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LABORATORY TEST PROCEDURES TO PREDICT THE THERMAL BEHAVIOUR OF CONCRETE

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A thesis submitted to the Faculty of Engineering, University of the Witwatersrand, Johannesburg, in fulfilment of the requirements for the degree of Doctor of Philosophy.

Johannesburg, November 1995

Declaration

I declare that this thesis is my own, unaided work, except where otherwise acknowledged. It is being submitted for the degree of Doctor of Philosophy in the University of the Witwatersrand, Johannesburg. It has not been submitted before for any degree or examination in any other University.

Signed this 2 day of November 1995

George James Gibbon.

Abstract

The cracking of mass and structural concrete due to thermal stress is a major problem in the concrete construction industry. Concrete will crack when the thermal stress exceeds the tensile strength of the concrete. Decisions on the type of concrete mix, cooling facilities and construction techniques to be used in the erection of a concrete structure can only be made if the thermal behaviour and strength of the concrete can be predicted during hydration. This thesis describes the development of a low cost, computer controlled, adiabatic calorimeter to determine the heat of hydration and a probe to determine the thermal conductivity of concrete samples. The main thrust of this thesis is the development of the thermal conductivity probe which, for the first time, can measure the thermal conductivity of concrete through all stages of hydration. A thermal model was also developed to verify the results, and the use of the calorimeter for temperature matched curing tests is also discussed. Results, obtained from the test procedures described, will provide far more accurate predictions of the temperatures in concrete structures than was possible in the past.

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Chapter 1

INTRODUCTION

The cracking of mass and structural concrete due to thermal stress is a major problem in the construction of concrete structures with large cross sections. Thermal stress is the result of internal strains within the structure due to temperature changes and gradients caused by the exothermic hydration process, or changes in the ambient temperature conditions.

A chemical reaction takes place as soon as water is mixed with cement. The four major components of the cement which react with the water are tricalcium silicate, dicalcium silicate, tricalcium aluminate plus gypsum and tetracalcium aluminoferrite [1, 2]. These reactions are all exothermic, producing what is known as the heat of hydration. The heat produced by each of these reactions differs as shown in table 1.1 and the relative proportions of these components alters the total heat produced.

Low heat producing cement is mainly manufactured by reducing the high heat evolving tricalcium compounds by increasing the content of ferric oxide during the manufacturing process. This, unfortunately, reduces the rate of strength gain in concrete made with this cement which could disrupt the construction process. The addition

Table 1.1: Heat of Hydration of Cement Constituents
(after Lerman [1])

Tricalcium silicate	500 kJ/kg
Dicalcium silicate	260 kJ/kg
Tricalcium aluminate	860 kJ/kg
Tetracalcium aluminoferrite	420 kJ/kg

of cement extenders, such as fly ash (FA) or blast furnace slag (GGBS) reduces the heating rate of the concrete, thus reducing the maximum temperature reached in a structure [3]. The percentage of cement in concrete and the water:cement ratio will also alter the heat produced during hydration, as well as the strength of the concrete [3].

The temperature changes, as a result of hydration, will cause changes in volume within the structure that are dependent on the coefficient of thermal expansion of the concrete. The magnitude of the thermal stress caused by this expansion is dependent on the elastic modulus of the concrete and the degree of restraint of the structure. All these factors are dependent on the degree of hydration and the cooling rate of the structure, and will therefore vary with time. Creep and drying shrinkage will also influence the cracking strain of the concrete, adding to the complexity of modelling the thermal stresses.

Concrete will crack if the thermal stress is greater than or equal to the tensile strength of the concrete [4].

The tensile strength of plain concrete cannot be increased without decreasing the water:cement ratio by increasing the cement content, resulting in an increase in the heat of hydration and increased thermal stress.

The thermal stress (σ) at any point of a concrete block lying on a rigid foundation is given as [4]:

$$\sigma = \frac{K_r \, E_{ef} \, \alpha \, \delta T}{1 - \mu} \tag{1.1}$$

where

K_r = Degree of restraint caused by the foundation and the hardening concrete

E_{ef} = Effective modulus of elasticity (influenced by the foundation and reduction of stress due to relaxation)

α = Thermal expansion

δT = The difference between the maximum concrete temperature and the surrounding air temperature

μ = Poisson's Ratio

K_r, E_{ef}, α and μ are all dependent on the geometry of the structure, the construction methods and the aggregates used in the concrete mix [4, 5, 6]. As these factors are very largely site dependent, the only controllable factor is the temperature drop (δT). The magnitude of δT is directly related to the maximum temperature obtained

during the hydration period. The heat of hydration, thermal conductivity and the ambient temperature all influence the maximum temperature in a concrete structure.

The dimensions of mass or large concrete structures are difficult to define as the type of cement and construction techniques used, as well as the physical dimensions, need to be considered. Any concrete structure where the thermal stress, induced by the heat of hydration, may exceed the tensile strength of the concrete should be considered as a mass concrete structure.

The physical properties of concrete are both time and temperature dependent, with the rise in temperature being catalytic to the hydration reaction [7]. To determine the actual tensile strength of the concrete in a structure, tensile strength tests should be conducted on concrete samples cured at the expected temperature profile that would be found at different depths within the structure. These are known as temperature matched curing (TMC) tests [8, 9, 10].

The choice of the correct concrete mix and possible cooling facilities for a structure are difficult to determine if the full information to create an accurate model is not available. For accurate models of thermal stress and strain in various structures to be determined, the heat of hydration and thermal conductivity of the concrete to be used in the structures need to be known throughout the entire hydration and cooling periods. This is important for both the control and management of any thermal cracking in continuous concrete pours and both crack control and prediction of cooling rates where joints need to be grouted after initial shrinkage of the structure has occurred. This second fact is very important in the construction planning stages of a project, as delays in grouting can result in construction delays and large expenses to the contractor.

The heat of hydration of a concrete mixture is normally derived using the heat of solution test [11], adiabatic calorimetry [12, 13, 7], the isothermal method [7] or conduction calorimetry [14].

The thermal conductivity of a concrete mix during the initial hydration period has, apparently, never been measured before. Traditionally the values for the thermal conductivity used for heat models of concrete structures have been based on the properties of the aggregate or the hardened concrete with a single value being assumed for all stages of hydration. This does not represent the actual conditions of the concrete during hydration and the need for a better test method was apparent. Concrete has two major problems associated with the measurement of its thermal conductivity during hydration. They are the change in state from a "semi-liquid"

to a solid within the first twenty four hours of hydration as well as the simultaneous production of heat.

The thesis describes the development of a computer controlled calorimeter, a thermal conductivity probe and a set of laboratory tests used to determine the heat generation and heat dissipation properties of a concrete sample throughout the hydration cycle. The main thrust of the work was the development of a test method to measure the thermal conductivity of concrete during the hydration period. In addition, a simple dynamic heat model, using the test results as input, was developed to estimate the temperatures obtained at different depths in a concrete structure. The development of the model was primarily to test the results obtained from the new test procedures. Similarly, unless otherwise stated, the various concrete mixes used in this thesis were chosen for their convenience for easy mixing and handling rather than any practical applications, and any comparison of the results should be considered in this light. The tests conducted only covered the early hydration period of the concrete, normally the first three to five days, to reduce the duration of a test during the development period of the apparatus. The heat being produced by the hydration had dropped to practically zero in all tests presented this thesis. There is no reason why the period cannot be extended further if this is necessary. The use of the calorimeter for temperature matched curing tests is also discussed.

The thesis has been divided into chapters covering the following topics:

- A literature review of the research undertaken and present practices to minimise damage in concrete structures due to thermal stress.
- The development and calibration of an adiabatic calorimeter for testing the thermal behaviour of 2 kg concrete samples.
- The determination of the heat of hydration of samples tested in the calorimeter.
- The development and calibration of a probe to measure the thermal conductivity of concrete samples during all stages of hydration.
- A thermal model to verify the results obtained from the calorimeter and thermal conductivity probe.
- A discussion of the use of the results obtained in practical applications, crack prediction and future research.

Chapter 2

REVIEW OF THE LITERATURE

The literature review examines research undertaken with the specific aim of minimising damage in concrete structures due to thermal stress. The review has been divided into five sections: The first two cover the development of measurement techniques used to determine the heat of hydration and thermal conductivity of concrete. The third section covers the measurement and calculation of the temperature increase in concrete structures, while the fourth describes ways to determine and control thermal stress. The fifth section briefly reviews current practices and recommendations. Although the literature review has been divided into the five sections for convenience, the subjects covered are all interrelated, with many researchers investigating more than one aspect of thermal stress in concrete.

2.1 Heat of Hydration

The four most common methods for the determination of the heat of hydration of concrete that were found in the literature are discussed below:

- The heat of solution [11] test is a chemical test where the difference in the heat produced by dry and hydrated cement samples, when mixed with a Nitric and Hydrofluoric acid mixture, are compared. The difference between the heat obtained from the two samples gives the heat of hydration during the period that the hydrated sample had been hydrating. Tests are conducted on 7 and 28 day hydrated samples. The heat of solution method only determines the total heat produced by the cement in a concrete, but does not indicate the rate of heat production at any point in time. The main attraction of the heat of solution test is the relatively low cost and simplicity of the test when compared

with other methods.

- Conduction calorimetry [14] measures the amount of heat removed from a sample of hydrating cement paste. This does not allow the sample to obtain the temperatures which it would in a concrete structure, and therefore does not simulate the true conditions, as the rate of hydration is affected by the temperature of the concrete.

- Adiabatic calorimetry [12, 13, 7] allows for both the total heat and the rate of heat produced by the concrete to be accurately determined, as there is no heat transfer from, or into, the test sample. Adiabatic conditions exist in mass concrete at depths greater than 0,5 m [7], so an adiabatic calorimeter will provide the conditions under which the bulk of a mass concrete structure will hydrate.

- The isothermal method [7] is a quasi-adiabatic method, using a Dewar or thermos flask to prevent heat loss, instead of an adiabatic control system. The heat loss from the flask is difficult to determine and will affect the rate of hydration giving incorrect results.

In 1932 Davey [15] described an adiabatic calorimeter which he used to determine the maximum rise in temperature that would be expected in mass concrete. As is stated in his technical paper [16], the observation and determination of the heat of hydration was first reported by Ribaucour in 1895, Howard in 1901 and Gary in 1906. Davey also compares the heat of solution method with his adiabatic calorimeter, as well as the calorimeter's ability to predict the temperature rise in mass concrete.

Blanks [17] and Meissner [18] described the development of large adiabatic calorimeter rooms, as well as the results obtained for various concrete mixes for an investigation into concrete for use in the construction of the Hoover Dam.

Carlson [19] correlates the various methods for determining the heat of hydration that were in common use at the time. He discusses the merits and disadvantages of the heat of solution method, adiabatic calorimetry and conduction calorimetry. He found that almost identical results could be obtained from all three methods, if due regard was paid to possible sources of error. These he defines as:

- The inability of adiabatic and conduction calorimeters to measure the immediate heat of hydration and the variations of the specific heat of concrete with temperature, which affects the results obtained from an adiabatic calorimeter.

Carlson defines the immediate heat of hydration as "the immediate and appreciable rise in temperature when cement is mixed with water". This heat production continues at a diminishing rate for about half an hour. Carlson believed that this heat is produced by the solution of free oxides and impurities, with only a small amount due to the hydration of the primary compounds or to the wetting of the cement grains. This heat amounts to about 5% of the total heat of hydration measured by the heat of solution method.

- Changes in the specific heat of the cement paste during hydration.
- Carbonation of the specimens introduces errors in the heat of solution method.
- The need for strict control with both mixing techniques and water:cement ratios.

Lerch [20] describes a conduction calorimeter used to determine the influence of gypsum on the hydration of cement and in 1948 [21], in a study of cement performance in concrete, he describes both conduction calorimetry and the heat of solution method for determining the heat of hydration. Ludwig [22] describes an improved conduction calorimeter patterned after the ones described by Carlson and Lerch.

In 1962 Klein [23] described methods to determine the thermal properties of concrete under adiabatic curing. His results for the heat of hydration proved unreliable, as was pointed out by McCoy in his discussion on the paper. Neither made any reference to Carlson's work which would have explained the errors.

Basson [7], on a visit to South Africa, compared adiabatic, isothermal and the heat of solution methods, for determining the heat of hydration of concrete using portland cement and blastfurnace slag. His results showed that the heat of solution method gave much lower values than the other two methods. He explained that this difference was due to the fact that the conservation of heat in the adiabatic and isothermal methods is catalytic to the hydration reaction. Basson's results contradict those reported by Carlson [19]. The reason for this may be that, compared to Carlson's work in 1938, the current heat of solution test ASTM C186-82 [11] specifies special handling techniques to prevent exposure to the air to prevent carbonation of the sample. Carlson reported values for the heat of hydration of up to 20% higher for samples that had been allowed to carbonate compared to samples where carbonation was prevented.

Monfore [14] describes an 'isothermal' conduction calorimeter used to study the early hydration reactions of portland cements.

The heat of solution test [11, 24] has become the standard method for determining the total heat of hydration of cement. Adiabatic calorimetry [25, 26, 27, 28] and conduction calorimetry [29, 30, 31, 32] methods are used where the heat evolution with respect to time is required.

Measurements of temperature increases in large concrete structures have also been undertaken by Dunstan [33], Gotsis [34] and Perfect [35] to determine the heat of hydration of the cement used in those structures.

Cannon [36] describes the effect that the changes in cement properties over a 50 year period have had on the heat of hydration of concrete. The basic changes to the composition of OPC have been a relative increase in the tricalcium silicate (C_3S) content and increased fineness of the product. Both these factors will lead to higher, and earlier, heats of hydration when todays cements are compared with those of the past. Opinion is that similar trends have taken place in the manufacture of South African cements, although this has not been documented.

2.2 Thermal Conductivity

Carmen [37] was the first person to obtain the absolute thermal conductivity of standard concrete mixtures. He refers to some earlier work by Nusselt (1909), Norton (1911) and Willard (1917). The method he used is the 'cylinder method', where heat is generated in a hole running axially through the centre of a cylinder of dried, hardened concrete and the radial temperature gradient of the heat flow is measured by temperature probes. This temperature gradient is then related to the thermal conductivity of the cured concrete. Yoshida, also working at the University of Illinois, describes an indirect method of determining the thermal diffusivity of concrete at temperatures below 10 degrees C [38]. His work is only valid at low temperatures where hydration has stopped. Results of both these researchers were discussed and used by Davey [16] in his determination of the temperature rise of hydrating concrete.

An investigation into the thermal conductivities of masonry, concretes and plaster was carried out by Griffiths [39] using the 'wall' or 'plate' method. He lists the thermal conductivities of solid, cavity and composite walls using various materials and a number of concrete and plaster mixes.

In a report on an investigation to determine the thermal properties of concrete

proposed for the Boulder Dam, Rippon [40] describes the apparatus and test methods used to determine the thermal conductivity, density, specific heat, and hence the thermal diffusivity of concrete samples. These procedures were included in the Handbook for Concrete and Cement [41] and updated in 1973 [42].

Tyner [43] uses a 'Guarded hot plate' method, based on the ASTM standard C177-42T(1942) to determine the thermal conductivity of limestone concrete.

Research conducted to determine the thermal conductivity of various concrete products [23, 44, 45, 46] used one of the methods described above, with the exception of Rousan [47], who used a thermal comparator method. This method consists of two thermo-couple junctions protruding from a cylinder of water kept at a constant temperature above that of the sample. One junction is brought into contact with the sample under test while the other is in contact with air. The difference in the temperature of the two junctions, after calibration, is then related to the thermal conductivity of the sample. The main advantage of this technique is that very little heat is introduced into the sample under test.

None of the tests found in the literature measure the thermal conductivity during hydration and are all conducted on cured and normally pre-dried samples. The use of dried concrete samples does not represent conditions found in concrete during or after the hydration period.

2.3 Temperature Measurement and Calculation

2.3.1 Temperature measurement

Davey [16], in a paper discussing all test and measurement procedures connected with the temperature rise in hydrating concrete, reports on extensive research into the rise of the temperature of cement during hydration conducted by Killig, Kaisai and Hossbach, in Germany during the years 1908 to 1910. This was followed by work by Beals, Cushman, Frey, Beckmann and Bates in America. Davey then describes methods to determine the heat of hydration, thermal conductivity and other thermal properties of concrete. In 1935 he published a paper [48] which correlated his laboratory results with temperatures observed in large dams. His work showed good correlation between tests undertaken in an adiabatic calorimeter and measurements taken at two dam sites. These two papers have become almost definitive in the field of temperature increases in large concrete structures, as they discuss, in

detail, the factors influencing the temperature rise in concrete and measurement techniques. Methods to reduce the heat generated during hydration and to control thermal stress are also discussed. Further work was carried out by Klein [23].

2.3.2 Temperature and heat flow calculation

Models and mathematical procedures were developed to help the engineer predict the temperatures in mass concrete structures. In 1935 Glover [49] published a mathematical method to predict the heat flow in dams. McHenry [50] tested this model with temperatures measured at the Norris Dam, and explained most of the discrepancies he found. One of the problems was the heat generated by previous lifts, and Glover proposed an improved model [51] in 1937. In the same year Carlson presented a simple method for the computation of temperatures in concrete structures [52].

2.4 Thermal Stress

The literature reviewed in this section is dependent on the results obtained from the work reviewed in the previous sections and describes ways to determine and control thermal stress in concrete structures.

Three papers were presented at the 34th Annual Convention of the American Concrete Institute in 1938 by Carlson [53], Blanks [54] and Kelly [55] in which thermal stress, cracking and temperature rise were discussed in some detail. These papers covered the theory, as well as laboratory and on site testing of mass concrete.

In 1945 Rawhauser [56] published a comprehensive paper (167 pages) on the control of temperature and the cracking of mass concrete, as a preliminary report on the work of a subcommittee of the ACI Committee 207. The full report was published in April 1970 [6] and has become the standard reference for mass concrete and dam construction [57]. During this time, other work was published on the subject of durability by Weiner [58] and on crack control by Waugh [59], the United States Department of the Interior [60] and Townsend [61].

The ACI Committee 207 report was followed by another three from ACI committees (224 and 207) on the control of cracking in concrete structures [62], reinforced structures [5] and mass concrete [57]. These too have become standard references.

These reports have been summarised, together with the findings of other researchers, in the chapters on Thermal Properties in two ASTM special technical publications 169A [63] and 169B [64].

At the congress on large dams in 1985, three papers dealing with measures to prevent cracking in mass concrete were presented, describing work undertaken in Austria (Widmann [65]), Brazil (Paulon [4]) and Japan (Fujisawa [66]).

Yamazaki described the measurement of thermal stress in a thick wall [67] and Hughes [68] detailed laboratory tests on the thermal stress in reinforced concrete. Springenschmid [69] described tests on concrete samples in a cracking test frame, which was followed by a paper by Schöppel [70] using the same apparatus.

Papers on mathematical models of the thermal stress in concrete include two with slag cements by Wainwright [26, 25] and two covering nonlinear analysis by Brauco [71] and Majorana [72].

2.5 Current Practices and Recommendations

Three sources of recommendations on the construction of mass concrete were investigated. These were the ACI Committee 207 report on mass concrete in the ACI Manual of concrete practice [57], the Portland Cement Association's report on "Concrete for Massive Structures" [73] and Fulton's Concrete Technology [3].

2.5.1 ACI Committee 207

This report [57] gives comprehensive recommendations for the construction of massive concrete structures. The thermal properties given are mainly based on information obtained from Rhodes [64]. Rhodes, in the ASTM Technical Publication 169B, both defines and gives parameters for thermal conductivity, specific heat, thermal diffusivity, thermal expansion and heat of hydration of concrete. He also describes test methods to determine the values of these parameters.

The ACI Committee 207 report gives a table listing the thermal properties of concrete measured at seventeen structures in the United States of America. Thermal conductivities were measured at all the sites using the U.S. Army Corps of Engineers procedure CRD-44 [42]. These tests were conducted on hardened concrete samples.

A method to predict the heat dissipation in bodies of mass concrete is described and charts and graphs are provided to simplify the method where the body to be analysed can be approximated to a known geometrical shape.

No specific method is given for the measurement of the heat of hydration of the concrete, although Rhodes does state that the Heat of Solution method [11] is the most popular method. The use of low heat generating cement is recommended as well as the possible use of extenders. The report suggests that the extenders should be considered as producing 50% of the heat of the cement they replace. Further temperature control procedures are also described. These include the pre-cooling of the constituents of the concrete, the addition of ice to the mixing water, and embedded pipe cooling in the structure after the placement of the concrete.

2.5.2 Portland Cement Association

The recommendations in the report [73] are based on the paper by Townsend [61] and the ACI Committee 207 report [57]. A method is given to calculate the adiabatic temperature rise in the concrete. The heat of hydration used in this method is determined using the Heat of Solution Method [11], with a recommendation to consider extenders as producing 40% of the heat of that of the cement. Type II cement is recommended for use in mass concrete in order to reduce the heat of hydration. Type II cement is characterised by a low tricalcium silicate (C_3S) and a high tetracalcium aluminoferrite (C_4AF) content. A table giving a range of thermal conductivities for mass concrete is presented with no explanation on how, or from where, these values were obtained.

Measures are suggested to control the maximum temperature in order to reduce the thermal stresses in the structure, and to prevent rapid changes in temperature, or thermal shock, to help prevent surface cracks. These include the pre-cooling of the concrete materials, limiting the temperature rise (by using low heat cement and/or extenders) and the cooling of the concrete after placement.

2.5.3 Fulton's Concrete Technology

Fulton's Concrete Technology [3] gives a good description of "rule of thumb" methods and precautions required in the casting of large masses of concrete. Three critical temperature conditions are discussed:

- It is recommended that the maximum temperature attained be restricted to 70 °C to prevent delays in the hardening process. Although a temperature of 70 °C is probably realistic, the reason given for this limit is not correct. The hydration reaction will be faster under high temperature conditions, with early strength development, but the long term strength of the concrete will be compromised [8, 9, 10].

- The maximum temperature gradient within the concrete should be controlled to prevent surface cracks forming. This temperature difference should be restricted to maximum of 15 °C between any two points within the structure.

- The maximum temperature difference between the maximum temperature reached by the concrete during hydration and the minimum temperature to which it will cool to, should be restricted to 17 °C to prevent thermal cracking of the structure. This implies that any concrete structure cooling more than 17 °C will crack, and Fulton recommends that reinforcement in three directions be used in these structures.

A comprehensive section on estimating the temperature rise of mass concrete is included for both mass and "less-massive" structures. This is based on the CIRIA report by Harrison [74]. A description of, and parameters for, the thermal conductivity of concrete is given based on papers by Campbell-Allen [44], Harmathy [45] and Rhodes [64]. A description and comparison of methods to determine the heat of hydration of cements, based on work by Basson [7], is also included.

As in the other two reports, methods to reduce the maximum temperature in the structure by using low heat producing cements and blends, pre-cooling, and post-cooling are discussed. There is a discussion on the limiting of lift sizes and the extension of periods between the placing of successive lifts as a passive means of post-cooling.

2.6 Summary

This literature review covers the development of the measurement and prediction techniques used to prevent damage to concrete structures caused by thermal stress, from 1895 to the present. Most of the information used in the current practices and recommendations is based on work conducted in the 1920's and 1930's and was related to the construction of large dams in the United States of America.

In the last three years very little work in this field has been published, as a CD ROM search was undertaken for 1992, 1993 and 1994 to date, with special reference to the heat of hydration and thermal conductivity measurements and crack prevention shows. There were no published developments in the measurement of the heat of hydration and only two papers on crack control and/or prediction were found. These were by Ram [75] and Barrot [76]. Four papers by Ashworth [77], Sona [78], Tan [79] and Hoffman [80] were found which dealt with the measurement of thermal conductivity in concrete .

A comprehensive bibliography, with abstracts, on the subject of mass concrete in dams from 1908 to 1962 [81] is included in ACI Special Publication SP-6.

2.7 Conclusions

In guiding the development of the project described in this thesis, this literature review has highlighted the following issues:

- For an accurate model of the temperature profiles within a concrete structure to be developed, accurate information of both the heat being produced and the thermal conductivity of the concrete, with respect to time, is required.
- Adiabatic calorimetry is the only test that measures the heat of hydration of a concrete sample with respect to time, and at conditions found within a concrete structure. As the heat of the sample is catalytic to the hydration reaction is is essential that the heat of hydration is measured at the same temperatures that would be experienced within a hydrating concrete structure.
- The thermal conductivity of concrete has never been measured during the hydration of the concrete. All previous tests have either been on hardened concrete samples or on the aggregate used in the concrete, with only a single value for the thermal conductivity being used in the heat model.
- As far as possible, any equipment or tests developed should be low cost and easy to use. It should be possible to determine the thermal conductivity of a concrete sample during all stages of hydration, with both the heat of hydration and thermal conductivity of the concrete sample being measured simultaneously with respect to time.

Chapter 3

ADIABATIC CALORIMETER

3.1 Introduction

The calorimeter described in this chapter was originally developed, by the author, for experiments conducted by Grieve [13]. Aniabatic calorimetry was chosen as the results are obtained under conditions similar to the conditions found in a mass concrete structure, as was discussed in section 2.1. A block diagram of the adiabatic calorimeter is shown figure 3.1 and an inter-connection diagram of the electronic circuitry is given in figure 3.2.

The basis of the operation of an adiabatic calorimeter is that the temperature surrounding the sample under test, in this case the 50 l water bath, is kept at the same temperature as the sample. This means that no heat is lost from, or gained by, the sample, and that the heat measured during a test is the result of the hydration of the cement.

The 500 l tank, although not essentially part of the adiabatic calorimeter, also follows the temperature of the sample or a pre-determined temperature profile, so that larger or multiple samples can be cured. These samples can then be used to measure various bulk properties of the concrete, such as strength and elastic modulus. This is known as temperature matched curing (TMC) testing.

The following sections describe the development of a low cost, computer controlled adiabatic calorimeter, as well as the calibration and verification procedures required to maintain adiabatic conditions. The section on the design of the calorimeter covers the choice of computer, temperature measurement, heaters and control circuitry, the sample holder and the two tanks. The development of the software and the control

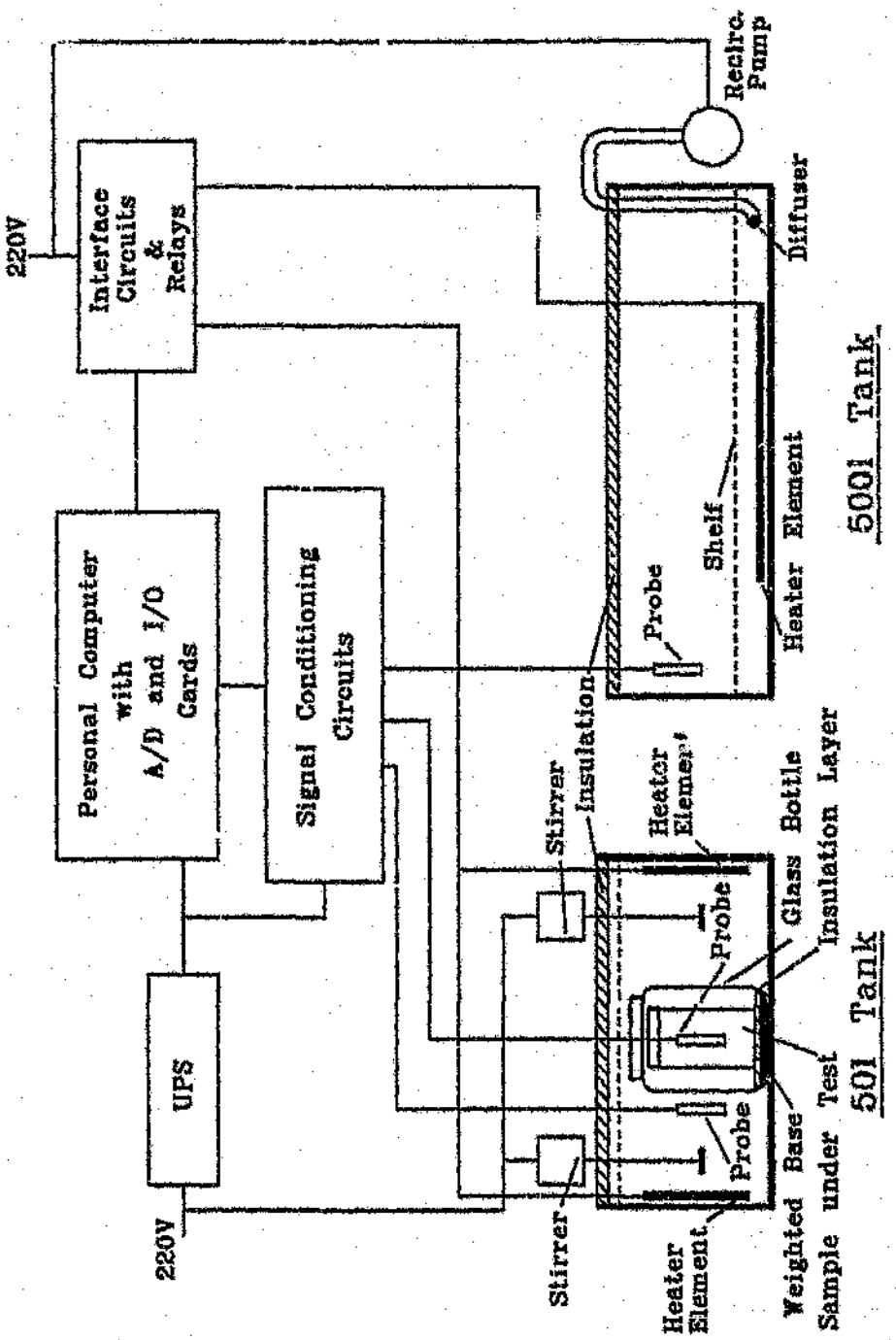


Figure 3.1: Adiabatic Calorimeter

algorithm is also explained. The section on the calibration procedures discusses the calibration of the temperature sensors, as well as the checks and corrections required to maintain adiabatic conditions.

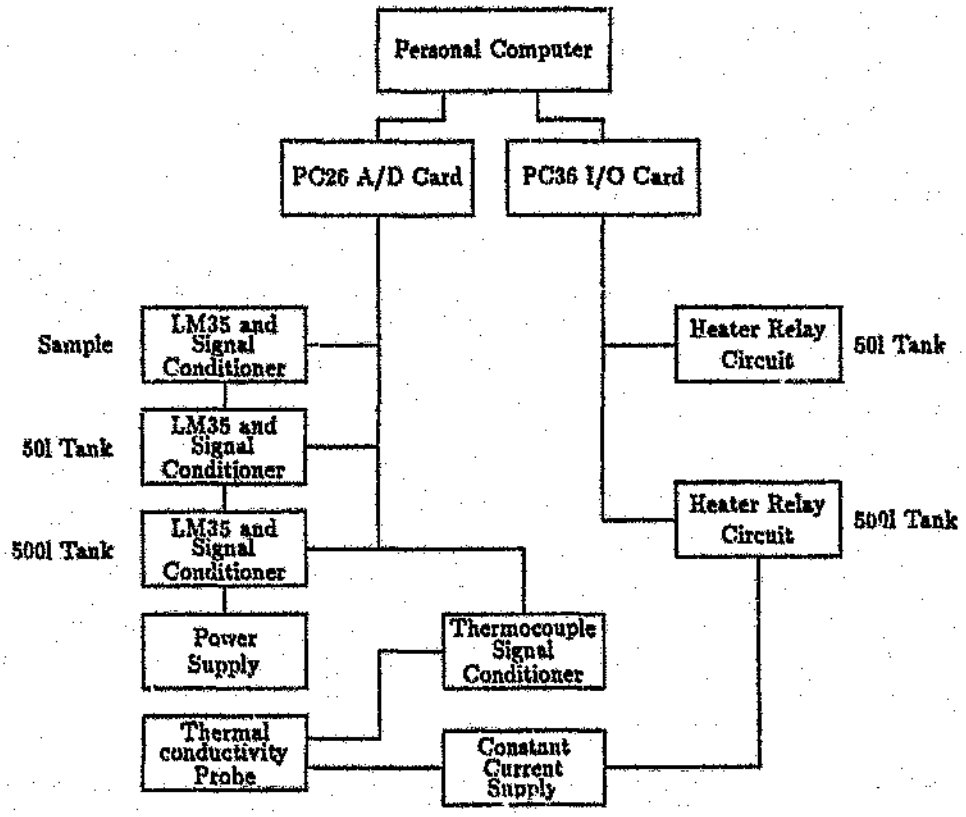


Figure 3.2: Block diagram of electronic components for the calorimeter

3.2 Calorimeter Design

Grieve, on a technical visit to Europe in 1986, investigated the availability of adiabatic calorimeters suitable for the testing of concrete samples. The cost of the calorimeter designs available were in excess of the funding budgeted, and it was decided to design and build a calorimeter with a low cost Personal Computer (PC) as the controller.

The use of a PC to control the calorimeter also increased its flexibility in the type of tests that could be conducted. This meant that the addition of one extra temperature sensor and a small modification of the software was all that was needed to add the conductivity probe, as described in chapter 5. The temperature matched curing tests, described in chapter 6, required only a change in the software.

3.2.1 Hardware

The computer used was an IBM PC compatible with a 286 mother board, 360k byte floppy disk and a 20 M byte Hard disk drive. Fitted into the computer was a 16 channel, 12 bit Analogue to Digital (A/D) card (PC-26) with a 0 to 10 Volt input, and a 24 line digital interface (I/O) card (PC-36).

A 200 W uninterruptable power supply was used to power the computer and the signal conditioning circuits. This allowed for power failures of up to 15 minutes without the disruption of a test. The software allowed for a re-start and continuation of the test, in the event of a power failure which was longer than 15 minutes. It was found, however, that long interruptions caused the tank temperature to drop to such an extent that the conditions were no longer adiabatic, and the results had to be discarded [13].

3.2.1.1 Temperature measurement

In the original system, as used by Grieve [13], PT100 platinum resistance thermometers with commercially available amplifiers were used to measure the temperature, as they are considered the most suitable temperature transducer for accurate and repeatable temperature measurements [82], providing an accuracy of 0,1 °C. It was found however, that the commercially available stainless steel probes were too bulky, causing heat to be absorbed from the sample. The amplifiers that were purchased were found not to be as reliable as expected and had to be calibrated regularly as they had long term stability problems. Because of this, less bulky and simpler temperature sensors were investigated.

It was decided to use National Semiconductor's LM35 temperature sensors, sealed in a 60 mm long copper tube with a diameter of 6 mm. The length of the tube was chosen to be about half the length of the sample to enable an average temperature to be read within the sample. The probe was smeared with "petroleum jelly" before inserting it into the sample to simplify the removal of the probe on completion of the test. The sensors have a guaranteed accuracy of 0,5 °C with an output of 10 mV/°C, with a supply voltage of 4 to 30 Volts. Simple signal conditioners to convert 0-100 °C to a 0-10 Volt output were designed and built (see Appendix A). No calibration facilities were included in the hardware as this was accomplished by including calibration factors in the software (see section 3.3).

The output voltage from the conditioners is read by the computer using the A/D

converter card. The A/D card, with a 12 bit resolution, will give a resolution of 0,024 °C.

3.2.1.2 Heaters and heater control

The heaters in both tanks are controlled by the computer through the PC-36 digital I/O card. Interface circuitry was built to provide a buffer between the I/O card and two 25 A solid state relays (one for each tank) and is designed to fail safe, off condition, in the event of computer failure. A low power, 5 Volt supply was also included, from which the computer can monitor any power failure conditions. The circuit diagram for the interface circuit is given in Appendix A.

As was noted by Grieve [13], the 50 l tank was heated with a 200W element, but after initial tests, was found not to produce a sufficient heating rate for all types of concrete mixes. A 1kW element was added and the total power of 1,2kW allows for a heating rate of 7 °C/hour, which is more than twice the maximum heating rate obtained from OPC concrete mixes (see Chapter 4). The 500 l tank was heated with a 2kW heater, with the option to add more power if this was found to be necessary.

3.2.1.3 50 l tank

Originally the sample was in contact with the water in the tank. This presented problems to the control system, which was designed as an "ON/OFF" control of the heater elements [13]. The problem was solved by placing the sample holder into the glass bottle as shown in figure 3.3, which provided an insulating layer of air and a damping, or integral, factor into the control system.

Figure 3.3 shows the sample holder and the glass bottle which was placed in the 50 l tank. The water level in the insulated walled tank was controlled by a float valve to replace the water lost due to evaporation, with the level set at 10mm above the glass bottle. Two stirrers were placed near the heater elements and kept the water in constant motion, in order to eliminate any variations in temperature in the tank. The temperature probe monitoring the tank water was attached to the outside of the glass bottle. Tests were undertaken to monitor variations in temperature around the bottle and, with the stirrers in operation, this was found to be less than 0,1 °C. The tank was covered with 100mm polystyrene sheet to reduce both evaporation and heat loss.

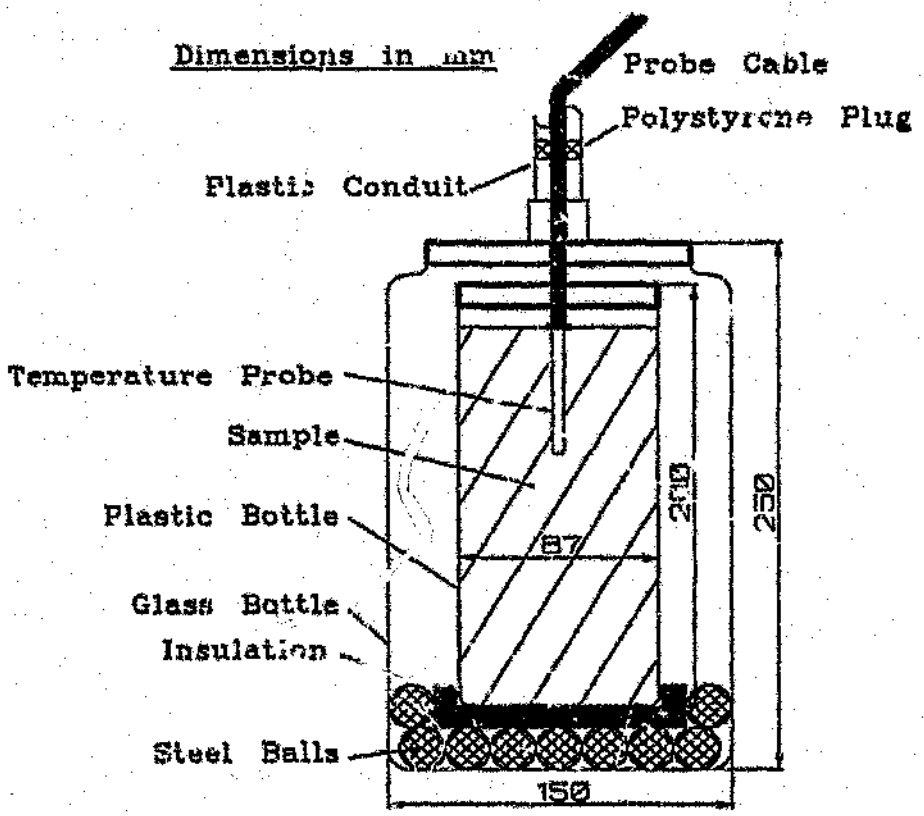


Figure 3.3: Sample Holder

3.2.1.4 500 l tank

The 500 l tank was constructed from un-insulated mild steel with an expanded steel shelf, 100mm above the tank's base, on which to place sample cubes or prisms. The heater was placed under this shelf with the outlet of the diffuser forcing the water across the element. The recirculating pump provided enough flow to keep the water in the tank in constant motion with a maximum temperature variation of 1 °C being measured during a test. The temperature sensor was placed at some convenient position among the samples in the tank.

3.2.2 Software

The software for the calorimeter was written in Turbo Pascal 6 [83, 84, 85] with the menu system being based on libraries developed by the Software Engineering Applications Laboratory, Department of Electrical Engineering, University of the Witwatersrand [86]. A listing of the software is given in Appendix B.

The test program allows the operator to enter information about the sample to be tested and modify test parameters such as reading intervals, control constants and test duration. The test parameters can also be modified while a test is being run. Two additional operations allow for old test data to be plotted and calibration the calorimeter [87].

3.2.2.1 Control algorithm

A simple "bang-bang" or "ON-OFF" control algorithm with hysteresis is used to control the temperature of the water in the tanks. The author was involved in the design and development of another adiabatic calorimeter, at the same time as the one described in this thesis was being developed, to determine the self-heating propensity of coal [88]. Although the calorimeters are dissimilar, as the calorimeter for the coal tests controls the temperature of an oven and a gas heat exchanger, both use similar computers and switching circuits. The calorimeter for the coal tests required proportional control of the heaters in the oven and the heat exchanger. The ability to implement this in the calorimeter used for the concrete tests was included in the hardware design, in case this was found to be necessary during the commissioning of the calorimeter. It was found that, because of the relatively slow rate of change in temperature and the damping affect of both the water in the bath and the air insulation around the sample, proportional control of the heaters was not necessary. The hysteresis of the system is due to the switching factors entered as test parameters which are obtained during calibration of the system (see section 3.3).

The air surrounding the sample holder provides an integral (low pass filter) function to the control algorithm.

3.3 Calibration Procedures

Calibration of the calorimeter consists of the calibration of the temperature sensors and the determination of the switching parameters to obtain an adiabatic system.

3.3.1 Calibration of the temperature sensors

As can be seen in the circuit diagram, no provision was made for any hardware calibration of the temperature sensors. This was implemented to reduce the number

of components which could be affected by environmental changes.

The three temperature sensors were tied together with a calibrating thermometer (accuracy of ±0,5 °C) and placed in the 50 l tank with the stirrers operating and the water at ambient temperature (between 18 °C and 23 °C). The system was left for approximately ten minutes to allow the readings to stabilise and then readings were taken from the three sensors and the calibrating thermometer. Calibration factors were then calculated to correct the temperature readings of the three temperature sensors to that of the calibrating thermometer and were then entered into the computer. This single point calibration of absolute temperature was considered sufficient as the specifications of the LM35 temperature sensor indicate that the error is linear, within the 0,5 °C accuracy, over its entire range. This was also confirmed with readings taken while the tank was being heated. The water in the tank was then heated from ambient temperature to 70 °C, and then allowed to cool back to ambient temperature. The difference in temperatures of the sensors for the two tanks, for both the heating and cooling cycles, with respect to the sample temperature sensor, was calculated and the results analysed.

The difference between the reading of the temperature sensor for the 500 l tank and that of the sample temperature sensor was found to be less than 0,5 °C for the entire temperature range (ambient to 70 °C). This was considered accurate enough for the samples being cured in the 500 l tank. A hysteresis of ±0.1 °C was implemented in the control software.

The 50 l tank's sensor output was also within 0,5 °C of that of the sample temperature sensor, but as this is used for the adiabatic control, a more accurate correlation of the two sensor outputs was necessary. It was observed that the difference between the two sensors was dependent on the measured temperature. MATLAB routines [89] were used to determine linear regression factors, which were then used in the software to correct the output of the 50 l tank's sensor. Figure 3.4 shows the difference between the two sensors after the correction factors have been applied. The mean of the differences is practically zero ($4,4 \times 10^{-16}$) with a standard deviation of 0,03 °C.

3.3.2 Calibration and check for adiabaticity

Although the errors in the temperature readings are extremely small, it was found that the adiabatic characteristic of the calorimeter was also influenced by external factors. These external influences are difficult to quantify and include.

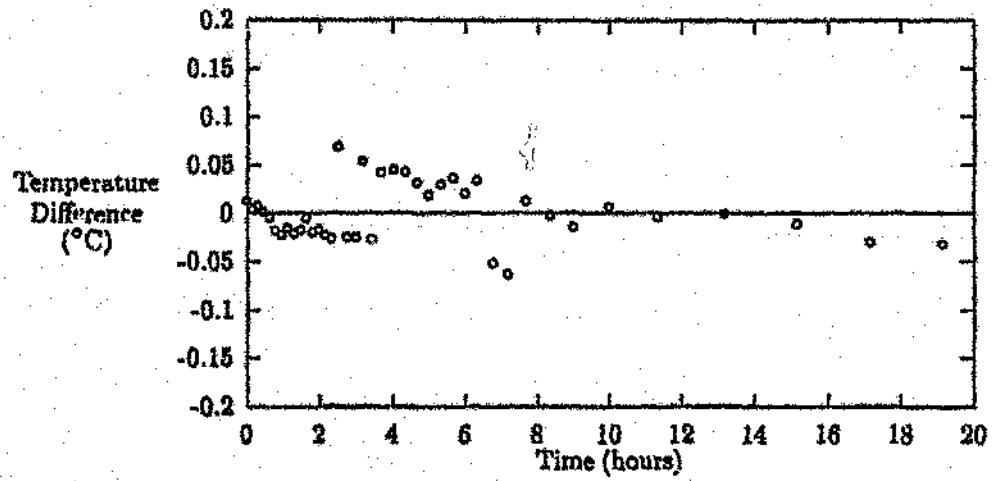


Figure 3.4: Temperature differences between sample and 50 l tank sensors after the correction factors were applied.

- Heat introduced into the water of the 50 l tank by the stirrers, both by friction and down the shafts from the electric motors.
- Heat loss from the sample to ambient through the cable of the temperature sensor and the thermal conductivity probe (see chapter 5). It is essential that the conduit where the cables enter the glass bottle is plugged to prevent air movement and therefore heat loss from the bottle.

To correct for these external factors, the calibration procedure explained in the next paragraph was developed.

An inert sample (sand, stone and water) was placed in the sample holder together with the temperature sensor and thermal conductivity probe (if used). The tank was heated to about 48 °C and, when the temperature of the sample had stabilised, the calorimeter was switched to adiabatic mode. The temperature of the sample was then observed over a number of hours and the software switching parameters adjusted until the temperature of the sample remained constant, as shown in figure 3.5.

The calibration procedure described above relies on a constant ambient temperature (± 2,5 °C). Large changes in ambient conditions, due to a faulty air conditioner, were found to have affected the adiabaticity of the calorimeter. The calorimeter must be

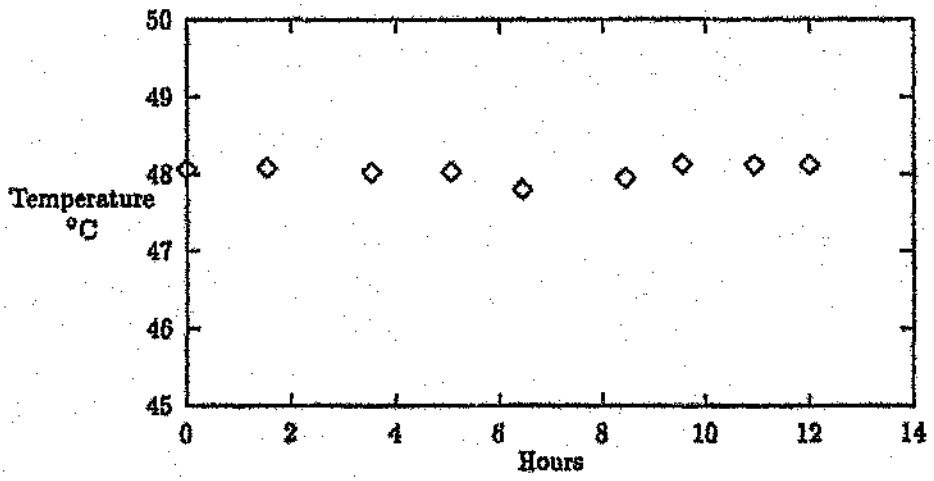


Figure 3.5: Results of test for Adiabaticity

calibrated and used in a relatively constant temperature environment, although the absolute ambient temperature is not important.

The adiabaticity of the calorimeter was then tested at ten degree intervals from ambient to 70 °C and found to be adiabatic over the whole range of temperatures. Calibration of the calorimeter by heating a sample of known specific heat was investigated. This method was ruled out as the homogeneous heating of a sample, as is the case with hydrating concrete, is almost impossible. If portions of the sample are at a higher temperature than where the temperature is being measured, heat will be lost to the water bath and conversely heat will be gained by the sample if the temperature is measured at a position where the temperature is greater than that of the average temperature of the sample. It was felt that as the calorimeter was found to be adiabatic over its full operating range using a pre-heated inert sample, further calibration procedures were unnecessary.

It was found, during the development of the calorimeter, that these calibration procedures should be carried out at least once a month, when any questionable results are obtained or if there are any significant changes in the ambient conditions to ensure accurate test results.

3.4 Temperature Matched Curing

As was expressed by Davey [90] in his paper describing an apparatus used to conduct temperature matched curing (TMC) tests, "The engineer is often puzzled by the magnitude of the variations in strength of concrete test-pieces made on the job" . He found that the early strength (after 24 hours) of rapid hardening concrete was dependent on the mixing and curing temperature. In a set of three papers Cannon describes the development [8], application [9] and future trends [10] in temperature matched curing. From his reported results it is clear that the temperature of concrete during the hydration period affects both its short and long term strengths.

Samples can be cured in the 500 l tank during tests for the heat of hydration with the temperature of the tank, and therefore the samples, following the temperature of the sample in the sample holder. This temperature profile is not necessarily the profile which would be found in a structure, as no cooling is accounted for. To accommodate for TMC tests representing the "real life" situation, a program has been written for the calorimeter to control the temperature of the tanks to any predicted temperature profile obtained either from field measurements or from a heat model (see chapter 6). Samples are then cured following the predicted temperature profile, and tested for parameters such as strength, elastic modulus, creep and shrinkage during, or after, the curing period. The strength and temperature profile of a concrete pour can then be predicted.

3.5 Conclusions

After solving the initial teething problems, results from the calorimeter have been found to be repeatable, provided the system is calibrated regularly. It must be pointed out, to emphasise the importance of calibration, that a 1 °C difference in actual temperature between the sample and the water bath, over a 24 hour period, will cause an error of about 18 % in the heat determined from a concrete sample over a 4 day test.

Descriptions of mixing and test procedures for the determination of the heat of hydration of concrete samples in the calorimeter are given in chapter 4.

Chapter 4

HEAT OF HYDRATION MEASUREMENT

4.1 Introduction

This chapter describes the use of the adiabatic calorimeter to determine the heat of hydration of concrete samples. The physical principles and possible errors in using the method are discussed, together with information on data collection and processing.

The rate of the heat of hydration (Q (J/sec)), at any point in time, is calculated from the temperature readings, obtained from a hydrating concrete sample under adiabatic conditions, and its specific heat [1] using the equation 4.1 [7].

$$Q = C_p m \Delta T \tag{4.1}$$

where

C_p = Specific heat of the sample (J/kg K)
m = Mass of the sample (kg)
ΔT = Rise in temperature (K/sec)

The specific heat of the sample is normally determined from the sum of the specific heats of its components [3]. There has been some discussion on the validity of this,

[1] Specific Heat (J/kg K) is a measure of a material's thermal capacity ie. The amount of heat required to raise 1 kg of the material by 1 °K. Rhodes [64] describes methods to determine the specific heats of hardened concrete, aggregates, cement and cement pastes.

Table 4.1: Specific Heat of Cement Paste (Carlson and Forbrich 1938)

Temperature (°C)	Specific Heat (J/kg K)	
	W:C=0,25	W:C=0,6
21	1109	1589
32	1159	1707
43	1268	1904
54	1423	2113
66	1674	2427

as the specific heat of the cement paste (cement and water) changes considerably during hydration (discussion by McCoy [23]). This matter had been investigated by Carlson in 1938 [19]. Tests conducted by Carlson showed that the specific heat of the cement paste changes by up to 40% during hydration and he suggested a linear interpolation of the specific heat of the known un-hydrated and "hydrated values". Carlson gives no indication as to the extent of hydration of his "hydrated" samples. The results for "well-hydrated" cement paste show variations with both temperature and the water:cement ratio (W:C). Table 4.1 shows the results obtained by Carlson (converted to SI units). These tests and recommendations made by Carlson were the only reference found in the literature which quantified changes in the specific heat of cement paste. The validity of his assumptions and recommendations have not been tested, and further research into this problem should be pursued.

Carlson's data was used, by the author, to quantify the error that the change of the specific heat of the cement paste would have on the heat of hydration values obtained from the adiabatic calorimeter. Second order polynomials were fitted to the temperature and specific heat values, and then a linear regression of the coefficients was determined between the two water:cement ratio values as shown in equation 4.2.

$$C_p = p_1 T^2 + p_2 T + p_3 \tag{4.2}$$

where

C_p = Specific heat of the cement paste (J/kg K)

T = Temperature (°C)

$p_1..p_3$ = coefficients determined from equation 4.3.

$$p_n = a_n \times (W:C) + b_n \tag{4.3}$$

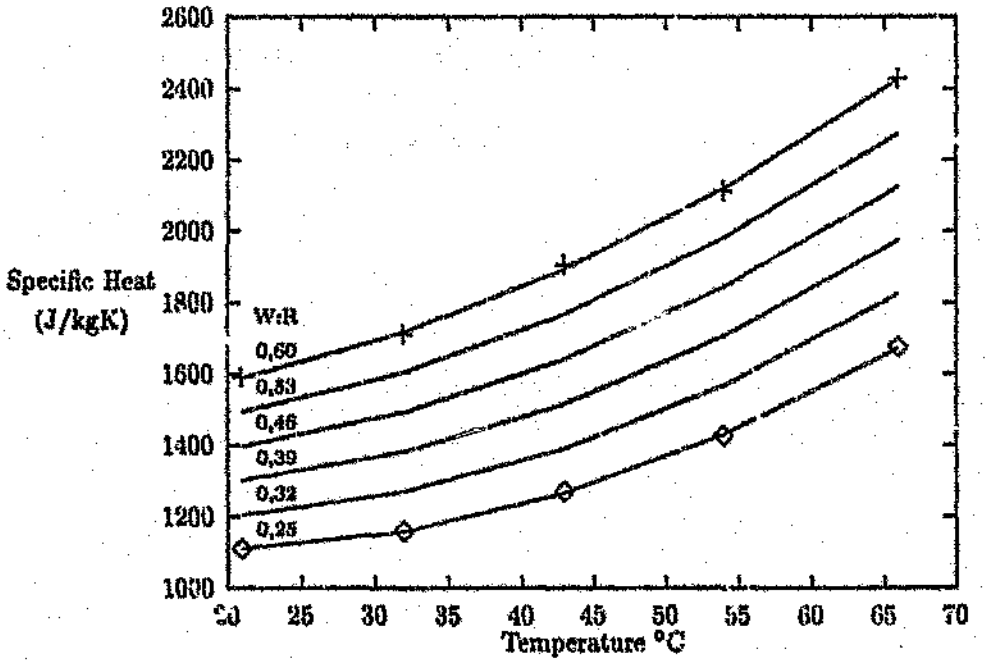


Figure 4.1: Specific heat of cement paste at different temperature and water:cement ratios

where

a_n *and* b_n = linear regression factors of the water:cement ratio.

A plot of the results is shown in figure 4.1.

Equations 4.2 and 4.3 were incorporated into the MATLAB program 'condat3.m' (used to process all the calorimeter data; see appendix B). The specific heat was calculated for hardened cement paste at each recorded temperature and, as suggested by Carlson, a linear interpolation between the specific heats of the unhydrated components and the calculated values was used. The interpolation makes the simplifying assumption that the cement paste is at the final state of hydration at the point when the maximum temperature is reached. The degree to which the specific heat has changed, from the sum of the unhydrated values to that of the hydrated values, is assumed to be dependent on the rate of heat evolution of the sample (ie. $\delta(heat)/\delta t$). Figure 4.2 shows the calculated change in the specific heat of an OPC concrete mix during hydration.

Table 4.2 gives details of the mixes used for the test results presented is this and

Table 4.2: Concrete mixes

MIX	OPC	OPC/FA	OPC/GGBS	Specific Heat
OPC	355g	249g	178g	880 J/kg K
FA	-	107g	-	880 J/kg K
GGBS	-	-	178g	880 J/kg K
SAND	794g	763g	780g	880 J/kg K
STONE	1,02kg	1.02kg	1.02kg	880 J/kg K
WATER	200ml	200ml	200ml	4187 J/kg K
COMPACTED DENSITY	$2523 kg/m^3$	$2491 kg/m^3$	$2534 kg/m^3$	

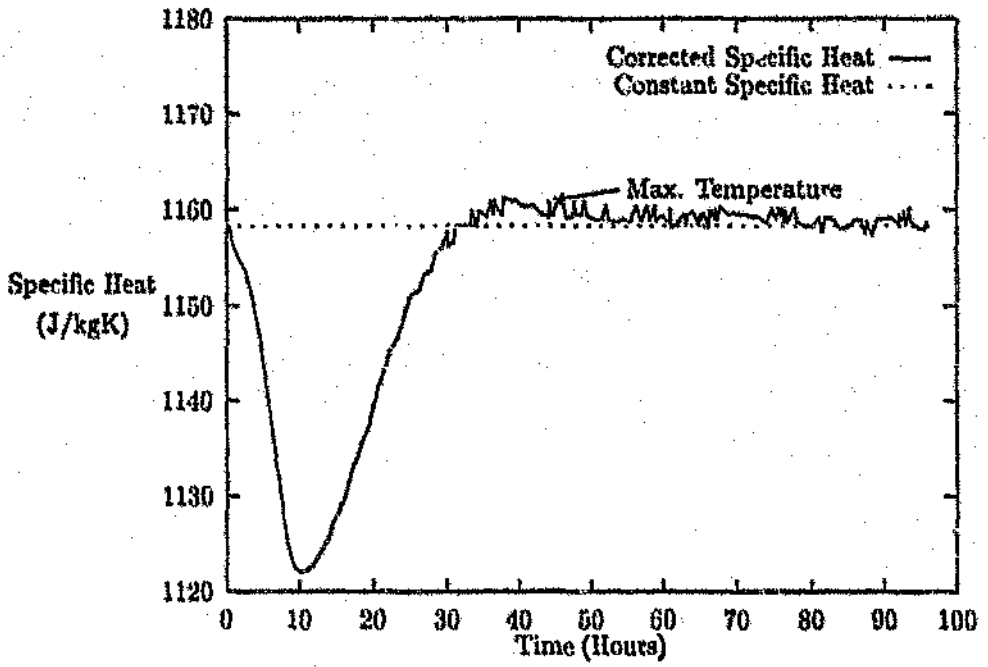


Figure 4.2: Variation in the Specific Heat of Concrete during Hydration calculated from Carlson's measurements

subsequent chapters. The specific heats of components used in the tests to calculate the specific heat of the samples were the generally accepted values obtained from Fulton's Concrete Technology [3]. If accurate tests for a particular site or project are required, the specific heats of all the components of the mix should be determined [23, 64].

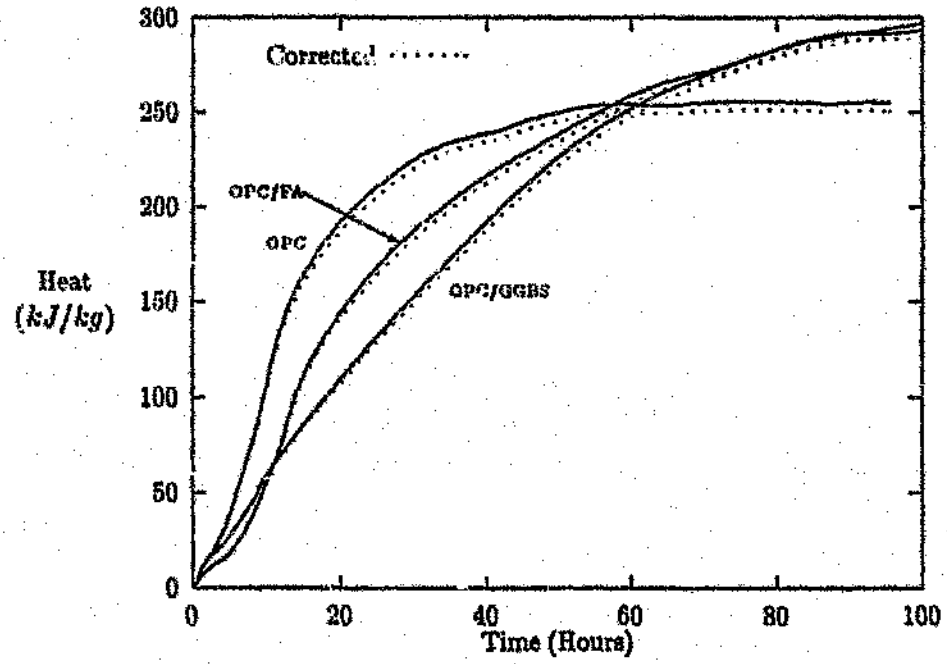


Figure 4.3: Comparison of Heat of Hydration determination methods

The heat of hydration obtained from the sum of the specific heats of the materials is compared with the heat of hydration obtained from the corrected specific heat in figure 4.3 for the three different concrete mixes.

The calculated heats of hydration, using the corrected specific heat values (dotted lines), are lower by about 2% than those calculated with the sum of the specific heats of the components with all the concrete mixes.

It should be noted that the corrected values for the specific heat are based on results obtained by Carlson in 1938. The chemical composition of cement has changed considerably since then [36] and no work has been undertaken to determine the changes in the specific heat of cement pastes with extenders added. As the error is less than 2% it was decided, in the absence of valid information on current cement pastes, to ignore any change in the specific heat of the cement paste during hydration. This is in line with other researchers [12, 13, 7] using adiabatic calorimetry to determine heat of hydration values.

4.2 Data Collection and Processing

4.2.1 Data Collection

A step by step procedure for conducting a test and processing the results is given below:

- All components of the mix, including the mixing water, should be batched out and stored at room temperature for at least 12 hours before the commencement of a test. This results in a homogeneous temperature within the mix at the start of a test.
- The temperature of the 50l tank should be set at about 1°C lower than ambient temperature by adding mains water or ice prior to commencement of the test. This prevents heat being introduced into the sample by the tank. The temperature difference will be corrected by the tank in less than 8 minutes after the start of a test.
- Start the computer program, implement all instructions and enter data up to the request for the mass of the sample.
- Mix the sample of concrete, about 2 kg, and place it in the 1 litre plastic bottle and compact.
  NOTE: Special care should be taken during the mixing stage of the test especially if comparative studies of various concrete samples are being undertaken. To prevent changes in the temperature of the components of the sample the mixer and paddles should be at the same temperature as the components and constant mixing (2 to 3 minutes) and compaction times must be used. Mixing and placement of the sample in the calorimeter should take place as fast as possible to reduce, as much as possible, the loss of the immediate heat of hydration.
- The sample should be weighed and the height of the sample in the bottle measured. The program calculates the compacted density of the sample from this value.
- Place the temperature probe, smeared with "petroleum jelly", into the center of the sample, ensuring that there is good contact with the mix.
- Place the plastic container in the glass bottle and carefully fit the lid onto the glass bottle.

- Put the glass bottle into the 50 l tank and plug the conduit to prevent air movement from the bottle.
- Enter the mass and height of the sample into the computer and start the test. Temperature readings are taken during the test if the temperature varies by more than 0,5 °C of the previous reading or at one hourly intervals. The time, sample temperature, tank temperatures and the ambient temperature are stored in a data file.
- Observe the test regularly during its duration. Data may be downloaded onto a disk for analysis on another computer while a test is being conducted.

4.2.2 Data Processing

On completion of the test, the stored data is manipulated by the MATLAB program 'condat3.m'. A full listing of this program is given in Appendix B and a flow chart shown in figure 4.4.

A brief description of the process is as follows. The data is interpolated to ten minute intervals and then filtered, to remove the variations due to the resolution of the temperature readings. The heat of hydration is then calculated to give a plot of the power generated during hydration in W/kg of binding material. An example of this is given in figure 4.5. Note the immediate heat of hydration (first 30 minutes) as described by Carlson [19]. The power generated is then integrated to give a plot of the total heat produced in J/kg of binding material as shown in figure 4.6.

The results shown in figures 4.3, 4.5 and 4.6 are from tests conducted during the development of the calorimeter where the mixes were chosen for their workability rather than the choice of practical mixes.

4.3 Conclusions

The change in the specific heat of the cement paste during hydration with, and without, extenders should be investigated. No information on the specific heat of OPC with extenders could be found and OPC has changed since Carlson's work in 1938. As it is very difficult to measure the specific heat of hydrating cement paste because of the heat being generated, the linear regression method suggested by Carlson [19] provides a simple means to correct for the change in specific heat.

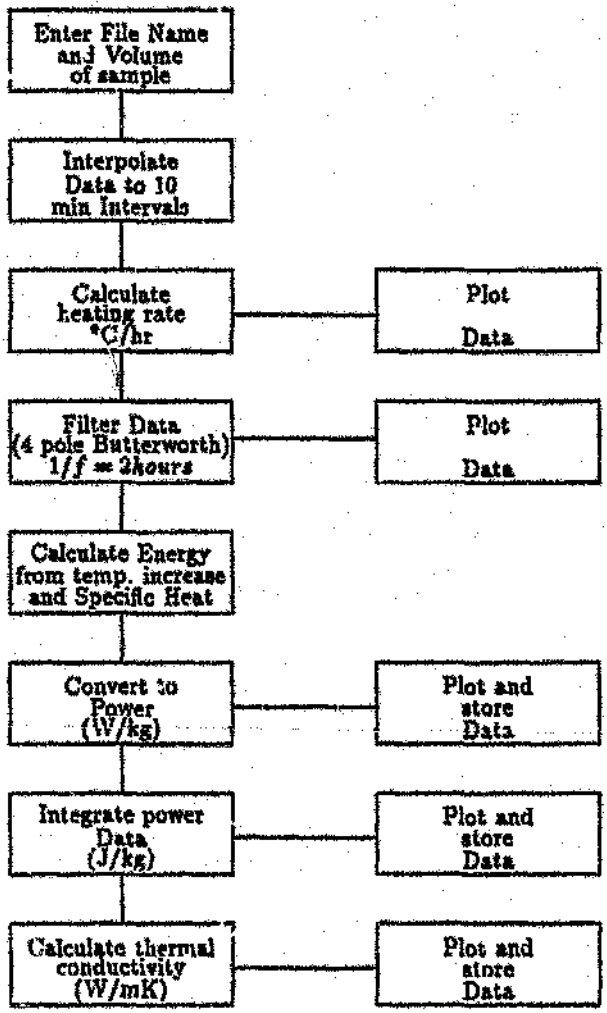


Figure 4.4: Flow chart of data processing program (CONDAT3.M)

as was shown, the error is less than 2% if the changes in the specific heat are ignored and, as no information on the changes in the specific heat of modern cementitious materials is available, a specific heat based on the specific heats of the components should be used until further information is available.

It is very difficult to make comparisons with results obtained by other research workers measuring the heat of hydration in adiabatic calorimeters or with any other measuring technique. Water:cement ratios, mixing techniques, time after mixing to the start of the test and starting temperature as well as the cement type and properties such as fineness and composition will influence the results obtained. However, the range of results obtained during the development of the calorimeter for various

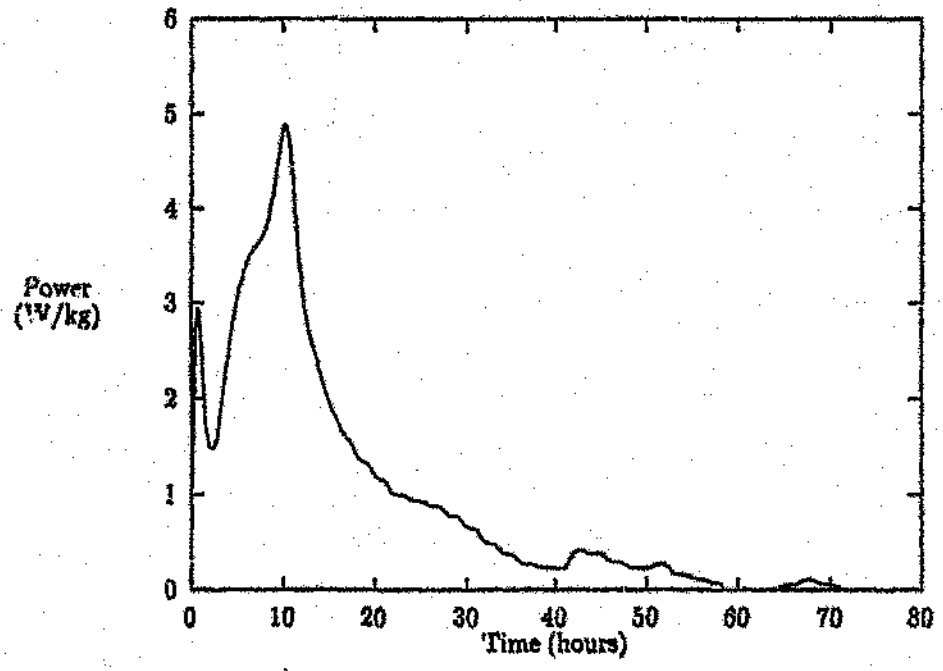


Figure 4.5: Power Generated by the OPC concrete mix

binder combinations (OPC 202-316 kJ/kg, 70/30 OPC/FA 189-298 kJ/kg and 50/50 OPC/GGBS 225-305 kJ/kg) were similar to the range of values given in Fulton [3] and by the Portland Cement Association [73] for the first 5 days of hydration.

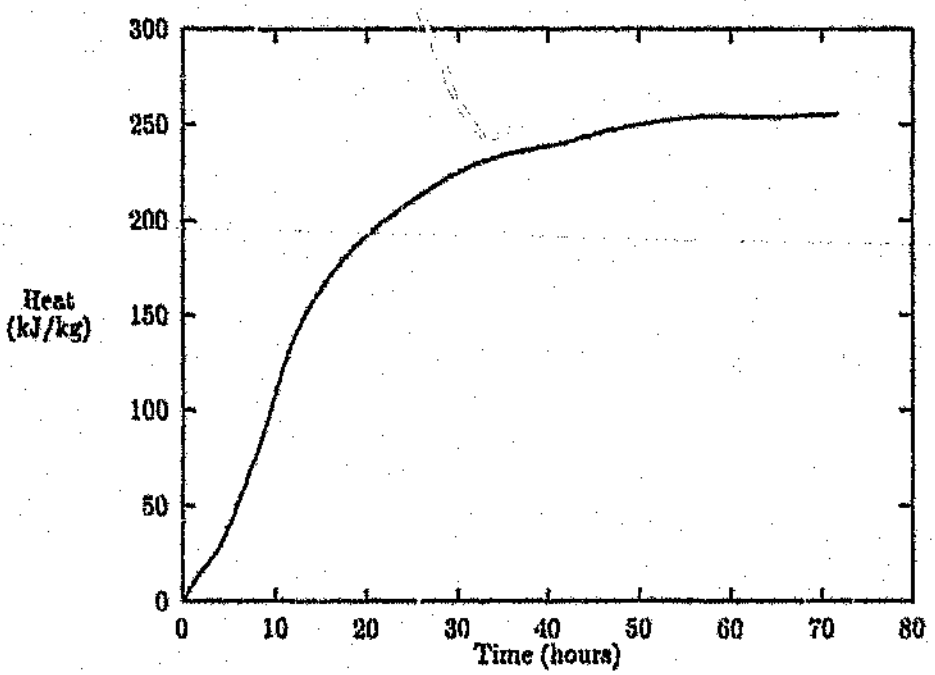


Figure 4.6: Heat Produced by the OPC concrete mix

Chapter 5

THERMAL CONDUCTIVITY MEASUREMENT

5.1 Introduction

The original contribution to the field of concrete technology is described in this chapter, covering the development of a thermal conductivity probe and for the first time a method to measure the thermal conductivity of a concrete sample during all stages of hydration.

Thermal conductivity is a measure of a material's ability to conduct heat. To enable the temperature in a concrete structure to be estimated over a period of time, the thermal conductivity of the concrete, during this period, is required.

The thermal conductivity of materials can be measured by either using steady state or dynamic measurement techniques with different procedures for solids, liquids and gasses. As concrete is producing heat during hydration, no steady state method can be used with any accuracy. Concrete also changes state from a 'semi-liquid' to a solid during the first 24 hours of hydration and a method had to be found that would be valid for all the physical states during the hydration process.

An investigation into various dynamic thermal conductivity measurement techniques was undertaken, with emphasis on the following three objectives:

- Simultaneous thermal conductivity and heat of hydration measurements.
- Low power, to minimise the amount of heat introduced into the sample.

- Ease of use.

All the standard thermal conductivity measurement techniques were investigated [91, 92, 93, 94, 95, 96] and only the thermal probe method was found to be suitable. This is the only method that can measure the thermal conductivity in both 'semi-liquids' and solids. The thermal probe method was first suggested by Schleiermacher in 1888 and again, independently, by Stalhane and Pyke in 1931 [97]. Jaeger [98] presented the theoretical analysis of the conduction of heat from a cylinder, which was followed by work by de Vries [97, 99] describing the use of the method for the measurement of the thermal conductivity of both dry and wet soils. The probe operates by heating a cylinder, with constant power, that is placed in the material under test. The temperature increase in the cylinder is measured and the rate of the temperature increase is proportional to the thermal conductivity of the material under test. The probe needs to be constructed out a high thermal conductivity material to allow for uniform heating of the probe. The formula which describes the operation of the thermal conductivity probe is [100]:

$$\Delta T = \frac{Q}{4\pi\lambda} ln \frac{t_2 - t_c}{t_1 - t_c} \tag{5.1}$$

where

ΔT = Rise in temperature (°C)
Q = Input Power (W)
λ = Thermal conductivity (W/m K)
t_2 = End time (sec)
t_1 = Start time (sec)
t_c = Calibration factor (time offset)

The formula 5.1 can be further simplified by keeping the start and end times constant, resulting in the equation 5.2 for measured thermal conductivity

$$\lambda = \frac{Q}{\Delta T} C \tag{5.2}$$

where the value of the constant (C) is determined during calibration of the probe.

Three different probe styles were tried in this investigation.

The first, using a soldering iron element (length of 60mm and diameter of 9mm) as the heat source with a thermocouple attached to it, proved to be too bulky, requiring

a lot of power to increase its temperature in order to enable the conductivity measurement to be obtained. This extra heat was then dissipated through the sample after the measurement and affected the hydration process.

The second attempt was to go to the other extreme as far as size was concerned, and a probe made from two thermocouple junctions, one as the heat source and the other to measure the temperature increase was tried. The probe, with a diameter of 1mm and a length of 5mm, was constructed for each test by soldering the two junctions together. A new probe was required for each test, as it could not be removed from the hardened sample without being damaged. Power was supplied from a constant current source, and the temperature increase was measured after 20 seconds. Tests were conducted in samples of hydrating concrete, granite and sand. The two problems that emerged from these tests were the variations in the characteristics of different probes due to construction variations and, because of the small size, there was the possibility of the probe measuring the thermal conductivity of a piece of aggregate, and not the average conductivity of the concrete sample.

The third probe tried and which proved successful, was a 64mm long brass probe with a diameter of 3,15 mm, the design and the calibration of which is described in the following sections.

5.2 Probe Design

5.2.1 Hardware

Figure 5.1 shows a diagram of the thermal conductivity probe. The length was chosen to be approximately a quarter of the length of the sample, so as to obtain an average measurement from the concrete, and the diameter was the smallest available brass tubing that could hold both the thermocouple and the heater element.

The thermocouple cable which was used was a fibre glass covered Type K pair, with a diameter of 1mm. The thermocouple junction was crimped and soldered into a small copper plug (diameter of 2,4mm and length of 3mm). Then 320mm of resistance wire, with a diameter of 0,13mm and a resistance of 36,5 Ω /m, was wrapped around the thermocouple cable and covered with a length of heat shrink sleeving. Heat sink compound (Dow Corning 340) was smeared over the sleeving to improve thermal contact with the brass tube, and the whole assembly was pushed into the tube. The copper plug was then soldered into the end of the brass tube

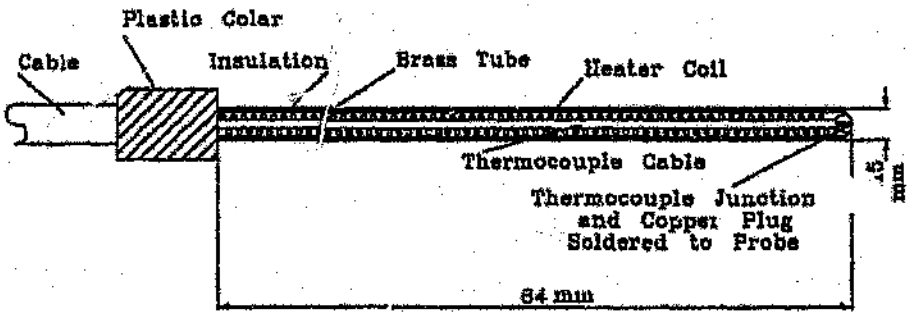


Figure 5.1: Thermal Conductivity Probe

and a plastic collar glued onto the other end, and then sealed onto the cables. The single temperature measuring point at the end of the probe is valid as the thermal conductivity of the brass is much greater than that measured in concrete, resulting in a uniform temperature profile along the whole length of the probe.

The thermocouple cable was connected to a signal conditioner, obtained commercially, which converted 0-100 °C to a 0-10 Volt output. This voltage was read by the computer using a spare channel on the A/D converter card used for the adiabatic calorimeter control.

The heater is supplied from a variable, constant current [illegible], the circuit diagram of which is given in Appendix A. The same solid state relay used to control the 500l tank is used to switch the supply to the probe. The use of the control circuitry for two purposes does not present a problem as it is unlikely that the curing of large samples for strength tests would be done simultaneously with a heat of hydration and thermal conductivity tests.

5.2.2 Initial tests, software development and probe calibration.

The program was written and modified during the initial calibration and testing of the probe to obtain accurate readings without introducing unnecessary heat into the sample.

Trial tests to determine the characteristics of the probe were carried out in blocks of carbon, teflon and polystyrene. The thermal conductivity values used in the calibration were:

- Polystyrene (moulded beads): 0,04 W/mK [illegible]

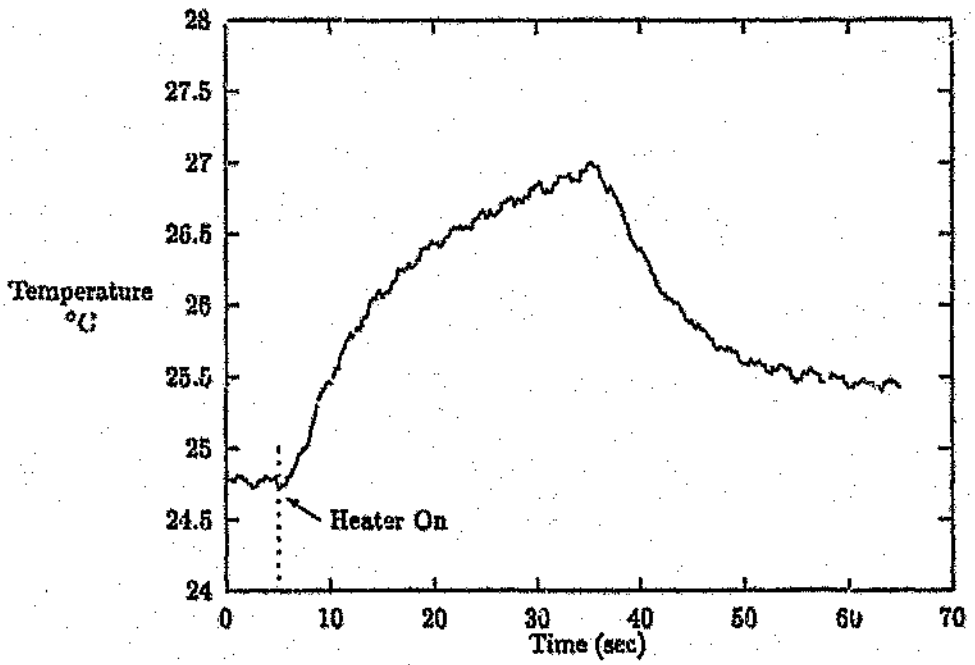


Figure 5.2: Heat pulse in carbon at 500 mA

- Teflon : 0,34 W/mK [94]
- Carbon: 0,94 W/mK (determined by using a simplified comparative method [100])

Tests were conducted in these materials at currents varying from 1A to 100 mA in 100 mA steps, so as to determine the optimum current for the probe by considering both the resolution of the temperature reading and the maximum input heat. A current of 500 mA was found to be the best compromise, allowing for sufficient temperature increase, in the high thermally conductive carbon sample, to obtain a relatively good resolution in the temperature reading while introducing the maximal possible heat into the sample under test. As examples of the tests undertaken, figures 5.2 and 5.3 show the heating curves at a current of 500 mA in both carbon and teflon samples. Readings were taken every 0,2 seconds during a test cycle where the heater was switched on for 30 seconds, 5 seconds after the readings started, with a complete cycle taking 65 seconds.

The temperature rise (ΔT) in equation 5.1 must be measured in the initial linear section of the curve [96]. By observation, both curves are most linear between 1

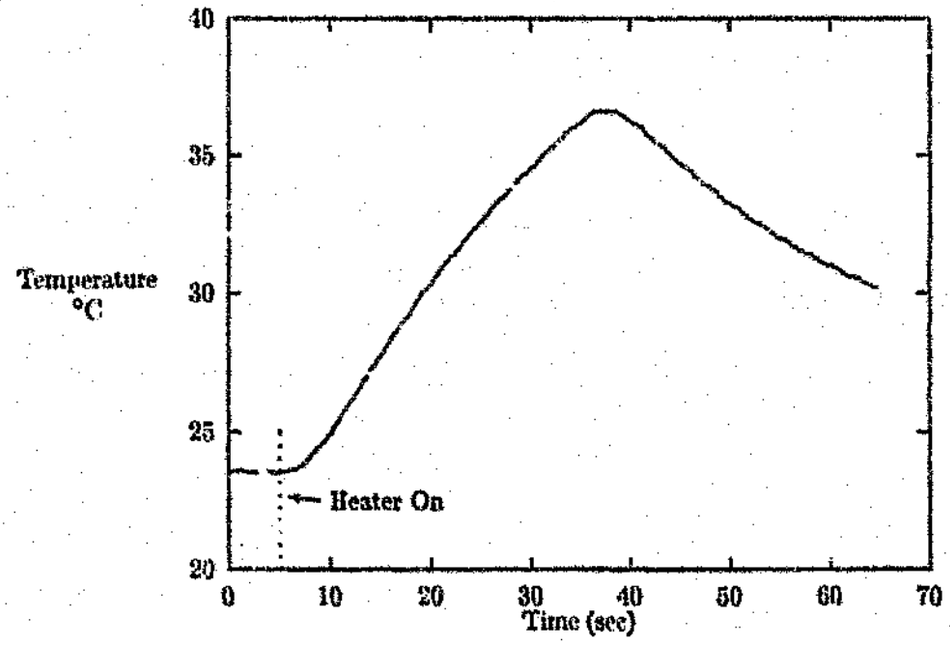


Figure 5.3: Heat pulse in teflon at 500 mA

and 15 seconds after the heater was switched on, and this period was used in the thermal conductivity tests.

As can be observed in figure 5.2 the initial linear section of the heating curve covers a temperature range of 2 °C. The resolution of the 12 bit analogue to digital converter card is 0,024 °C which results in resolution of 1,2% of the reading. This implies that readings in the carbon must be quoted as 0,94 ±0,02 W/mK.

Software was written to control the power supply to the probe and obtain temperature readings. The initial program switched on the power (500mA) to the probe, waited 1 second, took initial temperature readings, waited 10 seconds and then took a final temperature reading before switching the power off. The temperature increase was then corrected for any change in the temperature of the sample during the heat pulse (measured on the sample's temperature probe used by the adiabatic calorimeter). This temperature step was then related to the thermal conductivity of the materials tested, and the probe calibrated.

As the thermal conductivity measurements were conducted simultaneously with the

heat of hydration determination, a modified version of the control program was written with the aim of determining the amount of heat that the thermal conductivity tests add to the sample, and also to control the maximum temperature of the probe in low conductivity materials.

The revised control program switches on the heater, waits 1 second and then takes the initial temperature reading. The program subsequently monitors both time and probe temperature and will take the final temperature readings and switch off the heater when the temperature increase is 2 °C or the time elapsed is 10 seconds. If the temperature increase is less than 2 °C after 10 seconds, the program calculates the time at which the temperature would have reached 2 °C, based on a linear relationship. The time interval is then corrected for any changes in the sample temperature and related to the thermal conductivity of materials under test.

Because of the change from an output of temperature to an output of time, equation 5.2 becomes

$$\lambda = \frac{Q}{\Delta t} C \qquad (5.3)$$

where Δt is the time to reach 2 °C.

The calibration of the probe required two calibration steps. Firstly the power introduced by the probe at different temperatures was determined and then the probe was calibrated in samples of materials of known thermal conductivity.

5.2.2.1 Power calibration

The resistance of the heater wire in the probe was measured, at 10 °C intervals, from 25 °C to 90 °C and a linear regression curve fitted as shown in figure 5.4. From this relationship and the constant current of 500 mA, the power into the probe, at different temperatures, was obtained.

Not all the heat introduced into the probe heats the brass tube as the other materials of the probe are heated to the same temperature, and some heat is lost through the cables. To quantify the actual power used to heat the brass tube, the probe was placed in a block of polystyrene, to minimise the heat lost from the probe, and heated as in section 5.2.2. Figure 5.5 shows the results of the test showing both the heating rate, while the power was on, and the heat lost through the polystyrene with the power off. The rate of the temperature increase was added to the rate of the

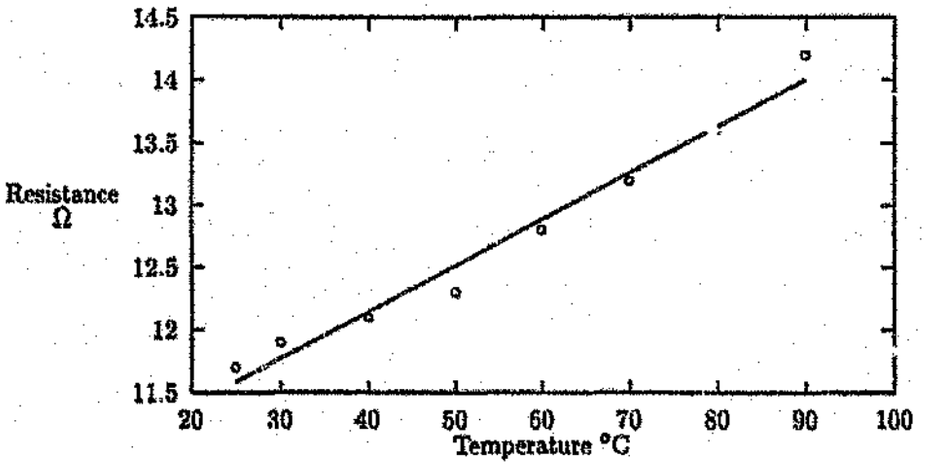


Figure 5.4: Calibration of Resistance Changes in Heater Wire

temperature decrease to determine a heating rate for the brass of 2,7 °C/sec. From the mass and specific heat [94] of the brass, it was calculated that the brass tube was absorbing 1,7 W of power. With input power of 2,8 W, an efficiency of 61 % was calculated for the probe. The value of Q in equation 5.3 can now be determined at different test temperatures.

5.2.2.2 Calibration factor

The choice of materials with which to calibrate the probe, proved to be one of the most difficult aspects of the probe's development. A large number of tests were conducted in the following materials:

- Water
- Oil
- Grease
- Polystyrene
- Cardboard
- Bee's wax
- Carbon

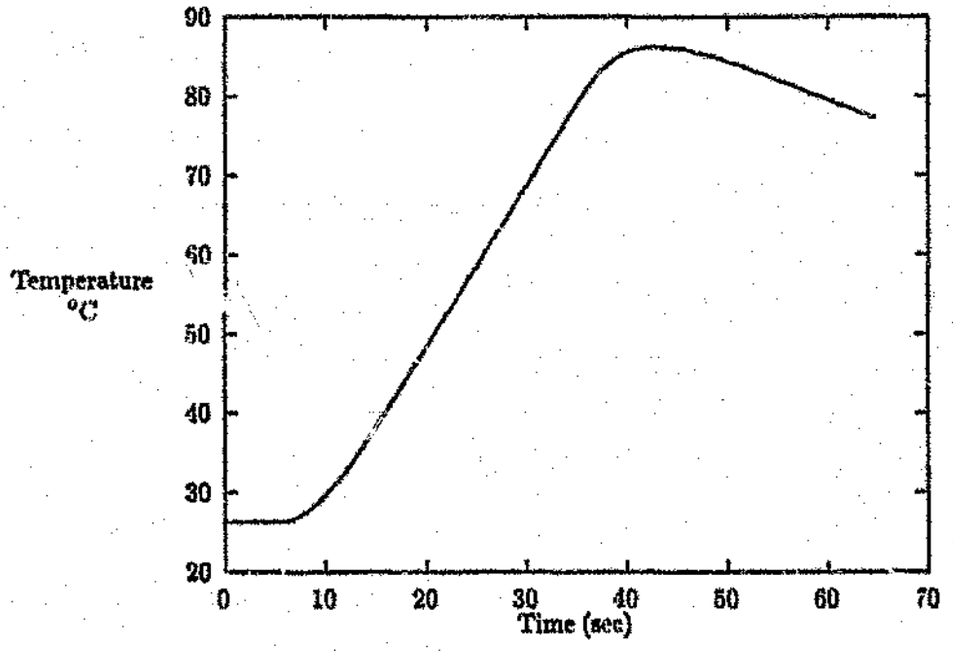


Figure 5.5: Heat pulse in polystyrene

- Teflon
- Heat sink compound
- Granite
- Cement Mortar
- Pine

Good results with the liquids and semi-liquids (water, oil, grease and heat sink compound) proved almost impossible, as the heat lost due to radiation and convection could not be accurately determined because of a lack of information on the emissivity of the probe and the actual thermal properties of the materials.

The samples of granite and mortar were ruled out because of the difficulty of drilling a 3,2mm hole to allow good contact with the probe. Although good results were obtained with both cardboard and polystyrene, tests in these materials were discontinued, as extreme care had to be taken when inserting the probe so as not to damage the material in such a way that contact between the probe and the material was incomplete.

It was decided to use the following materials for regular calibration of the probe, because of the ease of drilling holes into the material to obtain uniform and consistent contact with the probe.

- Bee's wax ($\lambda = 0,40 W/mK$) [101]
- Carbon ($\lambda = 0,94 W/mK$) (see section 5.2.2)
- Teflon ($\lambda = 0,35 W/mK$) [94]
- Pine ($\lambda = 0,11 W/mK$) [102]

Calibration was accomplished by taking at least 10 measurements in each of the listed materials, with a minimum of 10 minutes between readings. The 10 minute delay allows the probe, in the low conductivity materials, to cool to the sample's temperature before the next reading.

Two MATLAB programs (thermcon.m and probecal.m) were written to obtain calibration factors for the probe and are listed in Appendix B. The data obtained from the different materials are read by 'thermcon.m' and, with the corrections for power, a value '$\mathcal{F}$' was obtained, where:

$$\mathcal{F} = \frac{Q}{\Delta t} = \frac{\lambda}{C} \tag{5.4}$$

The values of $\mathcal{F}$ are tabulated in a data file with the actual values for the thermal conductivity of the material, and read by 'probecal.m'. A linear regression is fitted to the data and the factors stored in a file for use by the programs that process the thermal conductivity test results. The full scale error obtained for the probe is typically under 0,5%. A full scale value of $2 W/mK$ is used, as the resolution of the temperature readings at this thermal conductivity would provide an accuracy of better than 5%. Figure 5.6 shows a typical calibration result.

Experiments were undertaken in a sample of wet sand to determine whether a lubricant could be used to ease the removal of the probe from the cured concrete. Errors in the readings of 11% with petroleum jelly and 4% with heat sink compound resulted in the decision to allow direct contact between the probe and the concrete mix. Removal of the probe requires the careful breaking of the hardened concrete from around it.

To check that the probe has not been damaged while being removed from the hardened sample it is recommended that the probe's calibration is checked in the carbon

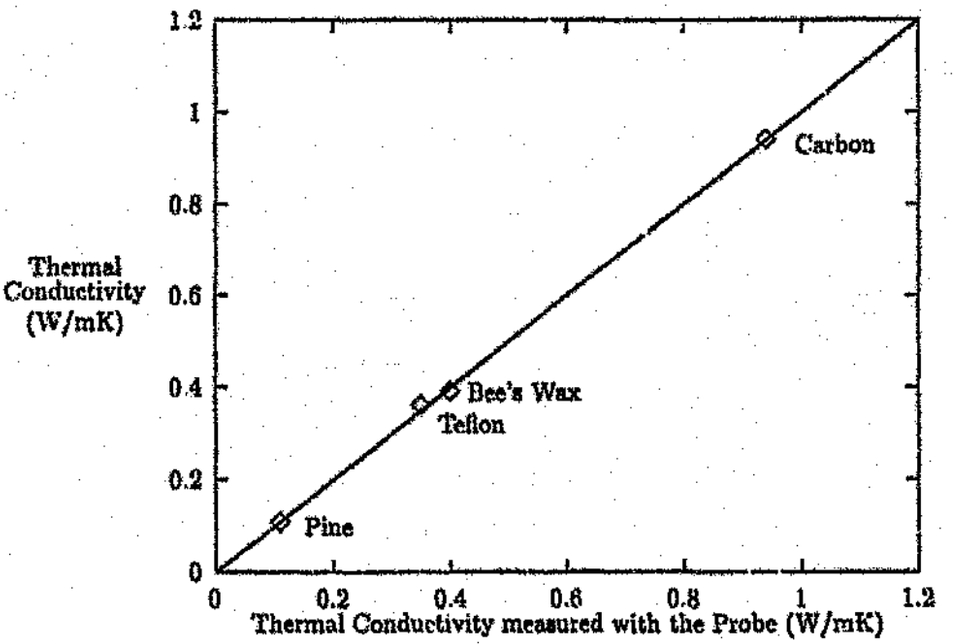


Figure 5.6: Thermal conductivity probe calibration curve

and teflon samples before each test, and a complete calibration undertaken if the full scale error in either reading is greater than 1%. The calibration procedure that should be followed is given in the next section.

5.2.3 Calibration procedure

The following steps should be implemented for regular calibration of the probe:

1. At least 10 measurements should be taken in samples of bee's wax, carbon, teflon and pine, with a minimum of 10 minutes between readings.
2. Each set of readings should be processed by the MATLAB program 'thermcon.m' to obtain the factor $\mathcal{F}$ (see equation 5.4).
3. The values of $\mathcal{F}$ should then be tabulated in a data file with the actual value for the thermal conductivity of the material.
4. Run the MATLAB program 'probecal.m', which will fit a linear regression to the data and store these factors in a file for use by the programs that process

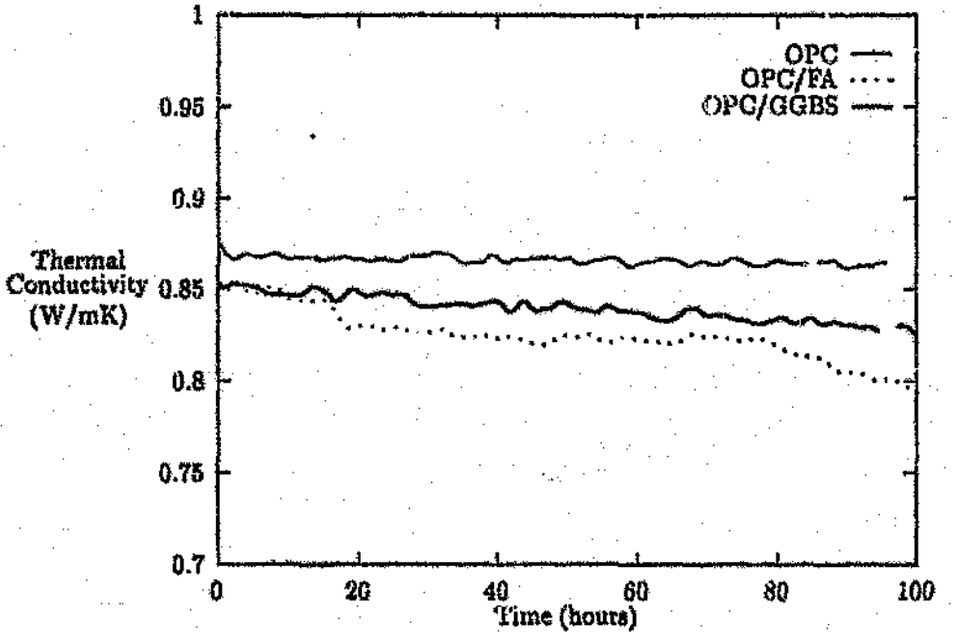


Figure 5.7: Thermal conductivity results

the thermal conductivity test results. A full scale error and a plot of the calibration results is also provided.

5.3 Data Collection and Processing

Preparation of the sample and placement into the calorimeter is the same as was described in section 4.2.1 with the exception that the conductivity probe is placed in the sample about 30mm from the temperature probe. This distance is sufficient to prevent the temperature probe influencing the results of the thermal conductivity readings. Thermal conductivity readings are taken at 10 minute intervals to reduce the amount of heat introduced into the sample. The time, pulse time and probe temperature are stored in a data file which, on completion of the test, is read by the MATLAB program 'condat3.m' (see Appendix B). This is the same program that processes the heat of hydration data as described in Chapter 4. The data is filtered in order to remove the variations due to the resolution of the temperature readings, in order to give a two hourly trend. Figure 5.7 shows the results of the same samples from which the heat of hydrations were determined in chapter 4. The program also

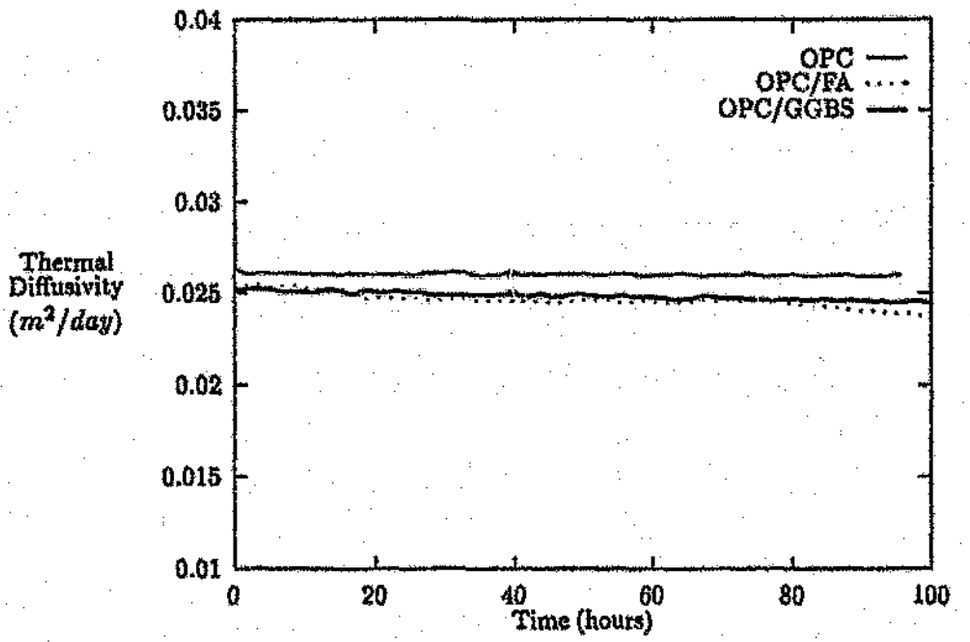


Figure 5.8: Thermal diffusivity results

calculates the thermal diffusivity of the concrete from the specific heat and density of the sample (see figure 5.8). Thermal diffusivity is defined as [3]:

$$D = \frac{\lambda}{cd} \tag{5.5}$$

where

D = Thermal Diffusivity (m^2/s)

λ = Thermal conductivity (W/mK)

c = Specific Heat (J/kgK) (Measured or recommended values)

d = Density (kg/m^3)[1]

The effect of the heat introduced into the sample by the thermal conductivity measurement was investigated. In the worst case, where the heater is on for 10 seconds, 28 J of heat is used for the measurement (2,8 W for 10 seconds) which, on average, will raise the temperature of the sample 0,01 °C. This increase is less than the resolution of the temperature measurement for the control system (0.024 °C) and will

[1]The density used is the compacted density of the sample measured before placement into the calorimeter.

Table 5.1: Comparison of Thermal Conductivity (λ)

	$\lambda(W/mK)$	Time after Mixing
Probe	0,6 - 1,2	0 - 4 days
Yoshida [38]	1,5 - 1,8	0 - 2 days
Rousan [47]	1,0 - 1,8	7 - 84 days
Davey [103]	0,8 - 2,3	not specified
ACI [57]	1,8 - 3,8	14 days

remain unnoticed by the control system. This will result in the heat being lost to the air and water surrounding the sample without affecting the adiabaticity, or the heat of hydration calculations. Tests undertaken using samples with, and without, the heat pulse, showed that there was no apparent heat introduced by the thermal conductivity measurement.

5.4 Discussion of Results

Numerous tests were conducted on various concrete mixes with different aggregates, mix ratios and extenders during the development of the probe. Figure 5.7 is typical of the results obtained with a declining trend in the conductivity of FA and GGBS concretes always evident when compared with the thermal conductivity trend of OPC concretes. The reason for this difference has not been investigated. Thermal conductivities in the range of 0,6 to 1,2 W/mK were recorded with the lower values obtained from mixes with dolomite aggregates and the higher values with granite aggregates. Table 5.1 shows the comparison of the results with those of other researchers.

The values obtained from the probe are lower than those obtained by other researchers. This is probably due to the fact that they all conducted their measurements on hardened concrete from 3 to 180 days after mixing, with the exception of Yoshida who took his measurements at temperatures between 0 °C and 10 °C, and neglected the heat of hydration in his results.

5.5 Conclusions

The development of the thermal conductivity probe will enable, for the first time, the determination of the thermal conductivity of concrete samples during all stages of hydration. The ability to measure the thermal conductivity of concrete during the early stages (first 48 hours) of hydration, when the heating rate from the hydration reaction is at its greatest, will help enormously in producing an accurate heat model of a concrete structure.

Numerous tests need to be undertaken on samples of concrete with various cementitious mixes and aggregates to classify concrete types and mixes with their "typical" thermal conductivities. This would provide the design engineer with valuable information on which to base future designs of mass concrete structures.

Chapter 6

HEAT MODEL AND VERIFICATION OF RESULTS

6.1 Introduction

As the results obtained from the thermal conductivity probe are significantly lower than those from other researchers and those recommended for design values for mass concrete [57, 73, 3], a simple heat model was developed to predict temperatures in a concrete structure in order to validate the results obtained from the heat of hydration and thermal conductivity tests. The results obtained from this model, using the heat production and thermal conductivity test results, were then compared to temperature measurements obtained from a test sample in semi-adiabatic conditions and a concrete structure.

6.2 Heat Model

The heat model is based on the Gauss-Seidel nodal iteration technique. The temperature at a particular node is defined as [95]:

$$T_i^{P+1} = \frac{\Delta\tau}{C_i}\left[q_i + \sum_j \frac{T_j^P - T_i^P}{Rij}\right] + T_i^P \qquad (6.1)$$

where

T_i^{P+1} = Temperature of node i one time interval after time P

Δr = Time interval (10 minutes)

C_i = Thermal Capacity of node

q_i = Heat generated by the node

T_i^P = Temperature at time P

$\sum_j \frac{T_j^P - T_i^P}{Rij}$ = Heat lost and/or gained by the node

where

$T_j^P - T_i^P$ = Temperature between the node and adjacent nodes

Rij = Thermal resistance between the node and adjacent nodes

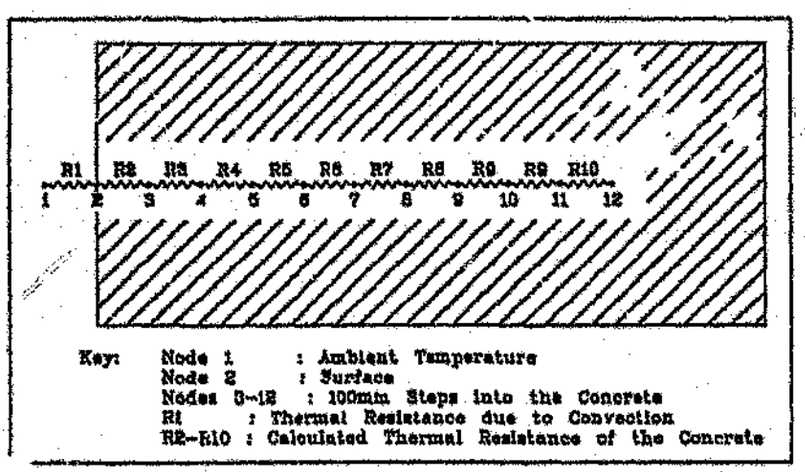


Figure 6.1: Heat Model

A MATLAB program 'heatmod.m' (see appendix B) was written to implement the model. The program calculates the temperature for each node as shown in figure 6.1, at ten minute intervals. The input data is from the files produced by 'condat3.m' containing the heat of hydration and thermal conductivity measurements obtained from a test sample. The model is thus based on the actual heat of hydration and thermal conductivity measured, and is updated in the model at the ten minute intervals. If the total time for the model exceeds that of the test, the assumption is made that the hydration process is not producing any more heat and that the thermal conductivity remains constant at the same value as the last reading. The expected temperature at each node, with respect to time, and a temperature profile after 24 hours is plotted. These are shown in figures 6.2 and 6.3 respectively.

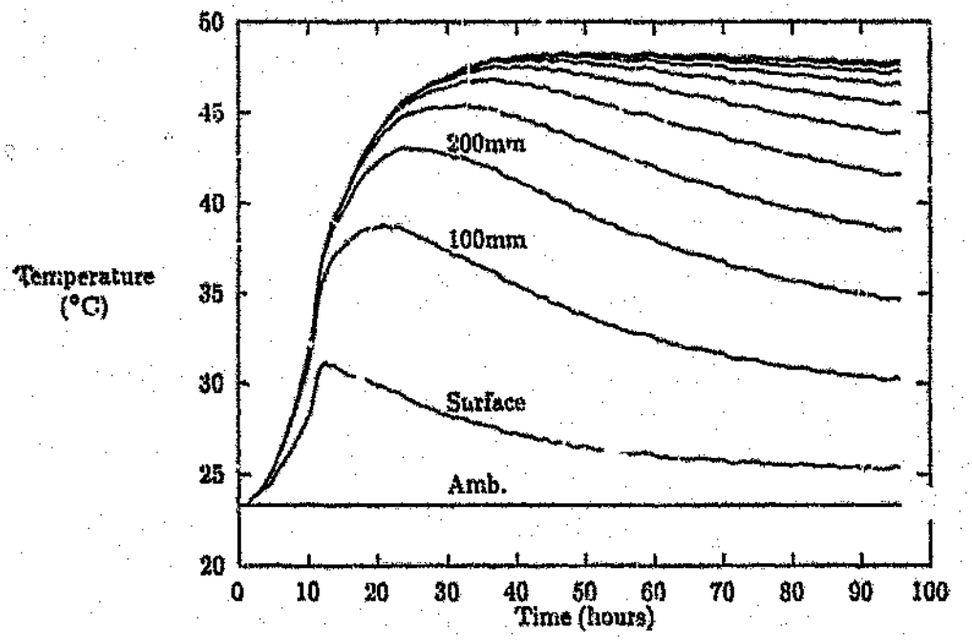


Figure 6.2: Predicted temperature in a concrete structure

6.3 Verification of the Model and Test Procedures

6.3.1 Polystyrene calorimeter

Figure 6.4 shows the calorimeter that was constructed, out of polystyrene, to verify the model and the data obtained from the heat of hydration and thermal conductivity tests.

A concrete sample was mixed in the same proportions as the OPC concrete mix given in table 4.2. The results of the power and heat obtained from the adiabatic calorimeter test of this mix are shown in figures 4.5 and 4.6 in chapter 4 and the thermal conductivity results in figure 5.7 in chapter 5. The mixed sample was placed in a thin plastic container, which was put into the hole in the polystyrene block. Complete contact with the polystyrene is not essential as long as air movement around the container is controlled. Thermocouple temperature probes were used to measure the ambient temperature, surface temperature and the temperatures of three points at 100mm intervals into the sample (see figure 6.4). Software was developed to use the adiabatic calorimeter's measuring system to monitor the temperature values and

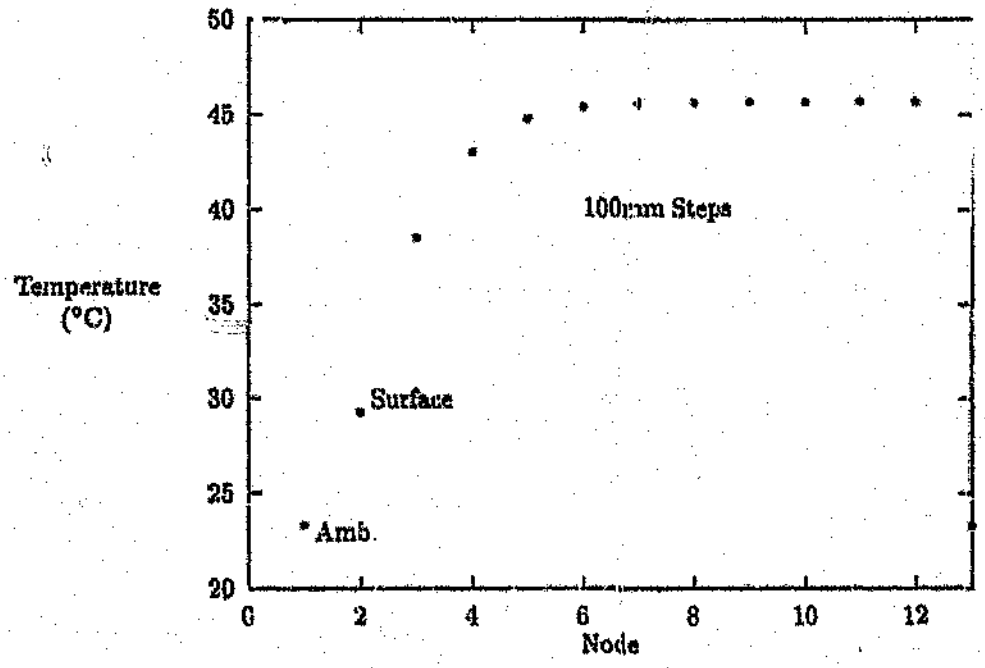
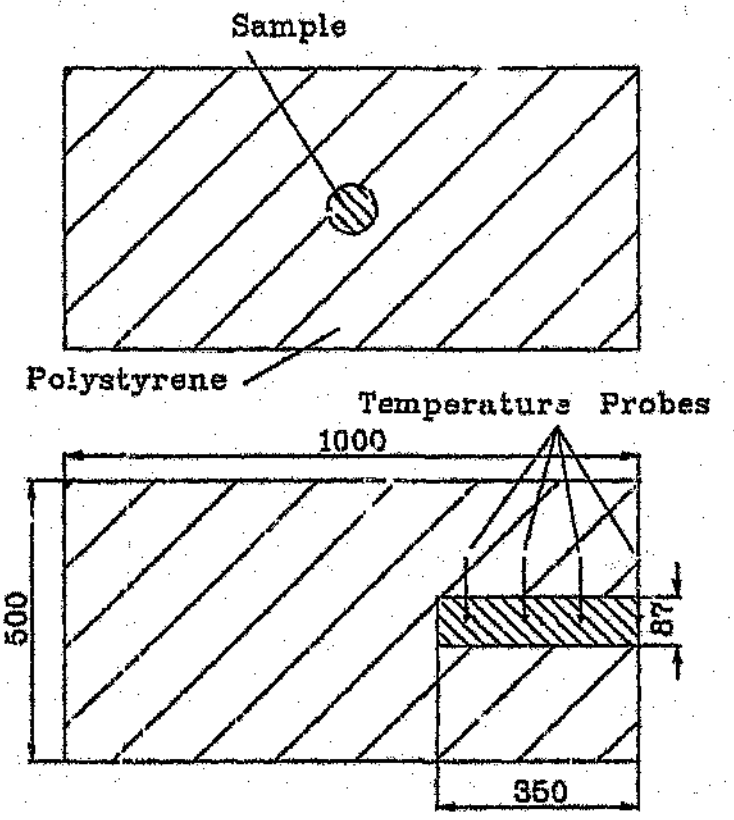


Figure 6.3: Predicted temperature profile after 24 hours

to store the data on file.

The model described in section 6.2 was modified to cater for the heat lost through the polystyrene. This was accomplished by subtracting the predicted heat lost from each node to the ambient temperature through the polystyrene as shown in figure 6.4. This heat loss, for various differences between the ambient and the node temperatures, was determined using a finite element software package. A MATLAB program 'heatmod2.m' (see appendix B) was written to model the expected temperatures in the test sample, taking into account the losses through the polystyrene. The thermal resistance due to the heat lost at the surface (R1 in figure 6.1) was then adjusted to give the best correlation, between the modelled results and the measured values of the surface temperature. After the program was re-run, with the corrected heat loss at the surface, the results for all the nodes were then compared to the actual values measured. Figures 6.5 and 6.6 show the comparison of the measured temperatures with those predicted by the model for the concrete mix.

The results at the nodes show an agreement within 2 °C. Variation at the surface node was as a result of the correction for the emissivity at the surface assuming a constant ambient temperature, which was not the case with the measured results.



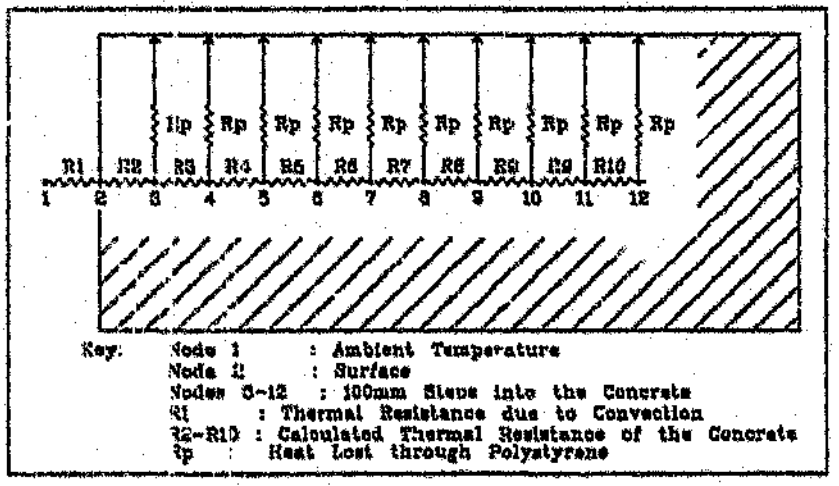


Figure 6.4: Polystyrene Calorimeter and Heat Model

This difference is also reflected in the other three nodes. For simplicity a constant ambient temperature was used although the model can accommodate a measured ambient temperature profile as input.

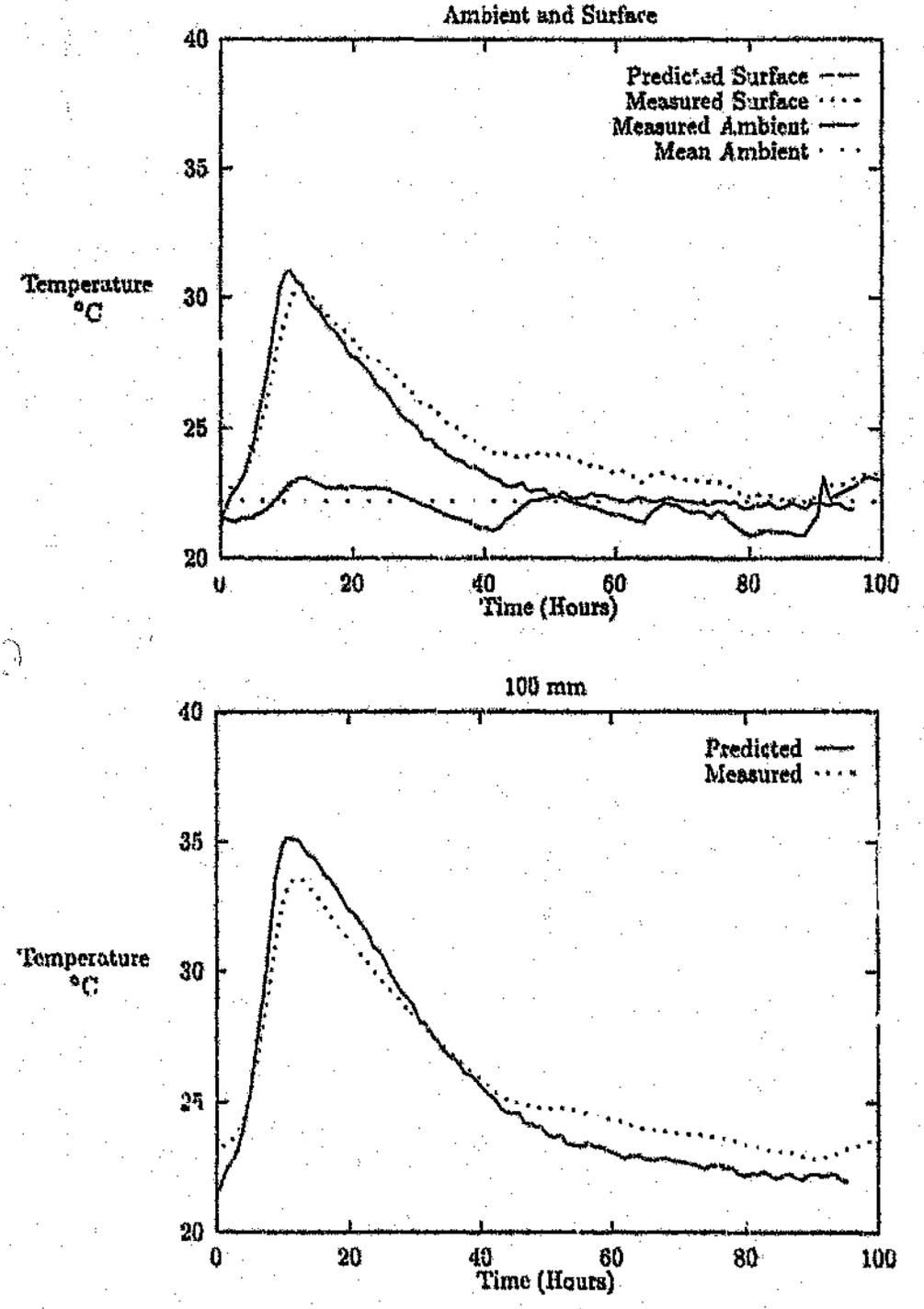


Figure 6.5: Comparison of Measured and Modelled Temperatures (Ambient, Surface and 100 mm)

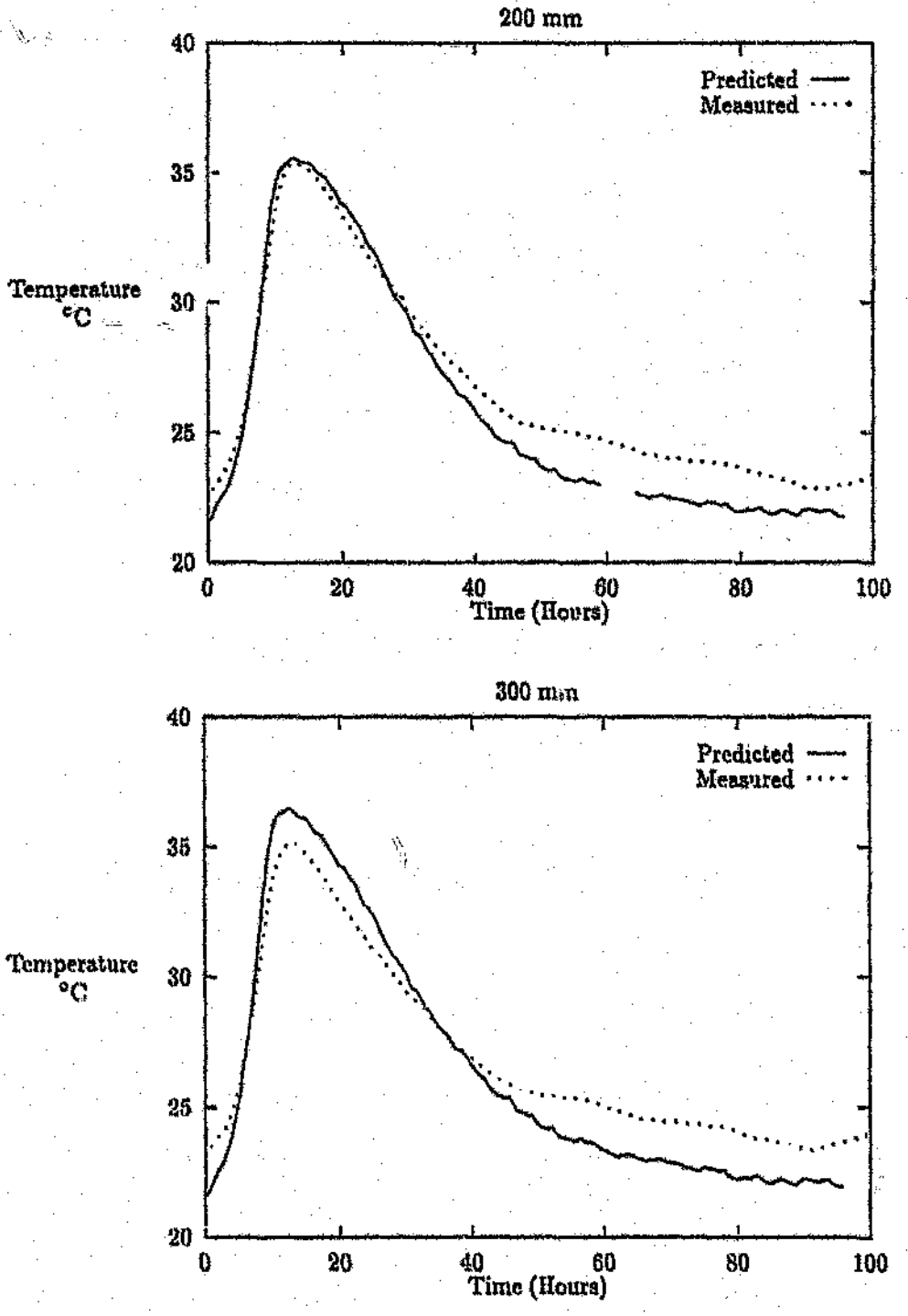


Figure 6.6: Comparison of Measured and Modelled Temperatures (200 mm and 300 mm)

6.3.2 Concrete structure

To further validate the results obtained from the calorimeter and the heat model, an actual concrete structure was examined. The structure was a bridge pier with approximate dimensions of 3m × 3m × 5m with the shuttering being removed sixty hours after casting. No precautions were taken to control the heat build up in the structure. The pier was constructed from 30 MPa concrete with a water:cementitious ratio of 0,47:1 and OPC/FA ratio of 70:30. Three temperature measuring points were installed monitoring the ambient temperature and depths of 50mm and 1,5m from the surface.

As the modelling was done after the pier was built, the concrete sample used for the heat of hydration and thermal conductivity tests was not made from the actual components used in the pier construction. The mix ratios (see table 6.1) were kept the same and similar aggregates were used. The specific heats used in the calculations were the values recommended in Fulton [3] for the aggregates used. The results for the heat of hydration and thermal conductivity are shown in figure 6.7.

The values for the power generated and the thermal conductivity were used by the heat model program (see chapter 6) with a modification to model the change in heat being lost at the surface after the shuttering was removed The ambient temperature measured at the site was used in the model. Figure 6.8 shows the predicted temperatures at 50mm and 1,5m, together with the ambient temperature measured at the site.

The predicted temperatures are compared with the measured temperatures in figures 6.9.

Table 6.1: OPC/FA Concrete mix

OPC	249g
FA	107g
SAND	763g
STONE	1.02kg
WATER	200ml
DENSITY	$2491kg/m^3$

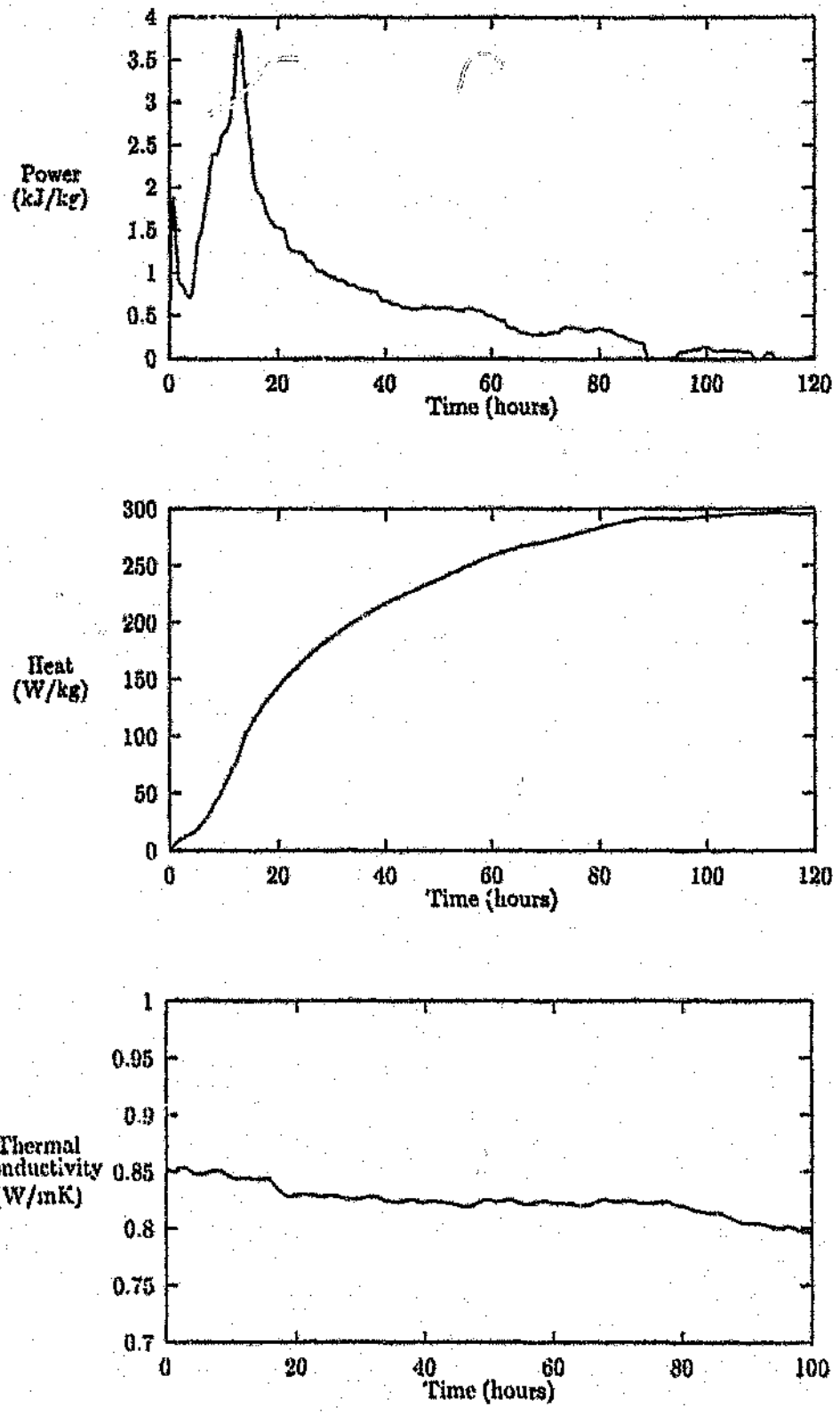


Figure 6.7: Thermal Results from the Adiabatic Calorimeter

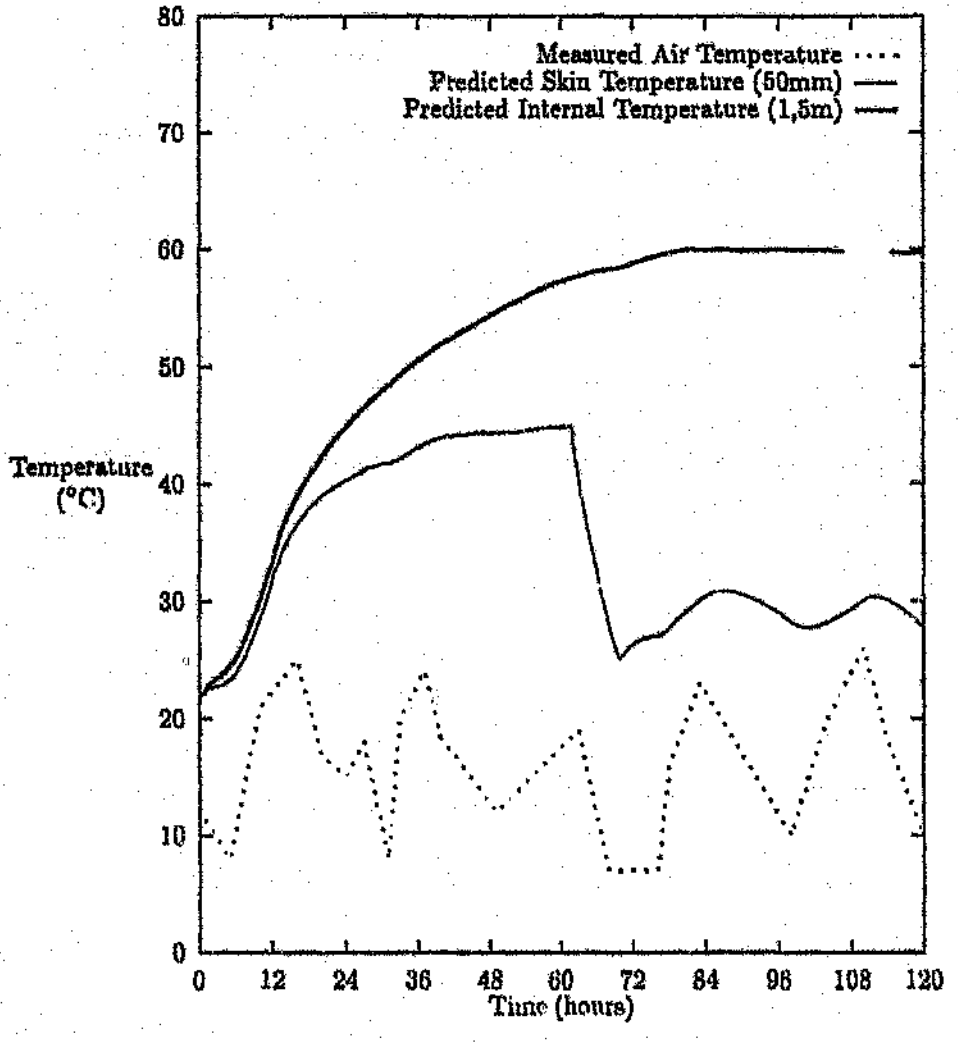


Figure 6.8: Predicted Surface and Internal Temperatures

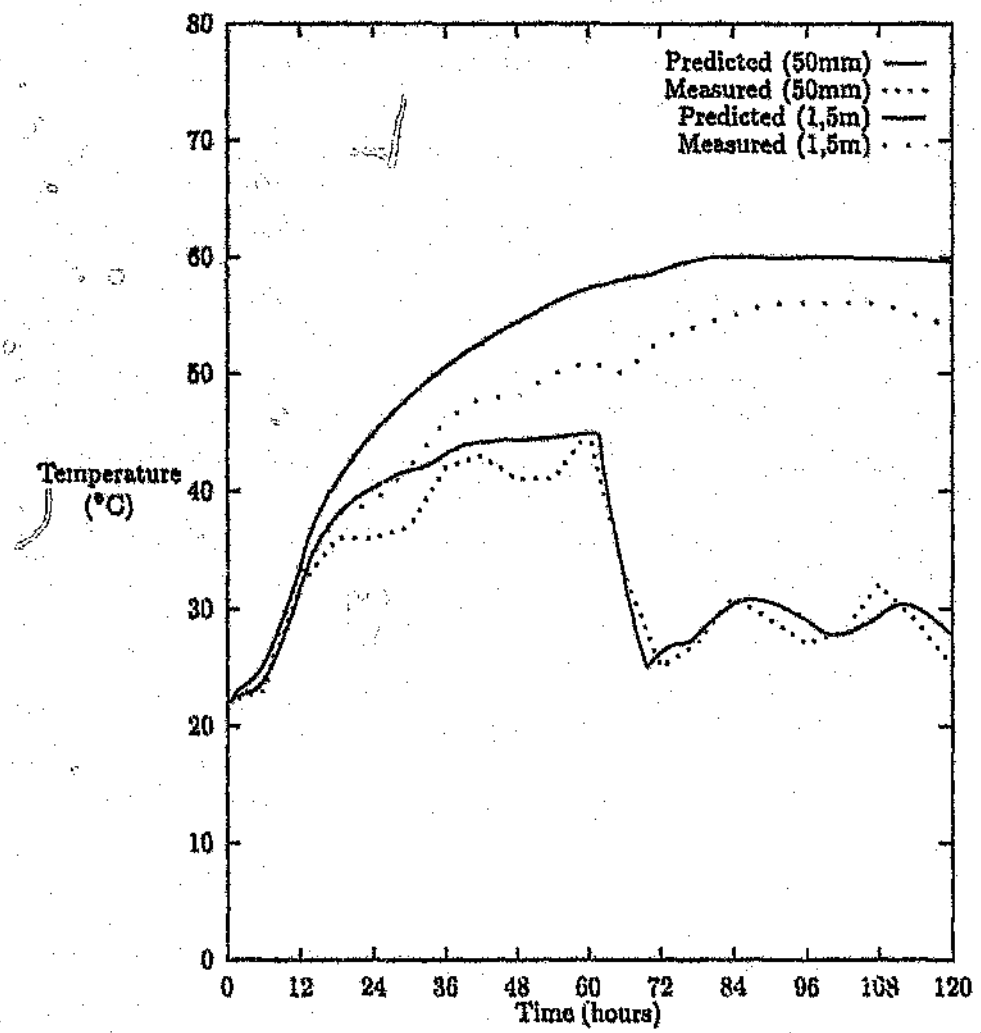


Figure 6.9: Predicted and Measured Temperatures in Bridge Pier

6.4 Discussion

The results from the polystyrene calorimeter show that the values obtained for the heat of hydration and thermal conductivity of curing concrete are correct within an error band of 6% (2 °C at the maximum temperature of 36 °C). This error may also be due to the fact that the model uses heat of hydration values determined in adiabatic conditions, where the temperatures are higher than those obtained in the polystyrene calorimeter. The higher curing temperatures in the adiabatic calorimeter result in faster hydration [3] and therefore higher heating rates. It should also be noted that the starting temperature, aggregate variations and mixing techniques affect the heat of hydration determined during tests in the adiabatic calorimeter.

The modelled temperatures at 1,5m for the bridge pier are within 13% of the measured readings. Considering that the laboratory tests were not conducted on the actual concrete mix used for the construction and that the specific heats used are the generalised values from Fulton [3] the results are well within the error bounds of the input information.

It should be noted that, as the modelling was done after the field measurements were taken, the model was adjusted to simulate the actual surface conditions. To use the model as a design tool, the thermal conductivity and emissivity of the shuttering to be used would have to be determined. With this information and the proposed time for the removal of the shuttering included in the model, more accurate temperature profiles within a concrete structure can be estimated.

6.5 Conclusion

The heat model was developed to validate the results from the adiabatic calorimeter and thermal conductivity tests described in the proceeding chapters. The correlation between the predicted and measured temperatures, in both the polystyrene calorimeter and the bridge pier, are within the limits of the experimental error for both situations. This correlation of the results indicates that the results obtained for the heat of hydration and thermal conductivity tests are correct.

Chapter 7

PRACTICAL APPLICATIONS AND FUTURE RESEARCH

7.1 Introduction

This chapter briefly examines the practical applications of the laboratory tests described in this thesis. These are temperature matched curing tests to determine a strength profile within the structure as well as crack formation prediction. A discussion on possible future research work to both improve and expand on the laboratory tests and prediction techniques is also included.

7.2 Temperature Matched Curing Tests

With the ability to predicted the temperature profiles within a concrete structure (as shown in chapter 6) it is possible to use these temperature profiles for temperature matched curing (TMC) tests in the calorimeter. Strength tests could then be performed on the samples and a strength profile of the structure, with respect to time, created. This would give the design engineer more and better quality information on which to base the construction of a large concrete structure.

7.3 Crack Prediction

The prediction and control of cracks in large concrete structures is of prime importance to the design engineer. A preliminary investigation was undertaken, by the author, into the use of the thermal information, determined by the tests described in this thesis, to predict the formation of thermal cracks. Two types of thermal cracking are found in mass concrete structures [3]:

Early Age Thermal Cracking This is due to a temperature gradient between the centre of the structure and the surface. This causes greater expansion in the interior than at the surface causing tensile stresses at the surface and thus surface cracking. This situation is reversed during cooling as the interior, which cools through a greater temperature range, contracts more than the surface. The now hardened surface offers restraint and tension develops in the interior causing hidden cracking. Fulton recommends that the temperature difference between any two points in the structure should not exceed 15 °C.

Restraint Cracking This form of cracking is caused by the thermal stress exceeding the tensile strength of the concrete at any point in the structure. The thermal stress was defined in equation 1.1 in the introductory chapter of this thesis and is dependent on the degree of restraint to which the structure is subjected and the modulus of elasticity and the coefficient of thermal expansion of the concrete and its adjoining materials, either foundation rock or previously cast concrete. Fulton recommends a maximum temperature difference of 17 °C between the maximum temperature during hydration and the base on which the concrete is cast. Care should be taken if the base material is at an elevated temperature, such as concrete cast earlier, as the whole structure will cool below this starting temperature with time, dependent on the ambient temperature conditions. In this case the maximum temperature difference of 17 °C should be related to the minimum temperature to which the structure will cool.

It should be noted that the limits of 15 °C and 17 °C are "rule of thumb" values and that the concrete will crack when the thermal strain exceeds the cracking strain of the concrete. Cracking strain is a function of strength, elastic modulus, creep, coefficient of thermal expansion and shrinkage, which are time dependent intrinsic factors. The recommended limits ignore variations in these factors which are dependent on construction techniques and concrete mixes. Drying shrinkage also has a large influence on surface crack formation.

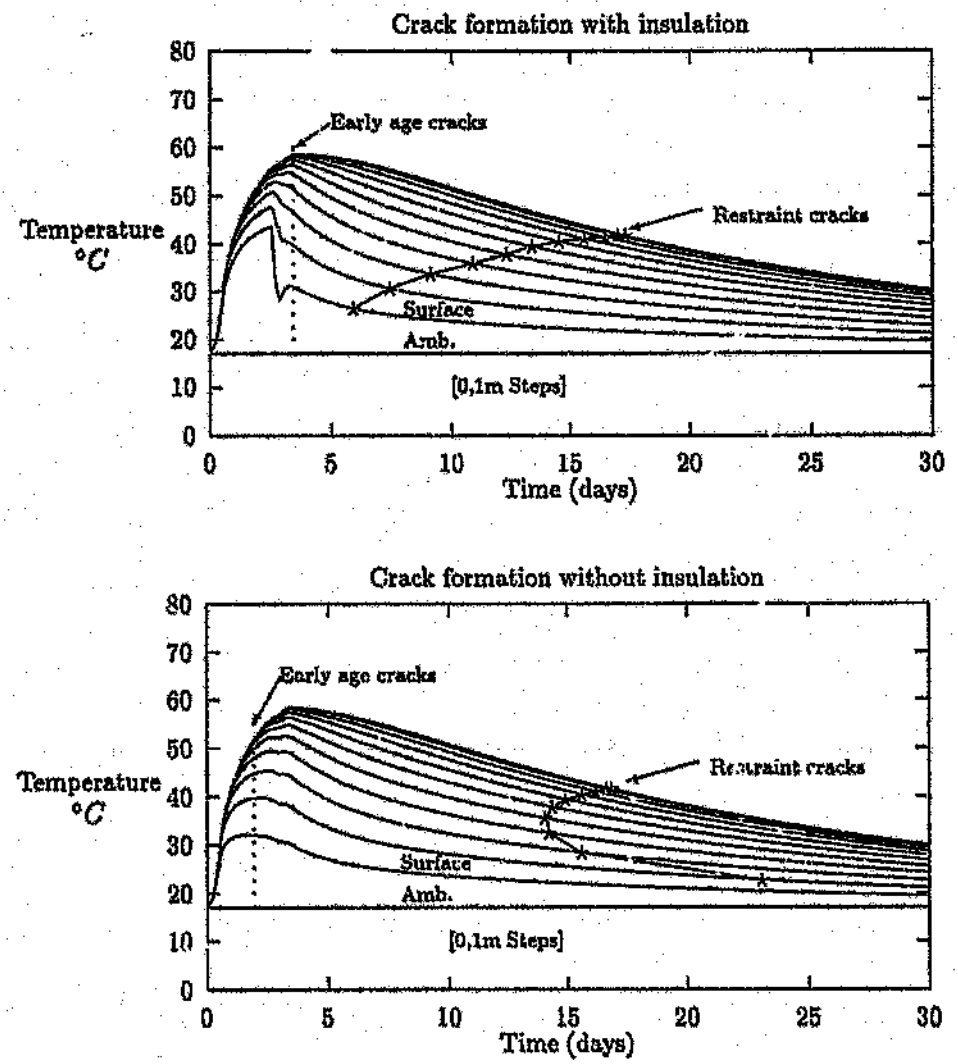


Figure 7.1: Prediction of crack formation

The model used for determining the temperatures in the bridge pier, described in chapter 6, was expanded to include a check for any temperature differences exceeding Fulton's recommended values of 15 °C and 17 °C. Figure 7.1 shows the time that both types of cracking would have occurred with the insulating shuttering that was used in the construction of the pier, as well as the cracking time if non-insulating shuttering had been used.

The early age cracking was determined to be the earliest point in time that there is a temperature difference of more than 15 °C within the structure. This indicates the time at which surface cracks would start forming due to the greater internal

expansion when compared with that at the surface.

Restraint cracking was calculated at the point in time that the node had cooled to more than 17 °C of the maximum temperature that it had reached.

From the two figures it is clear that active cooling methods would have to be employed to prevent the structure cracking. The use of insulating materials would have prevented the "early surface cracking" of the pier but would have had to remain in place until the centre had cooled to within 15 °C of the minimum ambient temperature. The insulation, however, would not have prevented the restraint cracking, although it would have delayed the development of the cracks. Reports indicate that the pier suffered from extensive cracking.

The thermal model predicts the time of the crack development and not the size or distribution of the cracks, which would be dependent on the size of the structure, how homogeneous it is and the pattern of any reinforcing that may be used.

It should be noted the these predictions of crack formation are based solely on the maximum temperatures recommended in Fulton, from work by Harrison [74] and Waugh [104]. To accurately predict the crack formation in a structure the degree of restraint, the moduli of elasticity and the coefficients of thermal expansion of the concrete and its adjoining materials need to be known. Drying shrinkage will also influence the stress in the cooling concrete structure, and increase the cracking tendency in the structure.

The above factors are all dependent on on the degree of hydration and temperatures within the structure and will change continuously during the hydration and cooling periods.

7.4 Future Research Work

Further investigation should be undertaken into the change in specific heat of various types of cement pastes during hydration. As was pointed out by Carlson [19], it is very difficult to measure the specific heat of a material while it is producing heat. The author suggests that this may be overcome by taking samples during hydration and determining the specific heat at low temperatures, when the rate of hydration would be comparatively small.

Development of the crack prediction model should be taken further and incorporated

with work of other researchers [67, 105, 106, 107, 108]. The work should include an investigation of past research into the parameters which influence the thermal stress in concrete, as well as both theoretical and practical methods to incorporate these parameters into a stress and heat model of any concrete structure.

An extensive test program needs to be conducted with the adiabatic calorimeter and thermal conductivity probe to classify the heat parameters of concretes with various South African cementitious mixes and aggregates. This would provide the design engineer with valuable information on which to base future designs of mass concrete structures. Simultaneously a temperature measurement program should be conducted in all new mass concrete structures, in conjunction with laboratory tests, to further verify the heat of hydration and thermal conductivity measurements in the calorimeter and the heat model.

The possible development of a larger portable thermal conductivity probe that can be used to measure the thermal conductivity of mass concrete 'in situ' should also be investigated.

Chapter 8

SUMMARY OF FINDINGS AND CONCLUSIONS

8.1 Heat of Hydration Measurements

The three most widely used methods for determining the heat of hydration of concrete are the heat of solution method, conduction calorimetry and adiabatic calorimetry.

The heat of solution method is most widely used in the specification of cements but only gives the total heat produced, with no indication of how this is related to time. Included in the total heat determined is an appreciable temperature rise almost immediately after mixing the cement and water [19], due to the solution of free oxides and impurities. This increase continues at a diminishing rate for about 30 minutes. Neither calorimetric method can measure this initial heat release, as the concrete is mixed out of the calorimeter with some of this initial heat being lost before adiabatic conditions are obtained. Quick mixing and placement into the calorimeter will reduce this heat loss.

Adiabatic calorimetry uses the specific heat of the sample in determining the heat of hydration from the temperature rise in the sample. As the specific heat of the cement paste changes during hydration [19, 23], errors will introduced into the calculation for the heat of hydration, as was discussed in chapter 4. Conduction calorimetry overcomes this problem by removing and measuring the heat produced by the sample. This, unfortunately, does not allow the sample to increase to the temperatures that would be found in a concrete structure, which changes the rate of the chemical reaction, and thus the heat of hydration. Adiabatic calorimetry allows the sample to

experience the conditions most likely to be found in mass concrete during hydration, and was chosen for this reason.

The calorimeter described in chapter 3 is a reliable and accurate system for the determination of the heat of hydration of concrete. The difference between the heat of hydration determined using a constant specific heat and a corrected specific heat in figure 4.3 (see chapter 4) is about 2%. Further investigation could be undertaken into the change in specific heat of various types of cement pastes during hydration.

8.2 Thermal Conductivity Measurements

The use of the thermal probe method, as described in chapter 5, is the first measurement of thermal conductivity of concrete in the early stages of hydration (first three days) since Yoshida [38]. Yoshida conducted his experiments at low temperatures and neglected the heat of hydration in his results. All other measurements have been conducted on samples of wet or dry hardened concrete from 3 to 180 days after mixing.

8.3 Thermal Model

The development of the thermal model and temperature measurement in insulated samples of concrete, as described in chapter 6, were designed to verify the results obtained from the calorimeter. Figures 8.1 and 8.2 show the comparison of results obtained with an OPC concrete mix (see table 6.1) at a depth of 300mm and 200mm respectively.

As can be seen, the results are within the accuracy of the thermocouple measurement system (±1 °C). The difference between using a specific heat calculated as the sum of the specific heats of the components of the concrete and using the corrected specific heat, is negligible.

The good corelation between the measured and modelled results indicate that accurate results were obtained from the heat of hydration and thermal conductivity measurements in the adiabatic calorimeter.

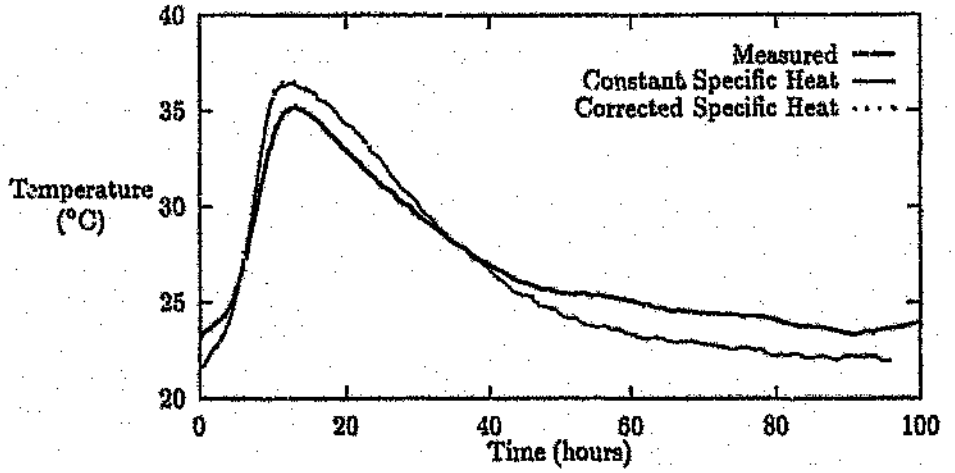


Figure 8.1: Verification of calorimeter results at 300mm

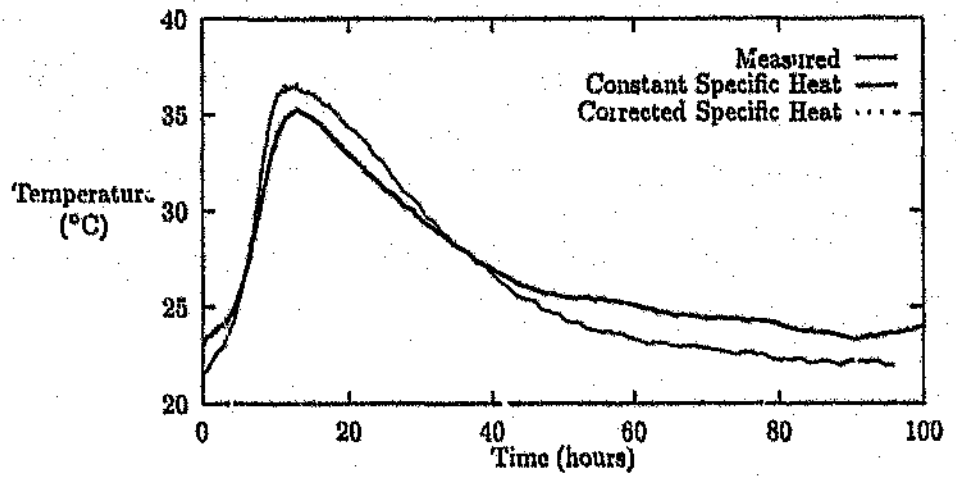


Figure 8.2: Verification of calorimeter results at 200mm

8.4 Conclusion

The development of the adiabatic calorimeter and conductivity probe described in this thesis has made it possible, for the first time, to determine the heat generation, thermal conductivity and thermal diffusivity of any concrete mix design, and therefore the ability to model the temperature profile of any concrete structure during

the hydration period. Three dimensional mathematical heat transfer models [109] and commercial finite element software packages such as ADINA [72] will allow the temperature profiles of more complex geometrical structures to be estimated.

Samples can then be cured, using the calorimeter, at the predicted temperatures, and strength tests performed to determine the quality of the concrete that would be found at various locations in a structure. From these predicted temperature and strength profiles of the structure and the prediction of crack formation (as discussed in chapter 7) decisions on concrete mixes, cooling facilities and construction techniques can be made, which will reduce problems experienced during the construction of large concrete structures.

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Appendix A

CIRCUIT DIAGRAMS

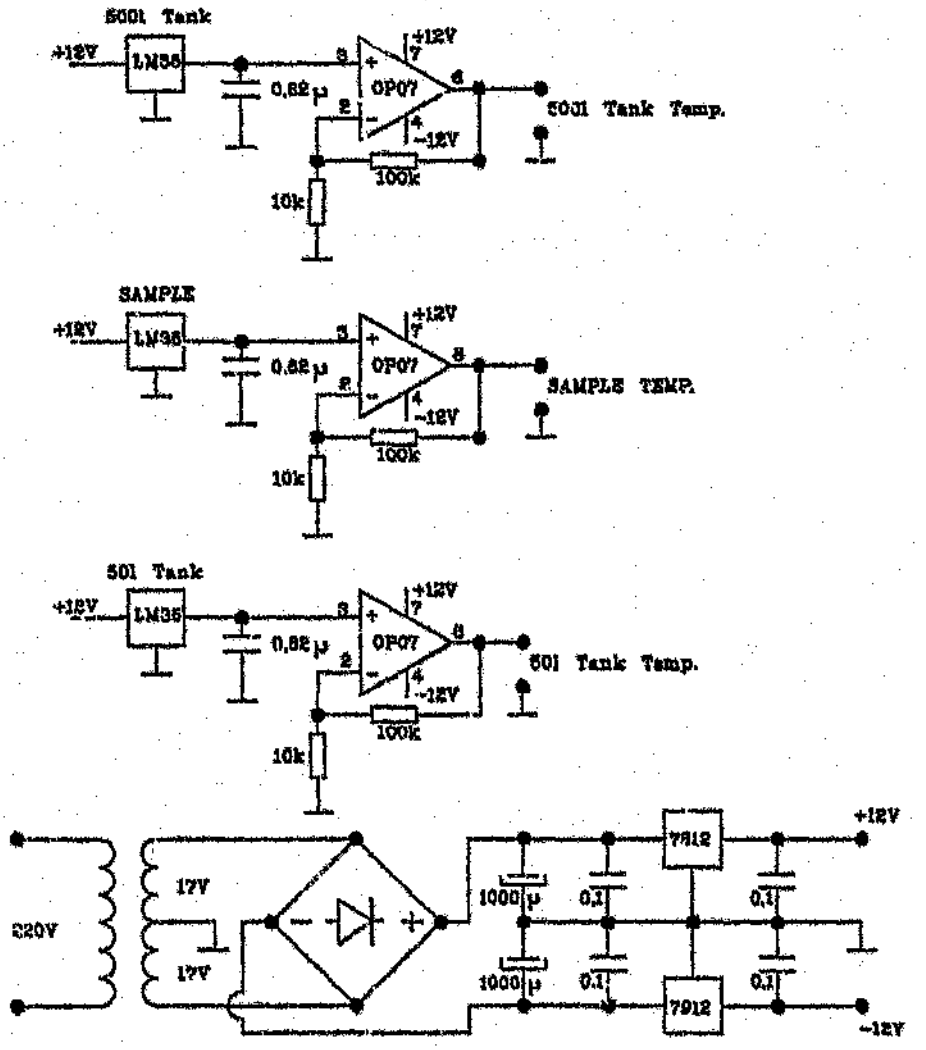


Figure A.1: Temperature probe signal conditioner circuits

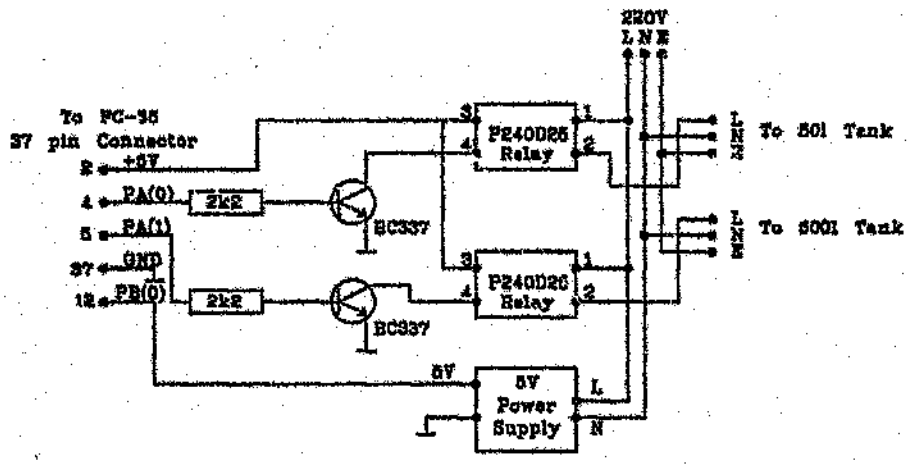


Figure A.2: Heater relay interface circuit

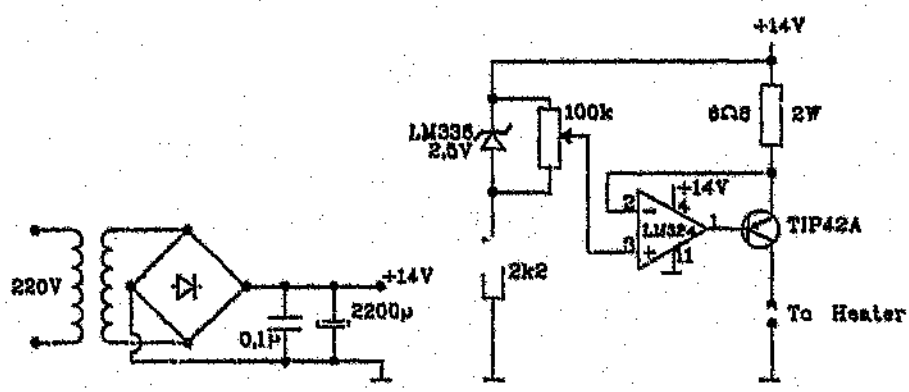


Figure A.3: Constant current supply for thermal conductivity probe

Appendix B

SOFTWARE LISTINGS

B.1 PHDCALTE.PAS

```
{$R+}    {Range checking on}
{$B+}    {Boolean complete evaluation on}
{$S+}    {Stack checking on}
{$I+}    {I/O checking on}
{$N-}    {no 8087}
{$M 8000,0,200000}
program calorimeter;


            {-------------------------------}
            {              by               }
            {          G.J.Fibbon           }
            {     Faculty of Engineering    }
            {        Wits University        }
            {-------------------------------}
Uses
  Crt,
  Dos,
  Printer,
  Graph,
  sml4gra,
  bgifont,
  bgidriv,
  calutils;

Var
   GraphDriver,GraphMode:integer;
   check_12,multi_resp:boolean;
```

```
{-------------------------------------------------------------------------}
procedure draw_axis(full_screen:boolean);

var
   X,Y,I,J:integer;
   Q:real;
   lable:screen_message;

begin
     SetViewPort(0,0,GetMaxX,GetMaxY,ClipOn);
     ClearViewPort;
     X:=GetMaxX;
     Y:=Main_screen_size;
     {draw border}
     Rectangle(0,0,X,Y);
     {draw axis}
     SetLineStyle(DottedLn,0,NormWidth);
     for I:=1 to 9 do
     begin
        Line(0,round((I*10)*Main_screen_size/100),X,round((I*10)
*Main_screen_size/100));
     end;
     for I:=1 to 13 do
     begin
        Line(round(X*I/14),0,round(X*I/14),Y);
     end;
     SetLinestyle(Sol dLn,0,NormWidth);
     SetTextStyle(Sm allFont,HorizDir,4);
     SetTextJustify(CenterText,BottomText);
     for I:=0 to 13 '
     begin
          Str(I:0,lable);
          OutTextXY(round(X/14*I+8),Y-5,lab'e);
     end;
     OutTextXY(round(X/14*13+32),Y-6,'Days');
     J:=80;
     for I:=1 to 4 do
     begin
          Str(J:0,lable);
          OutTextXY(10,round(Y/5*I-5),lable);
          J:=J-20;
     end;
(*     Q:=0.8;
     for I:=1 to 4 do
     begin
          Str(Q:3:1,lable);
          OutText( GetMaxX-15,round(Y/5*I-5),lalle);
          Q:=Q-0.2;
```

```
    end;
    OutTextXY(GetMaxX-20,18,'V/kg');
*)  OutTextXY(10,18,' '+chr(248)+'C');
    SetTextJustify(LeftText,BottomText);
    SetTextStyle(DefaultFont,HorizDir,1);
end;
{-------------------------------------------------------------------------}
procedure plot_data(re_plot,initial_plot,plot_2:boolean);

var
   X,Y1,Y2,Y3:real;
   I,J:integer;

begin
    X:=min;
    X:=X/60;
    X:=(X+hour)/24;
    X:=(X+test_day)*GetMaxX/14;
    for I:=1 to 2 do
    begin
        for J:=0 to 3 do
            if initial_plot then
            begin
                Y1:=data[J];
                Y1:=Main_screen_size-(Y1*Main_screen_size/100);
                PutPixel(round(X),round(Y1),white);
            end
            else
            begin
                Y1:=data[J];
                Y1:=Main_screen_size-(Y1*Main_screen_size/100);
                Y2:=last_data[J];
                Y2:=Main_screen_size-(Y2*Main_screen_size/100);
                Line(round(X_last),round(Y2),round(X),round(Y1));
            end;
    end;
    X_last:=X;
end;
{-------------------------------------------------------------------------}
procedure store_data;

var
   I:integer;
   s:string;

begin
    Assign(data_file,file_name);
    Append(data_file);
```

```
    write(data_file,test_day:3,hour:3,min:3,sec:3,sec100:3);
    for I:=0 to 3 do
    begin
        write(data_file,data[I]:8:3);
    end;
    writeln(data_file);
    close(data_file);
end;
{-------------------------------------------------------------------}
procedure power_check;

var
   present,power:boolean;
   power_file:text;
   failure_file:text;
   J:integer;

begin
    assign(power_file,'power.tst');
    assign(failure_file,'power.dat');
    power:= (PORT[port3] and 1)=1;
    if (not power) and (not power_off) then
    begin
        power_off:=true;
        MoveTo(0,round(23*GetMaxY/25));CLR_LINE;
        OutText('********** POWER FAILURE **********');
        rewrite(power_file);
        writeln(power_file,file_body);
        writeln(power_file,s_year:6,s_month:4,s_day:4,s_dow:4);
        writeln(power_file,s_hour:4,s_min:4,s_sec:4,s_sec100:4);
        if adiab_end then J:=1
        else J:=0;
        writeln(power_file,J);
        if day_inc then J:=1
        else J:=0;
        writeln(power_file,J);
        writeln(power_file,next_pulse);
        close(power_file);
        file_check('power.dat',present);
        if not present then
           rewrite(failure_file)
        else append(failure_file);
        GetTime(hour,min,sec,sec100);
        writeln(failure_file,test_day:4,' Days',hour:3,'
Hours',min:3,' Mins');
        close(failure_file);
    end;
    if (power) and (power_off) then
```

```
    begin
        Erase(power_file);
        power_off:=false;
        MoveTo(0,round(23*GetMaxY/25));CLR_LINE;
    end;
end;
{-------------------------------------------------------------------}
procedure print_test;

var
   I:integer;
   message:screen_message;

begin
    MoveTo(0,PROMPT_ROW);
    clr_line;
    ps_ufxy('Print the Test (Y/N) ',responce);
    ps_clear;
    if (responce='y') or (responce='Y') then
    begin
        Assign(data_file,file_name);
        Reset(data_file);
        writeln(lst,'Data Filed in ',file_name);
        for I:=1 to 20 do
        begin
            readln(data_file,message);
            writeln(lst,message);
        end;
        writeln(lst);writeln(lst);
        HardCopy(false,1,Main_screen_size);
        writeln(lst);
        write(lst,chr(12));
        ps_ufxy('** Print the Readings (Y/N) ',responce);
        ps_clear;
        if (responce='y') or (responce='Y') then
        begin
            Reset(data_file);
            repeat
                readln(data_file,message);
                writeln(lst,message);
            until eof(data_file);
            writeln(lst,chr($C));
        end;
        close(data_file);
    end;
end;
{-------------------------------------------------------------------}
procedure limit_set(multi:boolean);{sets temp limits for both baths}
```

```
var
   file_status:boolean;
   cal_file:text;
   I:integer;
   resp:char;
   X,Y:real;
   s,s1,s2,s3,s4:screen_message;

begin
     X:=4/80*screen_width;
     Y:=4/17*main_screen_size;
     OutTextXY(round(X),round(Y),'DRIVE TO STORE DATA              :=
'+data_drive);
     Y:=5/17*main_screen_size;
     Str(offset:7:4,s);
     OutTextXY(round(X),round(Y),'TEMPERATURE OFFSET (SMALL BATH) :=
'+s+' deg C');
     Y:=6/17*main_screen_size;
     Str(temp_step:3:1,s);
     OutTextXY(round(X),round(Y),'TEMPERATURE READING STEP         :=
'+s+' deg C');
     Y:=7/17*main_screen_size;
     Str(day_stop:3,s);
     OutTextXY(round(X),round(Y),'TEST DURATION                    :=
'+s+' Day/s');
     Y:=8/17*main_screen_size;
     Str(high_val:4:1,s);
     OutTextXY(round(X),round(Y),'MAXIMUM TEMPERATURE (Hold)       :=
'+s+' deg C');
     Y:=9/17*main_screen_size;
     if calibration then s:='Calibrate Mode'
     else
     s:='Normal Mode   ';
     OutTextXY(round(X),round(Y),'DISPLAY                          :='+s);
     Y:=10/17*main_screen_size;
     Str(pulse_min:3,s);
     OutTextXY(round(X),round(Y),'HEAT PULSE TIME INTERVAL         :=
'+s+' mins'),
     Y:=11/17*main_screen_size;
     Str(temp_cal[0],s1);
     Str(temp_cal[1],s2);
     Str(temp_cal[2],s3);
     Str(temp_cal[3],s4);
     OutTextXY(round(X),round(Y),'TEMPERATURE CALIBRATION FACTORS :=SAMPLE  ='+s1);
     Y:=12/17*main_screen_size;
     OutTextXY(round(X),round(Y),'                                 :=TANK    ='+s2);
     Y:=13/17*main_screen_size;
```

```
OutTextXY(round(X),round(Y),'                                  := AMBIENT = '+s5);
Y:=14/17*main_screen_size;
OutTextXY(round(X),round(Y),'                                  := PROBE   = '+s4);
Y:=15/17*main_screen_size;
Str(tank_cal[1],s1);
Str(tank_cal[2],s2);
OutTextXY(round(X),round(Y),'TANK CALIBRATION FACTORS          := a       = '+s1);
Y:=16/17*main_screen_size;
OutTextXY(round(X),round(Y),'                                  := b       = '+s2);


repeat
      ps_ofsy('Change the Settings (Y/N) ',resp);
until resp in ['Y','y','N','n'];
ps_clear;
if resp in ['y','Y'] then
begin
    ms_menu('limit',no_of_options);
    MoveTo(round(menu_margin+(36*screen_width/80)),choice_row);
    OutText(data_drive);
    next_line;
    MoveTo(round(menu_margin+(36*screen_width/80)),GetY);
    Str(offset:5:2,s);
    OutText(s+' deg C');
    next_line;
    MoveTo(round(menu_margin+(36*screen_width/80)),GetY);
    Str(temp_step:3:1,s);
    OutText(s+' deg C');
    next_line;
    MoveTo(round(menu_margin+(36*screen_width/80)),GetY);
    Str(day_stop:3,s);
    OutText(s+' Day/s');
    next_line;
    MoveTo(round(menu_margin+(36*screen_width/80)),GetY);
    Str(high_val:4:1,s);
    OutText(s+' deg C');
    next_line;
    MoveTo(round(menu_margin+(36*screen_width/80)),GetY);
    if calibration then s:='Calibrate Mode'
    else
    s:='Normal Mode   ';
    OutText(s);
    next_line;
    MoveTo(round(menu_margin+(36*screen_width/80)),GetY);
    Str(pulse_min:5,s);
    OutText(s+' mins');
end;
while resp in ['y','Y'] do
```

```
begin
    ms_options(option,no_of_options);
    case option of
        0 : begin
                if data_drive='A:' then
                    data_drive:='B:'
                else
                    data_drive:='A:';
                MoveTo(round(menu_margin+(36*screen_width/80)),choice_row);
                clr_line;
                OutText(data_drive);
            end;
        1 : begin
                ps_wfr('ENTER OFFSET (SMALL BATH) ',offset);
                ps_clear;
                MoveTo(1,choice_row);
                next_line;
                MoveTo(round(menu_margin+(36*screen_width/80)),GetY);
                clr_line;
                Str(offset:5:2,s);
                OutText(s+' deg C');
            end;
        2 : begin
                ps_wfr('ENTER TEMPERATURE READING STEP ',temp_step);
                ps_clear;
                MoveTo(1,choice_row);
                next_line,
                next_line;
                MoveTo(round(menu_margin+(36*screen_width/80)),GetY);
                clr_line;
                Str(temp_step:3:1,s);
                OutText(s+' deg C');
            end;
        3 : begin
                repeat
                    ps_wfi('ENTER TEST DURATION [1 to 14] ',day_step);
                until day_step in [1 ..14];
                ps.clear;
                MoveTo(1,choice_row);
                next_line;
                next_line;
                next_line;
                MoveTo(round(menu_margin+(36*screen_width/80)),GetY);
                clr_line;
                Str(day_step:3,s);
                OutText(s+' Day/s');
            end;
        4 : begin
```

```
            repeat
                  ps_wfr('ENTER MAXIMUM TEMPERATURE [1 to 85] ',high_val);
            until (high_val>=1) and (high_val<=85) ;
            ps_clear;
            MoveTo(1,choice_row);
            next_line;
            next_line;
            next_line;
            next_line;
            MoveTo(round(menu_margin+(36*screen_width/80)),GetY);
            clr_line;
            Str(high_val:4:1,s);
            OutText(s+' deg C');
        end;
    5 : begin
            if calibration then calibration:=false
            else
            calibration:=true;
            MoveTo(1,choice_row);
            next_line;
            next_line;
            next_line;
            next_line;
            next_line;
            MoveTo(round(menu_margin+(36*screen_width/80)),GetY);
            clr_line;
            if calibration then s:='Calibrate Mode'
            else
            s:='Normal Mode   ';
            OutText(s);
        end;
    6: begin
            repeat
                  ps_wfi('ENTER TIME BETWEEN HEAT PULSES [1 to 60] ',pulse_min);
            until (pulse_min>=1) and (pulse_min<=60) ;
            ps_clear;
            MoveTo(1,choice_row);
            next_line;
            next_line;
            next_line;
            next_line;
            next_line;
            next_line;
            MoveTo(round(menu_margin+(36*screen_width/80)),GetY);
            clr_line;
            Str(pulse_min:2,s);
            OutText(s+' mins');
        end;
```

```
            7: begin
                    Str(temp_cal[0],s);
                    ps_wfr('ENTER SAMPLE CALIBRATION FACTOR ('+s+') ',temp_cal[0]);
                    ps_clear;
                    Str(temp_cal[1],s);
                    ps_wfr('ENTER TANK CALIBRATION FACTOR ('+s+') ',temp_cal[1]);
                    ps_clear;
                    Str(temp_cal[2],s);
                    ps_wfr('ENTER AMBIENT CALIBRATION FACTOR ('+s+') ',temp_cal[2]);
                    ps_clear;
                    Str(temp_cal[3],s);
                    ps_wfr('ENTER PROBE CALIBRATION FACTOR ('+s+') ',temp_cal[3]);
                    ps_clear;
               end;
            8: begin
                    Str(tank_cal[1],s);
                    ps_wfr('ENTER TANK CALIBRATION FACTOR (a) ('+s+') ',tank_cal[1]);
                    ps_clear;
                    Str(tank_cal[2],s);
                    ps_wfr('ENTER TANK CALIBRATION FACTOR (b) ('+s+') ',tank_cal[2]);
                    ps_clear;
               end;
            9 : begin
                    assign(cal_file,'limit.cal');
                    rewrite(cal_file);
                    writeln(cal_file,data_drive);
                    writeln(cal_file,offset);
                    writeln(cal_file,temp_stop);
                    writeln(cal_file,day_stop);
                    writeln(cal_file,high_val);
                    if calibration then
                       writeln(cal_file,'1')
                    else
                       writeln(cal_file,'0');
                    resp:='N';
                    writeln(cal_file,pulse_min);
                    for I:=0 to 3 do
                        writeln(cal_file,temp_cal[I]);
                    for I:=1 to 2 do
                        writeln(cal_file,tank_cal[I]);
                    close(cal_file);
                end;
          end;{case}
          ps_clear;
      end;{while}
      ms_clear;
      low_val:=0;
end;
```

```
{-------------------------------------------------------------------------}
procedure data_capture(hold,multi:boolean);

var
   last_reading,time_check,diff:real;
   I,J,display_time:integer;
   load_limits,send_limits,stop_test,trans_files:boolean;
   complete,old,re_read:boolean;
   hold70,hold60,hold50,hold40,hold30,hold20:boolean;
   resp:char;
   F:text;
   out1,out2,out3,out4,out5,out6:screen_message;

procedure switch_off(heater:integer);
begin
(*     PORT[po.test] := $BB;      {set parrallel port A-out,BRC-in)}*)
     if her ar=2 then
     begin
          if (port_a and 1)=1 then
          begin
               port_a:=port_a and $FE;
               PORT[portA]:=port_a;
          end;
     end else
     begin
          if (port_a and 2)=2 then
          begin
               port_a:=port_a and $FD;
               PORT[portA]:=port_a;
          end;
     end;
end;

procedure switch_on(heater:integer);
begin
(*     PORT[portest] := $BB;      {set parrallel port A-out,BRC-in)}*)
     if heater=2 then
     begin
          if (port_a and 1) = 0 then
          begin
               port_a:=port_a+1;
               PORT[portA]:=port_a;
          end;
     end else
     begin
          if (port_a and 2) = 0 then
          begin
               port_a:=port_a+2;
```

```
            PORT[portA]:=port_a;
          end
      end;
end;

FUNCTION ADSAMPLE (channel:INTEGER): INTEGER;
VAR
   I:INTEGER;

BEGIN
        PORT [ADcon] := (channel SHL 4) + 2; { channel selection and   }
                                             {clear software-clock bit }
        PORT [ADcon] := (channel SHL 4) + 3; {channel selection and    }
                                          {setting of software-clock bit }
        FOR I:=1 TO 6 DO
          BEGIN                    {loop until end of conversion }
          END;

        ADSAMPLE :=((PORT[ADmsb] AND $0F) SHL 8) + PORT[ADlsb];
END;

procedure temp_read(I:integer);{reads a/d and corrects linearity}

var
   J:integer;
   cor_fact:real;

begin
     data[I]:=0;
     for J:=1 to 250 do
         data[I]:=data[I]+adsample(I);
     data[I]:=data[I]/250;
     data[I]:=data[I]+100/4095;
     data[I]:=data[I]*temp_cal[I];
     if I=1 then
        data[I]:=data[I]+(data[0]*tank_cal[1]+tank_cal[2]);
end;


procedure plot_store;{plots and stores data}

var
   I:integer;
   F:text;

begin
     old:=false;
     plot_data(old,first_plot,second_plot);
```

```
    if not first_plot then second_plot:=false;
    first_plot:=false;
    store_data;
    for I:=0 to 3 do
        last_data[I]:=data[I];
end;

procedure file_trans:{transfers files to network}

var
   s:string;
   in_file,out_file:text;
   net_on:boolean;
   I:integer;
   rate,time,rate_time,hold_time,hold_temp:real;
   data_trans:array[1..11] of real;

begin
    store_data;
    file_check('F:\dept\workshop\gibbon\concrete\contdir\neton.txt',net_on);
    if net_on then
    begin
{$I-}   {I/O checking off}
        Assign(in_file,file_name);
        Reset(in_file);
        Assign(out_file,'F:\dept\workshop\gibbon\concrete\results\'+file_body+'.txt');
        Rewrite(out_file);
        repeat
             readln(in_file,s);
             writeln(out_file,s);
        until eof(in_file);
        close(in_file);close(out_file);
        file_check(pulse_file_name,net_on);
        if net_on then
        begin
            Assign(in_file,pulse_file_name);
            Reset(in_file);
            Assign(out_file,'F:\dept\workshop\gibbon\concrete\results\'+file_body+'.pls');
            Rewrite(out_file);
            repeat
                 readln(in_file,s);
                 writeln(out_file,s);
            until eof(in_file);
            close(in_file);close(out_file);
        end;
        file_check(sph_file_name,net_on);
        if net_on then
        begin
```

```
            Assign(in_file,sph_file_name);
            Reset(in_file);
            Assign(out_file,'F:\dept\workshop\gibbon\concrete\results\'+file_body+'.sph');
            Rewrite(out_file);
            repeat
                  readln(in_file,s);
                  writeln(out_file,s);
            until eof(in_file);
            close(in_file);close(out_file);
         end;
         bleat;bleat;
         Assign(in_file,file_name);
         Assign(out_file,file_body+'.hra');
         Reset(in_file);
         Rewrite(out_file);
         for I:=1 to 21 do
            readln(in_file,s);
         repeat
              for I:=1 to 11 do
                  read(in_file,data_trans[I]);
              readln(in_file);
              time:=data_trans[1]*24+data_trans[2]+data_trans[3]/60
+data_trans[4]/3600+data_trans[5]/360000;
              writeln(out_file,time:10:4,data_trans[6]:10:3);
         until eof(in_file);
         close(in_file);
         close(out_file);
         Assign(in_file,file_body+'.hra');
         Reset(in_file);
         Assign(out_file,'F:\dept\workshop\gibbon\concrete\results\'+file_body+'.hra');
         Rewrite(out_file);
         repeat
              readln(in_file,s);
              writeln(out_file,s);
         until eof(in_file);
         close(in_file);close(out_file);

{$I+}    {I/O checking on}
     end;
end;

procedure pulse;{switches on or off heat pulse}

var
  I,J,k,Y:integer;
  s1,s2,s3,s4,s5,s:string;
  on_file:text;
  not_on:boolean;
```

```
  start_dat:array[0..5] of real;
  test_temp,min_calc,sec_calc,hour_calc,next_sec,new_sec:real;
  start_time,end_time:real;
  pulse_sec:word;

begin
        if (min=next_pulse) then
        begin
            if power_off then
            begin
                next_pulse:=round(min)+pulse_min;
                if next_pulse>59 then
                   next_pulse:=next_pulse-60;
                Assign(on_file,'power.tat');
                Reset(on_file);
                readln(on_file,s1);
                readln(on_file,s2);
                readln(on_file,s3);
                readln(on_file,s4);
                readln(on_file,s5);
                Close(on_file);
                Rewrite(on_file);
                writeln(on_file,s1);
                writeln(on_file,s2);
                writeln(on_file,s3);
                writeln(on_file,s4);
                writeln(on_file,s5);
                writeln(on_file,next_pulse);
                close(on_file);
            end else
            begin
                file_check('F:\dept\workshop\gibbon\concrete\contdir\neton.tat',net_on);
                if not_on then
                begin
{$I-}   {I/O checking off}
                    Assign(on_file,'F:\dept\workshop\gibbon\concrete\contdir\pulse.on');
                    Rewrite(on_file);
                    writeln(on_file,'Pulse On');
                    Close(on_file);
{$I+}   {I/O checking on}
                end;
                X:=0;
                Y:= ...(23*GetMaxY/25);
                Assign(pulse_file,pulse_file_name);
                Append(pulse_file);
                GetTime(hour,min,sec,sec100);
                next_pulse:=min+pulse_min;
                if next_pulse>59 then
```

```
                    next_pulse:=next_pulse-60;
                  J:=2; {1 sec}
                  MoveTo(X,Y);clr_line;
                  OutText('Pulse On ');
                  GetTime(hour,min,sec,sec100);
                  next_sec:=test_day;
                  next_sec:=next_sec*86400+hour*3600+min*60+sec+sec100/100;
                  next_sec:=next_sec+0.5;
                  switch_on(2);
                  repeat
                       GetTime(hour,min,sec,sec100);
                       new_sec:=test_day;
                       new_sec:=new_sec*86400+hour*3600+min*60+sec+sec100/100;
                       if new_sec>=next_sec then
                       begin
                            next_sec:=new_sec+0.5;
                            J:=J-1;
                       end;
                  until J=0;
                  temp_read(3);
                  start_dat[3]:=data[3];
                  start_dat[1]:=data[1];
                  GetTime(hour,min,sec,sec100);
                  start_time:=test_day;
                  start_time:=start_time*86400+hour*3600+min*60+sec+sec100/100;
                  repeat
                       temp_read(3);
                       GetTime(hour,min,sec,sec100);
                       new_sec:=test_day;
                       new_sec:=new_sec*86400+hour*3600+min*60+sec+sec100/100;
                  until (data[3]>start_dat[3]+2) or (new_sec>start_time+10);
{2 deg C or 10 sec}
                  switch_off(2);
                  MoveTo(X,Y);clr_line;
                  min_calc:=min;
                  sec_calc:=sec;
                  hour_calc:=(test_day*24)+(hour)+(min_calc/60)+(sec_calc/3600);
                  test_temp:=start_dat[3];
                  if data[3]<>start_dat[3] then
                    end_time:=(new_sec-start_time)*2/
((data[3]-start_dat[3])-
(data[1]-start_dat[1]));{scale time to 2 deg C}
                  else
                    end_time:=1000;{ERROR IN READING}
                  writeln(pulse_file,hour_calc,end_time,test_temp);
                  Close(pulse_file);
                  file_check('F:\dept\workshop\gibbon\concrete\contdir\neton.tst',net_on);
                  if net_on then
```

```
                    begin
{$I-}     {I/O checking off}
                       Erase(on_file);
{$I+}     {I/O checking on}
                    end;
                end;
            end;
end;

procedure display_1;{write to display}

begin
     MoveTo(20,2);
     Str(data[0]:6:2,out1);
     Str(low_val:6:2,out2);
     MoveTo(0,round(20*GetMaxY/25));CLR_LINE;
     OutText('SAMPLE : '+out1+' '+' deg C      CONTROL TEMP '+out2+' '+' deg C');
     Str(data[1]:6:2,out1);
     if data[1]>data[0] then
        out2:=' '+chr(24);
     if data[1]<data[0] then
        out2:=' '+chr(25);
     if (data[1]=data[0]) then
        out2:=' '+chr(18);
     if (port_a and 2)=0 then
        out3:='   HEATER OFF '
     else
        out3:='   HEATER ON';
     MoveTo(0,round(21*GetMaxY/25));CLR_LINE;
     OutText('TANK   : '+out1+' '+' deg C'+out2+out3+'                PROBE');
     Str(data[3]:9:1,out4);
        out3:='   HEATER ON';
     MoveTo(0,round(22*GetMaxY/25));CLR_LINE;
     Str(data[2]:6:2,out1);
     OutText('AMBIENT: '+out1+' '+' deg C                              '+out4+' deg C');
end;

procedure display_2;

begin
     Str(test_day:3,out1);
     Str(hour:3,out2);
     Str(min:3,out3);
     MoveTo(0,round(24*GetMaxY/25));CLR_LINE;
     OutText('Elapsed Time:'+out1+' Days'+out2+' Hours,'+out3+' Minutes');
     Str(day_stop:3,out3);
     OutText('        Test Duration:'+out3+' Days');
end;
```

```
procedure load_net_limits;

var
   file_status:boolean;
   cal_file:text;
   cali,I:integer;

begin
     file_check('F:\dept\workshop\gibbon\concrete\limit.cal',file_status);
     if file_status then
     begin
{$I-}    {I/O checking off}
          assign(cal_file,'F:\dept\workshop\gibbon\concrete\limit.cal');
          reset(cal_file);
          readln(cal_file,data_drive);
          readln(cal_file,offset);
          readln(cal_file,temp_step);
          readln(cal_file,day_stop);
          readln(cal_file,high_val);
          readln(cal_file,cali);
          calibration:=cali=1;
          readln(cal_file,pulse_min);
          for I:=0 to 3 do
              readln(cal_file,temp_cal[I]);
          for I:=1 to 2 do
              readln(cal_file,tank_cal[I]);
     end;
     close(cal_file);
{$I+}    {I/O checking on}
     assign(cal_file,'limit.cal');
     rewrite(cal_file);
     writeln(cal_file,data_drive);
     writeln(cal_file,offset);
     writeln(cal_file,temp_step);
     writeln(cal_file,day_stop);
     writeln(cal_file,high_val);
     if calibration then
          writeln(cal_file,'1')
     else
          writeln(cal_file,'0');
     writeln(cal_file,pulse_min);
     for I:= 0 to 3 do
         writeln(cal_file,temp_cal[I]);
     for I:=1 to 2 do
         writeln(cal_file,tank_cal[I]);
     close(cal_file);
end;
```

```
procedure send_limits_net;

var
   file_status:boolean;
   net_cal_file:text;
   cali,I:integer;

begin
{$I-}    {I/O checking off}
     assign(net_cal_file,'F:\dept\workshop\gibbon\concrete\limit.cal');
     Rewrite(net_cal_file);
     writeln(net_cal_file,data_drive);
     writeln(net_cal_file,offset);
     writeln(net_cal_file,temp_step);
     writeln(net_cal_file,day_step);
     writeln(net_cal_file,high_val);
     if calibration then
          writeln(net_cal_file,'1')
     else
     writeln(net_cal_file,'0');
     resp:='#';
     writeln(net_cal_file,pulse_min);
     for I:=0 to 3 do
         writeln(net_cal_file,temp_cal[I]);
     for I:=1 to 2 do
         writeln(net_cal_file,tank_cal[I]);
     close(net_cal_file);
{$I+}    {I/O checking on}
end;

begin
     display_time:=3;
     next_pulse:=pulse_min;
     if next_pulse=60 then next_pulse:=0;
     check_12:=true;
     hold70:=false;
     hold60:=false;
     hold50:=false;
     hold40:=false;
     hold30:=true;
     hold20:=false;
     if not test_cont then
     begin
          test_day:=0;
          day_inc:=true;
     end;
     last_data[0]:=0;
```

```
complete:=false;
adiab_end:=false;
last_reading:=0;
first_plot:=true;
second_plot:=true;
repeat
     repeat
          for I:=0 to 3 do
              temp_read(I);
          for I:=0 to 3 do
              re_read:=data[I]>last_data[I]+0.1;
          if re_read then
          begin
              for I:=0 to 3 do
                  temp_read(I);
          end;
          for I:=0 to 3 do
              re_read:=data[I]>last_data[I]+0.1;
          if re_read then
          begin
              delay(1000);
              for I:=0 to 3 do
                  temp_read(I);
          end;
          if calibration then display_1
          else
          begin
              display_time:=display_time-1;
              if display_time=0 then
                   display_1;
          end;
          diff:=data[0]-low_val;
          if diff>(abs(lim_small[1])+abs(lim_small[2]))/2
            then low_val:=data[0];
          if low_val>=high_val then adiab_end:=true;
          if multi then
          begin
              if hold70 then temp:=70;
              if hold60 then temp:=60;
              if hold50 then temp:=50;
              if hold40 then temp:=40;
              if hold30 then temp:=30;
              if hold20 then temp:=20;
          end;
          if hold then low_val:=temp;
          if (low_val+(lim_small[1]+offset))>data[1] then switch_on(1);
          if (low_val+(lim_small[2]+offset))<data[1] then switch_off(1);
          if data[1]>85 then switch_off(1);
```

```
if adiab_end then switch_off(1);
GetTime(hour,min,sec,sec100);
if multi then
begin
     if (hour=0) or (hour=12))
        and (not check_12) then
     begin
          check_12:=true;
          if multi then
          begin
               if hold60 then
               begin
                    hold60:=false;
                    hold70:=true;
               end;
               if hold50 then
               begin
                    hold50:=false;
                    hold60:=true;
               end;
               if hold40 then
               begin
                    hold40:=false;
                    hold50:=true;
               end;
               if hold30 then
               begin
                    hold30:=false;
                    hold40:=true;
               end;
               if hold20 then
               begin
                    hold20:=false;
                    hold30:=true;
               end;
          end;
     end;
     if (hour=1) or (hour=13) then
        check_12:=false;
end;
if (hour=0) and (not day_inc) then
begin
     test_day:=test_day+1;
     day_inc:=true;
end;
if (hour>0) then day_inc:=false;
if calibration then display_2
else
```

```
                begin
                    if display_time=0 then
                    begin
                        display_2;
                        display_time:=20;
                    end;
                end;
                time_check:=test_day*24+hour+min/60+sec/3600+sec100/360000;
                if     (time_check>=last_reading+1)
                    or (last_reading=0)
                    or (data[0]>=last_data[0]+temp_step) then
                begin
                    plot_store;
                    last_reading:=time_check;
                end;
                if not hold then
                   power_check;
                pulse;
                file_check('F:\dept\workshop\gibbon\concrete\contdir\stop.con',stop_test);
                file_check('F:\dept\workshop\gibbon\concrete\contdir\file.con',trans_files);
                file_check('F:\dept\workshop\gibbon\concrete\contdir\lim.con',load_limits);
                file_check('F:\dept\workshop\gibbon\concrete\contdir\lim.get',send_limits);
{$I-}   {I/O checking off}
                if stop_test then
                begin
                    complete:=true;
                    plot_store;
                    Assign(F,'F:\dept\workshop\gibbon\concrete\contdir\stop.con');
                    Erase(F);
                end;
                if trans_files then
                begin
                    file_trans;
                    Assign(F,'F:\dept\workshop\gibbon\concrete\contdir\file.con');
                    Erase(F);
                end;
                if load_limits then
                begin
                    load_net_limits;
                    Assign(F,'F:\dept\workshop\gibbon\concrete\contdir\lim.con');
                    Erase(F);
                end;
                if send_limits then
                begin
                    send_limits_net;
                    Assign(F,'F:\dept\workshop\gibbon\concrete\contdir\lim.get');
                    Erase(F);
                end;
```

```
{$I+}   {I/O checking on}
          until (keypressed) or (test_day>day_step-1) or (complete);
          if keypressed then
          begin
               resp:=ReadKey;
               if resp=#0 then
               begin
                    resp:=ReadKey;
                    if resp=#33 then file_trans;
                    if resp=#25 then print_test;
                    if resp=#16 then complete:=true;
                    if resp=#38 then
                    begin
                         SetActivePage(1);
                         SetVisualPage(1);
                         scr_format(false);
                         limit_set(multi);
                         SetActivePage(0);
                         SetVisualPage(0);
                    end;
               end;
          end else complete:=true;
     until complete;
     file_trans;
     PORT[portA] := 0;      {set heaters off}
     port_a:=0;
     MoveTo(0,round(20*GetMaxY/25));
     clr_line;
     MoveTo(0,round(21*GetMaxY/25));
     clr_line;
     MoveTo(0,round(22*GetMaxY/25));
     clr_line;
     MoveTo(0,round(23*GetMaxY/25));
     clr_line;
     MoveTo(0,round(24*GetMaxY/25));
     clr_line;
     MoveTo(0,round(25*GetMaxY/25));
     clr_line;
end;{capture data}
{-------------------------------------------------------------------------}

procedure close_down;

var
   message:screen_message;
   power_file:text;

begin
```

```
    scr_format(false);
    PORT[portA] := 0;       {set heaters off}
    port_a:=0;
    ps_wfsy('SWITCH OFF THE PUMP/STIRRER ',responce);
    ps_wfsy('SWITCH OFF THE HEATERS ',responce);
    ps_clear;
    file_check('power.dat',file_there);
    if file_there then
    begin
        ps_wfsy('Print Power Failure Times (Y/N) ',responce);
        ps_clear;
    end;
    if (responce='y') or (responce='Y') then
    begin
        writeln(lst,'POWER FAILURE/S AT THE FOLLOWING TIME/S :-');
        writeln(lst);
        assign(data_file,'power.dat');
        reset(data_file),
        repeat
            readln(data_file,message);
            writeln(lst,message);
        until eof(data_file);
        writeln(lst,chr(20));
    end;
        file_check('power.tst',file_there);
        if file_there then
        begin
            assign(power_file,'power.tst');
            Erase(power_file);
            power_off:=false;
            MoveTo(0,round(23*GetMaxY/25));CLR_LINE;
        end;
end;
{-------------------------------------------------------------------------}
procedure plot_old_data;

var
   J,I,K:integer;
   message:screen_message;
   old,ok:boolean;
   resp:char;


function open_old_file:boolean;{opens data file and reads parameters}

var
   id_status,file_status,file_ok:boolean;
   I,J:integer;
```

```
begin
    directory;
    file_status:=true;
    file_ok:=false;
    ss_clear;
    if not test_cmt then
    begin
        while not file_ok do
        begin
            ps_wfst('ENTER FILE NAME ',file_name);
            if length(file_name)<9 then file_ok:=true;
            if not file_ok then
            begin
                ss_write('Name must be less than 9 characters');
            end;
        end;
        ps_clear;ss_clear;
        file_name:='data_drive+file_name+'.txt';
    end else
    begin
        assign(data_file,'power.txt');
        reset(data_file);
        readln(data_file,file_body);
        file_name:='data_drive+file_body+'.txt';
        pulse_file_name:='data_drive+file_body+'.pls';
        readln(data_file,s_year,s_month,s_day,s_dow);
        readln(data_file,s_hour,s_min,s_sec,s_sec100);
        readln(data_file,J);
        adiab_end:=J+1;
        readln(data_file,J);
        day_inc:=J+1;
        readln(data_file,next_pulse);
        close(data_file);
    end;
    file_check(file_name,file_status);
    if file_status then
    begin
       assign(data_file,file_name);
       reset(data_file); {opens data file}
       open_old_file:=true;
    end else
    begin
        ss_write('FILE NOT ON DISK !!!');
        delay(2000);
        open_old_file:=false;
    end;
    Assign(pulse_file,pulse_file_name);
```

```
end;

begin
     ok:=open_old_file;
     first_plot:=true;
     second_plot:=true;
     if ok then
     begin
          for I:=1 to 20 do
              readln(data_file,message);
          readln(data_file,mess);
          draw_axis(false);
          repeat
               read(data_file,test_day,hour,min,sec,sec100);
               for J:=0 to 3 do
                   read(data_file,data[J]);
               read(data_file,resp);
               readln(data_file);
               old:=true;
               plot_data(old,first_plot,second_plot);
               if not first_plot then second_plot:=false;
               first_plot:=false;
               for K:=0 to 3 do
                   last_data[K]:=data[K];
          until eof(data_file);
          close(data_file);
          if not test_cont then
              print_test;
     end;
end;
{-------------------------------------------------------------------}
procedure re_start;
var
   X:real;
   hour_calc:integer;

begin
     plot_old_data;
     GetTime(hour,min sec,sec100);
     GetDate(year,month,day,dayofweek);
     hour_calc:=hour;

     if min<s_min then
     begin
          min:=min+60;
          hour_calc:=hour_calc-1;
     end;
     min:=min-s_min;
```

```
    if hour_calc<s_hour then
    begin
        hour_calc:=hour_calc+24;
        day:=day-1;
    end;
    hour:=hour_calc-s_hour;

    if day<s_day then
    begin
        if s_month in [1,3,5,7,8,10,12] then
          day:=day+31;
        if s_month in [4,6,9,11] then
          day:=day+30;
        if s_month=2 then
        begin
            if s_year=1996 then
              day:=day+29
            else
              day:=day+28;
        end;
    end;
    day:=day-s_day;
    SetTime(hour,min,0,0);
    test_day:=day;
    power_off:=false;
    data_capture(false,false);
    test_cont:=false;
end;
{-------------------------------------------------------------------------}

begin
    initialise;
    scr_format(true);
    file_check('power.tst',test_cont);{check if rebooted after power failure}
    repeat
        DetectGraph(GraphDriver,GraphMode);
        if (GraphDriver<>EGA) AND (GraphDriver<>VGA) AND (GraphDriver<>HercMono) then
        begin
            sa_write('** Display Device not Suitable **');
            delay(5000);
            Abort('Error');
        end;
        if (GraphDriver=EGA) or (GraphDriver=VGA) then
        begin
            if (GraphDriver=VGA) then
            begin
                GraphMode:=VGAMed;
```

```
                InitGraph(GraphDriver,GraphMode,'')
            end
            else
            begin
                GraphMode:=EGAHi;
                InitGraph(GraphDriver,GraphMode,'')
            end;
            scr_format(false);
        end;
        SetActivePage(0);
        SetVisualPage(0);
        SetTextStyle(DefaultFont,HorizDir,1);
        if not test_cont then
        begin
            ms_menu('main',no_of_options);
            ms_options(option,no_of_options);
            ms_clear;
        end else
           option:=0;
        case option of
            0: begin
(*                    RestoreCrtMode;
                   Exec('a:getclock.com','');
                   if DosError<>0 then
                   begin
                      bleat;
                      writeln('#',DosError);
                   end;
                   Delay(2000);
                   SetGraphMode(GetGraphMode);
                   scr_format(false);
*)                   if not test_cont then
                   begin
                       file_check('power.dat',file_there);
                       if file_there then
                       begin
                           ps_ufay('DELETE POWER FAILURE DATA FILE (Y/N)',responce);
                           if (responce='y') or (responce='Y') then
                           begin
                               assign(data_file,'power.dat');
                               erase(data_file);
                           end;
                           ps_clear;
                       end;
                       limit_set(false);
                       checklist;
                       input_details(false);
                       ps_ufay('Press <Enter> to Start Test',responce);
```

```
                end;
                if test_cont then re_start
                else
                begin
                    draw_axis(false);
                    GetDate(s_year,s_month,s_day,s_dow);
                    GetTime(s_hour,s_min,s_sec,s_sec100);
                    SetTime(0,0,0,0);
                    test_day:=0;
                    data_capture(false,false);
                end;
                print_test;
                close_down;
            end;

        1: plot_old_data;
        2: begin
(*                    RestoreCrtMode;
                Exec('a:getclock.com','');
                if DosError<>0 then
                begin
                   bleat;
                   writeln('#',DosError);
                end;
                delay(2000);
                SetGraphMode(GetGraphMode);
                scr_format(false);
*)                limit_set(false);
                checklist;
                input_details(true);
                ps_wfsy('Multiple Point Calibration (Y/N)? ',responce);
                multi_ramp:=(responce='Y') or (responce='y');
                ps_wfsy('Press <Enter> to Start Test',responce);
                draw_axis(false);
                GetDate(s_year,s_month,s_day,s_dow);
                GetTime(s_hour,s_min,s_sec,s_sec100);
                SetTime(0,0,0,0);
                test_day:=0;
                data_capture(true,multi_ramp);
                print_test;
                close_down;
            end;

        3: begin
(*                    RestoreCrtMode;
                Exec('a:getclock.com','');
                delay(1000);
                ClrScr;
```

```
                    Exec('a.command.com','/C date');
                    Exec('a:command.com','/C time');
                    delay(1000);
                    ClrScr;
                    Exec('a:\setclock.com','');
                    if DosError<>0 then
                    begin
                        bleat;
                        writeln('#',DosError);
                    end;
                    Delay(2000);
                    SetGraphMode(GetGraphMode);
*)                    no_clear;
                end;
            end;{case}
            scr_format(false);
        until option=4;
end.
```

B.2 CALUTILS.PAS

```
unit calutils;
          {-------------------------------}
          {              by               }
          {          G.J Gibbon           }
          {    Faculty of Engineering     }
          {        Wits University        }
          {-------------------------------}
Interface

Uses
  Crt,
  Dos,
  Printer,
  Graph,
  sml4gra,
  bgifont,
  bgidriv;

const
     ADlsb      = $700; {lsb from A/D Converter}
     ADmsb      = $701; {msb from A/D Converter}
     ADcon      = $702; {Control and Multiplexer Selection}
     ADset      = $703; {Control Word for A/D PPI}
     portA      = $708; {Port A}
     portB      = $709; {Port B}
     portC      = $70A; {Port C}
     portset    = $70B; {Control Word For PPI}
     Aconst:real = 3.90302e-3;
     Bconst:real = -5.802e-7;
     Ro:real = 100;

var
   cement,extender,sand1,sand2,stone1,stone2,
   admixture,file_body,file_name,pulse_file_name,sph_file_name:screen_message;
   match_file_name,match_file_body:screen_message;
   day_stop:integer;
   test_day,hour,min,sec,sec100,year,month,day,dayofweek:word;
   s_hour,s_min,s_sec,s_sec100,s_year,s_month,s_day,s_dow:word;
   temp_step,X_last,temp,cem,ext,natur,admix,mass,max_power:real;
   lim_large,lim_small,san,ston:array[1..2] of real;
   offset:real;
   data:array[0..6] of real;
   last_data:array[0..6] of real;
   temp_cal:array[0..3] of real;
   tank_cal:array[1..2] of real;
```

```
  low_val,high_val,pulse_off:real;
  pulse_file,sph_file,data_file,match_file:text;
  data_drive:string;
  response:char;
  port_a:byte;
  pulse_min,next_pulse,option,no_of_options:integer;
  calibration,first_plot,second_plot,test_cont,power_off,file_there:boolean;
  adlab_cmd,day_inc,trans_data:boolean;
  ExitSave:pointer;

procedure directory;
procedure Abort(Msg : string);
procedure HardCopy(Inverse : boolean; Mode : byte; max_y:word); { EPSON }
procedure open_file(hold:boolean);{opens data file and reads parameters}
procedure checklist;
procedure input_details(hold:boolean);
procedure Exit;{Controls termination process if there is an error}
procedure load_defaults;{loads values from default file}
procedure initialise;

Implementation
{-----------------------------------------------------------------------}
procedure directory;

var
  I,J:integer;
  DirInfo:SearchRec;
  file_string:PathStr;
  dir:DirStr;
  Name:NameStr;
  Ext:ExtStr;
  calc:real;
  resp:char;

begin
    MS_CLEAR;
    FindFirst(data_drive+'*.txt',AnyFile,DirInfo);
    file_string:=DirInfo.Name;
    if DosError <>0 then
    begin
        FSplit(file_string,dir,name,ext);
        calc:=12;
        calc:=calc*screen_width/80;
        MoveTo(round(calc),round(2*main_screen_size/19));
        OutText(name);
        J:=2;
        repeat
            for I:=1 to 17 do
```

```
                begin
                    repeat
                        FindNext(DirInfo);
                        if  DosError=0 then
                        begin
                            file_string:=DirInfo.Name;
                            FSplit(file_string,dir,name,ext);
                            calc:=12;
                            calc:=calc*screen_width/80;
                            MoveTo(round(calc),GetY);
                            OutText(name);
                        end;
                        J:=J+1;
                    until J>5;
                    next_line;
                    J:=1;
                end;
                if DosError=0 then
                begin
(*                    ps_wfky('Press <Enter> for Next Page :- ',resp);*)
                    ps_clear;
                    ms_clear;
                end;
            until DosError=18;
        end;
end;

{*****************************************************************}
procedure Abort(Msg : string);
begin
  Writeln(Msg, ': ', GraphErrorMsg(GraphResult));
  Halt(1);
end;
{*****************************************************************}
procedure HardCopy(Inverse : boolean; Mode : byte; max_y:word); { EPSON }
var
  I, J, Top : integer;
  ColorLoc, PrintByte : byte;

procedure DoLine(Top:integer);

var
   J:integer;

function ConstructByte(J, I : integer) : byte;
const
  Bits : array[0..7] of byte = (128,64,32,16,8,4,2,1);
var
```

```
  CByte, K : byte;
begin
  I := I shl 3;
  CByte := 0;
  for K := 0 to Top do
    if GetPixel(I, J + K)>0 then
      CByte := CByte or Bits[K];
  ConstructByte := CByte;
end; { ConstructByte }

begin { DoLine }
  For J:=1 to 10 do
     Write(lst,' ');
  if Mode = 1 then
   Write(Lst, ^['L')
  else
   Write(Lst, ^['*', Chr(Mode));
  Write(Lst, Chr(Lo(GetMaxX + 1)), Chr(Hi(GetMaxX + 1)) ;
  for J := 0 to GetMaxX do
  begin
    PrintByte := ConstructByte(J, I);
    if Inverse then
      PrintByte := not PrintByte;
    Write(Lst, Chr(PrintByte));
  end;
  if Mode <> 4 then
    WriteLn(Lst);
end; { DoLine }

begin { HardCopy }
  Top := 7;
  Mode := Mode and 7;
  if (Mode = 5) or (Mode = 0) then
    Mode := 4;
  Write(Lst, ^['3'#24);
  for I := 0 to ((max_y + 1) shr 3) - 1 do
    DoLine(7);
  I := ((max_y + 1) shr 3);
  if (max_y + 1) and 7 <> 0 then
    DoLine((max_y + 1) and 7);
  WriteLn(Lst, ^['2');
end; { HardCopy }

{**************************************************************}

procedure open_file(hold:boolean);{opens data file and reads parameters}

var
```

```
    id_status,file_status,file_ok:boolean;
    IO_error,I:integer;

begin
     directory;
     file_status:=true;
     while file_status do
     begin
         file_ok:=false;
         if not hold then
         begin
              while not file_ok do
              begin
                   ps_wfat('ENTER FILE NAME ',file_body);
                   if length(file_body)<9 then file_ok:=true;
                   if not file_ok then
                   begin
                        es_write('Name must be less th.n 9 characters');
                   end;
              end;
              ps_clear;es_clear;
              file_name:=data_drive+file_body+'.txt';
              pul.e_file_name:=data_drive+file_body+'.pls';
              sph_file_name:=data_drive+file_body+'.sph';
              file_check(file_name,file_status);
              if file_status then
              begin
                   es_write('FILE ALREADY PRESENT');
                   responce:=' ';
                   while not (responce in ['y','Y','n','N']) do
                   ps_wfsy('DESTROY OLD FILE (Y/N)',responce);
                   ps_clear;es_clear;
                   if responce in ['y','Y'] then
                      file_status:=false;
              end;
         end else
         begin
              file_status:=false;
              file_name:=data_drive+'hold.txt';
              file_body:='hold';
              pulse_file_name:=data_drive+file_body+'.pls';
              sph_file_name:=data_drive+file_body+'.sph';
         end;
         if not file_status then
         begin
              assign(data_file,file_name); {checks for valid file name}
              {$I-}
              rewrite(data_file); {opens data file}
```

```
            {$I+}
            IO_error:=IOResult;
            if IO_error=2 then
            begin
                file_status:=true;
                ss_write('Illegal Characters used in File Name');
            end;
            if (IO_error<>0) and (IO_error<>2) then
               rewrite(data_file); {opens data file to determine error}
        end;
    end;
(*    file_status:=false;
    while not file_status do
    begin
        ps_wfst('ENTER TEMPERATURE PROF  ,R FILE NAME ',match_file_body);
        match_file_name:=data_drive+match_file_body+'.dn2';
        ss_write(match_file_name);
        file_check(match_file_name,file_status);
        if not file_status then
        begin
            ss_write('FILE NOT PRESENT');
            bleat;bleat;
        end;
    end;
    ps_clear;ss_clear;ss_c  r;
    Assign(match_file,match_file_name);
    Reset(match_file);
 *)   Assign(data_file,file_name);
    Rewrite(data_file);
    Assign(pulse_file,pulse_file_name);
    Rewrite(pulse_file);
    Close(pulse_file);
    Assign(sph_file,sph_file_name);
    Rewrite(sph_file);
    Clos  sph_file);
end;
{-------------------------------------------------------------------}
procedure checklist;
begin
    ps_wfsy('IS PRINTER READY ? ',responce);
    ps_wfsy('ARE PUMP/IT.1BER OPERATING ? ',responce);
    ps_wfsy('ARE THERMOCOUPLES CONNECTED ? ',responce);
    ps_wfsy('IS THERE POWER TO THE HEATERS ? ',responce);
    ps_wfsy(' S THERE SUFFICIENT WATER IN TANKS ? ',responce);
    ps_clear;
end;

{-------------------------------------------------------------------}
```

```
procedure input_details;

var
   s:string;
   I:integer;

begin
     responce:='n';
     repeat
          if not hold then
          begin
               ps_wfst('ENTER CEMENT TYPE ',cement);
               ps_wfst('ENTER EXTENDER TYPE ',extender);
               ps_wfst('ENTER SAND TYPE 1 ',sand1);
               ps_wfst('ENTER SAND TYPE 2 ',sand2);
               ps_wfst('ENTER STONE TYPE 1 ',stone1);
               ps_wfst('ENTER STONE TYPE 2 ',stone2);
               ps_wfst('ENTER ADMIXTURE TYPE  ',admixture);
               ps_wfr('ENTER CEMENT CONTENT (kg) ',cem);
               ps_wfr('ENTER EXTENDER CONTENT (kg) ',ext);
               ps_wfr('ENTER SAND 1 CONTENT (kg) ',san[1]);
               ps_wfr('ENTER SAND 2 CONTENT (kg) ',san[2]);
               ps_wfr('ENTER STONE 1 CONTENT (kg) ',ston[1]);
               ps_wfr('ENTER STONE 2 CONTENT (kg) ',ston[2]);
               ps_wfr('ENTER WATER CONTENT (l) ',water);
               ps_wfr('ENTER ADMIXTURE CONTENT (l) ',admix);
               ps_wfr('ENTER MASS OF SAMPLE (kg) ',mass);
          end;
          s:='ENTER SAMPLE(START) TEMPERATURE (deg C) ';
          ps_wfr(s,temp);
          low_val:=temp;
          GetTime(hour,min,sec,sec100);
          GetDate(year,month,day,dayofweek);
          if hold then
          begin
               open_file(true);
               responce:='y';
          end
          else
          begin
               open_file(false);
               writeln(data_file,'CEMENT TYPE    : ',cement);
               writeln(data_file,'EXTENDER TYPE  : ',extender);
               writeln(data_file,'SAND TYPE 1    : ',sand1);
               writeln(data_file,'SAND TYPE 2    : ',sand2);
               writeln(data_file,'STONE TYPE 1   : ',stone1);
               writeln(data_file,'STONE TYPE 2   : ',stone2);
               writeln(data_file,'ADMIXTURE TYPE : ',admixture);
```

```
            writeln(data_file,'CEMENT CONTENT      :     ',cem:6:3,' (kg) ');
            writeln(data_file,'EXTENDER CONTENT    :     ',ext:6:3,' (kg) ');
            writeln(data_file,'SAND 1 CONTENT      :     ',san[1]:6:3,' (kg) ');
            writeln(data_file,'SAND 2 CONTENT      :     ',san[2]:6:3,' (kg) ');
            writeln(data_file,'STONE 1 CONTENT     :     ',ston[1]:6:3,' (kg) ');
            writeln(data_file,'STONE 2 CONTENT     :     ',ston[2]:6:3,' (kg) ');
            writeln(data_file,'WATER CONTENT       :     ',water:6:3,' (l)  ');
            writeln(data_file,'ADMIXTURE CONTENT : ',admix:6:3,' (l) ');
            writeln(data_file,'SAMPLE MASS         :     ',mass:4:3,' (kg)');
            writeln(data_file,'SAMPLE TEMPERATURE :     ',temp:4:3,' (deg C) ');
            writeln(data_file);
            writeln(data_file,day:2,'-',month:2,'-',year:4);
            writeln(data_file);
            writeln(data_file,mass:5:3);
            close(data_file);
            Rewrite(sph_file);
            writeln(sph_file,cem:6:2);
            writeln(sph_file,ext:6:2);
            writeln(sph_file,san[1]:6:2);
            writeln(sph_file,san[2]:6:2);
            writeln(sph_file,ston[1]:6:2);
            writeln(sph_file,ston[2]:6:2);
            writeln(sph_file,water:6:2);
            writeln(sph_file,admix:6:2);
            writeln(sph_file,mass:6:2);
            Close(sph_file);
            MS_CLEAR;
            RESET(data_file);
            READLN(data_file,s);
            OutText(s);
            next_line;
            I := 0;
            WHILE I <= 17 DO
            BEGIN
                 READLN(data_file,s);
                 OutText(s);
                 next_line;
                 I := I + 1;
            END;
            CLOSE(data_file);
            responce:='n';
            pc_wfsy('CORRECT (Y/N)',responce);
         end;
    until (responce='y')  or (responce='Y');
end;
{-----------------------------------------------------------------------}
{$F+}
procedure Exit;{Controls termination process if there is an error}
```

```
{$F-}
begin
     PORT[portA] := 0;       {set heaters off}
     port_a:=0;
     CloseGraph;
     ExitProc:=ExitSave;
end;
{------------------------------------------------------------------}
procedure load_defaults;{loads values from default file}

var
   file_status:boolean;
   cal_file:text;
   cali,I:integer;

begin
     lim_small[1]:=-0.05;{sets on then off limits}
     lim_small[2]:=0.05;
     lim_large[1]:=-0.1;{sets on then off limits}
     lim_large[2]:=0.1;
     file_check('limit.cal',file_status);
     if not file_status then
     begin
          assign(cal_file,'limit.cal');
          rewrite(cal_file);
          data_drive:='a:';
          offset:=0;
          temp_step:=0.1;
          day_stop:=14;
          high_val:=85;
          calibration:=false;
          pulse_min:=10;
          for I:=0 to 3 do
              temp_cal[I]:=1;
          for I:=1 to 2 do
              tank_cal[I]:=0;
     end
     else
     begin
          assign(cal_file,'limit.cal');
          reset(cal_file);
          readln(cal_file,data_drive);
          readln(cal_file,offset);
          readln(cal_file,temp_step);
          readln(cal_file,day_stop);
          readln(cal_file,high_val);
          readln(cal_file,cali);
          calibration:=cali=1;
```

```
        readln(cal_file,pulse_min);
        for I:=0 to 3 do
            readln(cal_file,temp_cal[I]);
        for I:=1 to 2 do
            readln(cal_file,tank_cal[I]);
    end;
    close(cal_file);
end;

{-------------------------------------------------------------------}
procedure initialise;

begin
    PORT[ADset] := $92;       {Initialization of A/D  PPI}
    PORT[portset] := $8B;       {set parrallel port A-out,B&C-in)}
    PORT[portA] := 0;           {set heaters off}
    port_a:=0;
    ExitSave:=ExitProc;
    ExitProc:=@Exit;
    load_defaults;
    { Register all the drivers }
    if RegisterBGIdriver(@CGADriverProc) < 0 then
       Abort('CGA');
    if RegisterBGIdriver(@EGAVGADriverProc) < 0 then
       Abort('EGA/VGA');
    if RegisterBGIdriver(@HercDriverProc) < 0 then
       Abort('Herc');
    if RegisterBGIdriver(@ATTDriverProc) < 0 then
       Abort('AT&T');
    if RegisterBGIdriver(@PC3270DriverProc) < 0 then
       Abort('PC 3270');

    { Register all the fonts }
    if RegisterBGIfont(@GothicFontProc) < 0 then
       Abort('Gothic');
    if RegisterBGIfont(@SansSerifFontProc) < 0 then
       Abort('SansSerif');
    if RegisterBGIfont(@SmallFontProc) < 0 then
       Abort('Small');
    if RegisterBGIfont(@TriplexFontProc) < 0 then
       Abort('Triplex');
    power_off:=false;
    low_val:=0;
end;
end.
```

B.3 CONDAT3.M

```
clear all
filename = input('Please enter the file name? ','s');
vol=input('Please enter the Volume of the Sample (m3)');

% Calculate the Heating Rate

loadname = [filename,'.hra']
eval(['load ',loadname]);
eval(['time=',filename,'(:,1);'])
eval(['Temp=',filename,'(:,2);'])
eval(['A_Temp=',filename,'(:,3);'])
eval(['I_Temp=',filename,'(:,4);'])


% Interpulate data  to constant sample rate
time=time-time(1);
MinT=min(time);
MaxT=max(time);
time2 = [MinT:1/6:MaxT];%10 min intervals
time2 = time2(:);
Temp2 = interp1(time,Temp,time2,'linear');%C/hr
Temp2=Temp2(:);
Temp2(1)=Temp2(2);
plot(time2,Temp2,time,A_Temp,time,I_Temp)
title('Temperature C')
pause

%calculate heating rate degree C/hr
for i=2:length(Temp2)
    Temp3(i)=(Temp2(i)-Temp2(i-1));
    Temp3(i)=Temp3(i)/(1/6);
    Temp2r(i)=(Temp2(i)-Temp2(i-1))/(1/6);
    Temp2r=Temp2r(:);
end

%Low pass filter Temp2
[B,A] = butter(2,20/120);% 2 hourly trend
Temp4 = filtfilt(B,A,Temp3);
Temp4=Temp4(:);

plot(time2,Temp4,time2,Temp3,'.')
title('Heat Rate C/hr')
pause
Temp3=Temp4;
```

```
%Calculate the Energy from the Specific Heat value

loadname = [filename,'.sph']
eval(['load ',loadname]);
eval(['mass=',filename,'(:);'])
%scale to sample mass
total_mass=sum(mass(1:8));
mass(1:8)=mass(1:8).*mass(9)./total_mass;
dens=mass(9)/vol

% SH of the water,cement,sand  etc J/K (total of mix)
SH(1:6)=880.*mass(1:6) %Fulton page 565
SH(7:8)=4178.*mass(7:8);%Incropera page A22
SHT=sum(SH)%total SH J/K
SHTkg=SHT/mass(9)

% SH of the water,cement,sand  etc J/K (with value for cement paste)
SH2(3:8)=880.*mass(3:8);%Fulton page 565
SH2(1)=0;
SH2(2)=0;
SH2(7)=0;
SH2(8)=0;

load sheat.dat %specific heat for cured motar (see Carlson(1938) p11^)
sht=sheat(:,1);
sh1=sheat(:,2);
sh2=sheat(:,3);
p1=polyfit(sht,sh1,2);
p2=polyfit(sht,sh2,2);
a1=[p1(1) p2(1)];
a1=a1(:);
a2=[p1(2) p2(2)];
a2=a2(:);
a3=[p1(3) p2(3)];
a3=a3(:);
e=ones(length(a1),1);
A=[.25 .6];
A=A(:);
A1=[e A];
A2=[e A];
A3=[e A];
b1=A1\a1;
b2=A2\a2;
b3=A3\a3;

plot(sht,sh1,'*',sht,sh2,'o')
hold on
J= 25;
```

```
for I=1:8
SHp=[J*b1(2)+b1(1) J*b2(2)+b2(1) J*b3(2)+b3(1)];
SHt(:,I)=polyval(SHp,sht);
J=J+.07;
end
plot(sht,SHt)
pause
hold off
data=[sht SHt];
save c:\phd\carlson.sht data -ascii



wcr=(mass(7)+mass(8))/(mass(1)+mass(2));%water/cement ratio
p=[wcr*b1(2)+b1(1) wcr*b2(2)+b2(1) wcr*b3(2)+b3(1)];
SHtemp=polyval(p,Temp2);
A=[min(Temp2) max(Temp2)];
A=A(:);
e=ones(length(A),1);
A1=[e A];
for I=1:length(SHtemp)
A2=[(sum(mass(1:2))*880+sum(mass(7:8)*4178))/(sum(mass(1:2))+sum(mass(7:8))) SHtemp(I)];
A2=A2(:);
b=A1\A2;
SHtemp(I)=Temp2(I)+b(2)+b(1);
end


SHtemp=SHtemp.*(mass(1)+mass(2)+mass(7)+mass(8));
SHtemp=SHtemp+sum(SH2);%total SH J/K
SHTkg2=SHtemp./mass(9);
plot(time2,SHTkg2);
title ('Specific Heat of the Concrete(J/Kg K)');
xlabel('Temperature deg C');
ylabel('J/Kg K'); pause
for i=1:length(time2)
SHT2(i)=SHT/mass(9);
end
SHT2=SHT2(:);
data=[time2 Temp2 SHTkg2 SHT2];
eval(['save ',filename,'.she ','data /ascii'])

Temp31=Temp3.*(SHT/3600/vol); %J/sec.m^3 (W/m^3) Of cement
Temp32=Temp3.*(SHtemp/3600/vol); %J/sec.m^3 (W/m^3) Of cement
plot(time2,Temp31./dens.*total_mass./mass(1),time2,Temp32./dens.*total_mass./mass(1))%W/kg
title('Heat rate (W/kg) of cement')
Mean_Heat=mean(Temp3)
data= [time2 Temp31./dens.*total_mass./mass(1) Temp32./dens.*total_mass./mass(1)];
```

```
eval(['save ',filename,'.hr2 ','data /ascii'])
pause

%Integrate the heating rate to give total heat produced

y1=Temp31(:);
int_data1=cumsum(y1).*600; %Joules
tot_heat1=max(int_data1)
y2=Temp32(:);
int_data2=cumsum(y2).*600; %Joules
tot_heat2=max(int_data2);
tot_heat_kg=max(int_data2)./dens.*total_mass./mass(1)
plot(time2,int_data1./dens.*total_mass./mass(1)./1000,time2,int_data2./dens.*total_mass./mass(1)./1000)
title('Total Heat Generated (kJ/kg)')
data=[.ime2 int_data ./dens.*total_mass./mass(1)./1000 int_data2./dens.*total_mass./mass(1)./1000];
eval(['save ',filename,'.int ','data /ascii'])
pause


loadname=[filename,'.plx']
eval(['load ',loadname])
eval(['Temp=',filename,'(:,2);'])
eval(['time=',filename,'(:,1);'])
eval(['TTemp=',filename,'(:,3);'])

%calculate max time of all pulses
for I=1:length(Temp)
T_time(I)=Temp(I);
if T_time(I)>10
T_time(I)=10;
end
end
max_time=max(T_time);
%calculate mean power
P=TTemp.*0.0372+10.555;%(Ohms page 155)
P=P.*(0.5^2);
max_power=max(P);
%calculate mean energy per pulse
max_en=max_power*max_time;
%calculate temp increase in sample
temp_step=max_en/SHTkg/mass(9)

% Filter the Max pulse temperature to 4 hourly trend

% Decimate data  to constant sample rate
time=time-time(1);
MinT=min(time);
MaxT=max(time);
```

```
time2 = [Min7:10/60:MaxT];%10 min intervals
time2=time2(:);
Temp2 = interp1(time,Temp,time2,'linear');
TTemp = interp1(time,TTemp,time2,'linear');
P=TTemp.*0.0372+10.558;%{Ohms page 153}
P=(P.*(0.5)^2).*.61;%61% of total power
k=P./Temp2;%see page 144
load probedat
k=k.*b(2)+b(1);%see page 156
Mean=mean(k);
ki=k-Mean;
[b,a]=butter(2,20/240);
k2=filtfilt(b,a,ki);
k2=k2+Mean;
plot(time2,k,'*',time2,k2)
%axis([0 80 0 1]);
title('Thermal Conductivity (W/mK)')
pause
data= [time2 k2 k];
eval(['save ',filename,'.p12 ','data /ascii'])
diff=k2/dens/SHTkg*3600*24;
plot(time2,diff)
title('Thermal Difusivity (M^2/Day)')
data= [time2 diff];
eval(['save ',filename,'.dif ','data /ascii'])
```

B.4 PROBECAL.M

```
clear all
clf
load powerii.cal
ka=powerii(:,1);
kp=powerii(:,2);
e=ones(length(kp),1);
A=[e kp];
b=A\ka;
save probedat b
%load probedat
b
kc=kp.*b(2)+b(1);
data=[ka kc]
save probecon.dat data -ascii

%p=polyfit(kp,ka,2)
%save probedat p
%kc=polyval(p,kp)
%pause

x=0:.2:.6;
x=x(:);
y=x.*b(2)+b(1);
%y=polyval(p,x);
kdiff=abs(ka-kc)
maxdiff=max(kdiff)
error_fs=(max(kdiff)*100/2)
error_string=num2str(ceil:(error_fs*10)/10);
yplus=y+max(kdiff);
yminus=y-max(kdiff);
plot(kp,ka,'*',x,yplus,x,yminus)
title 'Conductivity Probe Calibration'
xlabel('Probe Factor')
ylabel('k (W/mK)')
%axis([0 .8 0 1.2]);
text(0.3,1,['Error: +-' error_string ' fs'])
pause


x=0:.2:1.2;
x=x(:);
y=x;
x1=x+2*round(error_fs)/100;
x2=x-2*round(error_fs)/100;
y1=y+2*round(error_fs)/100;
```

```
y2=y-2*round(error_fs)/100;
%plot(ka,kc,'*',x1,y,x2,y)
plot(ka,kc,'*',x,y)
hold on
x1=[.12 .22];
y1=[.82 .82];
%plot(x1,y1,'--')
y1=[.86 .86];
%plot(x1,y1,'--')
hold off
%text(.24,.835,'2% fs Error Band')
axis([0 1.2 0 1.2])
title(['Conductivity Probe Calibration (' date ')'])
xlabel('Thermal Conductivity (W/mK)')
ylabel('Calculated Thermal Conductivity (W/mK)')
%text(.1,.04,'Cardboard')
text(.03,.15,'Pine')
text(.22,.38,'Teflon')
%text(.44,.4,'Bee's Wax')
%text(.836,.596,'Water')
text(.95,.92,'Carbon')
text(0.3,1,['Error: +-' error_string ' fs'])
```

B.5 HEATMOD.M

```
clear all
filename = input('Please enter the file name? ','s');

loadname = [filename,'.hr2']
eval(['load ',loadname]);
eval(['time=',filename,'(:,1);'])
eval(['heat_rate=',filename,'(:,2);'])
loadname = [filename,'.pl2']
eval(['load ',loadname]);
eval(['cond=',filename,'(:,2);'])
loadname = [filename,'.hra']
eval(['load ',loadname]);
eval(['Start_temp=',filename,'(1,2);'])
dT=600;%10 minutes steps
if length(time)<length(cond)
len=length(time);
else
len=length(cond);
end
for i=1:len
timap(i)=time(i);
end
time=timap;

%Calculate node capcity
dens=input('Please enter sample density? ');
dx=.1;%100mm between nodes
sh=input('Please enter the sample's specific heat? ');
C(1,1)=dens*dx/2*sh;
C(13,1)=C(1,1);
for i=2:12
    C(i,1)=dens*dx*sh;
end
for i=1:13
    T1(1,i)=Start_temp;
    T2(1,i)=Start_temp;
    T31(1,i)=Start_temp;
end
%Calculate node temperatures
for i=2:len
    for j=2:12
        q(j)=heat_rate(i-1)*dx*1000;%(W/unit area)
        R(12)=1/.000000001;%Loss on insulated side (k=0.026)
        R(1)=1/20;%Loss due to convection
        for k=2:11
```

```
          R(k)=1/(cond(i-1)/dx);
        end
        if j==2
          Sum(1)=Start_temp-T1(i,j);%Start_temp=ambient
        else
          Sum(1)=T1(i,j-1)-T1(i,j);
        end
        Sum(2)=T1(i,j+1)-T1(i,j);
        Sum(1)=Sum(1)/R(j-1);
        Sum(2)=Sum(2)/R(j);
        Sum(3)=Sum(1)-Sum(2);
HL(i,j)=q(j)+Sum(3);
        T2(i,j)=((dT/C(j,1))+(q(j)+Sum(3)))+T1(i,j);
        T2(i,1)=Start_temp;
        T2(i,13)=Start_temp;
        T1(i,j)=T2(i,j);
HL2(i,j)=q(j);%Adiabatic conditions
        T3(i,j)=((dT/C(j,1))+q(j))+T3i(i,j);%Adiabatic conditions
        T3(i,1)=Start_temp;
        T3(i,13)=Start_temp;
        T3i(i,j)=T3(i,j);
    end
end

loadname = [filename,'.hra']
eval(['load ',loadname]);
eval(['time1=',filename,'(:,1);'])
eval(['heat_rate1=',filename,'(:,2);'])

subplot(2,2,1)
plot(time,T2)
s=['Temperatures (' num2str(filename) ')'];
title(s)
xlabel('Hours')
ylabel('Deg C')
axis([0,100,20,60])

time=time(:);
data=[time T2];
eval(['save ',filename,'.moi ','data /ascii'])

subplot(2,2,2)
plot(time,T2(:,12),time,T3(:,7),':')
title 'Adiabatic Comp.'
xlabel('Hours')
ylabel('Deg C')
axis([0,100,20,60])
```

```
subplot(2,2,3)
plot(time,T3(:,7),time,heat_rate1,':')
title 'Test Comp.'
xlabel('Hours')
ylabel('Deg C')
axis([0,100,20,60])

xp=1:1:13;
subplot(3,2,4)
plot(xp,T2(144,:),'.')%,xp,T3(144,:))
title 'Profile at 24 hrs'
xlabel('Position')
ylabel('Deg C')
axis([0,12,20,60])
steps=num2str(dx);
text(.5,55,['Steps ' steps 'm'])
text(xp(1),T2(144,1),' Ambient')
text(xp(2),T2(144,2),' Surface')
%eval(['gtext ',filename]);

xp=xp(:);
Ttwo=T2(:);
ttwo=T2(144,:);
ttwo=ttwo(:);
data=[xp ttwo]
eval(['save ',filename,'.mo2 ','data /ascii'])
%pause

%subplot(1,1,1)
%plot(time,HL(:,3),time,HL2(:,3))
%title 'Polystyrene Insulated 'Adiabatic' Calorimeter'
%xlabel('Hours')
%ylabel('Power (W)')
%pause
%Loss=(cumsum(HL2(len,3)).*600)-(cumsum(HL(len,3)).*600)
%plot(time,Loss)
```

B.6 HEATMOD2.M

```
clear all
filename = input('Please enter the thermal information file name? ','s');
filename2 = input('Please enter the model test file name? ','s');
loadname = [filename,'.hr2']
loadname2 = [filename2,'.mod']
eval(['load ',loadname]);
eval(['load ',loadname2]);
eval(['time=',filename,'(:,1);'])
eval(['heat_rate=',filename,'(:,2);'])
eval(['Tm=',filename2,';'])
loadname = [filename,'.pl2']
eval(['load ',loadname]);
eval(['cond=',filename,'(:,2);'])
%loadname = [filename,'.hra']
%eval(['load ',loadname]);
if length(time)<length(cond)
len=length(time);
else
len=length(cond);
end
for i=1:len
timap(i)=time(i);
end
time=timap;
Tm(:,1)=Tm(:,1)-Tm(1:1);
MinT=min(Tm(:,1));
MaxT=max(Tm(:,1));
time2 = [MinT:10/60:MaxT];%10 min intervals
time2 = time2(:);
Tm = interp1(Tm(:,1),Tm,time2,'linear');



%Correct variations in sensor values with respect to surface temperature
tdiff=Tm(1,2)-Tm(1,5);
Tm(:,5)=Tm(:,5)+tdiff;
tdiff=Tm(1,2)-Tm(1,6);
Tm(:,6)=Tm(:,6)+tdiff;
tdiff=Tm(1,2)-Tm(1,7);
Tm(:,7)=Tm(:,7)+tdiff;
tmod=Tm(:,1);
amb_temp=Tm(:,4);
for i=1:len
    mean_amb_temp(i) = mean(amb_temp);
end
```

```
mean_amb_temp=mean_amb_temp(:);
Start_temp=amb_temp(1);
dT=600;%10 minutes steps

%Calculate node capcity
dens=input('Please enter sample density? ');
dx=.1;%100mm between nodes
sh=input('Please enter the sample's specific heat? ');
C(1,1)=dens*dx/2*sh;
C(13,1)=C(1,1);
for i=2:12
    C(i,1)=dens*dx*sh;
end
for i=1:13
    T1(1,i)=Start_temp;
    T2(1,i)=Start_temp;
    T3i(1,i)=Start_temp;
end
%Calculate node temperatures
R(1)=1/20;%Loss due to convection
for j=2:len
        for k=2:11
            R(k)=1/(cond(i-1)/dx);
        end
        j=2;
        q(j)=heat_rate(i-1)*dx*1000;%(W/unit area)
        Sum(1)=mean_amb_temp(i)-T1(i,j),
Sum(2)=T1(i,j+1)-T1(i,j);
        Sum(1)=Sum(1)/R(j-1);
        Sum(2)=Sum(2)/R(j);
        Sum(3)=Sum(1)+Sum(2);
NL(i,j)=q(j)+Sum(3);
        T2(i,j)=((dT/C(j,1))*(q(j)+Sum(3)))+T1(i,j);
        T2(i,1)=Start_temp;
        T2(i,13)=Start_temp;
        T1(i,j)=T2(i,j);
NL2(i,j)=q(j);%Adiabatic conditions
        T3(i,j)=((dT/C(j,1))*q(j))+T3i(i,j);%Adiabatic conditions
        T3(i,1)=Start_temp;
        T3(i,13)=Start_temp;
        T3i(i,j)=T3(i,j);
       for j=3:5
          q(j)=heat_rate(i-1)*dx*1000;%(W/unit area)
          Sum(1)=T1(i,j-1)-T1(i,j);
          Sins=mean_amb_temp(i)-T1(i,j);
   if j==3
     Rins=abs((1/(Sins*0.377+0.02))+(1/(Sins*0.1121-2e-3)));
%see page 137
```

```
            else
        Rins=abs(1/(Sins+0.377+0.02));%see page 137
            end
    Rplas=abs(1/(Sins*.6));
    Sins=Sins/Rins;
    Splas=Sum(1)/Rplas;
    Sum(2)=Ti(i,j+1)-Ti(i,j);
            Sum(1)=Sum(1)/R(j-1);
            Sum(2)=Sum(2)/R(j);
            Sum(3)=Sum(1)+Sum(2)+Sins+Splas;
HL(i,j)=q(j)+Sum(3);
            T2(i,j)=((dT/C(j,i))*(q(j)+Sum(3)))+Ti(i,j);
            T2(i,1)=Start_temp;
            T2(i,13)=Start_temp;
            Ti(i,j)=T2(i,j);
HL2(i,j)=q(j);%Adiabatic conditions
            T3(i,j)=((dT/C(j,i))*q(j))+T3i(i,j);%Adiabatic conditions
            T3(i,1)=Start_temp;
            T3(i,13)=Start_temp;
            T3i(i,j)=T3(i,j);
        end
    end
end

subplot(2,2,1)
plot(time,T2(:,2));
hold on
plot(tmod,Tm(:,2),':');
hold off
s=['Surface Temperature'];
title(s)
xlabel('Hours')
ylabel('Deg C')
axis([0,100,20,40])

subplot(2,2,2)
plot(time,T2(:,3));
hold on
plot(tmod,Tm(:,7),':');
hold off
s=['Temperature at 100mm'];
title(s)
xlabel('Hours')
ylabel('Deg C')
axis([0 100,20,40])


subplot(2,2,3)
```

```
plot(time,T2(:,4));
hold on
plot(tmod,Tm(:,6),':');
hold off
title 'Temperature at 200mm'
xlabel('Hours')
ylabel('Deg C')
axis([0,100,20,40])

subplot(2,2,4)
plot(time,T2(:,5));
hold on
plot(tmod,Tm(:,5),':');
hold off
title 'Temperature at 300mm'
xlabel('Hours')
ylabel('Deg C')
axis([0,100,20,40])

time=time(:);
data=[time T2(:,2) T2(:,3) T2(:,4) T2(:,5)];
eval(['save ',filename,'.mo3 ','data /ascii'])
```

B.7 HSHMOD.M

```
clear all
filename = input('Please enter the file name? ','s');

loadname = [filename,'.hr2']
eval(['load ',loadname]);
eval(['time=',filename,'(:,1);'])
eval(['heat_rate=',filename,'(:,2);'])
loadname = [filename,'.pl2']
eval(['load ',loadname]);
eval(['cond=',filename,'(:,2);'])
loadname = [filename,'.hra']
eval(['load ',loadname]);
eval(['Start_temp=',filename,'(1,2);'])
loadname = [filename,'.sha']
eval(['load ',loadname]);
eval(['sh=',filename,'(:,3);'])
dT=600;%10 minutes steps
if length(time)<length(cond)
len=length(time);
else
len=length(cond);
end
for i=1:len
timep(i)=time(i);
shp(i)=sh(i);
end
time=timep;
sh=shp;

%Calculate node capcity
dens=input('Please enter sample density? ');
dx=.1;%100mm between nodes
C(1,:)=dens*dx/2.*sh;
C(13,:)=C(1,:);
for i=2:12
    C(i,:)=dens*dx.*sh;
end
for i=1:13
    T1(i,1)=Start_temp;
    T2(1,1)=Start_temp;
    TS1(1,1)=Start_temp;
end

%Calculate node temperatures
for i=2:len
```

```
    for j=2:12
        q(j)=heat_rate(i-1)*dx*1000;%(W/unit area)
        R(12)=1/.000000001;%Loss on insulated side (k=0.025)
        R(1)=1/20;%Loss due to convection
        for k=2:11
          R(k)=1/(cond(i-1)/dx);
        end
        if j==2
           Sum(1)=Start_temp-T1(i,j);%Start_temp=ambient
        else
           Sum(1)=T1(i,j-1)-T1(i,j);
        end
        Sum(2)=T1(i,j+1)-T1(i,j);
        Sum(1)=Sum(1)/R(j-1);
        Sum(2)=Sum(2)/R(j);
        Sum(3)=Sum(1)+Sum(2);
HL(i,j)=q(j)+Sum(3);
        T2(i,j)=((dT/C(j,i))*(q(j)+Sum(3)))+T1(i,j);
        T2(j,1)=Start_temp;
        T2(i,13)=Start_temp;
        T1(i,j)=T2(i,j);
HL2(i,j)=q(j);%Adiabatic conditions
        T3(i,j)=((dT/C(j,i))*q(j))+T31(i,j);%Adiabatic conditions
        T3(i,1)=Start_temp;
        T3(i,13)=Start_temp;
        T31(i,j)=T3(i,j);
    end
end

loadname = [filename,'.hra']
eval(['load ',loadname]);
eval(['time1=',filename,'(:,1);'])
eval(['heat_rate1=',filename,'(:,2);'])

subplot(2,2,1)
plot(time,T2)
s=['Temperatures (' num2str(filename) ')'];
title(s)
xlabel('Hours')
ylabel('Deg C')
axis([0,100,30,60])

time=time(:);
data=[time T2];
eval(['save ',filename,'.mo4 ','data /ascii'])

subplot(2,2,2)
plot(time,T2(:,12),time,T3(:,7),':')
```

```
title 'Adiabatic Comp.'
xlabel('Hours')
ylabel('Deg C')
axis([0,100,20,60])

subplot(2,2,3)
plot(time,T3(:,7),time1,heat_rate1,':')
title 'Test Comp.'
xlabel('Hours')
ylabel('Deg C')
axis([0,100,20,60])

xp=1:1:13;
subplot(2,2,4)
plot(xp,T2(144 :),'.')%,xp,T3(144,:))
title 'Profile at 24 hrs'
xlabel('Position')
ylabel('Deg C')
axis([0,12,20,60])
steps=num2str(dx);
text(.5,55,['Steps ' steps 'm'])
text(xp(1),T2(144,1),' Ambient')
text(xp(2),T2(144,1),' Surface')
%eval(['gtext ',filename]);

xp=xp(:);
Ttwo=T2(:);
ttwo=T2(144,:);
ttwo=ttwo(:);
data=[xp ttwo]
eval(['save ',filename,'.mo5 ','data /ascii'])
%pause

%subplot(1,1,1)
%plot(time,HL(:,3),time,HL2(:,3))
%title 'Polystyrene Insulated 'Adiabatic' Calorimeter'
%xlabel('Hours')
%ylabel('Power (W)')
%pause
%Loss=(cumsum(HL2(len,3)).*600)-(cumsum(HL(len,3)).*600)
%plot(time,Loss)
```

B.8 HSHMOD2.M

```
clear all
filename = input('Please enter the thermal information file name? ','s');
filename2 = input('Please enter the model test file name? ','s');
loadname = [filename,'.hr2']
loadname2 = [filename2,'.mod']
eval(['load ',loadname]);
eval(['load ',loadname2]);
eval(['time=',filename,'(:,1);'])
eval(['heat_rate=',filename,'(:,2);'])
eval(['Tm=',filename2,';'])
loadname = [filename,'.p12']
eval(['load ',loadname]);
eval(['cond=',filename,'(:,2);'])
loadname = [filename,'.she']
eval(['load ',loadname]);
eval(['sh=',filename,'(:,3);'])
%loadname = [filename,'.hra']
%eval(['load ',loadname]);
if length(time)<length(cond)
len=length(time);
else
len=length(cond);
end
for i=1:len
timep(i)=time(i);
shp(i)=sh(i);
end
time=timep;
sh=shp;
Tm(:,1)=Tm(:,1)-Tm(1:1);
MinT=min(Tm(:,1));
MaxT=max(Tm(:,1));
time2 = [MinT:10/60:MaxT];%10 min intervals
time2 = time2(:);
Tm = interp1(Tm(:,1),Tm,time2,'linear');



%Correct variations in sensor values with respect to surface temperature
tdiff=Tm(1,2)-Tm(1,5);
Tm(:,5)=Tm(:,5)+tdiff;
tdiff=Tm(1,2)-Tm(1,6);
Tm(:,6)=Tm(:,6)+tdiff;
tdiff=Tm(1,2)-Tm(1,7);
Tm(:,7)=Tm(:,7)+tdiff;
```

```
tmod=Tm(:,1);
amb_temp=Tm(:,4);
for i=1:len
    mean_amb_temp(i) = mean(amb_temp);
end
mean_amb_temp=mean_amb_temp(:);
Start_temp=amb_temp(1);
dT=600;%10 minutes steps

%Calculate node capcity
dens=input('Please enter sample density? ');
dx=.1;%100mm between nodes
C(1,:)=dens*dx/2.*sh;
C(13,:)=C(1,:);
for i=2:12
    C(i,:)=dens*dx.*sh;
end
for i=1:13
    T1(1,i)=Start_temp;
    T2(1,i)=Start_temp;
    T31(1,i)=Start_temp;
end
%Calculate node temperatures
R(1)=1/20;%Loss due to convection
for i=2:len
        for k=2:11
            R(k)=1/(cond(i-1)/dx);
        end
        j=2;
        q(j)=heat_rate(i-1)*dx*1000;%(W/unit area)
        Sum(1)=mean_amb_temp(i)-T1(1,j);
Sum(2)=T1(i,j+1)-T1(1,j);
        Sum(1)=Sum(1)/R(j-1);
        Sum(2)=Sum(2)/R(j);
        Sum(3)=Sum(1)+Sum(2);
HL(i,j)=q(j)+Sum(3);
        T2(i,j)=((dT/C(j,i))*(q(j)+Sum(3)))+T1(1,j);
        T2(i,1)=Start_temp;
        T2(i,13)=Start_temp;
        T1(1,j)=T2(i,j);
HL2(i,j)=q(j);%Adiabatic conditions
        T3(i,j)=((dT/C(j,i))*q(j))+T31(1,j);%Adiabatic conditions
        T3(i,1)=Start_temp;
        T3(i,13)=Start_temp;
        T31(1,j)=T3(i,j);
       for j=3:5
          q(j)=heat_rate(i-1)*dx*1000;%(W/unit area)
          Sum(1)=T1(1,j-1)-T1(1,j);
```

```
            Sins=mean_amb_temp(i)-T1(i,j);
    if j==5
       Rins=abs((1/(Sins*0.377+0.02))+(1/(Sins*0.1121-2e-3)));%see page 137
            else
       Rins=abs(1/(Sins*0.377+0.02));%see page 137
            end
    Rplas=abs(1/(Sins*.6));
    Sins=Sins/Rins;
    Splas=Sum(1)/Rplas;
    Sum(2)=T1(i,j+1)-T1(i,j);
            Sum(1)=Sum(1)/R(j-1);
            Sum(2)=Sum(2)/R(j);
            Sum(3)=Sum(1)+Sum(2)+Sins+Splas;
HL(i,j)=q(j)+Sum(3);
            T2(i,j)=((dT/C(j,1))*(q(j)+Sum(3)))+T1(i,j);
            T2(i,1)=Start_temp;
            T2(i,13)=Start_temp;
            T1(i,j)=T2(i,j);
HL2(i,j)=q(j);%Adiabatic conditions
            T3(i,j)=((dT/C(j,1))*q(j))+T31(i,j);%Adiabatic conditions
            T3(i,1)=Start_temp;
            T3(i,13)=Start_temp;
            T31(i,j)=T3(i,j);
         end
     end
end

subplot(2,2,1)
plot(time,T2(:,2));
hold on
plot(tmod,Tm(:,2),':');
hold off
s=['Surface Temperature'];
title(s)
xlabel('Hours')
ylabel('Deg C')
axis([0,100,20,40])

subplot(2,2,2)
plot(time,T2(:,3));
hold on
plot(tmod,Tm(:,7),':');
hold off
s=['Temperature at 100mm'];
title(s)
xlabel('Hours')
ylabel('Deg C')
axis([0,100,20,40])
```

```
subplot(2,2,3)
plot(time,T2(:,4));
hold on
plot(tmod,Tm(:,6),':');
hold off
title 'Temperature at 200mm'
xlabel('Hours')
ylabel('Deg C')
axis([0,100,30,40])

subplot(2,2,4)
plot(time,T2(:,5));
hold on
plot(tmod,Tm(:,6),':');
hold off
title 'Temperature at 300mm'
xlabel('Hours')
ylabel('Deg C')
axis([0,100,20,40])

time=time(:);
data=[time T2(:,2) T2(:,3) T2(:,4) T2(:,5)];
eval(['save ',filename,'.mat ','data /ascii'])
```

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