	ABL	120.76	5.08	7.28	6.82	7.03
AVG 381-383	ABL	———	5.22	7.23	6.94	7.15

SPECIMEN No.	PCM	INITIAL WT. 9	INCREASE OVER INITIAL WEIGHT %			
			1st IMMERSION 240 MIN.	2nd IMMERSION 240 MIN.	3rd IMMERSION 240 MIN.	4th IMMERSION 240 MIN.
384	PUM					
385	PUM	92.58	8.01	8.72	10.59	9.94
386	PUM	96.80	9.45	9.97	8.72	11.78
AVG 384-386	PUM	———	8.73	9.35	9.66	10.86

TABLE A46 SHEET 1
PCM IMPREGNATION PROCEDURE: 20/7/89 - 31/7/89, PCM: PAR + 5% TURPENTINE,
IMMERSION TIMES: 1st - 240 MIN., 2nd - 240 MIN., 3rd - 240 MIN., 4th - 240 MIN.,
PCM TEMP. 90°C SPECIMEN TEMP. 20°C

SPECIMEN NO.	CON-CRETE	INIT. WT. g	1st IMMERSION			2ND IMMERSION			3RD IMMERSION			4TH IMMERSION			TOTAL GAIN	
			FINAL WEIGHT	GAIN		FINAL WEIGHT	GAIN		FINAL WEIGHT	GAIN		FINAL WEIGHT	GAIN			
			g	g	%	g	g	%	g	g	%	g	g	%	g	%*
387	REG	117.00	123.71	6.71	5.74	126.05	2.34	1.89	125.90	(0.15)	(0.12)	125.90	-	-	8.90	7.61
388	REG	126.95	133.95	7.00	5.51	136.35	2.40	1.79	135.85	(0.50)	(0.37)	136.01	0.16	0.12	9.06	7.14
389	REG	127.85	133.90	6.05	4.73	136.00	2.10	1.57	135.80	(0.20)	(0.15)	135.89	0.09	0.07	8.04	6.29
390	ABL	121.50	129.80	8.30	6.83	133.70	3.90	3.00	132.85	(0.85)	(0.64)	132.90	0.05	0.04	11.40	9.38
391	ABL	145.10	153.65	8.55	5.89	158.30	4.65	3.03	156.95	(1.35)	(0.85)	157.95	1.00	0.64	12.85	8.86
392	ABL	118.14	126.54	8.40	7.11	130.65	4.11	3.25	129.10	(1.55)	(1.19)	129.50	0.40	0.31	11.36	9.62
393	PUH	98.50	111.00	12.50	12.69	111.70	0.70	0.63	118.90	7.20	6.45	118.35	(0.55)	(0.46)	19.85	20.15
394	PUH	98.82	111.15	12.33	12.48	111.15	-	-	118.50	7.35	6.61	115.09	(3.41)	(2.80)	16.27	16.46
395	PUH	95.35	108.60	13.25	13.90	109.85	1.25	1.15	115.60	5.75	5.23	116.00	0.40	0.35	20.65	21.66

* BASED ON INITIAL WEIGHT

TABLE A46 SHEET 2
AVERAGES FOR TABLE A46 SHEET 1
PCM: PAR WITH 5% TURPENTINE

SPECIMEN No.	PCM	INITIAL WT. 9	INCREASE OVER INITIAL WEIGHT %			
			1st IMMERSION 240 MIN.	2nd IMMERSION 240 MIN.	3rd IMMERSION 240 MIN.	4th IMMERSION 240 MIN.
387	REG	117.00	5.74	7.74	7.61	7.61
388	REG	126.95	5.51	7.40	7.14	7.14
389	REG	127.85	4.73	6.37	6.29	6.29
AVG 387-389	REG	—	5.33	7.17	7.01	7.01

SPECIMEN No.	PCM	INITIAL WT. 9	INCREASE OVER INITIAL WEIGHT %			
			1st IMMERSION 240 MIN.	2nd IMMERSION 240 MIN.	3rd IMMERSION 240 MIN.	4th IMMERSION 240 MIN.
390	ABL	121.50	6.83	10.04	9.34	9.38
391	ABL	145.10	5.89	9.10	8.17	8.86
392	ABL	118.14	7.11	10.59	9.28	9.62
AVG 390-392	ABL	—	6.61	9.91	8.93	9.29

SPECIMEN No.	PCM	INITIAL WT. 9	INCREASE OVER INITIAL WEIGHT %			
			1st IMMERSION 240 MIN.	2nd IMMERSION 240 MIN.	3rd IMMERSION 240 MIN.	4th IMMERSION 240 MIN.
393	PUM	98.50	12.69	13.40	20.71	20.15
394	PUM	98.82	12.48	12.48	19.91	16.46
395	PUM	95.35	13.90	15.21	21.24	21.66
AVG 393-395	PUM	—	13.02	13.70	20.62	19.42

TABLE A47 SHEET 1
PCM IMPREGNATION PROCEDURE: 1/8/89 - 8/8/89, PCM: DD + 10% ETHANOL, IMMERSION TIMES: 1st - 240 MIN., 2nd - 240 MIN., 3rd - 240 MIN., 4th - 240 MIN., PCM TEMP. 70°C, SPECIMEN TEMP. 20°C

SPECIMEN NO.	CON-CRETE	INIT. WT. g	1st IMMERSION			2ND IMMERSION			3RD IMMERSION			4TH IMMERSION			TOTAL GAIN	
			FINAL WEIGHT	GAIN		FINAL WEIGHT	GAIN		FINAL WEIGHT	GAIN		FINAL WEIGHT	GAIN			
			g	g	%	g	g	%	g	g	%	g	g	%	g	%*
396	REG	183.89	193.15	9.26	5.04	193.15	-	-	193.10	(0.05)	(0.03)	192.85	(0.25)	(0.13)	8.96	4.87
397	REG	192.53	201.12	8.59	4.46	201.28	0.16	0.080	201.30	(0.02)	(0.01)	201.18	(0.12)	(0.06)	8.65	4.49
398	REG	126.70	133.10	6.40	5.05	133.40	0.30	0.23	133.35	(0.05)	(0.04)	133.20	(0.15)	(0.11)	6.50	5.13
399	ABL	118.86	125.70	6.84	5.75	126.30	0.60	0.48	126.20	(0.10)	(0.08)	126.50	0.30	0.24	7.64	6.43
400	ABL	114.69	123.10	8.41	7.33	123.90	0.80	0.65	123.90	-	-	123.25	(0.65)	(0.52)	8.56	7.46
401	ABL	133.78	142.00	8.22	6.14	142.40	0.40	0.28	142.10	(0.30)	(0.21)	142.60	0.50	0.35	8.82	6.59
402	PUM	89.20	97.70	8.50	9.53	98.20	0.50	0.51	99.50	1.30	1.41	99.50	(0.08)	(0.08)	10.30	11.55
403	PUM	97.25	105.68	8.43	8.67	105.72	0.04	0.04	107.25	1.53	1.45	107.25	-	-	10.00	10.28
404	PUM	102.60	111.70	9.10	8.87	112.10	0.40	0.36	113.42	1.32	1.18	116.63	0.21	0.18	14.03	13.67

* BASED ON THE INITIAL WEIGHT

TABLE A47 SHEET 2
AVERAGES FOR TABLE A47 SHEET 1
PCM: PAR WITH 10% ETHANOL

SPECIMEN No.	PCM	INITIAL WT. g	INCREASE OVER INITIAL WEIGHT %			
			1st IMMERSION 240 MIN.	2nd IMMERSION 240 MIN.	3rd IMMERSION 240 MIN.	4th IMMERSION 240 MIN.
396	REG	183.89	5.04	5.04	5.01	4.87
397	REG	192.53	4.46	4.54	4.56	4.49
398	REG	126.70	5.05	5.29	5.25	5.13
AVG 396-398	REG	———	4.85	4.96	4.94	4.83

SPECIMEN No.	PCM	INITIAL WT. g	INCREASE OVER INITIAL WEIGHT %			
			1st IMMERSION 240 MIN.	2nd IMMERSION 240 MIN.	3rd IMMERSION 240 MIN.	4th IMMERSION 240 MIN.
399	ABL	118.86	5.75	6.26	6.18	6.43
400	AB	114.69	7.33	8.03	8.03	7.46
401	ABL	133.78	6.14	6.44	6.22	6.59
AVG 399-401	ABL	———	6.41	6.91	6.81	6.83

SPECIMEN No.	PCM	INITIAL WT. g	INCREASE OVER INITIAL WEIGHT %			
			1st IMMERSION 240 MIN.	2nd IMMERSION 240 MIN.	3rd IMMERSION 240 MIN.	4th IMMERSION 240 MIN.
402	PUM	89.20	9.53	10.09	11.64	11.55
403	PUM	97.25	8.67	8.71	10.28	10.28
404	PUM	102.60	8.87	9.26	10.55	13.67
AVG 402-404	PUM	———	9.02	9.35	10.82	11.83

TABLE A48 SHEET 1
PCM IMPREGNATION PROCEDURE: 1/8/89 - 8/8/89, PCM: PAR + 10% TURPENTINE,
IMMERSION TIMES: 1st - 240 MIN., 2nd - 240 MIN., 3rd - 240 MIN., 4th - 240 MIN.,
PCM TEMP. 90°C SPECIMEN TEMP. 20°C

SPECIMEN NO.	CON-CRETE	INIT. WT. g	1st IMMERSION			2ND IMMERSION			3RD IMMERSION			4TH IMMERSION			TOTAL GAIN	
			FINAL WEIGHT	GAIN		FINAL WEIGHT	GAIN		FINAL WEIGHT	GAIN		FINAL WEIGHT	GAIN			
			g	g	%	g	g	%	g	g	%	g	g	%	g	%*
405	REG	195.70	210.50	14.80	7.56	206.90	(3.60)	(1.71)	210.30	3.40	1.64	207.05	(3.25)	(1.55)	11.35	5.80
406	REG	192.34	205.85	13.51	7.02	203.15	(2.70)	(1.31)	205.55	2.40	1.18	203.00	(2.55)	(1.24)	10.66	5.54
407	REG	189.70	201.95	12.25	6.46	198.90	(3.05)	(1.51)	201.80	2.90	1.46	198.98	(2.82)	(1.40)	9.28	4.89
408	ABL	136.27	146.00	9.73	7.14	146.75	0.75	0.41	146.30	(0.45)	(0.31)	148.60	2.30	1.57	12.33	9.05
409	ABL	161.51	174.12	12.61	7.81	175.15	1.03	0.59	174.40	(0.75)	(0.43)	177.76	3.36	2.08	16.25	10.06
410	ABL	129.30	138.80	9.50	7.35	139.20	0.40	0.29	139.25	0.05	0.04	140.45	2.35	1.20	10.95	8.47
411	PUH	106.15	116.75	10.60	9.99	121.22	4.47	3.83	126.78	5.56	4.59	126.33	(0.45)	(0.35)	20.18	19.00
412	PUH	104.75	113.60	8.85	8.45	117.60	4.00	3.52	122.30	4.70	4.00	122.66	0.36	0.29	17.91	17.10
413	PUH	98.95	107.65	8.70	8.79	111.85	4.20	3.90	116.80	4.95	4.43	116.30	(0.50)	(0.43)	17.35	17.53

* BASED ON THE INITIAL WEIGHT

TABLE A48 SHEET 2
AVERAGES FOR TABLE A48 SHEET 1
PCM: PAR WITH 10% TURPENTINE

SPECIMEN No.	PCM	INITIAL WT. 9	INCREASE OVER INITIAL WEIGHT %			
			1st IMMERSION 240 MIN.	2nd IMMERSION 240 MIN.	3rd IMMERSION 240 MIN.	4th IMMERSION 240 MIN.
405	REG	195.70	7.56	5.72	7.46	5.80
406	REG	192.34	7.02	5.62	6.87	5.54
407	REG	189.70	6.46	4.85	6.38	4.89
AVG 405-407	REG	———	7.01	5.40	6.90	5.41

SPECIMEN No.	PCM	INITIAL WT. 9	INCREASE OVER INITIAL WEIGHT %			
			1st IMMERSION 240 MIN.	2nd IMMERSION 240 MIN.	3rd IMMERSION 240 MIN.	4th IMMERSION 240 MIN.
408	ABL	136.27	7.14	7.69	7.36	9.05
409	ABL	161.51	7.81	8.45	7.98	10.06
410	ABL	129.30	7.35	7.66	7.70	8.47
AVG 408-410	ABL	———	7.43	7.93	7.68	9.19

SPECIMEN No.	PCM	INITIAL WT. 9	INCREASE OVER INITIAL WEIGHT %			
			1st IMMERSION 240 MIN.	2nd IMMERSION 240 MIN.	3rd IMMERSION 240 MIN.	4th IMMERSION 240 MIN.
411	PUM	106.15	9.99	14.20	19.43	19.00
412	PUM	104.75	8.45	12.27	16.75	17.10
413	PUM	98.95	8.79	13.04	18.04	17.53
AVG 411-413	PUM	———	9.08	13.17	18.07	17.88

TABLE A49 SHEET 1

PCM IMPREGNATION PROCEDURE: 1/8/89 - 4/8/89, PCM: DIMETHYL SULFOXIDE,
IMMERSION TIMES: 1st - 240 MIN., 2nd - 240 MIN., 3rd - 240 MIN., 4th - 240 MIN.,
IMMERSION TEMP. 70°C

SPECIMEN NO.	CON-CRETE	INIT. WT. g	1st IMMERSION			2ND IMMERSION			3RD IMMERSION			4TH IMMERSION			TOTAL GAIN	
			FINAL WEIGHT	GAIN		FINAL WEIGHT	GAIN		FINAL WEIGHT	GAIN		FINAL WEIGHT	GAIN			
			g	g	%	g	g	%	g	g	%	g	g	%	g	%*
414	REG	200.10	210.65	10.55	5.27	211.42	0.77	0.37	211.22	(0.20)	(0.10)	211.31	0.09	0.04	11.21	5.60
415	ABL	163.60	173.15	9.55	5.84	173.90	0.75	0.43	173.65	(0.25)	(0.14)	173.55	(0.10)	(0.06)	9.95	6.08
416	PUHC	84.70	93.65	8.95	10.57	95.00	1.35	1.44	95.45	0.45	0.47	95.45	-	-	10.75	12.69
417	REG + SIF + FA	160.65	168.35	7.70	4.79	168.90	0.55	0.33	169.11	0.21	0.12	169.15	0.04	0.02	8.50	5.29

* BASED ON THE INITIAL WEIGHT

TABLE A49 SHEET 2
AVERAGES FOR TABLE A49 SHEET 1
PCM: DIMETHYL SULFOXIDE

SPECIMEN No.	PCM	INITIAL WT. g	INCREASE OVER INITIAL WEIGHT %			
			1st IMMERSION	2nd IMMERSION	3rd IMMERSION	4th IMMERSION
414	REG	200.10	5.27	5.66	5.56	5.60
415	ABL	163.60	5.84	6.30	6.14	6.08
416	PUMC	84.70	10.57	12.16	12.69	12.69
417	REG + SF + FA	160.65	4.79	5.14	5.27	5.29

TABLE A50 SHEET 1
EFFECT OF CONCRETE TEMPERATURE ON PCM ABSORPTANCE
PCM TEMP. 80°C, DATE: 10/8/89 - 22/8/89,
IMMERSION TIME: 240 MIN.

CONCRETE TYPE	PCM	CONCRETE TEMPERATURE AT IMMERSION														
		20°C					80°C					100°C				
		SPEC NO.	INITIAL WEIGHT g	FINAL WEIGHT g	GAIN g	GAIN %	SPEC. NO.	INITIAL WEIGHT	FINAL WEIGHT g	GAIN* g	GAIN* %	SPEC. NO.	INITIAL WEIGHT	FINAL WEIGHT g	GAIN* g	GAIN* %
REG	DD	418	134.28	139.25	4.97	3.70	426	133.80	140.00	6.20	4.63	434	164.20	172.32	8.12	4.95
REG	PAR	419	158.20	164.00	5.80	3.67	427	144.78	151.50	6.72	4.64	435	146.51	154.14	7.63	5.21
ABL	BS	420	135.50	143.03	7.53	5.56	428	130.51	138.24	7.73	5.92	436	128.71	136.82	8.11	6.30
ABL	DD	421	131.89	138.50	6.61	5.01	429	127.95	135.43	7.48	5.85	437	123.24	131.38	8.14	6.60
ABL	PEG	422	136.94	147.75	10.81	7.89	430	126.15	136.60	10.45	8.28	438	149.15	163.50	14.35	9.62
ABL	PAR	423	151.76	162.22	10.46	6.89	431	140.98	151.32	10.34	7.33	439	148.59	159.09	10.50	7.07
PUM	DD	424	75.85	81.19	5.34	7.04	432	71.70	77.23	5.53	7.71	440	63.94	68.84	4.90	7.66
PUM	PAR	425	65.24	68.45	3.21	4.92	433	82.88	88.00	5.12	6.18	441	69.44	74.23	4.79	6.90

* GAIN IS RELATIVE TO ORIGINAL WEIGHT

TABLE A50 SHEET 2
EFFECT OF CONCRETE TEMPERATURE ON PCM ABSORPTANCE
PCM TEMP. 80°C, DATE: 10/8/89 - 22/8/89,
IMMERSION TIME: 240 MIN.

CONCRETE TYPE	PCM	CONCRETE TEMPERATURE AT IMMERSION															
		120°C					140°C					160°C					OVERALL INCREASE IN PCM ABSORBED BY RAISING CONCRETE TEMPERATURE FROM 20°C TO 160°C -%
		SPEC NO.	INITIAL WEIGHT g	FINAL WEIGHT g	GAIN g	GAIN %	SPEC. NO.	INITIAL WEIGHT	FINAL WEIGHT g	GAIN* g	GAIN* %	SPEC. NO.	INITIAL WEIGHT	FINAL WEIGHT g	GAIN* g	GAIN* %	
REG	DD	442	152.20	159.50	7.30	4.80	450	167.99	174.75	6.76	4.02	458	127.10	133.34	6.24	4.91	33
REG	PAR	443	191.75	200.60	8.85	4.62	451	136.67	143.03	6.36	4.65	459	130.86	138.59	7.73	5.91	61
ABL	BS	444	128.87	137.31	8.44	6.55	452	123.71	132.34	8.63	6.98	460	118.06	127.00	8.94	7.57	36
ABL	DD	445	120.32	127.91	7.59	6.31	453	122.80	131.80	9.00	7.33	461	116.21	124.51	8.30	7.14	43
ABL	PEG	446	136.23	149.30	13.07	9.59	454	154.10	169.30	15.20	9.86	462	139.50	155.31	15.81	11.33	44
ABL	PAR	447	131.98	141.40	9.42	7.14	455	153.35	165.82	12.47	8.13	463	139.03	150.42	11.49	8.26	20
PUM	DD	448	60.89	66.40	5.51	9.05	456	64.90	71.30	6.40	9.86	464	68.90	76.42	7.52	10.91	55
PUM	PAR	449	74.35	80.40	6.05	8.14	457	78.68	85.85	7.17	9.11	465	68.79	76.51	7.72	11.22	128

TABLE A51 SHEET 1

EFFECT OF PCM TEMPERATURE ON PCM ABSORPTANCE
TEMPERATURE AT IMMERSION 20°C, DATE: 10/8/89 TO 27/9/89,
IMMERSION TIME 240 MIN, PROGRESSIVE IMMERSION OF SAME SAMPLE

CONCRETE TYPE	PCM	PCM TEMPERATURE											
		80°C					100°C			120°C			
		SPEC NO.	INITIAL WEIGHT	FINAL WEIGHT	GAIN		FINAL WEIGHT	GAIN*		FINAL WEIGHT	GAIN*		
			g	g	g	g	g	g	%	g	g	%	
REG	DD	418A	150.54	156.80	6.26	4.16	157.98	7.44	4.94	159.38	8.84	5.87	
REG	PAR	419A	158.33	165.16	6.82	4.31	167.43	9.10	5.75	168.43	10.10	6.38	
ABL	BS	420A	157.76	167.21	9.45	5.99	168.66	10.90	6.91	169.69	11.84	7.51	
ABL	DD	421A	153.35	161.80	8.45	5.51	161.72	8.37	5.46	163.51	10.16	6.63	
ABL	PEG	422A	153.60	166.18	12.58	8.19	168.30	14.70	9.57	169.88	16.28	10.60	
ABL	PAR	423A	166.89	177.26	10.37	6.21	179.50	12.61	7.56	180.71	13.82	8.28	
FUM	DD	424A	83.38	89.10	5.72	6.86	90.56	7.18	8.61	91.15	7.77	9.32	
PUM	PAR	425A	81.55	86.60	5.05	6.19	88.51	6.96	8.53	90.32	8.77	10.76	

* GAIN IS RELATIVE TO ORIGINAL WEIGHT

TABLE A51 SHEET 2
EFFECT OF PCM TEMPERATURE ON PCM ABSORPTANCE
SPECIMEN TEMPERATURE AT IMMERSION 20°C, DATE: 10/8/89 TO 27/9/89,
IMMERSION TIME 240 MIN, PROGRESSIVE IMMERSION OF SAME SAMPLE

100°C			80°C			100°C			100°C		
FINAL WEIGHT	GAIN*		FINAL WEIGHT	GAIN*		FINAL WEIGHT	GAIN*		FINAL WEIGHT	GAIN*	
g	g	%	g	g	%	g	g	%	g	g	%
158.15	7.61	5.06	158.35	7.81	5.19	157.98	7.44	4.94	157.59	7.05	4.68
167.60	9.27	5.84	167.78	9.45	5.97	166.75	8.42	5.32	166.68	8.35	5.27
169.88	12.12	7.68	170.46	12.70	8.05	170.00	12.24	7.76	169.69	11.93	7.56
164.20	10.85	7.08	164.70	11.35	7.40	163.93	10.58	6.90	163.70	10.35	6.75
170.20	16.60	10.81	170.88	17.28	11.25	170.03	16.43	10.70	170.25	16.65	10.84
179.30	12.41	7.44	180.00	13.11	7.86	178.23	11.34	6.79	178.71	11.82	7.08
91.64	8.26	9.91	92.46	9.08	10.88	91.83	8.45	10.13	91.36	7.98	9.57
91.48	9.93	12.18	92.01	10.46	12.82	90.34	8.79	10.78	90.37	8.82	10.82

* GAIN IS RELATIVE TO ORIGINAL WEIGHT

APPENDIX B

FIGURES A1 - A 23

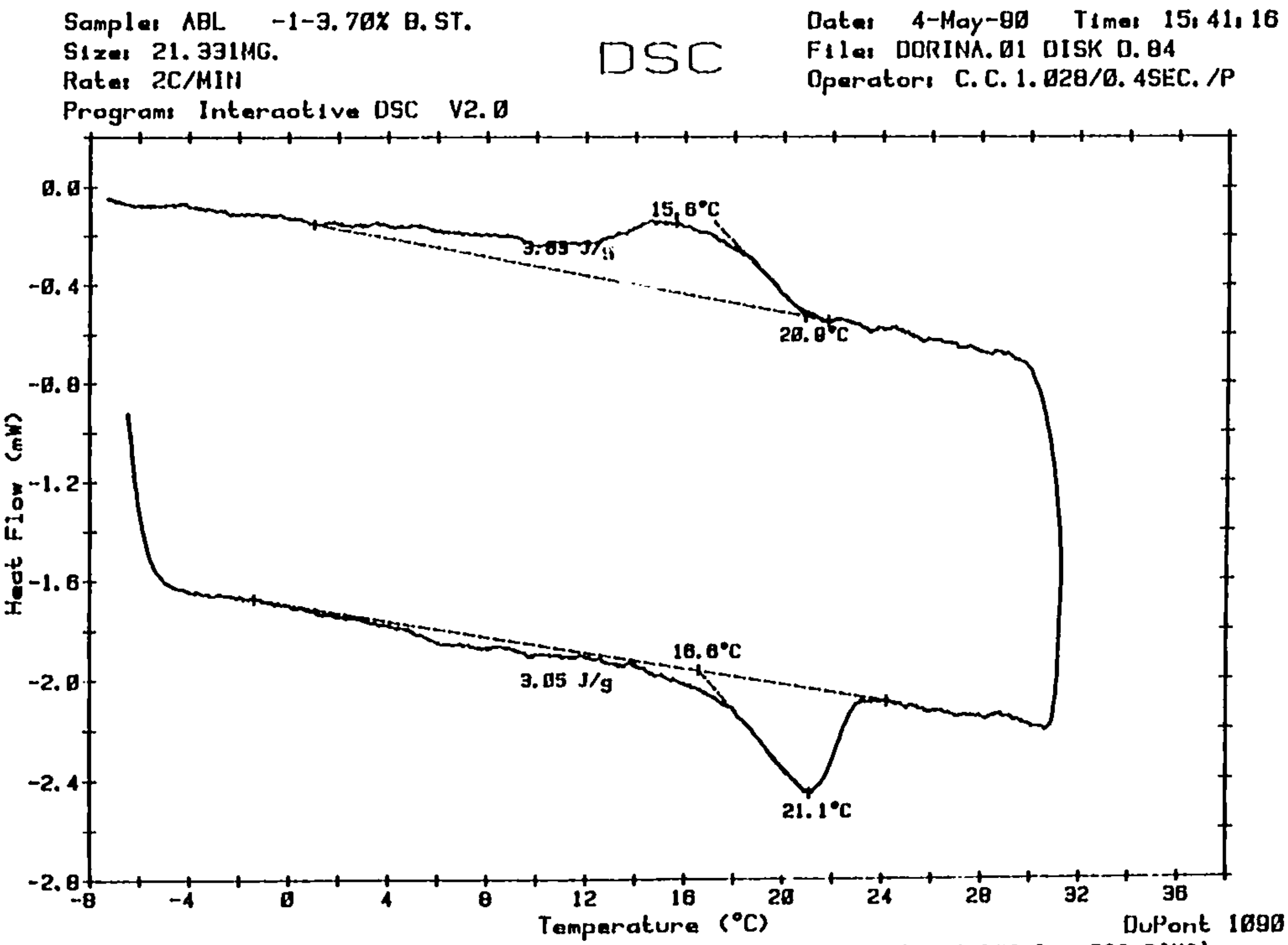


FIGURE A1 - DSC ANALYSIS OF BUTYL STEARATE IN AUTOCLAVED BLOCK (SPEC 1 - 590 DAYS)

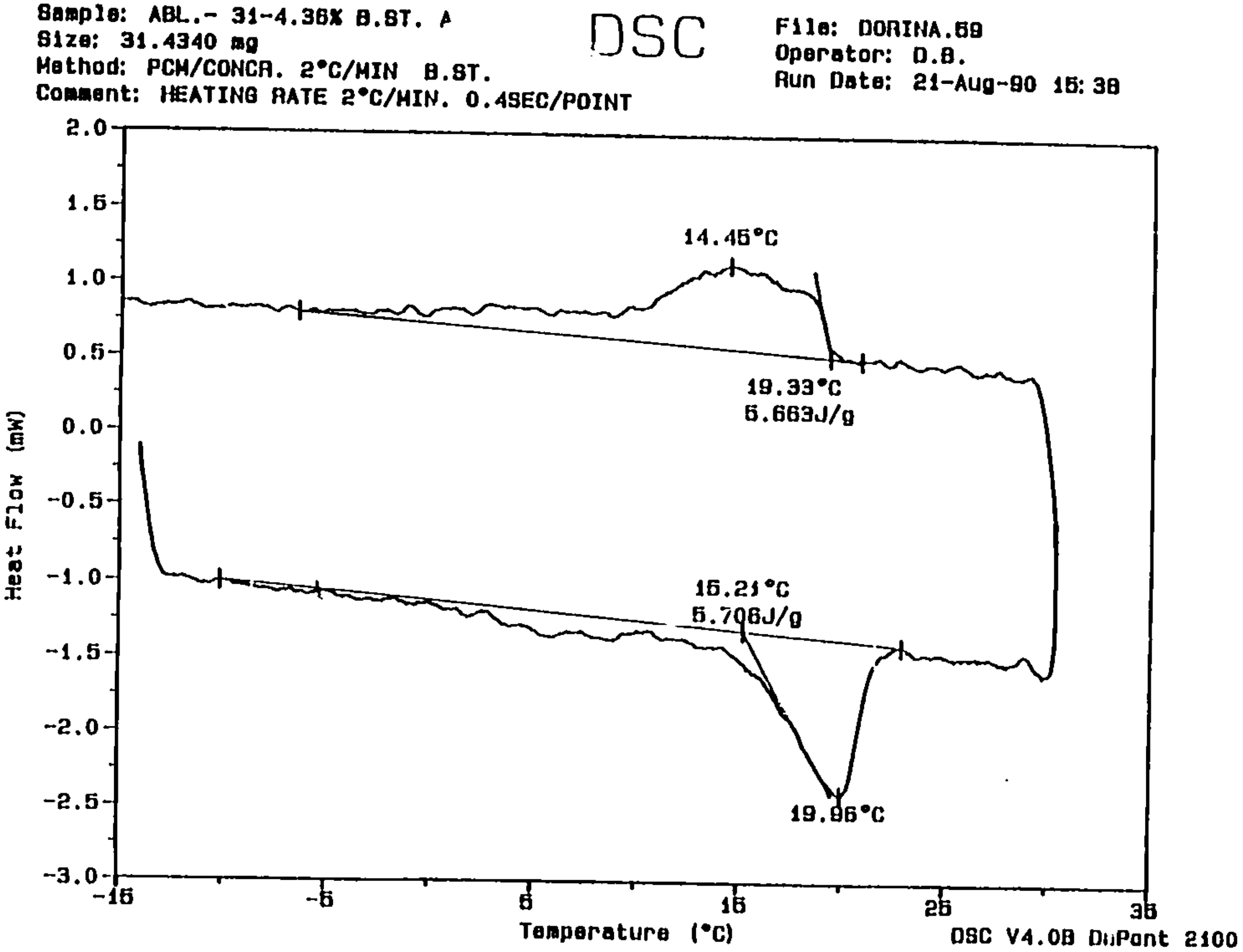


FIGURE A2 - DSC ANALYSIS OF BUTYL STEARATE IN AUTOCLAVED BLOCK (SPEC 31 - 692 DAYS)

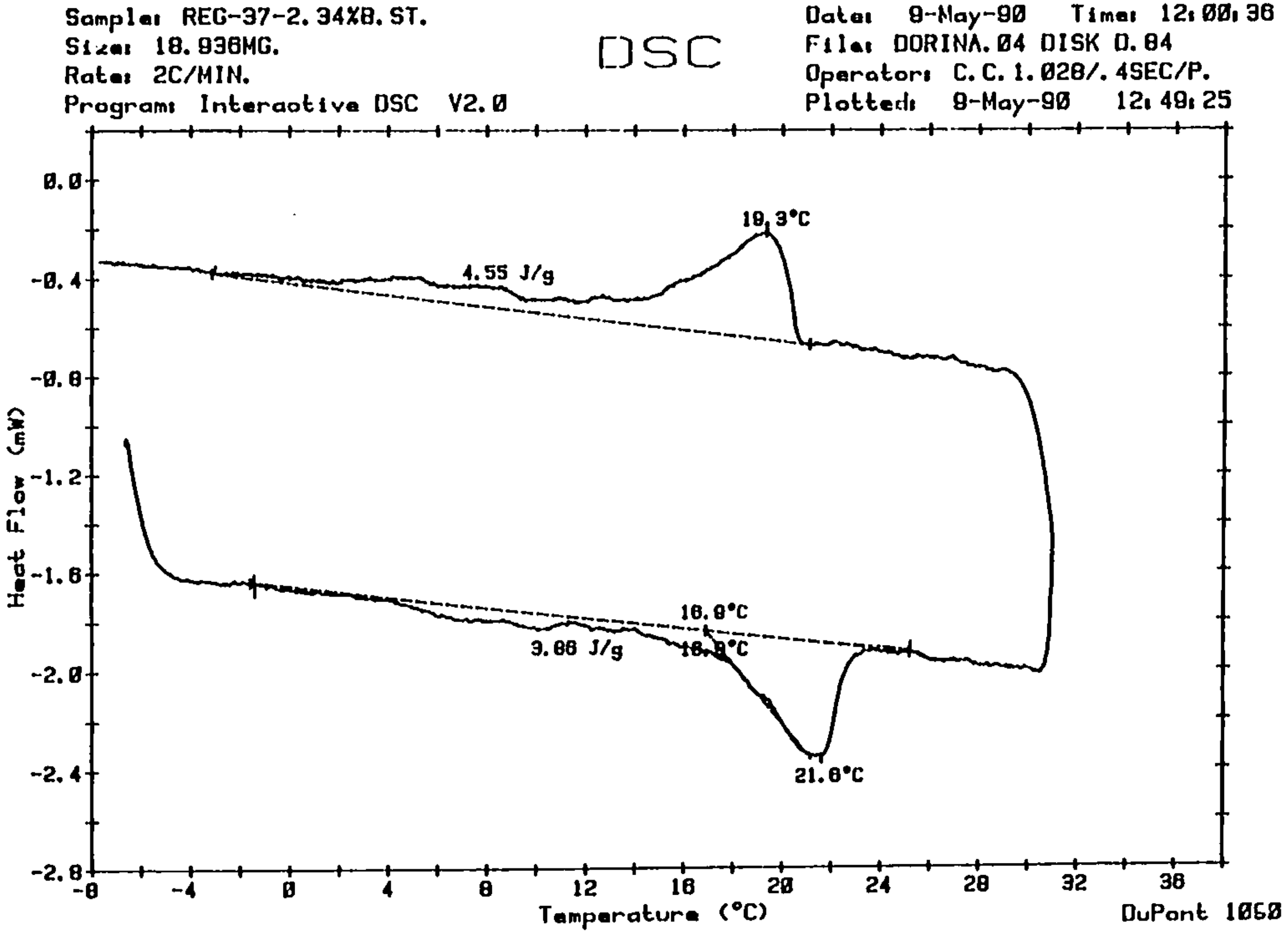


FIGURE A3 - DSC ANALYSIS OF BUTYL STEARATE IN REGULAR BLOCK (SPEC 37 - 588 DAYS)

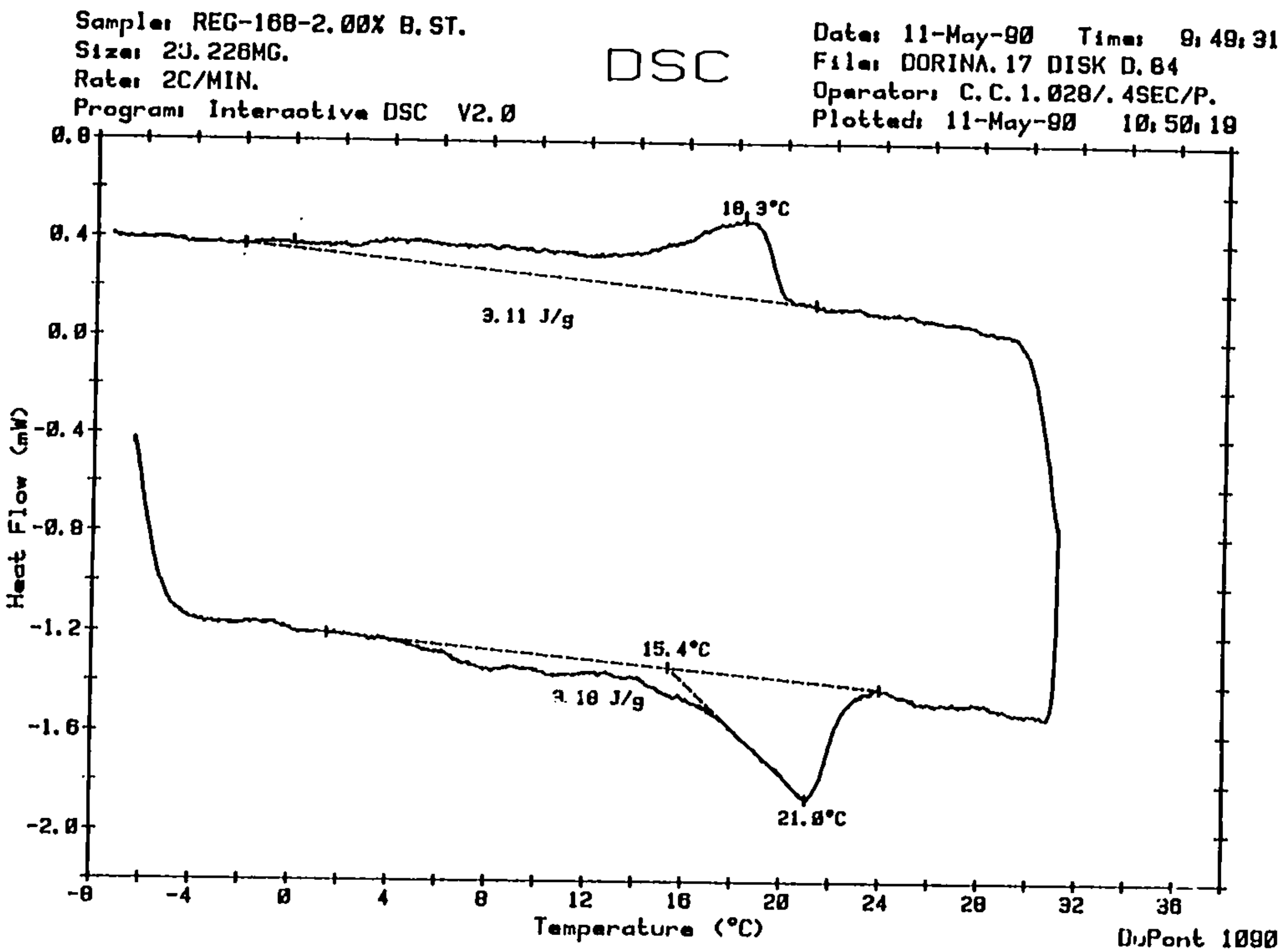


FIGURE A4 - DSC ANALYSIS OF BUTYL STEARATE IN MODIFIED REGULAR BLOCK (SPEC 168 - 373 DAYS)

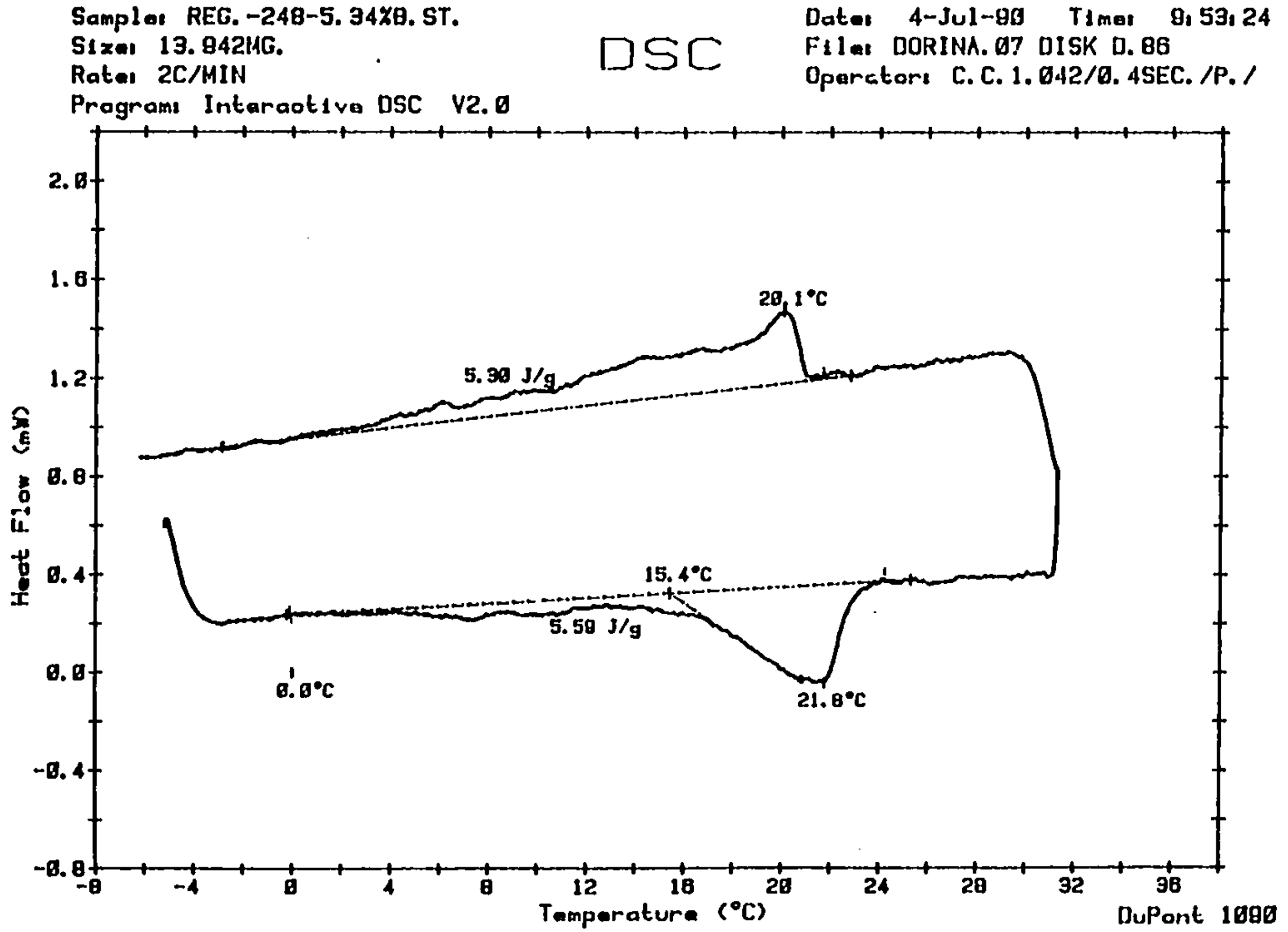


FIGURE A5 - DSC ANALYSIS OF BUTYL STEARATE IN MODIFIED REGULAR BLOCK (SPEC 248 - 391 DAYS)

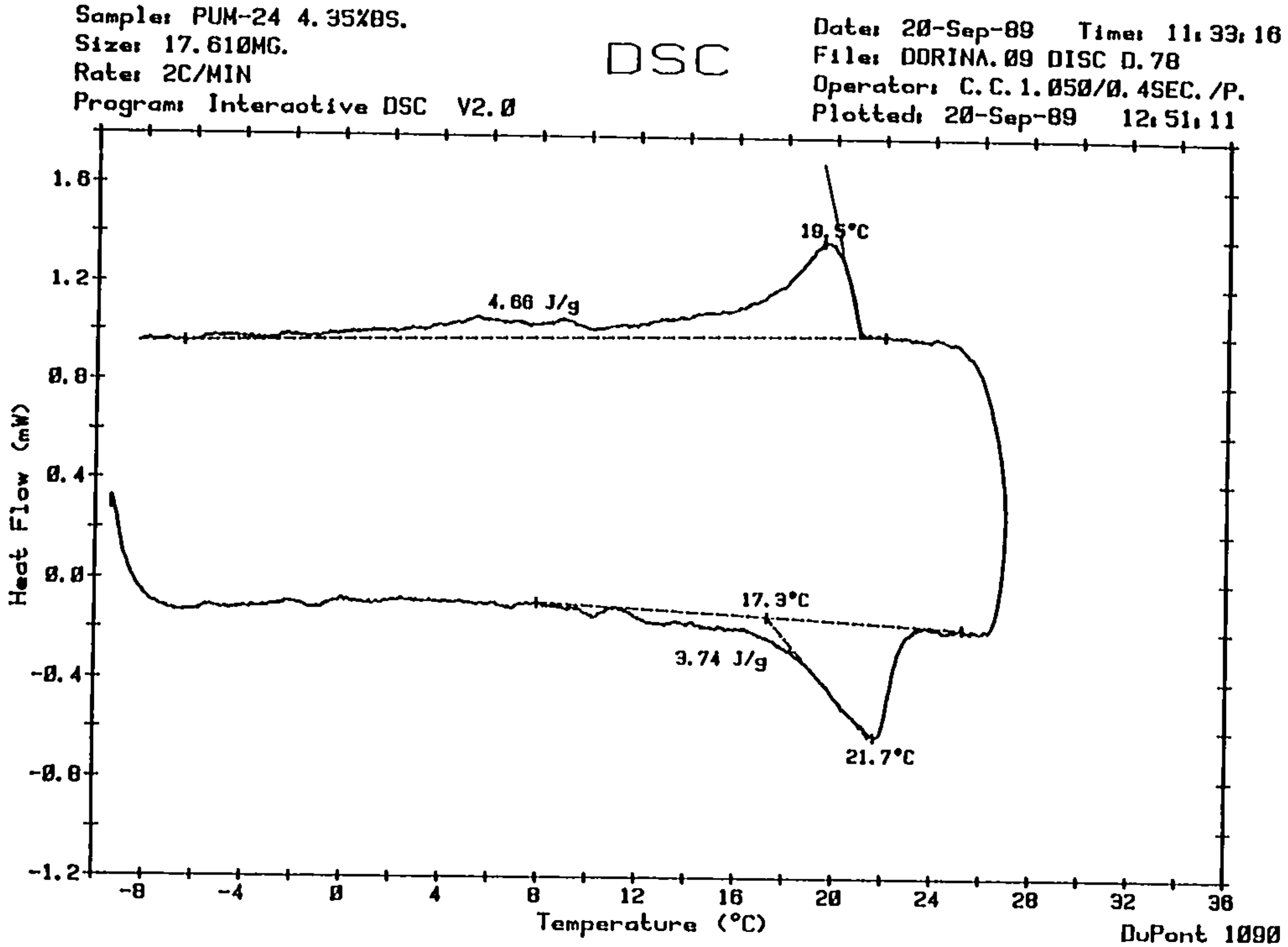
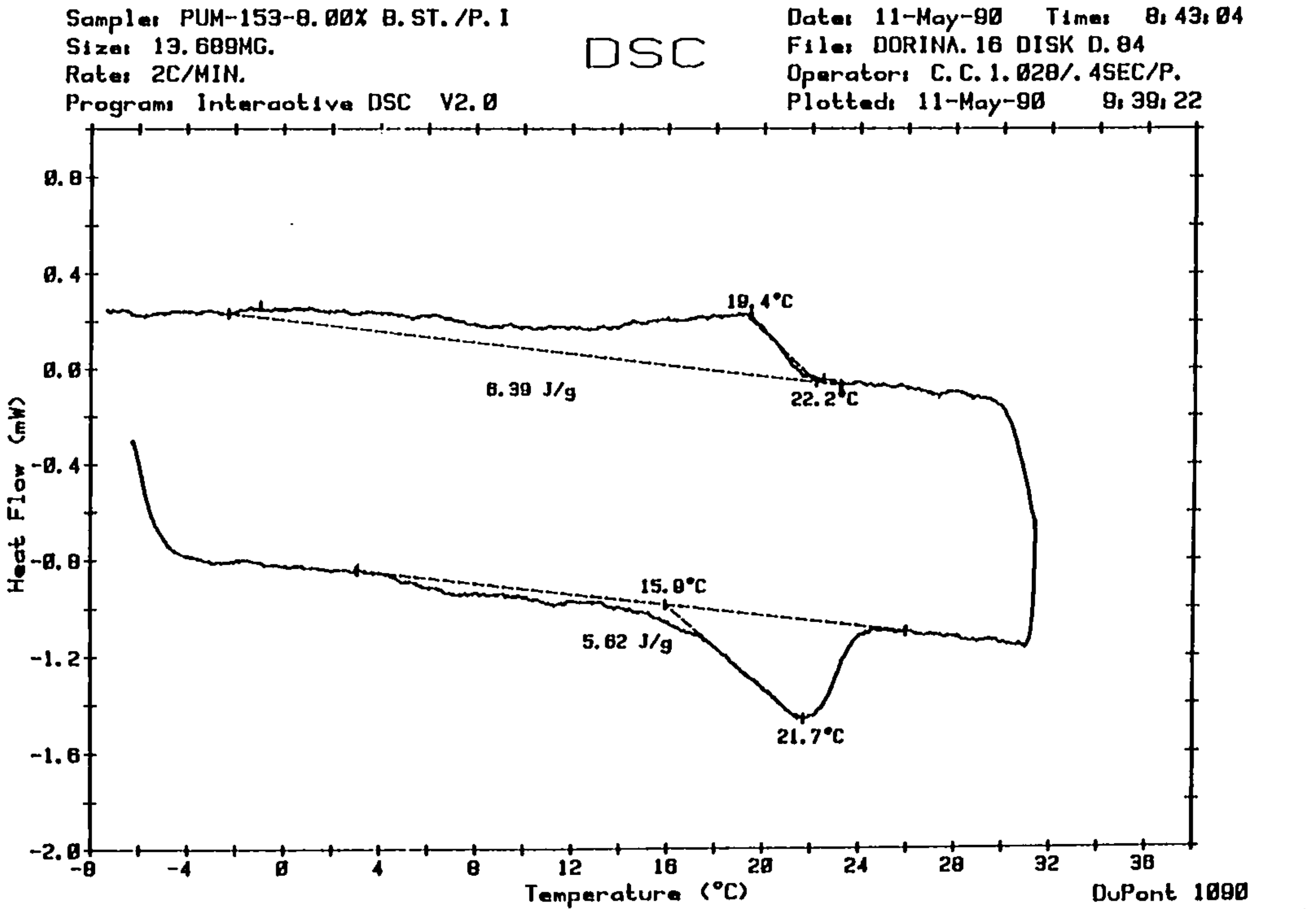


FIGURE A6 - DSC ANALYSIS OF BUTYL STEARATE IN PUMICE BLOCK (SPEC 24 - 364 DAYS)



Sample: PUM-153-8.00% B.ST./P.I
Size: 13.689MG.
Rate: 2C/MIN.
Program: Interactive DSC V2.0

Date: 11-May-90 Time: 8:43:04
File: DORINA.16 DISK D.84
Operator: C.C.1.028/.4SEC/P.
Plotted: 11-May-90 9:39:22

FIGURE A7 - DSC ANALYSIS OF PRE-IMPREG. BUTYL STEARATE IN MODIFIED PUMICE BLOCK (SPEC 153 - 423 DAYS)

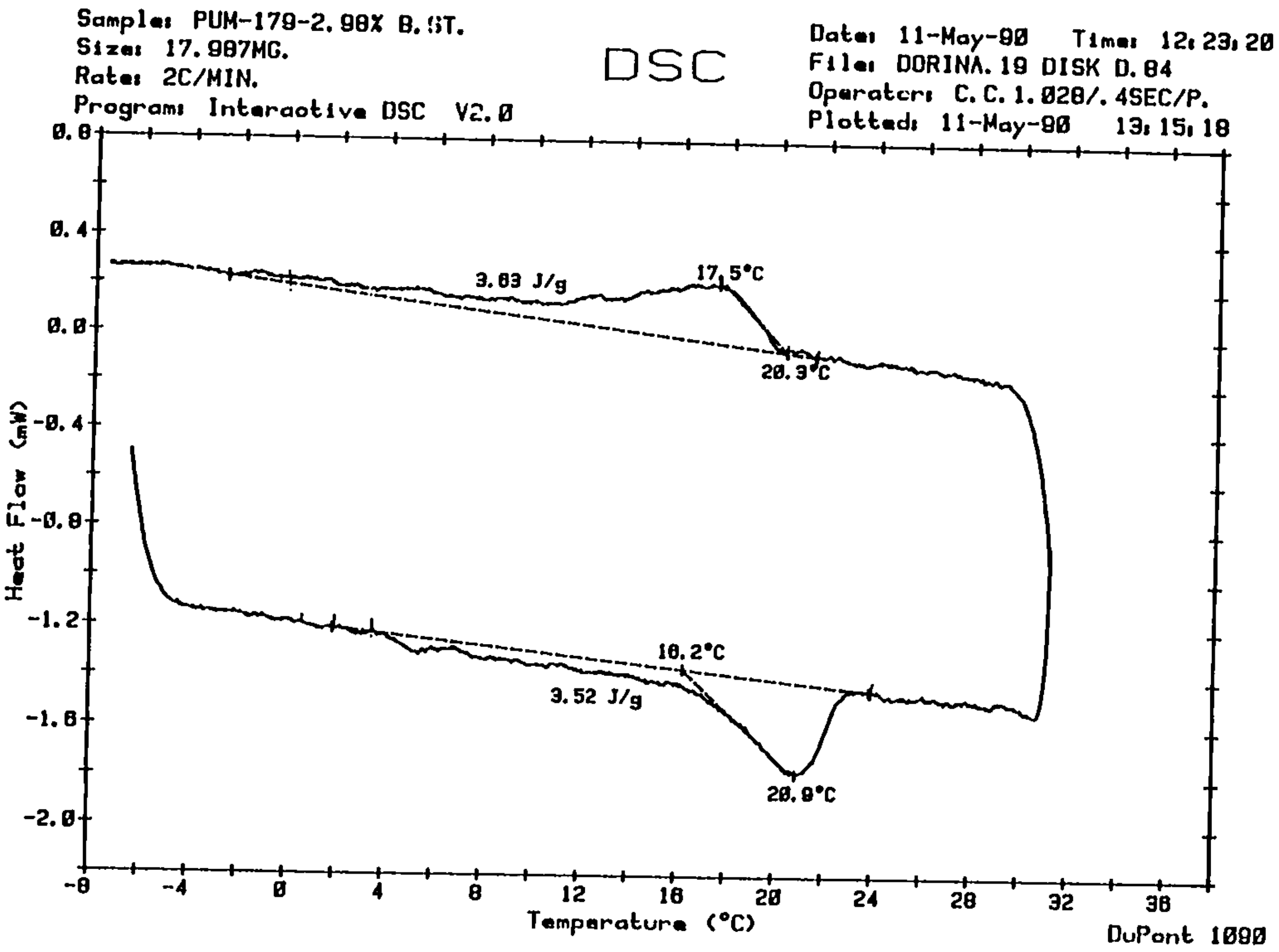


FIGURE A8 - DSC ANALYSIS OF BUTYL STEARATE IN MODIFIED PUMICE BLOCK (SPEC 179 - 373 DAYS)

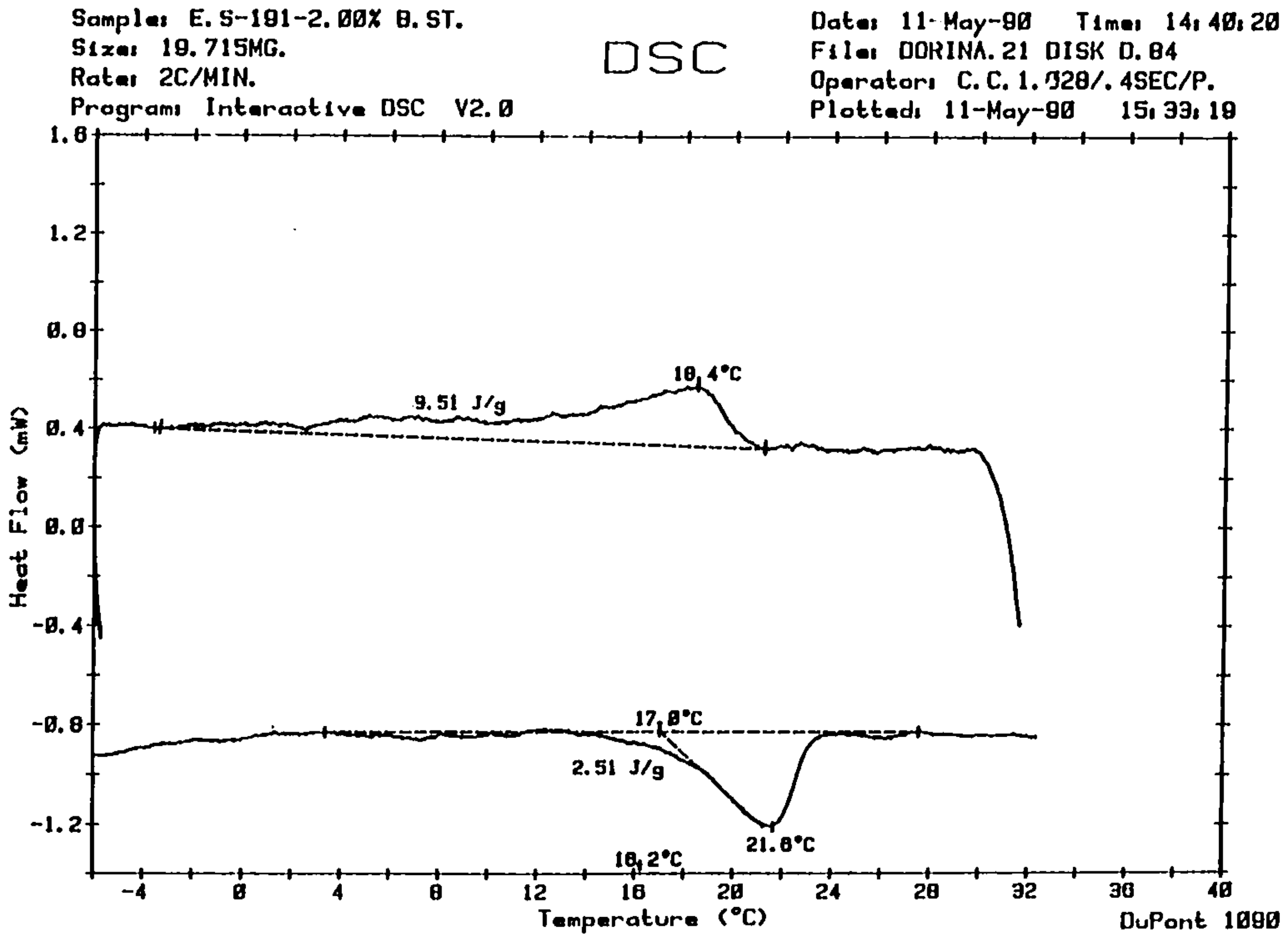
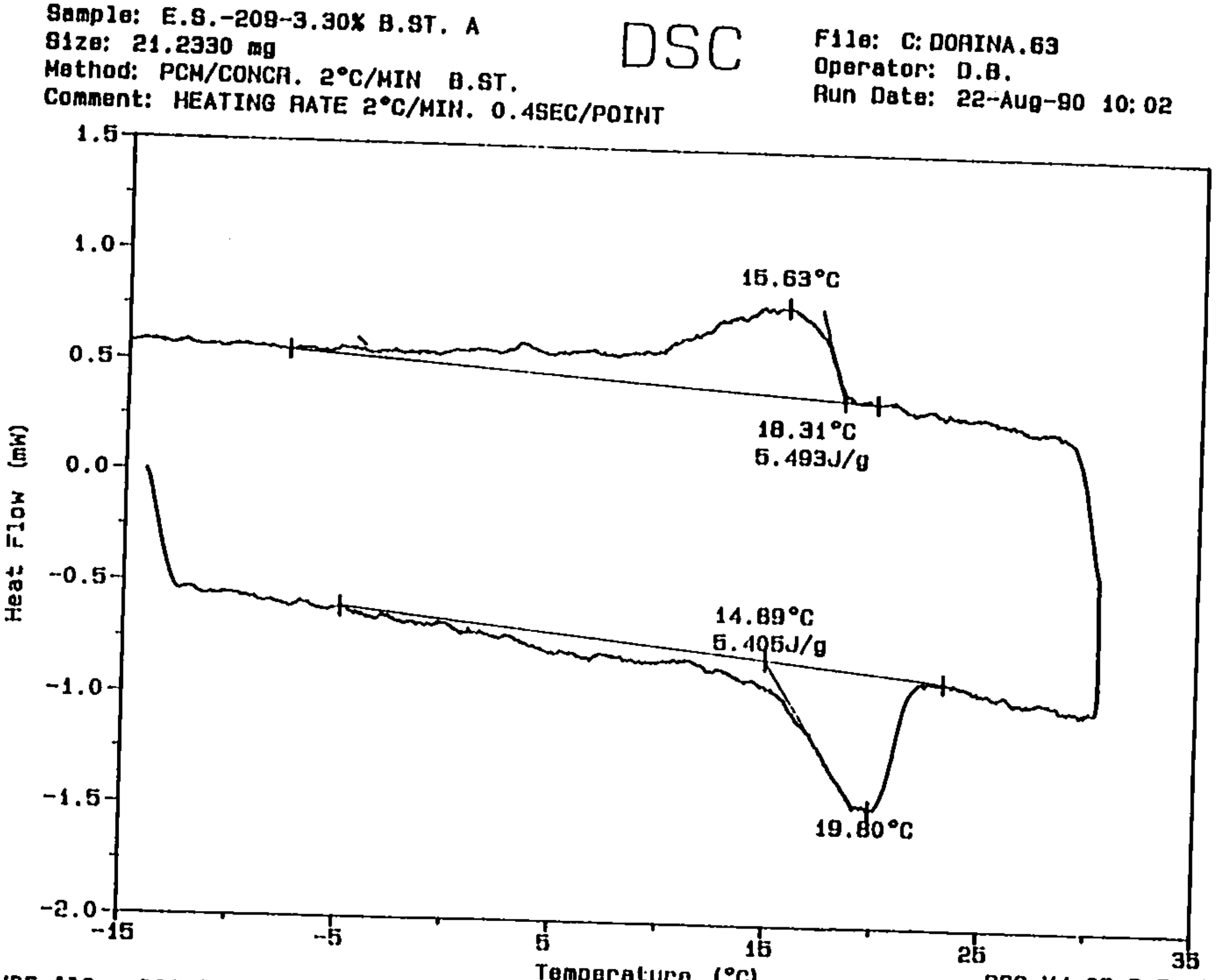


FIGURE A9 - DSC ANALYSIS OF BUTYL STEARATE IN MODIFIED EXPANDED SHALE BLOCK (SPEC 191 - 372 DAYS)



Sample: E.S.-209-3.30% B.ST. A
Size: 21.2330 mg
Method: PCM/CONCR. 2°C/MIN B.ST.
Comment: HEATING RATE 2°C/MIN. 0.4SEC/POINT

DSC

File: C:DORINA.63
Operator: D.B.
Run Date: 22-Aug-90 10:02

DSC V4.0B DuPont 2100

FIGURE A10 - DSC ANALYSIS OF BUTYL STEARATE IN MODIFIED EXPANDED SHALE BLOCK (SPEC 209 - 475 DAYS)

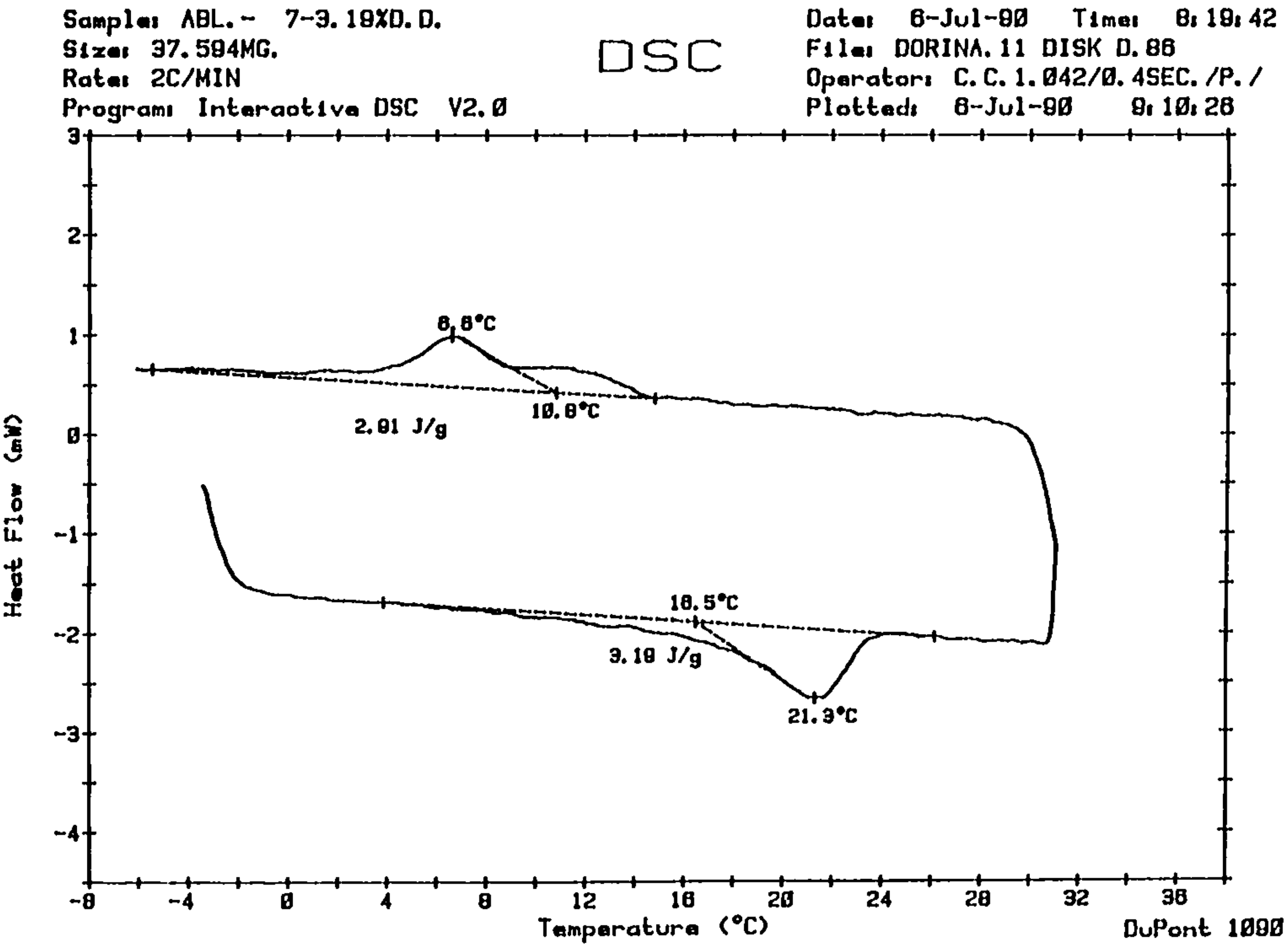


FIGURE A11 - DSC ANALYSIS OF DODECANOL IN AUTOCLAVED BLOCK (SPEC 7 - 653 DAYS)

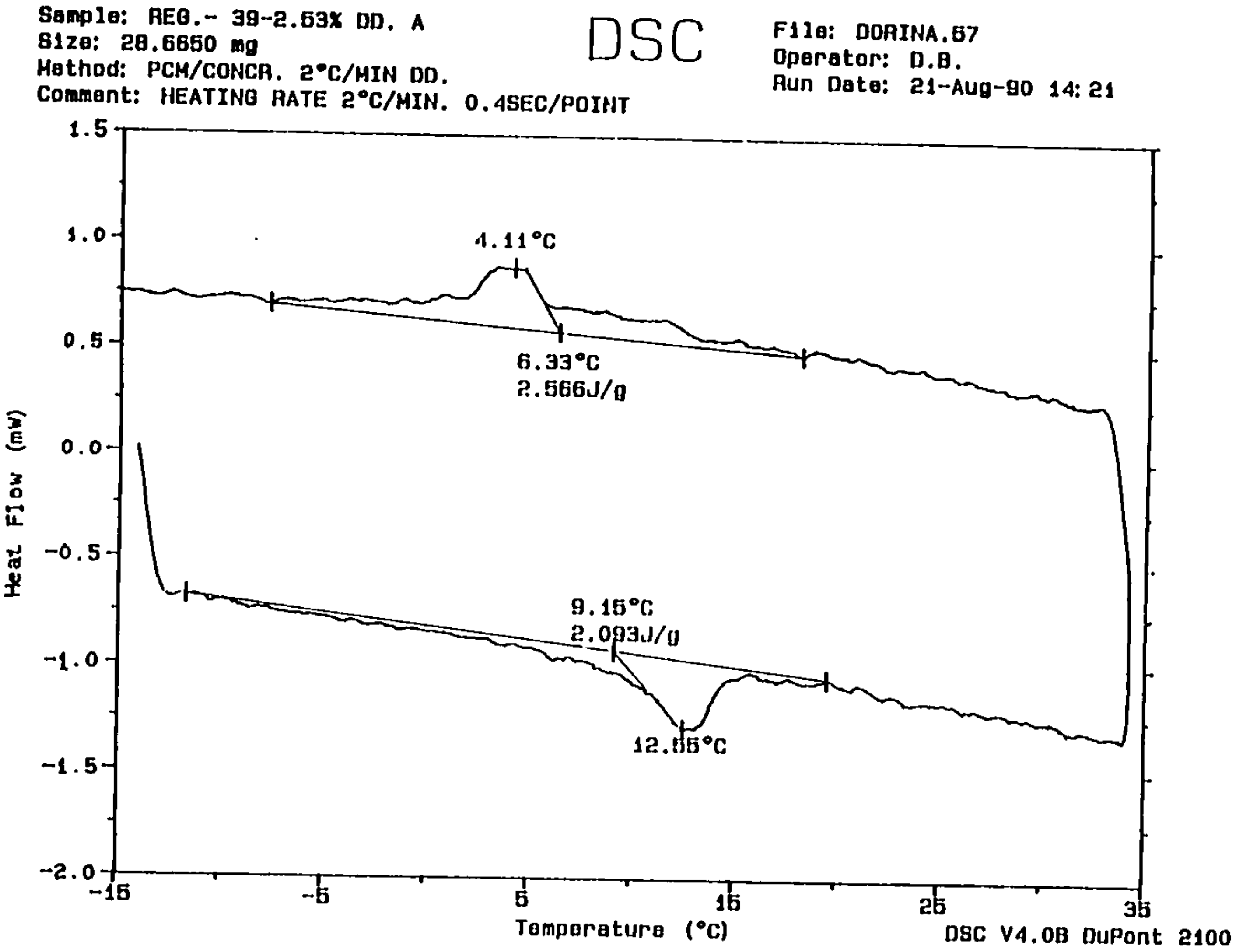


FIGURE A12 - DSC ANALYSIS OF DODECANOL IN REGULAR BLOCK (SPEC 39 - 693 DAYS)

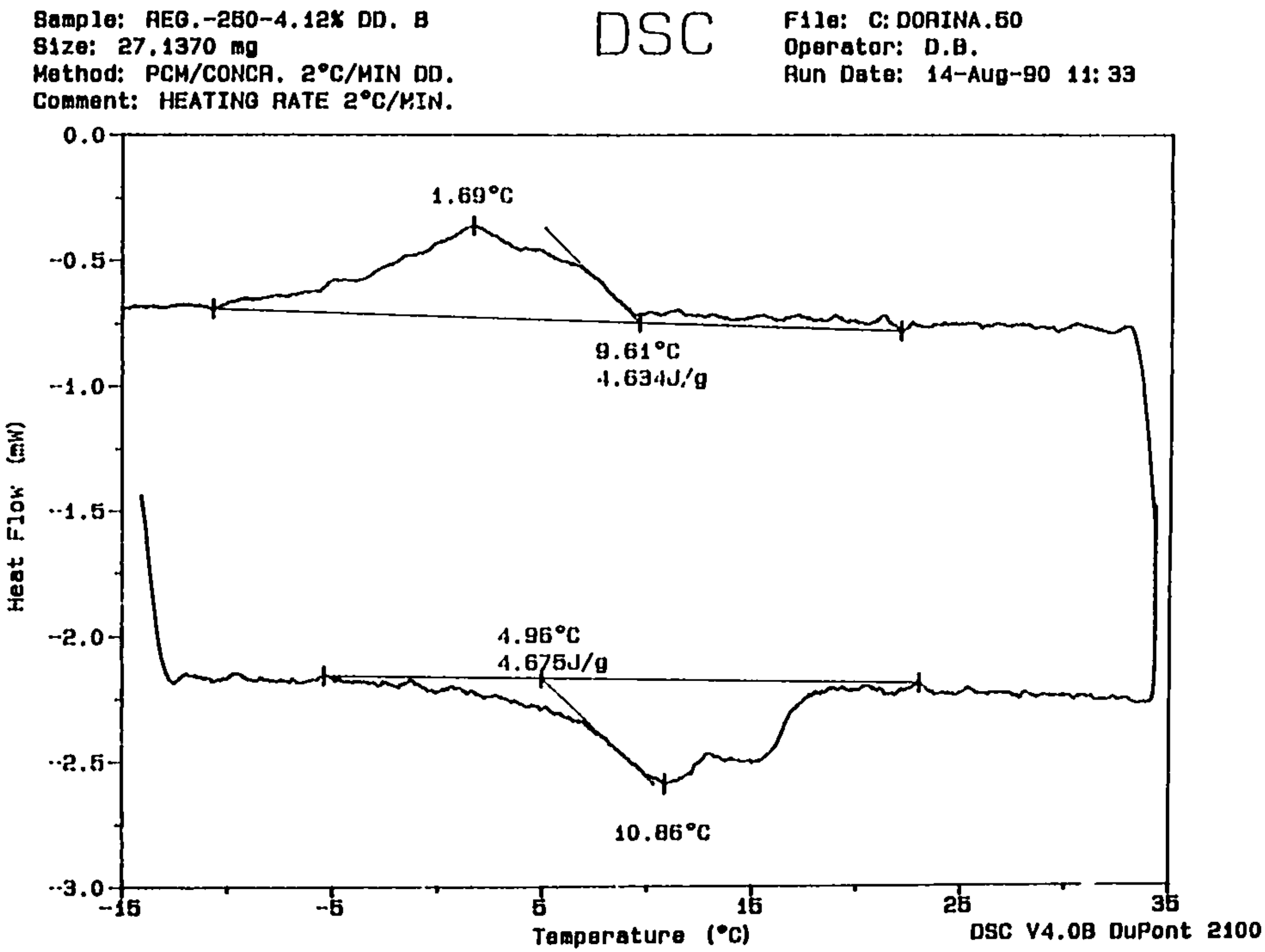


FIGURE A13 - DSC ANALYSIS OF DODECANOL IN MODIFIED REGULAR BLOCK (SPEC 250 - 432 DAYS)

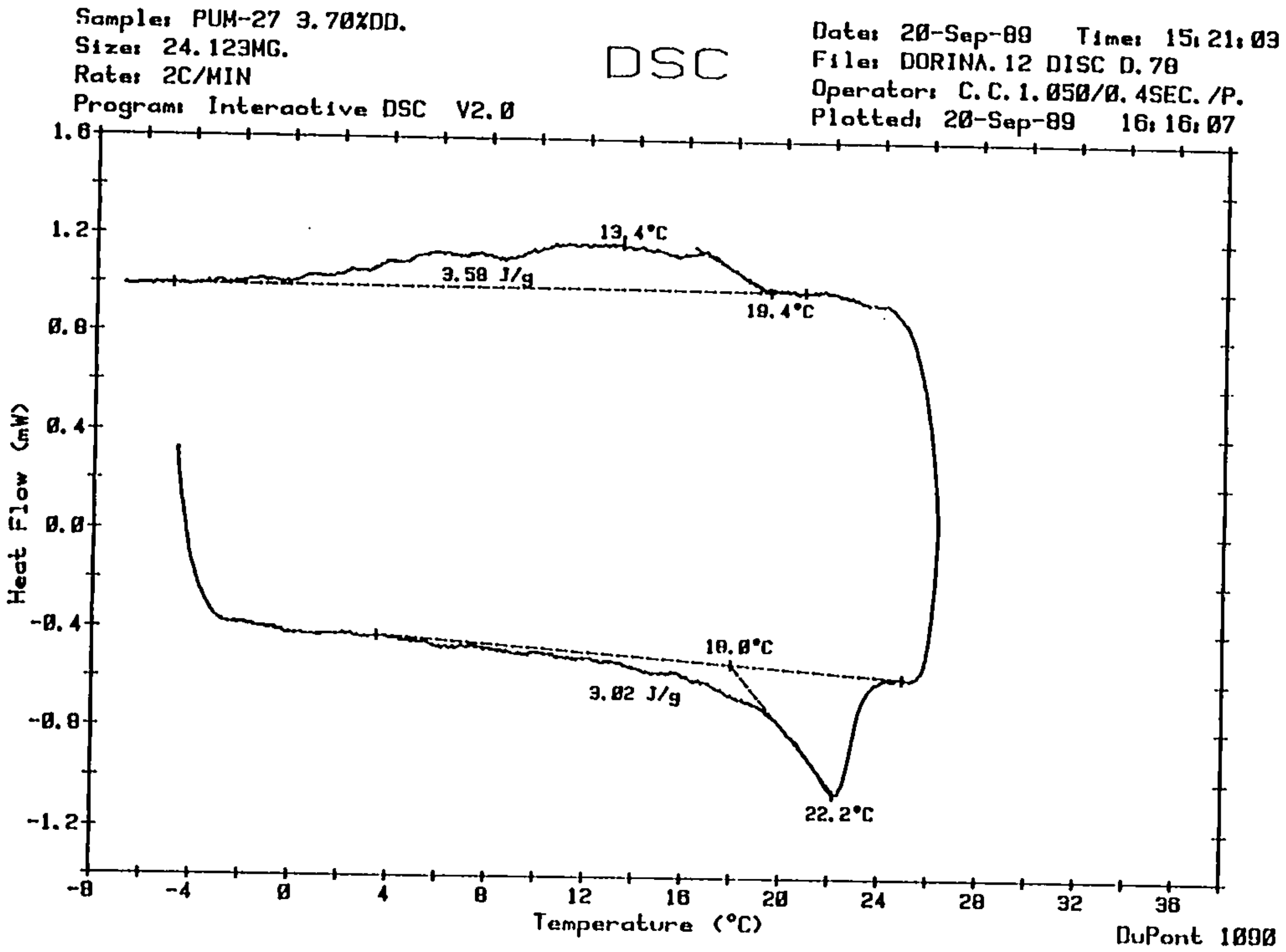


FIGURE A14 - DSC ANALYSIS OF DODECANOL IN PUMICE BLOCK (SPEC 27 - 364 DAYS)

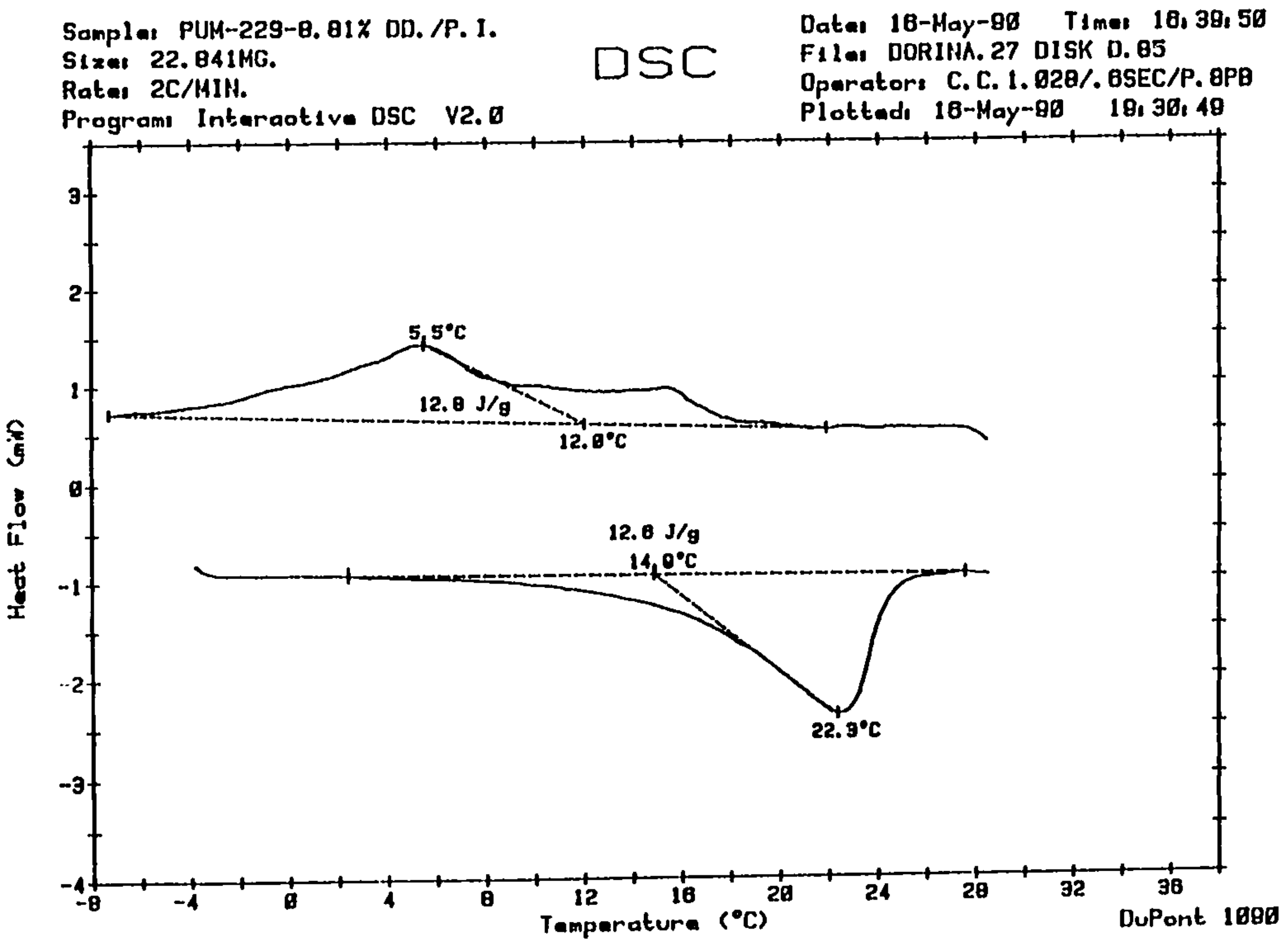


FIGURE A15 - DSC ANALYSIS OF DODECANOL IN MODIFIED PUMICE BLOCK (SPEC 229 - 377 DAYS)

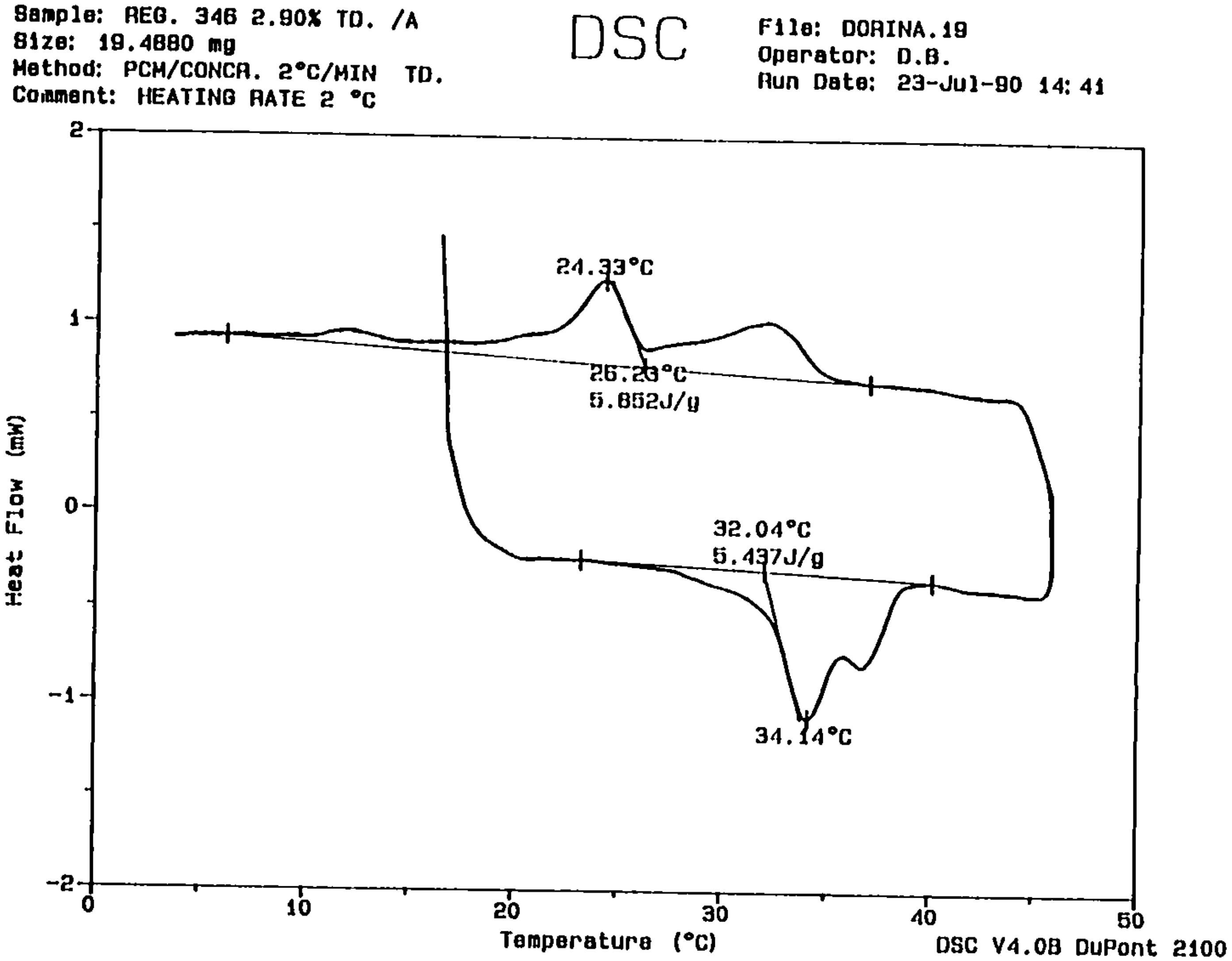


FIGURE A16 - DSC ANALYSIS OF TETRADECANOL IN MODIFIED REGULAR BLOCK (SPEC 346 - 405 DAYS)

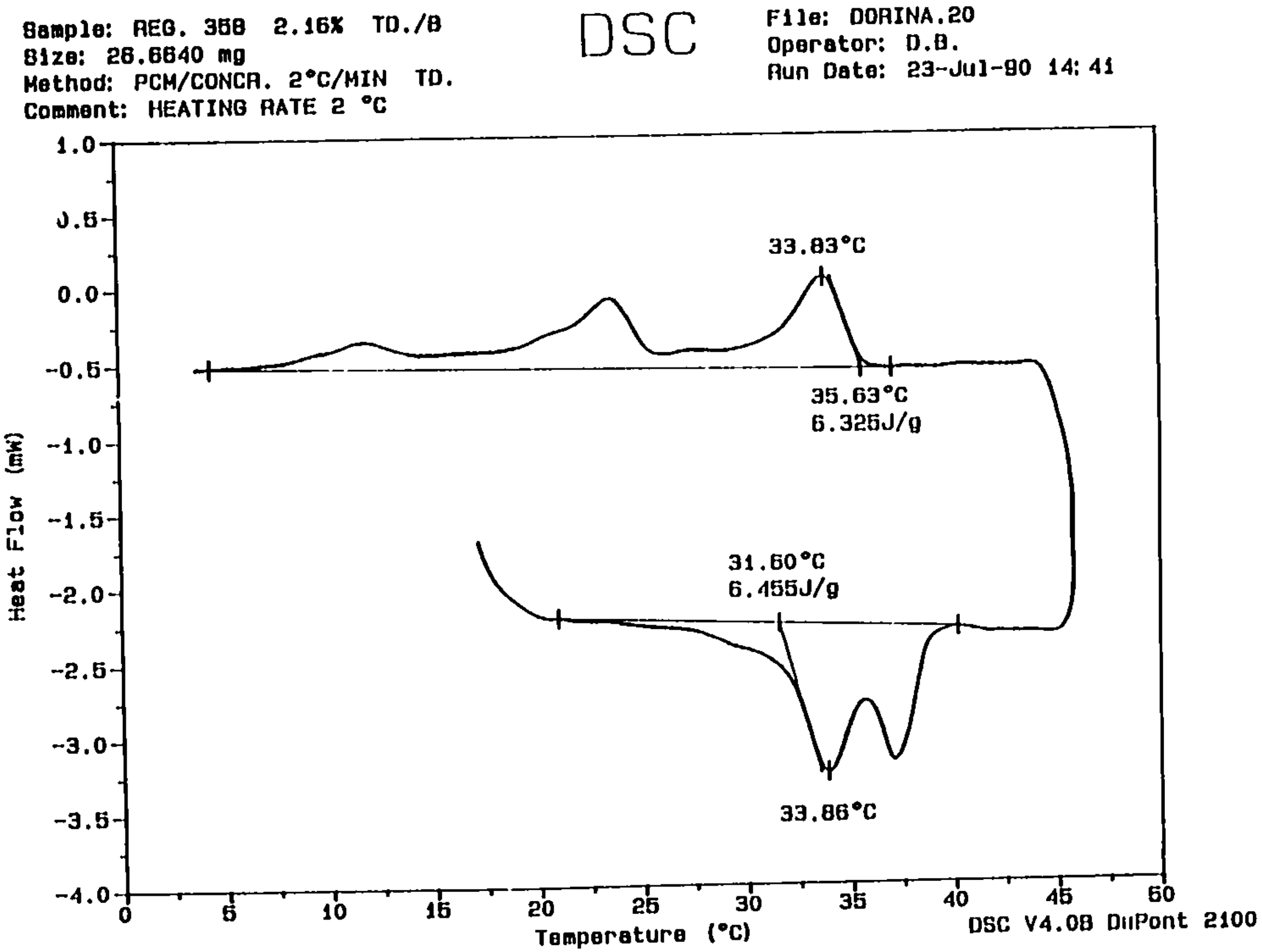


FIGURE A17 - DSC ANALYSIS OF TETRADECANOL IN MODIFIED REGULAR BLOCK (SPEC 358 - 403 DAYS)

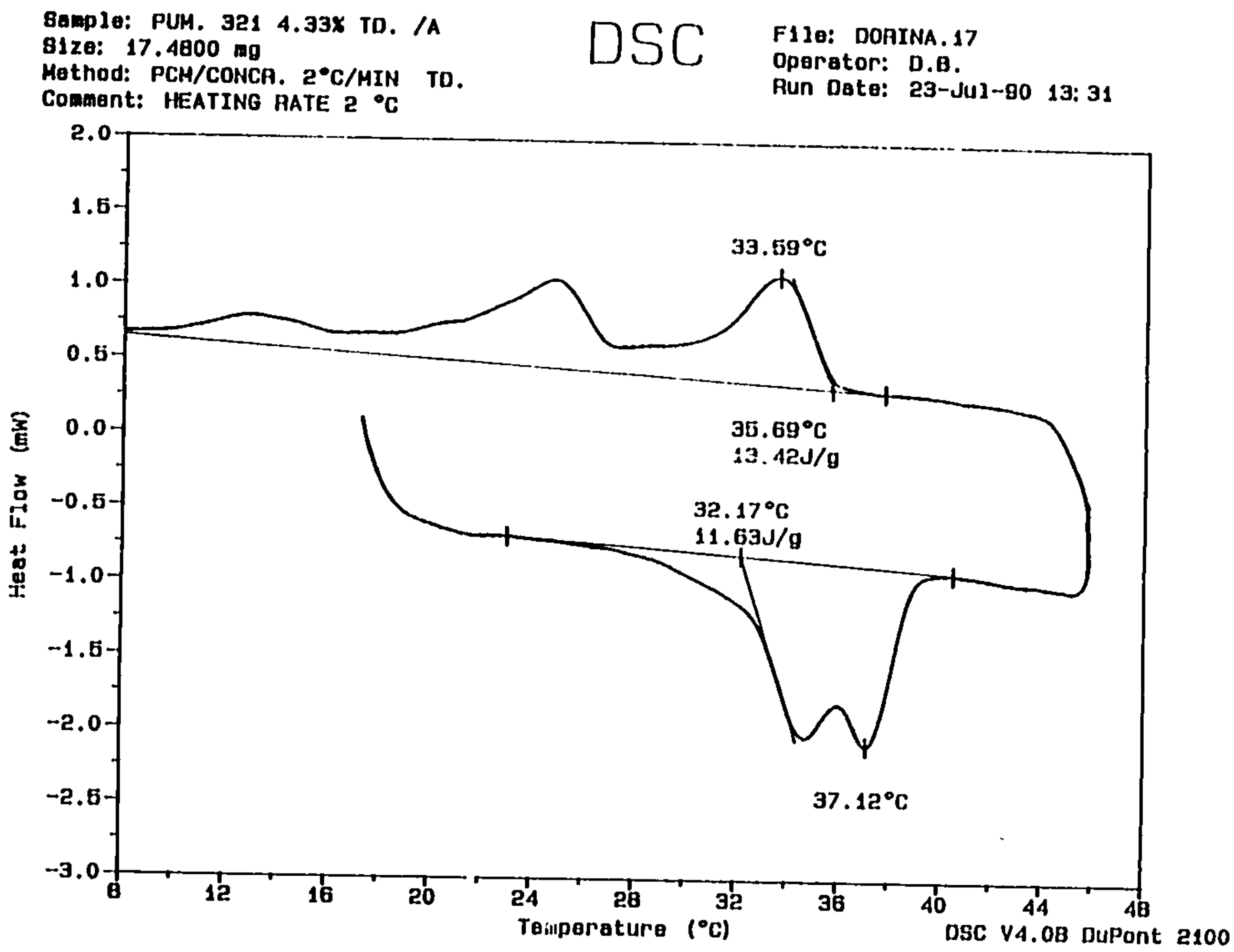


FIGURE A18 - DSC ANALYSIS OF TETRADECANOL IN MODIFIED PUMICE BLOCK (SPEC 321 - 404 DAYS)

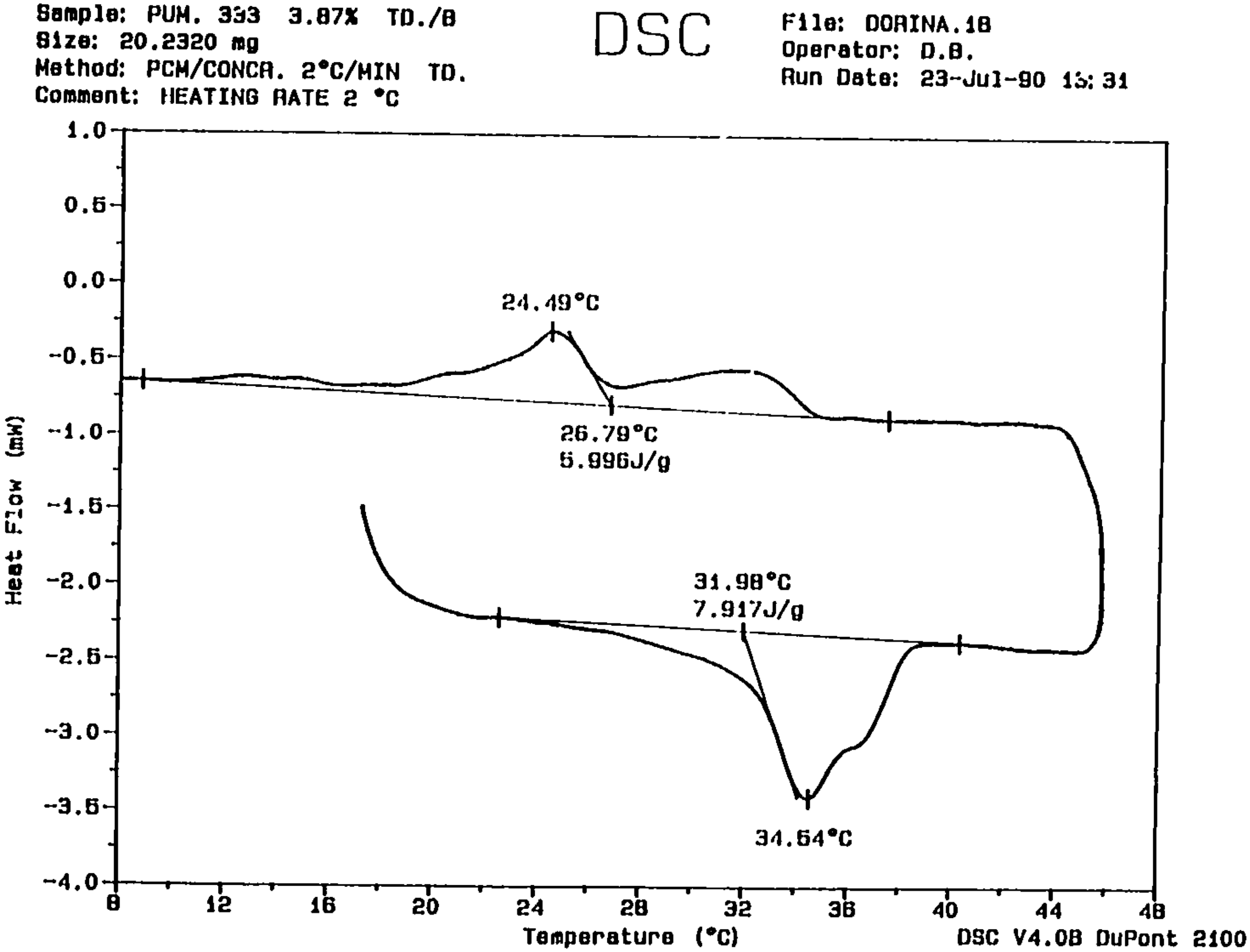


FIGURE A19 - DSC ANALYSIS OF TETRADECANOL IN MODIFIED PUMICE BLOCK (SPEC 333 - 403 DAYS)

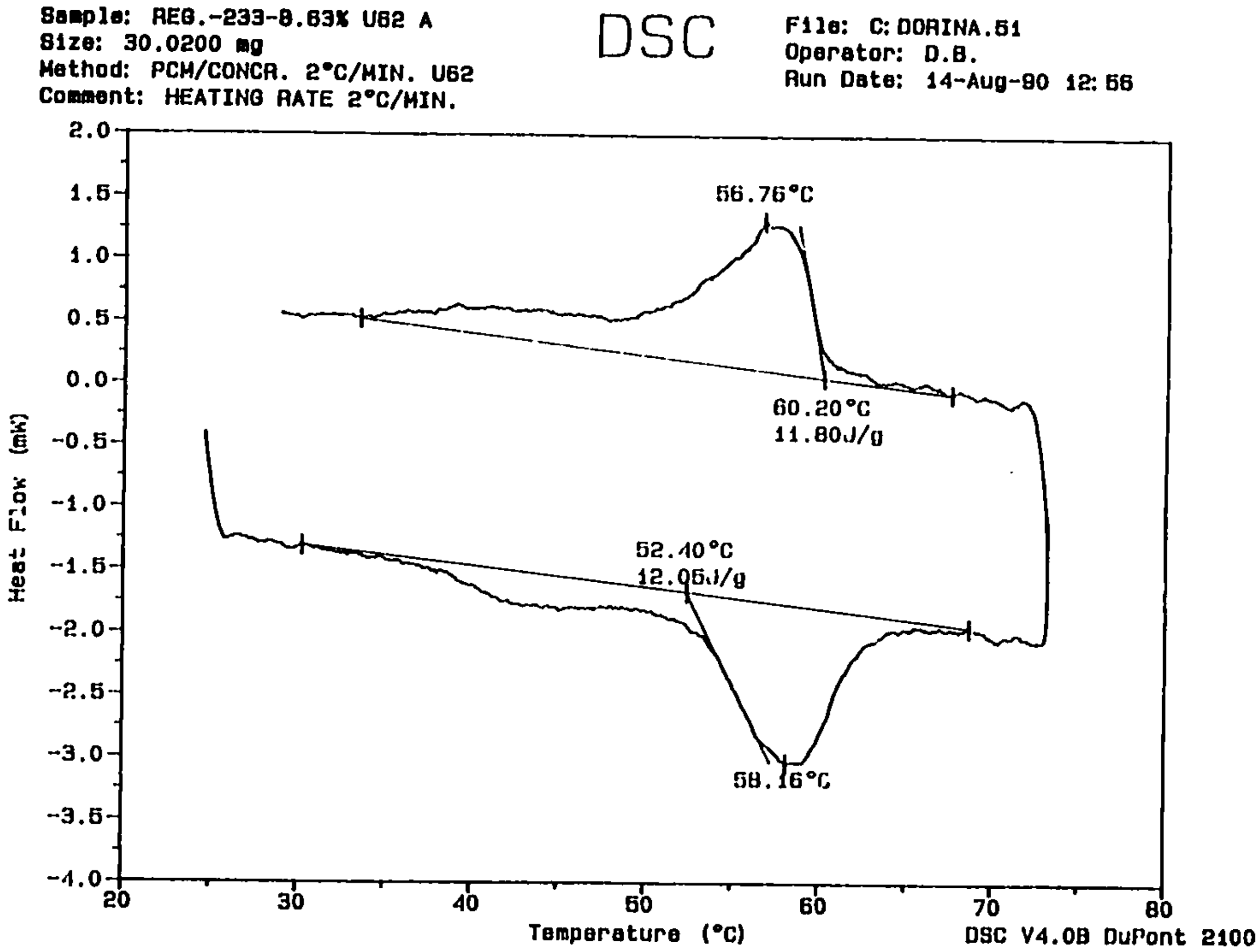


FIGURE A20 - DSC ANALYSIS OF PARAFFIN IN REGULAR BLOCK (SPEC 233 - 428 DAYS)

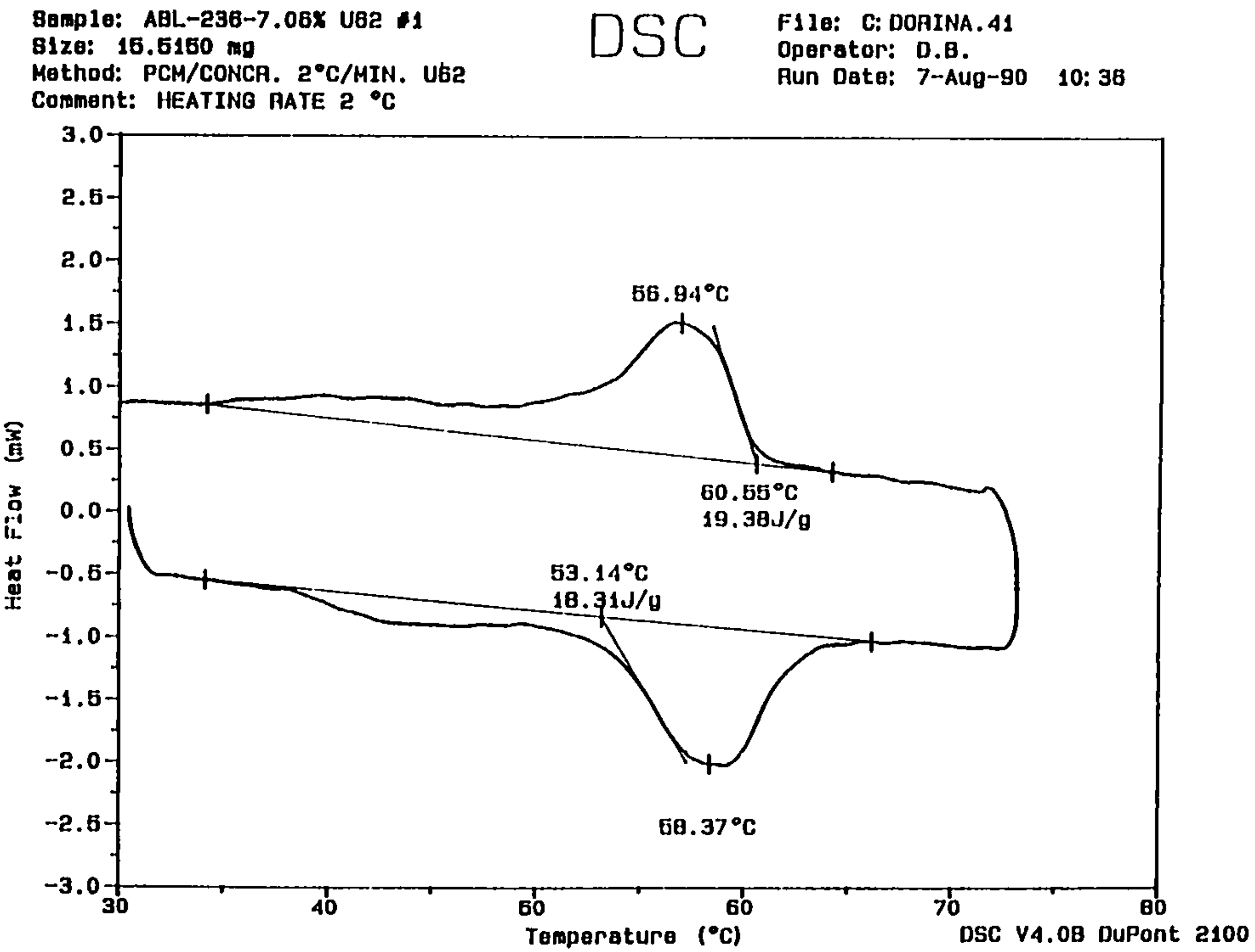


FIGURE A21 - DSC ANALYSIS OF PARAFFIN IN AUTOCLAVED BLOCK (SPEC 236 - 421 DAYS)

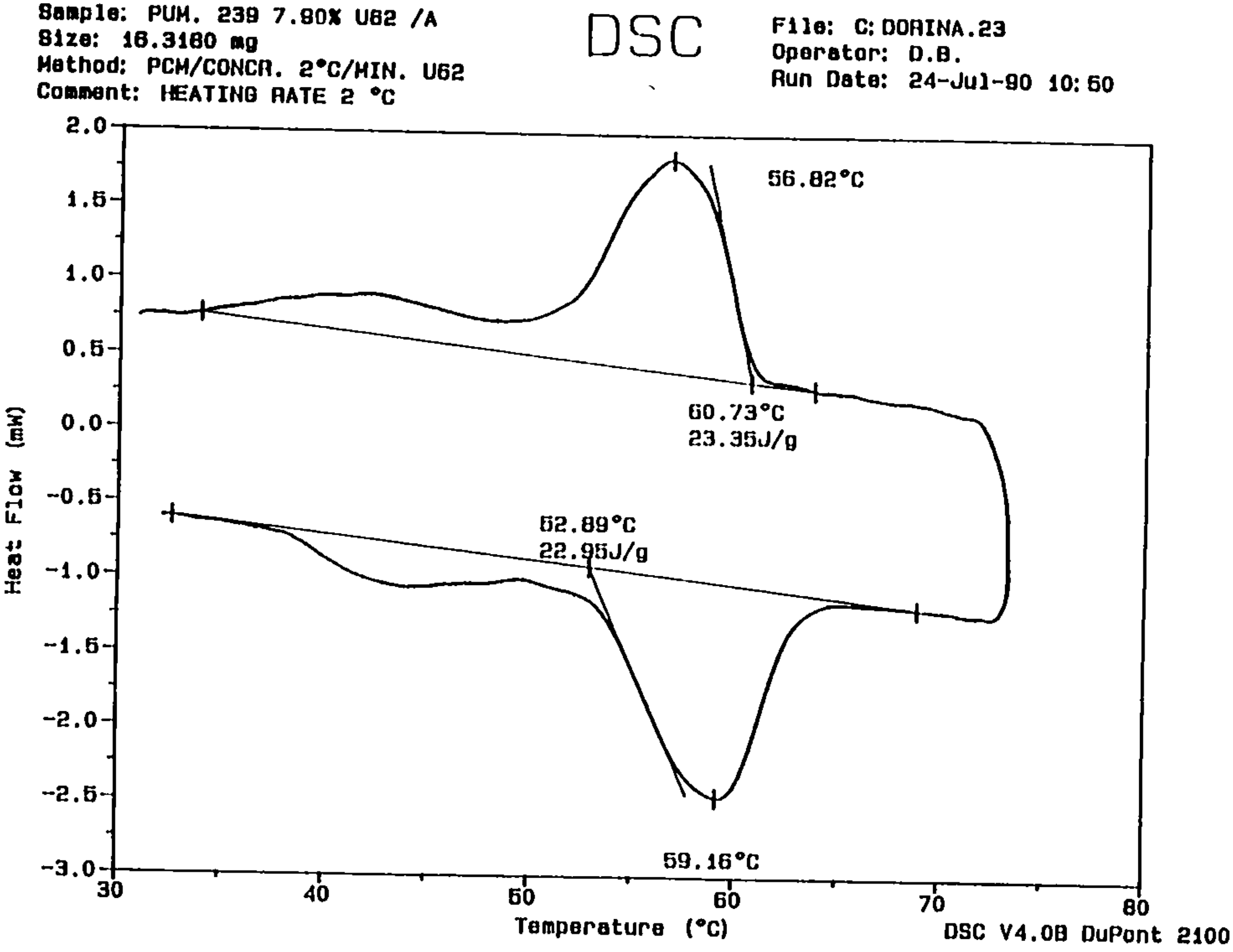


FIGURE A22 - DSC ANALYSIS OF PARAFFIN IN PUMICE BLOCK (SPEC 239 - 407 DAYS)

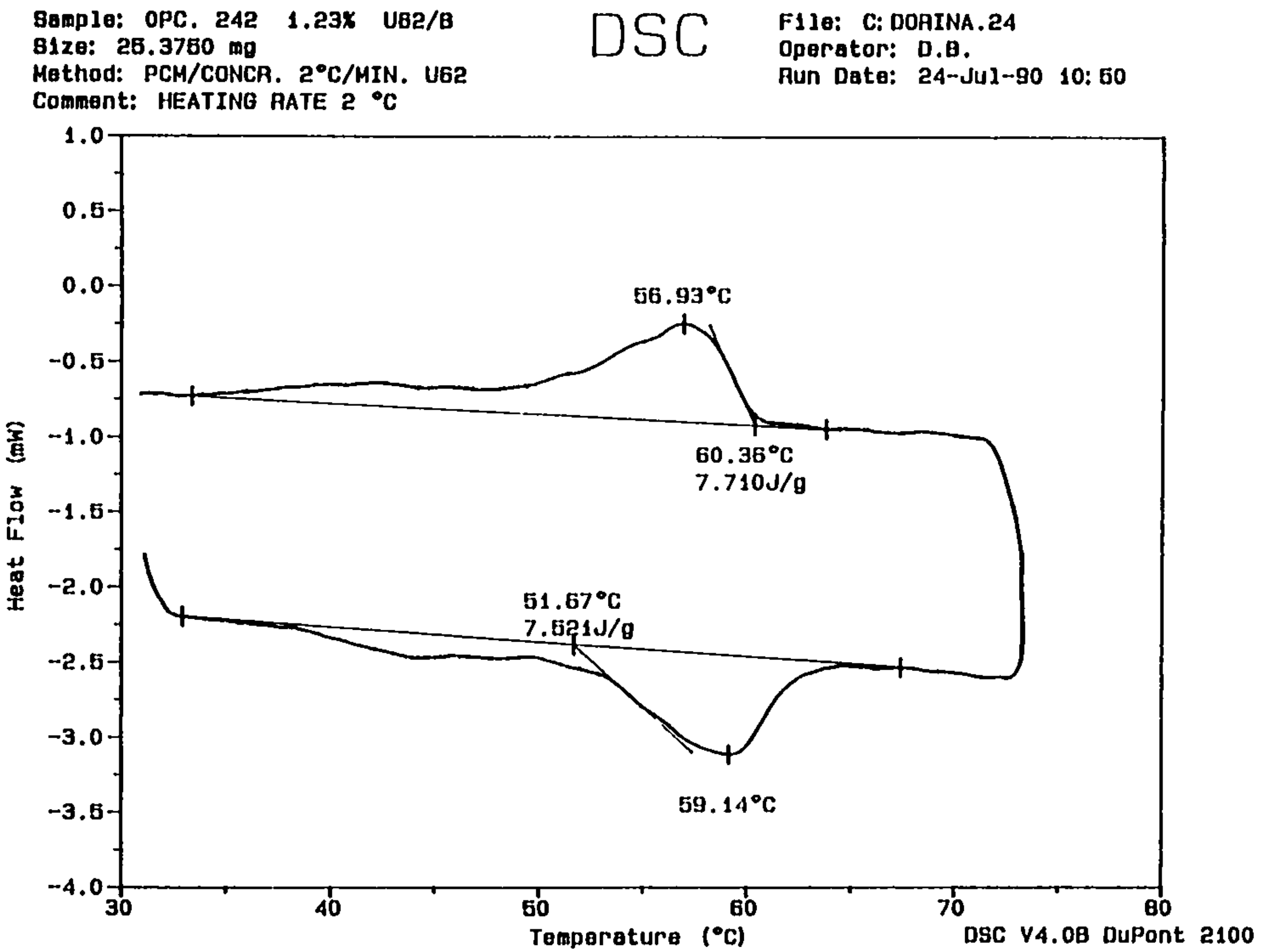


FIGURE A23 - DSC ANALYSIS OF PARAFFIN IN ORDINARY PORTLAND CEMENT CONCRETE (SPEC 242 - 407 DAYS)