PAVEMENT TEMPERATURE MODELS

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PART II – ANALYSIS OF TEMPERATURE MEASUREMENTS

EXECUTIVE SUMMARY
PAVEMENT TEMPERATURE MODELS: PARTS I AND II

The work of this project was directed towards establishing a suitable computer model for predicting pavement temperature regimes in New Zealand, based on measurements taken at four sites in previous projects. Surfaces consisting of a chipseal, with Grade 4 chip, and asphalt (AC) 50 and 150 mm thick were constructed at Dunedin, Blenheim, Napier and Cardrona (Central Otago), and instrumented with thermocouples at various depths.

1. Influence of temperature on design requirements

In Part I of this two-part report, a review is made of the type of temperature information that is required for modern pavement design and the computer programs and methods available for predicting temperature profiles in pavements.

Application of measured temperatures

A comparison is made between measured and computed temperatures at one of the test sites, and predictions are made of pavement temperature extremes using meteorological input conditions for days of high solar radiation.

It was found that a simple finite-difference procedure set up on a spreadsheet could be used to compute pavement temperatures. Uncertainty in the material thermal properties, and the appropriate meteorological conditions required for input to the analysis, limits the accuracy of predictions. However, the comparisons of computed and measured temperatures allowed the computer model to be refined to enable temperature predictions to be made of sufficient accuracy for design applications.

2. Analysis of temperature measurements

In Part II, the data collected from the four sites is reviewed and comparisons of the important results presented. Data from all four sites has been converted to spreadsheet format so that it can conveniently be used in future investigations or design applications. In addition, the data collected from the Blenheim site, which had not been previously analysed, has been reduced and presented in plotted form.

Temperature correlations

Reasonably good correlations were found to exist between monthly mean air temperatures and the monthly means of daily maxima, minima and hourly pavement temperatures. Correlation equations were derived that should provide a useful method of estimating pavement design temperatures at any site in New Zealand.

Conclusions

The study demonstrated that in most areas of New Zealand, pavement temperature regimes can be predicted using the correlation equations developed for predicting pavement temperatures from available meteorological parameters or by using the measured results directly. For special pavement studies, or in locations with more extreme meteorological conditions than previously investigated, a simple one-dimensional finite-difference model is recommended. Details of the required pavement material and meteorological inputs are presented.

ABSTRACT

Temperature regime data from trial pavement sections at four sites in New Zealand was reviewed for the purposes of this project, which was principally aimed at establishing a suitable computer model for predicting pavement temperature regimes.

Reasonably good correlations were found to exist between monthly mean air temperatures and the monthly means of daily maxima, minima and hourly pavement temperatures. Correlation equations have been derived that should provide a useful method of estimating pavement design temperatures at any site in New Zealand.

A review was also made of the type of temperature information that is required for modern pavement design and the computer programs and methods available for predicting temperature profiles in pavements.

It was found that a simple finite-difference procedure set up on a spreadsheet could be used to compute pavement temperatures. Uncertainty in the material thermal properties, and the appropriate meteorological conditions required for input to the analysis, limits the accuracy of predictions. However, the comparisons of computed and measured temperatures allowed the computer model to be refined to enable temperature predictions to be made of sufficient accuracy for design applications.

INTRODUCTION

Large daily variations in pavement surface temperatures are caused by gains in thermal energy through absorption of solar radiation and losses in energy by radiation to the low temperature night sky and surroundings and convective cooling. As a result of the changes with time of the energy inputs and losses, large temperature gradients can develop between the surface and points at depth in the pavement. These effects tend to be relatively extreme in bituminous pavements because of the dark colour that provides an efficient heat transfer surface. Temperatures in pavements also follow seasonal air temperature trends, and when these are added to the diurnal variations there may often be large differences between extreme maximum and minimum.

Design requirements

The physical properties, including the stiffness, of bitumen change significantly over the range of temperatures occurring on paved roads. This adds considerable complexity to the design of economical pavements where it is necessary to consider the ability of the pavement to spread wheel loads within acceptable levels of deformation and the stresses in the pavement and sub-grade.

To produce an economical and durable design, a detailed knowledge of the temperature regime in the pavement, and how it varies with both time and depth, is required. In addition, the sensitivity to temperature changes of the elastic modulus and fatigue-based failure criteria need to be established. Temperature histories can also assist in the prediction of the rate of oxidation hardening of the bitumen in chipseals and open-graded mixes, and thus indicate likely surface life.

Temperature effects are included in the simplified design methods currently used in New Zealand by using the weighted mean annual air temperature to estimate the deformation and fatigue performance. If reliable pavement temperature information is available, more refined design procedures can be used.

In one refined approach, temperature effects are included by specifying a histogram of the relative frequencies of axles passing when the surface temperature and temperature gradient are each within one of several specified classes. Different histograms may also be defined for each season or for each month.

Monitoring of temperatures at test sites

The Pavements Committee of the former Road Research Unit arranged for the construction and monitoring of the temperature regime in trial sections of chipseal and asphalt pavement at four sites. Untrafficked surfaces consisting of a chipseal, with Grade 4 chip, and asphalt concrete (AC) 50 and 150 mm thick were constructed at Dunedin, Blenheim, Napier and Cardrona (Central Otago) and instrumented with thermocouples at various depths. Monitoring of air and pavement temperatures was carried out for at least a year at each site.

Initially it was proposed that more than four test sites would be established but work was curtailed when it was recognised that temperatures could probably be predicted by computer modelling using meteorological data inputs.

Additional analyses and reduction of the data from all four sites was required to make it more useful for design application and to convert it to spreadsheet format so that it would be easy to use in future investigations and for design applications.

PROJECT OBJECTIVES AND SCOPE

The two main objectives of the research of this project were:

- to collate, process and compare the results from the pavement temperatures measured at four sites in New Zealand

- to compare the measured data with predictions using existing pavement temperature models and by this means identify the most appropriate models for New Zealand conditions.

The main tasks undertaken in the project were:

Part I

Review of Pavement Design

The type of temperature information that is relevant to pavement design was determined by review of current pavement design methods. This included both a literature review and discussions with pavement design engineers.

Review Pavement Temperature Models

A review of relevant computer programs and pavement models able to compute pavement temperature gradients was carried out.

Temperature Model Predictions

Predictions were made of the temperature profiles at several sites using local meteorological data and a finite-difference computer program. The results were compared with the recorded temperatures.

Extreme Temperature Prediction

Extreme temperature profiles were computed using information from New Zealand meteorological records of maximum solar radiation on clear windless days.

Part II

Review Temperature Data

The data obtained from the four Road Research Unit test sites was reviewed to ascertain its suitability for use in improving the pavement design methods currently in use in New Zealand, and the verification of a computer model method for predicting temperatures in New Zealand pavements.

Process Temperature Data

An important task was to compare and summarise in graphical form the data collected from the four sites. In addition, the data collected from the Blenheim site was fully analysed, as this was not completed at the time of the experimental work. General differences in the temperatures recorded at the four sites were identified and related to the meteorological conditions experienced over the recording periods.

Note: Plots of reworked data are given in the figures of Appendix B, C, D and E.

PART 1: DESIGN REQUIREMENTS, MODEL PREDICTIONS

1. INFLUENCE OF TEMPERATURE ON DESIGN

1.1 Pavements Incorporating Structural Asphaltic Concrete Layer

The two main modes of failure usually considered in the design of structural asphaltic concrete (AC) layers are failure by excessive deformation, or 'rutting', and failure by the gradual development of cracks in the bound layers of the pavement under the effects of traffic loads, or 'fatigue'.

1.1.1 Rutting

This appears to be the most likely of the two modes of failure in New Zealand if the recommended procedures for pavement design given in the State Highway Pavement Design and Rehabilitation Manual, 1989 (SHPDRM), or the recently adopted AUSTROADS (1992) pavement design guide, are followed.

The load spreading properties of AC are related to the elastic modulus of the composite and this is reduced significantly by an increase in temperature. Deflections at the surface and vertical strain at the top of the sub-grade both increase as the pavement temperatures increase. Permanent deformation of the structure, produced by repeated loading of vehicles, has been related to the creep behaviour of dense AC at temperatures greater than about 30°C. The permanent deformation can be visible either as rutting or as lateral deformation or shoving.

In the usually accepted criterion for controlling permanent deformation in the sub-grade, the allowable strain induced by a standard wheel load is related to design traffic loading N (in EDA units) by the following equation (Shell Pavement Design Manual, 1978):

$$\varepsilon_c = 0.028N^{-0.25} \qquad \text{(Equation 1)}$$

The general form of Equation 1 is widely used, although the multiplying and exponential coefficients may differ in some design recommendations. This simple sub-grade strain criterion is semi-empirical, being based on back-analysis of pavements with known performance at a single temperature. It is not modified directly to account for variations in pavement temperature, although the strain under a specified design wheel load is influenced by the temperature sensitivity of the stiffness of pavement materials.

Many computer-based methods are available for calculating the sub-grade strain beneath elastic multi-layered pavements. Although the computational procedure is straightforward, the results are clearly sensitive to the material properties assumed. The elastic modulus of AC is dependent on both the temperature and rate of loading, and since both these parameters vary over a wide range, the selection of the appropriate inputs requires a careful and rather complex assessment.

In many implementations of analytic procedures for computing the sub-grade strain, only one pavement temperature is used and the gradient ignored. The chosen temperature is usually some mean pavement temperature derived from mean air temperatures. A simple time-averaged temperature, however, accords the same weight to temperatures at night when the traffic is light to temperatures during the day when traffic is heavy. It is therefore preferable to define a traffic-weighted mean temperature.

In the assessment procedure described by Brown et al (1985), an average pavement temperature was determined for each of the 24 hours in a daily cycle, using recorded pavement temperature data for a depth of 102 mm, accumulated over a period of one year. From these average hourly pavement temperatures, an annual average traffic-weighted pavement temperature was determined using a typical traffic volume distribution. The conversion factor between the design pavement temperature derived by this method and the annual average air temperature was found to be 1.48.

In the SHPDRM design procedure, design charts are used to eliminate the need for computation of the strain in the sub-grade. The charts enable the required AC and granular base thicknesses to be determined from design loading N, sub-grade CBR and weighted air temperature. To develop these charts, a large number of computations were carried out using the BISTRO computer program for layered media. Temperature effects have been included by developing two sets of charts for weighted mean annual air temperatures (w-MAAT) of 12° and 16° C. The temperature weighting is based on the work of Edwards and Valkering (1974). By calculating accumulated fatigue damage on a month-by-month basis from mean monthly air temperatures (MMAT), they developed a temperature weighting that enables a single w-MMAT to be used for design.

The SHPDRM design charts incorporate both sub-grade strain (rutting) and fatigue failure criteria, but the document recommends avoiding pavements in which fatigue cracking is predominant. The same single w-MAAT temperature is used to cover both the failure criteria, although the weighting used appears to be based on fatigue considerations alone. More correctly, the charts should have considered a traffic-weighted temperature related to the sub-grade strain. For rutting, it is inappropriate to consider cumulative damage or fatigue since the empirical design equation is based on back-analysis of pavements with known performance at a single temperature (Brown, 1985).

The AUSTROADS pavement design guide is based on similar theoretical considerations to the SHPDRIM and provides design charts for typical pavements. The asphalt modulus is a required input parameter and typical values are given for w-MAAT's of 20°, 25° and 30° C that are appropriate for Australia.

1.1.2 Fatigue

The fatigue failure criterion is usually defined as a simple power law relating the number of load repetitions to the tensile strain amplitude at the base of the asphalt layers. The failure criterion is also dependent on temperature, but in general the effect of this parameter is greatly reduced if the results are expressed in terms of the initial tensile strain amplitude rather than in terms of load or stress amplitude (Thrower, 1979).

Brown et al (1985) have proposed a fatigue design procedure in which Miner's rule is used to calculate cumulative damage. Using twelve average monthly traffic-weighted pavement design temperatures (1.47 x air temperature) each month has a particular strain level and hence life (N_{Td}) associated with it. Therefore the total damage D can be expressed as:

$$D = \frac{N \sum \frac{1}{N_{Td}}}{12} \qquad \text{(Equation 2)}$$

where the number of axles at each monthly strain level is taken as one-twelfth of the total number of standard axles to failure, N.

From two damage factors for two carefully selected initial thicknesses of asphalt pavement, the minimum design thickness can be calculated – corresponding to a damage factor of one – by assuming a linear relationship for damage factor as a logarithmic function of thickness.

Using three climatic regions in the UK, and typical pavement data, equivalent fatigue cracking design temperatures were generated. These equivalent temperatures are such that they gave the same asphalt design thickness, based on asphalt tensile strain, as that calculated using the monthly temperatures and the accumulated damage method. It was found that the equivalent annual pavement design temperature corresponded to the average annual air temperature increased by a factor of 1.9.

In a parametric study of fatigue failure prediction, Thrower (1979) incorporated temperature effects by specifying a two-dimensional histogram giving the relative frequencies of axles passing while the surface temperature and temperature gradient are each within one of several specified classes. In this approach, different histograms can be defined for each season.

As mentioned above, in the SHPDRM design charts (for both deformation and fatigue) a weighted mean annual air temperature (w-MAAT) is used to determine the pavement design thickness. In this simplified approach, no direct account is taken of the traffic volume variation, which will generally result in more severe loading during the highest temperature regimes in the pavement. The neglect of daily traffic volume variations will therefore tend to result in a less durable design.

1.2 Unbound Pavements with a Thin Surfacing

The thin layer of seal or dense AC surfacing on an unbound pavement is subjected to a large range of temperatures and – under adverse conditions – to rapid changes of temperature. Surface temperatures from -3 to 72° C have been recorded in Australia. In inland Canada, very cold temperatures of down to -35°C have been recorded (Dickinson, 1981).

When constructed, the binder is chosen so that there will not be too much shear flow in the binder/aggregate composite at high pavement temperatures. At the same time, there needs to be sufficient flow at low temperatures to avoid cracking. The binder is exposed to varying degrees of chemical reaction by the atmospheric oxygen. This produces hardening, which is much more rapid at high temperatures (roughly doubled for each 10° C increase in temperature). Eventually the binder can become so hard that cracking takes place under the combined effect of loading and thermal contraction when the pavement cools down in winter. A knowledge of the temperature regime can assist in optimisation within the design parameters and will provide an indication of the pavement life.

Dickinson (1981) found that the amount of reaction taking place for surface hardening during any given period, relative to the amount that would take place at a constant temperature of 30° C, can be calculated from the pavement surface temperature distributions over a year. Further, the rate of reaction was closely correlated with the yearly average of the daily maximum temperature (YMMT) for the particular sites investigated in Australia.

In the Dickinson study, the best average indicator of the severity of low temperature conditions that affect brittle cracking was found to be the monthly average of the minimum screen temperature (MIN MMAT) for the coldest month of the year. There was found to be some correlation between this indicator and the percentage of the year the surface temperatures were below 6° C.

Road surface temperatures must also be considered in chipsealing practice. During pavement sealing the binder is cut back to give the best viscosity, at road temperatures, to allow chip adhesion to occur, while still preventing chip loss from traffic loads. The viscosity will also affect the rate at which a chipseal is compacted by construction and traffic loads. Pavement surface temperatures are also important in considering the problem of 'bleeding' of the binder in chipseals during hot weather.

1.3 Concrete Pavements

Solar radiation may cause high temperature gradients in concrete pavements, although the heat inputs are less than for bituminous pavements because of the lighter surface colour and hence lower thermal absorptivity. Unlike bituminous pavements, the elastic modulus is not sensitive to the temperatures and rates of loading normally occurring in pavements. However, the high stiffness can result in significant temperature-induced stresses and curling effects at construction and movement joints. Temperature curling together with drainage deficiencies, can lead to pumping and failure of the sub-grade materials.

It is uncommon to include temperature effects in the simplified design procedures frequently used for concrete pavements. However, for the design of major or unusual pavement structures, temperature induced stresses and movements should be investigated.

1.4 Cemented Sub-base

The strength development in cement stabilised sub-base materials is dependent on the temperature and time available for curing – usually measured in 'degree days'. A knowledge of the temperature regime through the pavement and sub-base materials can assist in minimising construction periods and establishing the length of season during which curing can satisfactorily be carried out.

1.5 Evaluation of Pavement Performance

The surface deflection (and rebound) of a bituminous pavement is a readily measurable response to load and can be used as part of the evaluation process for overlay design. Correlation between loads and deflections may be improved by adjusting measured deflections to an equivalent deflection at a common base temperature. Under normal conditions, only the surface temperature of the pavement can be conveniently measured. However in a study by Southgate and Deen (1975), it was found that mean pavement temperatures can be estimated from the measured surface temperature at the time of measurement and the mean daily air temperatures for the previous five days as an indication of the air temperature history.

Schmidt and Sharp (1988) have summarised the results from Australian Road Research Board (ARRB) deflection-temperature tests. An attempt was made to determine the depth at which the temperature which best represents the effective temperature of a single asphalt layer should be measured. This was done by correlating back-calculated moduli and pavement temperature when the asphalt was modelled as a single layer and when it was sub-divided into several layers. Good correlations were achieved for a range of pavement depths.

2. SUMMARY OF RECORDED TEMPERATURE DATA

A summary of the pavement temperature recording periods in the Road Research Unit field measurement project is shown in Table 1.

Table 1 Summary of Pavement Temperature Records

Location	Start Month	End Month	Record Length Days
Dunedin Airport	Oct 1981	Sep 1992	365
Blenheim	Mar 1983	Feb 1984	365
Napier	Dec 1984	Nov 1985	365
Cardrona	Apr 1988	Apr 1989	261

Difficulties were experienced with the logging equipment used in the Cardrona investigation, resulting in the capture of only about 71% of the available time during the recording year.

A detailed description of the instrumentation, temperature measurements made, and site meteorological conditions is given in Part II of this report.

3. APPLICATION OF MEASURED TEMPERATURES

The pavement temperatures monitored at the four sites in the trial seal and asphalt pavement sections can be used for future design and research studies in one or more of the following ways:

- The recorded temperatures can be used directly as an indication of the temperature regime in similar pavements at nearby locations, or locations that are expected to have similar climatic conditions. Before direct use can be made, it is necessary to ascertain whether the temperature-recording period coincided with climatic conditions that were close to average conditions. If climatic conditions differ markedly from average conditions, it might be necessary to make adjustments or select periods where agreement between the recorded and average conditions is reasonably good.

- The recorded pavement temperatures can be correlated with air temperatures or other relevant climatic factors, such as air temperature history, insolation and wind speed. If acceptable correlations can be found, the relationships can be used to predict pavement temperatures at other locations with different climatic conditions.

- The recorded pavement temperatures can be used to verify and calibrate a computer model based on a standard 'finite-difference' equation representation of the thermal-diffusion equation for one-dimensional heat flow. The model would enable pavement temperatures to be predicted from climatic factors such as solar radiation, air temperature, wind speed and cloud cover.

  This type of investigative tool can be used to extend pavement temperature knowledge in lieu of tedious and expensive temperature observations of actual pavements. In particular, the model can be conveniently used to predict the coldest and hottest conditions in the upper layers of the pavement that occur when there are clear sky conditions (maximum insolation) and low wind speeds on days near the winter and summer solstices. (Pavement temperatures can be predicted for other climatic conditions but this would require a considerable volume of meteorological input data.)

4. REVIEW OF TEMPERATURE MODELS

Essentially there are two basic types of numerical techniques used in heat transfer analysis. These are the 'finite-element' and 'finite-difference' methods. Most commercially available computer codes for heat transfer analysis are based on the finite-element method. However, the finite-difference method has been widely used in the past, particularly before the development of finite-element programs, and has advantages for research projects that often require special-purpose features not always available on commercial programs developed for more general application.

4.1 Previous Research

The first researchers to publish a detailed description of a computer-based pavement temperature model were Straub, Scheneck and Przybycein (1968). They used a finite-difference one-dimensional transient heat-flow programme to make comparisons with observed pavement temperatures in 150 mm and 300 mm thick test pavements. Their model had 13 nodes, representing 25 mm-thick layers in the asphaltic concrete and a 280 mm layer in the underlying gravel base.

Fifteen-minute time steps were used with recorded air temperature and solar radiation used as the meteorological inputs. A forward-difference or explicit solution technique was used. The pavement temperature profiles recorded in the pavement at 6:00 am were used as the starting point in the analyses carried out for the comparisons with the recorded temperatures. By making arbitrary variations to these early morning profiles the researchers showed that the maximum diurnal temperatures were not very sensitive to the initial temperatures. The properties assumed for the asphaltic concrete pavement material were as shown in Table 2.

Table 2 Straub et al Model Properties

Parameter	Value and Units
Density	2.2 Mg/m^3
Conductivity	1.21 W/m °K
Specific Heat	0.92 kJ/kg °K
Heat Capacity	2.0 MJ/m^3 °K
Surface Absorptivity	1.0
Surface Emissivity	0.9

The finite-difference model based on the above parameters gave very good predictions of the temperatures on the surface and at depth in the asphaltic concrete pavements on clear sunny days. Attempts at predicting winter temperatures were less successful, probably because small heat flows are difficult to predict and minor errors have large temperature effects. However, the researchers noted that minimum temperatures on the pavement surface seldom dropped below the lowest air temperatures, barring an unusually clear night producing a 'radiation' frost.

Both the recorded and computed results indicated that the thickness of the pavement did not have a strong influence on the distribution of temperature with depth. This was thought to be mainly a result of the similarity between the thermal properties of the asphaltic concrete and the sub-grade materials.

Dickinson (1981) developed a pavement temperature finite-difference model as part of a study involving the collection of the temperature regimes in asphaltic concrete and sprayed seal pavements from six sites in Australia over a period of a year or more. The finite-difference input was simplified to enable the pavement temperatures to be calculated for a 24-hour period at any location in Australia when the sky is clear and wind speed low (conditions when the highest and lowest pavement temperatures are encountered).

A forward difference in time (explicit) solution method was adopted. An adiabatic (or non-conducting) boundary was assumed to exist at a depth of 300 mm below the surface. The depth increment was taken as 25 mm and the time step as three minutes. The calculation was started when the temperature gradient was a minimum (early morning) and the initial temperatures were obtained from a correlation between the monthly average of the daily maximum air temperature at the site. Solar radiation for the day under consideration was taken from tables previously published for population centres in Australia. Analytical expressions for the variation of the insolation flux and the rate of energy loss by the pavement with time during the day (radiation, free- and forced-convection, and moisture evaporation) were developed to simplify the input for the analysis.

Samples of the asphaltic concrete used at the Brisbane, Canberra and Darwin sites were cut from the pavements and their thermal conductivity measured by the guarded hot plate method (standard ASTM test procedure). The values obtained are shown in Table 3.

For general calculations, Dickinson recommended adopting a pavement-specific heat value of 0.84 kJ/kg °K and a density of 2.24 Mg/m^3. The surface absorptivity value that gave the best fit to recorded temperatures was found to vary between 0.8 to 0.95.

Table 3 Thermal Conductivity of Dickinson's Asphaltic Concrete Samples

Site	**Canberra**	**Brisbane**	**Darwin**
Aggregate Used	Porphyry (quartz, biotite and feldspar)	River gravel (high content of quartzitic rock)	Quartzite
AC Bulk Density (Mg/m^3)	2.03	2.23	2.10
AC Thermal Conductivity (W/m °K)	1.23	1.80	2.90
Air Void Content (% Vol)	14.5	6.2	12.4

Robinson (1985) developed a finite-element model to enable pavement temperatures to be predicted from data on solar radiation, air temperature, wind speed and amount of cloud. His analysis procedure, like those described above, was based on the standard finite-difference equation representation of the thermal diffusion equation for one-dimensional heat flow. The only significant difference was that an implicit-solution procedure was adopted to solve the finite-difference equations. The performance of the model was assessed by comparing predictions with temperatures measured at two experimental sites. An indication of the influence of the various parameters affecting pavement temperatures was obtained by sensitivity analyses.

As with the other models described above, the variables that need to be input to use the model consist of the meteorological conditions, plus:

- the values of heat capacity and thermal conductivity for the different pavement layers
- the surface absorptivity and emissivity
- the levels or depth increments with the pavement at which the temperatures are to be computed
- the temperature at the lower boundary
- the initial pavement and sub-grade temperatures.

For each pavement layer at the two sites investigated, the heat capacity was found by summing the heat capacities of the different constituents that would, on average, be found in the materials. Values for overall density and the proportions of the constituent materials were generally obtained from construction measurements and the specific heats of the constituent materials were taken from published sources. Thermal conductivity values for the layers of unbound materials were determined by applying previously-published empirical equations.

Thermal conductivities for the bound materials were calculated from the measured amplitude of average daily temperature variations over a 20-day period and the values of heat capacity of the bound layers. These estimates were based on an analysis of the proportion of the sinusoidal (sine curve) temperature waves in layered media, the pavement being taken as a 100 mm layer representing the wearing course and base-course on top of a layer of infinite depth representing the base. A summary of the various material parameters derived from these procedures is shown in Table 4.

Table 4 Thermal Properties of Robinson's Pavement Layers

Site	Pavement Layer	Heat Capacity $MJ/m^3\ ^oK$	Density Mg/m^3	Thermal Conductivity $W/m\ ^oK$
Alconbury By-Pass	Rolled Asphalt	1.98	2.40	2.28
	Gravel base	1.95	2.40	1.79
	Hoggin sub-base	2.30	2.29	2.47
	Clay sub-grade	2.83	2.25	2.08
Grangemouth	Rolled asphalt	2.00	2.42	1.92
	RA - base	1.97	2.43	1.54
	Shale sub-base	2.39	1.88	1.56
	Silt sub-grade	2.88	1.85	1.26

Values of surface absorptivity were measured as 0.93 and 0.94 at the Alconbury and Grangemouth sites respectively.

The temperature calculation points were taken at 10 mm depth increments down to a depth of 1.0 m and at 100 mm increments below this depth. One hour was chosen as the time step to coincide with meteorological records. Lower boundary temperatures for the models representing the pavements at the two sites were based on nearby records of soil temperature averaged over a period of one year for a depth of 1.0 m. A uniform initial pavement temperature profile was assumed, and results obtained for the first month discarded, to ensure that the model results were not dependent on the initial conditions to any significant extent.

Over a range of measured pavement temperatures from -15°C to 45° C and at depths within the pavement of 10 mm to 250 mm the mean difference between model predicted and measured temperatures was less than 2° C. The sensitivity analyses showed that the surface temperatures are most sensitive to the meteorological variables. For example, a 15% decrease in solar radiation reduced pavement surface temperatures by 5° C. A 25% change in thermal conductivity of the wearing and base course layers resulted in a maximum change of only 1.4° C in the predicted surface temperature.

A number of less detailed descriptions of finite-difference modelling of pavement temperature are given in the literature. Dempsey et al (1986) described a Climatic-Materials-Structural Analysis program (CMS) set up to introduce climatic effects into the analysis of multi-layered flexible pavement systems. The analysis program consisted of several sub-models that were combined to analyse the behaviour of multi-layered flexible pavement systems. The climatic model takes climatic and material data as inputs and calculates temperature and moisture profiles as they vary with time. This information is used to calculate the asphaltic concrete, base course, sub-base and sub-grade stiffness characteristics. The output can then be combined with load data and input into selected structural analysis models to generate data for analysing the stresses in flexible pavements.

The climatic model uses a standard one-dimensional finite-difference heat transfer analysis procedure. A detailed description is given of the factors involved in the heat transfer at the pavement surface. Information is also presented on the procedure used to analyse the heat transfer associated with freeze/thaw in the pavement layers.

Thompson et al (1987) provide information on the application of the CMS computer described above (Dempsey et al, 1986). The development and use of a comprehensive Illinios climatic database is presented. Air temperature data were summarised on a weekly mean basis with a straight-line variation assumed between the diurnal minimum and maximum temperatures for input to the pavement heat-transfer model. The percent sunshine and wind speed were analysed on a monthly basis and presented as isolines of average monthly conditions on a state map. Thermal properties used in the analysis of typical pavement heat transfer problems are summarised in Table 5.

Table 5 Pavement Material Properties Used by Thompson et al (1987)

Material	Density Mg/m^3	Heat Capacity MJ/m^3 °K	Thermal Conductivity W/m °K
Asphaltic concrete	2.37	2.2	1.2
Stabilised base	2.34	2.3	3.3
Portland cement concrete	2.40	2.2	2.2
Cohesive sub-base	2.07	1.9	1.6

Pufahal et al (1990) describe the integration of the CMS model with a precipitation model, infiltration and drainage model and a freeze-thaw settlement model. The paper presents an overview of this large integrated pavement analysis model and gives some typical results for various climatic regions in United States. The final report on the project and the computer program are available through the United States National Technical Information Service.

4.2 Finite-element Method

The finite-element method is widely used for stress analysis and many of the more sophisticated codes such as Nastran, Ansys, Cosmos and Algor Supersap have heat-transfer solution modules. Some of the higher level programs such as Ansys have a simultaneous thermal-structural analysis procedure that calculates a stress solution based on the temperature and displacement data from a previous iteration.

Most of the programs developed particularly for PC's and commonly used in New Zealand, such as SAP2000 and MSC/Nastran, carry out thermal stress analyses with temperature data as input, but do not solve the initial transient heat conduction problem that is necessary for pavement temperature analysis.

The main disadvantage of the finite-element method is that most of the more sophisticated programs with sufficient capability for solving the pavement transient heat flow problem are expensive and not at present widely available or used in New Zealand. A further disadvantage is that the boundary heat-transfer equation options available in many programs are not specifically set up for pavement surfaces where a complex non-linear radiation and convection heat transfer occurs.

The main advantage of finite elements is that the method can be applied to solve both the heat transfer and the stress analysis problems with a single computer model. A further advantage is that any order of precision can generally be obtained by adjusting the element size and the time steps used in the transient analysis. The method is also of particular advantage for the analysis of complex three-dimensional shapes where the application of finite-difference equations becomes more complex. However, pavement heat-transfer and temperature-stress analysis problems can generally be solved using simple one- or two-dimensional models.

A review of recent literature found no published examples of the application of the finite-element method to the solution of pavement heat transfer problems.

4.3 Finite-difference Method

Because of the large lateral extents of most pavements, the analysis of heat transfer can usually be simplified to a one-dimensional problem with the heat flow occurring in a vertical direction normal to the pavement surface. At the pavement surface it is assumed that the heat interchange arises from incident solar radiation, incident long-wavelength radiation, emitted long-wavelength radiation and convection. Adopting the one-dimensional assumption, the heat balance at the surface can be described by the equation:

$$H_s + H_1 - H_r - H_c = -k\frac{\partial T_1}{\partial z} \qquad \text{(Equation 3)}$$

where

H_s = input from solar radiation
H_l = long-wavelength radiation input
H_r = long-wavelength radiation loss
H_c = convection loss
k = thermal conductivity
T_l = temperature at the surface
z = depth in the pavement

The solar radiation input is available from climatological records obtained at main meteorological centres. The heat loss by radiation can be obtained by the Stefan-Boltzmann Law for grey bodies:

$$H_r = \varepsilon\sigma T_1^4 \qquad \text{(Equation 4)}$$

where

ε = surface emissivity
σ = Stefan-Boltzmann constant

Robinson (1985) gives the following empirical equations for estimating the long-wave radiation input and the convective loss:

$$H_l = 0.53\,(1 + 0.22\,M^2)\,(T_a/100)^6 \text{ W/m}^2 \qquad \text{(Equation 5)}$$

$$H_c = Q\,(T_l - T_a) \qquad \text{(Equation 6)}$$

$$Q = 0.82\,(T_l + T_a)^{0.3}\,U^{0.7} + 0.68\,(T_l - T_a)^{0.3} \text{ W/m}^2/^\circ\text{K} \qquad \text{(Equation 7)}$$

where

M = fraction of sky covered by clouds
U = wind speed in m/s at a height of 2 m
T_a = air temperature in °K.

Within the pavement the heat flow is by conduction and the basic equation governing the heat transfer is:

$$\rho c \frac{\partial T}{\partial t} = k \frac{\partial^2 T}{\partial z^2} \qquad \text{(Equation 8)}$$

where:

ρ = material density
c = material specific heat
t = time

The above partial differential Equations 3 and 8 can be expressed in the following finite-difference forms:

$$\Delta T_1 = 2\frac{\Delta t}{\rho c \Delta z}\left[q - \frac{k}{\Delta z}(T_1 - T_2)\right] \qquad \text{(Equation 9)}$$

$$\Delta T_i = \frac{k\Delta t}{\rho c \Delta z^2}(T_{i-1} - 2T_i + T_{i+1}) \qquad \text{(Equation 10)}$$

where

ΔT_1 = change in temperature at the surface during time interval Δt
q = net heat input at the surface
ΔT_i = change in temperature at node point i during the time interval
Δz = thickness of the material layer

Equation 10 only applies within a layer having uniform thermal properties. A slightly more complex version of Equation 10 can be written for application at an interface between two different materials and where the layer thickness changes.

If the pavement, base course and sub-base layers are divided into a number of layers down to a depth where the temperature is assumed to be constant with time, Equations 9 and 10 can be applied to compute the layer temperature variation with time in each layer. Input parameters required to define the heat input and losses on the pavement surface are the solar radiation, wind speed, cloud cover, air temperature and the absorptivity and emissivity of the surface. Material input parameters required for the analysis are the thermal conductivity, density and specific heat. In addition, the initial temperature profile at the commencement of the time period of interest needs to be known.

The Equation 9 and 10 nodal temperatures at the surface and within the layers (T_1 and T_i) can be taken as the temperatures at either the commencement of the time step or at the completion of the time step. If the temperatures are assumed to be at the commencement of the time step, then the finite-difference scheme is known as an 'explicit' one and if the temperatures are taken at the end of the step the scheme is called 'implicit'. It is also possible to set up a solution scheme using an average of the temperatures at the commencement and end of the time step.

In the explicit finite-difference procedure, the temperature increment at each node in every time step is simply calculated directly from Equations 9 and 10 commencing with the initial temperature profile at time zero. The new temperature profile at each step is then obtained by adding the temperature increments to the previous temperature profile. This procedure is very easy to program and can be conveniently set-up on a spreadsheet to give quick solutions and temperature profile plots using a PC.

The accuracy of the solution depends on the magnitude of the depth and time increments and these must be within certain limits to ensure a stable numerical solution. For the pavement transient heat transfer problem, convenient values of depth increment (layer thickness) are in the range of 25-50 mm and corresponding time steps need to be in the range of 2-5 minutes to ensure stability of the numerical process.

The implicit procedure results in a set of simultaneous algebraic equations for the temperatures at each node. The number of equations is equal to the number of nodes. For the pavement problem, the number of nodes is within the range of 20-40 so that the solution can be conveniently be carried out on a PC, although the programming is rather more complex than for the explicit procedure. The main advantage of the implicit method is that the numerical process is stable for any range of the depth and time increments.

5. TEMPERATURE MODEL PREDICTIONS

5.1 Meteorological Data

The meteorological information collected from the four sites in the Road Research Unit project was unfortunately quite limited. At each site, the ambient air temperature was recorded at the 10-minute time interval used to record the pavement temperatures. At Cardrona, solar radiation was also recorded at 10-minute intervals. It was planned to record wind speeds but problems with the recording equipment resulted in no useful wind data being recorded. Solar radiation and wind speed measurements were not attempted at the other three sites.

Apart from Cardrona, all three sites were reasonably close to airports where meteorological data is recorded on a regular basis. However, at Napier and Blenheim airports no records are kept of solar radiation. Daily minimum and maximum temperatures and maximum gust speeds were recorded at these two locations, but the available records do not have detailed information, such as the hourly logs of these data. For Dunedin, daily solar radiation totals and sunshine hours are available, together with more detailed wind speed records.

Only for the Cardrona site was the meteorological information complete enough to allow a detailed computer model prediction of pavement temperatures and a satisfactory comparison between predicted and measured temperatures. In addition to the recorded solar radiation and ambient air temperature, it is necessary to have wind speed and cloud cover information. These data were recorded at three-hourly intervals at Queenstown airport, located about 30 km from the test pavement site. Although the applicability of Queenstown data to Cardrona is questionable, on days of maximum pavement temperatures reasonably clear skies and light winds are expected, and under these conditions errors in the cloud cover and wind speed parameters do not have a large affect on computed temperatures.

The daily solar radiation data for Dunedin were converted to hourly (or 10-minute) intervals to allow an approximate prediction of pavement temperatures, but these predictions were considered to be less reliable than those made for Cardrona, where more detailed information was recorded.

5.2 Material Thermal Properties

At each of the four sites, temperatures were recorded in test strips containing three different types of pavement: a chipseal, and 50 mm and 150 mm thick AC surfacing. Each pavement was laid on a base course to give a total thickness from the pavement surface to the underside of the base course of 200 mm.

No measurements were made of the thermal properties of the pavement and sub-base materials used at any of the four sites. Measurement of in-situ thermal properties is difficult and although laboratory tests could be carried out to predict some of the parameters, the very important thermal conductivity parameter is sensitive to moisture content and specimen preparation technique. Probably the best method of determining the thermal properties is by back-analysis (or trial and error fitting) of the field-recorded pavement temperatures. Ideally, this process requires reliable meteorological input data. Otherwise the number of unknowns and uncertainty becomes too great.

Comparisons were made between recorded and measured pavement temperatures at the Cardrona site using a special-purpose explicit finite-difference procedure set up on a spreadsheet. Material properties were adjusted by trial and error until reasonable agreement was obtained between the measured and predicted temperatures. The properties were kept within the range of published material properties. Table 6 lists the possible ranges taken from the literature and Table 7 gives the values adopted for the analyses.

Table 6 Range of Material Thermal Properties

Property	Asphaltic concrete	Base course	Sub-grade
Emissivity	0.8 - 0.9		
Absorptivity	0.8 - 0.95		
Density (Mg/m^3)	2.0 - 2.4	1.8 - 2.4	1.8 - 2.4
Specific heat (kJ/kg °K)	0.7 - 1.0	0.75 - 1.2	0.9 - 1.6
Heat capacity (MJ/m^3 °K)	1.8 - 2.0	1.9 - 2.2	2.3 - 2.9
Conductivity (W/m °K)	1.2 - 2.9	1.8 - 2.0	1.3 - 2.5
Diffusivity (mm^2/s)	0.6 - 1.7	0.8 - 1.1	0.4 - 1.1

Table 7 **Material Thermal Properties used in Analyses**

Property	Bitumen Seal	50 mm Asphaltic Concrete	150 mm Asphaltic Concrete
Emissivity	0.7	0.8	0.8
Absorptivity	0.7	0.9	0.9
Density (Mg/m^3)	2.0	2.2	2.2
Specific heat (kJ/kg °K)	0.90	0.91	1.0
Heat Capacity (MJ/m^3 °K)	1.8	2.0	2.2
Conductivity (W/m °K)	2.2	2.2	2.2
Diffusivity (mm^2/s)	1.2	1.1	1.0

5.3 Model Details

The pavement model extended to a depth of 2000 mm with the pavements, base course and sub-base modelled by 50 mm-thick uniform increments of depth. The input data recorded at 10-minute intervals was interpolated to allow time steps of 300 seconds to be used.

Models were set up for each of the three pavement types. For each type it was assumed that the thermal properties were constant with depth. That is, the same parameters were used for the surfacing, base course and sub-base within each model, although small variations were made between models, as shown in Table 7. Initially, it was intended to refine the models by using different thermal properties for the respective materials. However, the initial computations with the simplified models gave good predictions of the measured temperatures and it became apparent that the asphaltic concrete material had very similar thermal properties to at least the basecourse, and probably also to the sub-base.

As indicated in Table 7, a better fit between measured and predicted temperatures was obtained by increasing the heat capacity as the thickness of the asphaltic concrete increased. This indicates that the heat capacity of the asphaltic concrete should be somewhat higher than for the soil materials. However, this refinement was not incorporated in the present models as it was difficult to confirm more reliable predictions of the thermal properties of the soil materials because of the uncertainty in some of the meteorological inputs.

The main difference between the thermal properties of the three types of pavements was found to be in the surface absorptivity, which was found to be significantly lower for the chipseal than for the asphaltic concrete. The absorptivity is mainly a function of colour and the chipseal at Cardrona was believed to be considerably lighter in colour than the asphaltic concrete, which is a relatively dense black when new.

Experience elsewhere has shown quite a significant drop in the absorptivity of AC concrete, with weathering and lightening of the colour over time. Therefore, the difference between AC and chipseal may typically not be as great as observed with the trial pavements, which were investigated in the year following laying.

Initial temperatures in the model upper layers were deduced by interpolation of the measured temperatures at the time corresponding to the model initial time. Initial temperatures were assumed constant below the deepest recording probe located 400 mm below the surface.

A typical Excel spreadsheet used for the analyses is shown in Table 8. Temperatures were calculated simultaneously for all points in the pavement depth and for all time steps using the standard explicit finite-element procedure (forward-difference). Although this requires the full capabilities of a modern PC, it was found that this approach was easy to set up and to verify, as well as allowing a single output plot of the pavement temperature history to be generated directly from the spreadsheet.

The cell formulae for the computed heat inputs and losses at the surface and the computed temperature profile were identical to those given in Section 4.3 (Equations 3-6, 9 and 10). An adiabatic, or non-conducting, boundary was assumed at a depth of 2000 mm below the surface. In computing the solar radiation input at each time increment, the average value of the input at the time step being computed and the preceding time step was used. Temperatures were computed for the pavement surface and at 50 mm depth increments. For comparison with recorded results, temperatures were interpolated between the computed values.

Table 8 **Transient Heat Flow Analysis by Finite Difference Equations 50 mm Thick Asphalt Pavement**

Item	Symbol	Value	Units	Formula
Input Parameters				
Cloud cover	M	0.15		
Wind speed scale factor	Wf	2.0		Used to scale wind speed
Ambient temperature scale factor	Tf	1.0		Used to scale ambient temp.
Pavement emissitivity	E	0.75		
Pavement absorptivity	A	0.90		
Pavement conductivity	k	2.2	W/m/°C	
Pavement material heat capacity	Ca	2.0	MJ/m^3/°C	density x specific heat
Analysis time increment	dt	300	s	
Analysis depth increment	dz	0.05	m	
Calculated Parameters				
Finite difference coefficient	F	0.1320		$= k.dt/(Ca\ dz^2.10^6)$
Surface coefficient	Fs	0.0060	m^2 °C/W	$= 2.dt/(Ca\ dz.10^6)$

Table 8 (cont) Calculated Temperature Profile as a Function of Time

	Input Parameters			Computed Inputs and Losses			Computed Temperatures						
Time hr:min	Air Temp °C	Wind Speed m/s	Solar Radiation W/m^2	Long Wave Radiation W/m^2	Convective Loss W/m^2	Radiation Loss W/m^2	Surface Temp. °C	Temp at depth 50 mm °C	100 mm °C	150 mm °C	200 mm °C	250 mm °C	300 mm °C
06:00	4.9	0.00	24	245	5.7	273	10.0	14.0	16.0	18.5	20.0	21.0	21.0
06:05	4.9	0.00	26	245	7.1	277	11.0	13.7	16.1	18.4	19.9	20.9	21.0
06:10	4.9	0.00	27	245	8.1	279	11.6	13.7	16.1	18.3	19.9	20.8	21.0
06:15	4.9	0.00	28	245	8.8	281	12.1	13.7	16.0	18.2	19.8	20.7	21.0
06:20	4.9	0.00	29	245	9.3	282	12.4	13.8	16.0	18.1	19.7	20.6	20.9
06:25	5.0	0.00	89	246	9.8	284	12.8	13.9	16.0	18.0	19.6	20.5	20.9
06:30	5.1	0.00	149	246	10.7	286	13.5	14.0	16.0	18.0	19.5	20.4	20.9
06:35	5.4	0.00	203	248	11.6	290	14.3	14.2	16.0	17.9	19.4	20.4	20.8
06:40	5.6	0.00	256	249	12.8	293	15.2	14.5	16.0	17.9	19.4	20.3	20.8
06:45	6.4	0.00	272	253	13.0	297	16.1	14.8	16.1	17.8	19.3	20.2	20.7
06:50	7.1	0.00	288	257	13.2	300	16.9	15.1	16.1	17.8	19.2	20.2	20.7
06:55	8.1	0.00	305	263	12.8	304	17.7	15.5	16.2	17.7	19.2	20.1	20.7
07:00	9.0	0.00	322	268	12.6	307	18.5	15.9	16.3	17.7	19.1	20.1	20.6
07:05	9.8	0.00	339	272	12.6	310	19.3	16.3	16.4	17.7	19.0	20.0	20.6
07:10	10.5	0.00	356	277	12.8	314	20.0	16.7	16.6	17.7	19.0	20.0	20.5
07:15	11.1	0.00	374	280	13.1	317	20.8	17.1	16.8	17.7	19.0	19.9	20.5
07:20	11.7	0.00	391	284	13.4	320	21.6	17.6	16.9	17.8	18.9	19.9	20.5
07:25	11.9	0.00	408	285	14.5	324	22.4	18.0	17.1	17.8	18.9	19.8	20.4
07:30	12.0	0.00	425	285	15.7	327	23.2	18.5	17.3	17.9	18.9	19.8	20.4
07:35	12.3	0.00	441	287	16.5	331	23.9	18.9	17.6	17.9	18.9	19.7	20.4
07:40	12.5	0.00	457	288	17.5	334	24.7	19.4	17.8	18.0	18.9	19.7	20.3
07:45	12.7	0.00	473	290	18.5	337	25.4	19.9	18.0	18.1	18.9	19.7	20.3
07:50	12.9	0.00	488	291	19.6	341	26.2	20.4	18.3	18.2	18.9	19.6	20.3
07:55	12.9	0.00	504	291	21.0	344	26.9	20.9	18.5	18.3	18.9	19.6	20.2
08:00	12.9	0.00	520	291	22.4	347	27.6	21.4	18.8	18.4	18.9	19.6	20.2
08:05	13.2	0.00	537	293	23.3	351	28.3	21.8	19.1	18.5	18.9	19.6	20.2
08:10	13.4	0.00	554	294	24.4	354	29.1	22.3	19.4	18.6	19.0	19.6	20.1
08:15	13.4	0.00	567	294	25.9	358	29.8	22.8	19.7	18.8	19.0	19.6	20.1
08:20	13.4	0.00	579	294	27.3	361	30.5	23.3	20.0	18.9	19.0	19.6	20.1
08:25	13.6	0.00	599	295	28.4	364	31.3	23.9	20.3	19.1	19.1	19.6	20.1
08:30	13.7	0.00	618	296	29.8	368	32.0	24.4	20.6	19.2	19.2	19.6	20.1
08:35	14.1	0.00	634	298	30.5	372	32.8	24.9	20.9	19.4	19.2	19.6	20.1
08:40	14.4	0.00	649	300	31.5	375	33.5	25.4	21.2	19.6	19.3	19.6	20.0
08:45	14.4	0.00	664	300	33.1	379	34.3	25.9	21.6	19.8	19.4	19.6	20.0
08:50	14.4	0.00	679	300	34.8	383	35.0	26.4	21.9	20.0	19.5	19.6	20.0
08:55	14.7	0.00	695	302	35.7	386	35.8	27.0	22.2	20.1	19.5	19.7	20.0
09:00	14.9	0.00	710	303	37.0	390	36.5	27.5	22.6	20.3	19.6	19.7	20.0
09:05	15.3	0.00	732	306	37.8	394	37.3	28.0	22.9	20.5	19.7	19.7	20.0
09:10	15.6	0.00	754	308	38.9	398	38.1	28.6	23.3	20.8	19.8	19.8	20.0
09:15	15.4	0.00	772	306	41.3	403	38.9	29.2	23.7	21.0	20.0	19.8	20.0
09:20	15.1	0.00	789	305	43.8	407	39.7	29.7	24.0	21.2	20.1	19.9	20.1
09:25	15.3	0.00	800	306	45.1	411	40.5	30.3	24.4	21.4	20.2	19.9	20.1
09:30	15.4	0.00	811	306	46.7	415	41.3	30.9	24.8	21.7	20.3	20.0	20.1
09:35	15.5	0.00	817	307	48.1	419	42.0	31.4	25.2	21.9	20.5	20.0	20.1
09:40	15.6	0.00	823	308	49.5	422	42.7	32.0	25.6	22.1	20.6	20.1	20.1
09:45	16.0	0.00	834	310	50.2	426	43.3	32.6	26.0	22.4	20.7	20.2	20.1
09:50	16.4	0.00	845	313	50.9	430	44.0	33.1	26.4	22.6	20.9	20.2	20.2
09:55	16.3	0.00	855	312	52.8	433	44.7	33.7	26.8	22.9	21.0	20.3	20.2
10:00	16.1	0.00	864	311	54.9	437	45.4	34.2	27.2	23.2	21.2	20.4	20.2

5.4 Analysis Periods

The recorded pavement surface and ambient temperatures over the three summer months of December 1988 and January and February 1989 are shown in Figure 1. Of particular interest for analysis were the periods of 3-5 December 1988 and 25-27 January 1989. Over these periods, the chipseal surface temperatures reached peaks in excess of 40°C on three successive days. (As discussed below, the surface temperatures in the AC contained instrumentation errors over this complete summer recording period.) The highest temperature recorded on the chipseal surface was 47°C on the 1 February 1989, but this peak was preceded and followed by days of relatively low temperatures.

Figure 1 **Recorded Pavement Surface Temperatures**

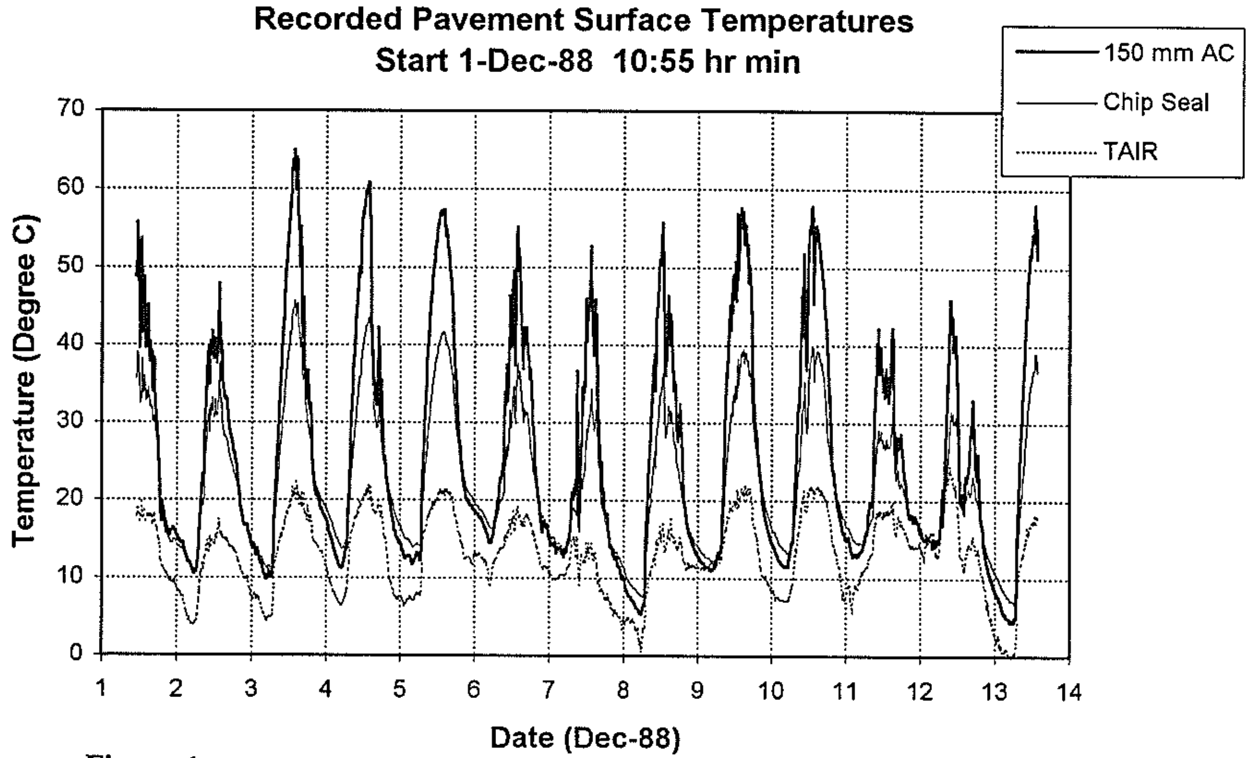


Figure 1a

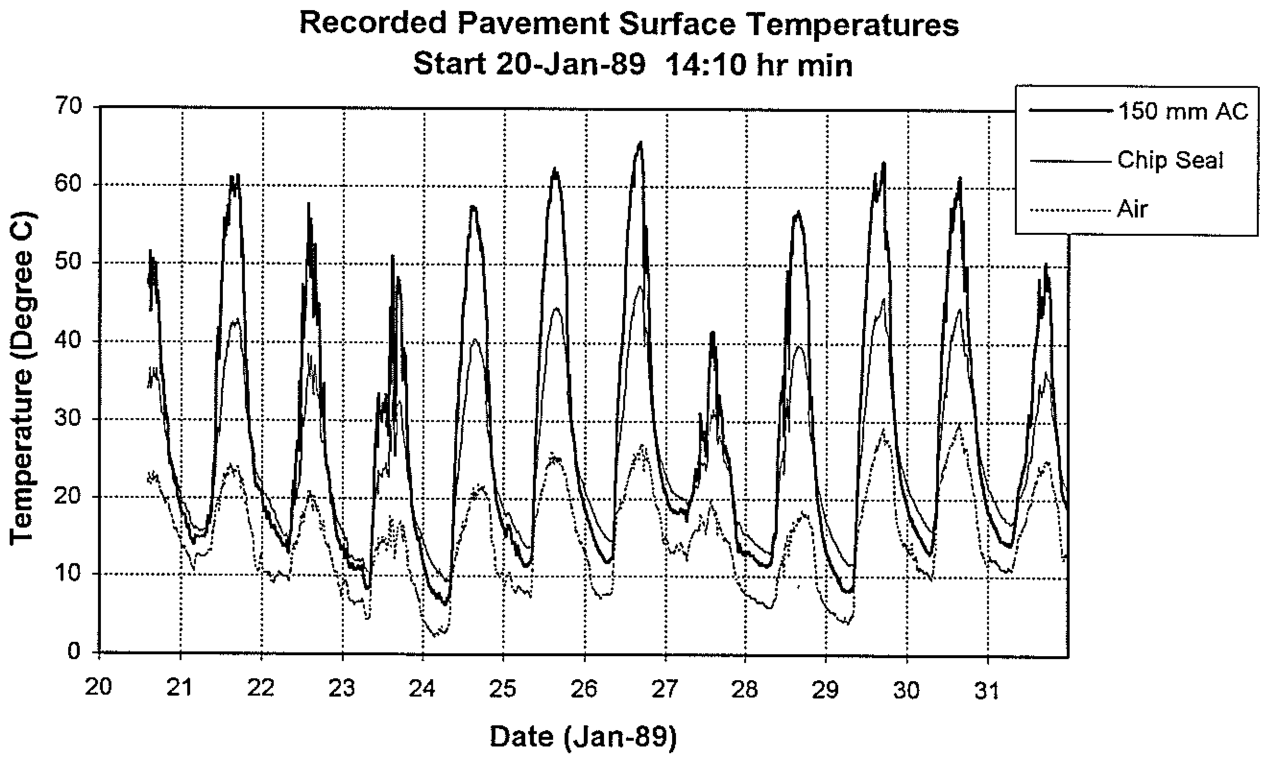


Figure 1b

Figure 1 (cont) Recorded Pavement Surface Temperatures

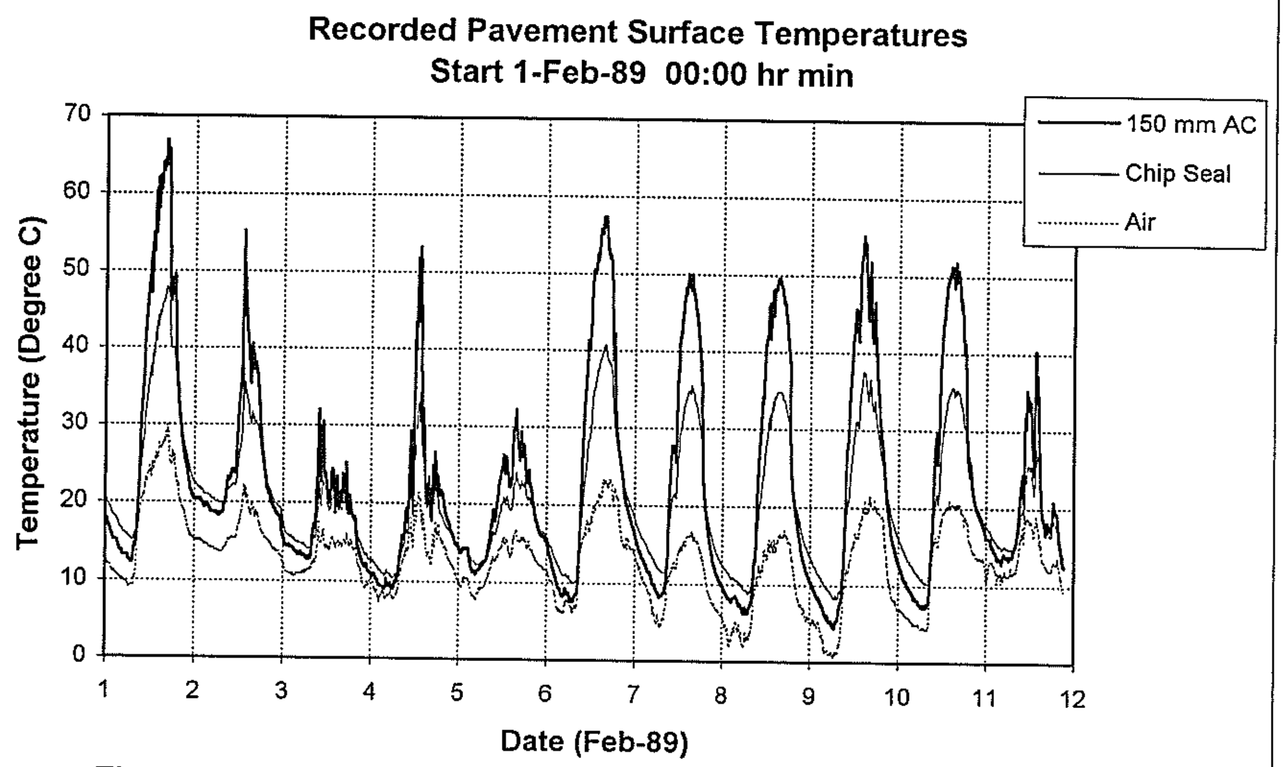


Figure 1c

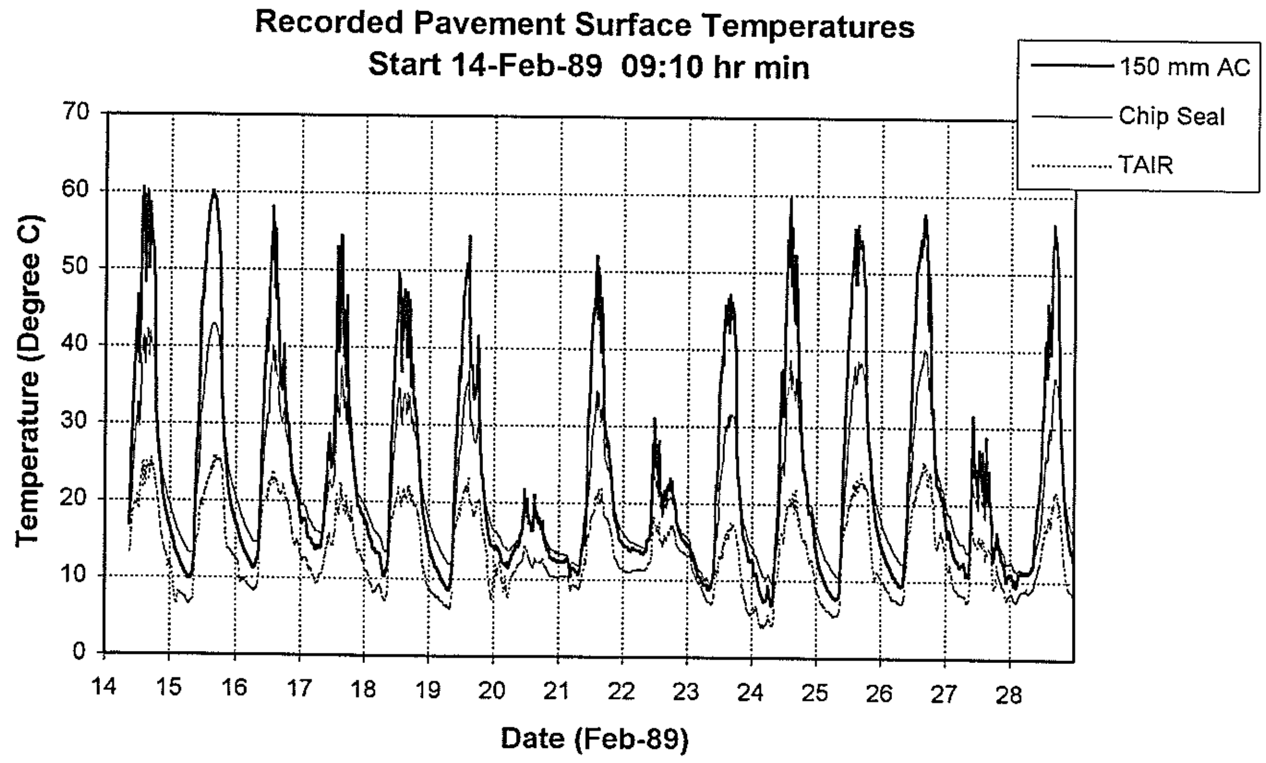


Figure 1d

Solar radiation measured during the three summer months is shown in Figure 2. As indicated by these plots, the radiation over the two periods of three days of high surface temperatures was also high, with relatively little interruption by cloud cover – particularly for the second of the two periods. (The spikes in the radiation plots are mainly due to clouds causing relatively sudden drops in the radiation reaching the pavement, but some of the high spikes reaching values greater than 1200 W/m^2 are thought to be due to an equipment malfunction.)

Figure 2 **Solar Radiation**

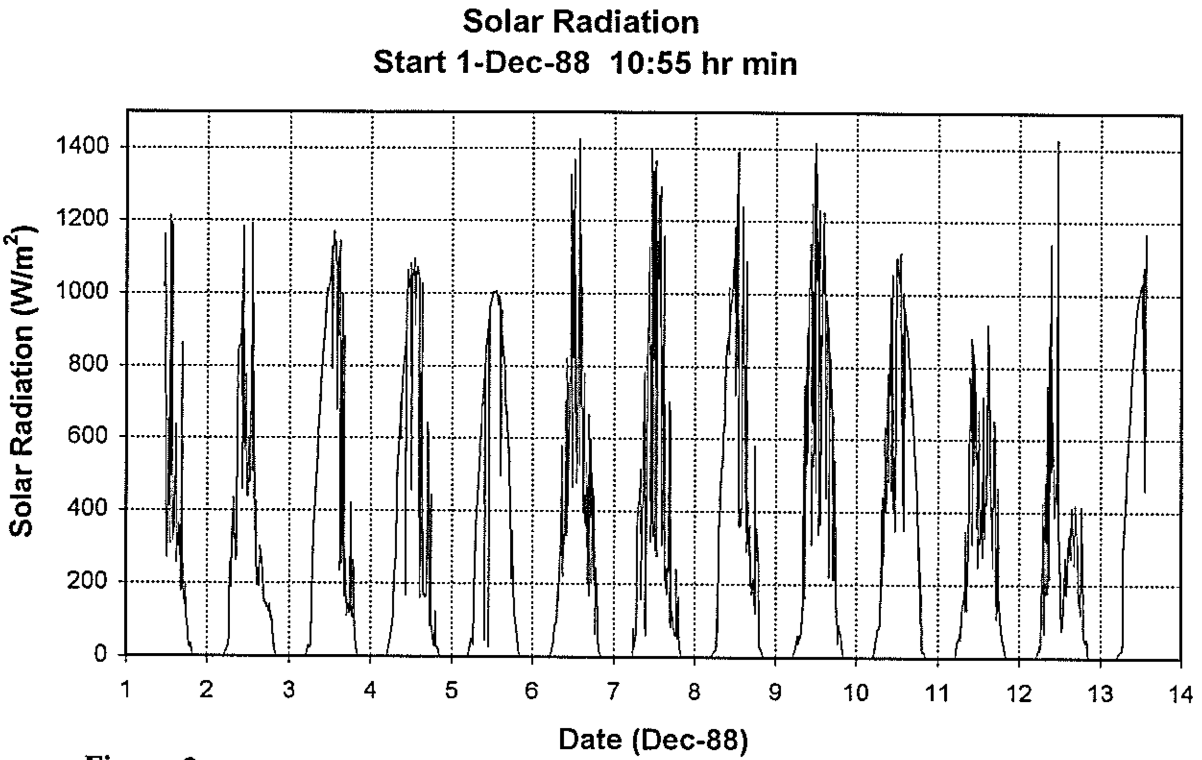


Figure 2a

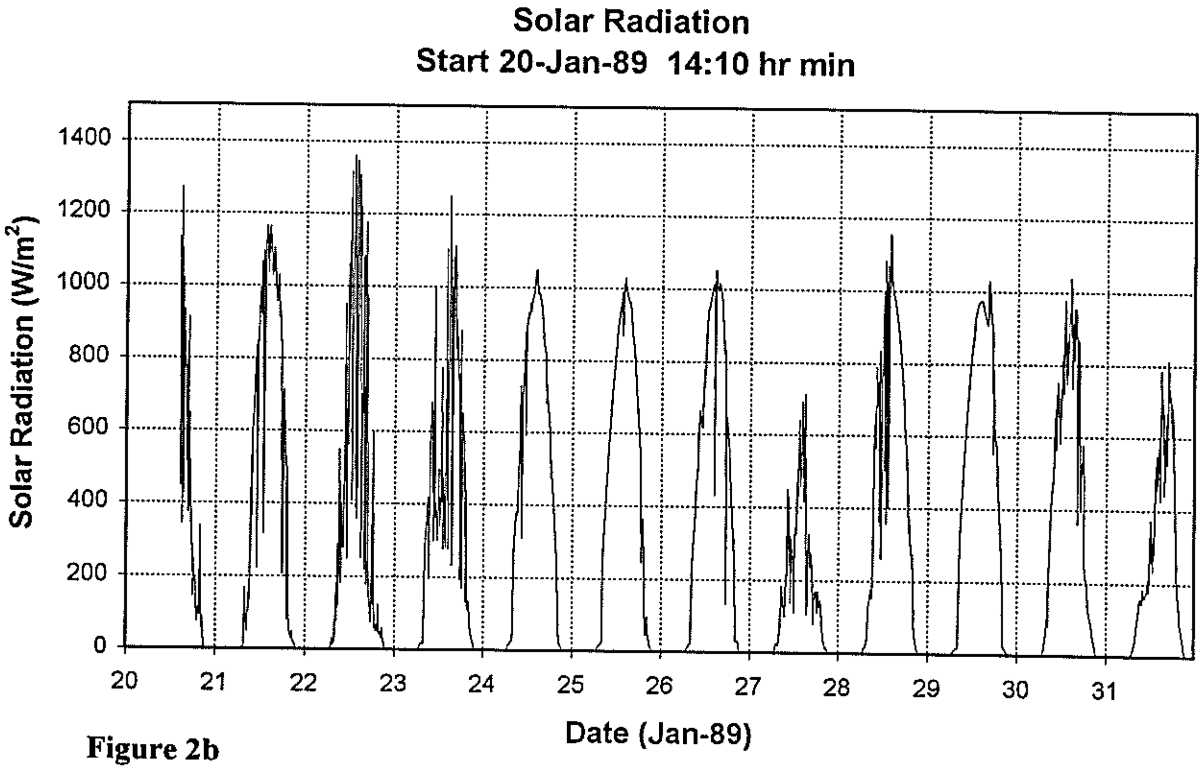


Figure 2b

Figure 2 (cont) **Solar Radiation**

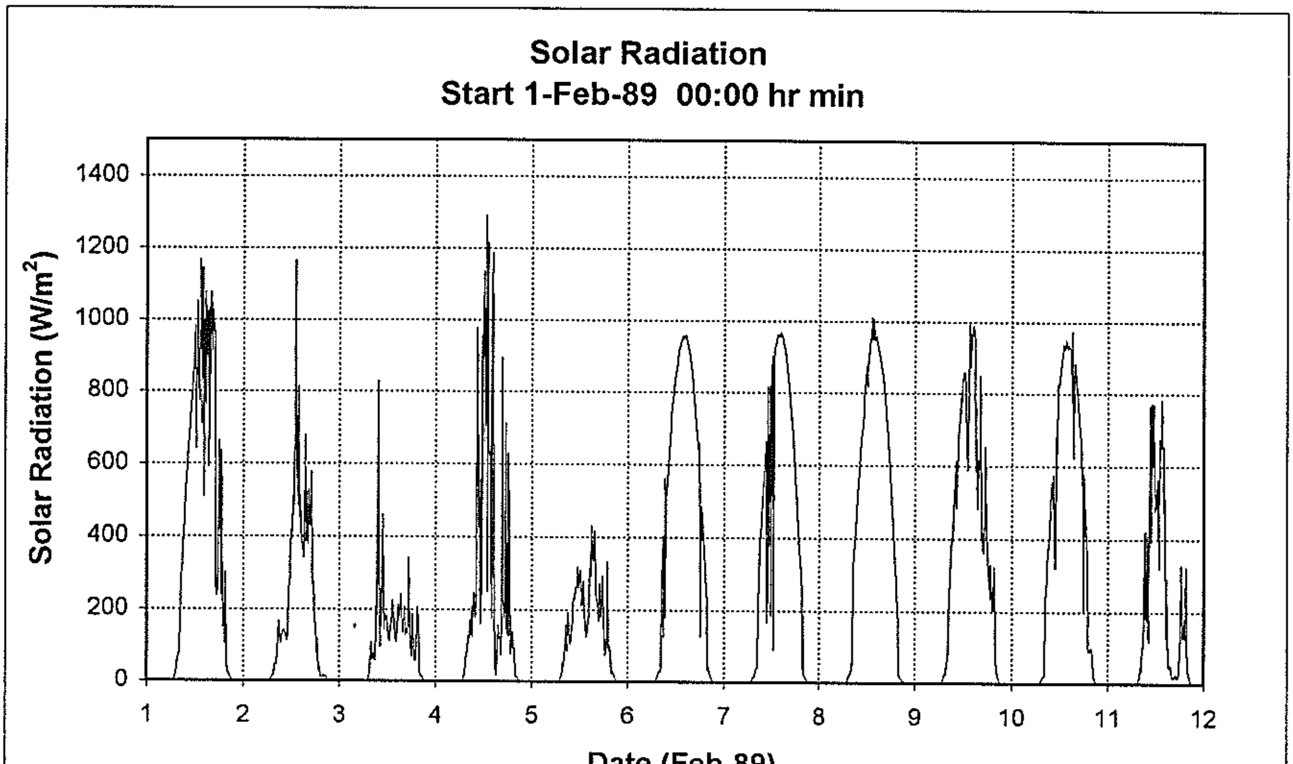


Figure 2c

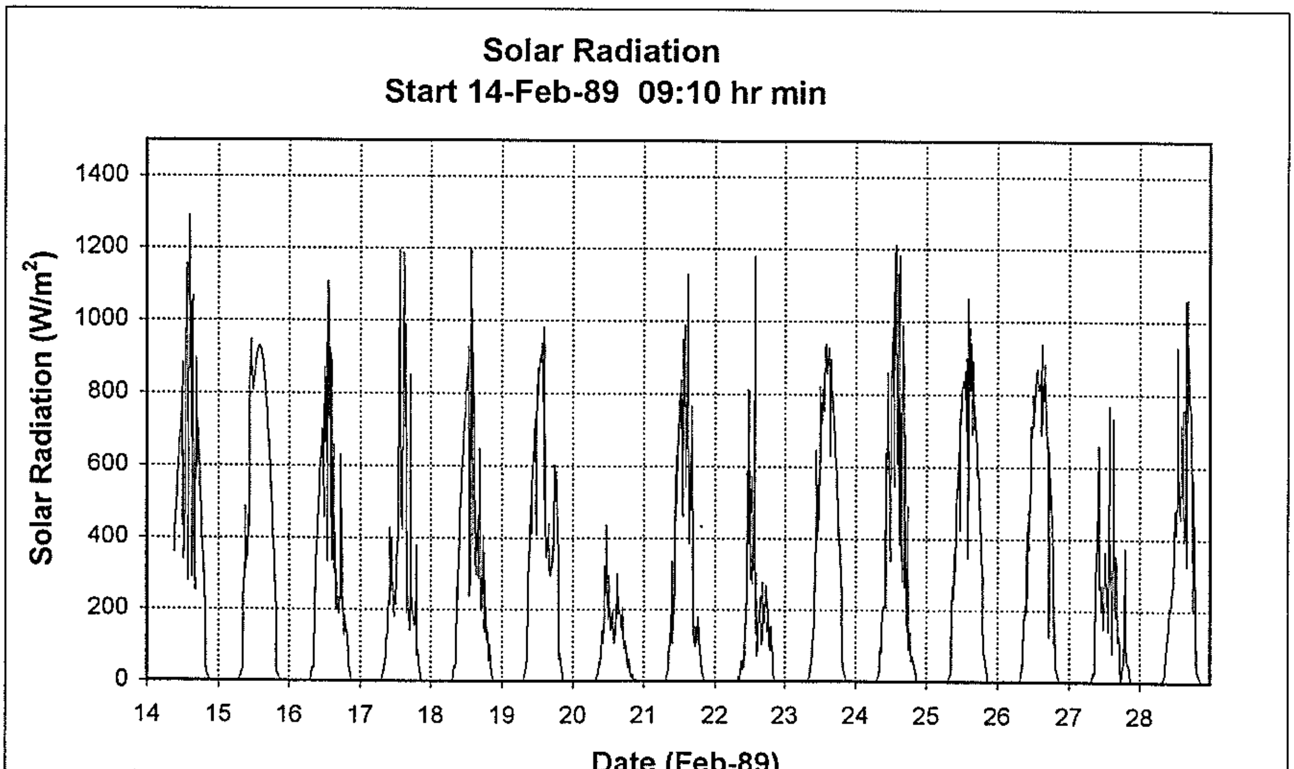


Figure 2d

In order to remove, as far as possible, the influence in the temperature predictions of the uncertainty in the wind speed and cloud cover inputs, the two sequences of three days with high surface temperatures and uninterrupted solar radiation were used for the analyses. These sequences were obviously periods of relatively clear skies and light winds and this was confirmed by inspection of the Queenstown Airport meteorological records.

5.5 Analysis Results

Comparisons between measured and calculated temperatures for the three-day period commencing at 6.00 hours on 3 December 1988 are shown in Figures 3-5 for the three different pavement types. The solar-radiation input record for this time period is shown in Figure 6 and the air temperature and wind speed records in Figure 7. The plotted wind speed is from the Queenstown Airport records.

A better prediction of the surface temperatures was obtained by increasing the Queenstown wind speeds by a factor of 2.0. This modification was used for the calculated results shown in Figures 3 to 5. Variations in wind speed between the recording site and Queenstown of this order could easily occur because of the difference in elevations and topography.

Figure 3 shows very good agreement between measured and calculated results for the chipseal. The calculated surface temperature plot is more 'jagged' than the measured plot. This is mainly caused by the recording interval of 10 minutes being too long to correctly capture the relatively rapid variations in radiation with cloud movements.

Figures 4 and 5 show reasonably good agreement between measured and recorded temperatures for the two AC pavements, with the exception of the surface temperatures. Ball (1990) reported that at some stage during the summer months of 1988, the surface thermo-couples lifted from the asphalt resulting in erroneous readings.

Measured and calculated temperature profiles for the 150 mm thick AC concrete are shown in Figure 8 for times in the middle of the day of 3 December 1988 when high temperature gradients existed in the pavement. Although the measured surface temperatures contain errors, it is apparent that the measured gradients are rather greater than the computed gradients. This suggests that the conductivity assumed for the model is perhaps too low. Some minor refinement of the thermal properties might result in better agreement.

Figure 3 **Recorded and Calculated Temperatures in Chip Seal Pavement**

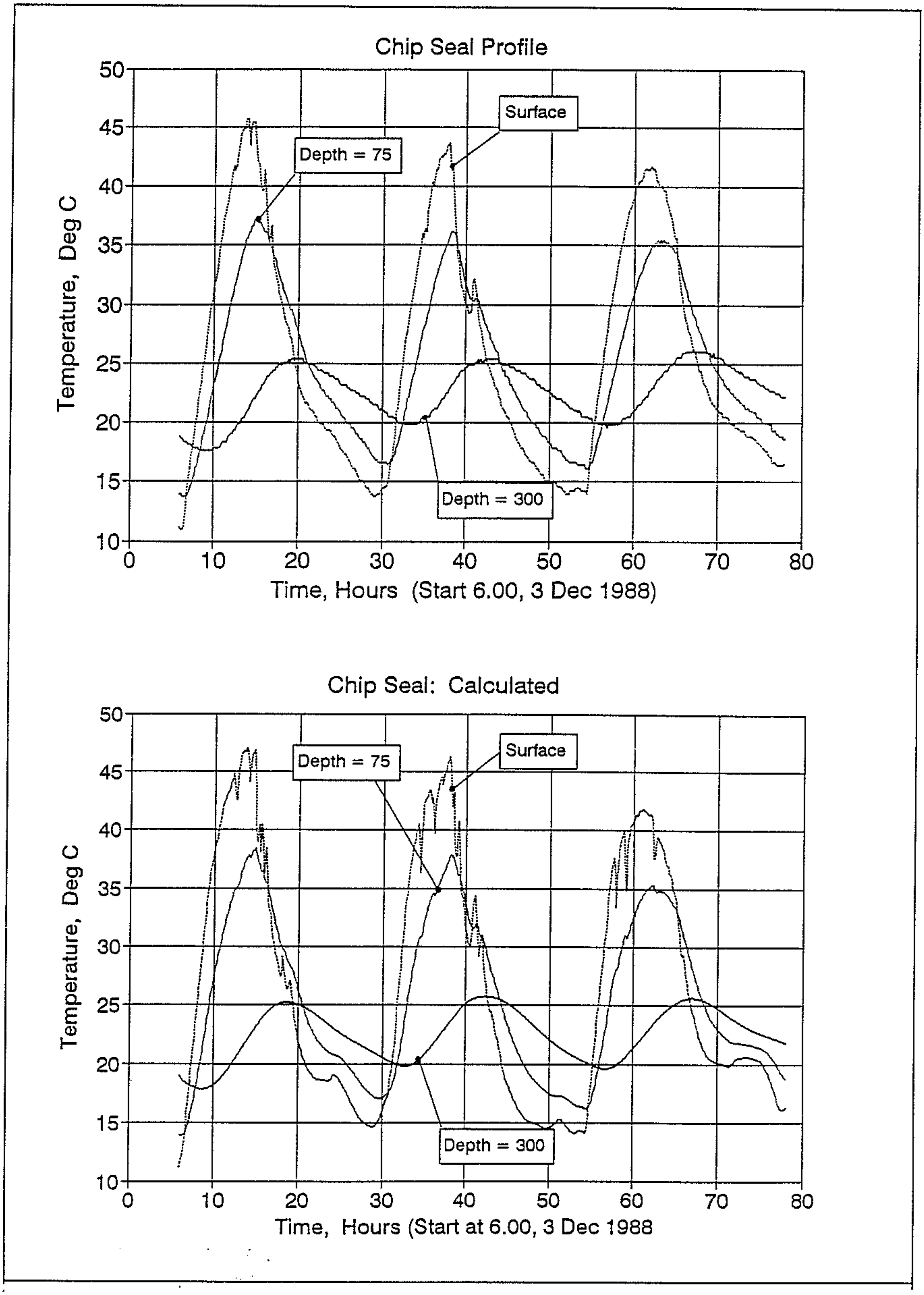


Figure 4 **Recorded and Calculated Temperatures in 50 mm Asphaltic Concrete**

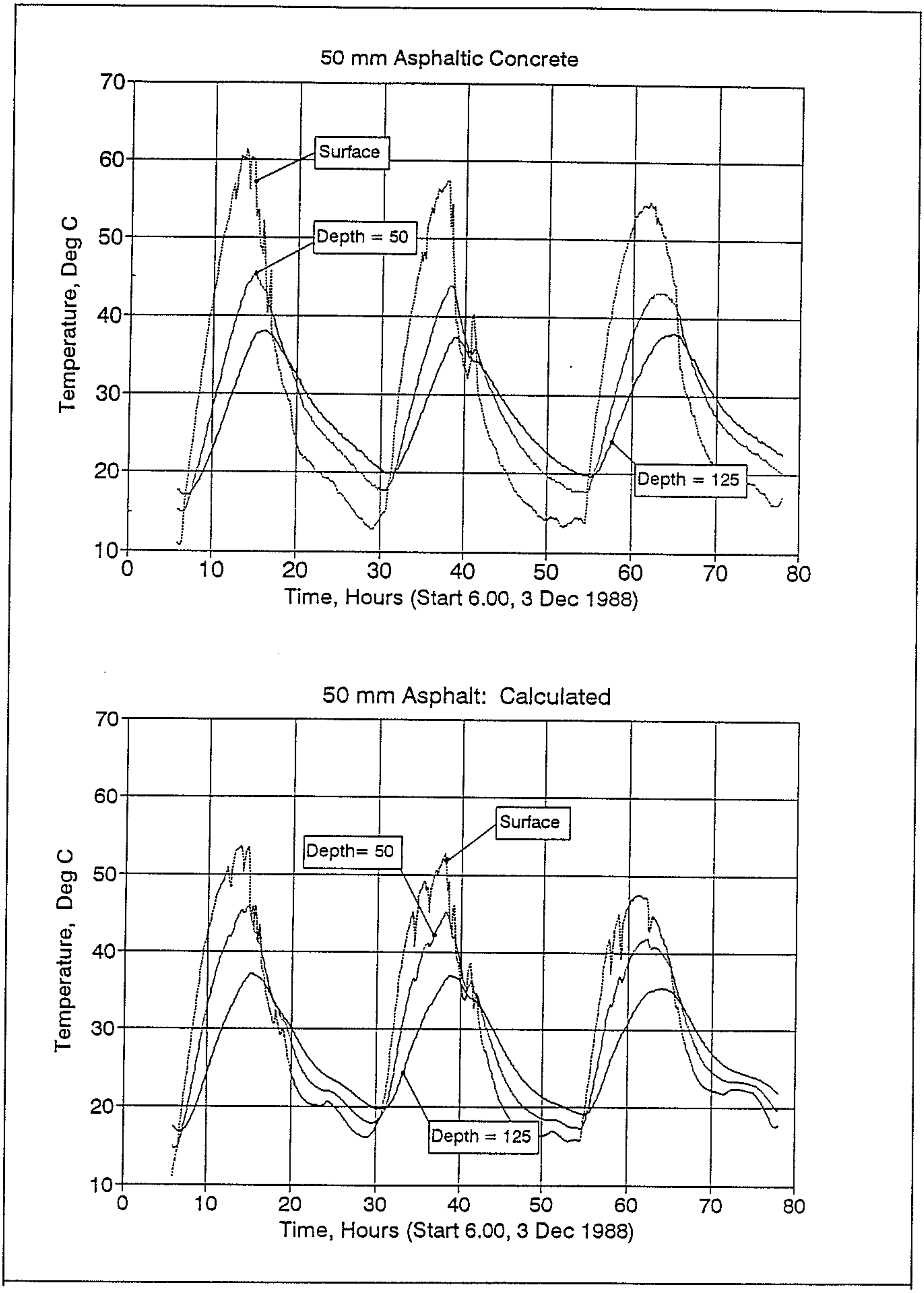


Figure 5 **Recorded and Calculated Temperatures in 150 mm Asphaltic Concrete**

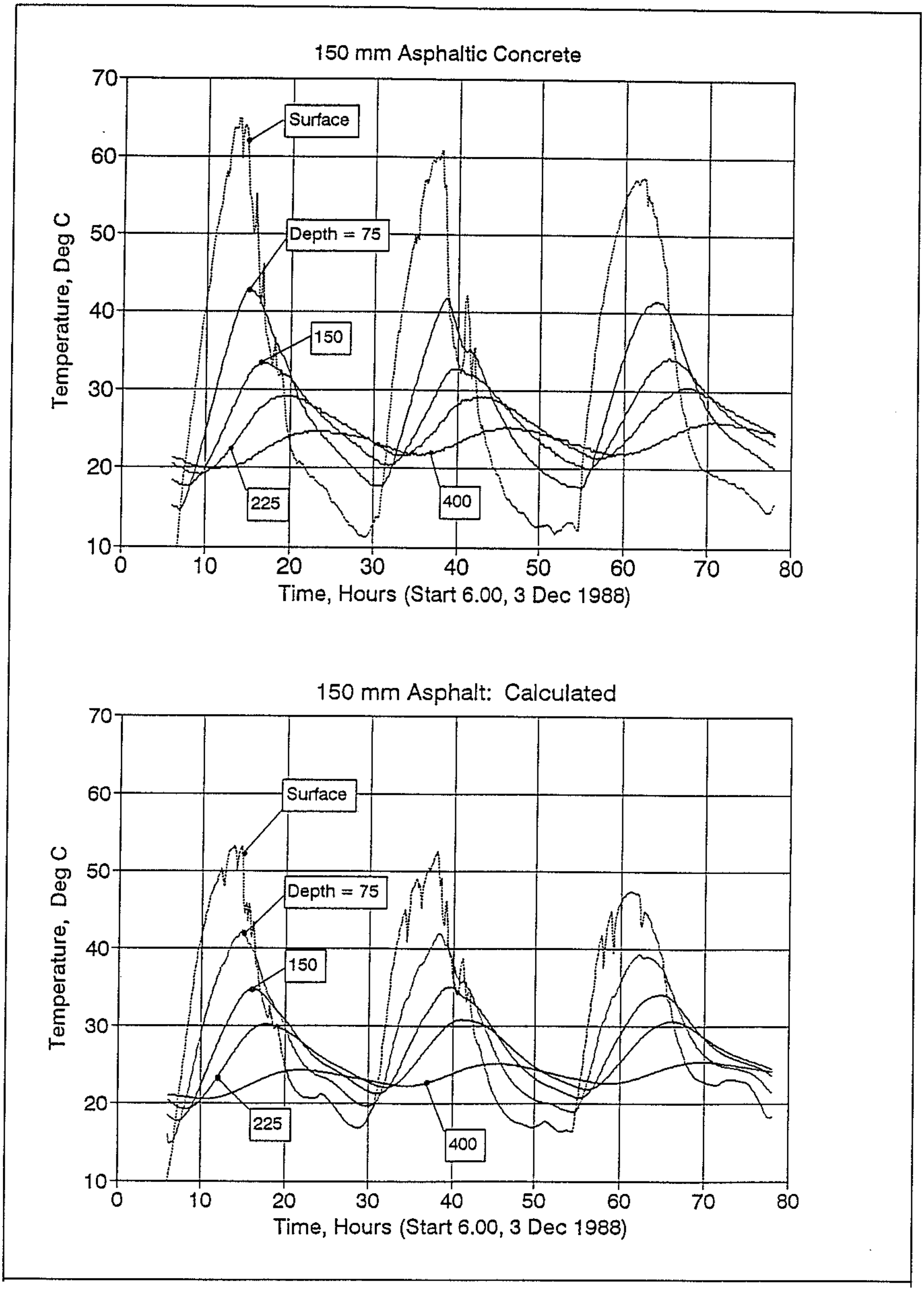


Figure 6 **Solar Radiation Input**

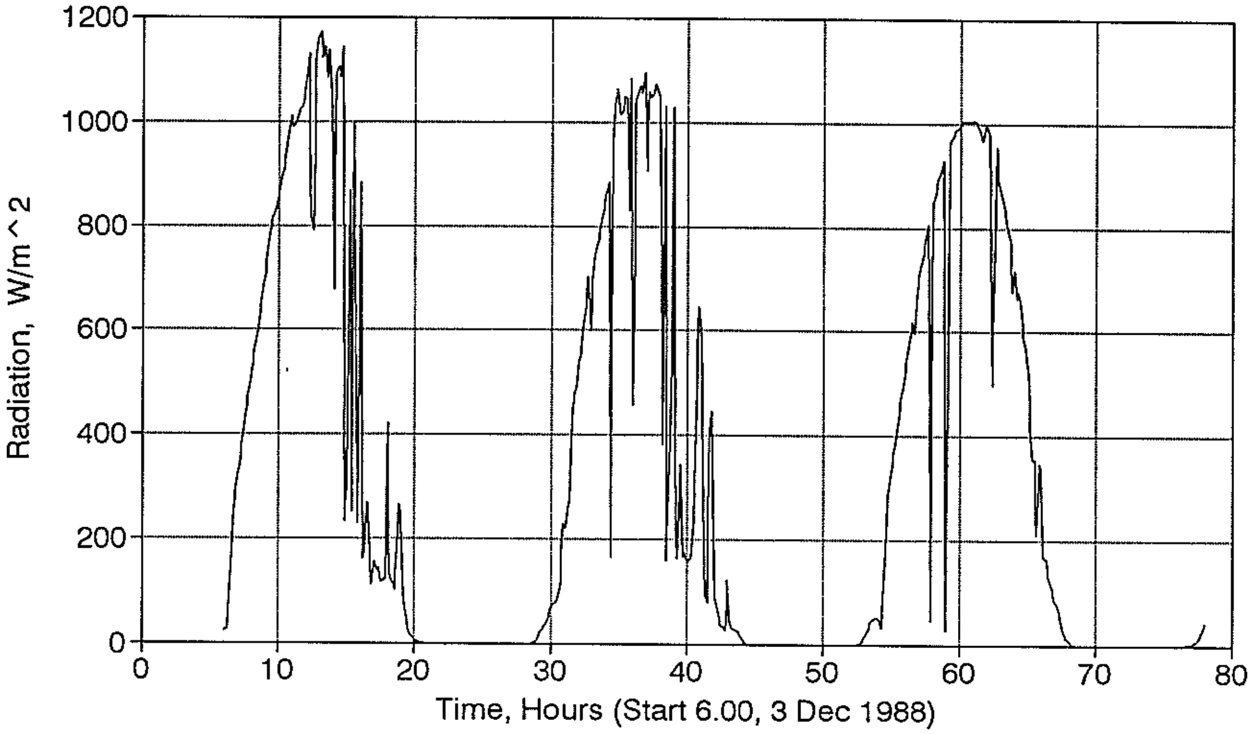


Figure 7 **Air Temperatures and Wind Speed Inputs**

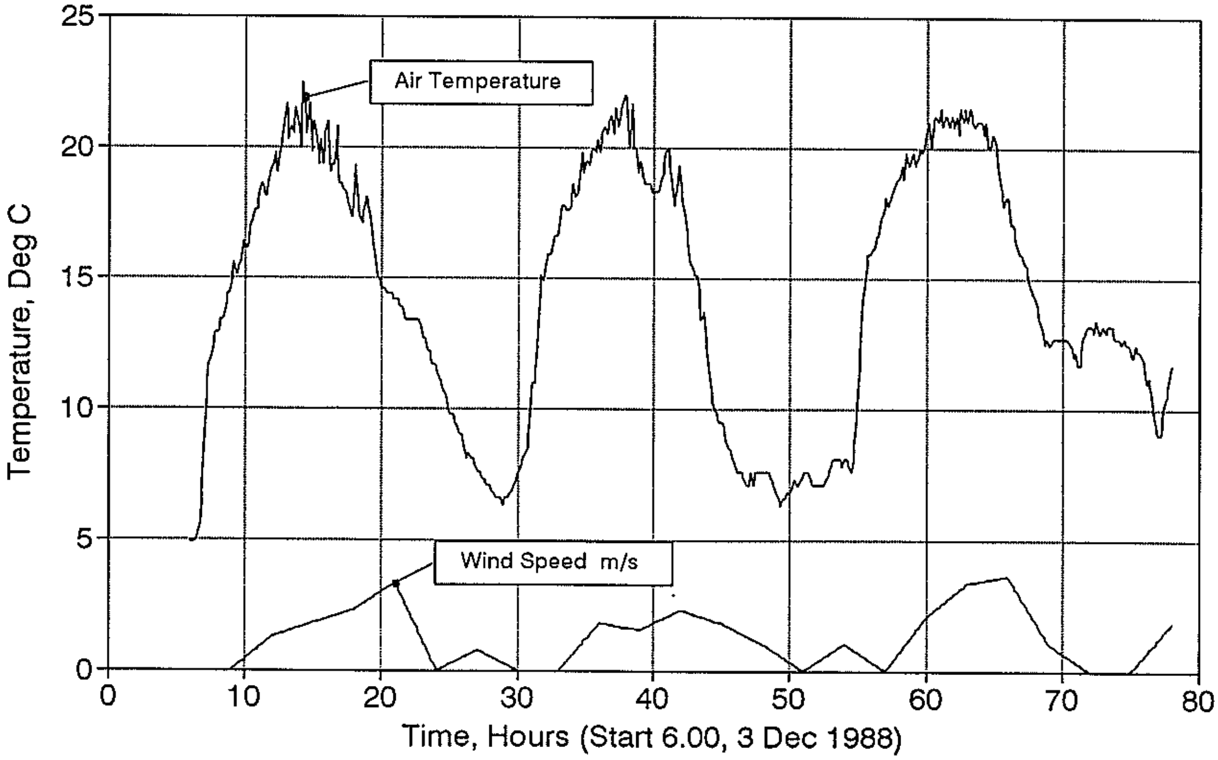
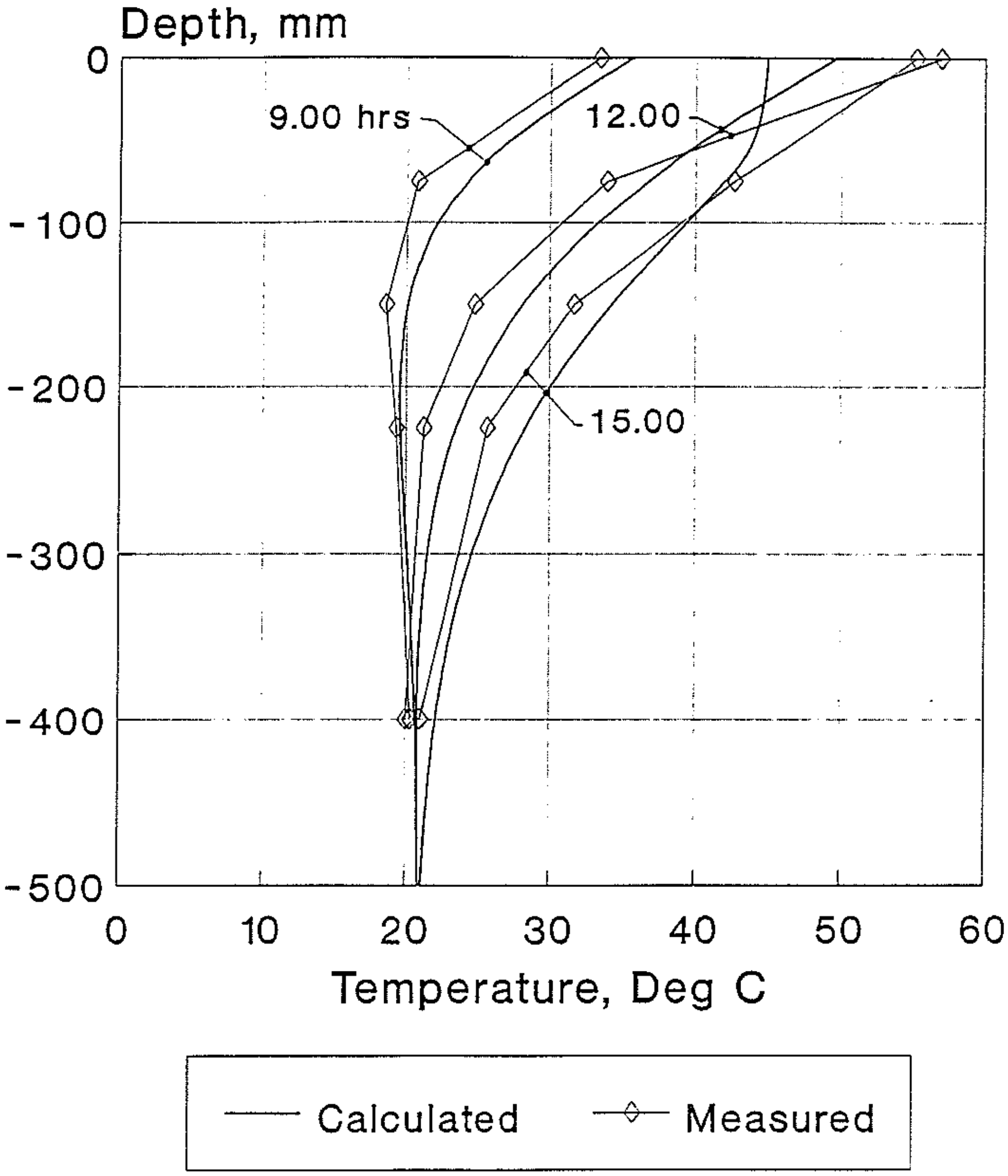


Figure 8 **Temperature Profiles in 150 mm Asphaltic Concrete (3 Dec 1988)**



5.6 Extreme Temperature Predictions

The effect of scaling the air temperature and wind speed inputs to give more extreme conditions than recorded was investigated for the 150 mm-thick asphaltic concrete pavement. Calculated results for two sets of scale factors are shown in Figures 9 and 10. Figure 9 shows the results obtained by reducing the Queenstown wind speeds by a factor of 0.5. This reduction caused a significant increase in the peak surface temperatures of about 9°C. Figure 10 shows the calculated results for the wind speed reduced by 0.5 (the same reduction used for the previous analysis) with the air temperatures scaled up by a factor of 1.3. This results in a further increase of the peak surface temperatures by about 4 °C to give a peak value close to 66 °C. The scaling of the air temperature input effectively raised the maximum air temperatures from about 22 °C to 29 °C. Changes of this order where considered to be possible under more extreme weather conditions.

A 'worst' day analysis was carried out by using the 3 December 1988 recorded meteorological inputs at Cardrona followed by a day of inputs recorded at Kelburn on 5 January 1975. This Kelburn record is thought to be one of the most extreme records, in terms of solar radiation and air temperatures, recorded in New Zealand. (Comparable radiation and temperatures probably occur reasonably frequently in some areas of New Zealand but they have not been recorded.)

The combined inputs for the two-day period of the analysis are shown in Figures 11 and 12. The Kelburn radiation was only recorded at hourly intervals, and for the purpose of the analysis, interpolation was used to give values at 300-second intervals. This resulted in some smoothing of the recorded data. The wind speeds shown in Figure 11 are the actual recorded values. For the purpose of generating more extreme conditions for the analysis, they were reduced by a factor of 0.5.

Pavement material properties for the worst day analysis were taken to be the same as used in the previous analyses (see Table 7).

Results from the 'worst' day calculations are shown in Figures 13 and 14 for the chipseal and the 50 mm AC. Peak surface temperatures reach 62 °C for the seal and 69 °C for the AC.

Figure 9 **Calculated Temperatures for Wind Speed Scaled by 0.5**

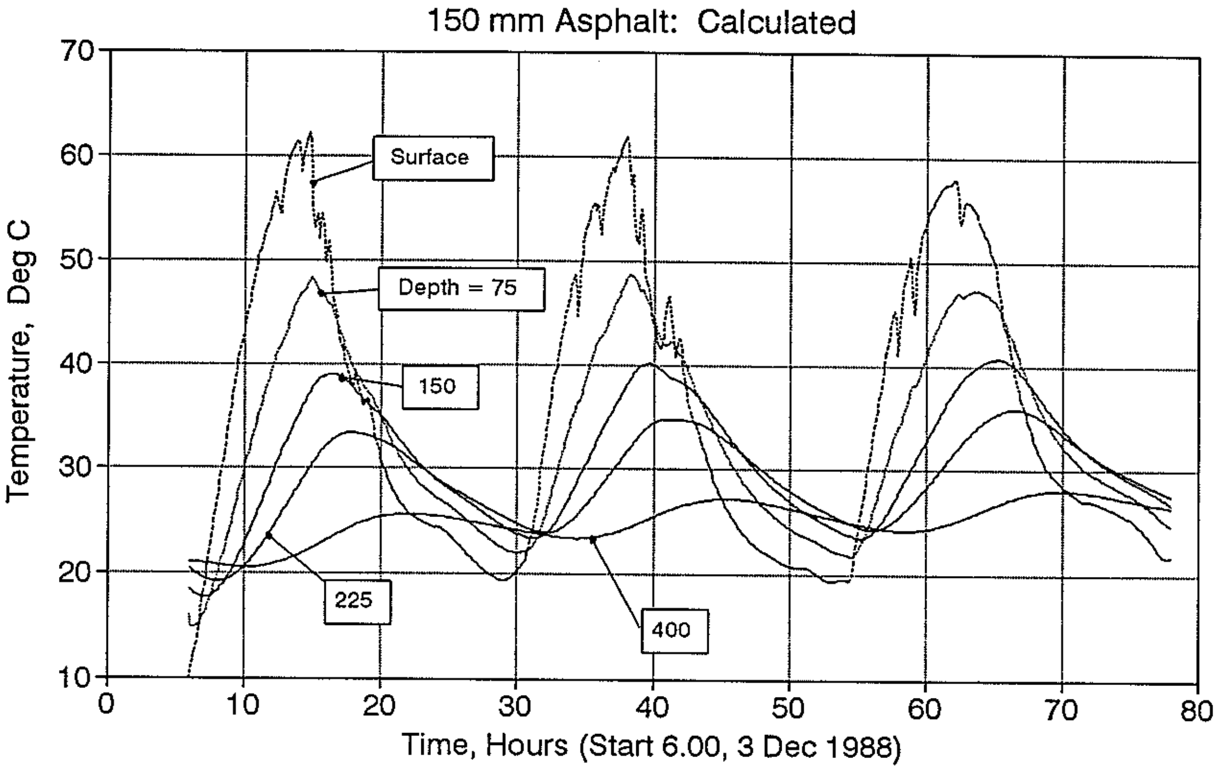


Figure 10 **Calculated Temperatures for Wind Speed Scaled by 0.5 and Air Temperatures by 1.3**

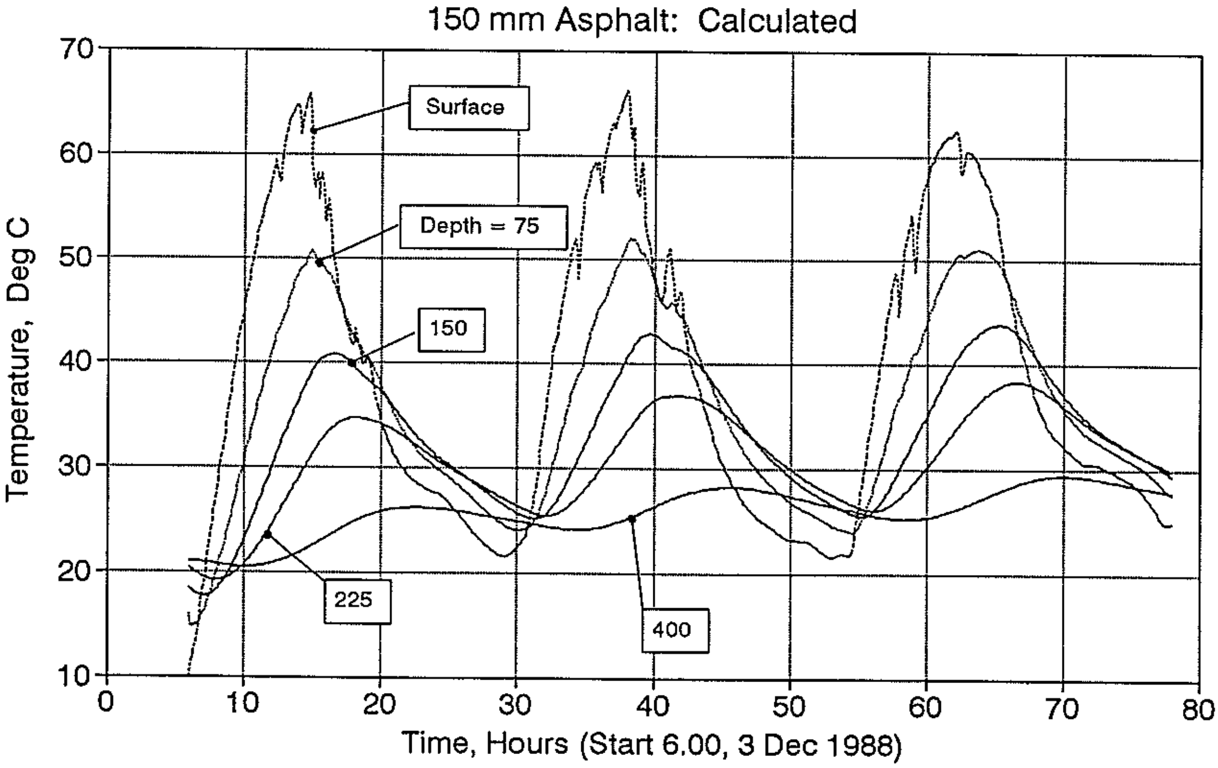


Figure 11 Solar Radiation Input for Worst Day Analysis

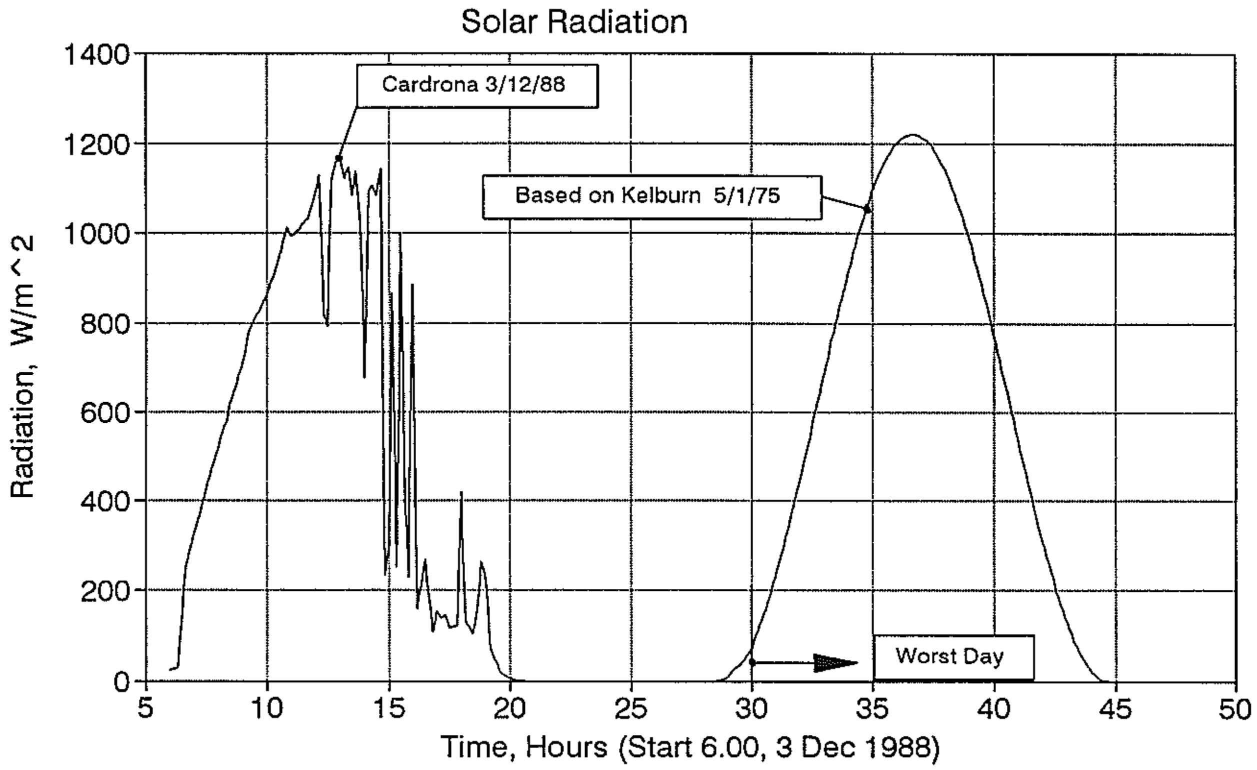


Figure 12 Air Temperature and Wind Speed Inputs for Worst Day Analysis

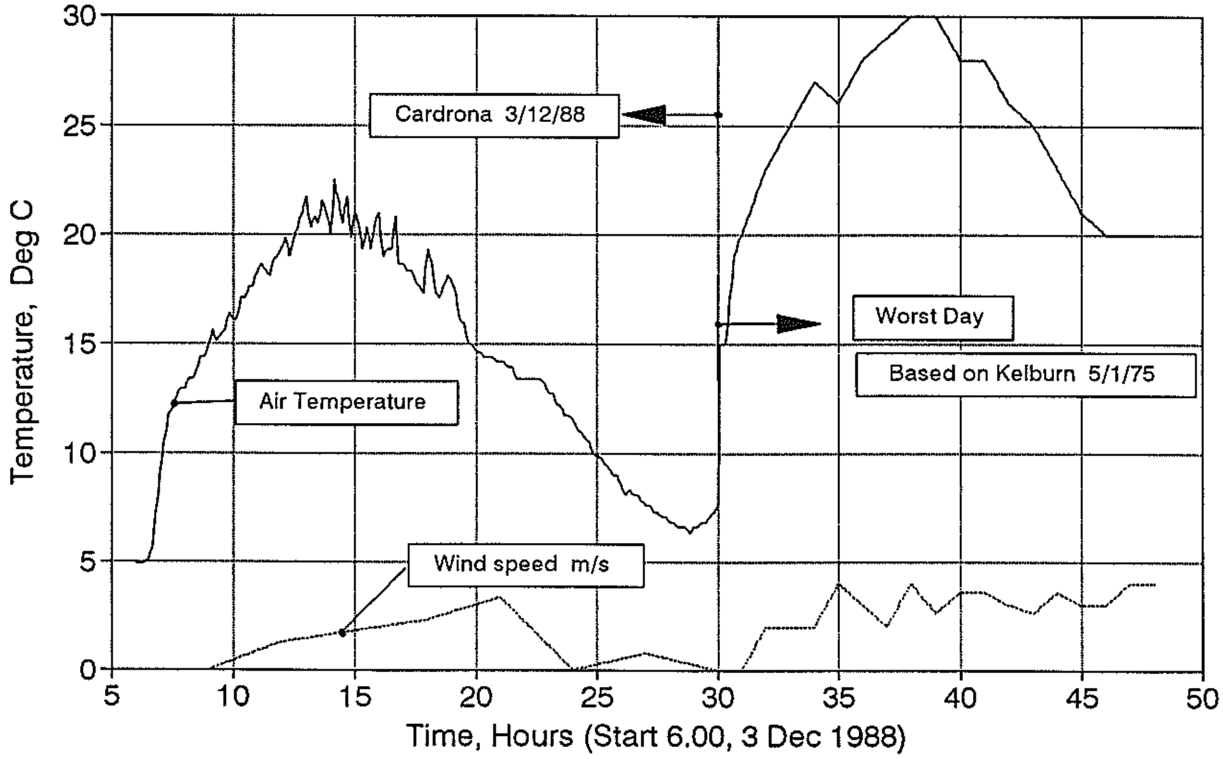


Figure 13 **Chip Seal Pavement Temperatures from Worst Day Analysis**

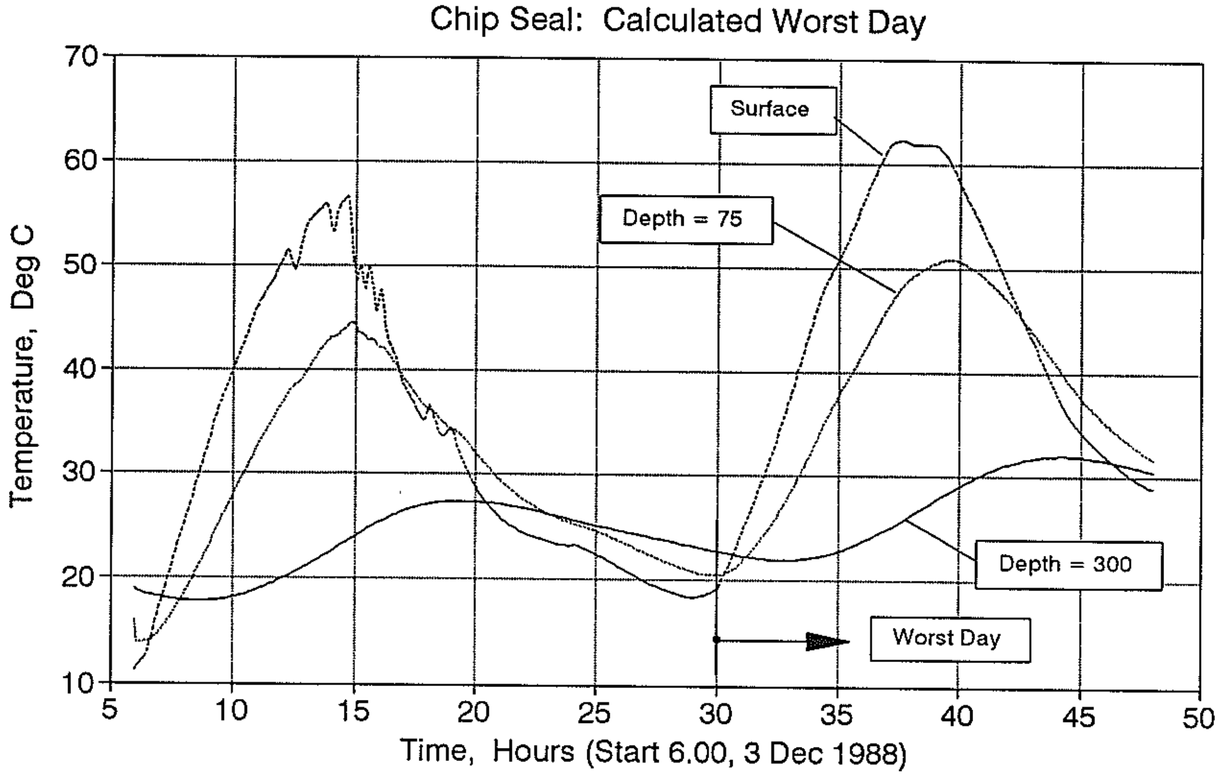
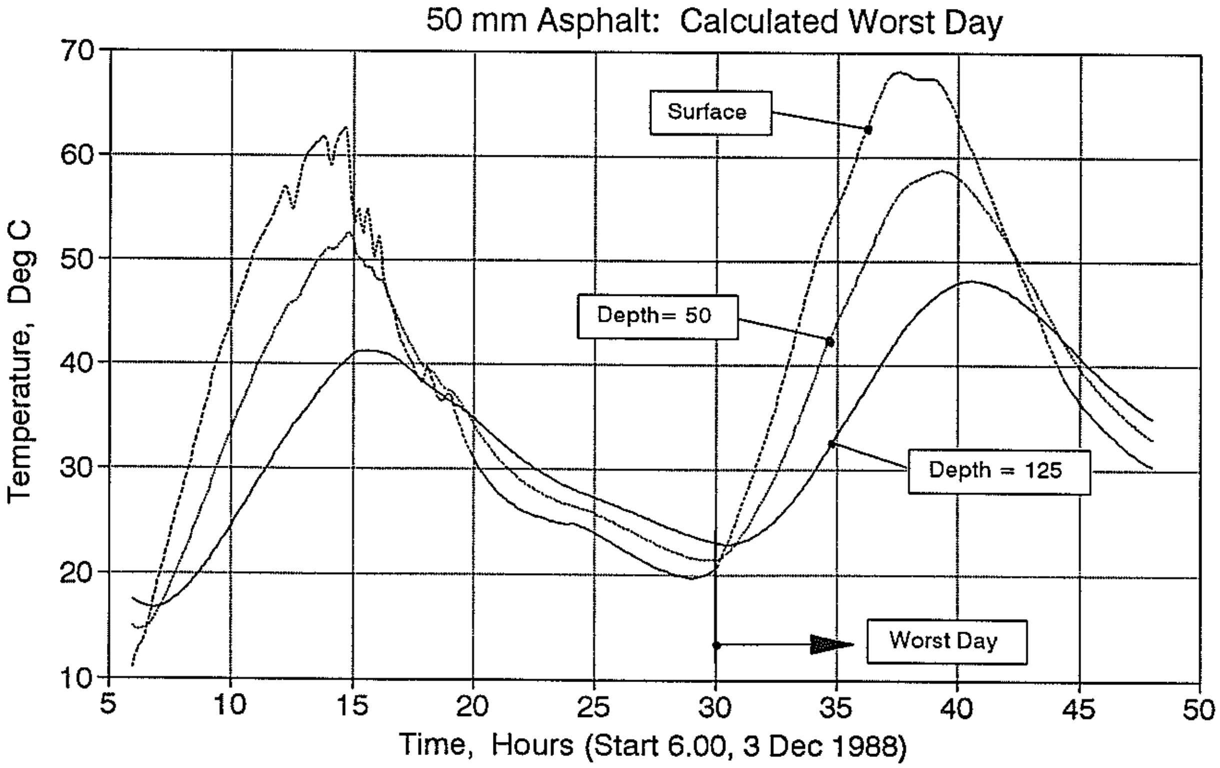


Figure 14 **50 mm Asphaltic Concrete Temperatures from Worst Day Analysis**



6. TEMPERATURE STRESSES

6.1 Pavement Model

Methods of calculating the stresses induced in the pavement materials by temperature gradients were investigated. The finite-element method was found to be the most satisfactory of the analytical options. Most of the more recently developed finite-element programs (including PC versions) have the capability of elastic temperature stress analysis. As mentioned above, the most sophisticated finite-element programs can solve both heat-transfer and temperature-stress analysis problems with the heat transfer analysis output being used directly as the input for the stress analysis.

A trial finite-element stress analysis (FEA) of a pavement section was carried out using the program MSC/NASTRAN (for windows). This program can solve both heat-transfer and temperature-stress analysis problems. However, only temperature-stress analysis was performed, as the heat-transfer module was not available at the time of the investigation.

The geometry of the two-dimensional trial section analysed is shown in Figure 15. 'Plane strain' conditions were assumed across the width of the pavement (z-direction) and displacements at the ends of the model were restrained along the horizontal axis (x-direction). In the vertical direction, the model was fixed at the base but free to expand in the vertical direction (y-direction) at the surface. These boundary restraint conditions are those normally used for the analysis of pavements of large lateral extent, and provide a good approximate to the stress conditions at locations remote from the pavement edges.

The model was chosen to represent the 150 mm-thick AC test pavement and was set up with a total depth, including the AC layer, of 500 mm. The elastic moduli of the AC layer was assumed to be a factor of two greater than the underlying soil, and Poisson's ratio was taken as 0.2 for both the AC and soil. The coefficient of linear expansion was also assumed to be the same in both materials. The analysis was undertaken for the vertical temperature profile computed for the 150 mm AC Cardrona test pad at 12.00 pm on 3 December 1988. This profile is shown in Figure 8.

Figure 15 **Finite Element Model for Pavement Temperature Stress Analysis**

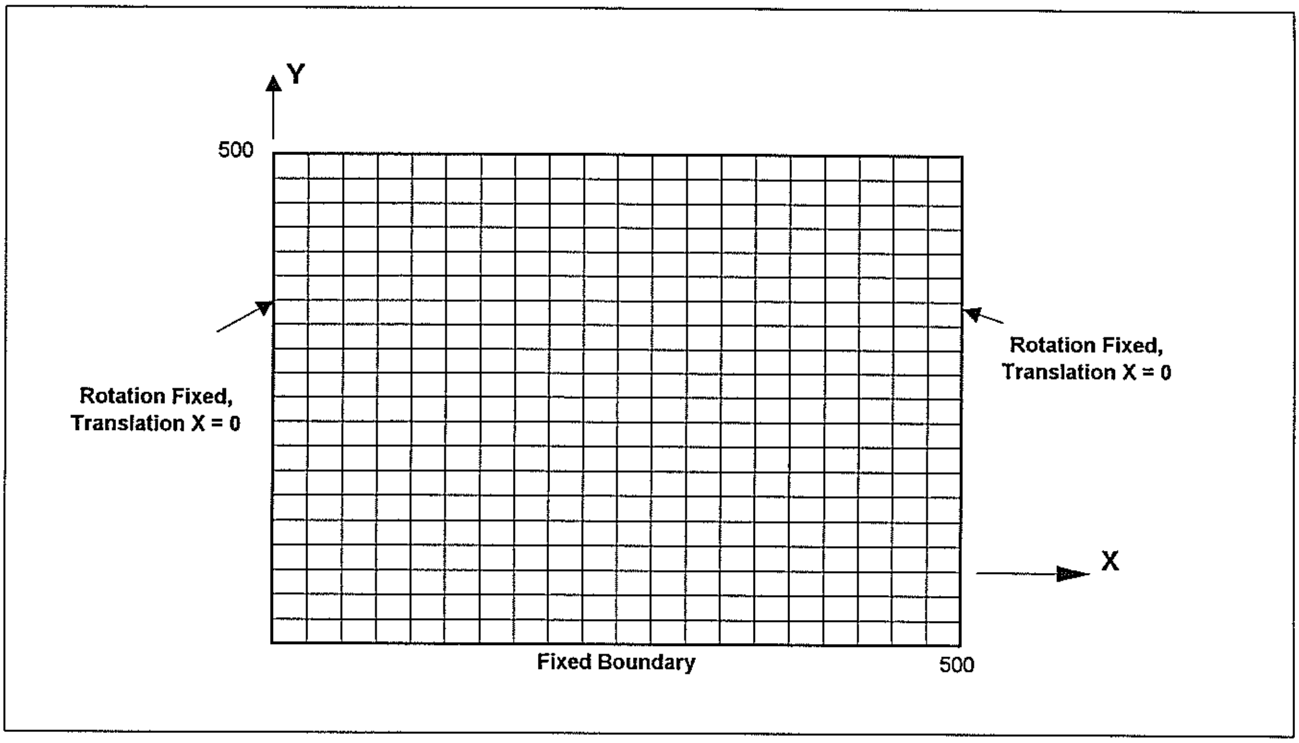
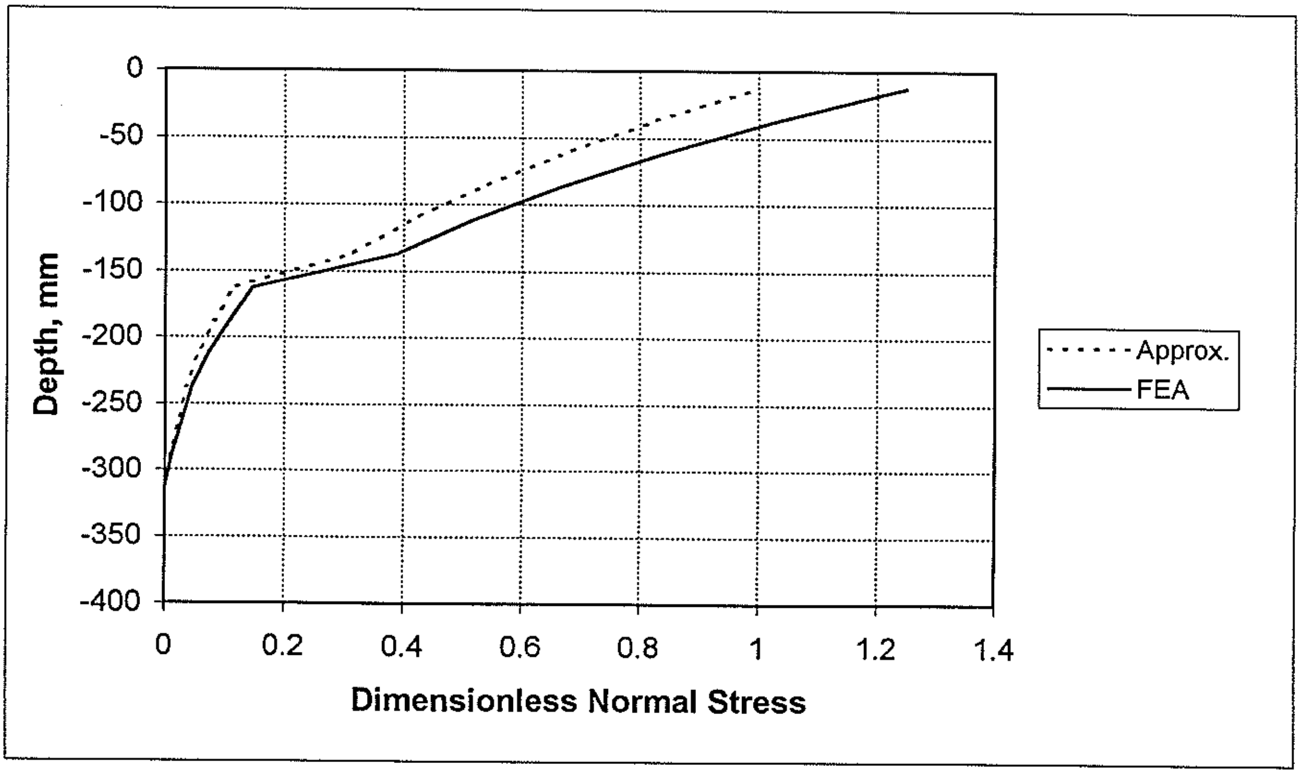


Figure 16 **Normal Stresses in 150 mm AC Pavement. (Cardrona: 3 Dec 1988 12.00 hrs temperature input)**



6.2 Stress-Analysis Results

The normal stress (x-direction) computed by the finite-element analysis (FEA) is compared in Figure 16 with the solution from an approximate analysis. The stresses are plotted in a dimensionless form to allow the computed results to be applicable for a similar model with any selected values of Young's modulus and coefficient of linear expansion. (Strictly speaking, the results are only valid when the elastic moduli for the AC are a factor of two greater than in the soil layers, Poisson's ratio = 0.2 in both materials, and both materials have the same coefficient of linear expansion.) The actual normal stress, σ_x, is determined from the plotted dimensionless value using:

$$\sigma_x = \hat{\sigma}.E.\alpha.\Delta T_1 \qquad \text{(Equation 11)}$$

Where:

$\hat{\sigma}$ = plotted dimensionless stress
E = Young's modulus for AC layer
α = coefficient of linear expansion
ΔT_1 = temperature rise on the AC surface

The approximate stress solution shown in Figure 16 was obtained by assuming that the AC and soil layers can be sub-divided horizontally into layers of constant temperature, with each layer acting independently of the other layers. That is, no shear stresses are transmitted between the adjacent surfaces of the layers. This approximation gives normal stresses that are about 25% lower than the more exact FEA results.

Results from the stress analyses show that the stresses produced by high surface temperatures, in the absence of other loading, are unlikely to cause pavement distress. For typical gradients with the surface hotter than the underlying layers, the pavement (remote from the edges) is stressed into moderate levels of compression. However, when a 'negative' temperature gradient develops in cold surface conditions, the normal stresses at the surface will be tensile, and this may lead to cracking damage.

7. RECOMMENDED PAVEMENT TEMPERATURE MODEL

Work undertaken on the analysis of recorded temperatures at four sites in New Zealand and the correlation of these temperature histories with meteorological records is described in Part II of this report. This study demonstrated that in most areas of New Zealand, pavement temperature regimes can be predicted using correlation equations between pavement temperatures and available meteorological parameters, or by using the measured results directly. Both the temperature recording and pavement model computational studies have shown that the temperatures are not very sensitive to the pavement thickness or the thermal properties of the layers below the pavement-wearing surface.

As indicated by the summaries of the material thermal properties presented in Sections 4.1 and 5.2, the thermal properties of most materials likely to be used in pavement construction are quite similar and have reasonably limited ranges of values. Thus wide variations from the presently available temperature information would not be expected from types of pavement different in depth and composition from those investigated.

For special pavement studies, or in locations with more extreme meteorological conditions than previously investigated, it is recommended that the one-dimensional finite-difference model described in Sections 4.3 and 5.3 be used. Material properties can be obtained from the summaries of information given above. Metrological records of solar radiation, ambient temperature, cloud cover and wind speed are required as inputs. These can be obtained from the nearest meteorological station. If 'worst day' temperatures are to be computed, only extreme radiation and temperature records are required as inputs, and the values used in the analyses described in Section 5.6 are likely to be appropriate.

8. CONCLUSIONS

1. Pavement temperatures recorded at Cardrona were not particularly extreme, with the peak temperature on the surface of the chipseal reaching a moderately-high value of 47 °C. Although the surface AC peaks were not reliably recorded, the model computations showed that these would have peaked at about 55 °C. By comparison, a 'worst day' analysis indicated possible peaks of 62 °C and 69 °C on the seal and AC respectively.

2. Inspection of the Queenstown meteorological records showed that during December 1988 and February 1989, the sunshine hours were significantly higher than the average. However, there were less sunshine hours in January 1989 than average. Mean daily maximum and mean temperatures were higher than average in all three months. Overall, it appeared that the recording year was reasonably representative of average meteorological conditions.

   Because of the relatively high elevation of Cardrona, temperatures are lower and wind speeds are probably higher than in lower more sheltered areas. It would therefore appear that the records obtained do not represent summer extremes that might occur in some inland locations.

3. The records and calculated results clearly show that pavement temperatures are very sensitive to the amount of daily solar radiation absorbed through the surface as well as the wind speed, which affects the degree of convective cooling. Further work is being undertaken to determine whether useful information on the relative frequency of the combination of high solar radiation and low wind speeds can be obtained from the meteorological records at the main recording stations. If useful data can be extracted, it might be informative to compare it with the pavement temperature frequency distributions recorded at the four test sites.

4. Pavement temperatures can be readily computed using simple finite-difference schemes set up on a spreadsheet. Alternatively the more sophisticated of the finite-element programs available may be used, but modelling the heat transfer conditions on the pavement surface may limit the applicability of some programs. Because of uncertainty in the thermal properties of the pavement materials and the lack of precision in the mathematical description of the surface heat transfer, it is difficult to make accurate predictions of the pavement temperature regime. However, by calibrating the computer models against site measurements it was found that temperatures could be computed to sufficient accuracy for pavement design applications.

5. To reliably predict temperature-induced stresses in pavements it is necessary to use finite-element methods. Computer programs are available that enable stress analysis to be conveniently and rapidly undertaken on a PC.

6. High surface temperatures are unlikely to produce critical stress conditions in most pavements but may need to be considered in combination with other pavement loads. Under cold conditions, tensile stresses may develop leading to crack development.

7. In most areas of New Zealand, pavement temperature regimes can be predicted using the correlation equations developed for predicting pavement temperatures from available meteorological parameters, or by using the measured results directly. For special pavement studies, or in locations with more extreme meteorological conditions than previously investigated, the simple one-dimensional finite-difference model can be used.

PART 11: ANALYSIS OF TEMPERATURE MEASUREMENTS

1. REVIEW OF RECORDED TEMPERATURE DATA

The construction procedure for the test pads at all four sites was similar and is described by McQueen (1985) in his report on the Dunedin pavement temperature investigation. The pads for the three different pavement surfaces were each three metres square. To form the three pads, an area of 9.5 m x 3.5 m was excavated to a depth of 400 mm below ground level. A 200 mm thickness of 65 AP sub-base was compacted in 100 mm lifts, with the upper 200 mm formed from M/4 or M/5 basecourse and the paving surface as shown in Figure 1. The temperatures were monitored at various depths with copper-constantan thermocouple probes (Honeywell Type PS050) inserted at the depths indicated in Figure 1, and a Pacific datalogger (manufactured by Solid State Equipment of Gracefield, Lower Hutt).

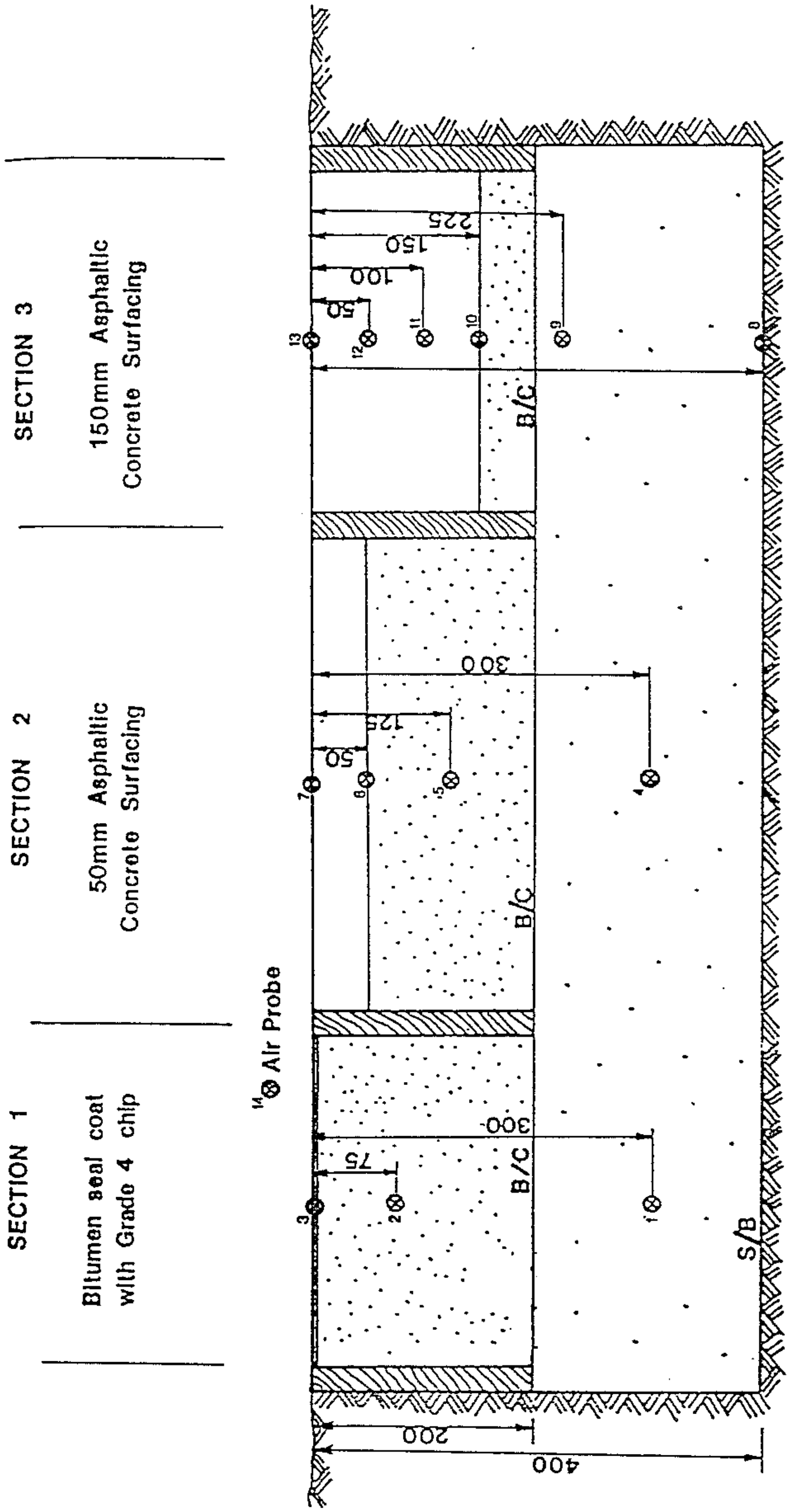
A summary of the temperature recording periods at the four sites is given in Table 1 below.

Table 1 Summary of Pavement Temperature Records

Location	Start Month	End Month	Record Length Days
Dunedin Airport	Oct 1981	Sep 1992	365
Blenheim	Mar 1983	Feb 1984	356
Napier	Dec 1984	Nov 1985	365
Cardrona	Apr 1988	Apr 1989	261

Difficulties were experienced with the logging equipment used in the Cardrona investigation, resulting in the capture of only about 71% of the available time during the recording year.

Figure 1 **Test Site Sections and Probe Locations**



1.1 Results from Dunedin Airport

The three test pads for the Dunedin project were constructed on Dunedin Airport about 10 m from the southern end of the tarmac adjacent to the crash fire road. The airport is located near State Highway 1 about 30 km to the south of central Dunedin. The site is in an open level area free from traffic, shadows or wind sheltering effects. Meteorological records are maintained at both Dunedin Airport and Dunedin City.

McQueen (1985) reported on the records from the Dunedin Airport investigation presenting the main results in the following form:

1. Plots of the daily variation of the pavement temperatures on a hot day with no cloud cover and little wind.

2. A table of the daily maximum and minimum temperatures for a period of one year.

3. A table of the monthly means of the daily maximum and minimum temperatures.

4. A plot of all pavement temperatures over the month of November 1981.

5. Histograms of the temperature distribution (6 °C intervals) with time, expressed as a percent of a year, generated for the probe on the surface of the chipseal and at 50 mm depth in the 150 mm thick AC pavement. These were plotted for both the summer months (November-February, inclusive) and the whole year.

6. Plots of the temperature gradients on the hottest and coldest day in the period of the temperature recording.

7. A plot showing the variation of the temperature gradients in the 150 mm AC pavement during the hottest day.

8. The number of days where the difference between maximum and minimum daily temperature of greater than (a) 35° C or (b) 30° C occurred at the surface of the chipseal pavement.

9. A correlation function between the daily maximum air temperature and the daily maximum surface temperature of the chipseal.

10. Features of the meteorological records. This included histograms for monthly periods showing sunshine hours, days with significant rainfall, days with ground frost and days with wind above Beaufort 4.

1.2 Blenheim Data Records

The three test pads for the Blenheim project were constructed near State Highway 6 adjacent to Woodbourne Airbase, about 7 km west of Blenheim. The trial site is approximately at latitude 41° 30' 30" S, longitude 173 ° 51' E, and is on the north side of State Highway 6. The nearest meteorological stations are those at Blenheim Airport (41° 30' S, 173 ° 48' E) and Blenheim (41 ° 30' S, 173 ° 54' E).

The site is surrounded by the highway and farmland and is very open, being near the centre of a wide flat valley. Although there are hills rising from the valley floor some kilometres from the site, the total insolation received and wind speeds did not appear to be significantly altered by topographic features. The site was free of significant shadows from structures and trees. The meteorological conditions at the site were thought to be well represented by the records obtained at Blenheim and Blenheim Airport which are also in areas largely uninfluenced by topographical features.

After the monitoring was completed, Opus Central Laboratories read the data cassettes and commented on the suitability of the data for analysis. Temperature data were successfully recorded for the greater part of the period 18 February 1983-16 April 1984. Details of the recording tapes and information on sections of data lost are given in a report by Ball (1987).

Some corrections were made to the records prior to their use in the present project. Summertime recordings were changed to standard time. A number of anomalous short-term signals were edited out of the data. An anomalous increase in all temperature readings of approximately 4° C took place on 7 April 1983, and remained present for the rest of the recording period. Its cause was unknown and the data was corrected by subtracting 4° C from each subsequent reading.

1.3 Results from Napier

The test pads for the Napier investigations were constructed on the site of the District Laboratory of the former Ministry of Works and Development on Taradale Road about 4 km to the west of central Napier at latitude 39° 30' S and longitude 176° 52' E. The site is level and the topography flat for some kilometres in the surrounding area. There are single-storey industrial buildings in the vicinity of the site, but it is open to the north and free from shadows. The site is approximately 5 km to the south of the meteorological station at Napier Airport and about 4 km to the west of the central Napier meteorological station. It was considered that the Airport meteorological records would be more representative of the test site than the central Napier records.

The data from the Napier site has been analysed by Ball (1987) with results summarised in a similar form to that described above for the Dunedin Airport site. The temperature presentation format differs from Dunedin Airport as follows:

- the daily maximum and minimum temperatures for a period of one year are plotted instead of tabulated

- the monthly means of the daily maximum and minimum temperatures have not been presented

- the correlation between the daily maximum air temperature and the daily maximum surface temperature of the chipseal was more thoroughly investigated with checks made to see whether including maximum air temperatures on preceeding days improved the prediction for pavement surface temperatures.

1.4 Results from Cardrona

The test site was on the east side of State Highway 89, some 1.3 km south of the Cardrona Hotel and 26 km from Wanaka, in Central Otago, approximately: longitude 169° 00' E, latitude 44° 53' S, and altitude 600 m. The area is about 10 m below road level in a valley running NNE, between the state highway and the Cardrona River that flows in a southerly direction down the valley. The test site was on level ground in an area of farmland and scrub and free from the shadows of large trees or other structures. However, the floor of the valley is only about 50 m wide with moderately steep slopes rising from the valley floor. The hills and trees on the slope to the west of the site probably reduced the total solar radiation received during early morning and late afternoon hours. However, at these times radiation levels are relatively low, so that in terms of the total radiation received, the influence of the hills would not be very significant. Wind speeds in the valley would probably be lower than is typical in the surrounding areas.

Cardrona is about 27 km from the Queenstown Meteorological Station to the south and 22 km from the Wanaka Station to the north. Because of the range of hills between these two locations, there are significant differences in the meteorological records. The site was thought to be more closely represented by the conditions at Wanaka, but there was more detailed information available in the Queenstown records.

Cardrona was the last of the sites investigated and it was intended that this work would extend the information from the other sites by providing:

- an extension of the database on pavement temperature variation in New Zealand into an area where the range of temperatures is believed to be near the upper limit for the country

- an indication of the lowest temperatures likely to be obtained in basecourse materials. These data can be used in investigating susceptibility of such materials to frost damage

- meteorological data recorded simultaneously with the pavement temperature data to assist in the future development of computer models for predicting pavement temperature from available meteorological information.

Initial analyses of the data and presentation of the main results from the Cardrona site were carried out by Ball (1987). The analyses undertaken were not as complete as those performed for the Dunedin Airport and Napier sites. Insolation was recorded at the site, providing more reliable information for verification of pavement temperature prediction models than at other sites. Unfortunately, the recording of wind speeds at the site was unsuccessful. The following results were presented:

1. The daily variation of the pavement temperatures on both a hot and cold day with little cloud cover and little wind.

2. Histograms of the temperature distribution (6° C intervals) with time, expressed as a percent of a year, generated for the probe on the surface of the chipseal and at 50 mm depth in the 150 mm thick AC pavement. These were plotted for both the summer months and the whole year.

3. Plots of the daily maximum and minimum pavement temperatures for a period of one year.

4. The number of days where the difference between maximum and minimum daily temperature was greater than 35° C or 30° C at the surface of the chipseal pavement.

5. The number of days in the recording year for which the maximum temperature for a given probe position was 0° C or lower.

2. METEOROLOGICAL DATA

The meteorological daily data recorded at Blenheim Airport during the project monitoring period from March 1983-February 1984 is summarised in Table 2 below.

Table 2 Blenheim Airport Meteorological Data
March 1983 - February 1984

Month	Rainfall Days > 1 mm	Total Rainfall (mm)	Days Wind > 4*	Days With Ground Frost	Air Temp (°C) Min.	Air Temp (°C) Max.
March	3	22.0	12	0	2.0	32.3
April	5	147.5	3	2	1.1	22.5
May	12	47.7	5	8	-3.0	21.5
June	7	20.2	5	15	-3.1	16.9
July	4	99.0	1	20	-4.0	15.7
August	7	61.9	3	16	-1.5	18.1
Sept	12	100.1	9	5	-1.2	21.1
Oct	10	92.7	5	1	1.6	26.1
Nov	6	39.7	4	0	2.1	24.0
Dec	5	84.8	8	0	3.4	25.4
Jan	3	11.8	10	0	3.2	27.8
Feb	6	69.7	3	0	5.7	30.6
Totals	80	797.1	68	67		

* *The wind strength was measured at 9 am, and given on the Beaufort scale. A value of 4 represents a wind speed of 10 knots.*

Similar meteorological data for the Dunedin and Napier sites is presented in the reports by McQueen (1985) and Ball (1987) in the form of histograms.

Air temperatures and sunshine hours recorded at the appropriate meteorological stations near to the four sites suitably instrumented during the respective project measurement periods are compared in Figures 2 to 5. Figure 2 shows the mean daily maximum temperatures for each month; Figure 3 the mean daily minimum temperatures; Figure 4 the monthly mean of the hourly temperatures, and Figure 5 the monthly sunshine hours. The Meteorological stations were all within 8 kms of the trial pavement sites except for Cardrona, which is about 27 km from the Queenstown Meteorological Station to the south and 22 km from Wanaka Station to the north. Comparisons have been made with the Queenstown records, as they are more detailed than the Wanaka records.

Figure 2 **Monthly Means of Daily Maximum Temperatures at Meteorological Stations Nearest to Sites**

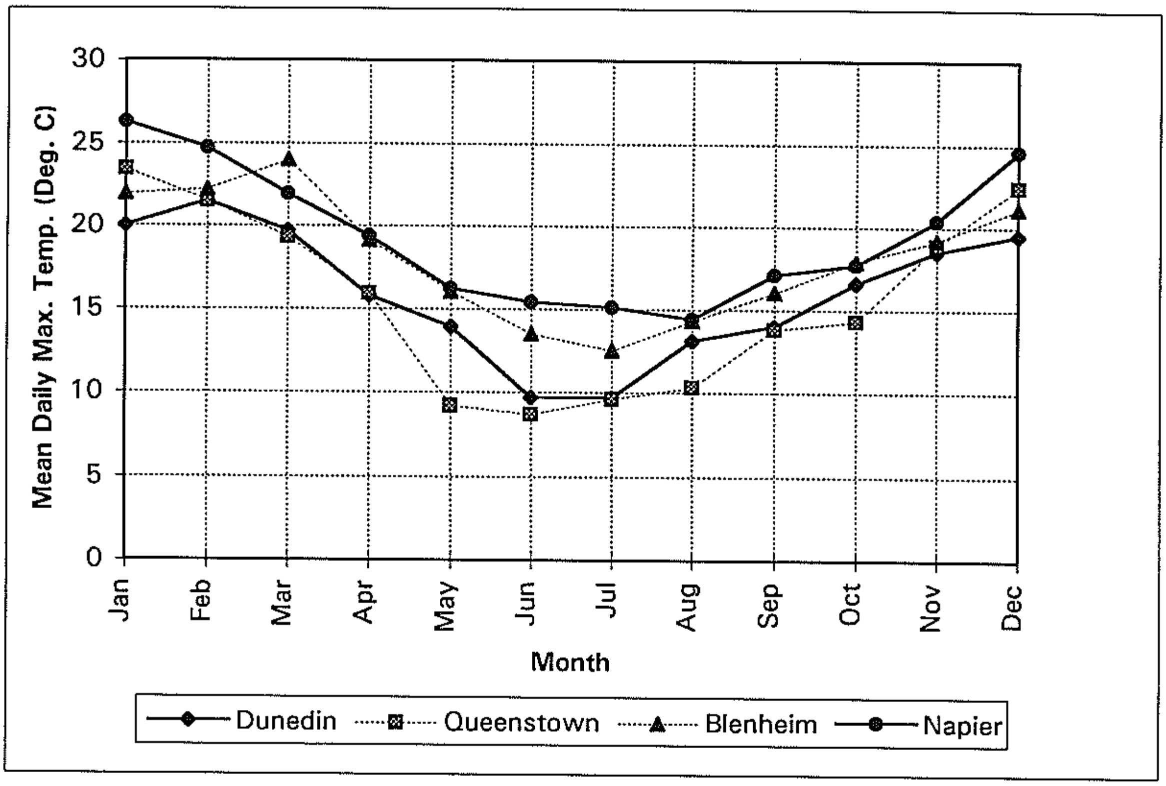


Figure 3 **Monthly Means of Daily Minimum Temperatures at Meteorological Stations Nearest to Sites**

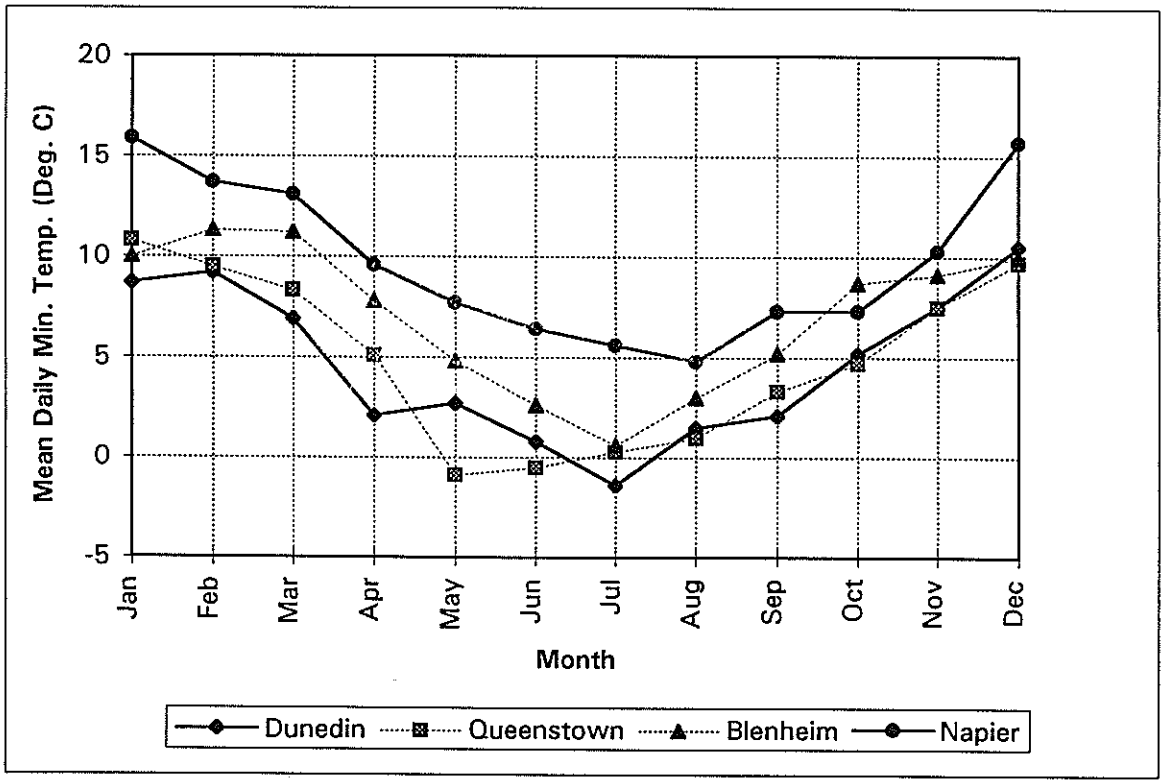


Figure 4 **Monthly Means of Daily Mean Temperatures at Meterological Stations Nearest to Sites**

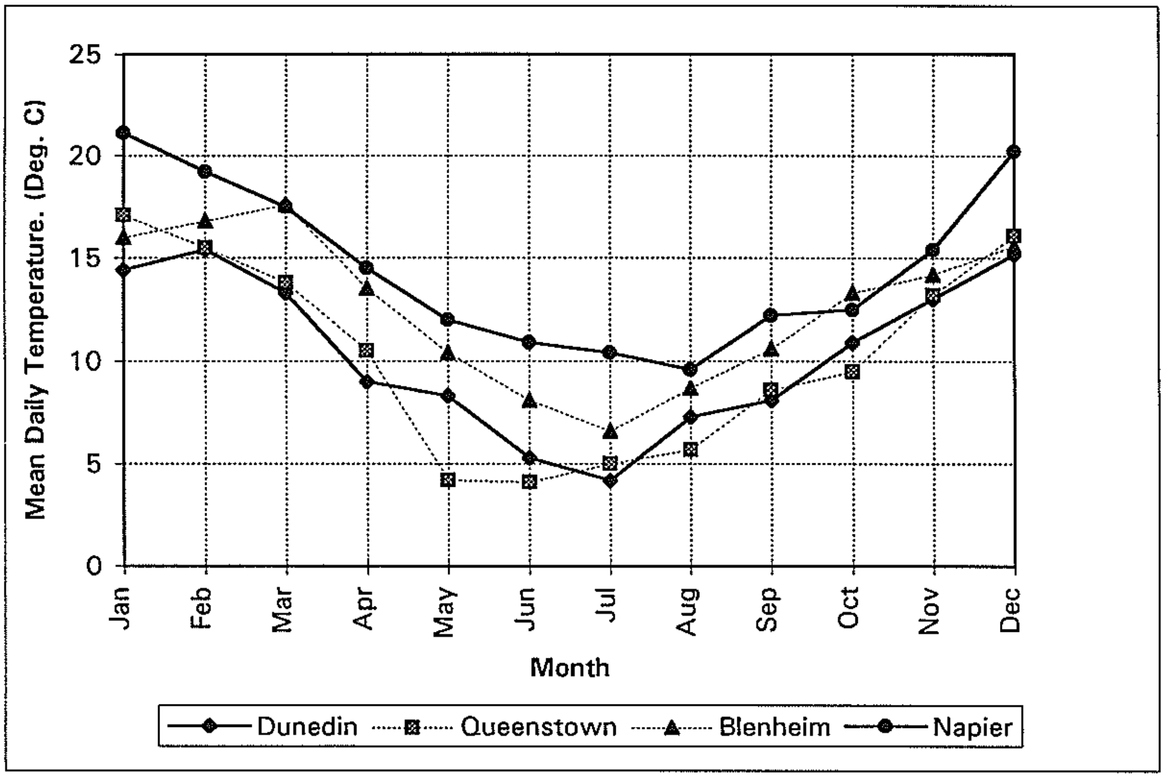
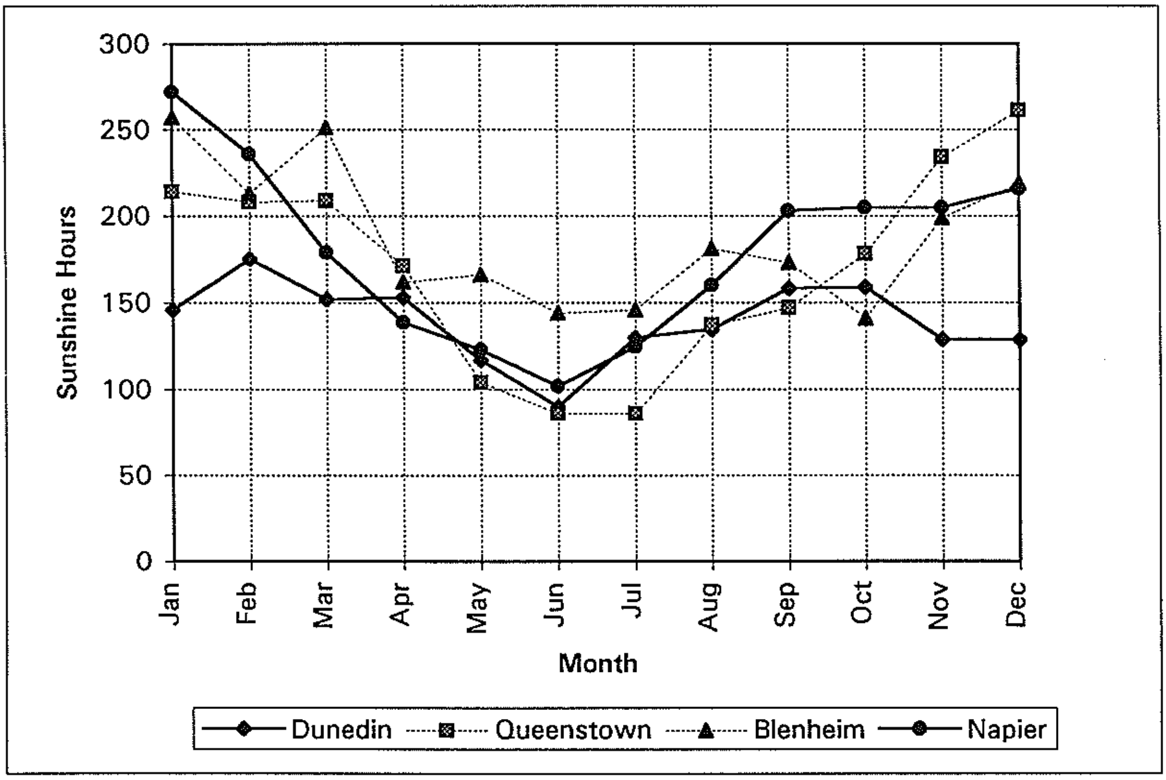


Figure 5 **Sunshine Hours at Meteorological Stations Nearest to the Sites**



The temperature comparisons indicate that Napier has the warmest climate and that both Blenheim and Napier were significantly warmer than Dunedin and Queenstown over most months during the recording periods. During the summer months (November-February), the total sunshine hours recorded at Queenstown, Blenheim and Napier were similar and significantly higher than the hours recorded in Dunedin. Over the winter months, the sunshine hours recorded in Blenheim were significantly greater than in the other three locations, which had similar total hours.

A comparison of the relevant climatic summary parameters obtained from the appropriate meteorological station records near to the sites for the respective trial investigation periods is given in Table 3, below.

Note: More complete details of the meteorological station records for the recording periods are given in Appendix A.

Table 3 Summary of Meteorological Data for Recording Periods

	Dunedin	Q'town	Wanaka	Blenheim (Town)[1]	Napier
Recording start	Oct '81	May '88	May '88	Mar '83	Dec '84
Recording finish	Sep '82	Apr '89	Apr '89	Feb '84	Nov '85
Days with > 1 mm rain	94	(85)[2]		79	93
Total annual rainfall (mm)	583	(719)[2]		694	812
Total annual sunshine hours	1673	2035		2252	2165
Days wind > Beaufort 4	88			68	88
No. days ground frost	111	130	84	57	41
Extreme max. temp. °C	30.4	29.8	31.8	32.0	31.3
Extreme min. temp. °C	-7.9	-10.6	-9.0	-7.1	-6.4
Mean of daily max. temps. °C	16.0	15.5	17.0	18.1	19.4
Mean of daily min. temps. °C	4.7	4.7	4.9	7.0	9.8
Mean temp. for period °C	10.4	10.1	10.9	12.6	14.6

[1] *Records at Blenheim town. Note that Table 2 is from Blenheim Airport data.*

[2] *Records taken at Cardrona.*

It is informative to know whether the climatic conditions during the recording periods at the respective test sites were typical of the long-term average conditions. Table 4 gives the differences between the relevant climatic summary parameters and the same parameters derived for the respective recording periods.

Table 4 **Differences Between Meteorological Data for Recording Periods and Long-term Averages**

	Dunedin	Q'town	Wanaka	Blenheim (Town)	Napier
Days with > 1 mm rain	-10	(+4)[1]		-2	-2
Total annual rainfall (mm)	-76	(+79)[1]		+23	-18
Total annual sunshine hours	-21	+170		-197	-22
No. days ground frost	+6	+22	-13	-29	+2
Mean of daily max. temps. °C	+0.3	+0.7	+0.5	-0.1	+0.4
Mean of daily min. temps. °C	+0.3	+0.7	+0.5	-0.5	+0.3
Mean temp. for period °C	+0.3	+0.7	+0.5	-0.3	+0.3

[1] *Records taken at Cardrona.*

In terms of the most relevant parameters for heat input to the pavements of air temperatures and sunshine hours, the climatic conditions in both Dunedin and Napier during the test periods were quite close to the long-term average conditions. The climate at Cardrona over the test year was significantly sunnier and warmer than for the long-term average conditions whilst at Blenheim the sunshine hours were lower and temperatures slightly cooler than for the long-term averages.

3. ANALYSIS OF BLENHEIM DATA

Note: All figures and tables referred to in section 3 coded with B are contained in Appendix B.

As part of the present project, the data from all four recordings was converted to Microsoft Excel spreadsheet format. Data was logged at 10-minute intervals, but in this form it was found to be inconvenient for easy manipulation and plotting. As part of the conversion process to Excel spreadsheets, averages were taken of the six points recorded in each hour to reduce the data to mean hourly records. Each set of data was divided into spreadsheets for each calendar month.

The averaging of the 10-minute records produced some 'smoothing' of the records, with the extreme values being reduced by between 0.2-1.5 °C. The hourly mean temperatures are considered to be more appropriate for engineering applications than the 'unsmoothed' 10-minute interval recorded data.

3.1 Blenheim Maximum Temperatures

The daily maximum temperatures for the complete recording period are shown in Figures B.2 (for the chipseal), B.3 (for the 50 mm AC) and B.4 (for the 150 mm AC). For reference, the air temperature recorded at the test site (probe T14) is plotted in each figure. These plots are reproduced using the recorded time sequence (start 18 February 1983 – finish 23 March 1984) without any additions or interpolations over periods where data was not recorded. The main periods of unrecorded data were: 11-30 June 1983; 23 July-4 August 1983, and 30 November-8 December 1983.

The maximum chipseal surface temperature was 47.6 °C, recorded on 9 January 1984. The corresponding maximum daily air temperature was 31.6 °C (recorded at the test site). For comparison, the maximum chipseal surface temperatures at the other sites were: Cardrona, 47.1 °C (1 February 1989); Dunedin, 49.8 °C (25 December 1981), and Napier 54.5 °C (7 February 1985).

The maximum surface temperatures on the 50 mm and 150 mm AC were 57.0 °C and 56.8 °C respectively, also recorded on 9 January 1984. The difference between maximum measured asphalt surface temperature and maximum chipseal temperature of around 8 °C compares with the approximately 8 °C obtained for both the Dunedin and Napier sites (damaged thermocouples on the AC trial sections at Cardrona made it difficult to make precise comparisons).

3.2 Blenheim Minimum Temperatures

The daily minimum temperatures for the complete recording period are shown in Figures B.5 (for the chipseal), B.6 (for the 50 mm AC), and B.7 (for the 150 mm AC). For reference, the air temperature recorded at the test site (probe T14) is plotted in each figure.

The minimum surface temperatures were recorded on 4 July 1983 and were -2.8 °C (for the chipseal), -4.2 °C (for the 50 mm AC) and -4.5 °C (for the 150 mm AC). The minimum daily air temperature recorded at the test site was -4.2 °C, and occurred on 4 July 1983. In comparison, the surface temperature minima obtained at Cardrona and Dunedin were in the range -7 to -10 °C. Surface minima at Napier did not fall below 0 °C (although the air temperature did).

3.3 Blenheim Temperature Histories

The probe temperature histories for the day of the maximum surface temperature (9 January 1984) are shown in Figures B.8, B.9 and B.10 for the chipseal, 50 mm AC and 150 mm AC respectively. In all three test sections, the surface temperatures rise from a low of about 14 °C at 5:00 am to the peak value (47-57 °C) at about 1:00 pm. Of particular interest is the similarity between the histories for the surface and 50 mm deep probes in the 50 mm and 150 mm AC test sections. This suggests that the thermal properties of the pavement asphalt and the basecourse are similar.

The daily variation of the temperature gradients in the pavements, basecourse and sub-base materials can be seen in temperature history plots (Figures B.8-B.10). The maximum gradient in the top 50 mm of the AC sections is about 11 °C (Figure B.9) and occurs at about 10:00 am. The daily variation of the temperature at the base of the test pits (probe T8, 400 mm below the surface) is quite small, with temperatures varying from about 24-27 °C.

Temperature histories for the chipseal during the recording periods in the summer months of November 1983, December 1983, January 1984 and February 1984 are shown in Figures B.11-B.14. Similar plots for the 50 mm thick AC are shown in Figures B.15-B.17. These plots can be used to obtain the frequency of high temperature 'excursions' at the various levels within each of the two pavements. For example, the chipseal surface temperatures exceeded 40 °C four times in November, five times in December, 15 times in January and 10 times in February, and exceeded 45 °C on two days in January and on one day in February. The AC surface temperature exceeded 50 °C twice in November, three times in December, 14 times in January and six times in February.

Usually, at the times of the maximum surface temperatures (see Figures B.13 and B.17 for January 1984) there is a gradual build-up of temperatures over two or three presumably fine clear days. With a succession of clear days, there is apparently a build-up of the stored heat at the lower levels, with the maximum gradients in the top 50 mm or so not changing significantly at the time of the maximum temperatures.

Temperature histories over the winter month of July 1983 are shown in Figures B.19 and B.20 for the chipseal and 50 mm AC. Surface temperatures dropped below 0^o C for a significant number of days (nine for the chipseal and 10 for the 50 mm AC) during the recording period of 22 days. However, the duration of the freezing conditions was generally less than 12 hours. Of interest is that the troughs of the minimum surface temperature follow quite closely the corresponding troughs of the air temperature. The probes in the sub-base (probes T1 and T4, 300 mm below the surface) did not drop below 4 °C. Probes T2 in the base course dropped below 0 °C for short periods (a few hours) on three days. However, probe T5 (not plotted) in the base course beneath the 50 mm AC did not reach freezing level.

3.4 Differences between Daily Maximum and Minimum Temperatures

Differences between daily maximum and minimum temperatures on the surface of the chipseal and the 50 mm AC are plotted in Figures B.21 and B.22. A criterion used previously to indicate extreme temperature changes is the number of days in which the chipseal surface varied by greater than 30 °C. For Blenheim, this occurred on 16 days (between 26 October 1993 and 13 February 1994). This was less than the corresponding number of days for the other sites, which were: 38 for Dunedin, 21 for

Cardrona (estimated by interpolation because of recording problems) and 22 in Napier. (These results are based on the one-hour average of the 10-minute interval records.) Of interest is the observation that the differences between daily maximum and minimum temperatures are significantly greater during summer months than during winter months.

Figure B.23 shows the difference between daily maximum and minimum temperatures at the base of the test section (probe T8 at 400 mm below the surface). For most days the variation in temperatures at this level is less than 3.5 °C

3.5 Monthly Mean Temperatures

The monthly means of the daily maximum temperatures recorded from all probes in the three pavement sections are given in Table B.1. Results from the most important probes (all except T5 and T9) are plotted in Figures B.24 and B.25. The corresponding results for monthly means of daily minimum temperatures are given in Table B.2 and Figures B.26 and B.27.

The monthly mean of the maximum daily surface temperatures during July 1983 (the coldest month) were 13 °C, 16.6 °C and 15 °C for the chipseal, 50 mm AC and 150 mm AC respectively. The highest monthly mean of the maximum temperatures were recorded in January 1984 and had values of 37.7 °C (for the chipseal), 45.9 °C (for the 50 mm AC) and 44.4 °C (for the 150 mm AC).

The monthly mean of the minimum daily surface temperatures during July 1983 were 1.4 °C, 0.6 °C and 0.5 °C for the chipseal, 50 mm AC and 150 mm AC respectively. The highest monthly mean minimum surface temperatures were recorded in February 1983 and had values of 16 °C, 16 °C and 15.9 °C respectively for the three pavements.

The monthly means of the hourly temperatures are listed in Table B.3 and are plotted in Figures B.28-B.30 for the important probes in the three pavements. These plots show that in most months there are only small differences between the mean temperatures at the various depths in the pavement, basecourse and sub-base profile. A further feature of interest is the obvious strong correlations between the monthly mean air temperature and the monthly means of the hourly pavement temperatures.

3.6 Monthly Mean Temperatures by Hour

Monthly mean temperatures for each hour of the day were computed for the chipseal surface and the probe at 50 mm deep in the 150 mm AC. These means are listed in Tables B.4 and B.5 and are plotted in Figures B.31 and B.32. For the purpose of this analysis, the February 1984 month has been used (the February 1983 data was discarded) and the periods from 25-31 March 1983 combined with 1-23 March 1984 to give the March mean. The data point for each hour refers to the mean of all the recorded data within the period to the following hourly data point. For example, the point at hour 0 is the mean of the data from 0:0:0 to 0:50:0 (hr:min:sec).

In Figure B.31 there is some unevenness between hour 11 and 12 on the December curve. A detailed inspection of the data showed no obvious reason for this, but the December record was incomplete due to a recording malfunction. Also, corrections have been made to account for logger malfunctions and shifts from summer time to standard time, and there is some uncertainty about the accuracy of these adjustments (Ball, 1987).

The information of mean temperatures by hour has potential applications in pavement fatigue analysis studies where the hourly distribution of the volume of heavy vehicles in known.

3.7 Yearly Mean Temperatures

Yearly mean temperatures and summer mean temperature (four months, November-February inclusive) for each probe are given in Table B.3. Yearly mean temperatures for each hour of the day are also summarised in Tables B.4 and B.5 for the surface of the chipseal and the probe 50 mm deep in the 150 mm AC. To compute these yearly and summer mean values it has been assumed that sections of unrecorded data had the same mean value as calculated for the recorded days in the respective month.

3.8 Temperatures/Time Distributions

Histograms for the time distribution of the temperatures at the surface of the chipseal and at a depth of 50 mm in the 150 mm thick asphalt during a full year of recording from 25 March 1983–23 March 1984 are shown in Figures B.33 and B.34. Temperatures were grouped in 6 °C intervals to be consistent with the previous analysis work carried for the other sites. The data has been corrected for unrecorded segments by assuming the missing data had the same distributions on a monthly basis as the recorded data. Similar histograms for the chipseal surface and 50 mm deep probe in the AC, showing the time distribution of the temperatures for the summer months of November 1983–February 1984 inclusive, are shown in Figures B.35 and B.36.

3.9 Temperature Correlations

Correlation methods to predict maximum pavement surface (or near surface) temperatures were investigated by McQueen (1985) for the Dunedin test site data, and Ball (1987) for Napier. They both investigated correlations between maximum daily temperatures and maximum pavement temperatures. These investigations showed that there was a relatively poor correlation between air and maximum pavement temperatures. The pavement temperatures are obviously influenced by solar radiation heat input and convective losses from air movement, and these meteorological factors are only weakly correlated to air temperatures.

As part of the present project, relationships between the monthly means of maximum, minimum and mean pavement temperatures, and the corresponding air temperatures, have been investigated. Linear regression lines for the Blenheim monthly mean data are shown in Figures B.37-B.42 for the surface of the chipseal and the probe at a depth of 50 mm in the 150 mm thick AC. Figures B.37 and B.38 show the correlation between the monthly mean of the maximum daily temperatures; Figures B.39 and B.40 the correlation between the monthly means of the minimum daily temperatures; and Figures B.41 and B.42 the correlation between the monthly means of the hourly temperatures.

The air temperatures used in the correlation analyses were the site-measured values but similar results would be obtained using meteorological records as these did not differ markedly from the site records. In all cases there is a good correlation between pavement and air temperatures. For example, the R^2 values for the monthly means of the hourly data were 0.96 and 0.95 respectively for the chipseal surface and 50 mm deep probe in the 150 mm AC (Figures B.41 and B.42).

4. COMPARISON OF RESULTS FROM THE FOUR SITES

4.1 Yearly Mean Temperatures

Figures 6 and 7 show comparisons between the yearly and summer mean temperatures at all four recording sites for the surface of the chipseal and the 50 mm deep probe in the 150 mm AC. Yearly mean air temperatures, as obtained from the nearest meteorological stations, are plotted for comparison with the pavement temperatures. Standard deviations of the pavement temperatures are also plotted to give an indication of the temperature variability over the analysis period.

The yearly mean pavement temperatures at the four test sites follow the same trends as the yearly mean air temperatures but are significantly higher, particularly for Blenheim and Napier where the pavement means are about 3 and 5 °C higher respectively.

Figure 6 **Chip Seal Surface Temperatures – Comparison of Yearly Means and Standard Deviations**

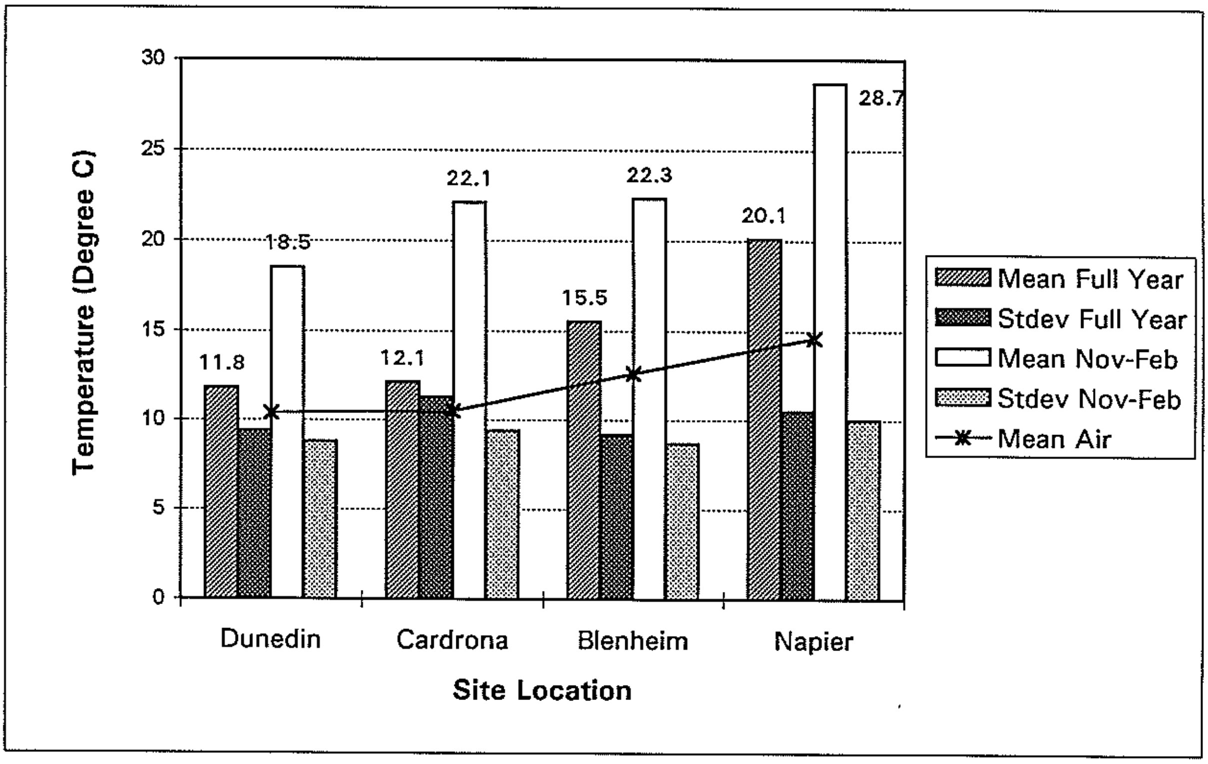
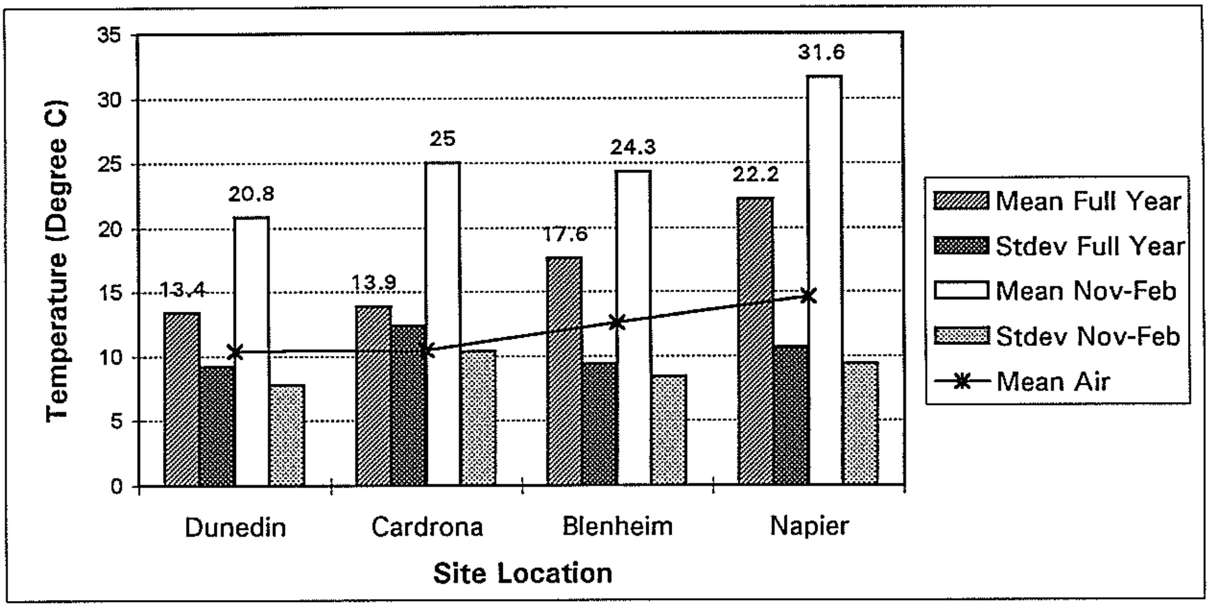


Figure 7 **50 mm Deep in 150 mm AC Temperatures – Comparison of Yearly Means and Standard Deviations**



4.2 Comparison of Means and Temperature/Time Distributions

Combined histograms of the time distributions of the temperatures on the surface of the chipseal and at a depth of 50 mm in the 150 mm AC for all four test sites are shown in Figures 8 to 11.

The temperature regime of the pavements at the Cardrona site is quite similar to that at the Dunedin trial, with the mean temperatures being approximately equal, but the spread of results for Cardrona is greater. The Cardrona mean temperatures for the November-February period are 3.6 °C and 4.2 °C above those for Dunedin, whereas those for the full year are similar to Dunedin's, reflecting a hotter climate in summer and a cooler one in winter for Cardrona. This can also be seen by comparing the tails of the time- distribution histograms for Cardrona and Dunedin, where Cardrona has a higher percentage of time than Dunedin in the upper temperature range (eg. 36-42 °C) in summer, and a greater proportion of time in the range of -6 to 0 °C for the whole year.

The means of the summer temperatures at Blenheim were similar to Cardrona but the means for the full year were 3.4 °C and 3.7 °C higher (Figures 6 and 7), reflecting a significantly warmer winter climate in Blenheim. Again, this is reflected in the time-distribution histograms, which are similar for the two sites over the summer months but differ significantly for the full year.

The means of both the summer and full year pavement temperatures for Napier are significantly higher than for the other test sites. For example, the summer mean and the full year mean chipseal surface temperatures were 6.4 °C and 4.6 °C higher than at Blenheim. As shown in the histograms of Figures 10 and 11, the time that the pavements were in the upper temperature ranges (from 42-60 °C) was significantly greater at Napier than at the other test sites.

Figure 8 Surface of the Chip Seal – Full Year

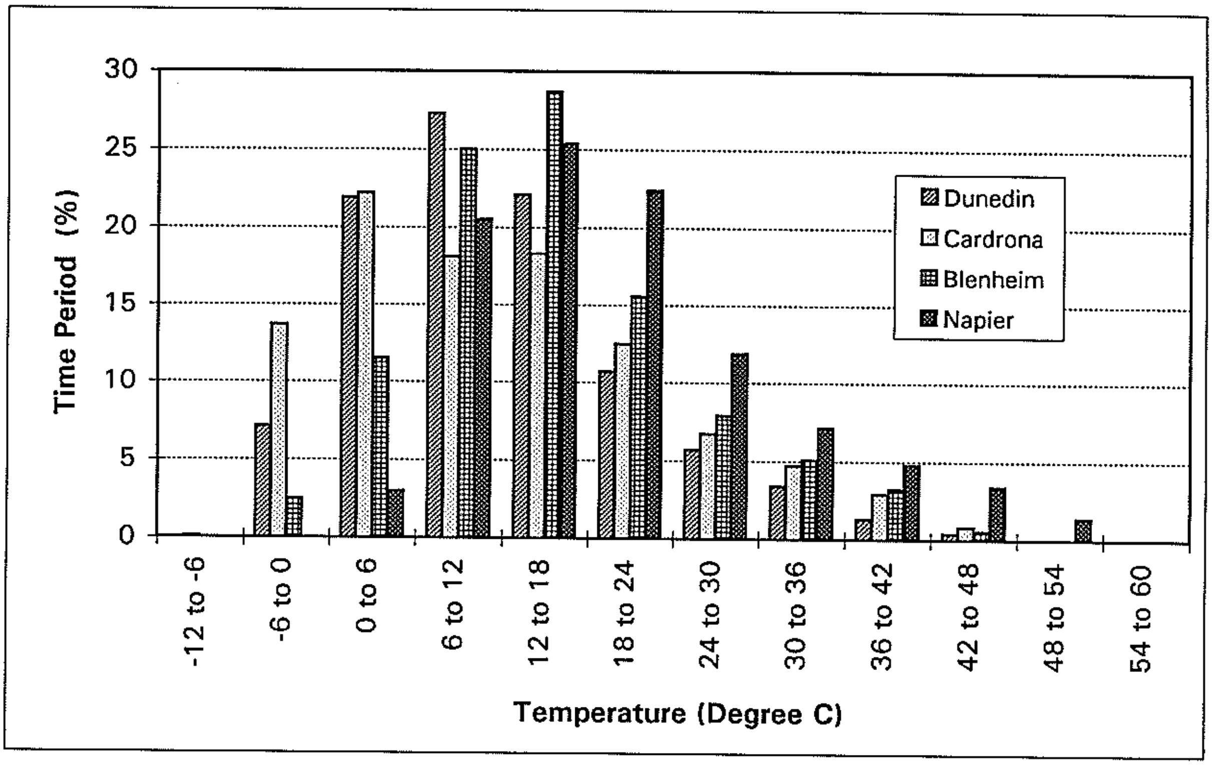


Figure 9 50 mm Deep in 150 mm AC – Full Year

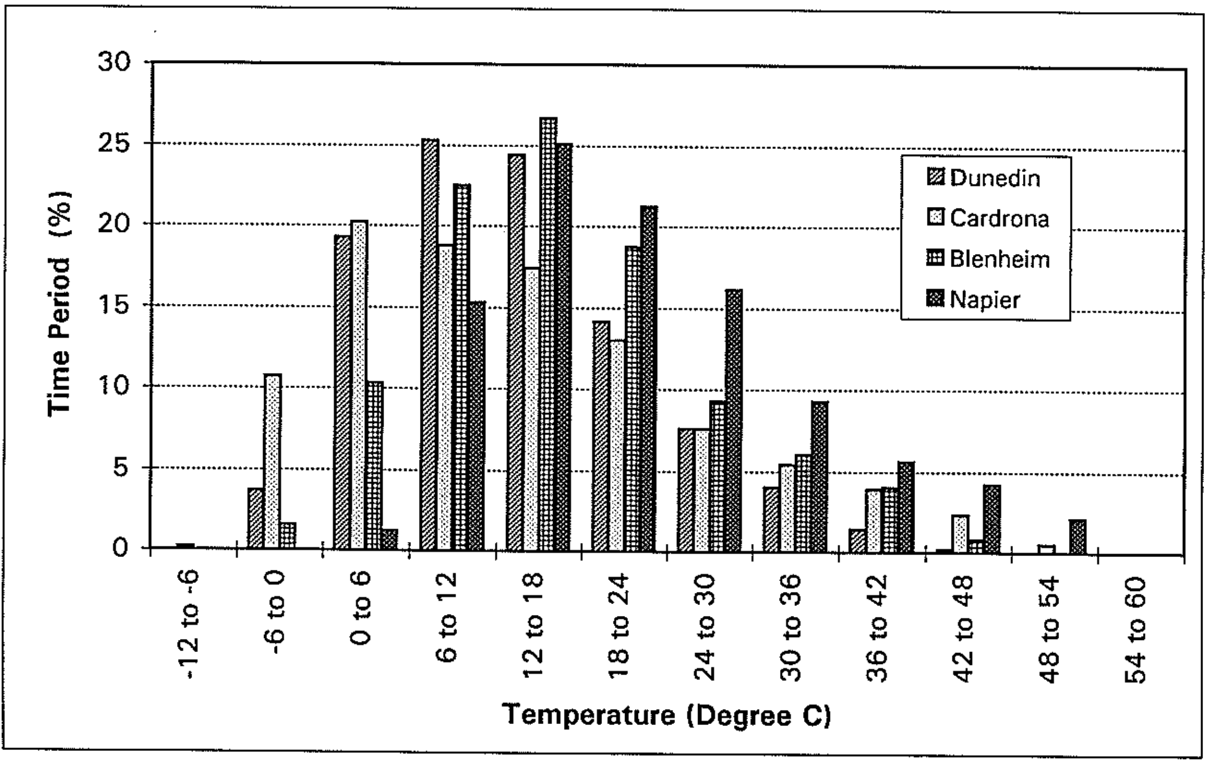


Figure 10 **Surface of Chip Seal – November-February**

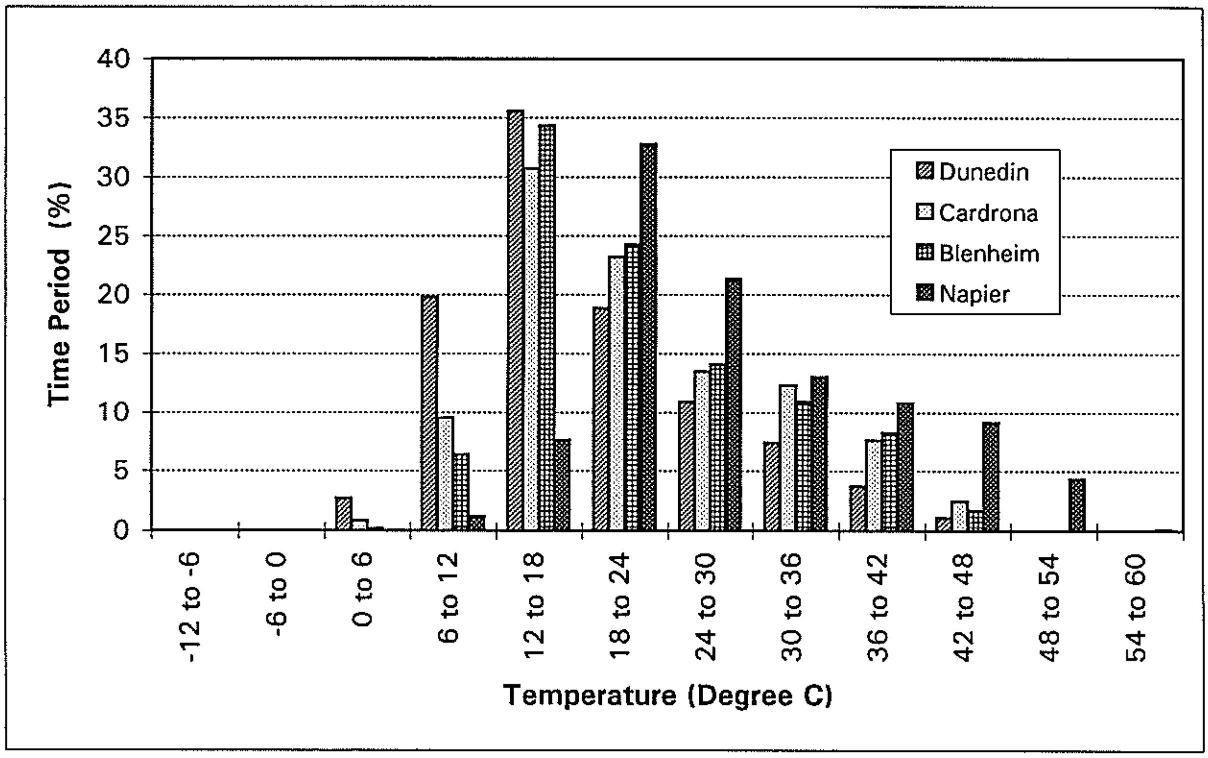
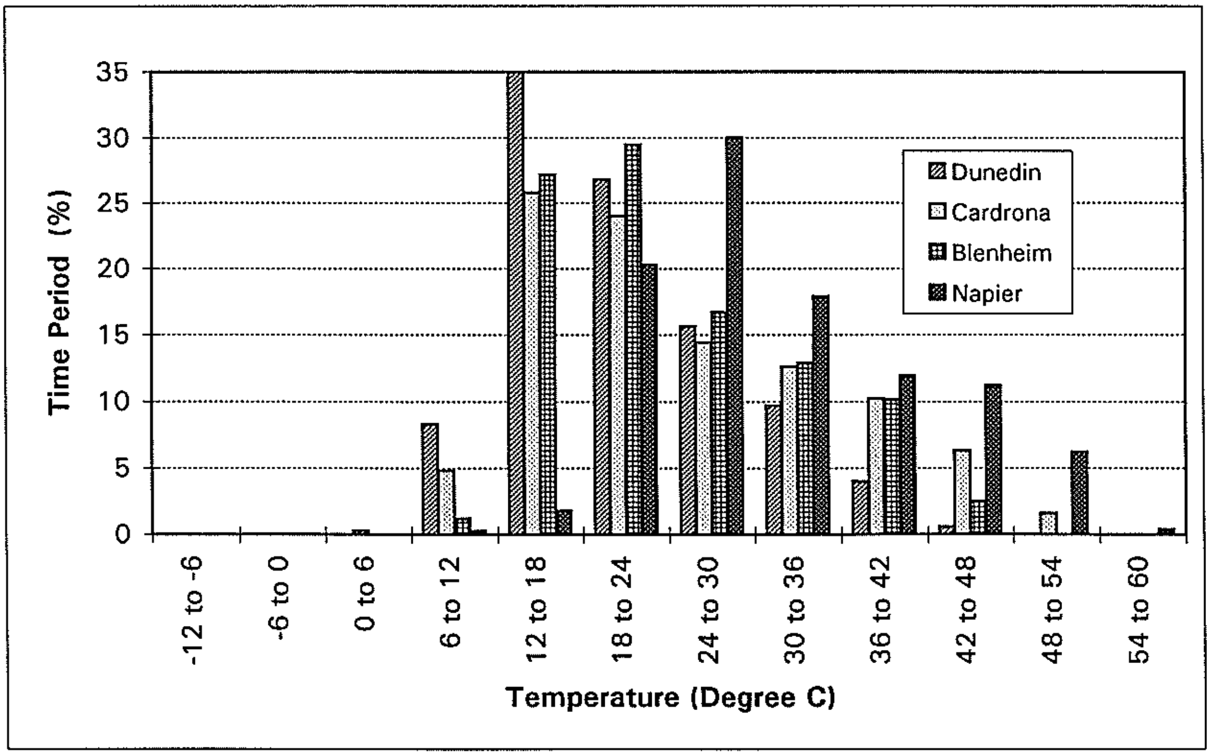


Figure 11 **50 mm Deep in 150 mm AC – November-February**



4.3 Temperature Correlations

The correlation between the monthly mean of the maximum daily pavement and air temperatures for the surface of the chipseal, using combined results from the four test sites, is shown by the linear regression line in Figure 12. A similar correlation is shown in Figure 13 for the probe 50 mm deep in the 150 mm thick AC. There is a reasonably good correlation for both pavement types, with R^2 values for the chipseal and 150 mm AC being 0.92 and 0.91 respectively.

For many practical design applications, mean monthly temperatures are likely to be more useful than extreme maximum and minimum temperatures. The correlation equations shown in Figures 12 and 13 will be of value for estimating the required monthly mean pavement temperatures for any location within New Zealand. It seems likely that extreme temperature values can be estimated to an acceptable level of precision by using the mean values and a statistical measure of the variability of the monthly data. However, the statistical analysis of the data is not straightforward, as it is not normally distributed. Further analysis work is required to fit the data with appropriate frequency distributions and to derive suitable statistical parameters for the suggested procedure of estimating extreme values.

Figure 12 **Surface of Chip Seal – Correlation of Monthly Means of Max. Daily Pavement and Air Temperatures**

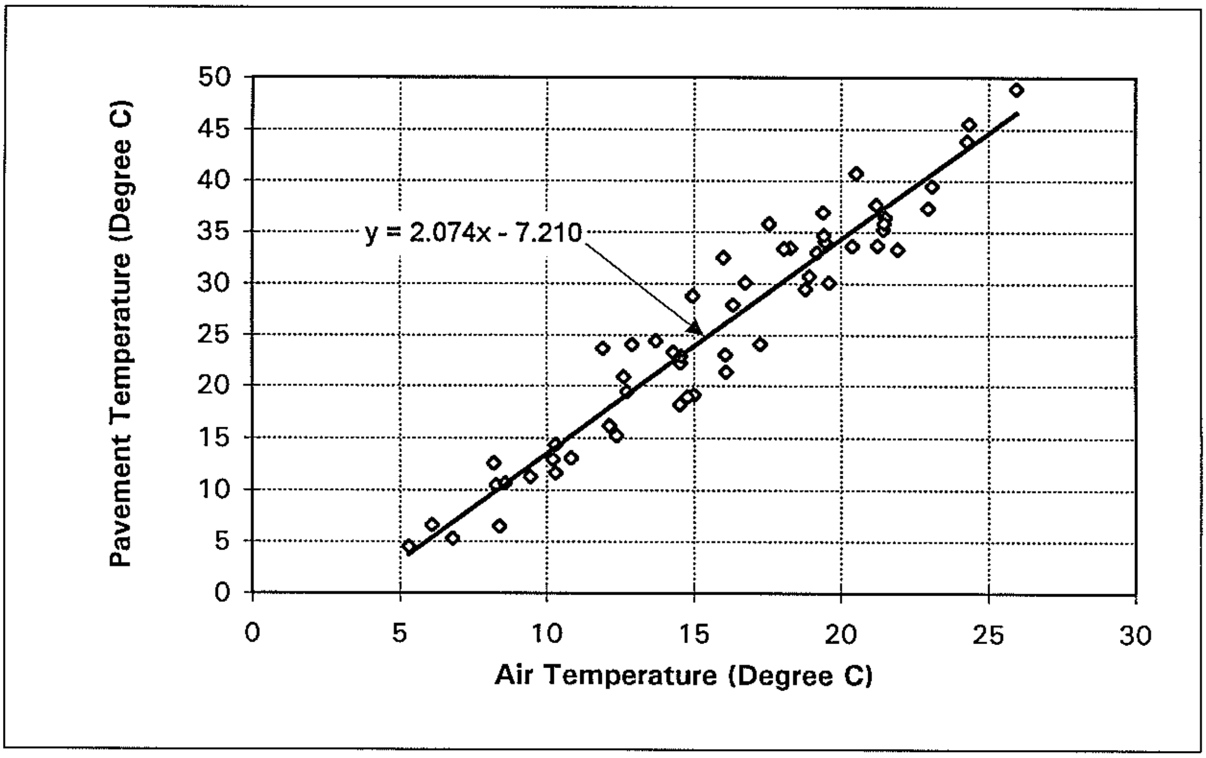
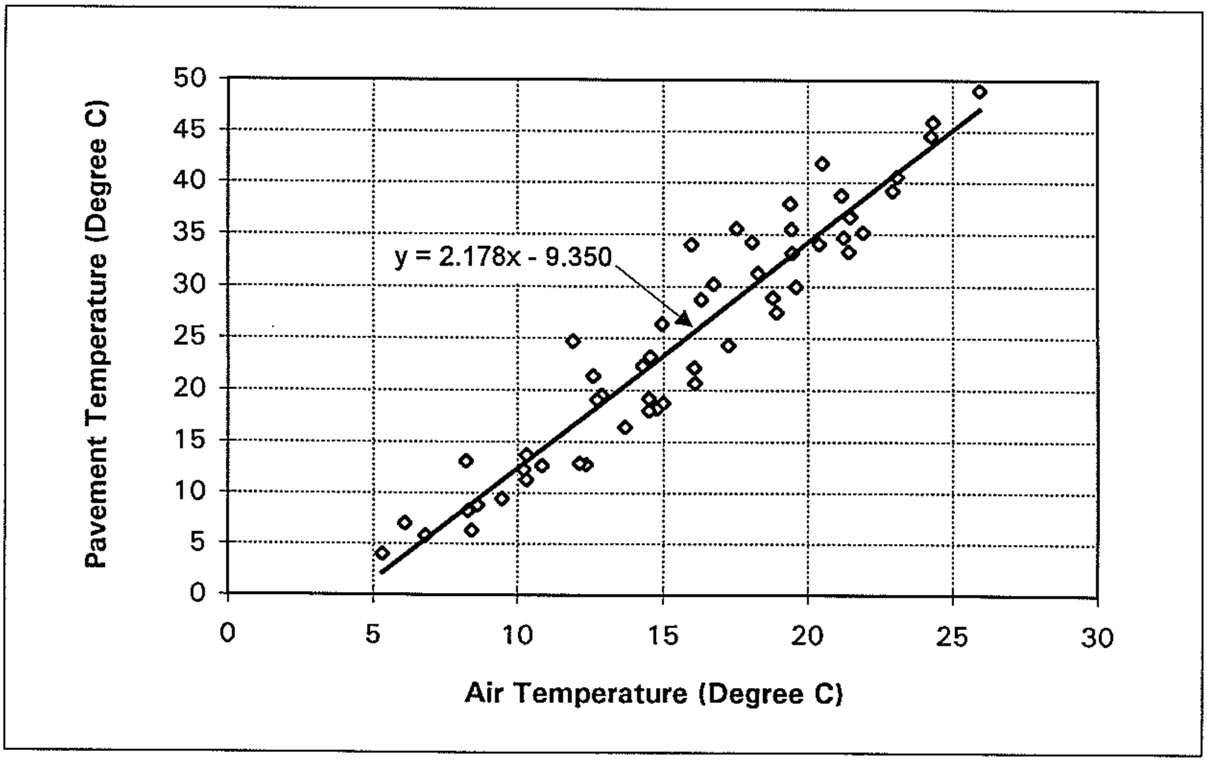


Figure 13 **50 mm Deep in 150 mm AC – Correlation of Monthly Means of Max. Daily Pavement and Air Temperatures**



5. CONCLUSIONS

1. Converting the recorded temperature data into personal computer spreadsheet format has made the recorded pavement temperature information accessible for further investigation and design applications. Condensing the data into monthly records of hourly temperatures was found to give a convenient database of information.

2. Analysis and presentation of the records from the Blenheim test site has added to the pavement temperature information available from the other three sites. Climatic conditions were less extreme than at the other two South Island sites and this was also reflected in the pavement temperatures. The means of the summer pavement temperatures were similar to Cardrona but the winter temperatures were significantly warmer. However, pavement mean summer temperatures at Napier were significantly higher than at Blenheim.

3. Reasonably good correlations were found to exist between monthly mean air temperatures and the monthly means of daily maxima, minima and hourly pavement temperatures. The correlation equations presented should provide a useful method of estimating pavement design temperatures at any site in New Zealand. With further statistical analysis it should be possible to develop simple ‘expressions’ for estimating the extreme maximum and minimum temperatures, as well as the monthly means.

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APPENDIX A

Meteorological Station Records

Table A.1 Dunedin Airport October 1981 to September 1982

	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Period
Rainfall total. mm	56	18	63	109	50	38	28	91	45	23	32	30	583
Dep. from average	+6	-55	-4	+39	+6	-24	-29	+32	-6	-24	-8	-9	-76
Days. 1mm or more	10	5	10	12	6	8	5	8	7	8	8	7	94
Dep. from average	+1	-5	0	+2	-1	0	-4	-2	0	0	0	-1	-10
Sunshine. hrs	159	129	129	146	175	152	153	117	90	130	135	158	1673
Dep. from average	-5	-39	-48	-36	+10	+11	+26	+13	-7	+28	+9	-3	-21
Ground frost. days	8	3	0	0	0	3	17	11	15	22	17	15	111
Dep. from average	+2	0	-1	-1	-1	+1	+10	-2	-5	+1	-2	+3	+6
Gale. days	1	0	0	1	0	1	0	3	1	1	0	0	8
Dep. from average	-1	0	-1	0	0	0	-1	+2	0	0	0	-1	0
Snow. lying										1			1
Dep. from average										0			+1
Temp. Screen (C)													
Extreme maximum	26.9	24.7	27.6	29.4	30.4	29.1	20.7	20.5	20.1	14.7	19.2	20.2	30.4
Mean daily max.	16.6	18.5	19.9	20.0	21.5	19.7	15.8	13.9	9.7	9.7	13.1	14.0	16.0
Dep. from average	+0.4	+0.9	+0.8	-0.5	+1.0	+0.7	-0.6	+1.0	-0.6	-0.2	+1.2	-0.3	+0.3
Mean	10.9	13.0	15.2	14.4	15.4	13.3	9.0	8.3	5.3	4.2	7.3	8.1	10.4
Dep. from average	+0.3	+1.0	+1.6	-0.3	+0.9	+0.1	-1.6	+0.8	+0.2	-0.4	+1.0	-0.4	+0.3
Mean daily min.	5.2	7.5	10.5	8.7	9.2	6.9	2.1	2.7	0.8	-1.4	1.5	2.1	4.7
Dep. from average	+0.3	+1.1	+2.5	-0.1	+0.7	-0.4	-2.7	+0.7	+1.0	-0.7	+0.9	-0.6	+0.3
Extreme minimum	-0.4	1.0	6.0	-1.1	2.9	1.1	-0.5	-3.2	-4.5	-7.9	-7.9	-5.2	-7.9
Grass Temp. (C)													
Mean daily min.	2.8	6.0	9.3	7.1	8.3	5.1	-0.5	1.2	-1.2	-3.1	-1.0	0.0	2.8
Dep. from average	+0.3	+1.9	+3.0	0.0	+1.6	-0.5	-3.4	+0.9	-1.2	-0.4	+0.5	-0.6	+0.3
Extreme minimum	-3.3	-2.4	2.8	-3.8	0.5	2.1	-2.4	-6.0	-5.6	-10.0	-10.1	-6.6	-10.1

Table A.2 Queenstown May 1988 to April 1989

	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	Period
Sunshine. hrs	104	86	86	137	147	178	234	261	214	208	209	171	2035
Dep. from average	+16	+13	+3	+23	-11	-7	+34	+29	-21	+9	+35	+46	+170
Ground frost. days	20	19	23	21	15	13	1	0	0	1	0	-	113
Dep. from average	+5	+4	+2	+3	+1	+5	-2	-1	0	0	-3	-	+14
Gale. days		2	1					1	4				8
Dep. from average		+2	+1					+1	+4				+8
Snow. lying	13	1	0	1									15
Dep. from average	+13	0	-1	+1									+13
Temp. Screen (C)													
Extreme maximum	16.8	14.6	13.8	16.4	19.8	20.1	24.2	29.8	28.2	27.6	27.2	20.0	29.8
Mean daily max.	9.2	8.7	9.6	10.3	13.8	14.3	18.9	22.4	23.4	21.5	19.3	15.9	15.6
Dep. from average	-1.8	+0.7	+2.0	+0.5	+1.2	-0.9	+1.7	+2.5	+1.9	+0.4	+0.6	+0.9	+0.8
Mean	4.2	4.1	5.0	5.7	8.6	9.5	13.2	16.1	17.1	15.5	13.8	10.5	10.3
Dep. from average	-1.9	+0.8	+2.1	+1.0	+1.3	-0.2	+1.6	+2.2	+1.8	+0.5	+0.7	+0.7	+0.9
Mean daily min.	-0.9	-0.5	0.3	1.0	3.3	4.7	7.5	9.7	10.8	9.5	8.3	5.1	4.9
Dep. from average	-2.1	+0.9	+2.2	+1.5	+1.4	+0.5	+1.5	+1.8	+1.7	+0.7	+0.8	+0.5	+1.0
Extreme minimum	-8.8	-5.0	-3.5	-4.5	-1.0	1.5	0.0	4.1	4.5	2.9	2.9	-1.2	-8.8
Grass Temp. (C)													
Mean daily min.	-3.2	-2.8	-2.2	-2.0	-0.6	0.2	4.4	6.8	8.1	6.9	5.9	-	1.9
Dep. from average	-1.8	+0.3	+1.1	+0.4	+0.6	-0.8	+1.2	+0.6	+0.8	+0.8	+1.6	-	+0.4
Extreme minimum	-10.6	-7.5	-6.4	-8.0	-6.5	-4.2	-1.2	0.0	1.5	-1.4	0.0	-	-10.6

Table A.3 Wanaka May 1988 to April 1989

	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	Period
Ground frost. days	17	20	17	18	8	1	1	0	0	0	0	2	84
Dep. from average	+3	-2	-5	-1	-4	-3	-1	0	0	0	0	-2	-16
Gale. days								1					1
Dep. from average								+1					0
Snow. lying	1												1
Dep. from average	+1												+1
Temp. Screen (C)													
Extreme maximum	17.7	14.6	14.7	15.3	19.0	21.0	26.0	30.8	31.8	28.9	28.8	22.5	31.8
Mean daily max.	10.8	9.0	10.1	11.1	15.1	14.8	21.0	24.3	26.0	23.3	20.9	17.8	17.0
Dep. from average	-1.7	+0.3	+1.6	+0.1	+0.8	-2.0	+1.9	+2.1	+2.1	0.0	+0.3	+0.9	+0.6
Mean	5.0	3.7	4.9	5.7	9.2	10.2	14.6	17.7	19.3	16.8	14.8	11.0	11.1
Dep. from average	-1.9	0.0	+1.5	+0.5	+1.0	-0.6	+1.7	+2.1	+2.3	+0.1	+0.4	+0.1	+0.7
Mean daily min.	-0.9	-1.6	-0.4	0.3	3.2	5.6	8.2	11.0	12.5	10.2	8.6	4.2	5.1
Dep. from average	-2.1	-0.3	+1.4	+0.9	+1.1	+0.8	+1.6	+2.0	+2.5	+0.2	+0.4	-0.6	+0.7
Extreme minimum	-7.5	-6.9	-5.1	-4.6	-3.3	-0.3	0.0	4.2	5.8	3.1	1.2	-2.8	-7.5
Grass Temp. (C)													
Mean daily min.	-1.5	-2.2	-1.4	-0.7	2.0	4.1	7.7	10.5	12.0	9.5	8.0	3.1	4.3
Dep. from average	-1.5	+0.4	+0.9	+0.8	+1.3	-0.7	+2.6	+3.0	+3.1	+0.6	+1.0	-1.2	+1.0
Extreme minimum	-9.0	-7.3	-6.0	-5.7	-4.1	-1.9	-1.3	3.0	4.7	2.4	0.0	-3.6	-9.0

Table A.4 Blenheim March 1983 to February 1984

	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Period
Rainfall total. mm	27	115	41	16	82	58	99	82	32	77	10	55	694
Dep. from average	-26	+52	-31	-41	+16	-10	+52	+25	-19	+19	-41	+17	+23
Days. 1mm or more	5	5	12	6	5	5	12	9	5	5	4	6	79
Dep. from average	-1	-1	+5	-1	-3	-3	+5	+1	-2	-2	-1	+1	-2
Sunshine. hrs	251	162	166	144	146	181	173	141	199	219	257	213	2252
Dep. from average	+43	-29	+1	-10	-15	+4	-21	-93	-40	-19	-3	-15	-197
Ground frost. days	0	0	6	14	19	12	6	0	0	0	0	0	57
Dep. from average	-1	-4	-6	-4	0	-3	-5	-5	-1	-1	0	0	-29
Snow. lying				1									1
Dep. from average				+1									0
Temp. Screen (C)													
Extreme maximum	32.0	25.6	21.9	17.5	16.3	18.5	20.5	26.0	23.9	25.7	26.0	28.4	32.0
Mean daily max.	24.0	19.1	16.0	13.5	12.5	14.3	16.0	17.9	19.2	21.1	21.9	22.2	18.1
Dep. from average	+2.3	+0.2	+0.4	+0.4	0.0	+0.6	0.0	-0.3	-1.0	-0.8	-1.6	-1.2	-0.1
Mean	17.6	13.5	10.4	8.1	6.6	8.7	10.6	13.3	14.2	15.6	16.0	16.8	12.6
Dep. from average	+1.2	-0.1	0.0	+0.4	-0.6	+0.2	-0.1	+0.4	-0.6	-1.0	-1.9	-1.1	-0.3
Mean daily min.	11.2	7.8	4.8	2.6	0.6	3.0	5.2	8.7	9.1	10.0	10.0	11.3	7.0
Dep. from average	+0.2	-0.4	-0.3	+0.4	-1.2	-0.3	-0.2	+1.2	-0.2	-1.3	-2.2	-1.0	-0.5
Extreme minimum	3.2	1.0	-3.1	-2.8	-4.4	-2.0	-0.7	1.4	2.1	4.2	4.9	5.9	-4.4
Grass Temp. (C)													
Mean daily min.	9.5	5.8	2.9	0.5	-1.5	0.9	2.9	7.3	7.5	8.4	7.6	9.6	5.1
Dep. from average	+2.0	+1.2	+1.5	+1.8	+0.1	+1.1	+1.2	+3.5	+1.8	+0.5	-1.1	+0.4	+1.1
Extreme minimum	1.0	-0.8	-7.1	-5.0	-7.0	-4.4	-3.3	0.3	0.1	1.4	3.4	3.6	-7.1

Table A.5 Napier December 1984 to November 1985

	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Period
Rainfall total, mm	53	24	8	125	64	74	101	224	22	18	42	57	812
Dep. from average	-24	-26	-54	+44	-6	-10	+7	+144	-60	-43	-19	+13	-18
Days, 1mm or more	8	6	2	7	7	12	14	10	5	6	7	9	93
Dep. from average	+1	-1	-4	0	0	+3	+5	0	-5	-2	-1	+2	-2
Sunshine, hrs	216	272	236	179	139	123	102	125	160	203	205	205	2165
Dep. from average	-6	+35	+38	-17	-25	-22	-25	-12	+13	+28	-9	-20	-22
Ground frost, days	0	0	0	0	0	0	8	7	12	8	3	3	41
Dep. from average	0	0	0	0	-1	-4	-2	-4	+4	+4	+2	+3	+2
Snow, lying						1							1
Dep. from average						+1							-1
Temp. Screen (C)													
Extreme maximum	29.9	30.6	31.3	29.5	24.6	21.4	21.2	20.4	19.5	22.9	23.3	27.1	31.3
Mean daily max.	24.6	26.3	24.7	21.9	19.4	16.2	15.4	15.1	14.4	17.1	17.7	20.4	19.4
Dep. from average	+2.2	+2.3	+0.9	22.4	-0.5	-0.6	+1.1	+1.5	0.0	+0.6	-1.1	-0.8	+0.4
Mean	20.2	21.1	19.2	17.5	14.5	12.0	10.9	10.4	9.6	12.2	12.5	15.4	14.6
Dep. from average	+2.4	+1.9	0.0	-0.1	-0.5	-0.1	+1.4	+1.5	-0.3	+0.3	-0.6	-0.8	+0.3
Mean daily min.	15.7	15.9	13.7	13.1	9.6	7.7	6.4	5.6	4.8	7.3	7.3	10.3	9.8
Dep. from average	+2.6	+1.5	-0.8	+0.3	-0.5	+0.4	+1.7	+1.4	-0.6	+0.1	-1.7	-0.8	+0.3
Extreme minimum	10.0	10.6	7.5	6.4	4.4	3.7	0.1	-0.5	-2.0	1.7	3.5	2.1	-2.0
Grass Temp. (C)													
Mean daily min.	12.7	13.1	11.2	10.9	6.8	5.2	3.9	2.7	0.4	3.4	3.8	6.7	6.7
Dep. from average	+2.9	+2.0	-0.2	+0.8	-0.5	+0.9	+2.2	+1.3	-1.8	-0.2	-1.9	-1.0	+0.3
Extreme minimum	5.8	8.2	4.7	3.0	-0.5	0.1	-2.5	-4.8	-6.4	-2.4	-1.4	-4.2	-6.4

APPENDIX B

Blenheim Temperature Records

Table B.1 Monthly Means of Daily Maximum Temperatures (Deg C)

Month	Probe Number												
	T1	T2	T3	T4	T5	T6	T7	T8	T10	T11	T12	T13	T14
Feb-83	26.8	32.6	37.3	29.1	32.5	39.1	45.7	26.3	31.8	35.2	39.3	44.9	23.0
Mar-83	24.3	29.3	33.3	25.5	29.4	35.3	41.1	24.0	28.7	31.6	35.2	40.1	21.9
Apr-83	17.9	20.9	24.1	18.1	20.3	24.5	28.9	17.5	19.8	21.8	24.3	28.1	17.3
May-83	13.4	15.6	18.2	13.0	14.9	18.5	22.5	12.5	14.3	15.9	18.1	21.2	14.5
Jun-83	9.6	10.9	13.1	9.1	10.4	13.4	16.8	8.8	9.7	10.9	12.7	15.2	10.8
Jul-83	8.7	10.5	13.0	7.9	9.6	13.0	16.6	7.4	8.9	10.3	12.3	15.0	10.2
Aug-83	11.6	15.8	19.5	11.4	14.6	19.5	24.2	10.2	13.8	16.1	19.1	23.2	12.7
Sep-83	14.3	19.0	22.9	14.5	18.1	23.3	28.8	13.3	17.4	19.9	23.3	27.9	14.6
Oct-83	18.9	23.9	28.0	19.4	23.2	28.8	34.5	17.8	22.6	25.3	28.8	33.6	16.3
Nov-83	22.4	28.4	33.4	23.4	27.7	34.4	41.4	21.8	27.0	30.3	34.3	40.2	18.1
Dec-83	23.6	29.8	34.7	24.6	29.1	35.7	42.2	23.0	28.5	31.6	35.5	41.0	19.4
Jan-84	26.2	32.7	37.7	27.4	32.0	39.1	45.9	25.6	31.5	34.6	38.8	44.4	21.2
Feb-84	25.6	31.4	35.9	26.4	30.5	36.8	42.7	24.7	29.8	32.9	36.7	41.8	21.5
Mar-84	24.4	29.5	33.7	25.1	28.6	34.5	40.3	24.0	28.1	31.1	34.7	39.6	21.3

Table B.2 Monthly Means of Daily Minimum Temperatures (Deg C).

Month	Probe Number												
	T1	T2	T3	T4	T5	T6	T7	T8	T10	T11	T12	T13	T14
Feb-83	22.9	18.8	16.0	17.8	21.8	18.7	16.0	23.7	21.4	20.1	18.3	15.9	10.8
Mar-83	20.8	15.6	12.6	21.7	18.7	15.2	12.5	21.7	18.6	16.8	14.7	12.4	9.0
Apr-83	15.7	11.4	9.3	15.6	13.3	10.8	8.9	16.0	13.1	11.7	10.3	8.7	7.4
May-83	11.7	7.3	5.1	11.2	8.9	6.4	4.5	11.4	8.7	7.4	6.1	4.5	3.8
Jun-83	8.1	4.0	2.2	7.4	5.3	3.0	1.5	7.8	5.1	3.9	2.7	1.4	1.6
Jul-83	7.1	3.3	1.4	6.2	4.3	2.2	0.6	6.3	4.1	3.0	1.8	0.5	0.8
Aug-83	9.5	5.7	3.5	8.9	7.1	4.9	3.0	8.8	6.8	5.7	4.4	2.9	1.9
Sep-83	11.9	7.9	5.7	11.7	9.8	7.3	5.4	11.7	9.7	8.4	7.0	5.4	4.3
Oct-83	16.0	12.3	10.2	15.9	14.3	12.0	10.0	15.9	14.2	13.0	11.7	10.0	7.6
Nov-83	19.1	14.3	11.6	19.6	17.3	14.0	11.5	19.7	17.2	15.5	13.7	11.5	7.8
Dec-83	20.1	15.2	12.5	20.7	18.4	15.1	12.6	20.9	18.2	16.5	14.7	12.5	8.4
Jan-84	22.3	16.3	13.4	23.2	20.3	16.4	13.5	23.3	19.7	18.0	15.9	13.4	9.0
Feb-84	22.0	17.1	14.5	22.3	20.1	17.0	14.4	22.5	19.9	18.2	16.4	14.4	10.2
Mar-84	21.5	16.9	14.4	21.9	19.5	16.7	14.5	22.1	19.5	17.9	16.4	14.5	11.7

Table B.3 Monthly Means of Hourly Temperatures (Deg C)

Month	Probe Number													No. hrs Record.
	T1	T2	T3	T4	T5	T6	T7	T8	T10	T11	T12	T13	T14	
Feb-83	24.7	24.7	24.6	24.1	26.6	27.2	27.5	24.8	26.2	26.6	26.9	27.2	16.7	251
Mar-83	22.5	21.7	21.3	23.5	23.6	23.8	23.8	22.9	23.3	23.3	23.3	23.4	15.6	672
Apr-83	16.8	15.4	14.9	16.8	16.5	16.2	16.1	16.7	16.2	16.0	15.9	15.8	12.2	712
May-83	12.5	10.8	10.3	12.1	11.6	11.2	11.0	12.0	11.2	11.0	10.8	10.6	9.0	745
Jun-83	8.8	6.7	6.0	8.2	7.4	6.9	6.6	8.2	7.0	6.7	6.4	6.2	5.2	229
Jul-83	7.9	6.3	5.8	7.0	6.7	6.5	6.3	6.8	6.3	6.1	6.0	5.9	4.7	505
Aug-83	10.5	9.8	9.5	10.0	10.4	10.5	10.5	9.5	9.9	10.0	10.0	10.1	6.9	634
Sep-83	13.0	12.6	12.5	12.9	13.5	13.8	14.0	12.4	13.1	13.3	13.5	13.7	9.3	719
Oct-83	17.2	17.2	17.1	17.4	18.2	18.8	19.0	16.7	18.0	18.2	18.5	18.8	11.9	747
Nov-83	20.7	20.4	20.3	21.4	22.1	22.6	22.9	20.6	21.8	22.0	22.2	22.6	13.0	685
Dec-83	21.8	21.9	21.8	22.6	23.5	24.2	24.6	21.8	23.1	23.5	23.8	24.2	13.9	545
Jan-84	24.1	23.9	23.7	25.1	25.8	26.4	26.7	24.2	25.4	25.7	25.9	26.2	15.3	745
Feb-84	23.6	23.4	23.2	24.2	24.8	25.3	25.5	23.4	24.5	24.7	24.9	25.2	15.9	697
1-23 Mar 84	22.9	22.1	21.8	23.4	23.6	23.7	23.7	23.0	23.4	23.5	23.5	23.6	16.2	544
25-31 Mar 83	20.4	18.5	17.7	21.0	20.5	20.1	19.9	20.6	20.1	19.9	19.6	19.4	13.4	154
Mar-83 & 84	22.4	21.3	20.9	22.9	22.9	22.9	22.9	22.5	22.7	22.7	22.7	22.7	15.6	698
Year Mean	16.6	15.8	15.5	16.7	16.9	17.1	17.1	16.2	16.6	16.6	16.7	16.8	11.1	
Summer Mean	22.6	22.4	22.3	23.3	24.1	24.6	24.9	22.5	23.7	24.0	24.2	24.5	14.5	

Note:

Year Mean = sum of (monthly mean x days in month)/(days in year)

Summer Mean = sum of (monthly mean x days in month for Nov, Dec, Jan, Feb)/(sum of days in months)

Table B.4 Monthly Means of Temps (Deg. C) for Each Hour of Day: Surface of Chip Seal

Hour	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Mean For Yr
0	16.3	17.5	16.2	11.5	7.9	3.7	3.4	6.0	8.7	12.6	14.0	14.9	11.0
1	15.6	16.8	15.6	11.0	7.5	3.5	3.1	5.5	8.2	12.2	13.4	14.2	10.5
2	14.9	16.2	15.1	10.8	7.1	3.4	2.9	5.1	7.7	11.9	12.9	13.7	10.1
3	14.3	15.7	14.6	10.5	6.9	3.2	2.7	4.7	7.3	11.5	12.5	13.2	9.8
4	13.9	15.2	14.1	10.2	6.7	3.3	2.6	4.4	6.8	11.2	12.1	12.8	9.4
5	13.6	14.8	13.7	9.9	6.4	3.2	2.4	4.1	6.4	10.7	12.0	12.9	9.2
6	15.3	15.3	13.7	9.7	6.1	3.2	2.3	3.9	6.1	10.6	13.4	14.9	9.5
7	19.0	17.4	14.7	9.9	5.9	3.1	2.2	3.9	6.4	11.2	16.2	18.7	10.7
8	23.4	20.8	17.4	12.1	6.8	3.4	2.4	5.2	8.1	13.3	19.9	23.1	13.0
9	28.0	25.0	20.9	14.9	9.0	4.7	3.9	8.0	11.0	16.6	23.4	27.5	16.1
10	31.8	28.8	25.3	17.6	11.9	7.0	6.3	11.5	14.4	20.2	27.3	31.0	19.4
11	34.1	32.6	28.7	20.2	14.3	9.3	9.2	14.8	17.4	23.3	30.1	32.8	22.2
12	36.1	34.7	31.3	22.2	16.6	11.3	11.4	17.7	20.0	25.6	31.1	32.2	24.2
13	36.9	34.8	32.1	23.6	17.6	12.5	12.8	19.0	22.0	26.8	31.9	32.4	25.2
14	36.4	34.3	31.3	23.2	17.6	12.9	13.2	18.9	22.0	26.9	31.1	31.8	24.9
15	34.2	33.1	30.2	21.9	16.4	11.6	11.7	17.7	20.7	25.9	29.6	30.2	23.6
16	31.8	31.0	27.6	19.8	14.1	9.7	9.6	15.4	19.2	24.7	27.3	27.7	21.5
17	29.1	28.2	24.6	17.3	12.1	7.9	7.8	12.4	17.0	22.3	24.7	25.3	19.0
18	25.9	25.0	22.0	15.5	10.8	6.5	6.5	10.4	14.6	19.3	21.6	22.7	16.7
19	22.9	22.5	20.2	14.4	10.0	5.6	5.6	9.1	12.8	17.0	19.1	20.4	15.0
20	20.7	20.9	19.1	13.6	9.3	5.0	4.9	8.2	11.6	15.5	17.5	18.8	13.7
21	19.4	19.8	18.1	12.9	8.7	4.5	4.5	7.5	10.8	14.5	16.4	17.5	12.9
22	18.2	18.9	17.3	12.4	8.4	4.1	4.0	7.0	10.1	13.7	15.6	16.6	12.2
23	17.2	18.2	16.7	11.9	8.0	3.6	3.6	6.5	9.7	13.0	14.8	15.8	11.6
Mean for Mth	23.7	23.2	20.9	14.9	10.2	6.1	5.8	9.4	12.5	17.1	20.3	21.7	15.5

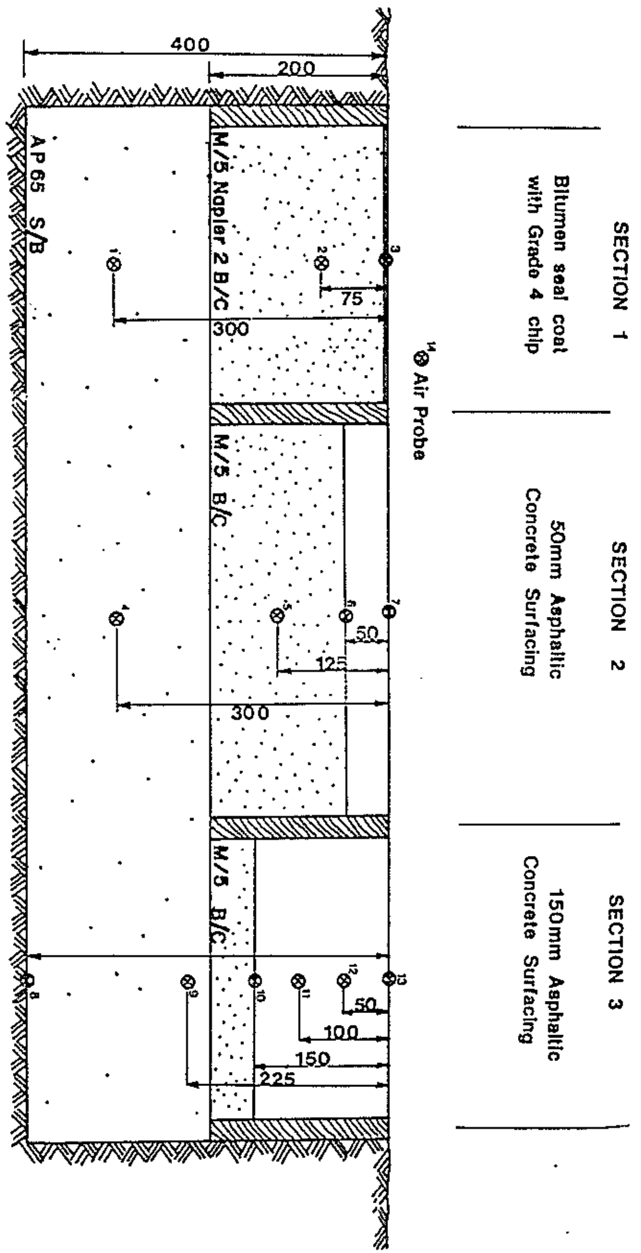


Figure B.1 Test Site Pavement Sections and Probe Locations

Table B.5 Monthly Means of Temps. (Deg. C) for Each Hour of Day: 50mm Deep in 150mm AC

Hour	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Mean For Yr
0	19.5	19.9	18.5	13.0	8.7	4.6	4.0	7.1	10.3	14.6	16.7	17.7	12.9
1	18.6	19.2	17.8	12.4	8.4	4.3	3.7	6.5	9.7	14.0	15.9	16.9	12.3
2	17.8	18.5	17.3	12.1	8.0	4.1	3.4	6.1	9.2	13.5	15.3	16.2	11.8
3	17.1	17.9	16.8	11.8	7.7	3.8	3.2	5.7	8.7	13.1	14.8	15.6	11.3
4	16.5	17.3	16.2	11.5	7.5	3.7	3.0	5.3	8.2	12.7	14.3	15.1	10.9
5	16.0	16.8	15.8	11.2	7.2	3.7	2.8	4.9	7.8	12.3	13.9	14.8	10.6
6	16.4	16.6	15.4	10.9	6.9	3.5	2.6	4.7	7.4	11.9	14.2	15.6	10.5
7	18.5	17.5	15.6	10.6	6.7	3.4	2.4	4.5	7.2	11.9	15.9	17.8	11.0
8	21.9	19.7	16.9	11.5	6.8	3.4	2.3	4.9	7.9	13.0	18.7	21.3	12.3
9	25.9	23.1	19.5	13.5	7.9	4.0	2.9	6.5	9.8	15.3	22.0	25.4	14.6
10	30.0	26.8	23.3	15.9	10.0	5.7	4.7	9.2	12.6	18.4	25.7	29.4	17.6
11	33.2	30.5	27.2	18.8	12.2	7.7	7.0	12.3	15.6	21.7	29.1	32.4	20.6
12	35.7	33.7	30.4	21.2	14.9	9.7	9.3	15.5	18.6	24.6	31.3	33.2	23.1
13	37.6	35.3	32.7	23.3	16.8	11.3	11.2	17.8	21.2	26.7	33.0	33.8	25.0
14	38.4	35.7	33.0	24.0	17.7	12.6	12.4	18.8	22.6	27.9	33.5	34.1	25.9
15	37.7	35.6	33.0	23.6	17.6	12.4	12.1	18.6	22.3	27.7	32.8	33.4	25.6
16	36.0	34.4	31.6	22.4	16.4	11.5	11.1	17.6	21.3	27.5	31.4	31.8	24.4
17	33.7	32.4	29.2	20.5	14.4	9.9	9.4	15.3	19.8	25.8	29.2	29.8	22.4
18	31.1	29.7	26.6	18.3	12.7	8.3	7.9	12.9	17.8	23.0	26.6	27.4	20.2
19	28.1	27.0	24.1	16.7	11.5	7.1	6.8	11.2	15.7	20.7	23.8	24.8	18.1
20	25.3	24.6	22.4	15.6	10.6	6.4	6.0	9.9	14.1	18.7	21.5	22.8	16.5
21	23.4	23.0	21.0	14.7	9.9	5.7	5.4	9.0	12.9	17.2	19.9	21.0	15.2
22	21.9	21.8	20.0	14.0	9.4	5.2	4.8	8.2	12.0	16.1	18.7	19.8	14.3
23	20.6	20.8	19.2	13.4	9.0	4.7	4.4	7.6	11.3	15.2	17.6	18.7	13.5
Mean for Mth	25.9	24.9	22.7	15.9	10.8	6.5	6.0	10.0	13.5	18.5	22.3	23.7	16.7

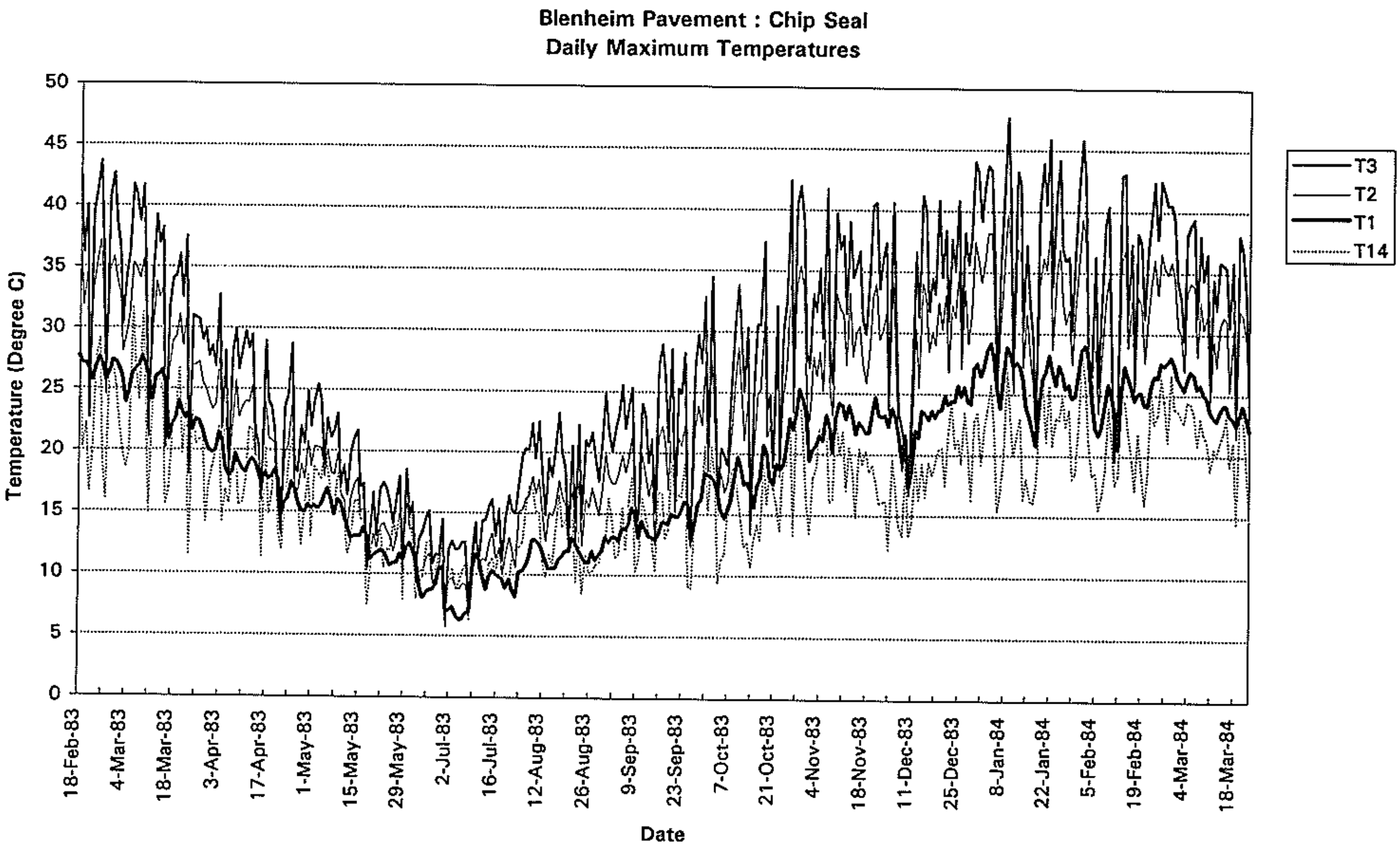


Figure B.2

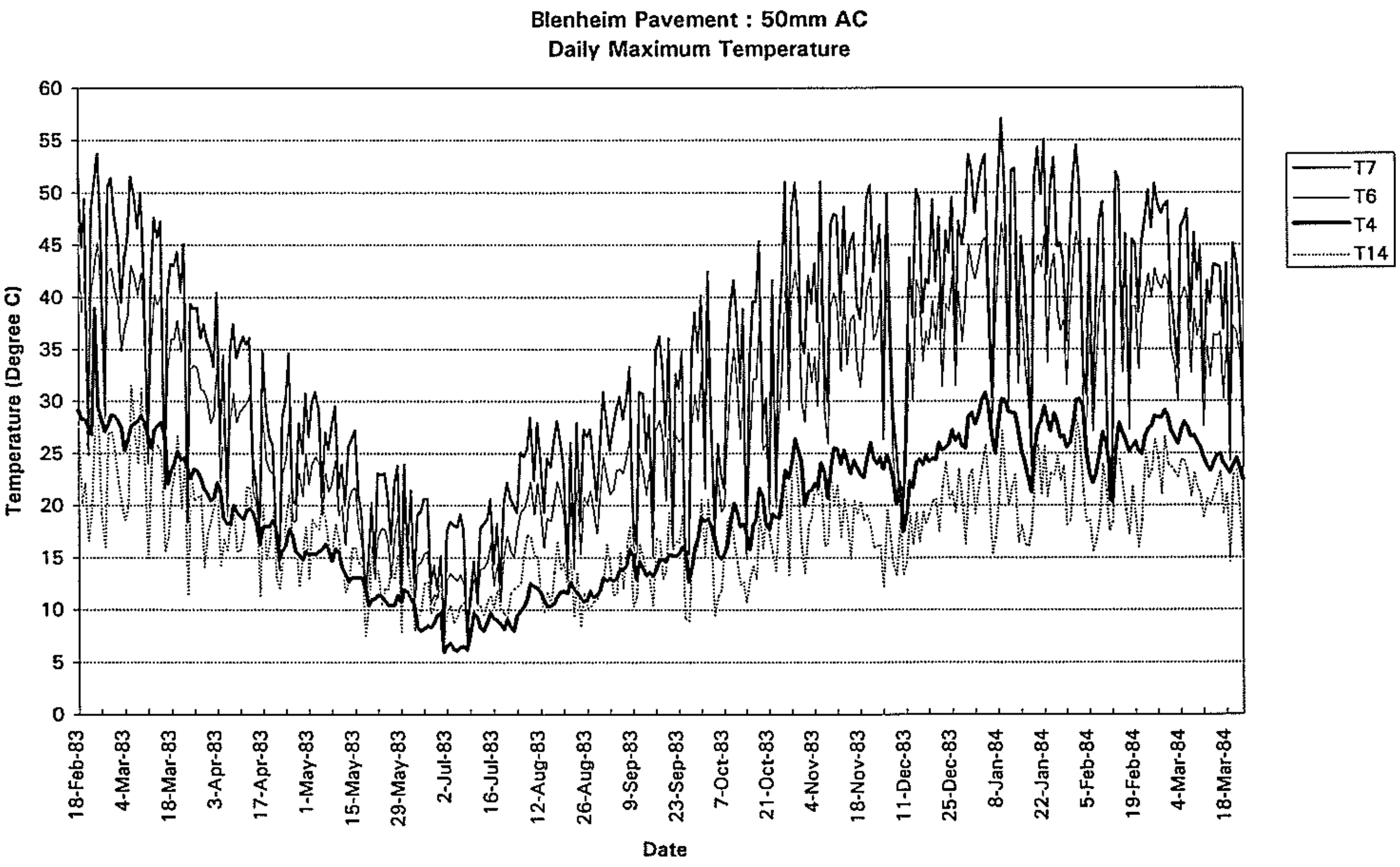


Figure B.3

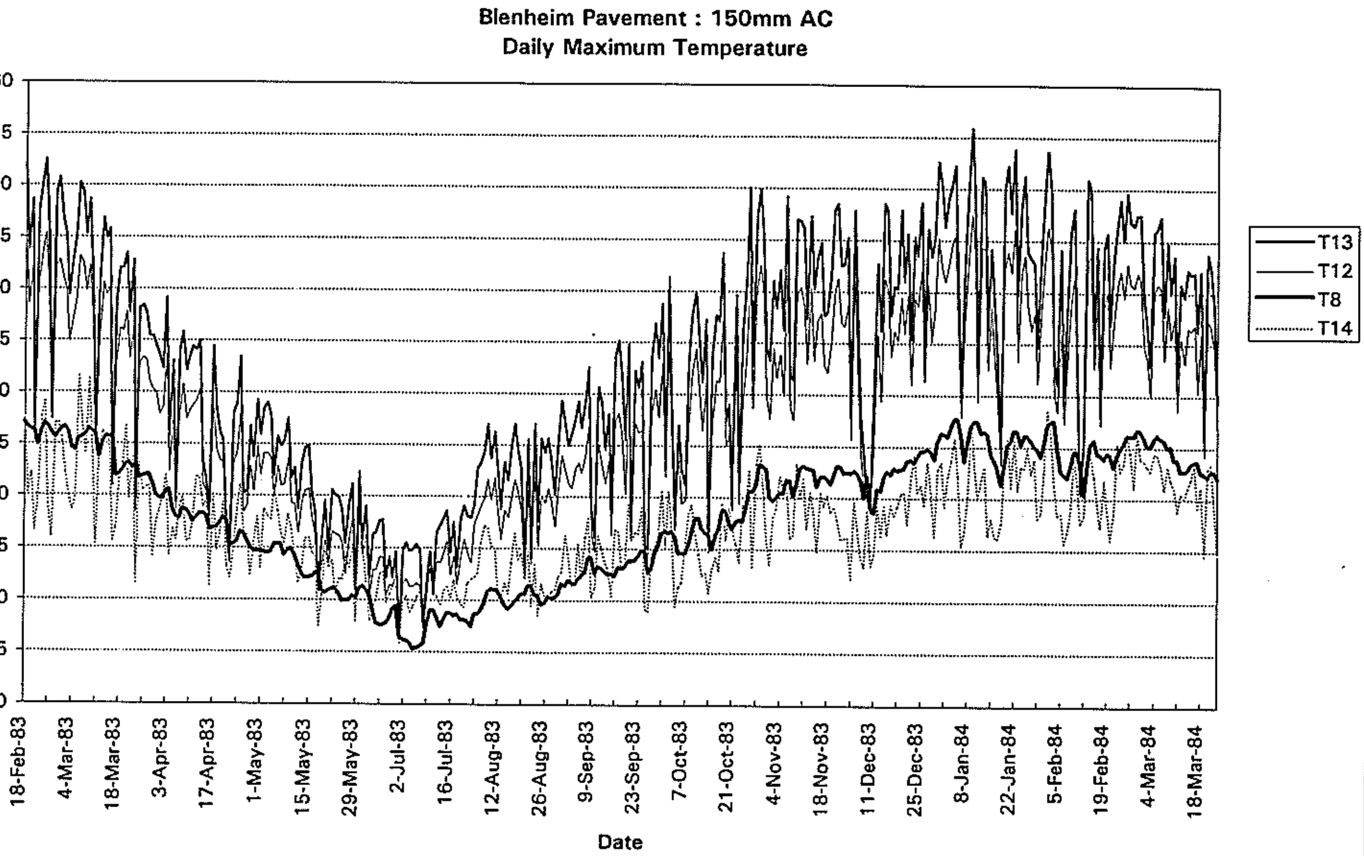


Figure B.4

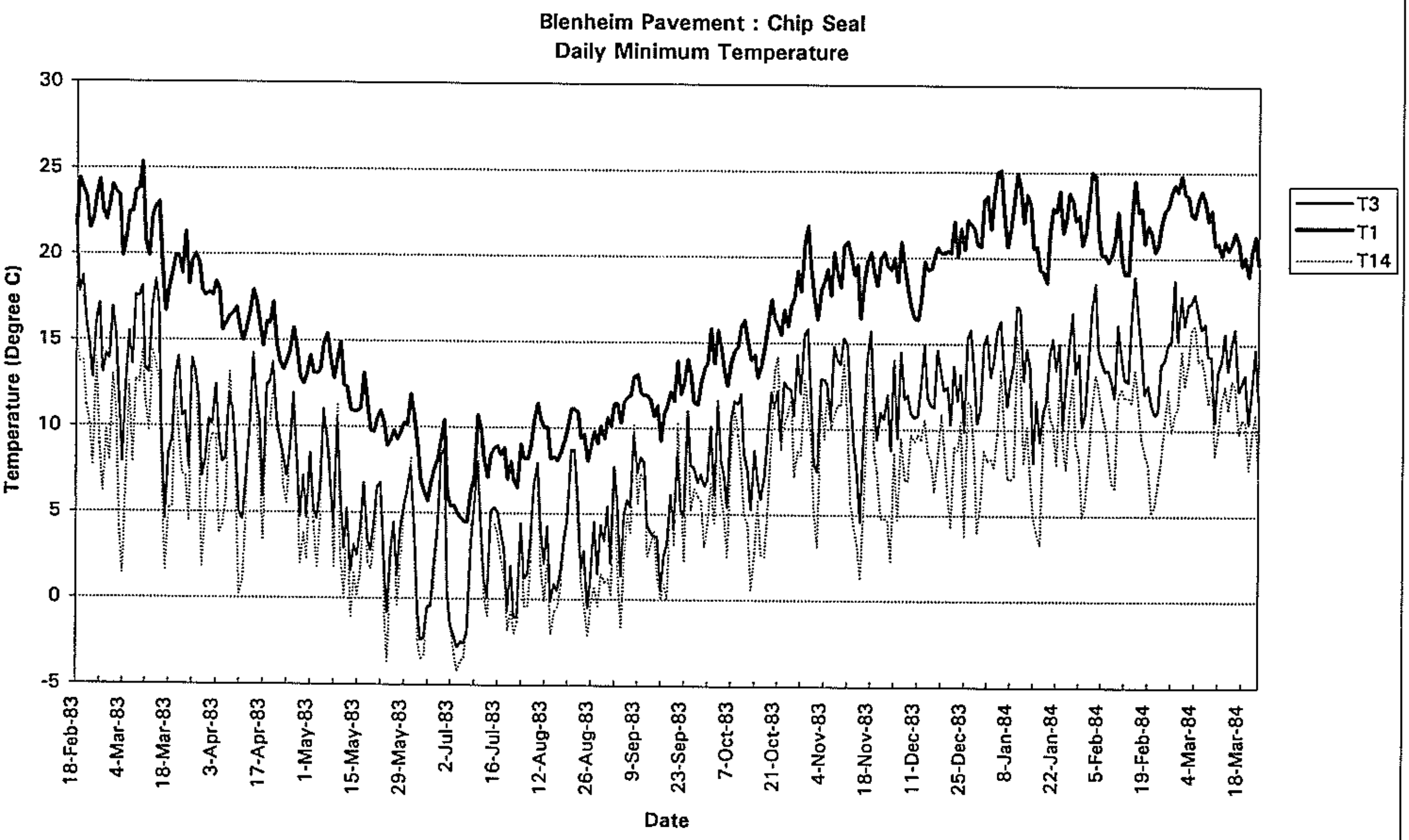


Figure B.5

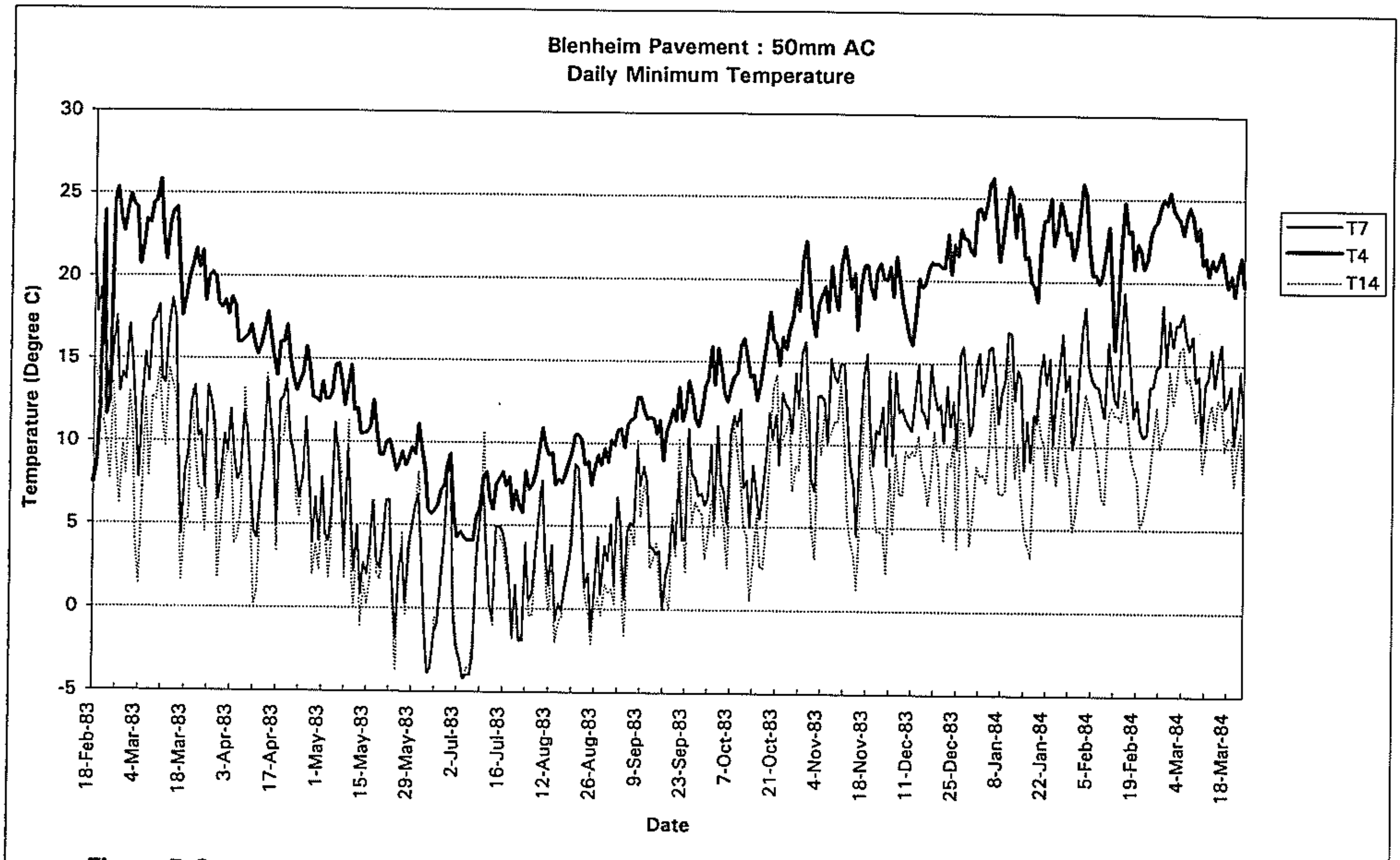


Figure B.6

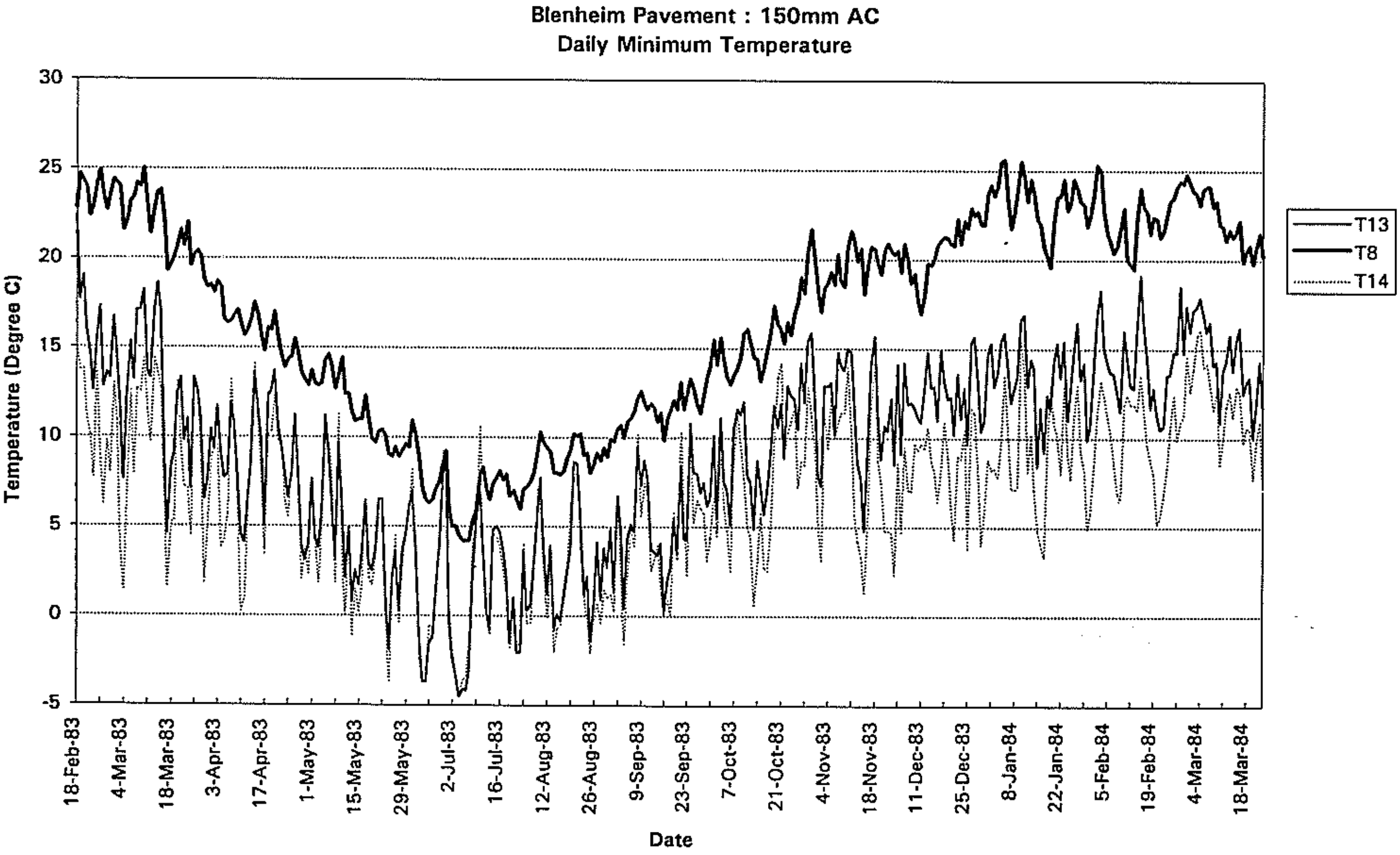


Figure B.7

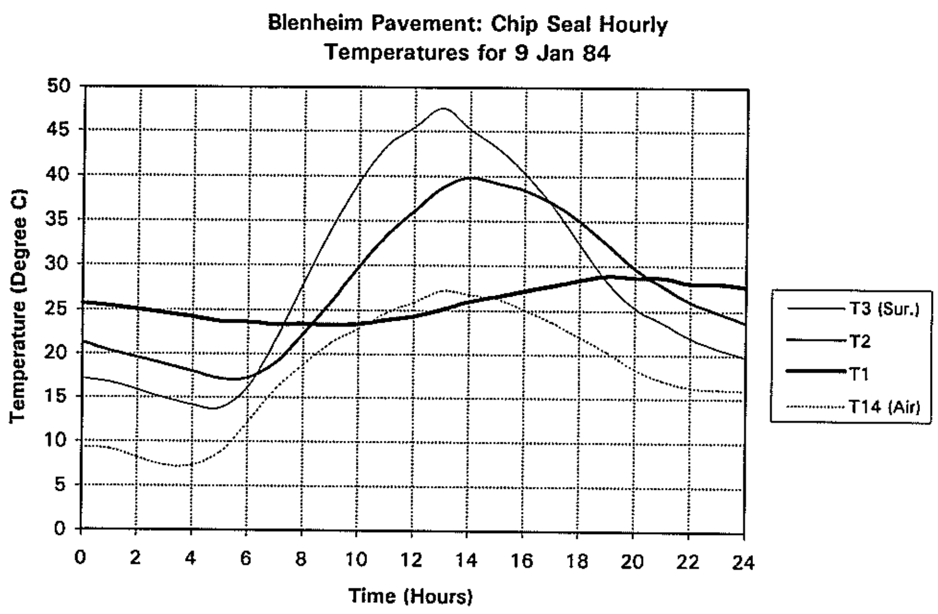

Blenheim Pavement: Chip Seal Hourly Temperatures for 9 Jan 84

Figure B.8

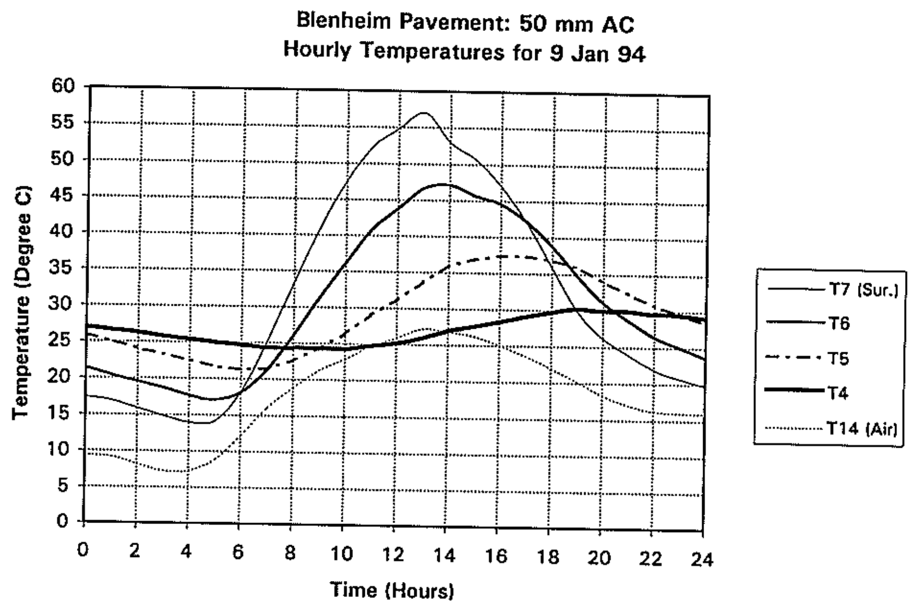

Blenheim Pavement: 50 mm AC Hourly Temperatures for 9 Jan 94

Figure B.9

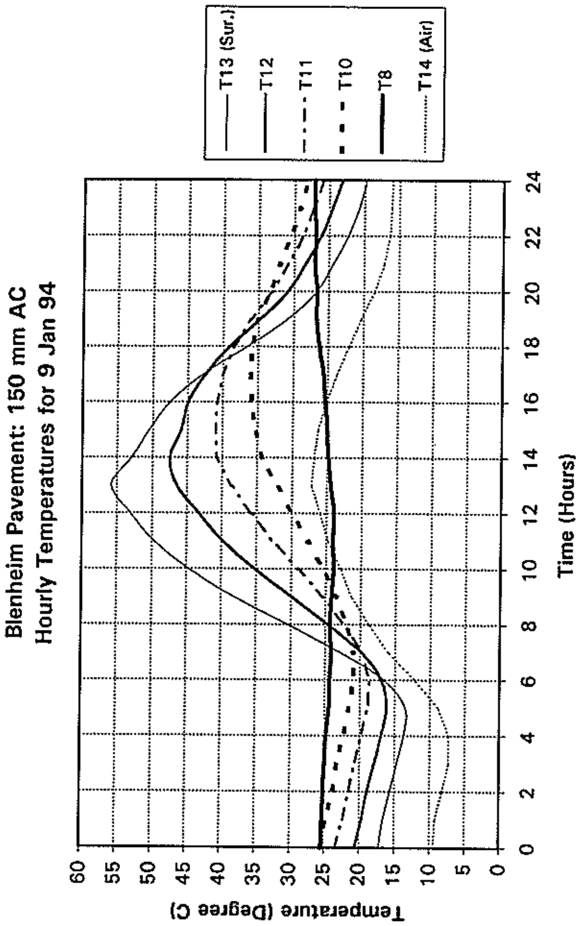


Figure B.10

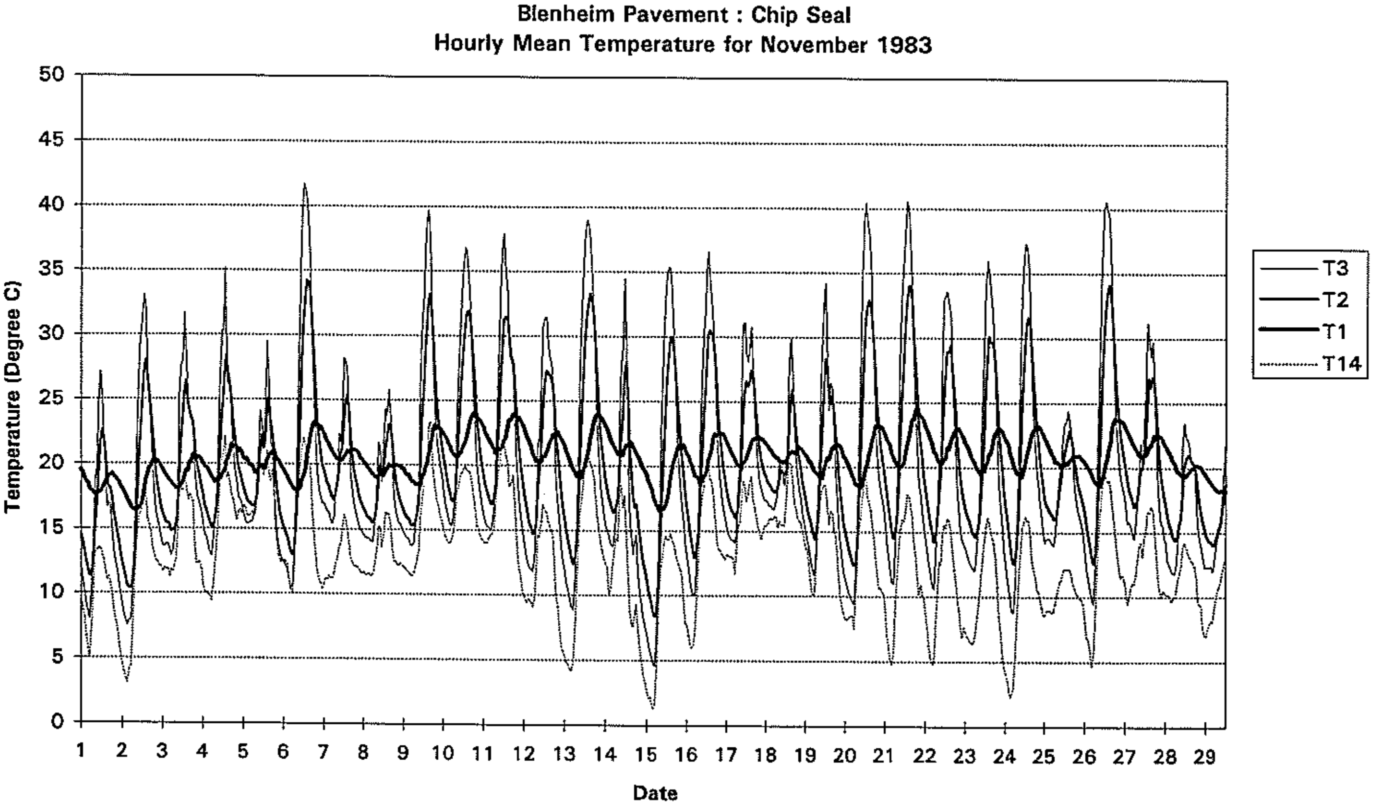


Figure B.11

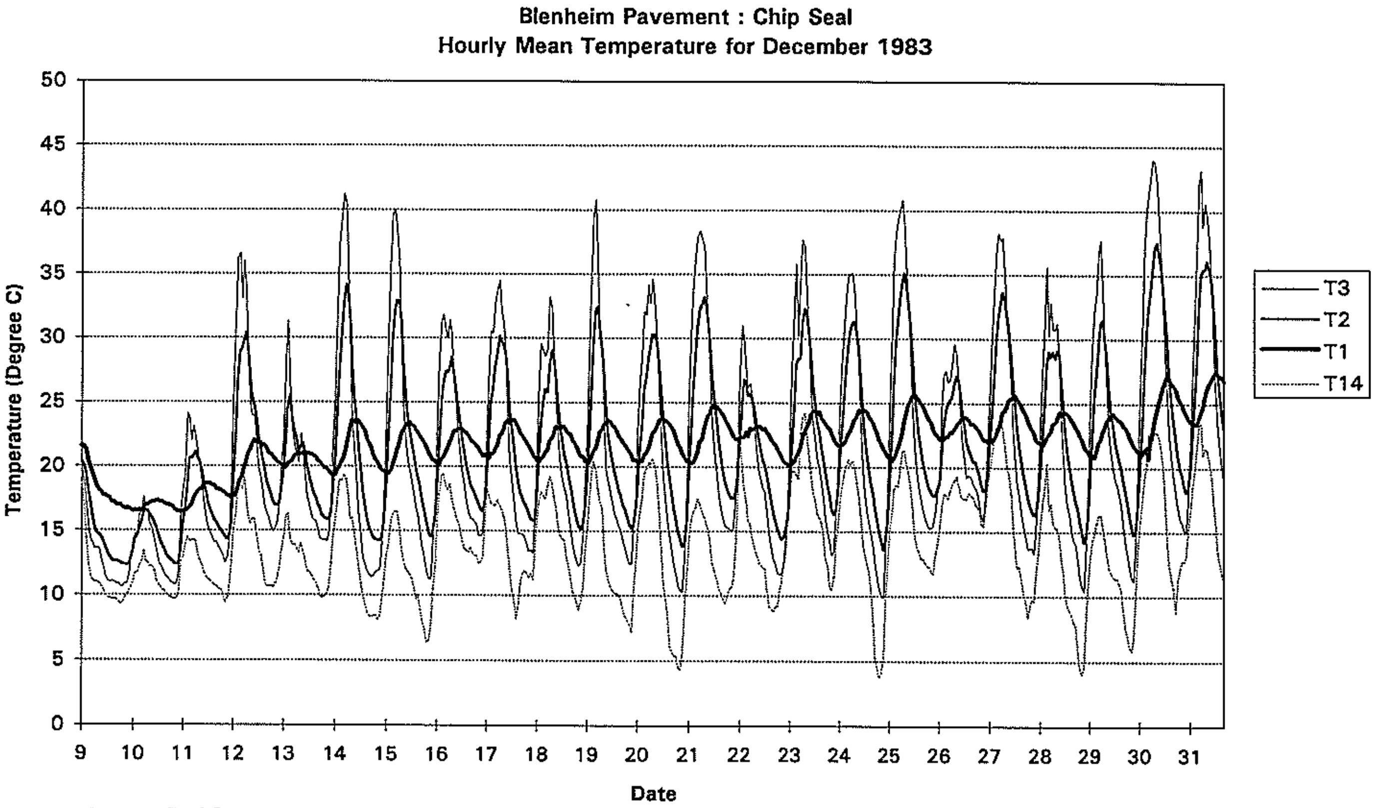


Figure B.12

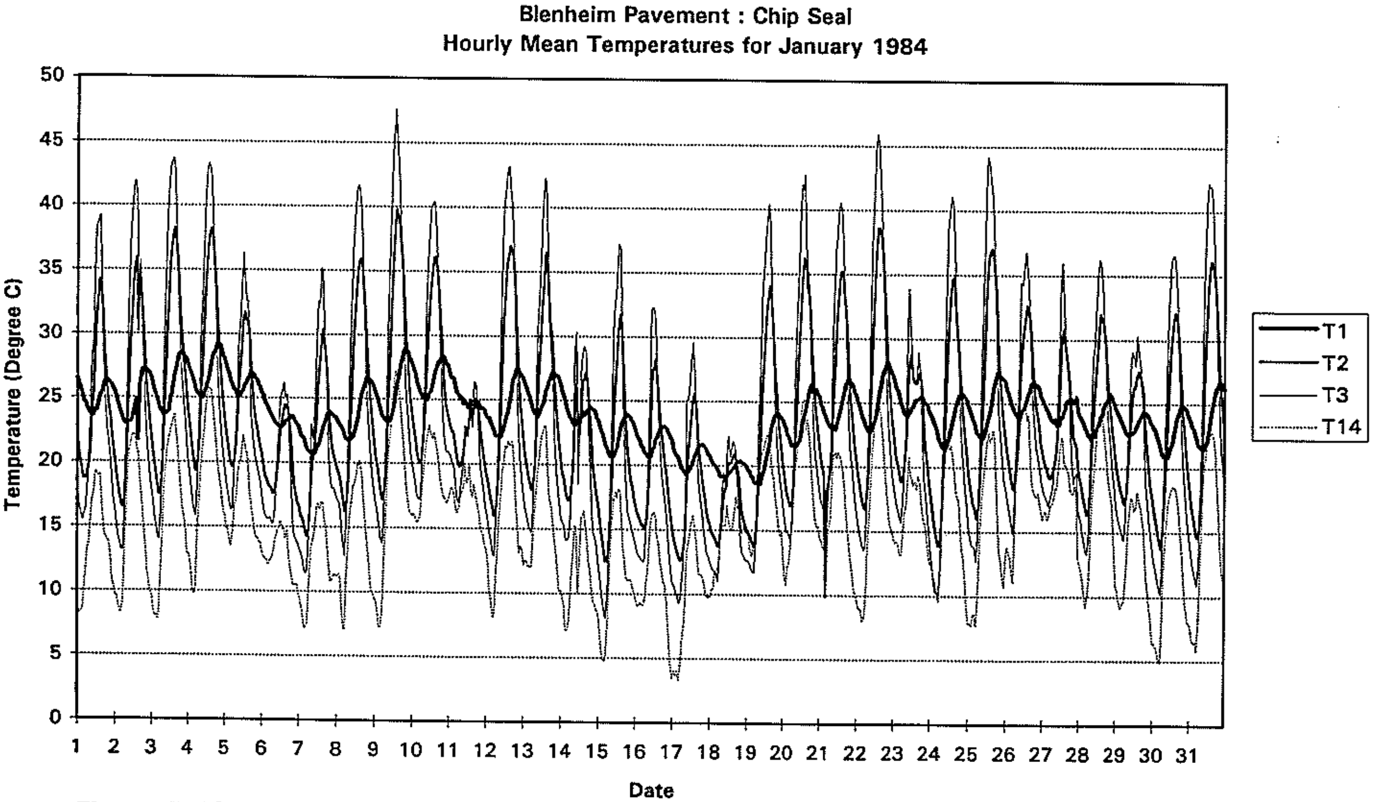


Figure B.13

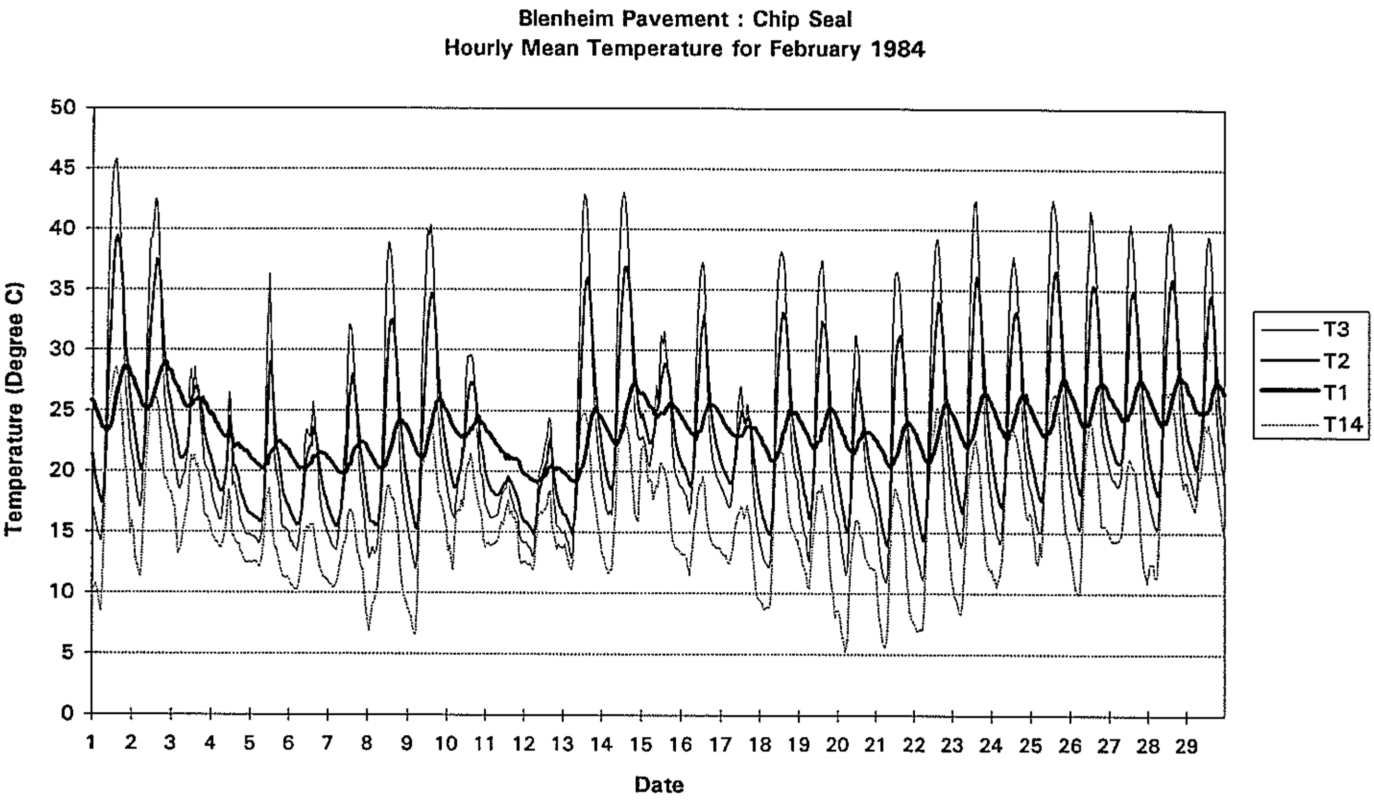


Figure B.14

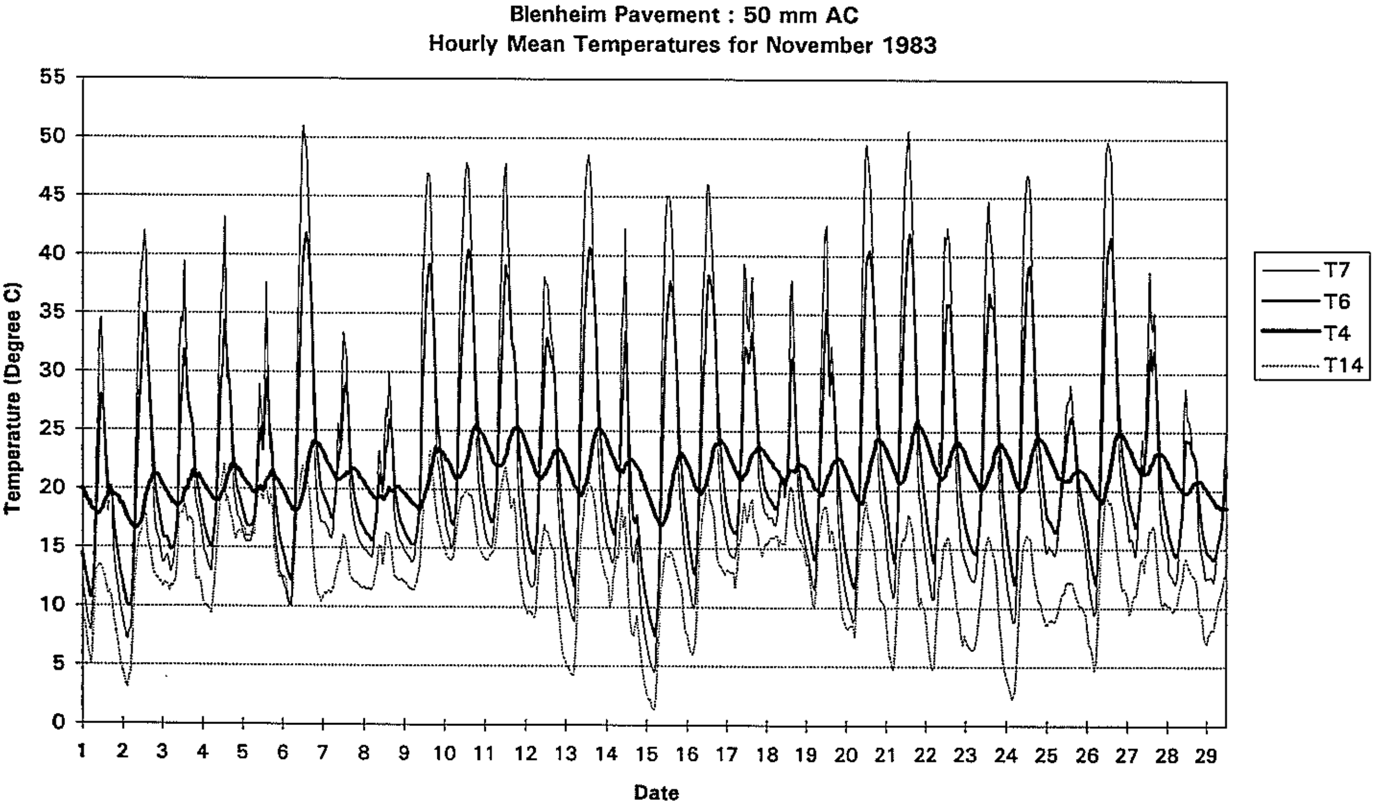


Figure B.15

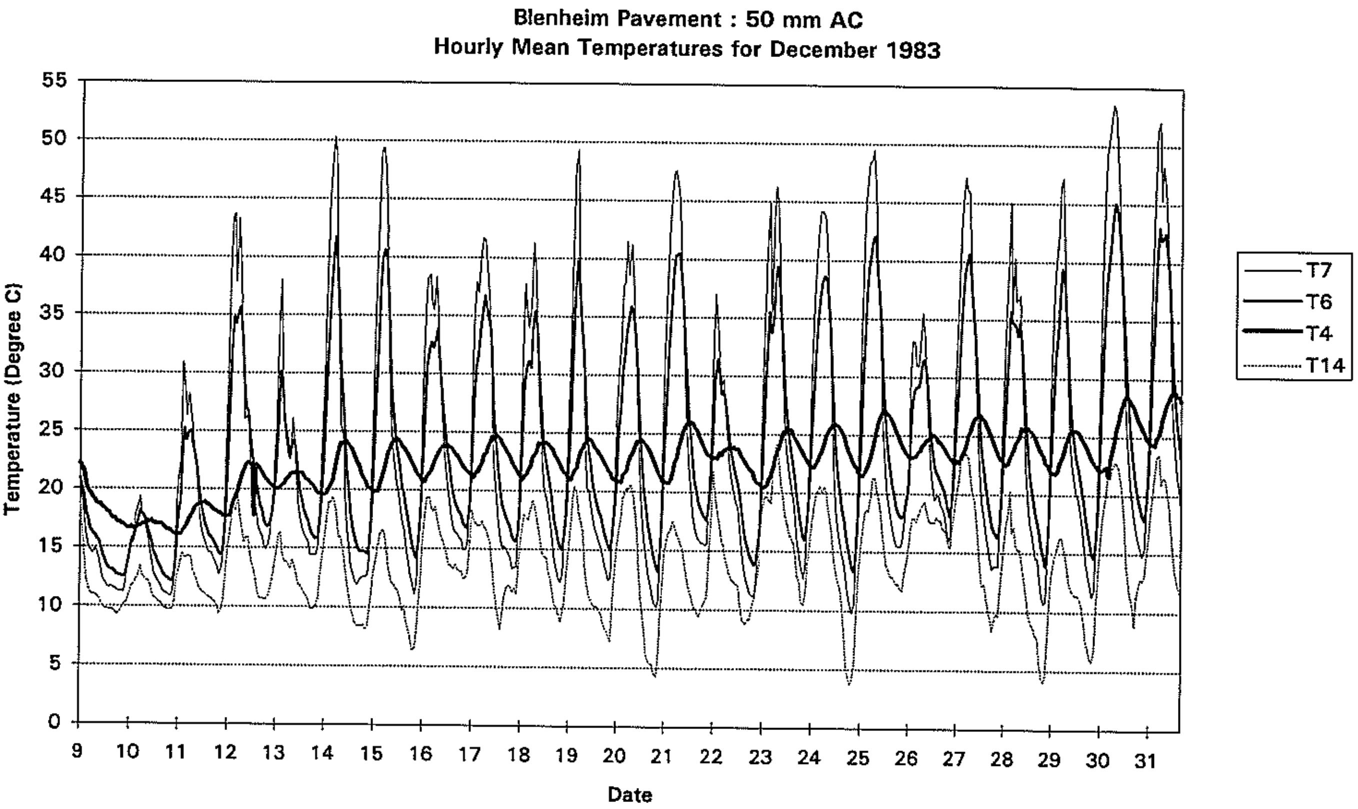


Figure B.16

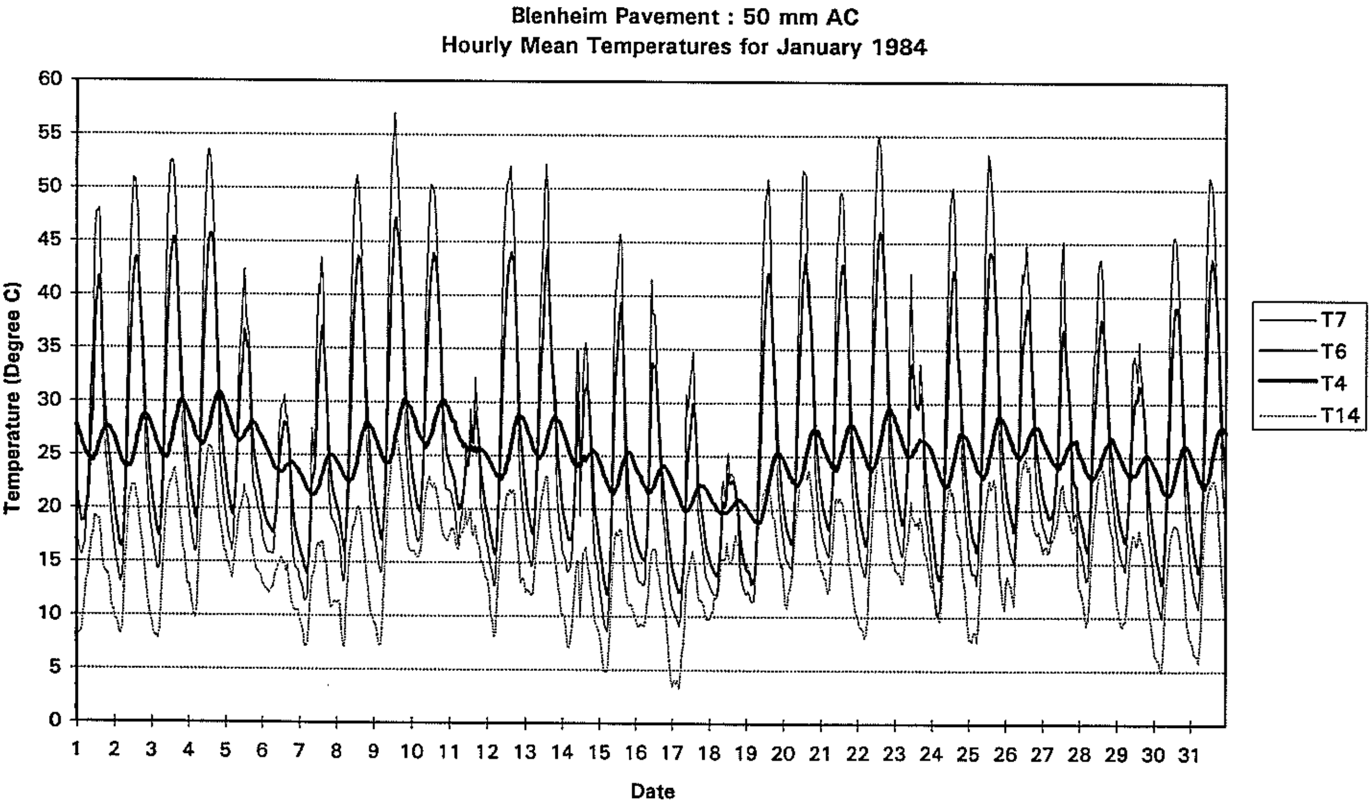
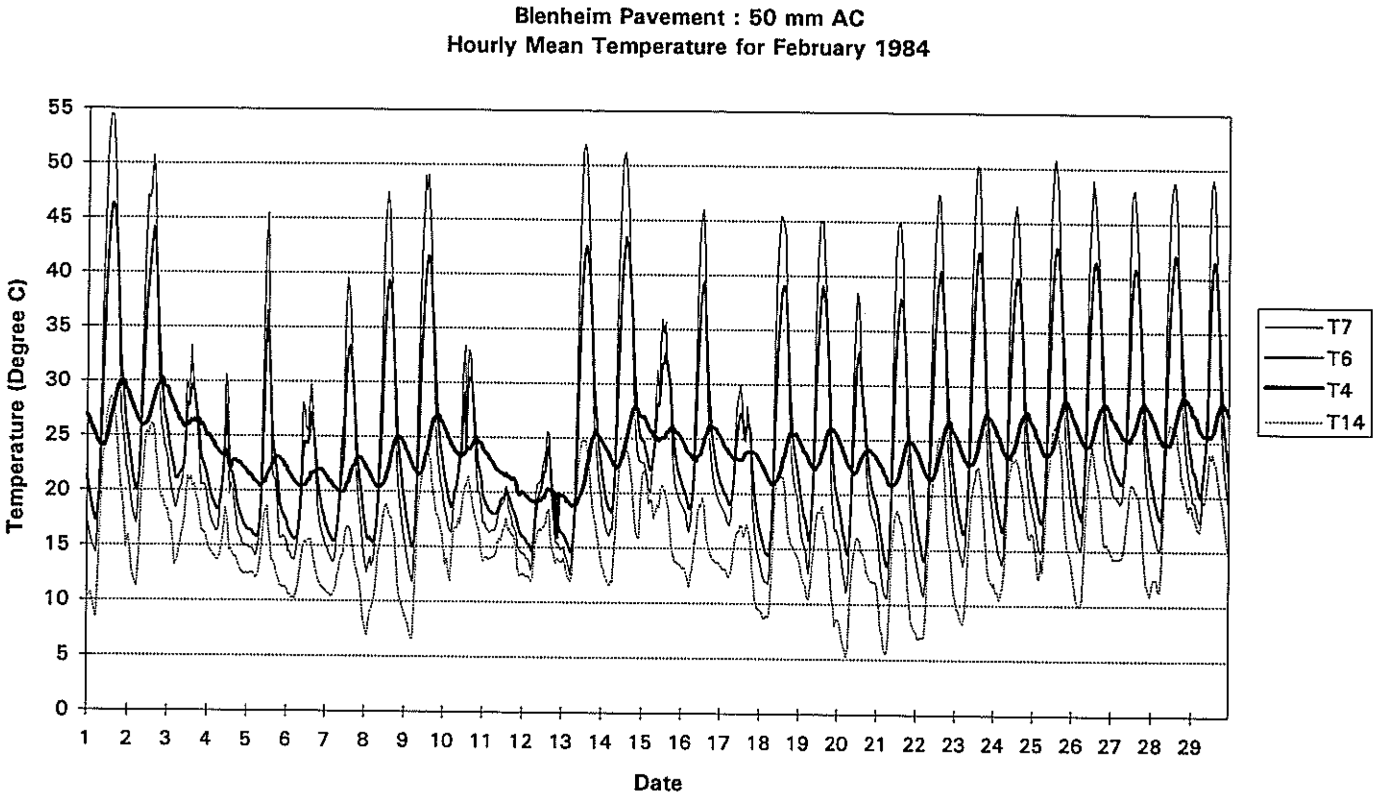
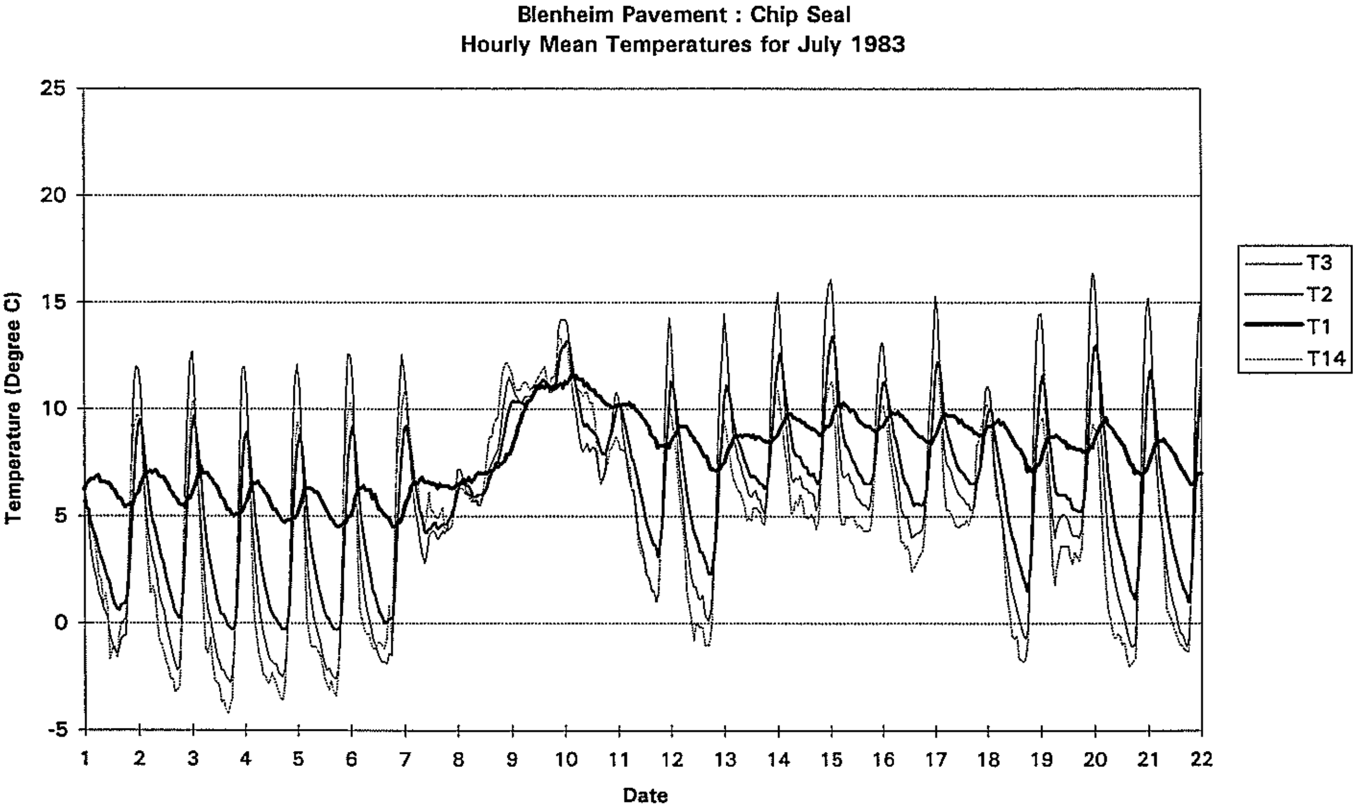


Figure B.17



Blenheim Pavement : 50 mm AC
Hourly Mean Temperature for February 1984

Figure B.18



Blenheim Pavement : Chip Seal
Hourly Mean Temperatures for July 1983

Figure B.19

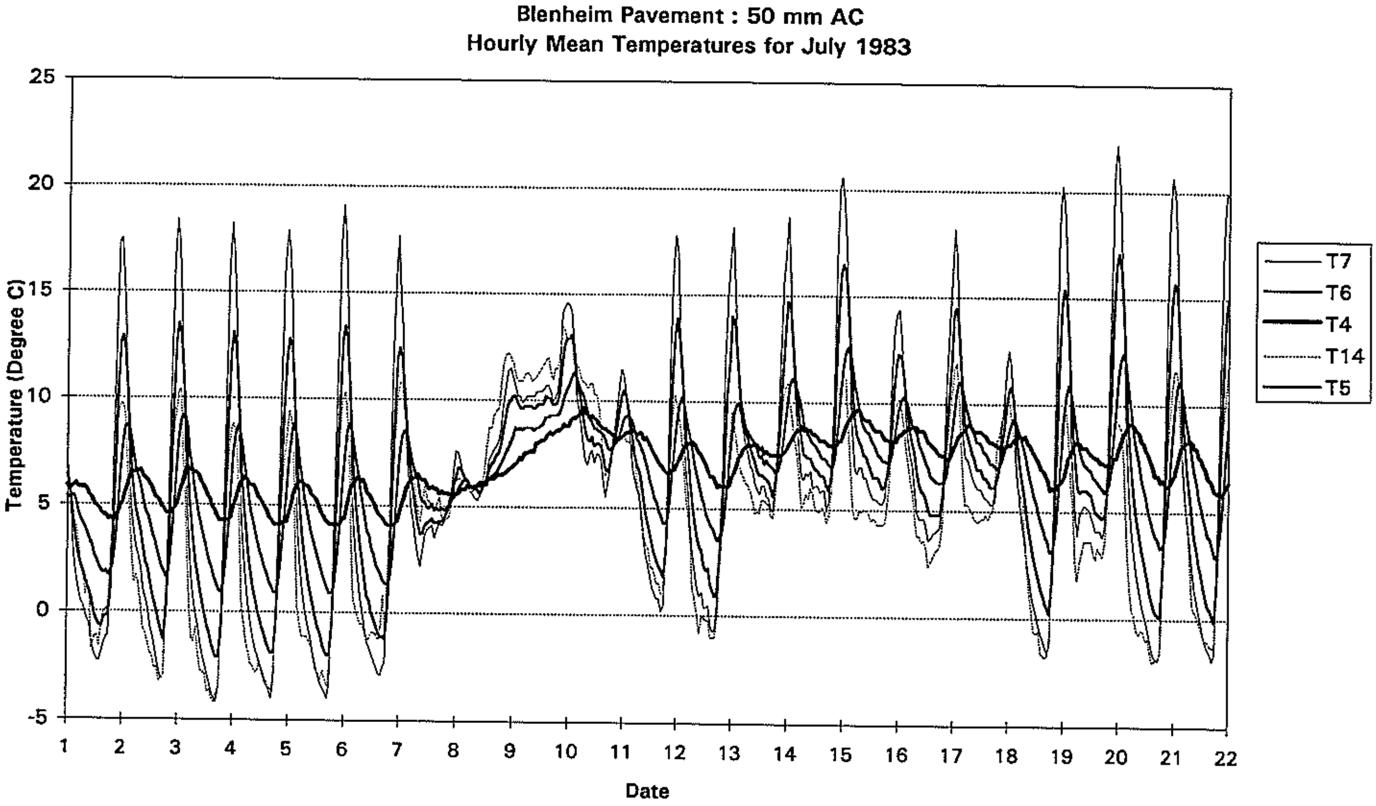

Blenheim Pavement : 50 mm AC
Hourly Mean Temperatures for July 1983

Figure B.20

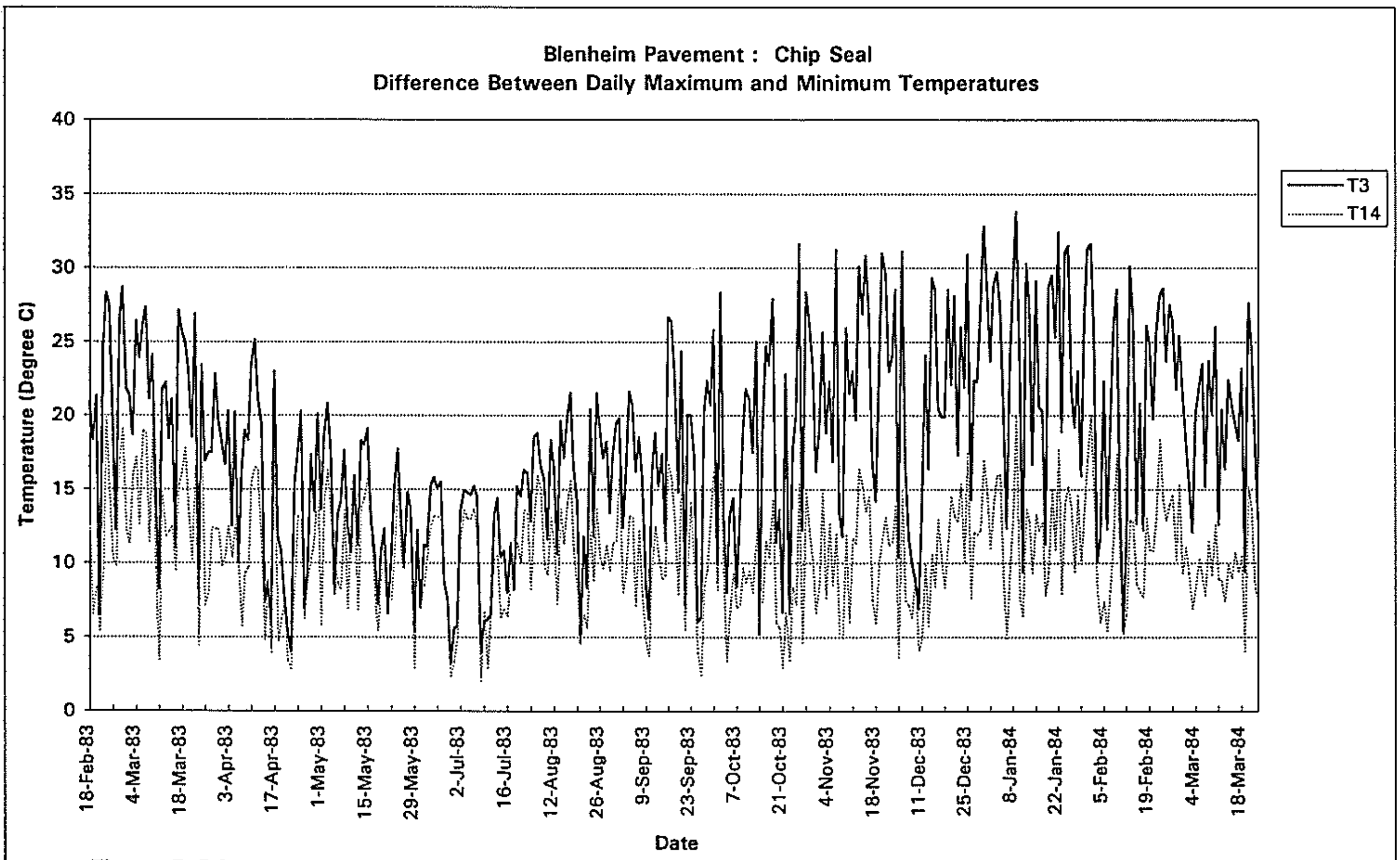

Blenheim Pavement : Chip Seal
Difference Between Daily Maximum and Minimum Temperatures

Figure B.21

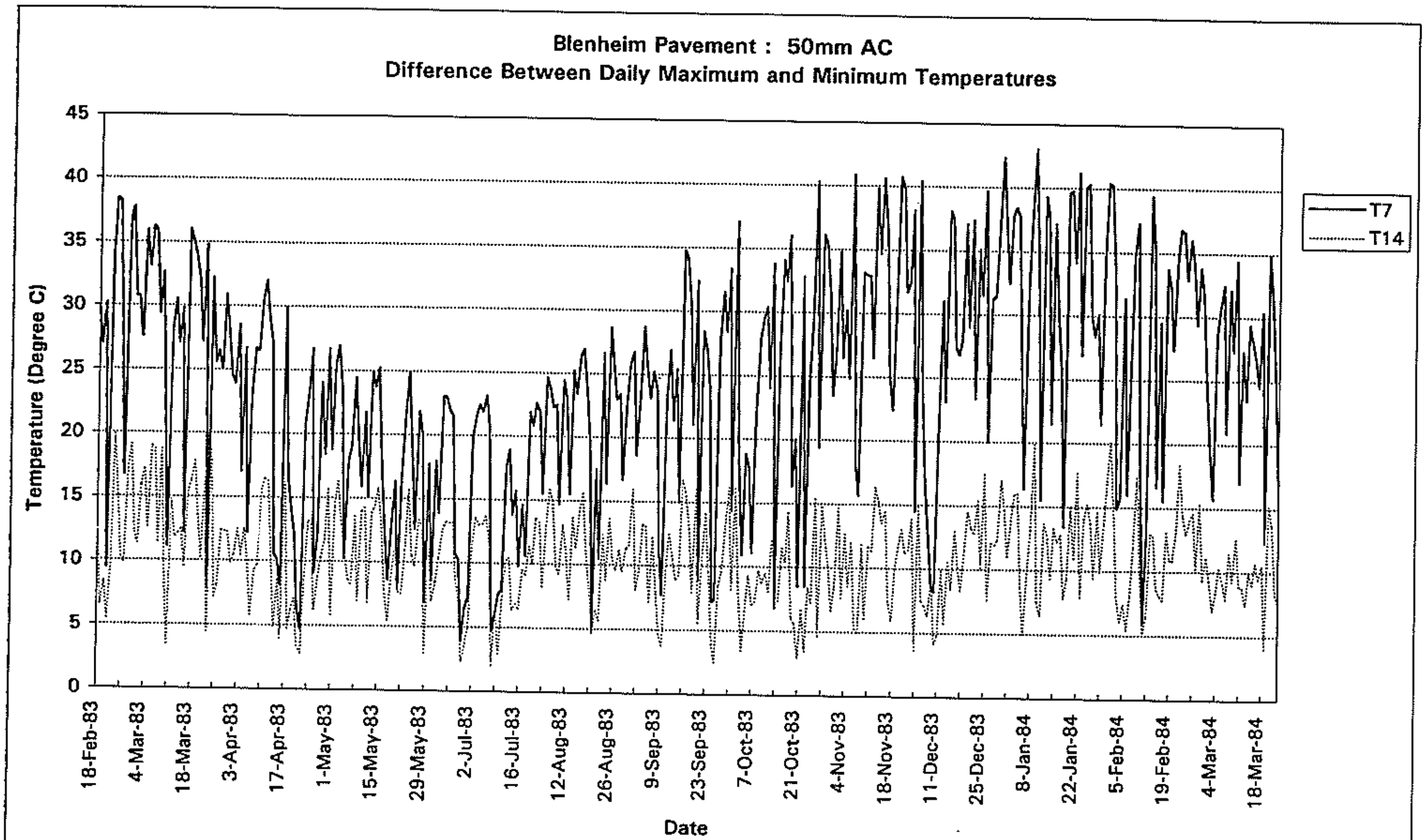


Figure B.22

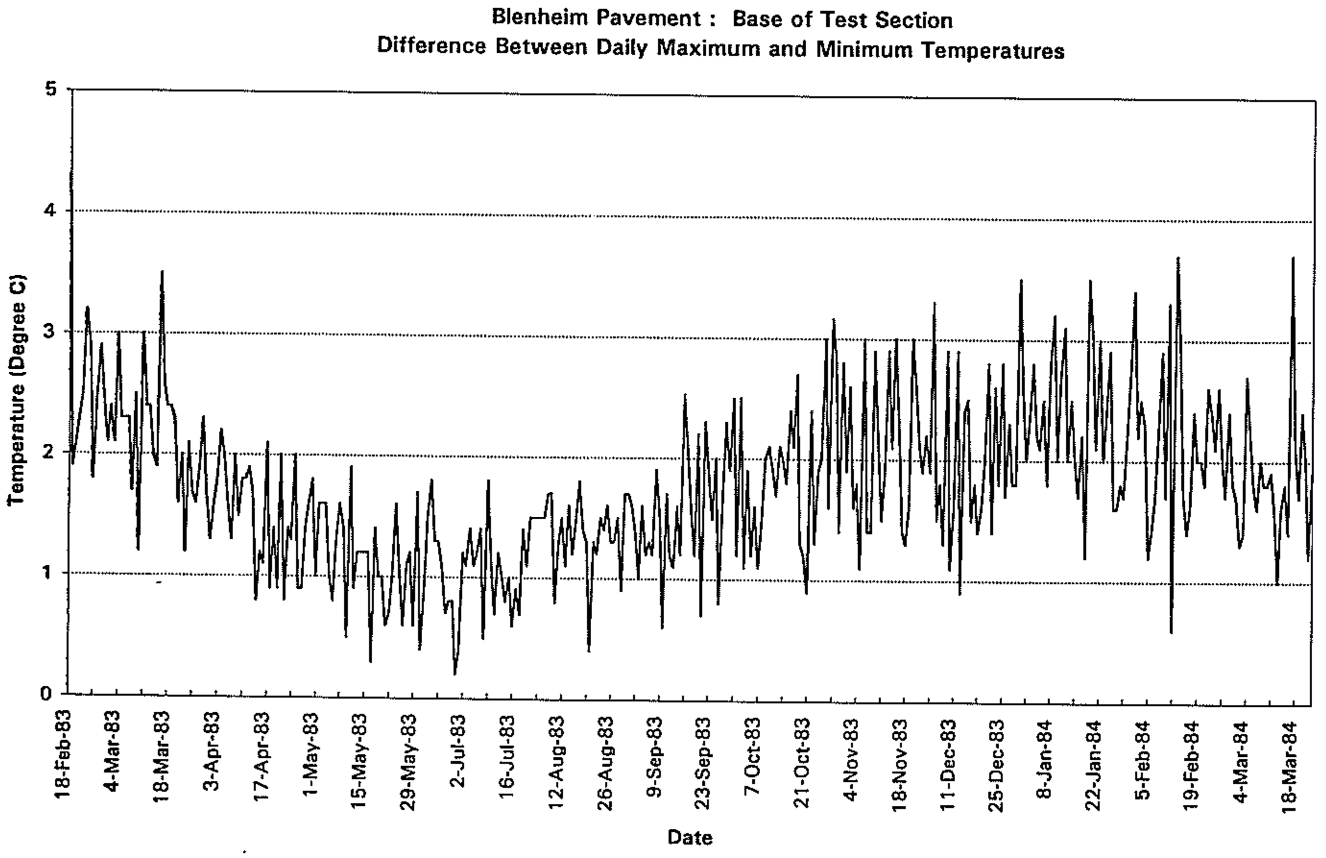


Figure B.23

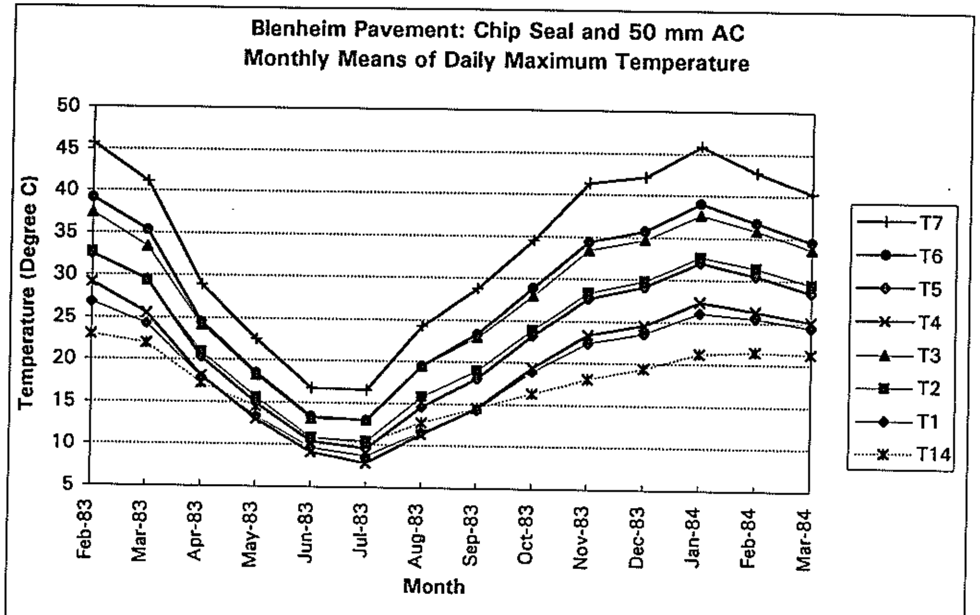


Figure B.24

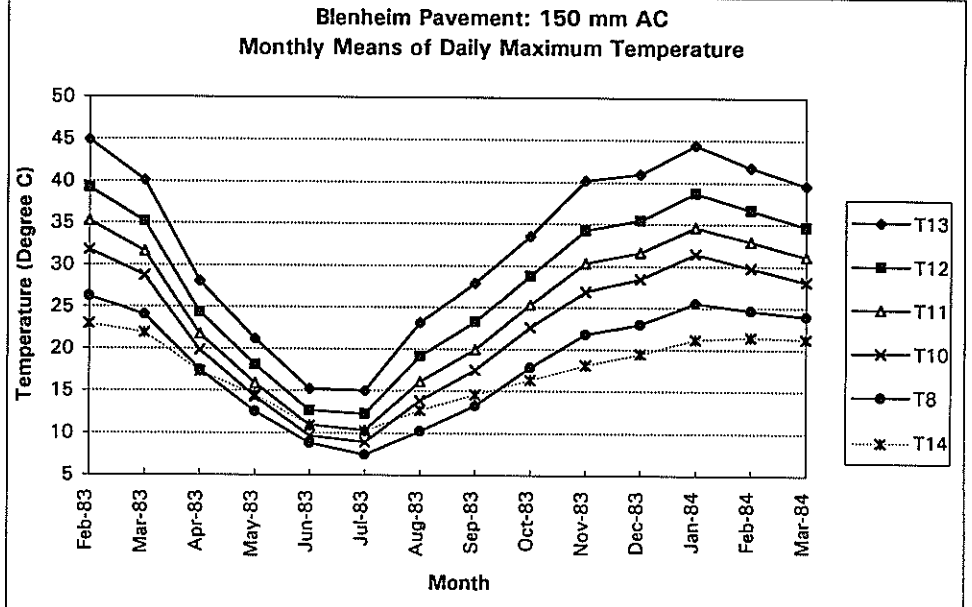


Figure B.25

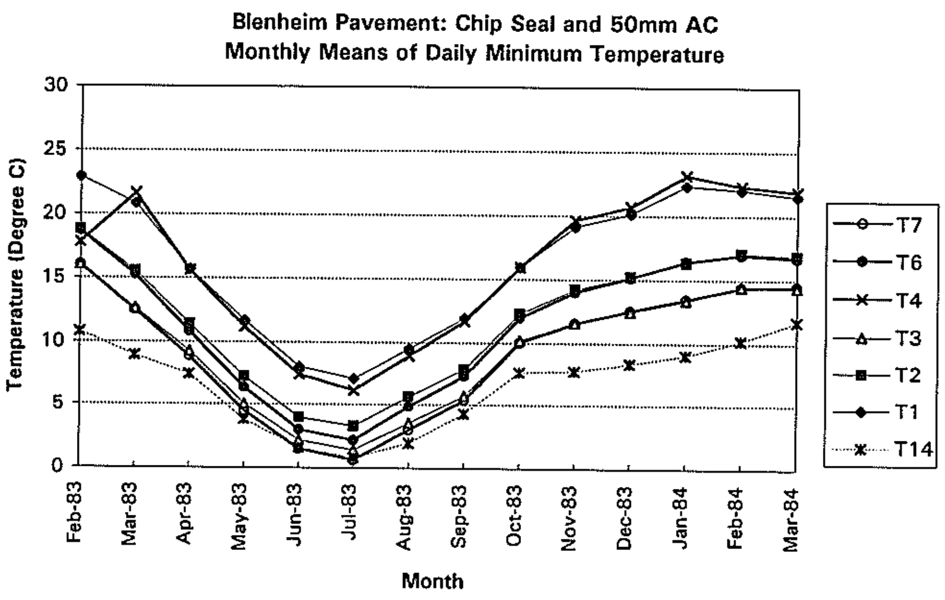


Figure B.26

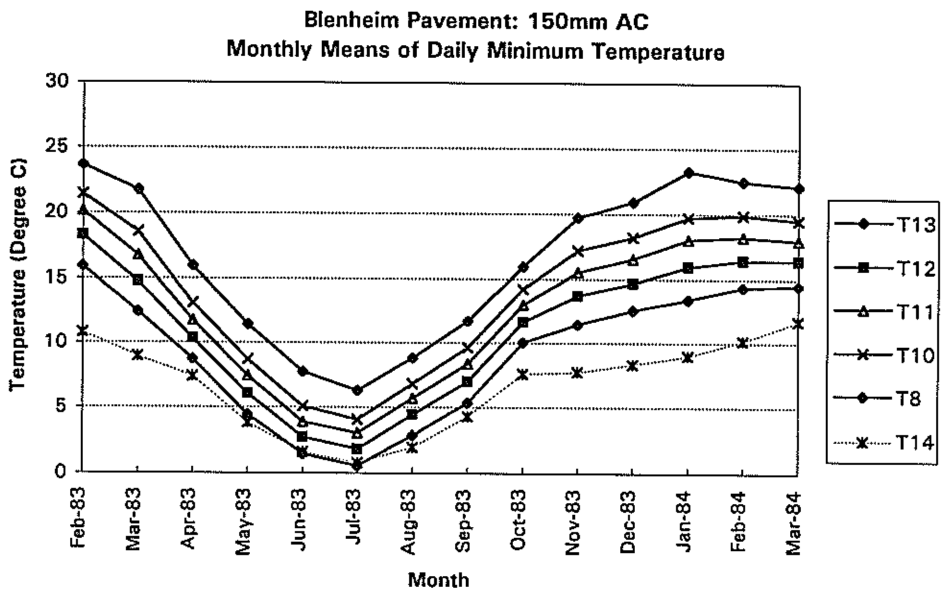


Figure B.27

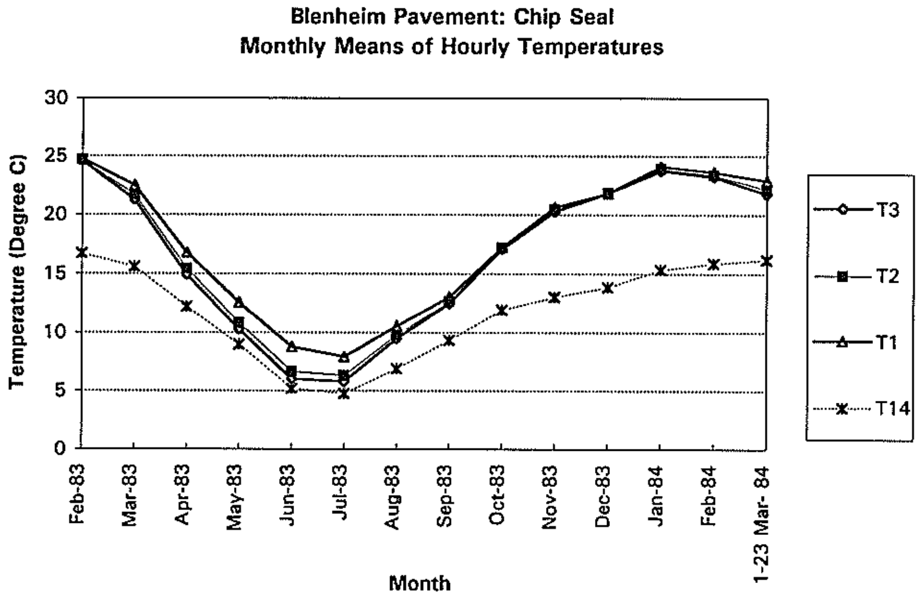


Figure B.28

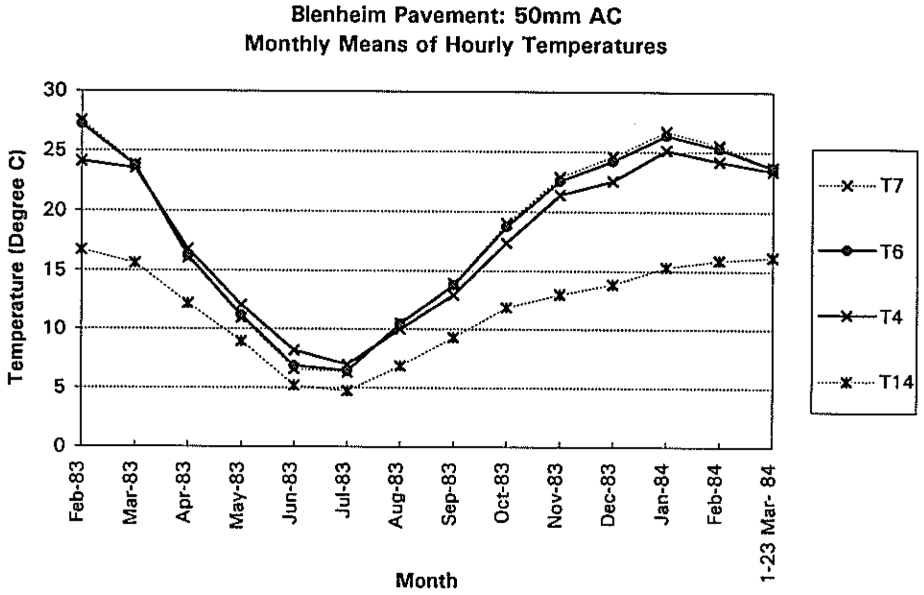


Figure B.29

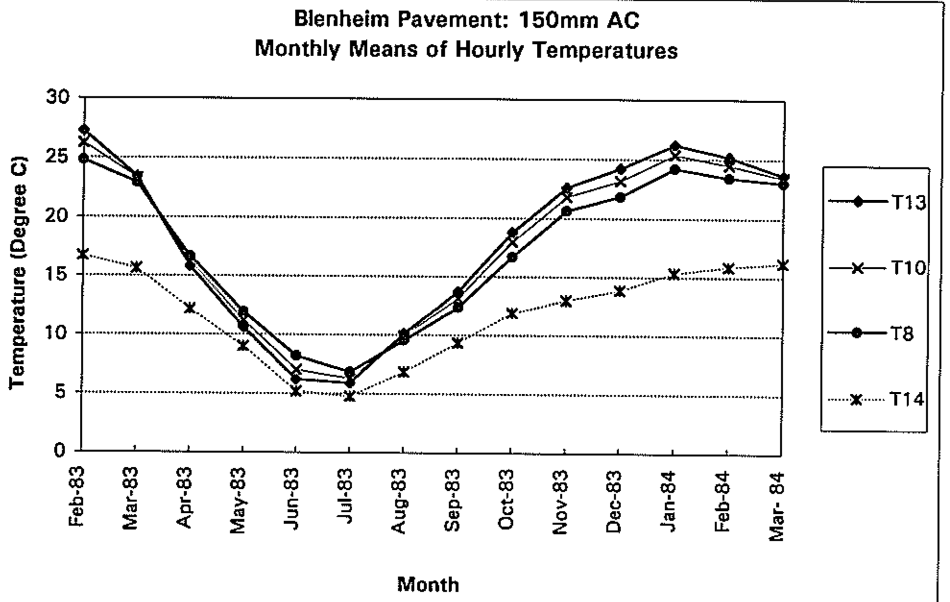


Figure B.30

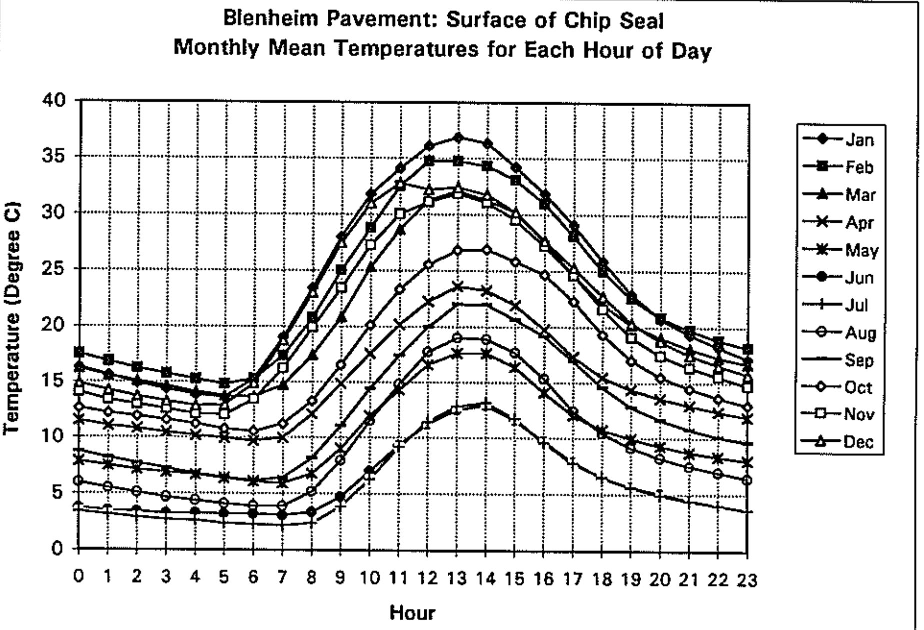


Figure B.31

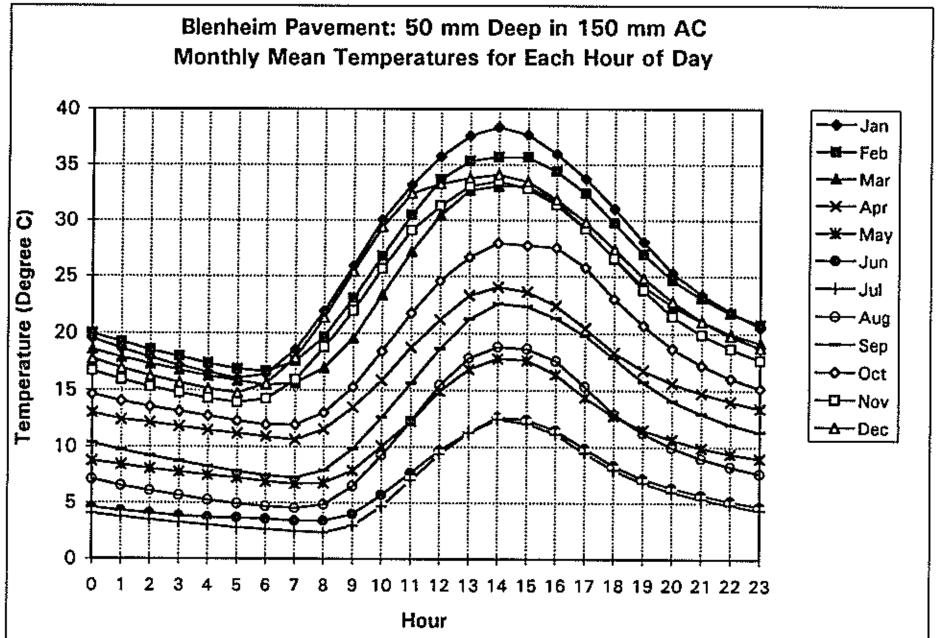


Figure B.32

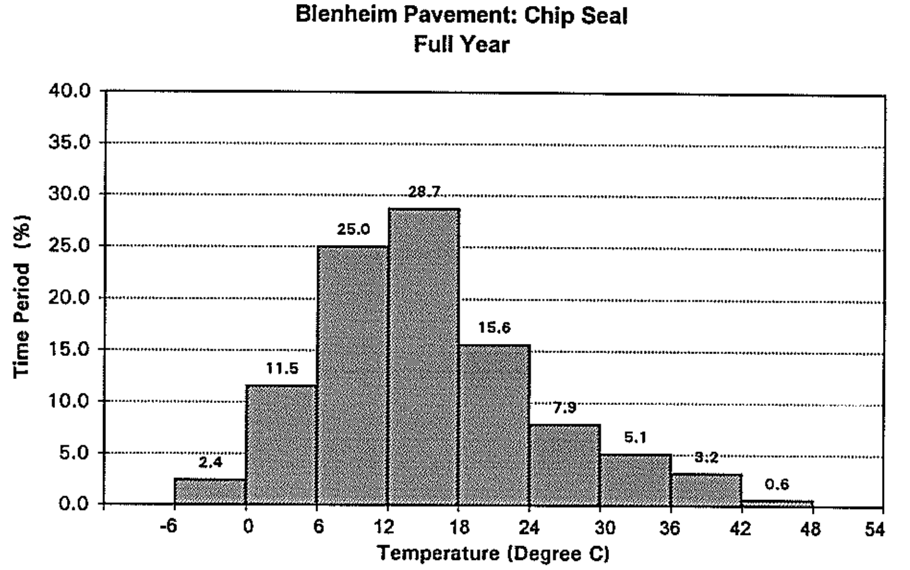


Figure B.33

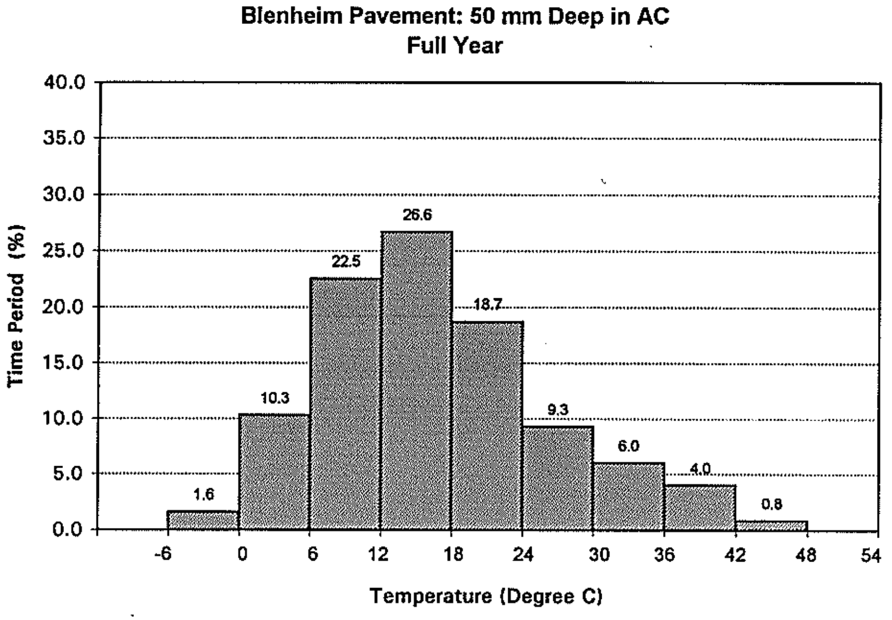


Figure B.34

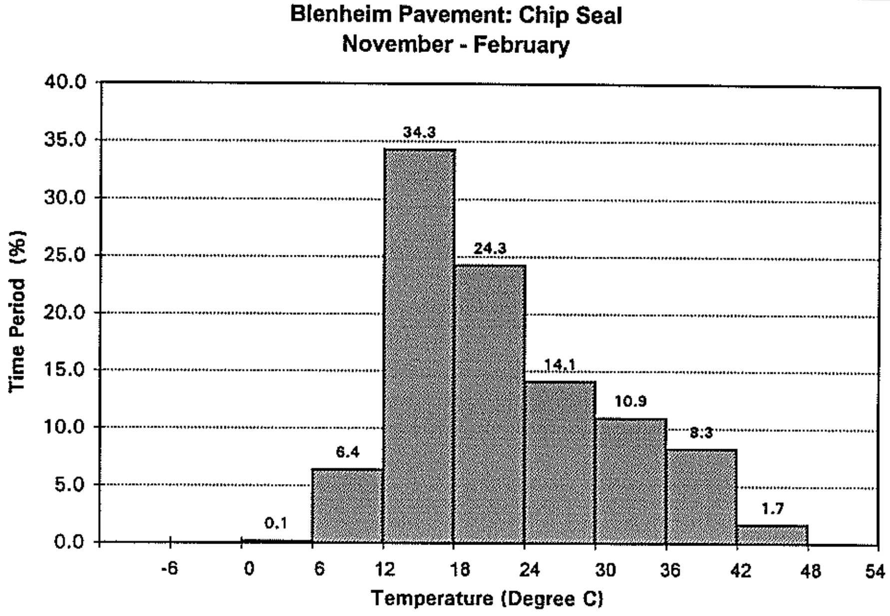
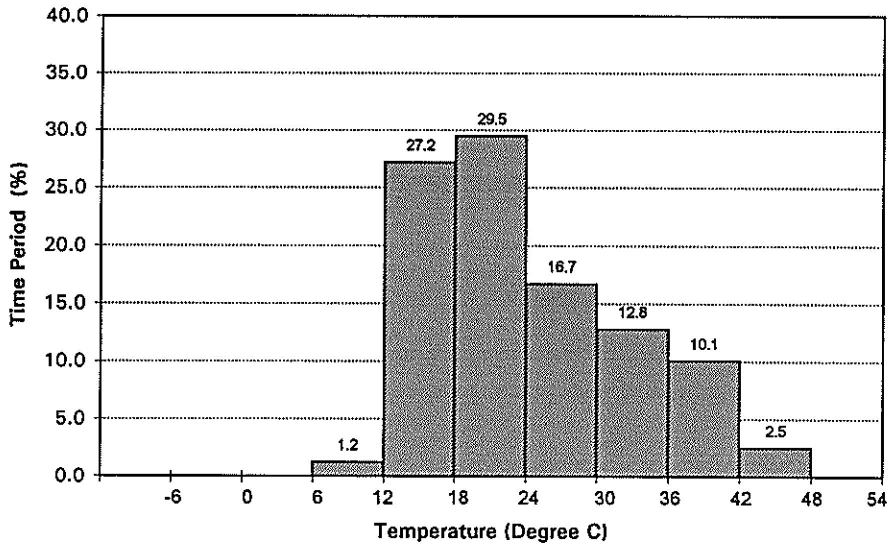
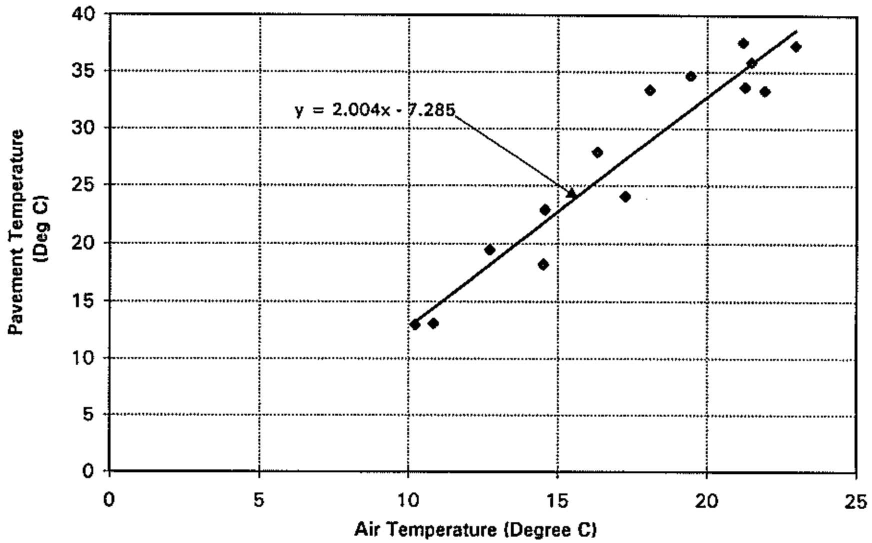


Figure B.35



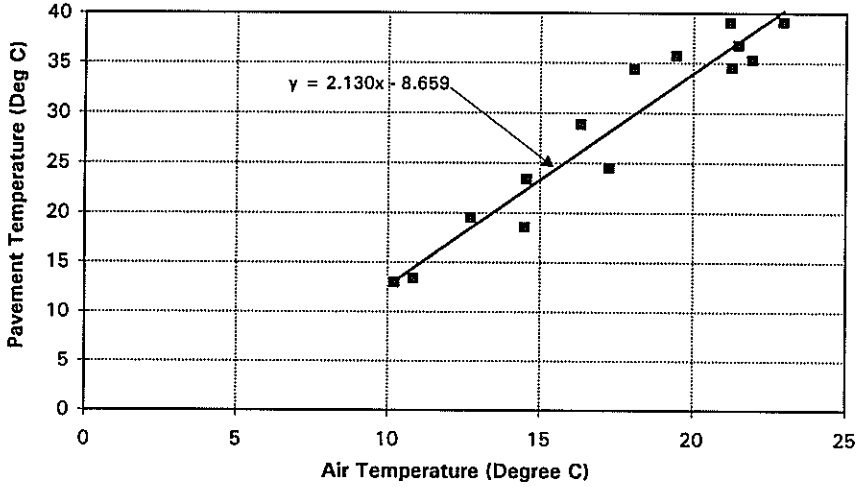
Blenheim Pavement: 50 mm Deep in AC
November - February

Figure B.36



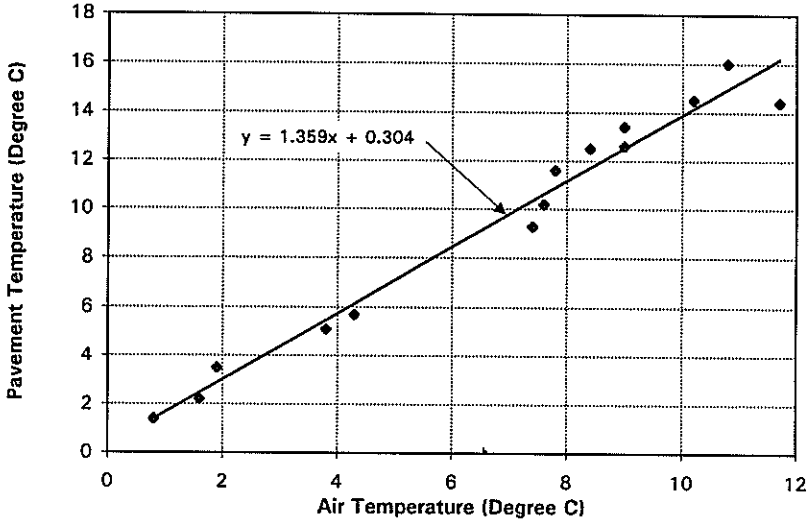
Blenheim Pavement: Surface of Chip Seal
Correlation Between Monthly Means of Max. Daily Pavement and Air Temperatures

Figure B.37



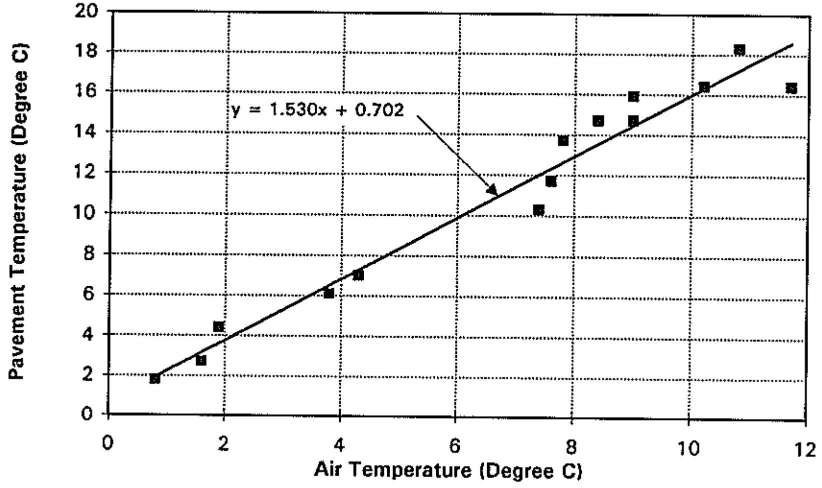
Blenheim Pavement: 50 mm Deep in 150 mm AC
Correlation Between Monthly Means of Max. Daily Pavement and Air Temperatures

Figure B.38



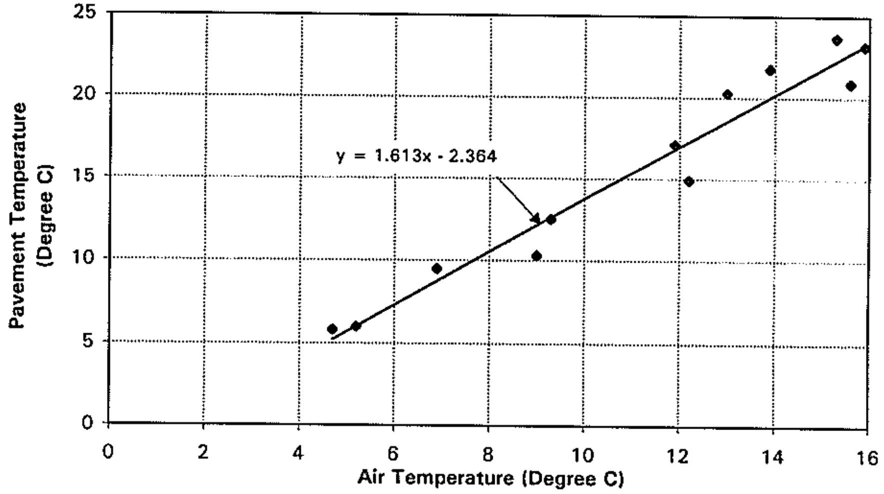
Blenheim Pavement: Surface of Chip Seal
Correlation Between Monthly Means of Min. Daily Pavement and Air Temperatures

Figure B.39



Blenheim Pavement: 50 mm Deep in 150 mm AC
Correlation Between Monthly Means of Min. Daily Pavement and Air Temperatures

Figure B.40



Blenheim Pavement: Surface of Chip Seal
Correlation Between Monthly Means of Pavement and Air Temperatures

Figure B.41

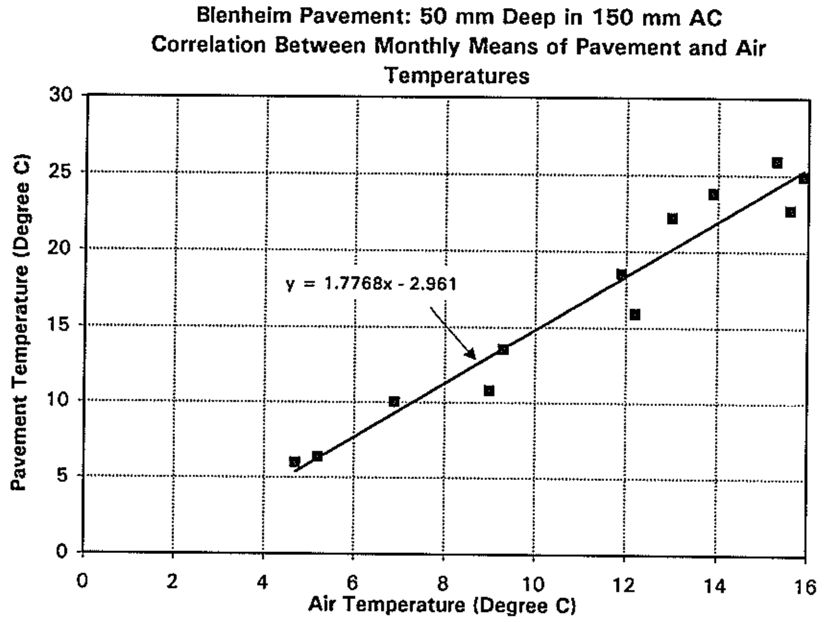

Blenheim Pavement: 50 mm Deep in 150 mm AC
Correlation Between Monthly Means of Pavement and Air Temperatures
Pavement Temperature (Degree C)
30
25
20
15
10
5
0
Air Temperature (Degree C)
0
2
4
6
8
10
12
14
16
y = 1.7768x - 2.961

Figure B.42

APPENDIX C

Cardrona Temperature Records

Table C.1 Monthly Means of Daily Maximum Temperatures (Deg C) and Solar Radiation (W/m^2)

Month	Probe Number												
	T1	T2	T3	T4	T5	T6	T7	T8	T9	T10	T11	TAir	Sun
Apr-88	10.4	16.8	24.4	13.6	16.4	21.3	11.8	12.4	13.6	17.0	23.2	13.7	535
May-88	4.7	6.9	10.7	6.6	8.8	13.2	5.0	5.3	5.9	8.7	14.7	8.6	404
Jun-88	2.4	3.3	5.3	3.9	5.8	9.5	2.6	3.0	3.4	5.7	10.4	6.8	215
Jul-88	2.6	4.4	6.6	4.9	7.0	10.7	3.1	3.5	4.1	6.4	11.2	6.1	309
Aug-88	5.2	9.0	12.6	9.9	13.1	18.4	5.8	7.1	8.5	12.1	19.2	8.2	496
Sep-88	10.6	16.2	20.9	17.5	21.4	28.6	10.8	13.1	15.4	20.1	29.5	12.6	655
Oct-88	13.1	18.7	23.7	20.9	24.7	33.1	13.7	16.3	18.5	23.4	34.4	11.9	807
Nov-88	19.3	26.9	32.5	29.1	34.0	43.5	19.6	22.9	26.2	33.0	46.2	16.0	911
Dec-88	23.7	30.9	36.9	33.4	38.0	49.5	24.6	27.6	30.2	36.4	51.8	19.4	972
Jan-89	26.2	33.8	39.5	35.9	40.6	53.1	26.5	30.0	32.9	39.3	54.8	23.1	927
Feb-89	22.8	28.6	33.6	30.5	34.1	46.0	23.3	26.0	28.1	32.9	46.9	20.4	800
Mar-89	19.0	25.0	30.1	26.1	30.0	42.0	19.7	21.9	23.9	28.9	42.9	19.6	695
Apr-89	12.4	17.0	21.4	17.6	20.7	31.7	13.1	14.7	16.3	20.0	32.8	16.1	552
May-89	6.9	8.9	11.7	9.4	11.3	19.1	7.8	8.1	8.8	10.9	19.5	10.3	362
Jun-89	3.0	4.3	6.5	4.8	6.3	13.4	3.6	3.9	4.5	6.3	13.7	8.4	282
Jul-89	0.3	0.8	4.5	1.4	4.0	15.6	1.0	0.9	2.1	6.1	17.8	5.3	417
Aug-89	5.9	10.4	14.4	10.5	13.7	23.8	6.1	7.7	9.4	13.3	24.5	10.3	494

Table C.2 Monthly Means of Daily Minimum Temperatures (Deg C)

Month	Probe Number											
	T1	T2	T3	T4	T5	T6	T7	T8	T9	T10	T11	TAir
Apr-88	6.3	2.8	0.6	4.9	3.7	1.7	9.5	8.4	7.1	4.9	1.9	0.5
May-88	2.7	-0.2	-1.8	1.0	-0.2	-2.0	3.3	2.4	1.3	-0.5	-2.9	-3.0
Jun-88	1.0	-0.6	-1.8	0.0	-1.0	-2.7	1.2	0.8	0.0	-1.5	-3.6	-2.9
Jul-88	1.3	-0.3	-1.5	0.2	-0.6	-2.4	1.6	1.1	0.3	-1.1	-3.1	-2.6
Aug-88	2.8	0.6	-0.9	1.9	0.8	-1.3	3.7	3.1	2.3	0.6	-1.9	-2.8
Sep-88	7.0	4.6	2.6	6.6	5.2	3.0	8.3	7.9	6.9	5.3	2.4	0.5
Oct-88	9.1	6.4	4.5	8.9	7.5	5.0	10.7	10.4	9.4	7.5	4.4	0.9
Nov-88	13.6	10.7	8.3	14.1	12.2	8.6	16.1	15.2	13.9	12.0	7.2	3.0
Dec-88	18.8	15.3	12.8	19.3	17.1	12.5	21.2	20.8	19.8	17.2	11.3	6.2
Jan-89	20.3	17.2	14.5	20.7	18.5	13.0	22.5	22.2	21.0	18.5	12.1	8.0
Feb-89	17.8	14.7	12.6	17.6	15.8	11.1	19.9	19.3	17.9	15.6	10.4	7.4
Mar-89	14.8	12.1	10.1	14.5	12.9	8.3	16.6	16.0	14.9	12.9	7.8	5.1
Apr-89	9.0	6.2	4.4	8.0	6.5	2.6	10.7	9.8	8.7	6.8	2.4	1.7
May-89	5.0	2.7	1.2	3.8	2.7	-0.4	6.2	5.3	4.4	2.9	-0.6	-0.1
Jun-89	1.4	-0.3	-1.6	0.4	-0.5	-3.6	2.1	1.3	0.6	-0.9	-4.0	-2.2
Jul-89	-0.4	-2.9	-4.8	-2.0	-3.4	-7.6	0.0	-0.6	-1.8	-4.1	-8.6	-7.2
Aug-89	3.0	1.1	-0.5	2.0	0.8	-3.0	3.9	3.2	2.3	0.8	-3.2	-2.6

Table C.3 Monthly Means of Hourly Temperatures (Deg C) and Radiation (W/m^2)

Month	Probe Number													No. hrs
	T1	T2	T3	T4	T5	T6	T7	T8	T9	T10	T11	TAir	Sun	Record
Apr-88	8.5	8.3	8.7	8.8	8.7	8.6	10.4	10.3	9.9	9.7	9.4	5.9	128	206
May-88	3.7	2.6	2.5	3.4	3.2	3.0	4.1	3.8	3.4	3.1	2.9	2.0	411	742
Jun-88	1.6	1.0	0.9	1.6	1.5	1.3	1.8	1.8	1.5	1.3	1.2	1.4	40	715
Jul-88	1.9	1.5	1.3	2.1	2.1	2.0	2.3	2.3	2.1	1.9	1.9	1.2	59	508
Aug-88	4.0	3.9	3.8	5.3	5.4	5.5	4.6	5.0	5.0	5.1	5.4	1.8	113	376
Sep-88	8.9	9.9	9.6	11.3	11.6	12.0	9.5	10.5	10.7	11.2	11.9	6.2	151	720
Oct-88	10.9	11.6	11.8	14.2	14.5	15.0	12.1	13.1	13.4	14.0	14.7	6.2	196	721
Nov-88	16.5	18.0	18.6	21.0	21.7	22.4	17.7	19.0	19.7	21.1	22.3	9.5	294	353
Dec-88	20.9	22.0	22.4	25.3	25.8	26.4	22.6	24.0	24.4	25.3	26.5	13.0	293	292
Jan-89	22.9	24.4	24.8	27.5	28.0	28.5	24.3	25.7	26.4	27.4	28.5	14.9	295	274
Feb-89	20.1	20.8	20.9	23.4	23.7	23.7	21.3	22.3	22.5	23.0	23.5	13.4	226	613
Mar-89	16.8	17.5	17.6	19.6	19.8	19.9	18.1	18.9	19.0	19.4	19.8	11.6	181	516
Apr-89	10.7	10.7	10.6	12.2	12.2	12.0	11.9	12.2	12.1	12.1	12.1	7.8	127	669
Year Mean May-88 to Apr-89	11.5	11.9	12.0	13.9	14.1	14.3	12.5	13.2	13.3	13.7	14.2	7.4	199	
Summer Mean Nov-88 to Feb-88	20.1	21.3	21.7	24.4	24.9	25.3	21.5	22.8	23.3	24.2	25.3	12.7	278	
May-89	5.9	5.2	4.9	6.1	6.0	5.5	6.9	6.7	6.4	6.1	5.7	4.1	67	732
Jun-89	2.0	1.5	1.4	2.1	2.0	1.9	2.7	2.5	2.2	2.1	2.0	2.3	56	237
Jul-89	-0.2	-1.2	-1.6	-0.6	-0.8	-1.4	0.4	0.0	-0.4	-0.9	-1.4	-2.7	84	184
Aug-89	4.4	4.7	4.7	5.6	5.7	5.7	5.0	5.4	5.5	5.6	5.9	2.5	115	485

Note:

Year Mean = sum of (monthly mean x days in month)/(days in year)

Summer Mean = sum of (monthly mean x days in month for Nov, Dec, Jan, Feb)/(sum of days in months)

Table C.4 Monthly Means of Temp (Deg C) for each Hour of Day: Surface of Chip Seal

Hour	Jan 89	Feb 89	Mar 89	Apr 89	May 88	Jun 88	Jul 88	Aug 88	Sep 88	Oct 88	Nov 88	Dec 88	Mean For Yr
0	18.7	16.5	13.4	7.5	-0.1	-0.4	-0.5	0.5	5.4	6.8	11.7	15.2	7.8
1	17.8	15.7	12.7	7.0	-0.3	-0.4	-0.5	0.3	4.9	6.3	10.8	14.6	7.4
2	16.8	14.9	12.1	6.6	-0.5	-0.5	-0.6	0.2	4.5	5.9	9.8	13.9	6.9
3	16.0	14.2	11.6	6.2	-0.7	-0.6	-0.8	0.0	4.1	5.5	9.1	13.3	6.4
4	15.4	13.6	11.1	5.8	-0.9	-0.7	-0.8	-0.2	3.7	5.1	8.6	12.8	6.1
5	14.9	13.2	10.7	5.4	-1.1	-0.8	-0.7	-0.2	3.4	4.9	8.2	12.6	5.8
6	14.4	12.9	10.5	5.1	-1.3	-0.8	-0.7	-0.3	3.2	5.0	8.8	13.4	5.8
7	14.3	12.7	10.2	4.7	-1.4	-0.9	-0.8	-0.4	3.3	6.5	12.6	16.9	6.4
8	16.4	13.7	10.4	4.5	-0.8	-1.0	-0.8	0.5	5.3	9.7	17.2	21.1	8.0
9	20.7	17.1	12.3	5.2	1.6	-0.2	-0.2	3.1	9.0	12.7	21.7	26.2	10.7
10	25.1	21.0	16.7	8.3	4.6	1.4	1.4	6.5	12.2	15.8	26.6	30.6	14.1
11	28.3	24.7	21.0	12.3	7.4	3.1	3.3	8.6	15.8	19.0	29.3	33.0	17.1
12	32.4	28.2	24.7	16.0	9.5	3.9	5.2	10.8	18.8	21.1	30.7	34.5	19.6
13	35.9	31.1	27.0	19.1	10.3	4.8	6.4	12.5	20.0	21.7	31.4	35.0	21.2
14	38.2	31.8	28.7	20.9	9.3	5.0	6.8	12.3	20.1	21.6	30.1	34.4	21.5
15	38.6	31.7	29.1	20.8	6.9	3.2	5.0	10.2	18.6	20.7	28.4	32.3	20.4
16	38.5	31.1	28.5	19.1	5.2	2.3	3.7	8.1	15.8	18.8	26.7	30.0	18.9
17	36.5	29.5	25.3	16.8	3.7	1.4	2.5	5.9	13.2	16.4	24.0	27.4	16.8
18	32.9	26.7	21.3	14.0	2.7	1.0	1.7	4.1	11.2	13.7	21.1	24.0	14.5
19	28.5	23.5	19.6	11.9	2.0	0.7	1.2	3.0	9.7	11.6	18.3	21.4	12.6
20	25.8	21.2	17.5	10.5	1.6	0.5	0.8	2.3	8.5	10.2	16.3	19.4	11.2
21	23.3	19.4	15.9	9.6	1.1	0.2	0.4	1.7	7.6	9.1	14.9	17.9	10.0
22	21.4	18.3	14.8	8.7	0.7	-0.1	0.1	1.2	6.8	8.2	13.8	17.0	9.2
23	20.0	17.3	13.8	8.1	0.3	-0.2	-0.2	0.9	6.1	7.4	12.7	16.1	8.5
Mean for Mth	24.6	20.8	17.5	10.6	2.5	0.9	1.3	3.8	9.6	11.8	18.5	22.2	12.0

Table C.5 Monthly Means of Temp (Deg C) for each Hour of Day:
75 mm Deep in 150 mm Thick AC

Hour	Jan 89	Feb 89	Mar 89	Apr 89	May 88	Jun 88	Jul 88	Aug 88	Sep 88	Oct 88	Nov 88	Dec 88	Mean For Yr
0	24.6	21.1	17.6	10.8	1.6	0.1	0.7	2.8	8.5	10.7	15.9	20.8	11.2
1	23.2	20.0	16.7	10.1	1.2	-0.1	0.4	2.4	7.9	10.0	15.4	19.8	10.5
2	22.0	19.2	15.9	9.5	0.9	-0.2	0.1	2.1	7.3	9.4	14.4	18.9	9.9
3	21.0	18.3	15.2	9.0	0.7	-0.4	-0.2	1.7	6.8	8.9	13.5	18.1	9.3
4	20.1	17.6	14.6	8.6	0.4	-0.5	-0.4	1.4	6.4	8.4	12.9	17.4	8.9
5	19.3	17.0	14.1	8.2	0.2	-0.6	-0.6	1.2	6.0	8.0	12.1	16.8	8.4
6	18.7	16.4	13.6	7.8	0.0	-0.7	-0.5	1.1	5.6	7.7	11.9	16.5	8.1
7	18.1	15.9	13.2	7.3	-0.2	-0.9	-0.6	0.8	5.4	7.7	12.5	17.0	8.0
8	17.9	15.7	12.9	7.0	-0.3	-1.0	-0.7	0.8	5.7	8.8	14.6	19.0	8.3
9	18.9	16.3	13.0	6.8	0.2	-0.9	-0.7	1.8	7.2	10.7	18.0	22.2	9.4
10	21.6	18.3	14.5	7.5	1.6	0.0	0.2	3.9	9.5	13.1	22.0	26.2	11.5
11	24.7	21.2	17.1	9.5	3.7	1.4	1.9	5.9	12.2	15.8	25.2	29.4	14.0
12	28.0	24.1	20.1	12.2	5.8	3.2	3.8	8.2	15.0	18.7	27.9	32.1	16.6
13	31.3	27.1	23.0	14.9	7.6	4.7	5.6	10.3	17.5	20.7	29.9	34.0	18.8
14	34.2	29.6	25.5	17.5	8.9	5.6	6.9	12.0	19.3	22.0	30.5	35.1	20.5
15	36.7	31.0	27.4	19.3	8.6	5.5	6.8	12.3	19.9	22.5	32.3	35.4	21.4
16	38.1	31.8	28.4	19.9	7.6	4.5	5.9	11.5	19.2	22.4	31.3	34.5	21.2
17	38.9	31.9	28.4	19.5	6.2	3.4	4.8	9.8	17.4	20.9	29.2	33.4	20.3
18	38.2	31.1	25.9	18.0	5.1	2.6	3.9	8.2	15.5	18.9	27.1	31.7	18.8
19	36.3	29.1	24.9	16.2	4.2	2.0	3.1	6.7	13.8	16.9	24.9	29.5	17.2
20	33.4	27.0	22.8	14.6	3.5	1.5	2.5	5.6	12.4	15.2	22.7	27.0	15.6
21	30.7	24.9	21.0	13.4	2.9	1.0	2.0	4.7	11.2	13.7	20.8	24.9	14.2
22	28.3	23.5	19.4	12.4	2.4	0.7	1.5	4.0	10.3	12.6	19.0	23.2	13.1
23	26.3	22.0	18.2	11.5	1.8	0.4	1.1	3.5	9.4	11.6	17.7	21.9	12.1
Mean for Mth	27.1	22.9	19.3	12.1	3.1	1.3	2.0	5.1	11.2	14.0	20.9	25.2	13.6

Table C.6 Monthly Means of Temp (Deg C) for each Hour of Day:
50 mm Deep in 150 mmThick AC

Hour	Jan 89	Feb 89	Mar 89	Apr 89	May 88	Jun 88	Jul 88	Aug 88	Sep 88	Oct 88	Nov 88	Dec 88	Mean For Yr
0	24.4	21.1	17.5	10.8	1.7	0.3	0.6	2.7	8.4	10.6	16.2	20.5	11.2
1	23.1	20.1	16.6	9.4	1.4	0.2	0.4	2.2	7.8	9.9	15.4	19.5	10.4
2	21.9	19.2	15.8	9.2	1.1	0.1	0.1	1.9	7.2	9.3	14.3	18.6	9.8
3	20.9	18.3	15.1	8.7	0.8	0.0	-0.1	1.6	6.7	8.8	13.4	17.9	9.3
4	20.0	17.6	14.5	8.3	0.6	-0.1	-0.3	1.3	6.3	8.3	12.8	17.2	8.8
5	19.2	17.0	13.9	7.8	0.4	-0.2	-0.2	1.2	5.8	7.9	12.1	16.6	8.4
6	18.6	16.4	13.5	7.4	0.2	-0.3	-0.2	1.1	5.5	7.6	12.0	16.4	8.1
7	18.1	16.0	13.1	7.0	0.0	-0.4	-0.2	0.9	5.2	7.9	13.3	17.7	8.2
8	18.3	15.9	12.8	6.6	0.0	-0.5	-0.3	1.1	5.9	9.6	16.5	20.6	8.8
9	20.6	17.4	13.4	6.7	0.8	-0.3	-0.1	2.4	8.2	12.0	20.2	24.4	10.4
10	24.0	20.1	15.8	8.0	2.4	0.8	0.8	5.0	11.0	14.9	24.6	28.9	13.0
11	27.2	23.3	18.9	10.2	4.5	2.1	2.5	7.4	14.1	17.9	28.3	32.1	15.7
12	30.6	26.5	22.2	13.3	6.4	3.5	4.5	9.9	17.1	20.8	30.7	34.6	18.3
13	34.0	29.5	25.1	16.2	8.0	4.8	6.3	11.9	19.5	22.5	32.4	36.2	20.5
14	36.7	31.7	27.5	18.8	9.0	5.7	7.4	13.2	20.9	23.4	32.7	36.9	21.9
15	38.8	32.6	28.9	20.3	8.2	5.1	6.8	12.7	20.9	23.4	32.3	36.6	22.2
16	39.8	33.0	29.5	20.3	7.0	4.0	5.6	11.4	19.5	22.9	31.6	35.2	21.6
17	40.0	32.6	28.8	19.5	5.7	3.0	4.5	9.5	17.3	21.4	29.6	33.8	20.4
18	38.6	31.5	25.8	17.5	4.7	2.3	3.6	7.8	15.3	19.2	26.7	31.0	18.6
19	35.7	29.3	24.6	15.7	3.9	1.8	2.8	6.4	13.6	17.0	24.3	28.4	16.9
20	32.6	26.9	22.5	14.1	3.4	1.4	2.3	5.3	12.2	15.2	22.1	26.1	15.3
21	30.0	24.9	20.7	12.9	2.9	1.0	1.8	4.5	11.1	13.7	20.3	24.2	13.9
22	27.8	23.4	19.2	11.9	2.5	0.8	1.4	3.8	10.2	12.6	18.6	22.8	12.9
23	25.9	22.0	18.0	11.1	2.0	0.5	1.0	3.3	9.3	11.6	17.5	21.6	11.9
Mean for Mth	27.8	23.6	19.7	12.2	3.2	1.5	2.1	5.4	11.6	14.5	21.6	25.7	14.0

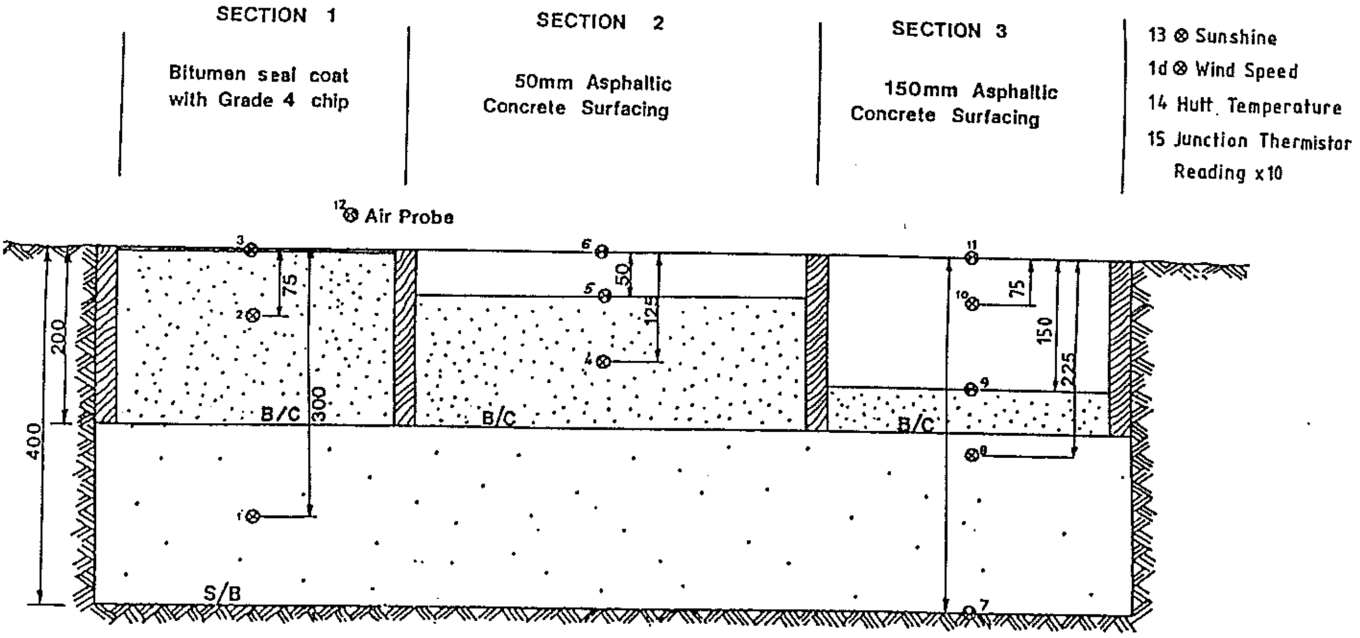


Figure C.1 Test Site Pavement Sections and Probe Locations

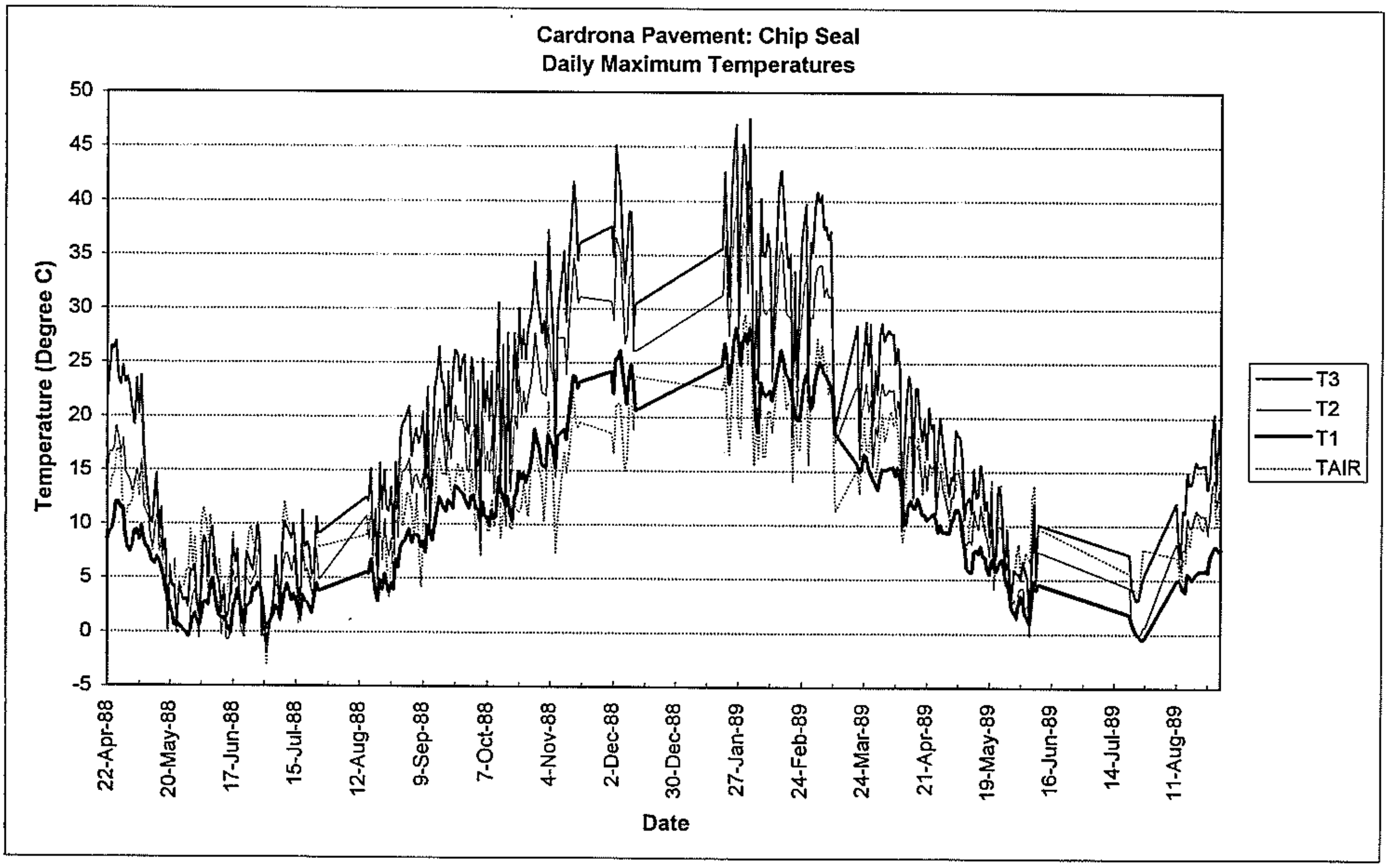


Figure C.2

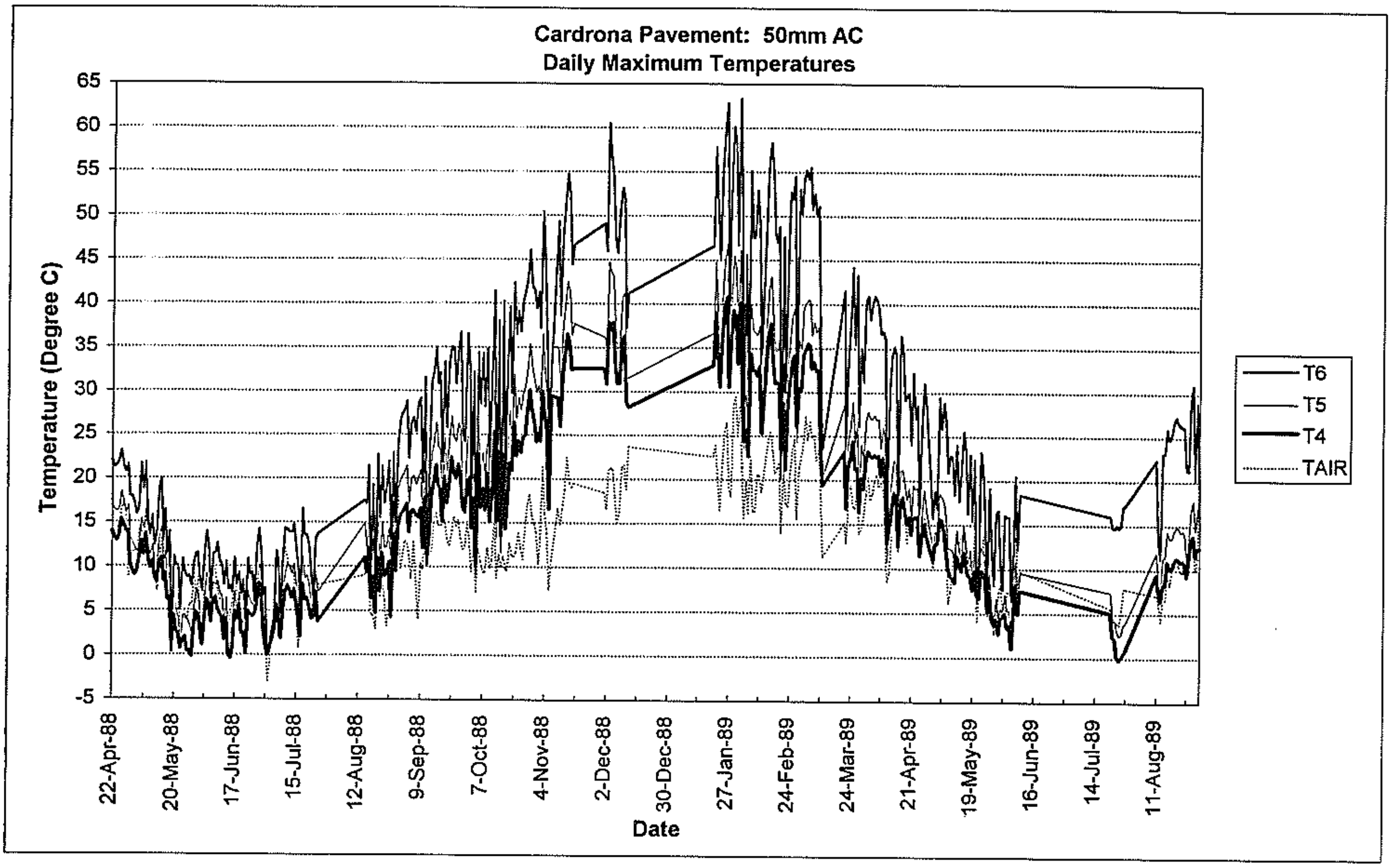


Figure C.3

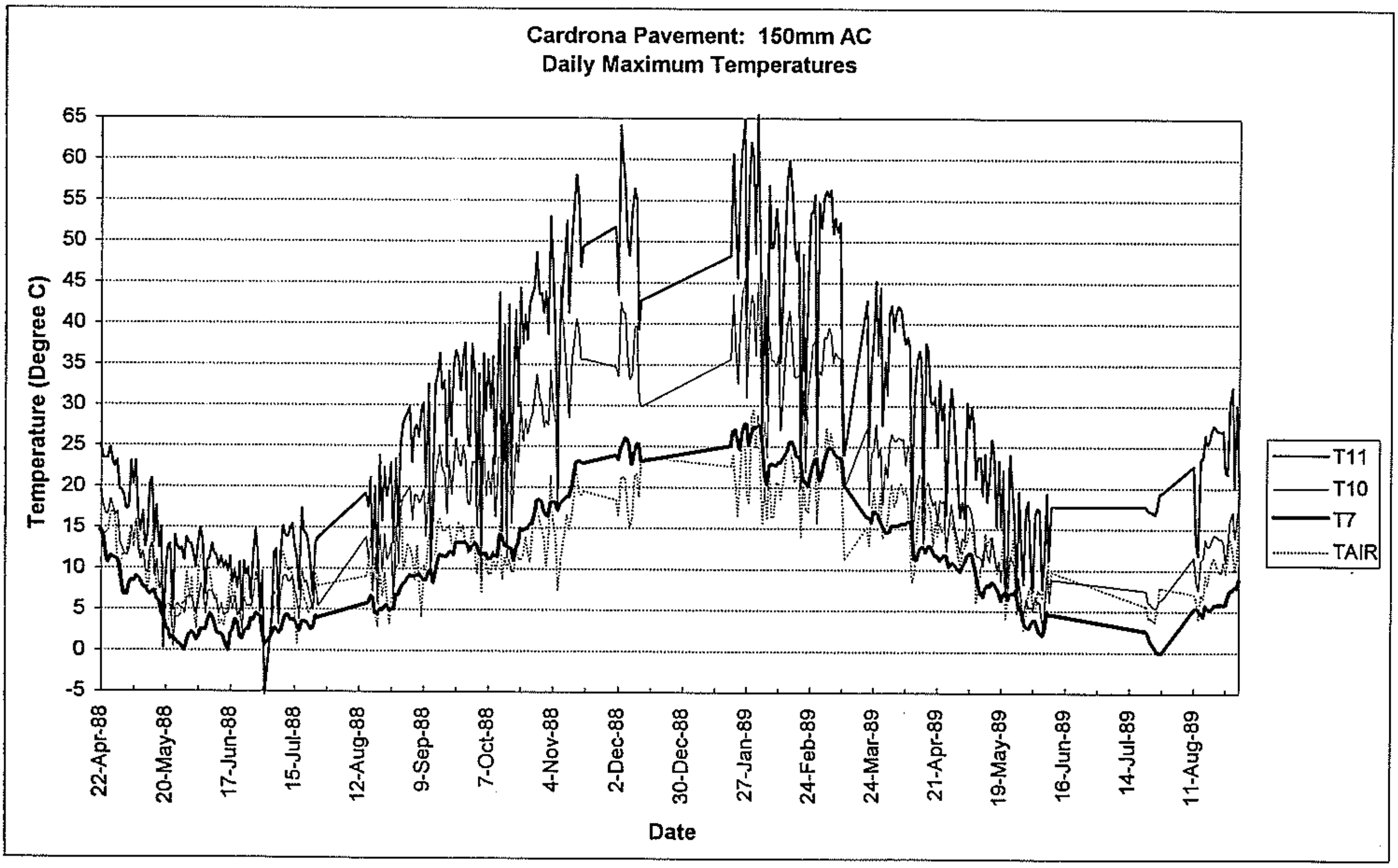


Figure C.4

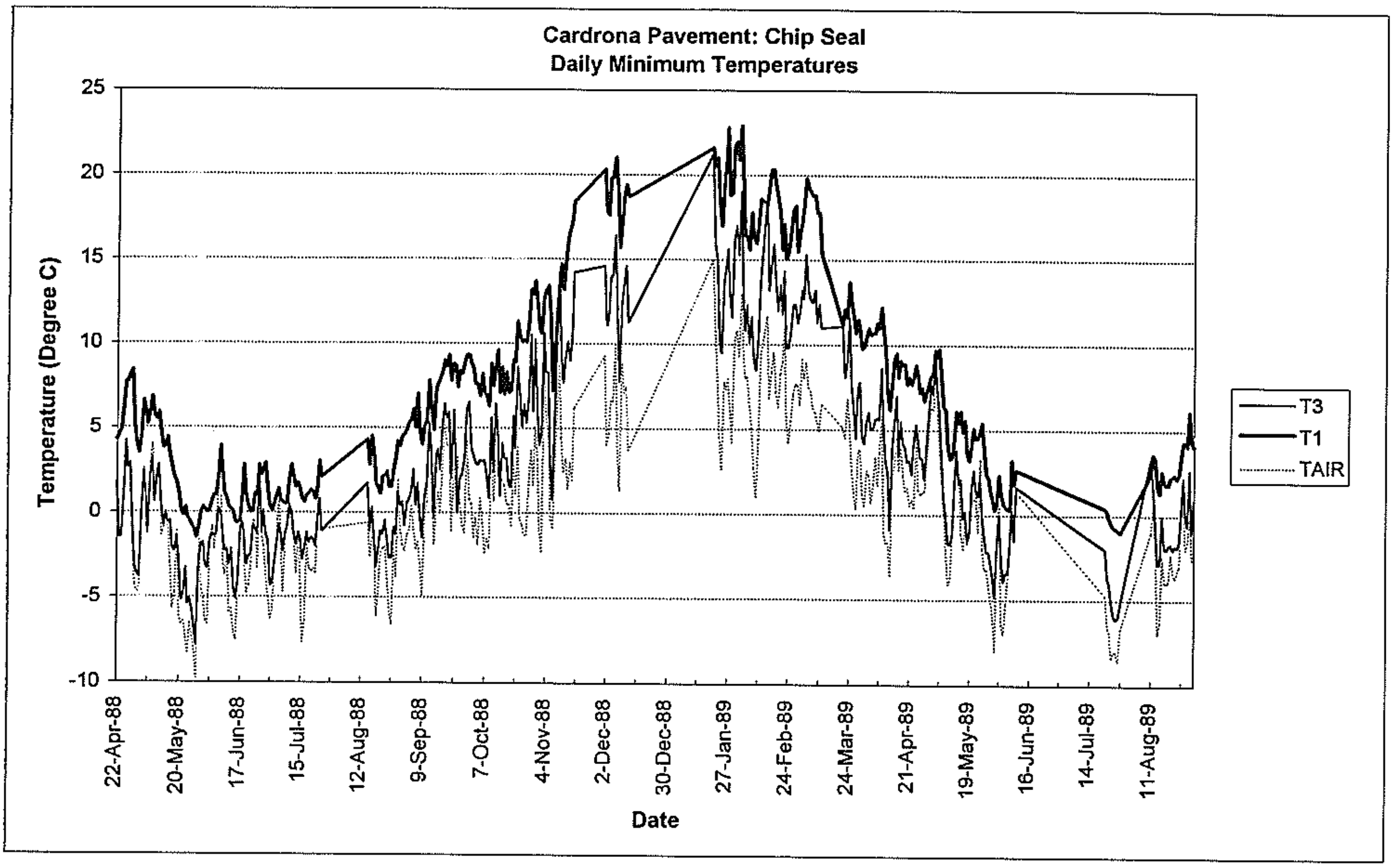


Figure C.5

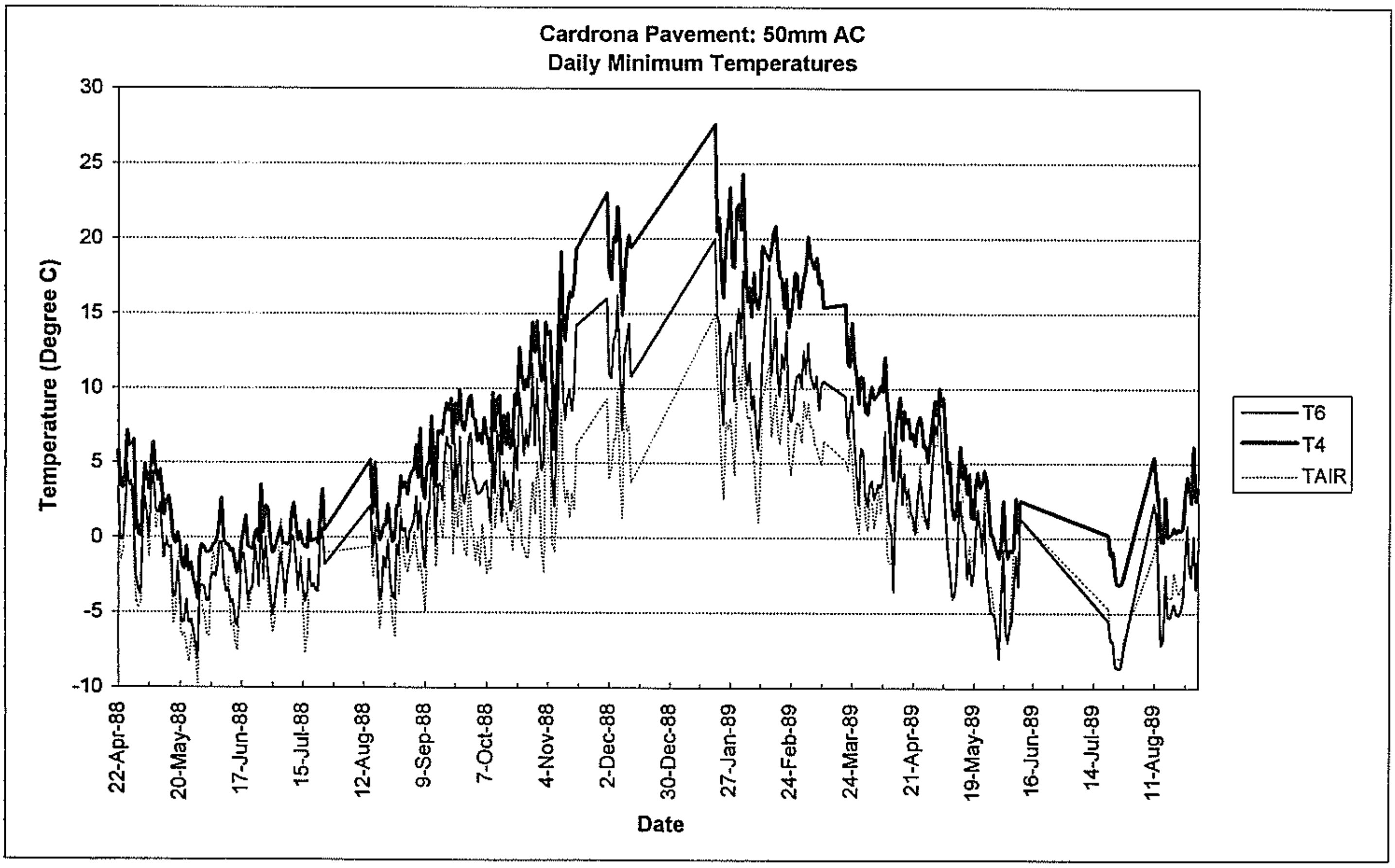


Figure C.6

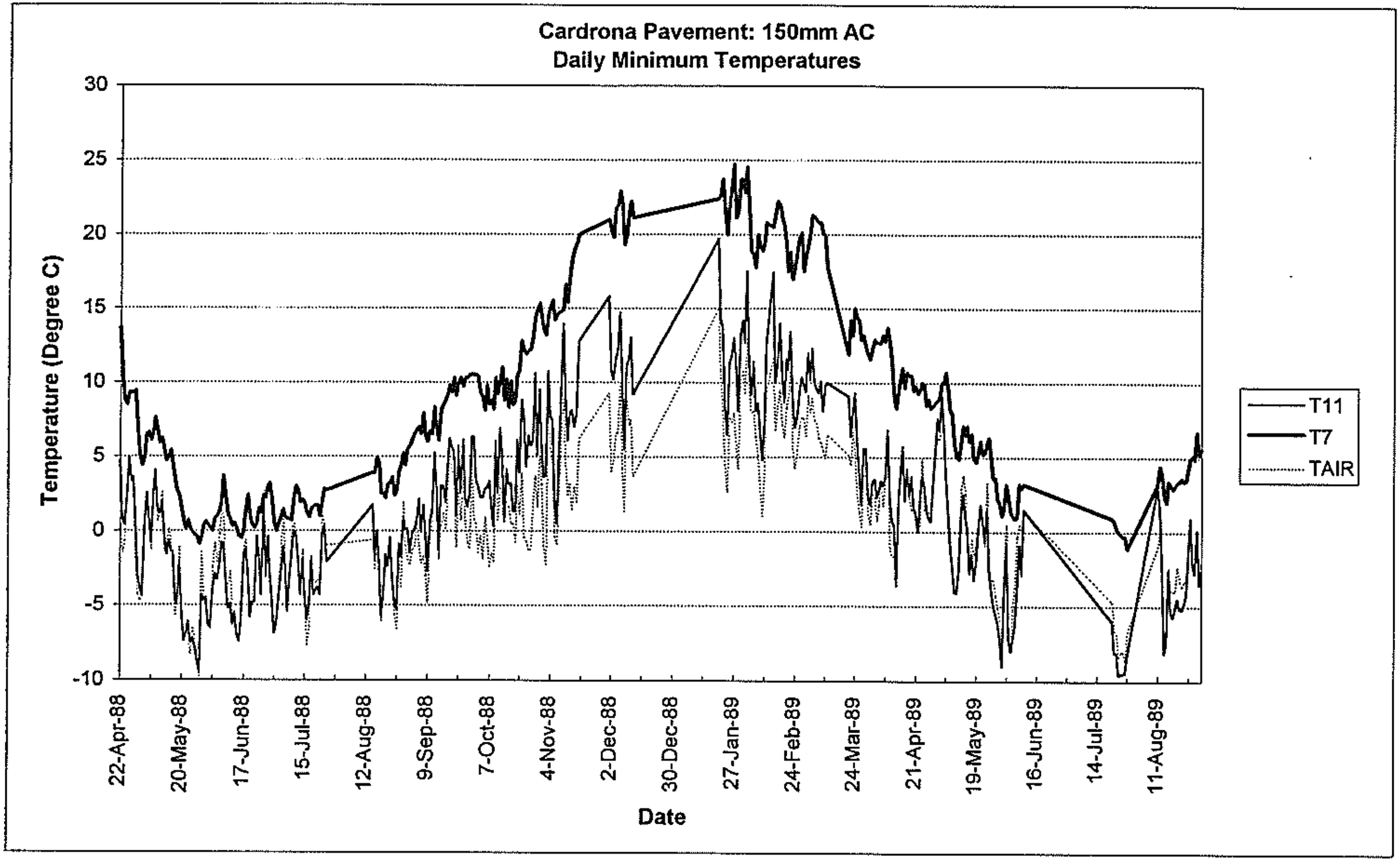


Figure C.7

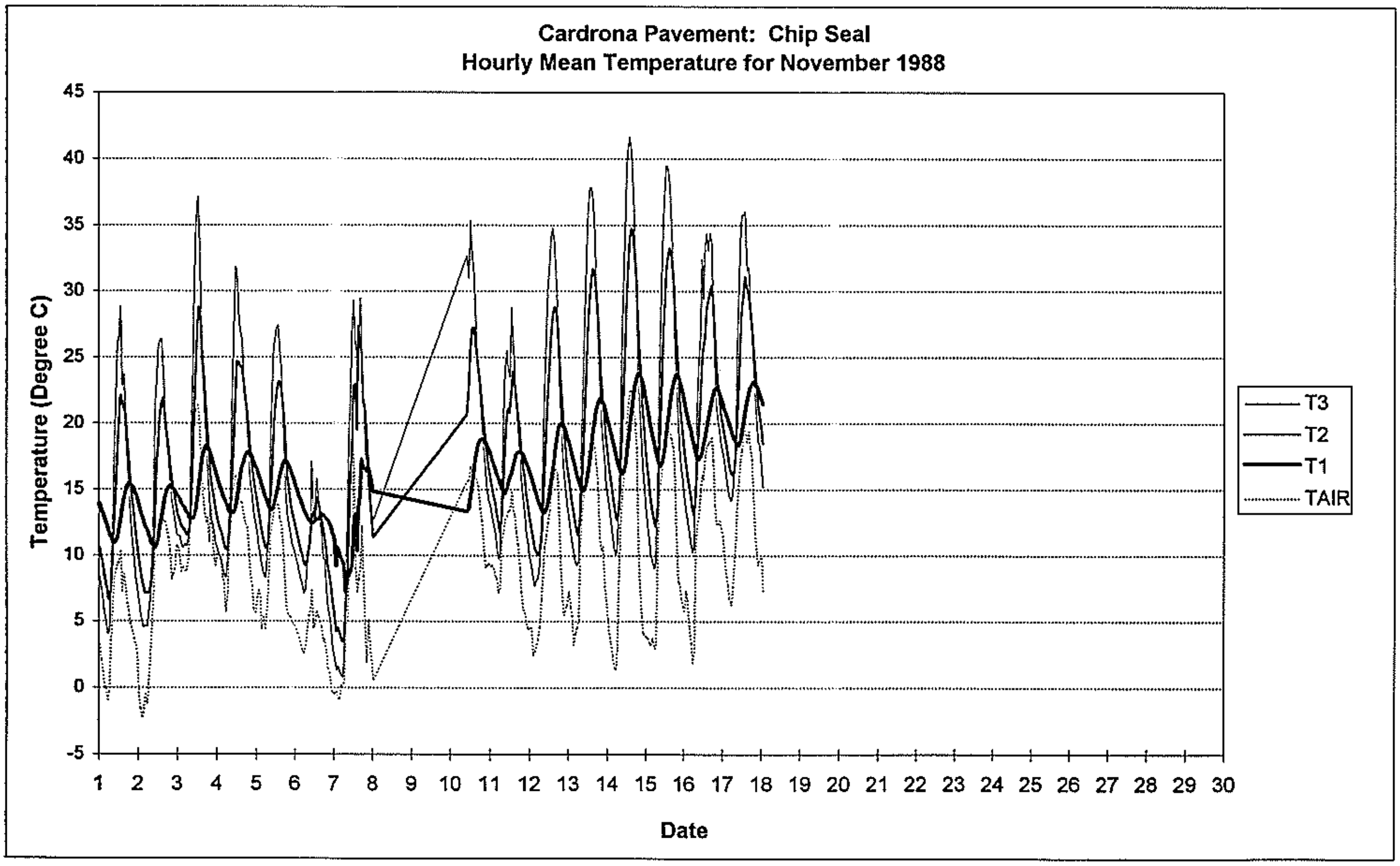
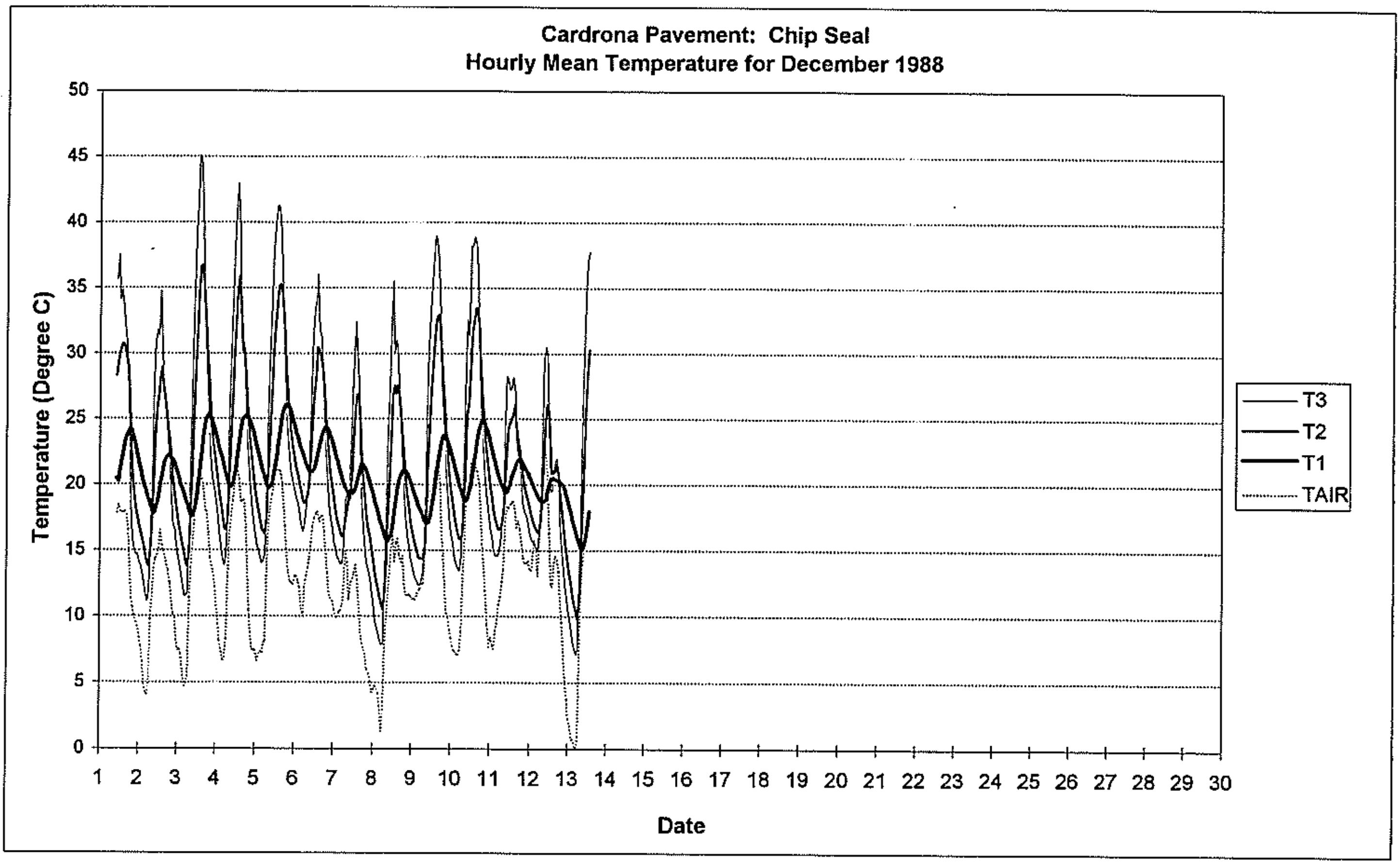


Figure C.8



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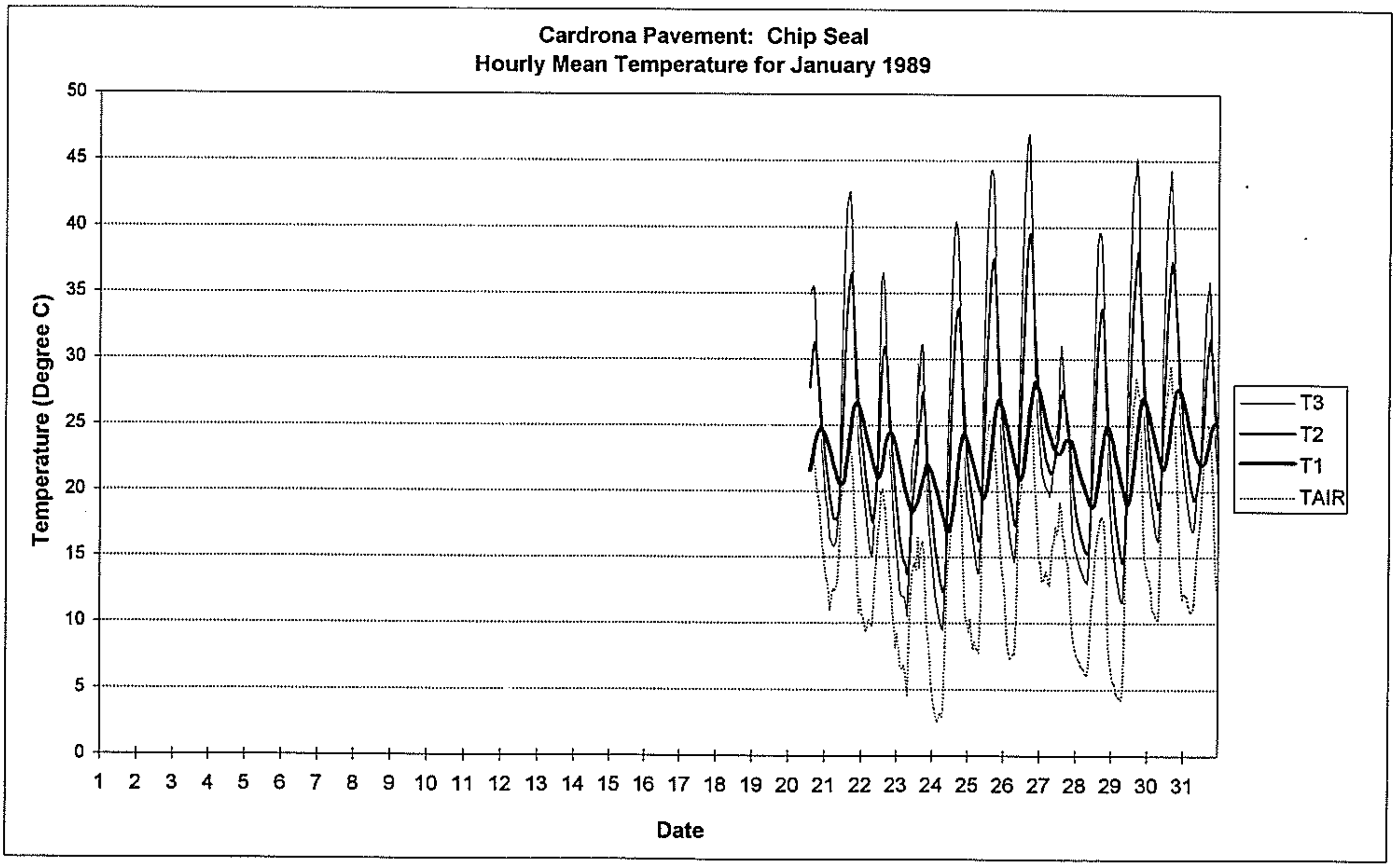


Figure C.10

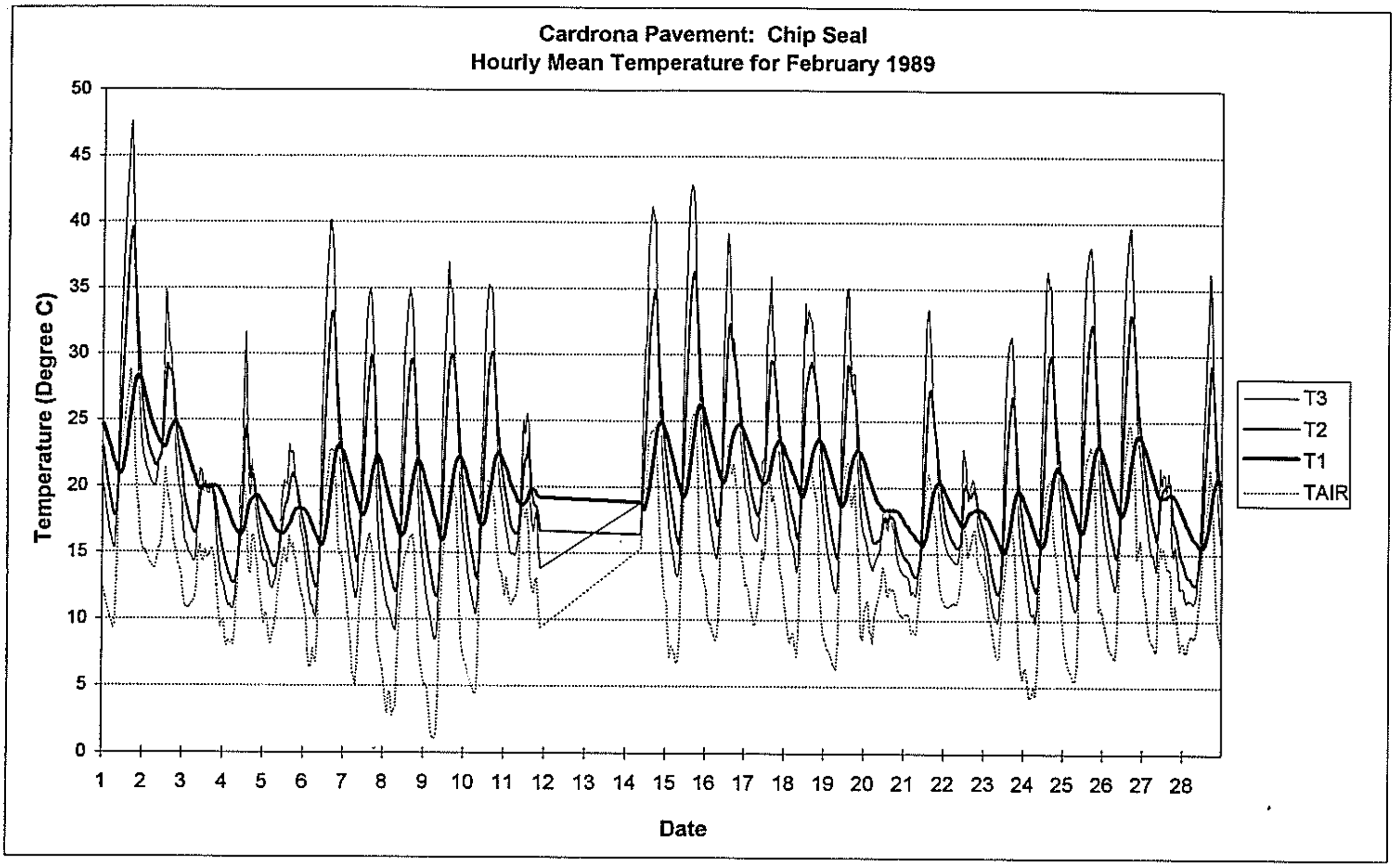


Figure C.11

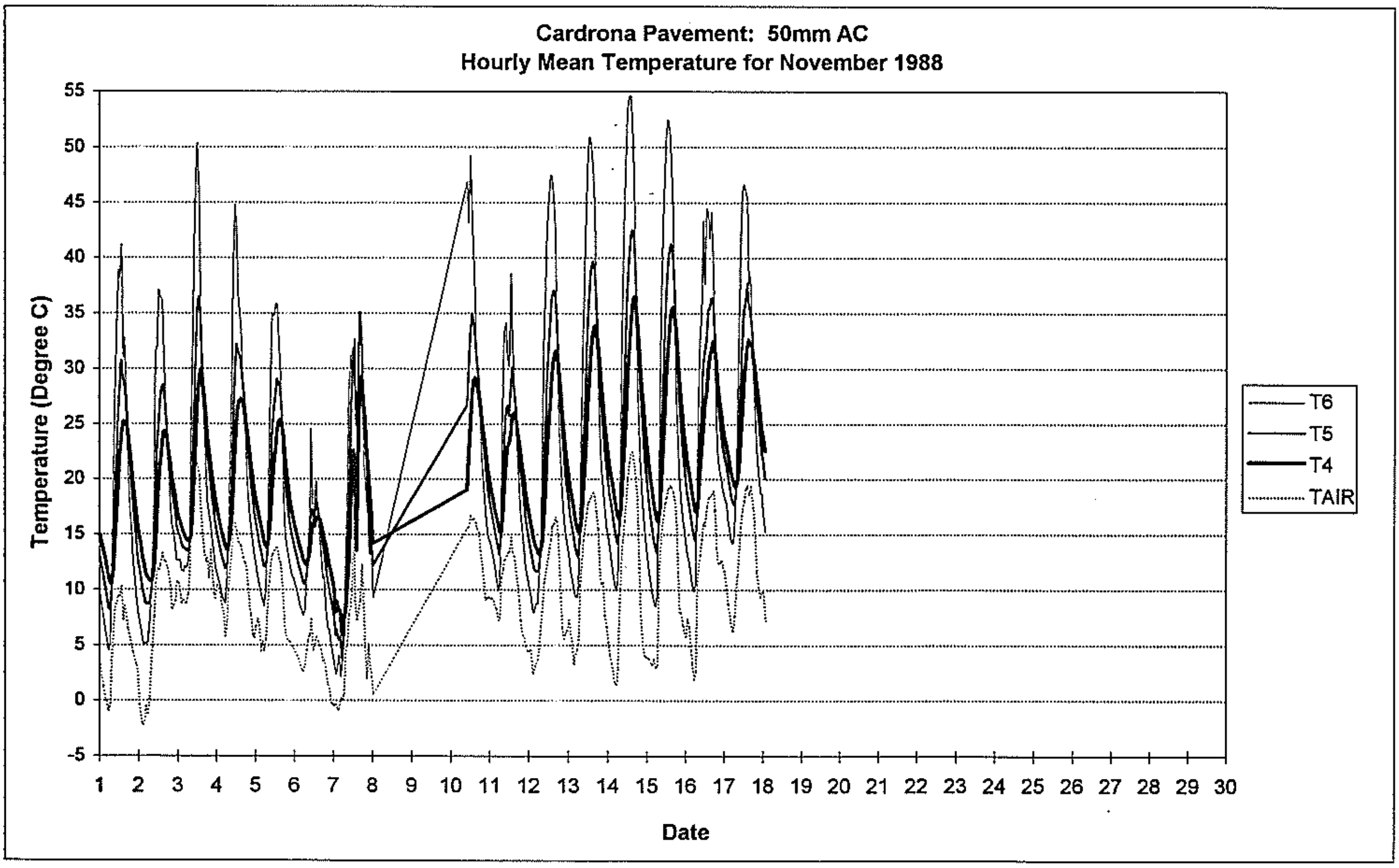


Figure C.12

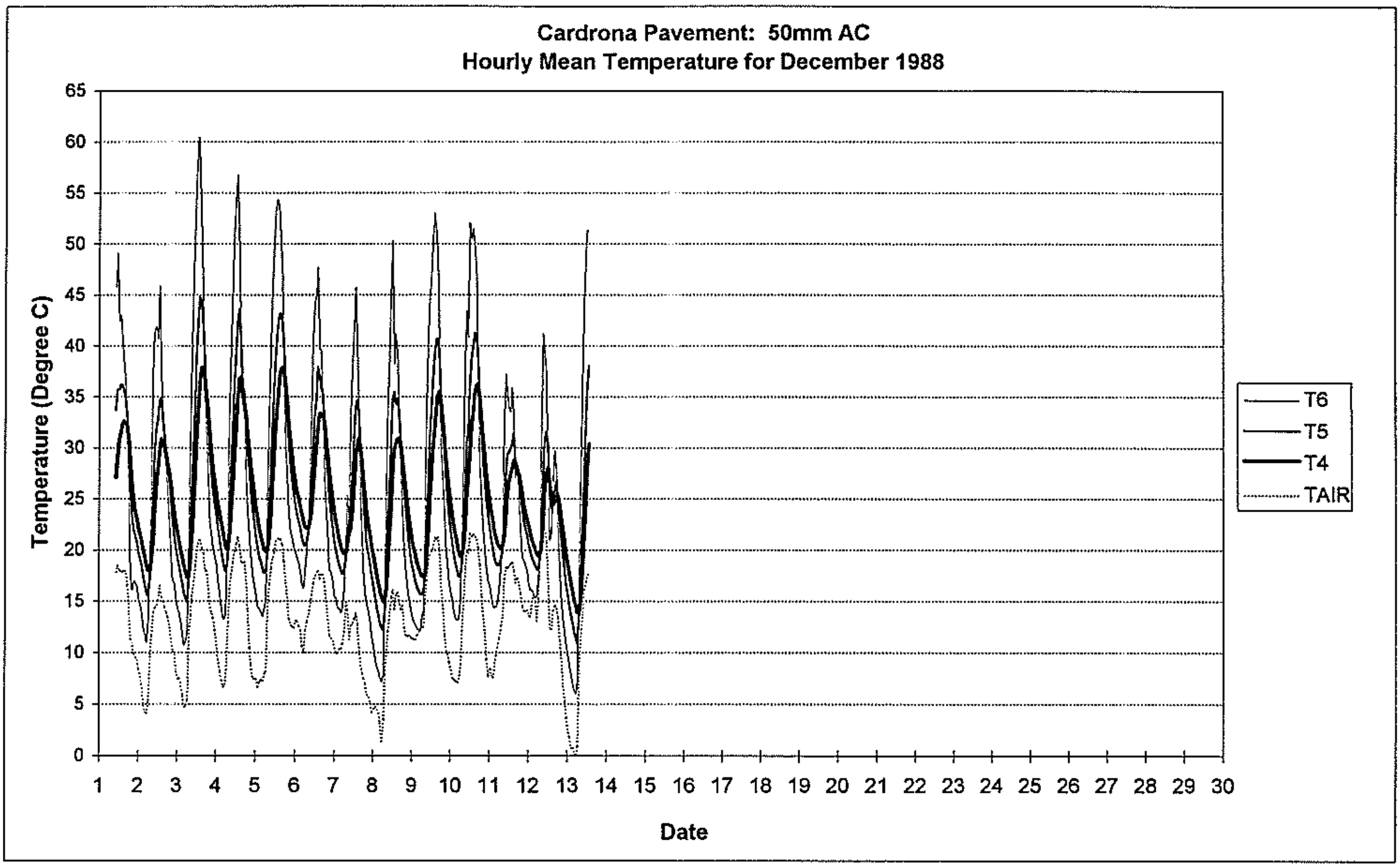


Figure C.13

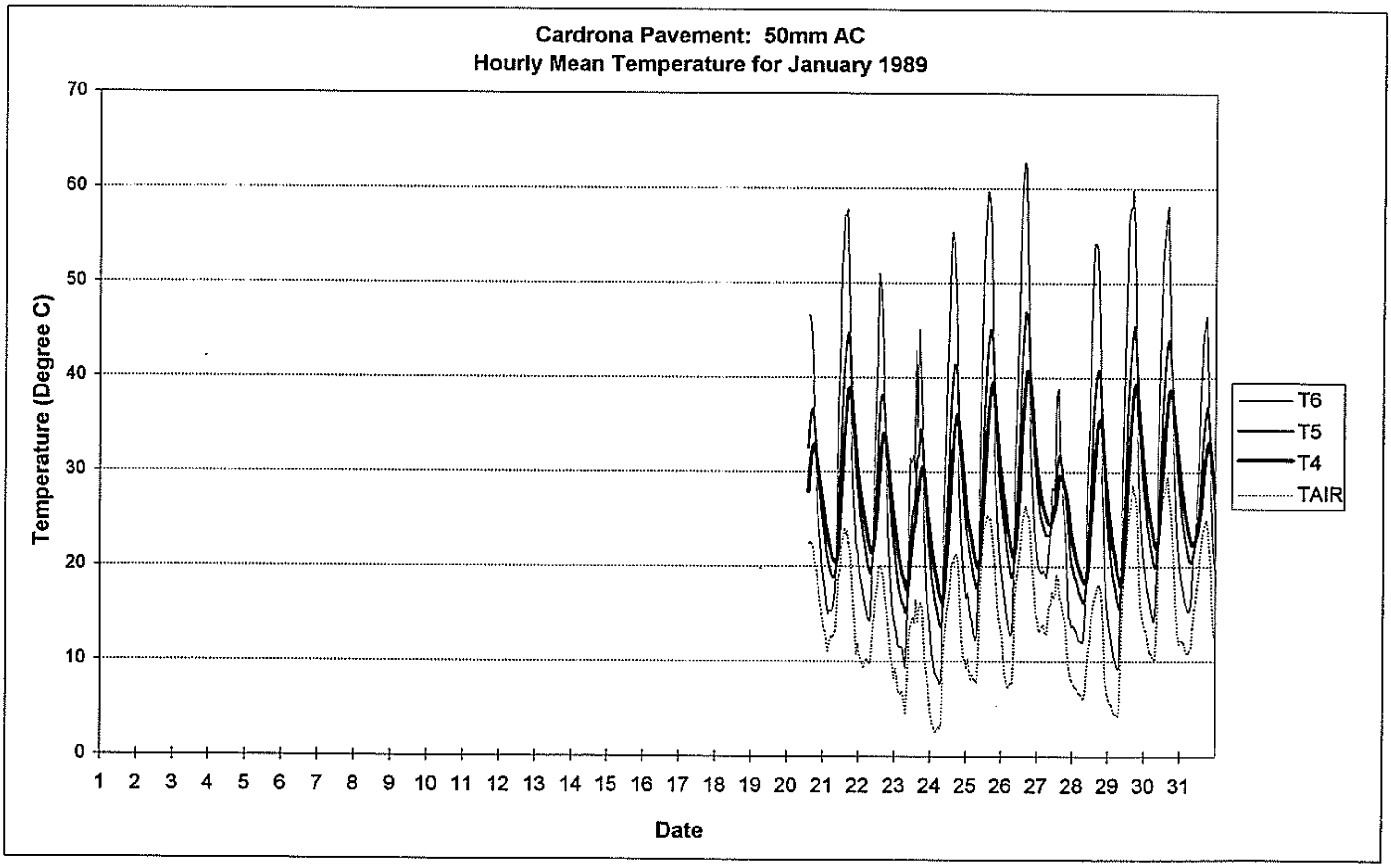


Figure C.14

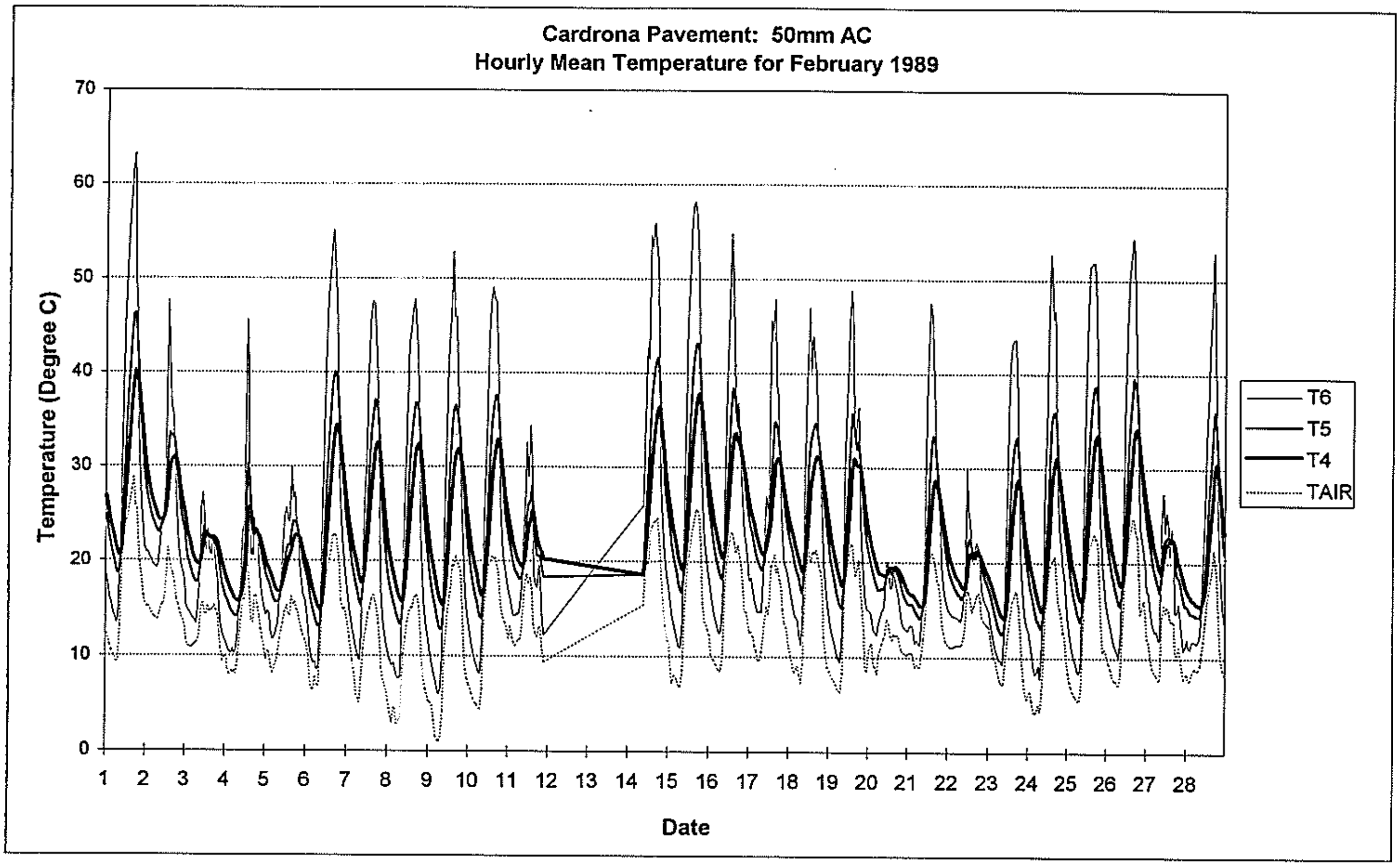


Figure C.15

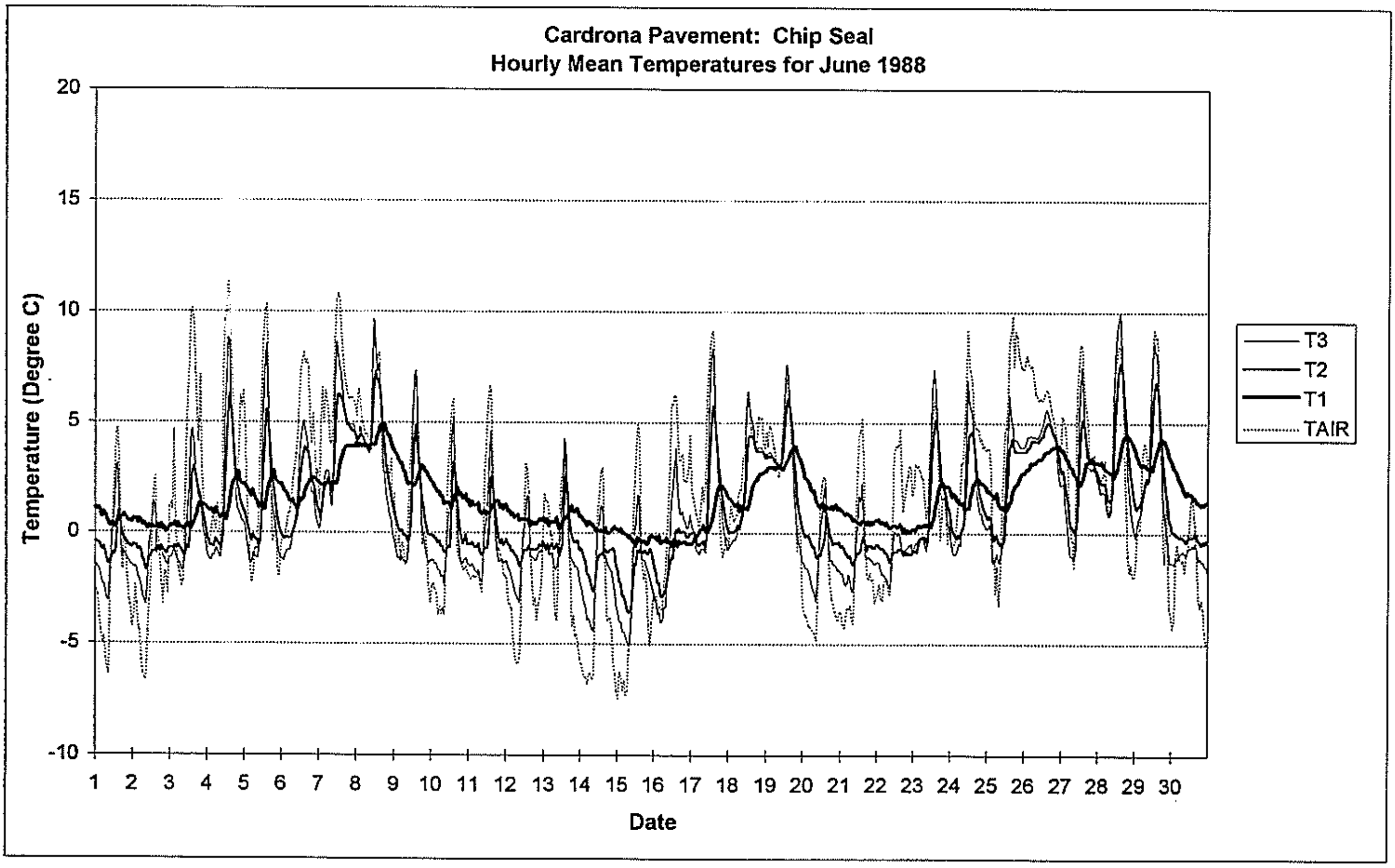
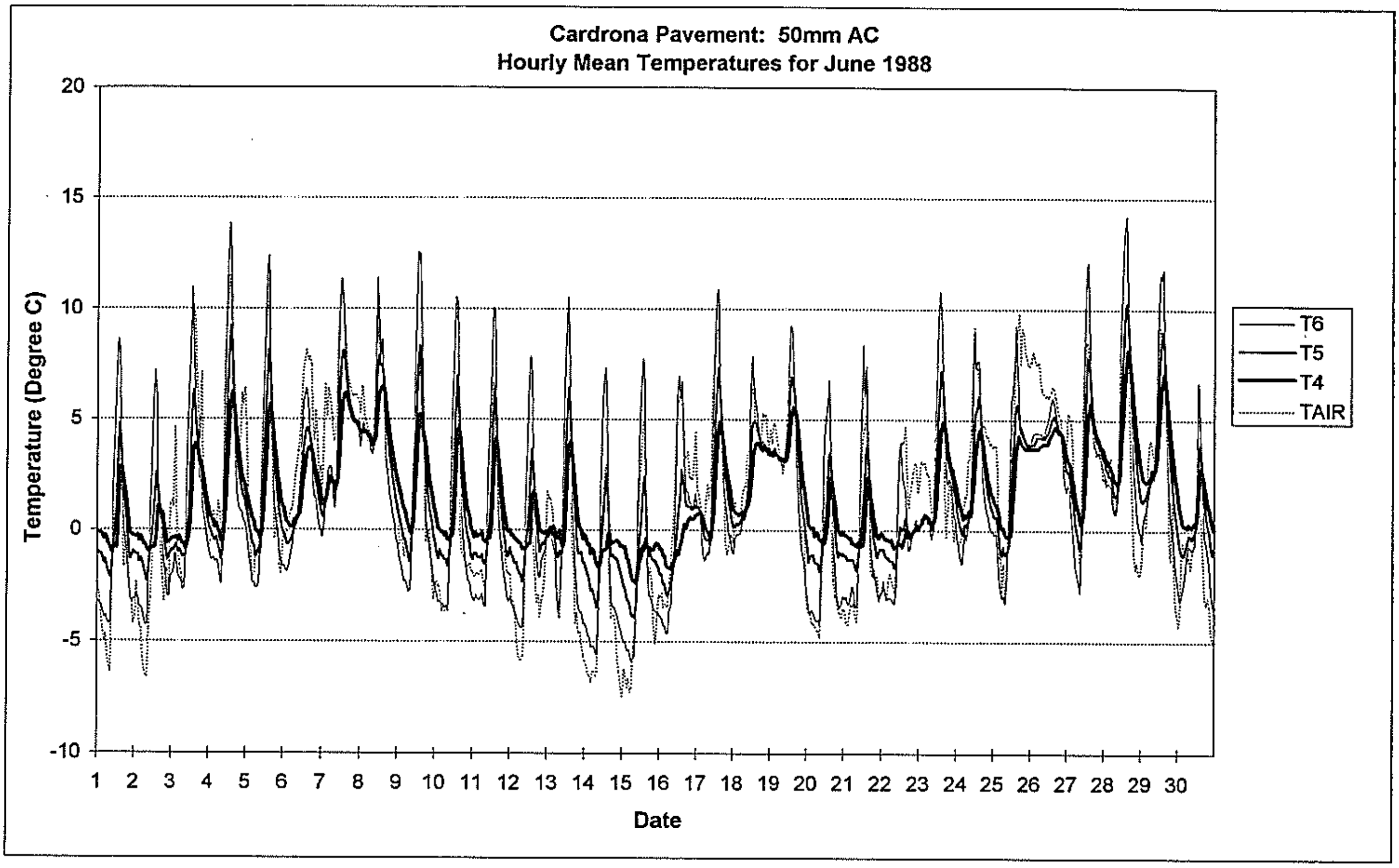


Figure C.16



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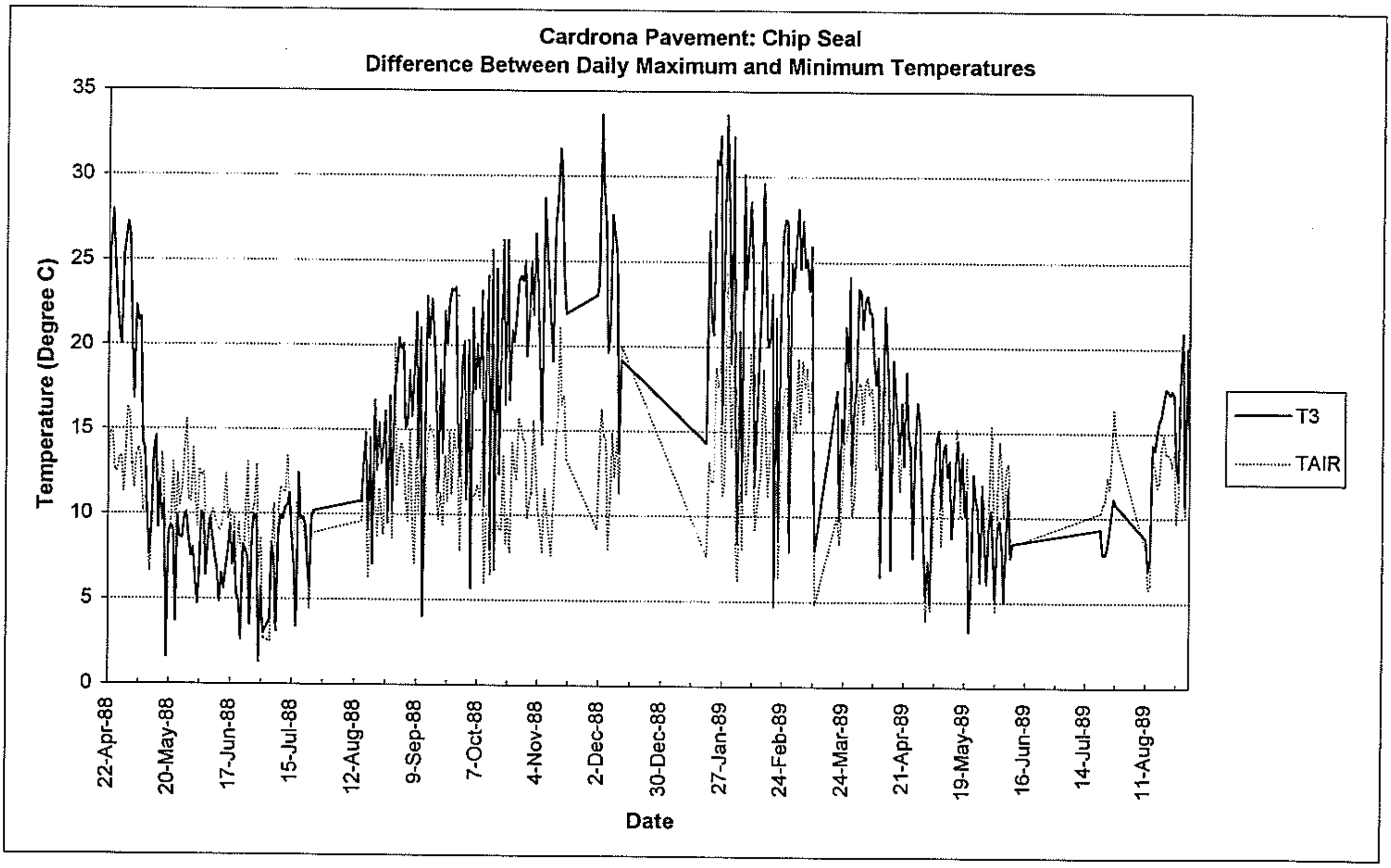


Figure C.18

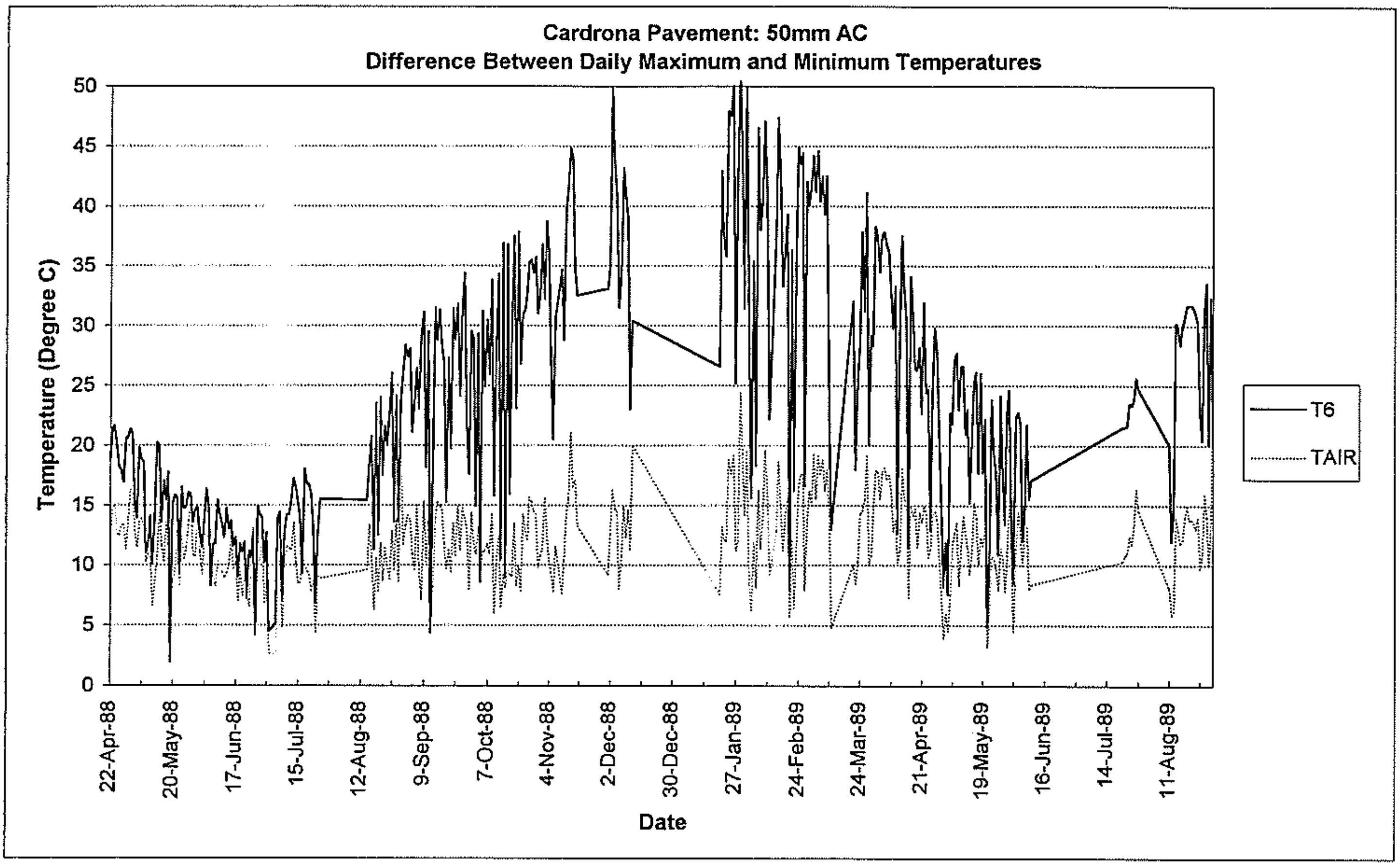


Figure C.19

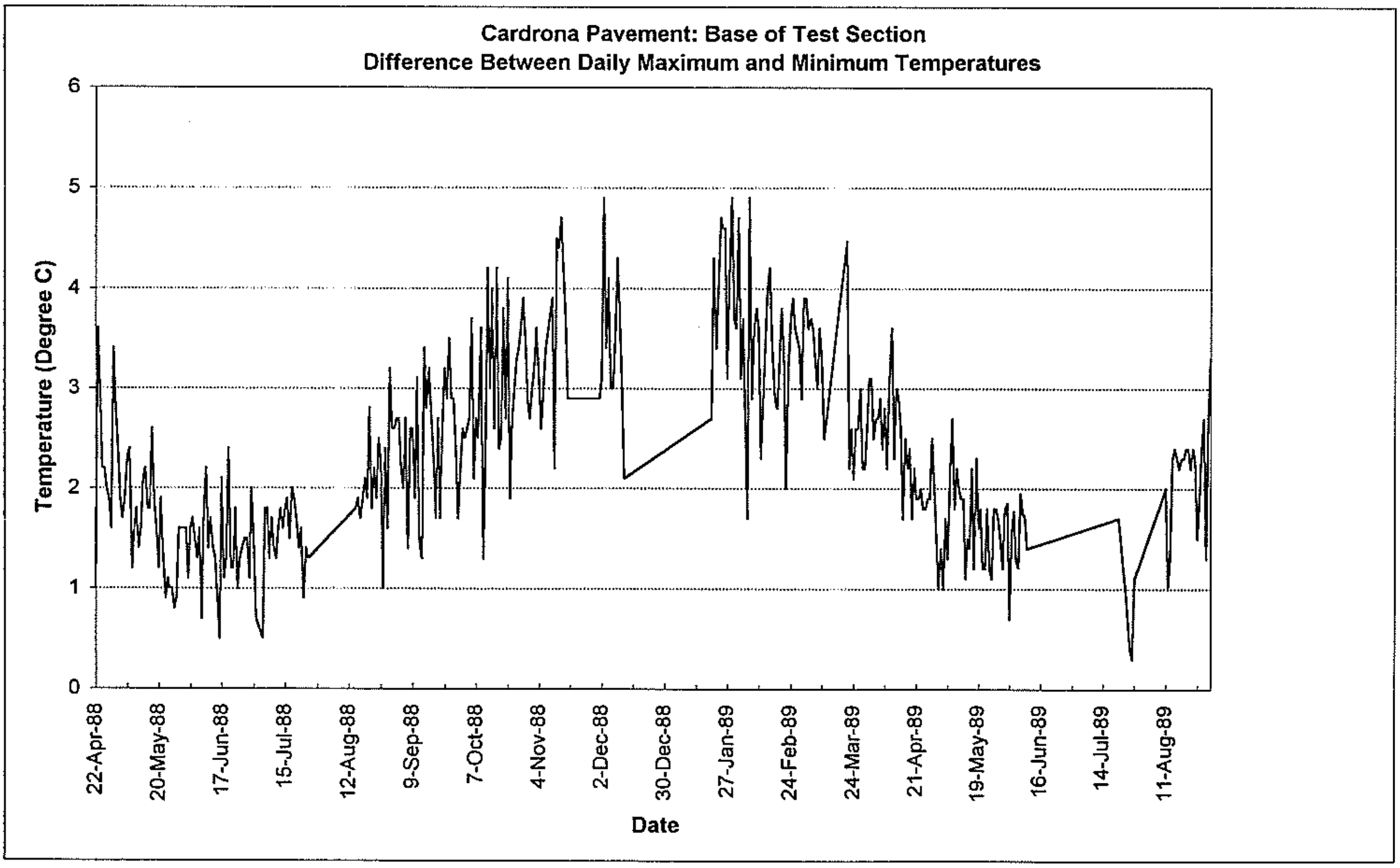


Figure C.20

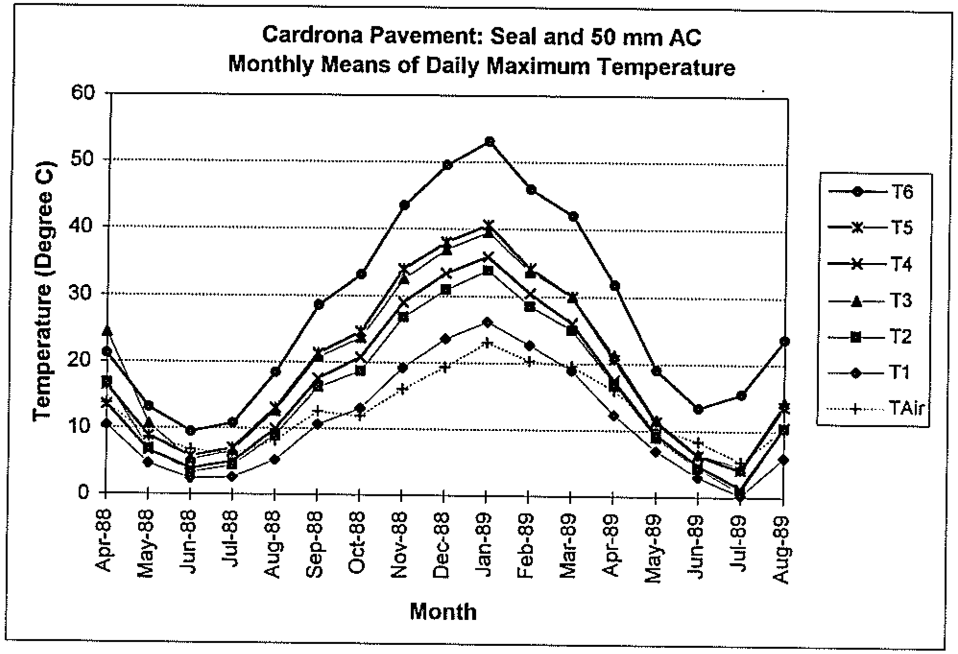


Figure C.21

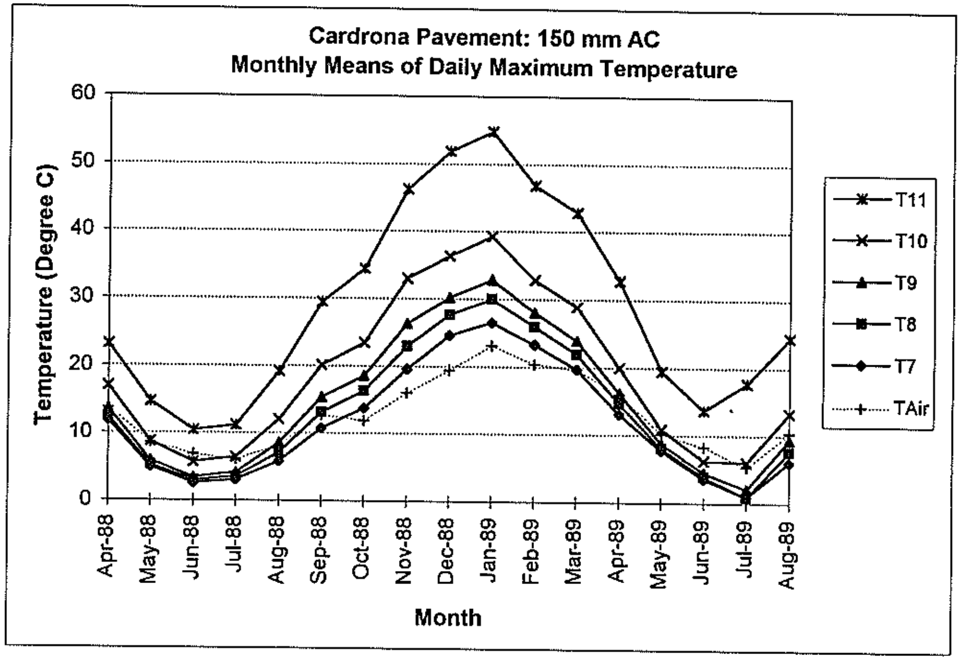


Figure C.22

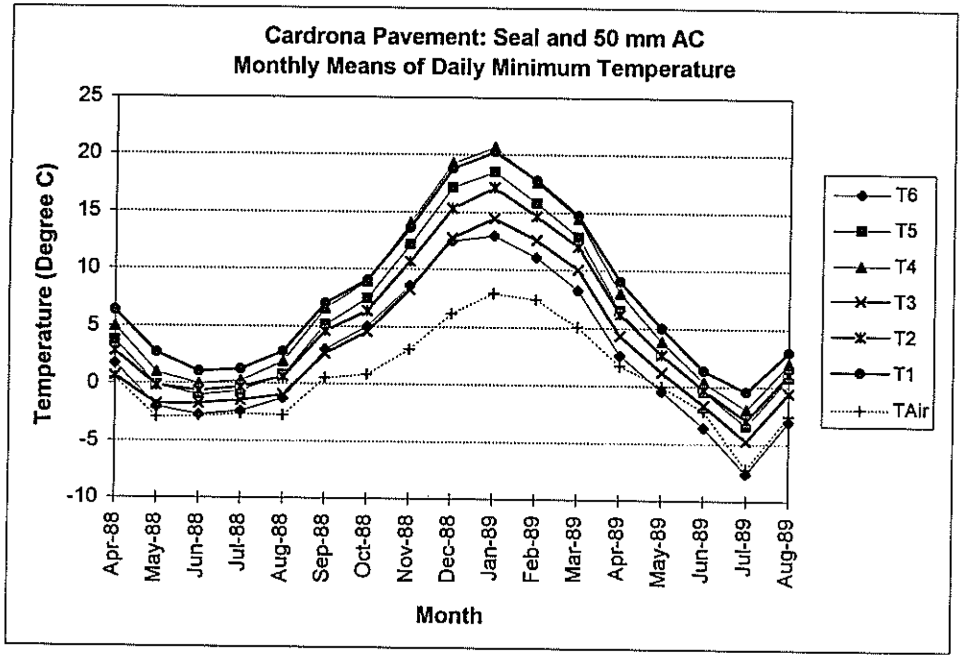


Figure C.23

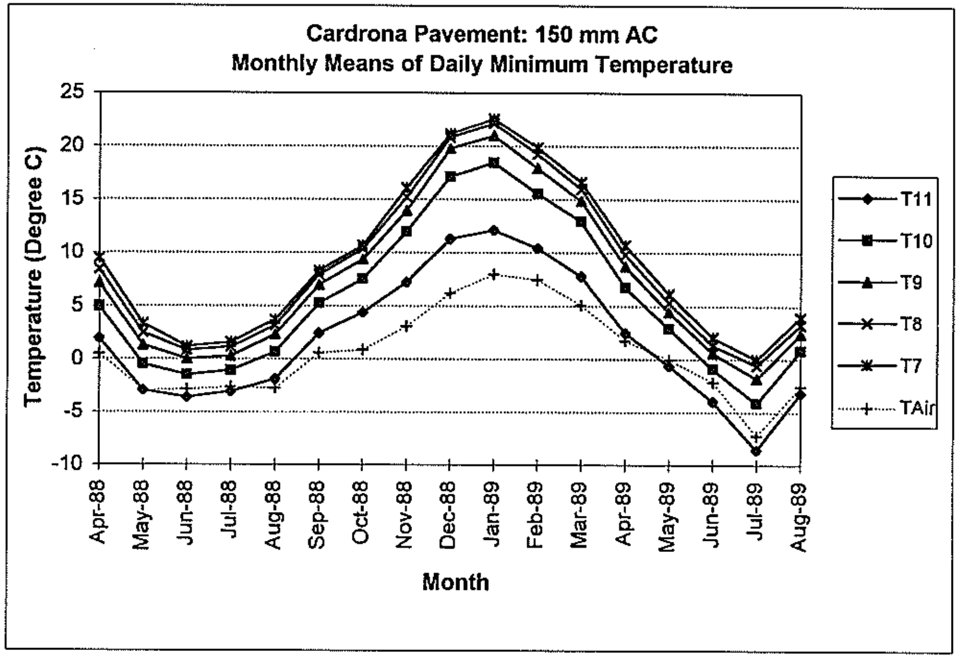


Figure C.24

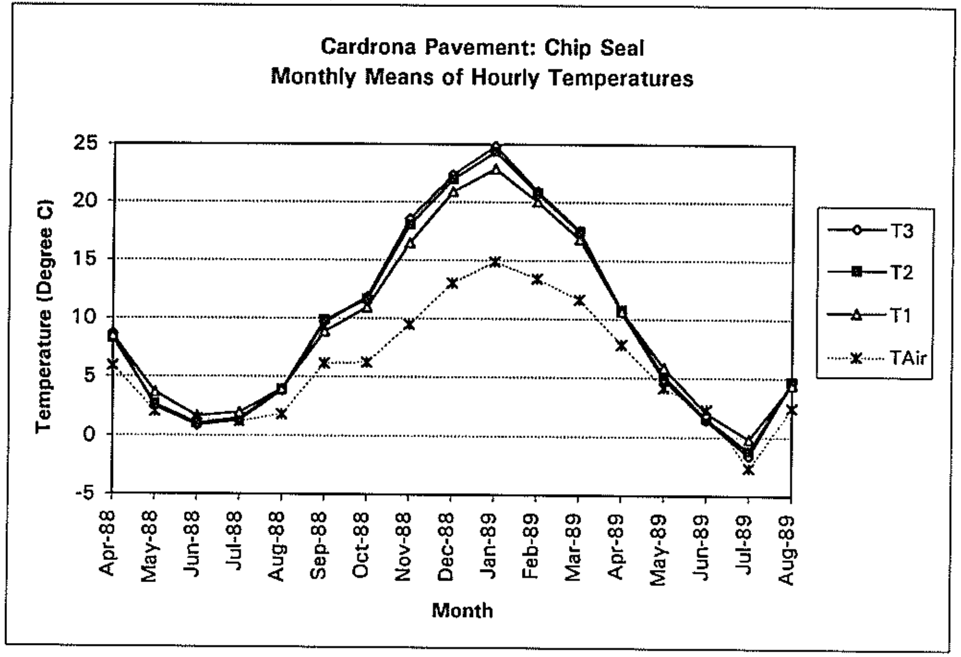


Figure C.25

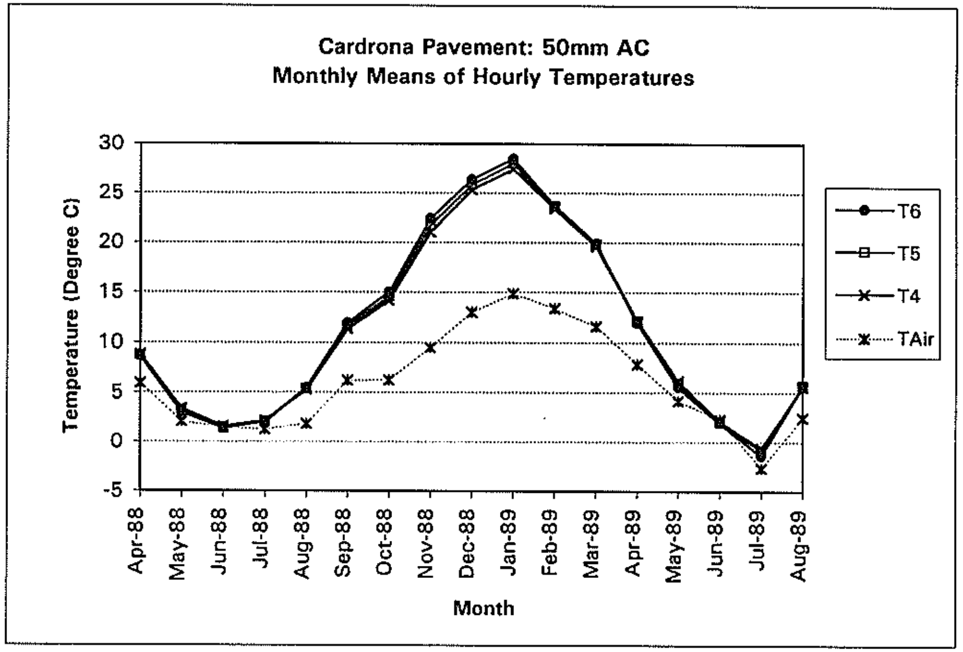


Figure C.26

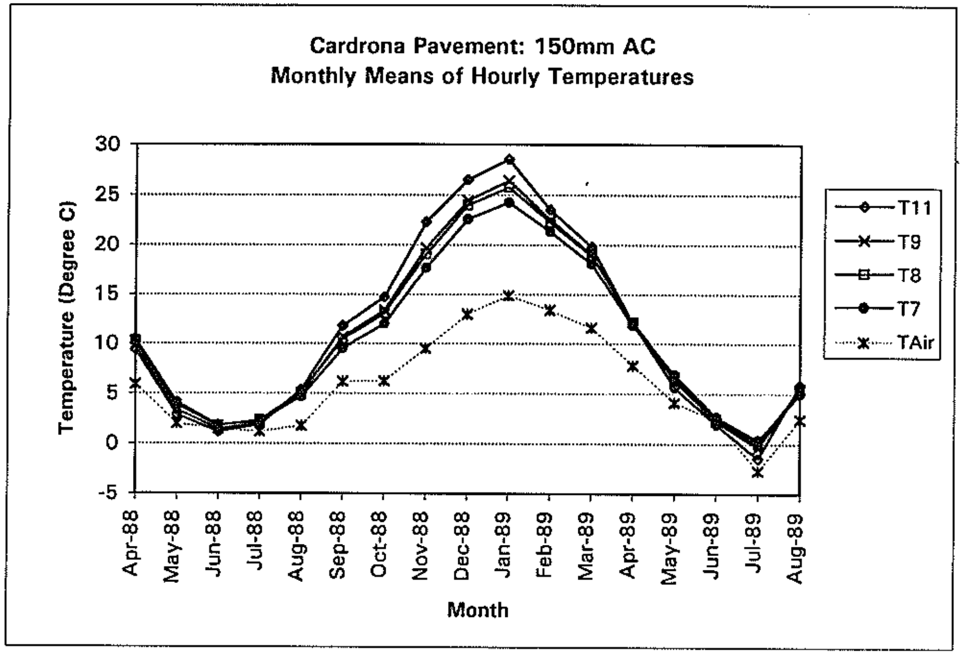


Figure C.27

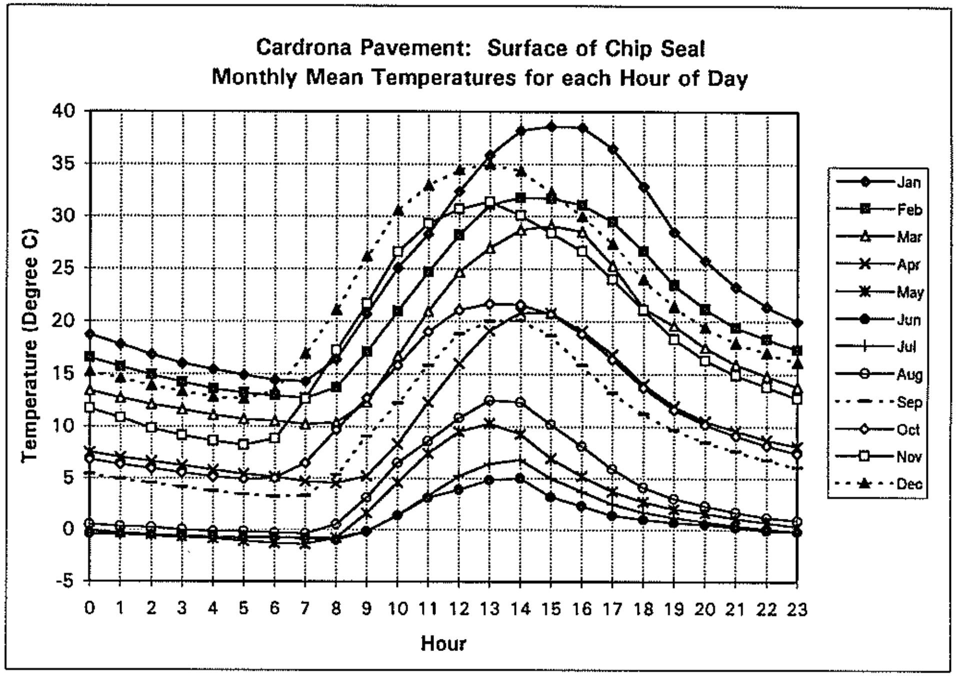


Figure C.28

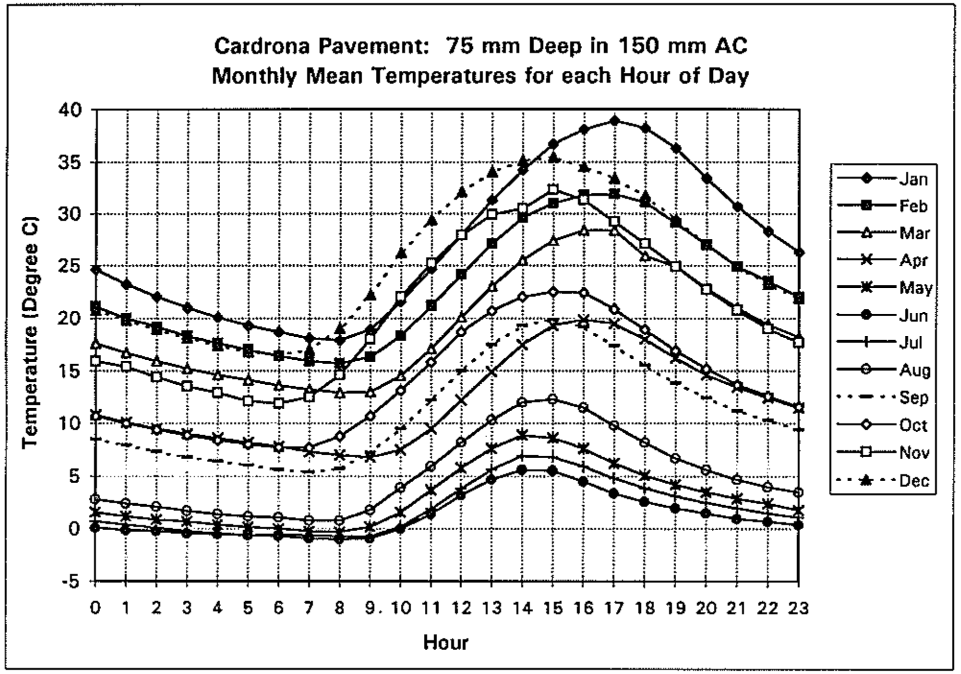

Cardrona Pavement: 75 mm Deep in 150 mm AC
Monthly Mean Temperatures for each Hour of Day

Figure C.29

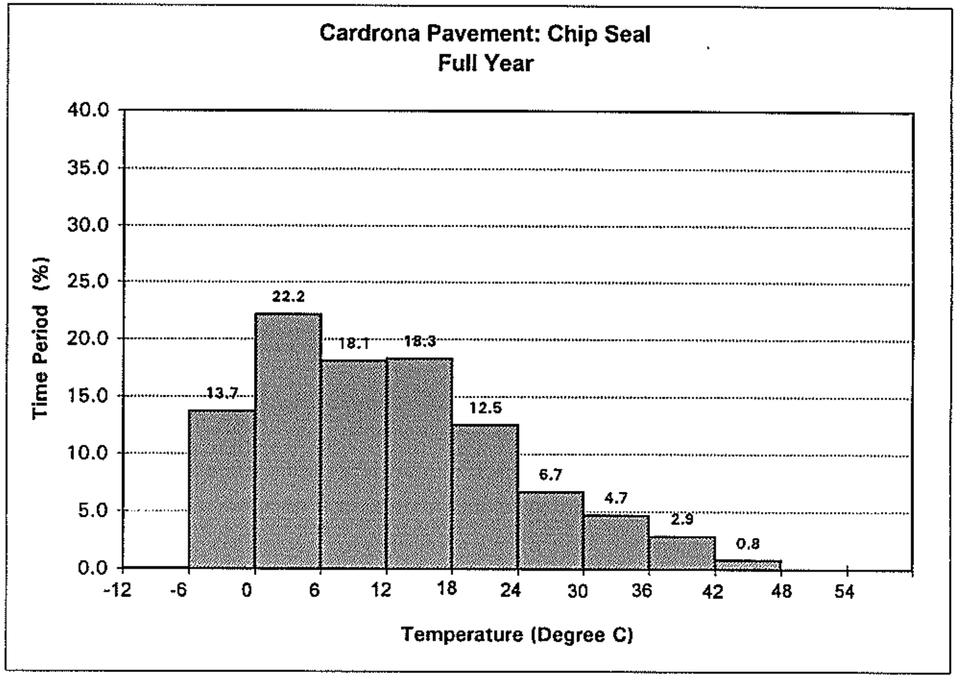

Cardrona Pavement: Chip Seal
Full Year

Figure C.30

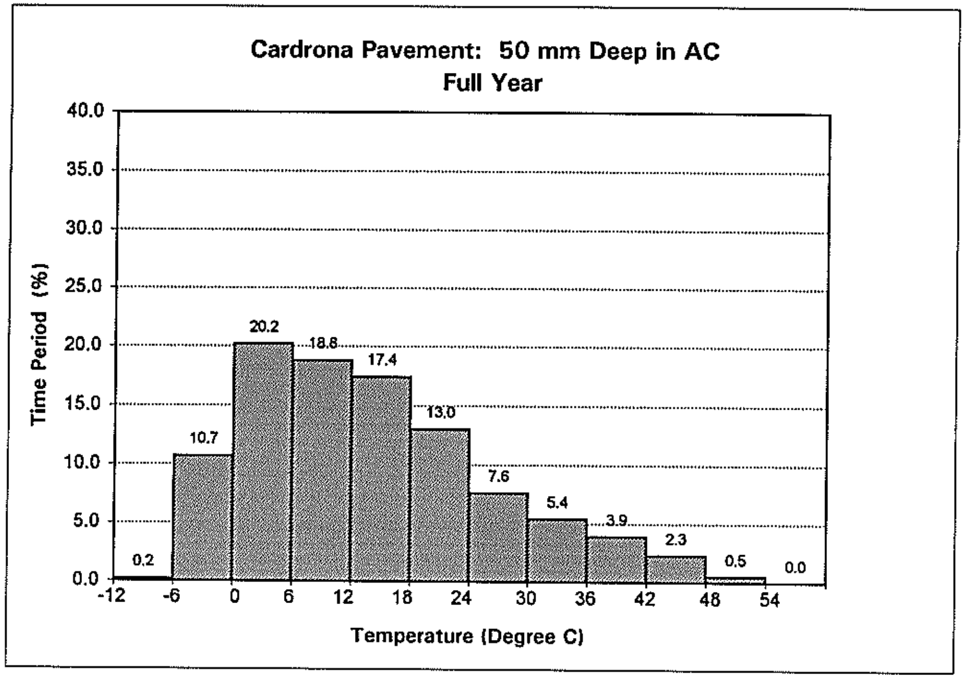


Figure C.31

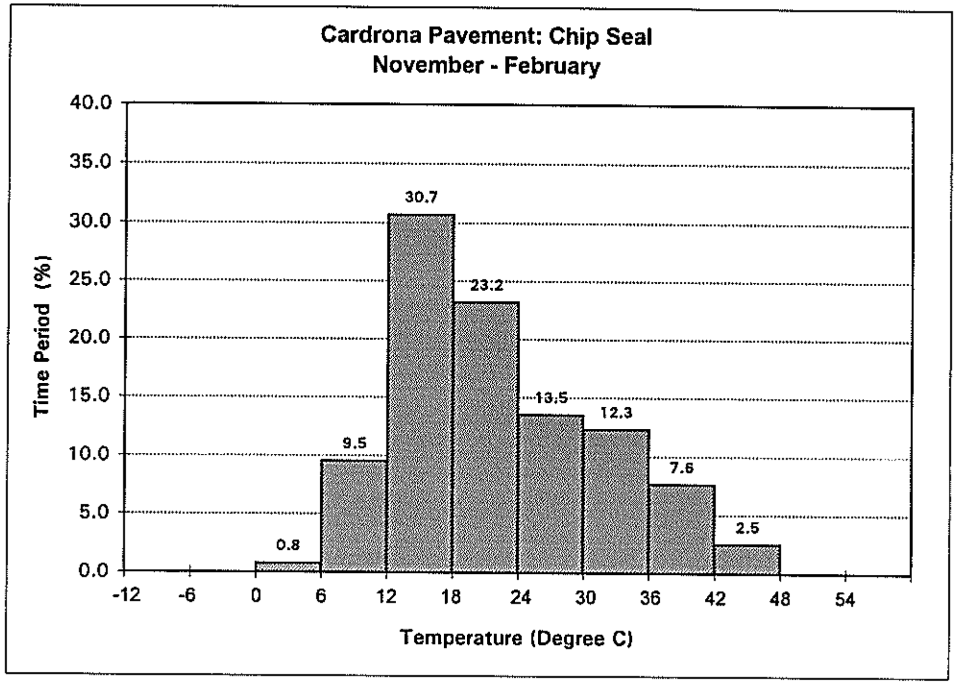


Figure C.32

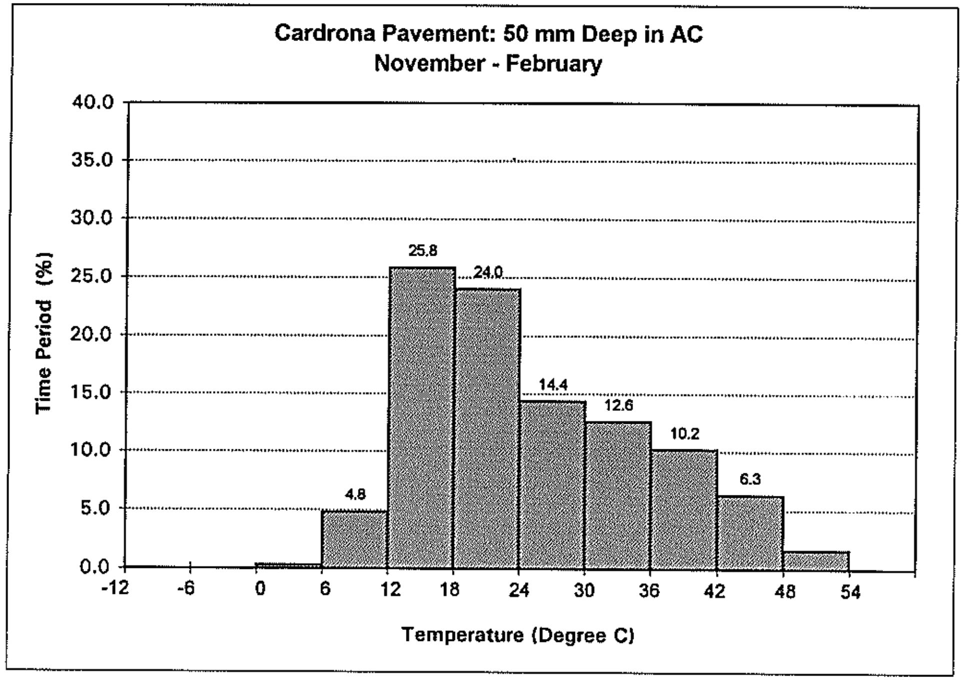


Figure C.33

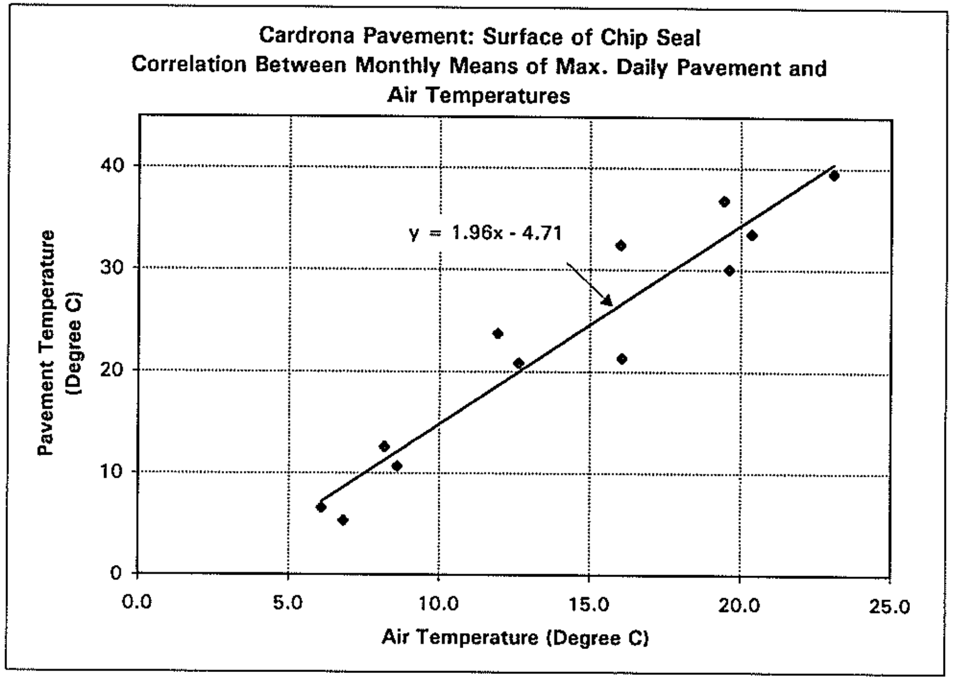


Figure C.34

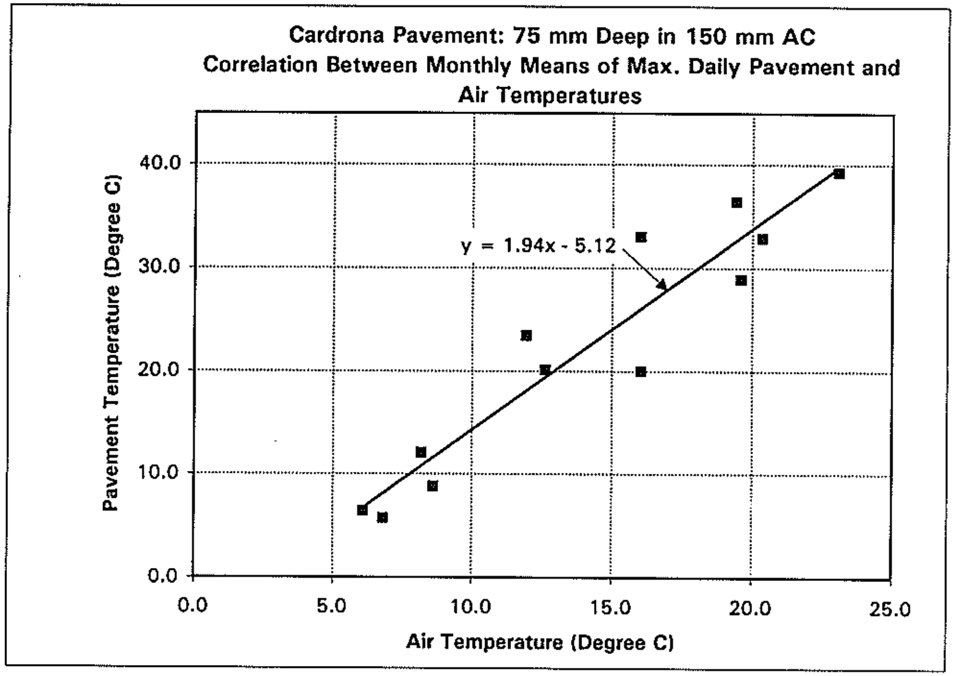


Figure C.35

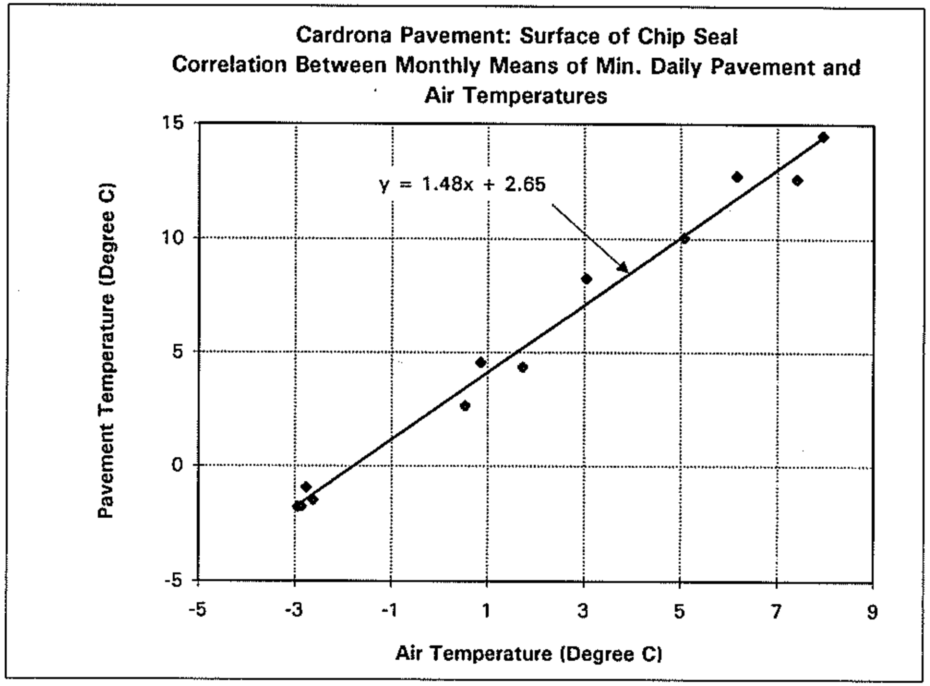


Figure C.36

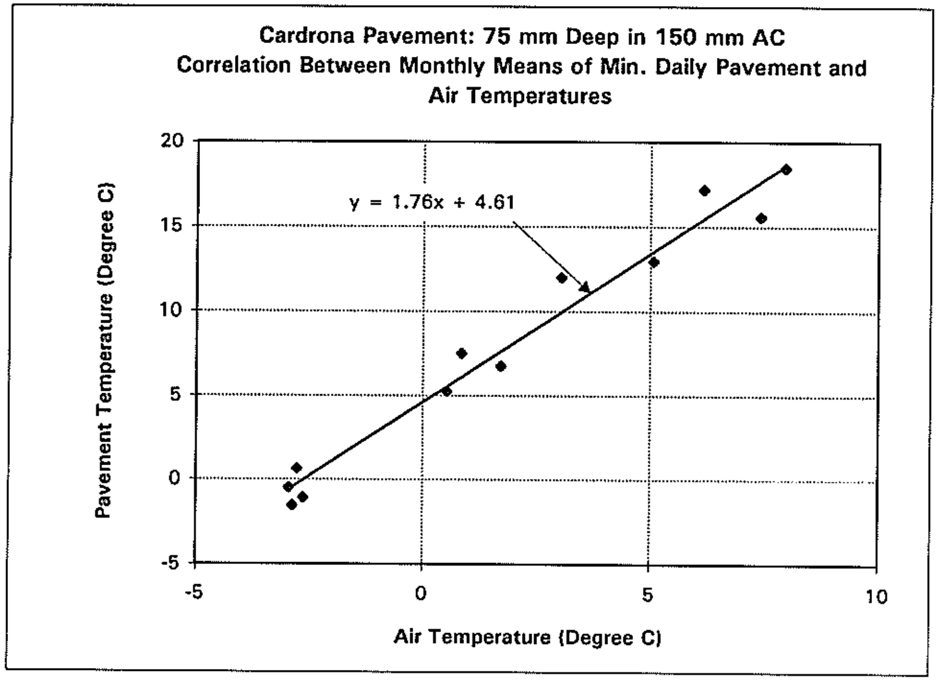


Figure C.37

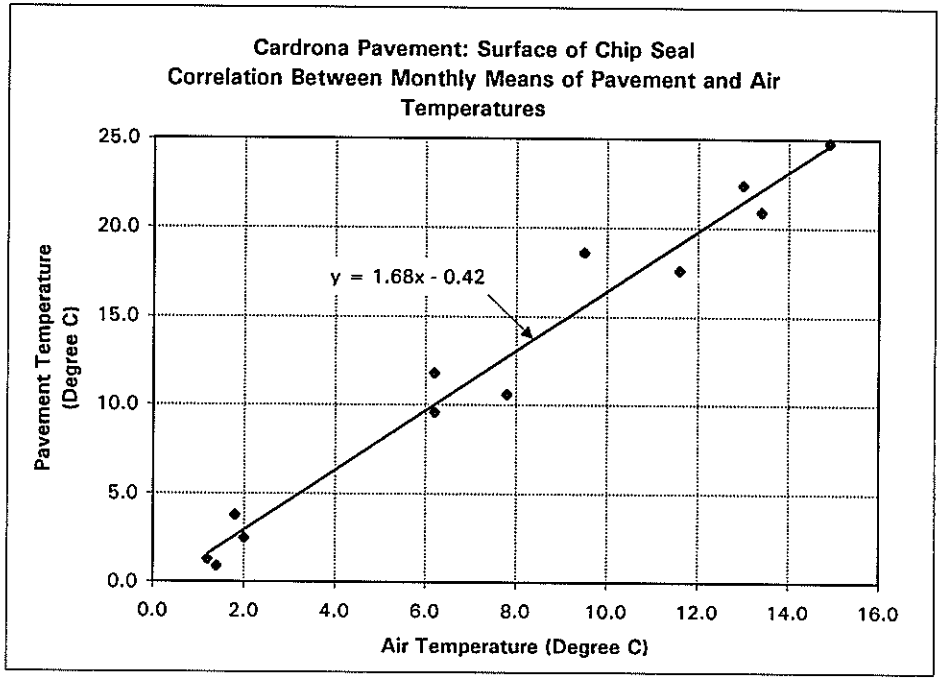


Figure C.38

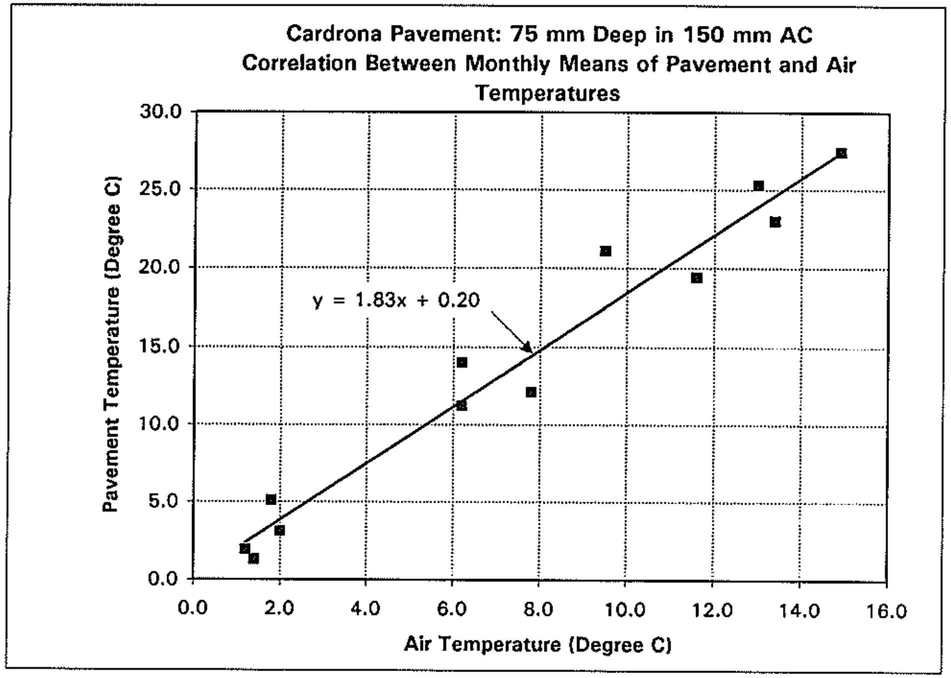

Cardrona Pavement: 75 mm Deep in 150 mm AC
Correlation Between Monthly Means of Pavement and Air Temperatures
Pavement Temperature (Degree C)
30.0
25.0
20.0
15.0
10.0
5.0
0.0
0.0
2.0
4.0
6.0
8.0
10.0
12.0
14.0
16.0
Air Temperature (Degree C)
y = 1.83x + 0.20

Figure C.39

APPENDIX D

Napier Temperature Records

Table D.1 Monthly Means of Daily Maximum Temperatures (Deg C)

	Probe Number													
Month	T1	T2	T3	T4	T5	T6	T7	T8	T9	T10	T11	T12	T13	TAIR
Dec-84	30.8	36.0	44.3	34.0	38.3	44.6	50.5	32.0	34.9	38.0	41.1	45.4	51.3	23.7
Jan-85	32.3	38.2	47.7	35.7	40.7	47.7	54.1	33.5	36.5	40.2	43.7	48.4	54.8	25.3
Feb-85	30.0	34.8	42.9	33.0	37.0	43.4	48.9	31.5	33.6	36.8	39.9	44.1	49.6	23.6
Mar-85	25.3	28.8	35.5	27.0	30.5	35.7	40.5	26.3	28.0	30.4	32.8	36.4	41.0	21.0
Apr-85	20.3	22.7	28.5	21.7	23.7	28.1	32.4	21.3	22.2	23.9	25.7	28.8	32.6	18.3
May-85	15.6	17.1	21.8	16.4	17.6	21.0	24.3	16.4	16.8	17.9	19.2	21.6	24.6	15.5
Jun-85	13.4	14.5	18.4	13.7	14.6	17.2	20.0	13.9	14.2	15.0	16.1	18.1	20.5	14.5
Jul-85	12.3	14.0	18.5	12.7	13.9	17.0	20.1	12.9	13.2	14.3	15.6	17.9	20.6	14.4
Aug-85	13.5	16.2	22.3	14.4	16.6	21.2	25.6	14.0	15.1	17.0	18.9	22.0	25.9	13.9
Sep-85	17.7	21.9	29.1	19.5	23.1	28.8	34.2	18.3	20.5	23.4	26.0	29.9	34.7	16.4
Oct-85	21.7	26.6	35.0	24.0	27.9	34.5	40.2	22.5	24.9	28.0	30.9	35.7	40.6	17.5
Nov-85	27.9	33.1	40.6	30.8	35.0	41.4	46.5	28.6	31.7	34.9	37.7	42.5	46.8	20.9

Table D.2 Monthly Means of Daily Minimum Temperatures (Degree C).

	Probe Number													
Month	T1	T2	T3	T4	T5	T6	T7	T8	T9	T10	T11	T12	T13	TAIR
Dec-84	27.0	24.5	20.5	29.2	27.2	24.4	21.1	29.0	28.5	27.1	25.9	23.0	20.8	16.3
Jan-85	28.6	25.4	20.4	31.0	28.4	25.1	21.7	30.7	29.6	28.1	26.7	23.6	21.1	16.3
Feb-85	26.7	23.4	18.5	28.7	26.1	22.7	19.7	28.7	27.8	25.9	24.4	21.6	19.1	14.4
Mar-85	22.4	19.5	15.6	21.7	21.5	18.9	16.5	24.2	22.9	21.3	20.2	18.2	16.1	13.0
Apr-85	18.2	15.5	12.2	19.0	16.9	14.7	12.7	19.8	18.4	16.9	15.9	14.3	12.5	10.2
May-85	13.9	11.6	9.2	14.3	12.5	10.8	9.4	15.1	13.9	12.6	11.8	10.6	9.2	8.5
Jun-85	11.8	9.9	7.7	11.9	10.4	9.1	7.8	12.7	11.6	10.6	9.9	8.9	7.6	7.4
Jul-85	10.6	8.8	6.5	10.9	9.3	7.9	6.6	11.6	10.6	9.6	8.9	7.7	6.5	6.5
Aug-85	11.2	8.8	6.1	11.7	9.9	8.0	6.4	12.5	11.3	9.8	9.0	7.6	6.1	5.6
Sep-85	14.9	12.5	9.4	15.8	14.0	11.9	9.9	16.4	15.5	14.0	13.1	11.4	9.6	7.9
Oct-85	18.4	15.3	11.0	19.9	17.5	14.7	11.8	20.3	19.2	17.4	16.1	14.1	11.6	7.9
Nov-85	24.1	21.7	16.8	26.1	24.3	21.4	17.7	25.9	25.5	24.0	22.9	20.8	17.5	13.0

Table D.3 Monthly Means of Hourly Temperatures (Deg C)

Month	Probe Number														No. hrs. Record
	T1	T2	T3	T4	T5	T6	T7	T8	T9	T10	T11	T12	T13	TAIR	
Dec-84	28.8	29.8	30.0	31.5	32.5	33.1	32.7	30.4	31.5	32.2	32.8	32.5	32.7	20.1	744
Jan-85	30.4	31.3	31.3	33.2	34.2	34.9	34.5	32.0	33.0	33.8	34.4	34.2	34.4	20.9	744
Feb-85	28.3	28.6	28.4	30.9	31.3	31.6	31.4	30.0	30.7	31.1	31.4	31.3	31.3	19.4	672
Mar-85	22.4	23.2	23.4	24.1	25.0	25.9	26.0	23.4	24.3	25.0	25.6	25.9	26.1	16.2	744
Apr-85	19.2	18.7	18.2	20.3	20.0	19.9	19.7	20.5	20.2	20.0	20.0	19.9	19.6	14.3	720
May-85	14.3	13.6	13.1	14.8	14.2	14.1	13.9	15.2	14.8	14.4	14.3	14.1	13.8	11.5	711
Jun-85	12.6	11.9	11.6	12.8	12.3	12.2	12.1	13.3	12.9	12.6	12.6	12.4	12.1	10.9	702
Jul-85	11.5	11.0	10.9	11.7	11.4	11.5	11.4	12.1	11.8	11.7	11.7	11.6	11.4	10.3	744
Aug-85	12.4	12.1	12.0	13.1	12.9	13.2	13.2	13.2	13.2	13.1	13.2	13.2	13.1	9.7	744
Sep-85	16.2	16.7	17.0	17.6	18.1	18.8	19.0	17.3	17.9	18.2	18.6	18.9	18.9	12.3	720
Oct-85	20.0	20.4	20.4	21.9	22.3	23.0	22.8	21.3	21.9	22.3	22.7	23.0	22.7	12.8	563
Nov-85	25.9	27.0	26.5	28.3	29.3	30.1	29.2	27.1	28.3	29.1	29.6	30.1	29.2	17.1	446
Year Mean	20.1	20.3	20.2	21.6	21.9	22.3	22.1	21.3	21.7	21.9	22.2	22.2	22.1	14.6	8254
Summer Mean	28.4	29.2	29.1	31.0	31.8	32.5	32.0	29.9	30.9	31.6	32.1	32.0	32.0	19.4	

Note:

Year Mean = sum of (monthly mean x days in month)/(days in year)

Summer Mean = sum of (monthly mean x days in month for Nov, Dec, Jan, Feb)/(sum of days in months)

Table D.4 Monthly Means of Temperature (Deg C) for each Hour of Day: Surface of Chip Seal

Hour	Dec 84	Jan 85	Feb 85	Mar 85	Apr 85	May 85	Jun 85	Jul 85	Aug 85	Sep 85	Oct 85	Nov 85	Mean For Yr
0	23.0	23.0	21.6	18.1	14.2	11.0	9.5	8.5	8.3	11.9	13.9	19.2	15.1
1	22.3	22.4	20.7	17.7	13.8	10.8	9.3	8.3	8.0	11.3	13.2	18.7	14.6
2	21.7	21.9	20.2	17.4	13.6	10.6	9.0	8.1	7.6	10.9	12.6	18.1	14.2
3	21.2	21.4	19.6	17.0	13.3	10.3	8.8	7.9	7.2	10.4	12.0	17.7	13.8
4	20.7	20.9	19.1	16.8	13.0	10.1	8.8	7.6	6.9	10.1	11.6	17.1	13.5
5	21.0	20.7	18.6	16.4	12.8	9.9	8.6	7.5	6.7	9.8	11.1	17.0	13.3
6	22.9	22.3	19.2	16.3	12.6	9.6	8.3	7.3	6.5	9.6	12.3	19.3	13.7
7	26.6	26.6	23.2	17.9	13.1	9.6	8.1	7.1	6.7	11.5	16.3	23.6	15.6
8	30.7	31.5	28.1	21.4	15.6	10.5	8.4	7.6	8.3	15.8	21.4	27.4	18.6
9	34.7	36.9	33.0	25.5	19.5	13.6	10.0	9.7	12.4	20.2	26.5	31.0	22.4
10	38.6	40.8	36.7	29.4	23.0	16.9	13.5	13.2	16.2	23.5	30.7	34.8	26.1
11	41.1	44.1	39.4	32.4	25.7	18.8	15.5	15.4	19.0	26.6	32.3	37.2	28.6
12	42.0	46.2	41.3	34.2	27.2	20.8	17.4	17.1	21.1	28.2	33.1	39.1	30.3
13	42.2	45.9	41.6	34.4	27.5	21.4	18.4	17.9	21.6	28.3	33.3	39.3	30.7
14	41.7	44.8	41.1	33.8	27.3	20.8	17.9	17.5	20.9	27.6	31.8	38.7	30.0
15	39.5	42.1	39.0	31.9	25.3	19.0	16.2	16.0	18.6	25.7	29.3	36.2	27.9
16	37.3	39.5	35.9	29.3	22.8	16.9	14.2	14.0	16.6	22.6	26.2	33.3	25.5
17	34.2	36.4	32.5	26.1	20.1	14.9	12.7	12.0	14.0	19.2	23.1	30.0	22.7
18	30.9	32.3	29.0	23.4	18.2	13.7	11.9	11.0	12.2	16.6	20.0	26.8	20.3
19	27.9	29.2	26.5	21.6	17.2	13.0	11.3	10.4	11.2	15.2	18.3	24.3	18.7
20	26.2	27.2	25.1	20.6	16.3	12.4	10.8	9.9	10.4	14.2	17.2	22.7	17.6
21	25.1	25.9	24.0	19.8	15.6	12.0	10.4	9.4	9.8	13.5	16.2	21.7	16.8
22	24.3	24.8	23.1	19.1	15.0	11.7	10.0	9.1	9.2	12.9	15.4	20.8	16.1
23	23.6	23.9	22.2	18.4	14.6	11.4	9.8	8.8	8.7	12.4	14.6	20.0	15.6
Mean for Mth	30.0	31.3	28.4	23.3	18.2	13.7	11.6	10.9	12.0	17.0	20.4	26.5	20.1

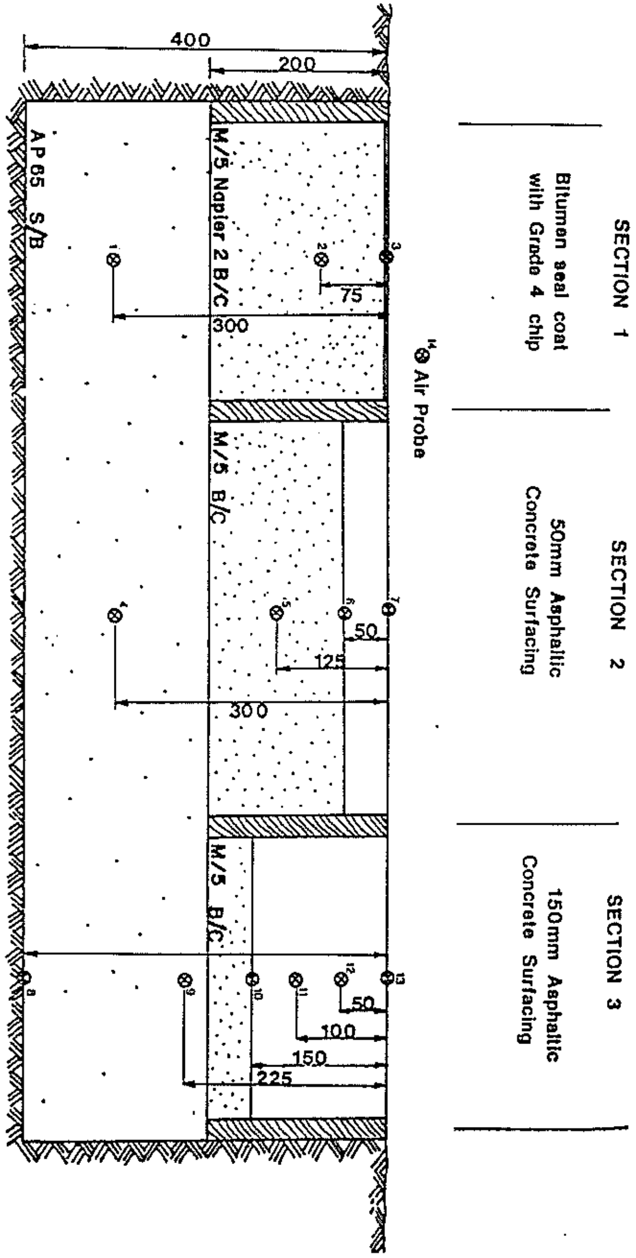


Figure D.1 Test Site Pavement Sections and Probe Locations

Table D.5 Monthly Means of Temp (Deg C) for each Hour of Day:
50mm Deep in 150 mm Thick AC

Hour	Dec 84	Jan 85	Feb 85	Mar 85	Apr 85	May 85	Jun 85	Jul 85	Aug 85	Sep 85	Oct 85	Nov 85	Mean For Yr
0	26.4	27.3	25.7	21.1	16.6	12.7	10.9	9.7	10.2	14.5	17.7	24.1	17.9
1	25.6	26.4	24.7	20.5	16.2	12.3	10.6	9.4	9.8	13.9	16.9	23.2	17.3
2	24.8	25.6	23.9	20.1	15.8	12.0	10.2	9.2	9.3	13.3	16.2	22.5	16.7
3	24.2	24.9	23.3	19.6	15.4	11.8	10.0	8.9	8.9	12.8	15.5	21.9	16.3
4	23.5	24.3	22.6	19.2	15.1	11.5	9.8	8.7	8.5	12.3	14.9	21.2	15.8
5	23.2	23.8	22.0	18.8	14.8	11.3	9.6	8.5	8.2	11.9	14.3	20.7	15.4
6	23.9	24.1	21.7	18.5	14.5	11.0	9.4	8.3	7.9	11.6	14.2	21.3	15.4
7	26.2	26.4	23.3	18.8	14.5	10.8	9.2	8.1	7.8	11.8	15.9	23.7	16.1
8	29.3	30.0	26.7	20.6	15.3	11.0	9.1	8.1	8.2	13.8	19.1	26.7	17.9
9	32.8	34.3	30.5	23.5	17.8	12.2	9.5	8.7	10.1	17.2	23.1	29.9	20.4
10	36.8	38.6	34.5	27.2	20.7	15.0	11.4	11.0	13.2	20.7	27.7	33.6	23.8
11	40.1	42.4	38.0	30.7	23.7	17.7	13.8	13.4	16.6	24.2	30.8	36.6	27.0
12	42.3	45.4	40.9	33.4	26.2	19.3	15.6	15.2	19.1	27.1	33.0	39.3	29.4
13	43.6	47.1	42.7	35.2	27.7	21.0	17.4	16.9	21.0	28.8	34.4	41.0	31.0
14	44.3	47.4	43.5	35.7	28.5	21.6	18.2	17.7	21.6	29.5	34.6	41.9	31.7
15	43.6	46.6	43.2	35.4	28.1	21.0	17.8	17.4	21.1	29.1	33.6	41.1	31.1
16	42.2	44.8	41.6	33.9	26.5	19.7	16.5	16.1	19.8	27.4	31.5	39.5	29.6
17	39.9	42.7	39.1	31.5	24.2	17.9	14.9	14.4	17.6	24.7	29.0	37.0	27.4
18	37.0	39.3	35.9	28.8	22.1	16.4	13.9	13.1	15.6	21.8	26.1	34.1	25.0
19	33.9	35.9	32.8	26.5	20.5	15.4	13.1	12.3	14.2	19.7	23.7	31.3	23.0
20	31.4	33.2	30.6	24.8	19.4	14.6	12.4	11.5	13.1	18.3	22.1	29.1	21.4
21	29.6	31.2	28.9	23.5	18.5	14.0	11.9	11.0	12.2	17.1	20.7	27.5	20.3
22	28.3	29.7	27.6	22.6	17.7	13.5	11.5	10.5	11.5	16.1	19.6	26.2	19.3
23	27.2	28.5	26.5	21.7	17.1	13.1	11.1	10.1	10.8	15.3	18.6	25.0	18.5
Mean for Mth	32.5	34.2	31.3	25.5	19.9	14.8	12.4	11.6	13.2	18.9	23.0	30.1	22.0

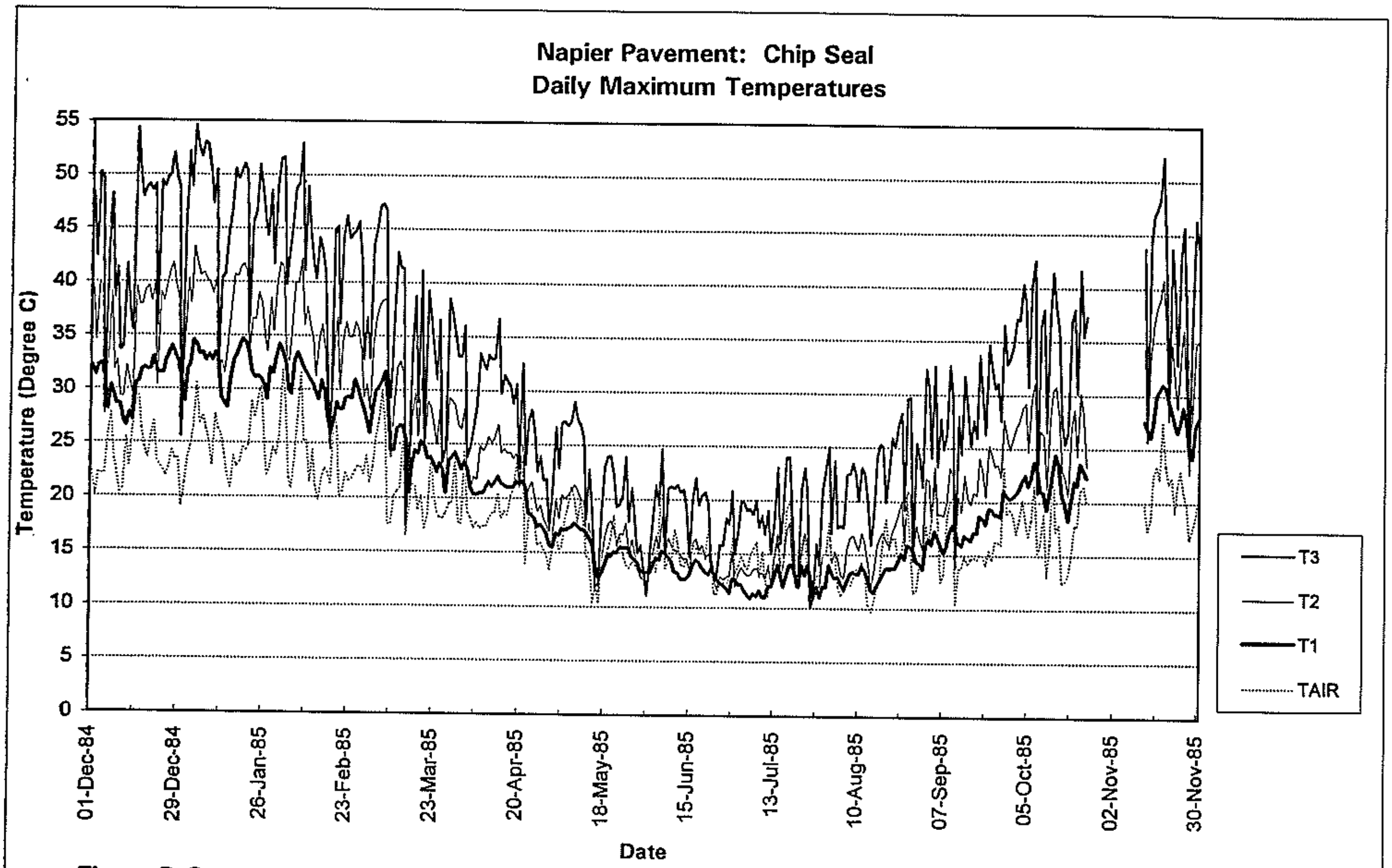
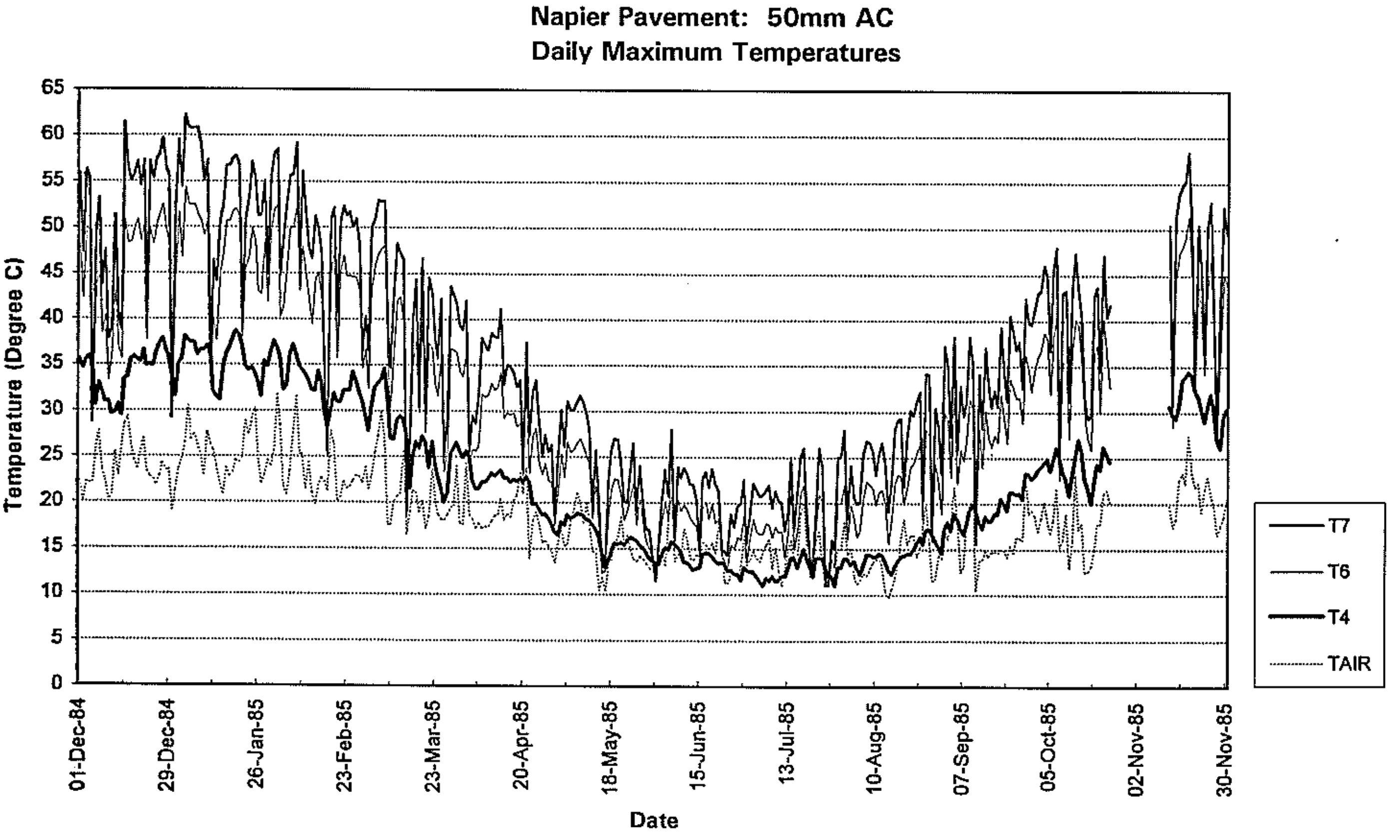


Figure D.2



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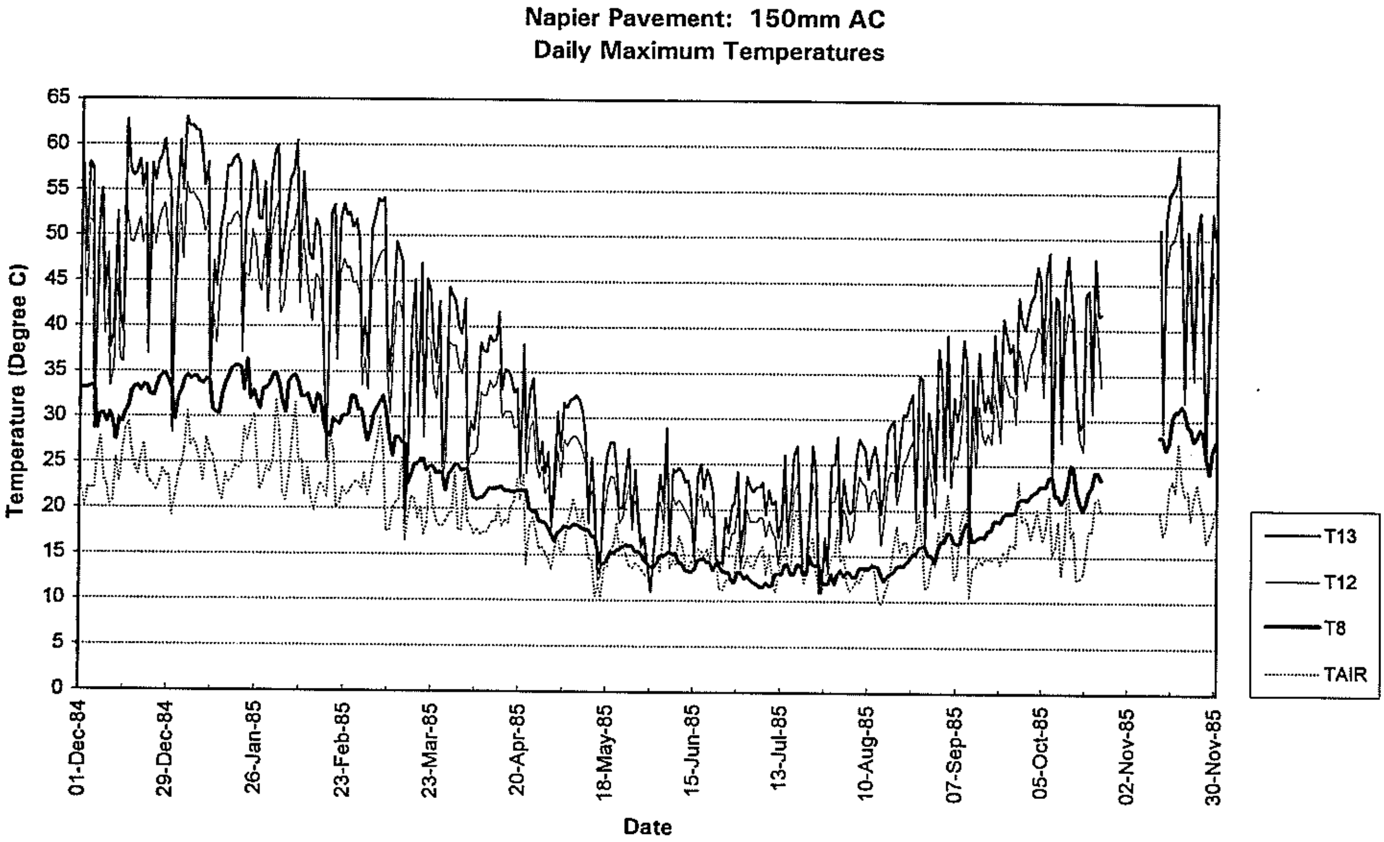

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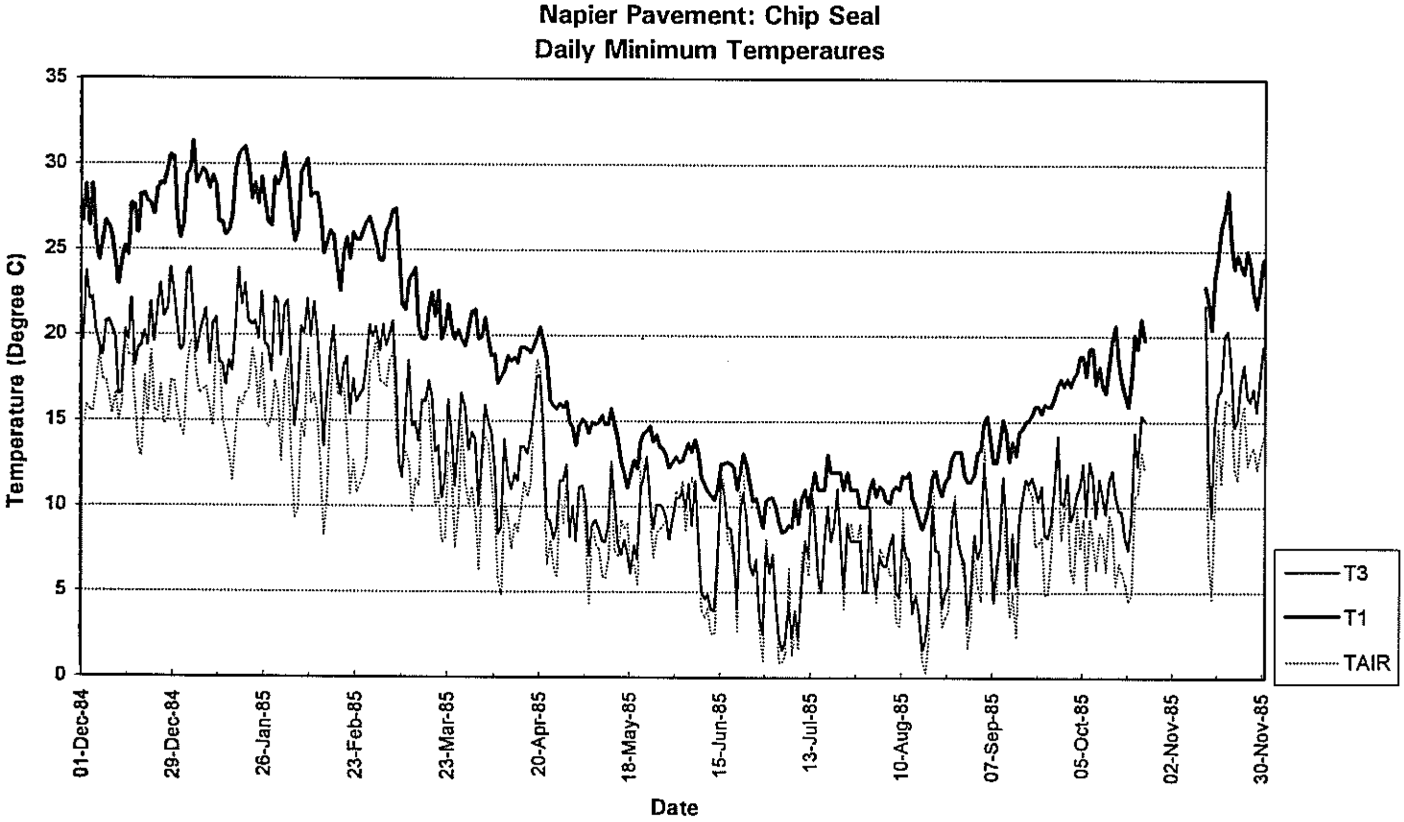

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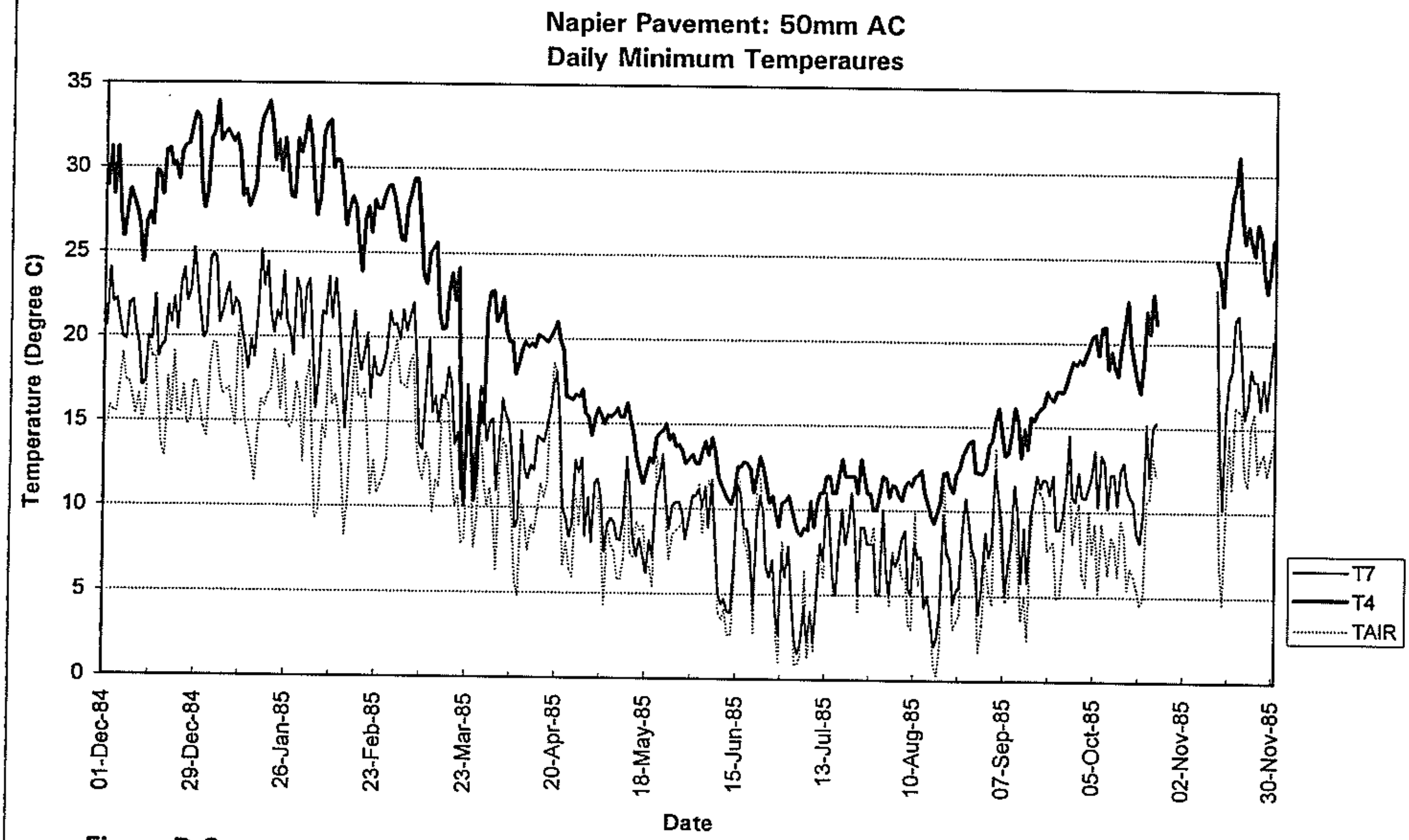
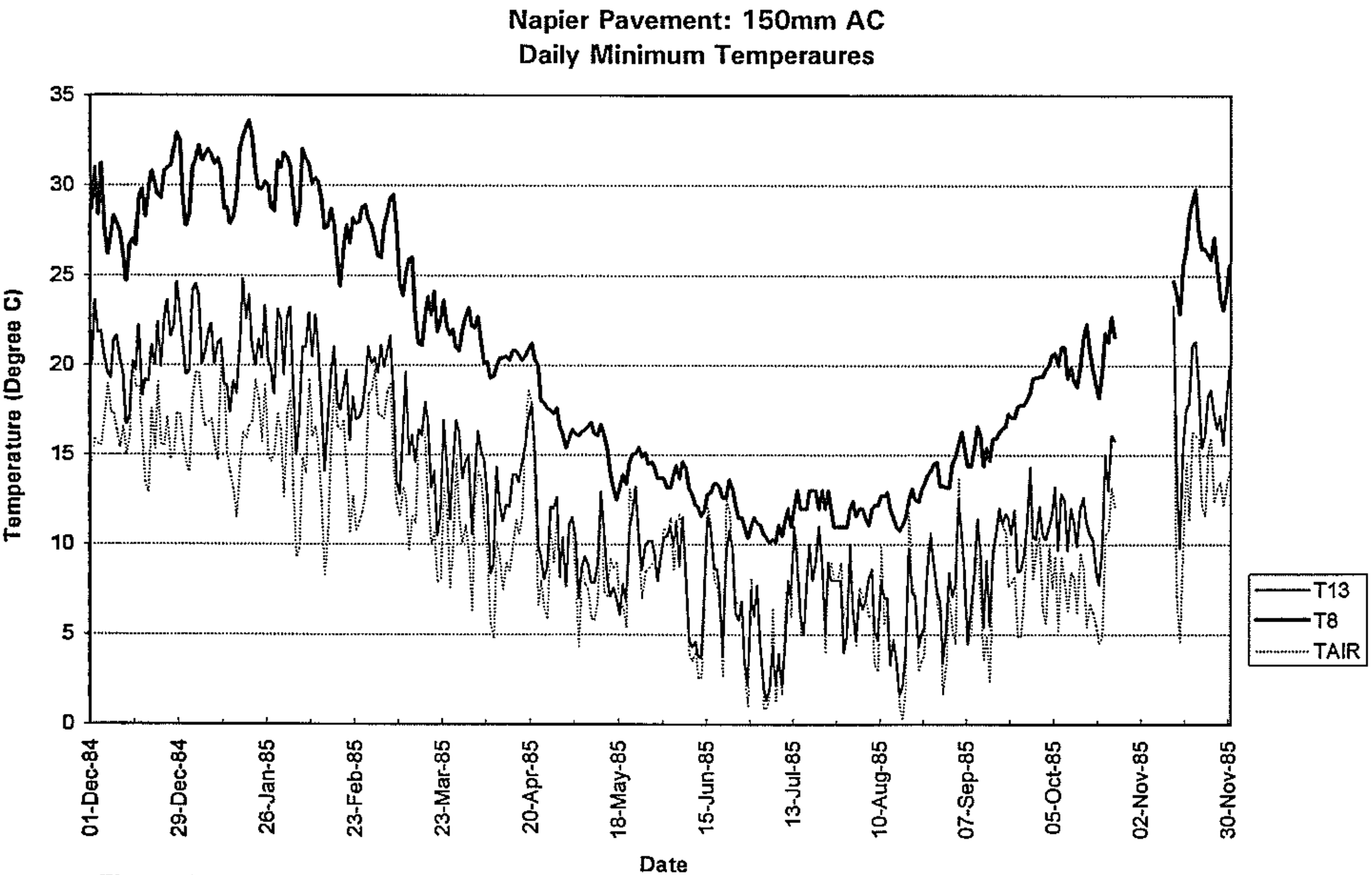


Figure D.6



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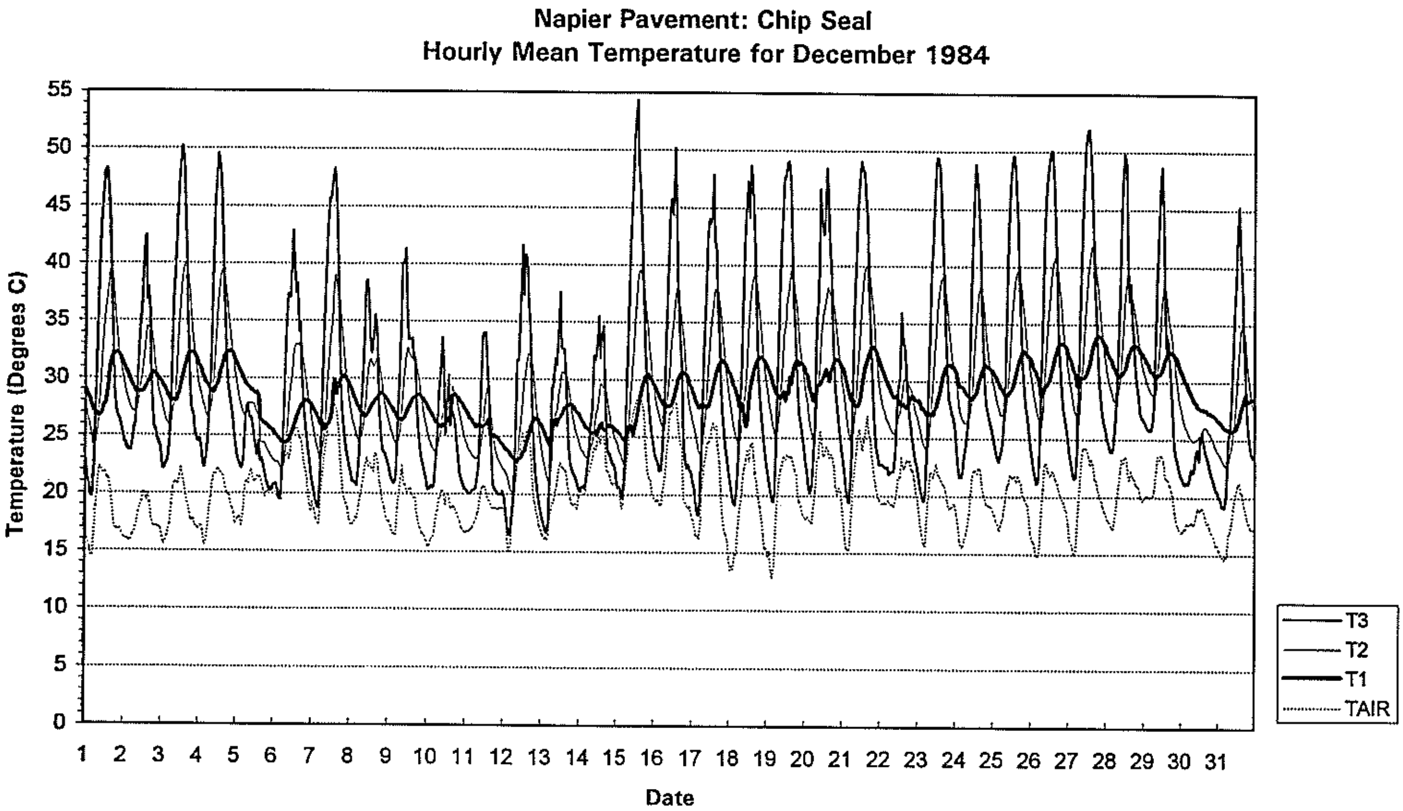


Figure D.8

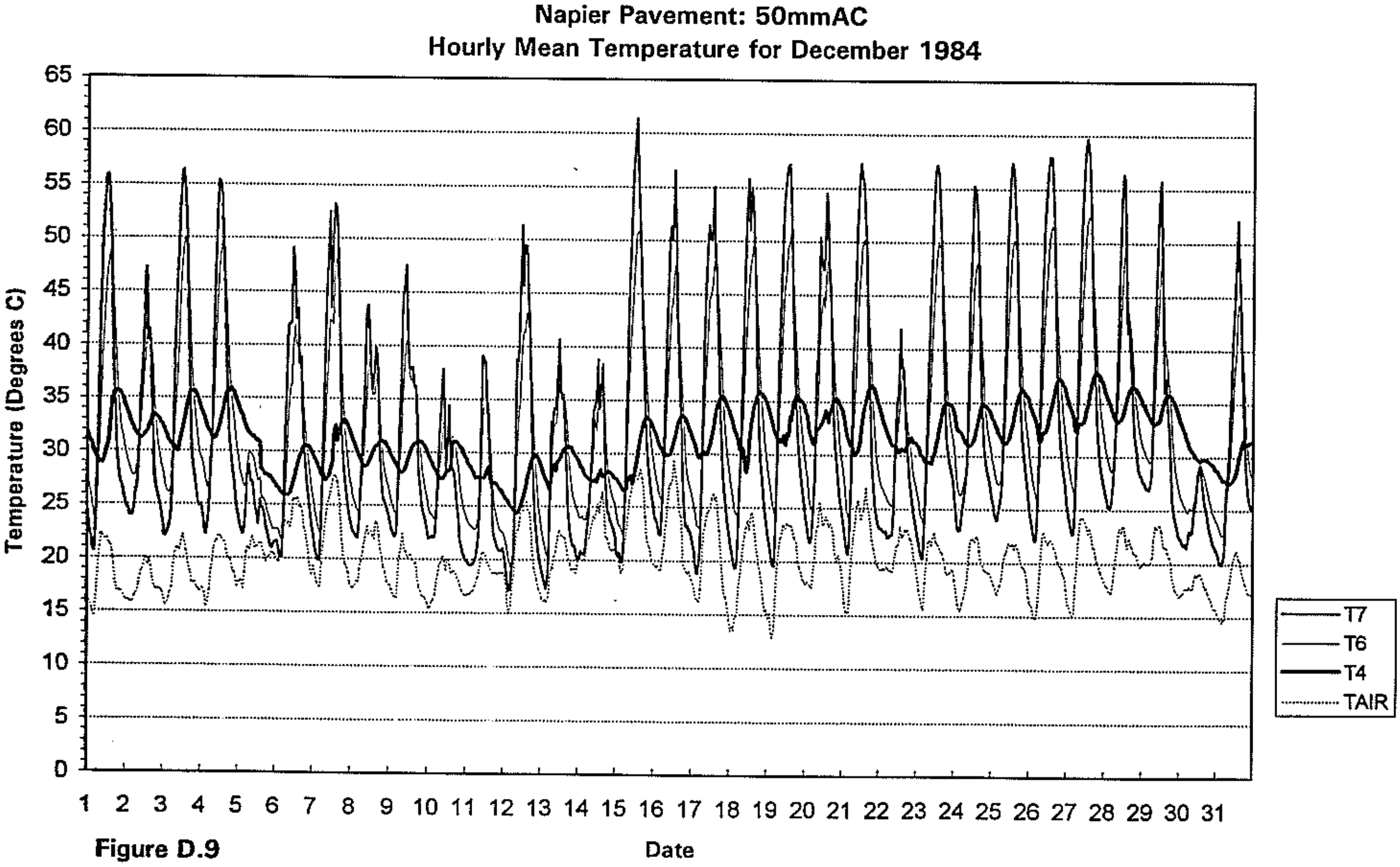
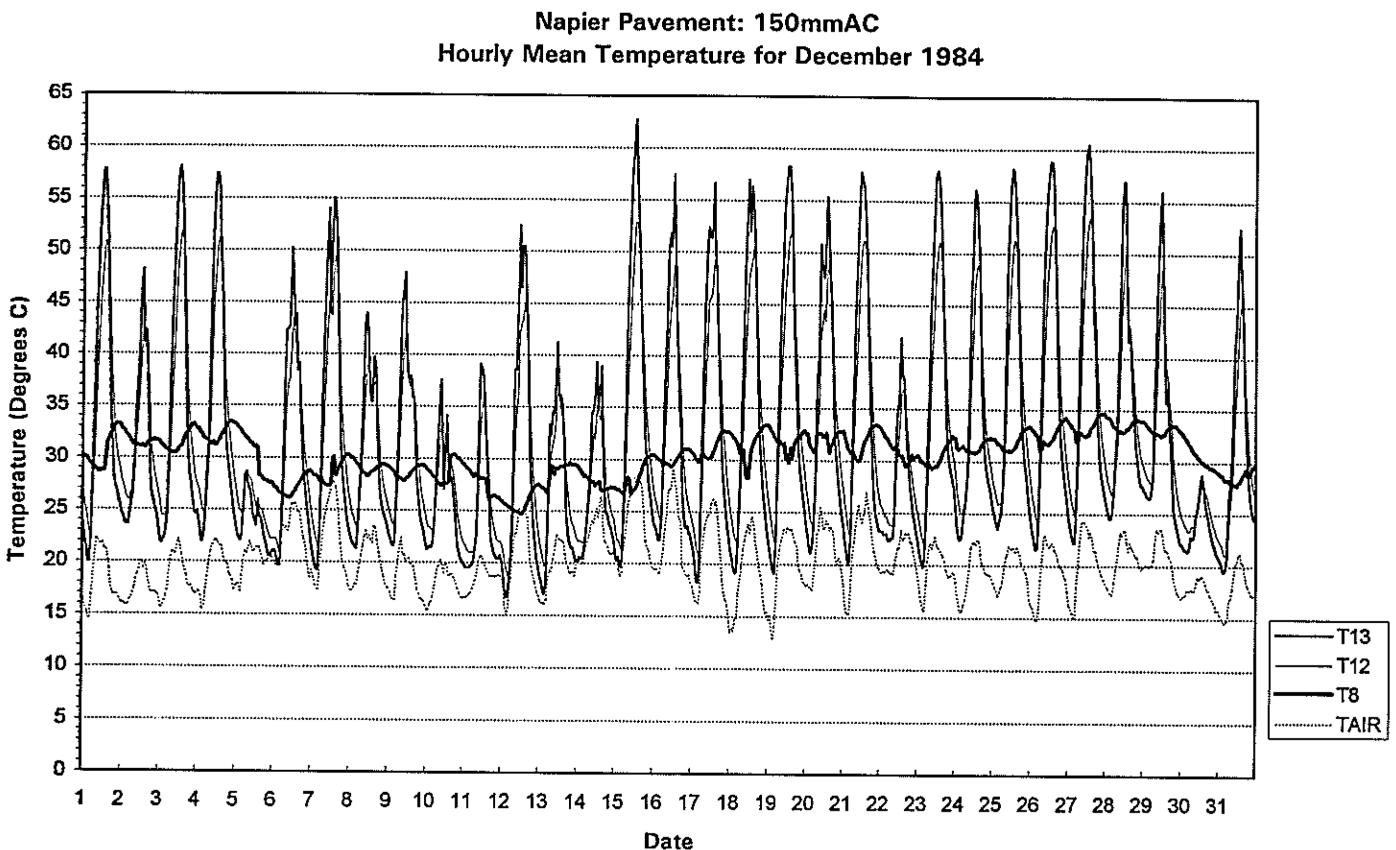


Figure D.9



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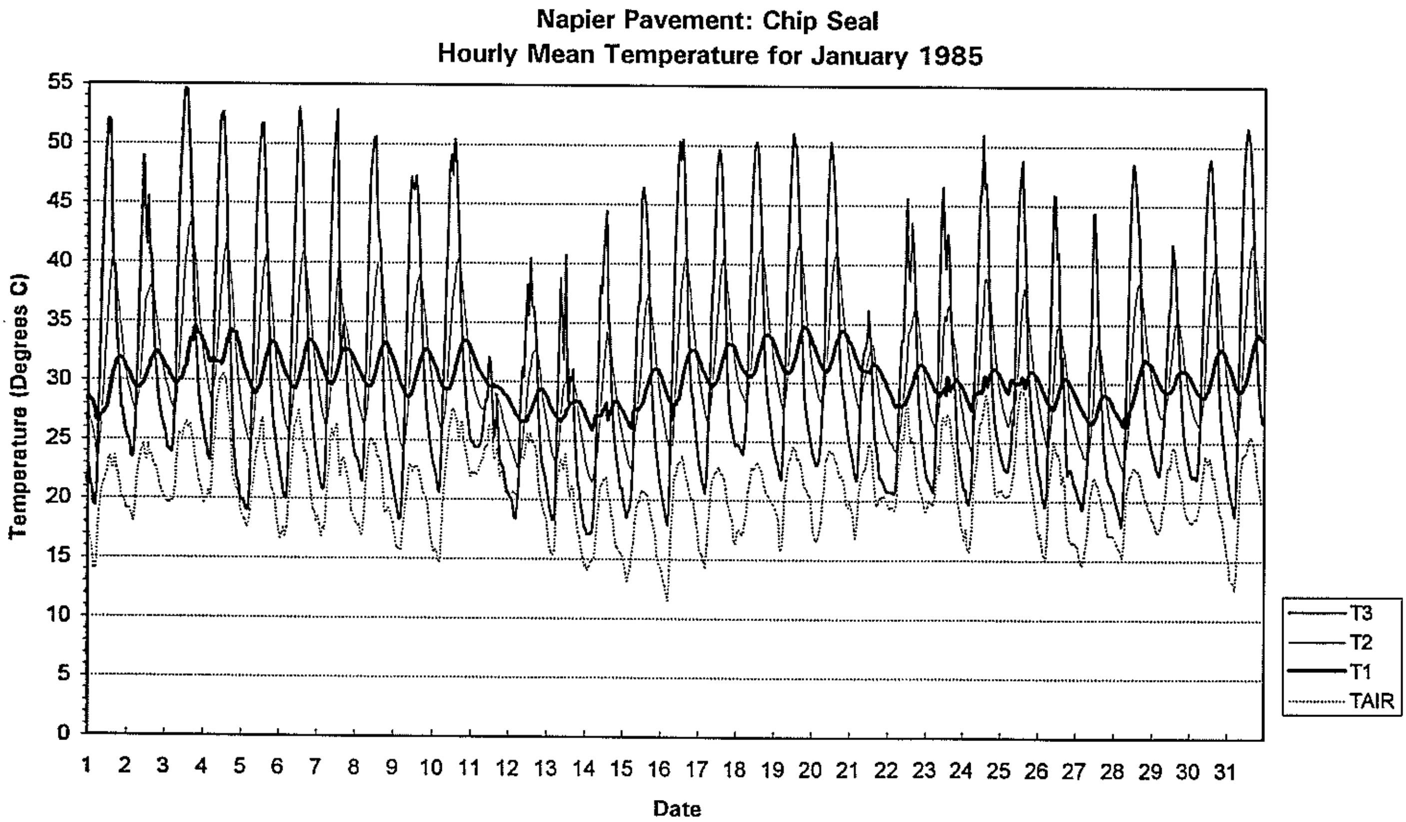


Figure D.11

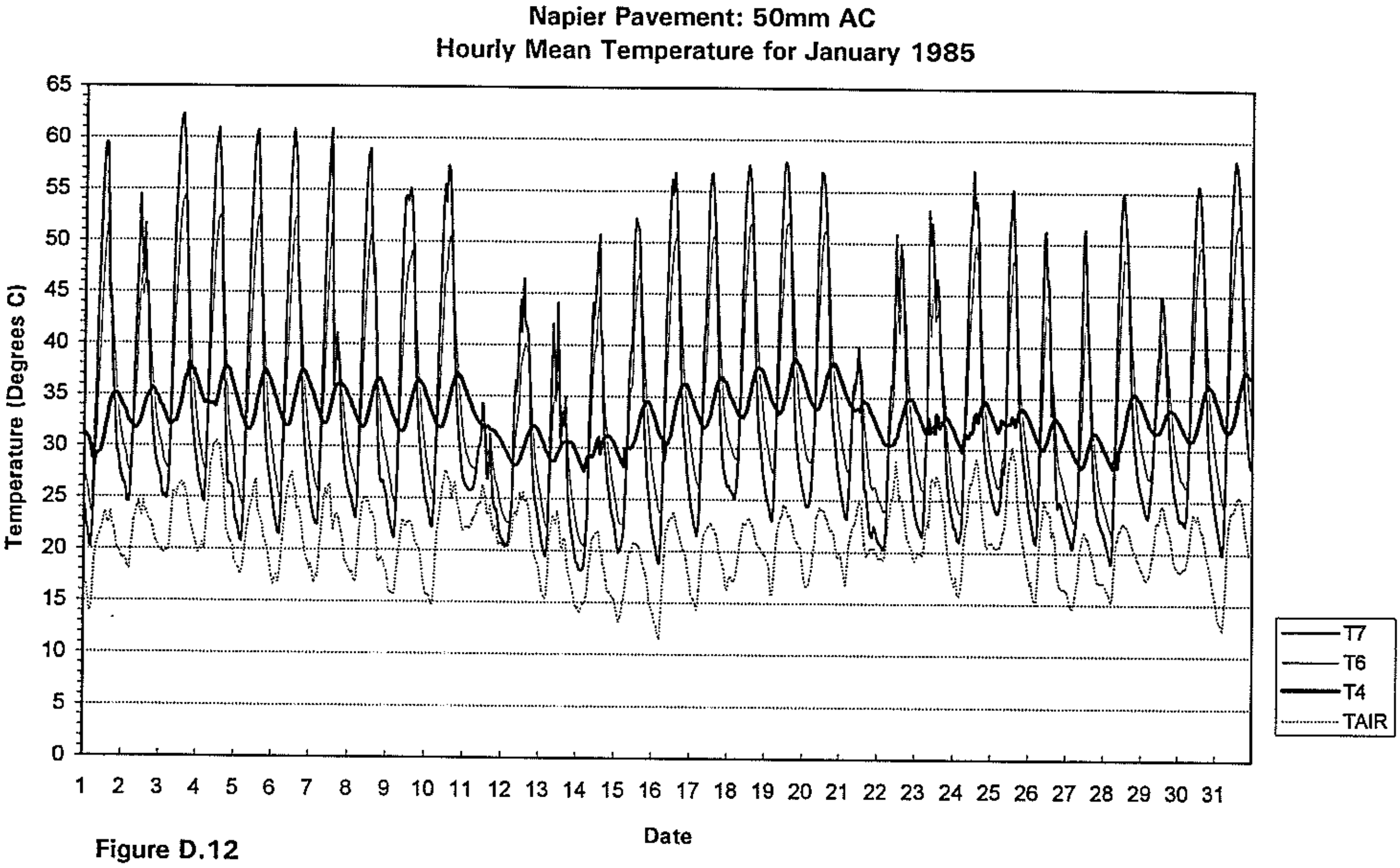


Figure D.12

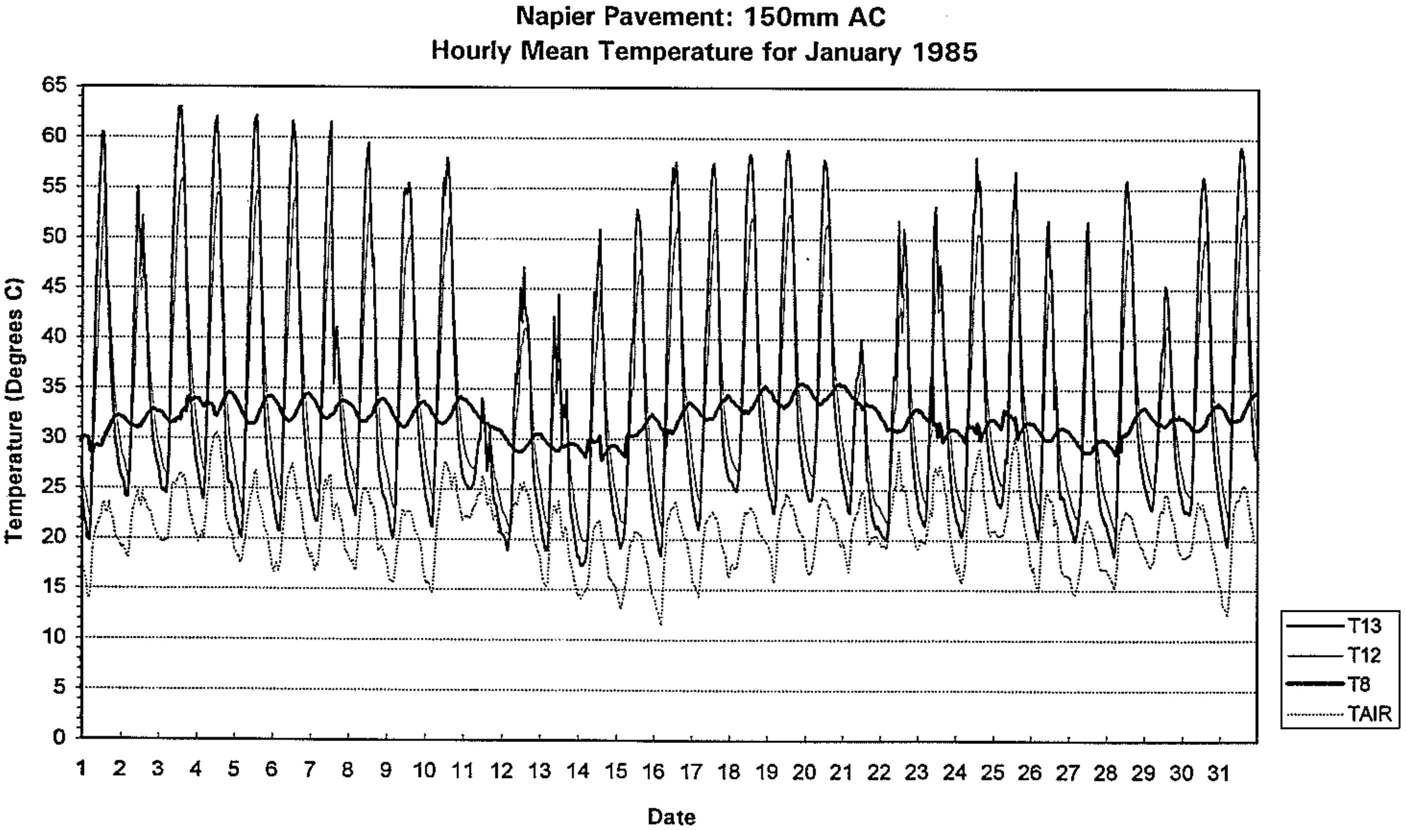
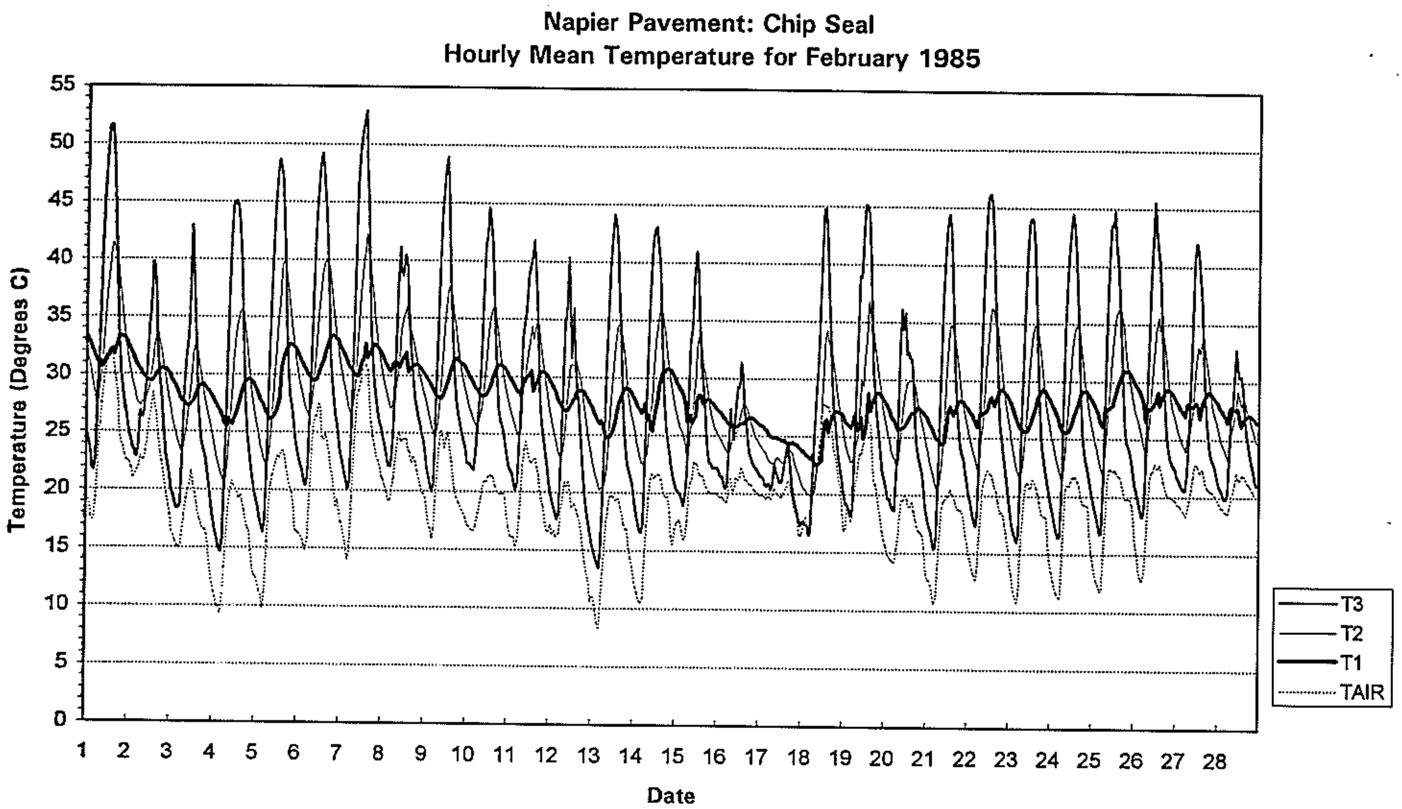


Figure D.13



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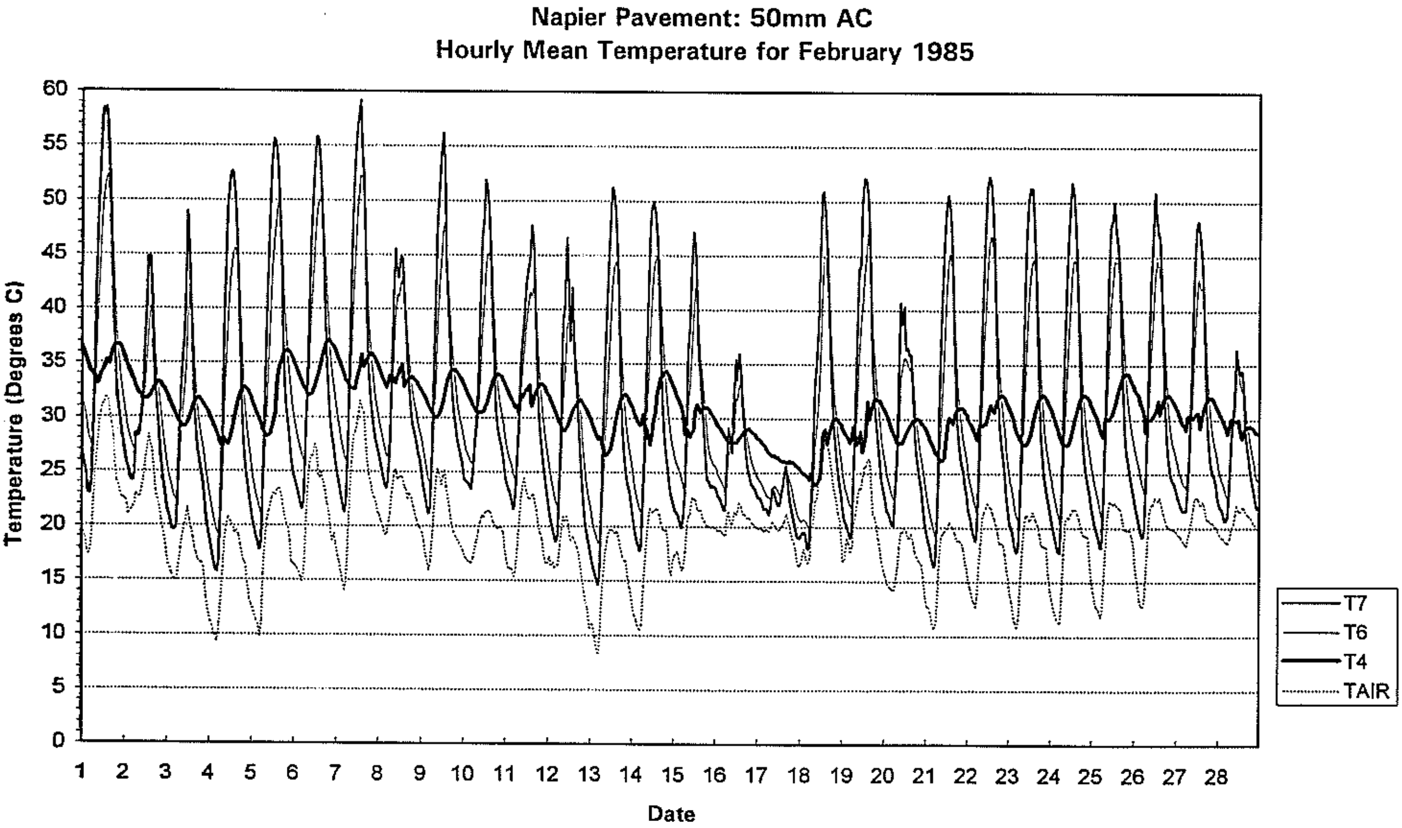


Figure D.15

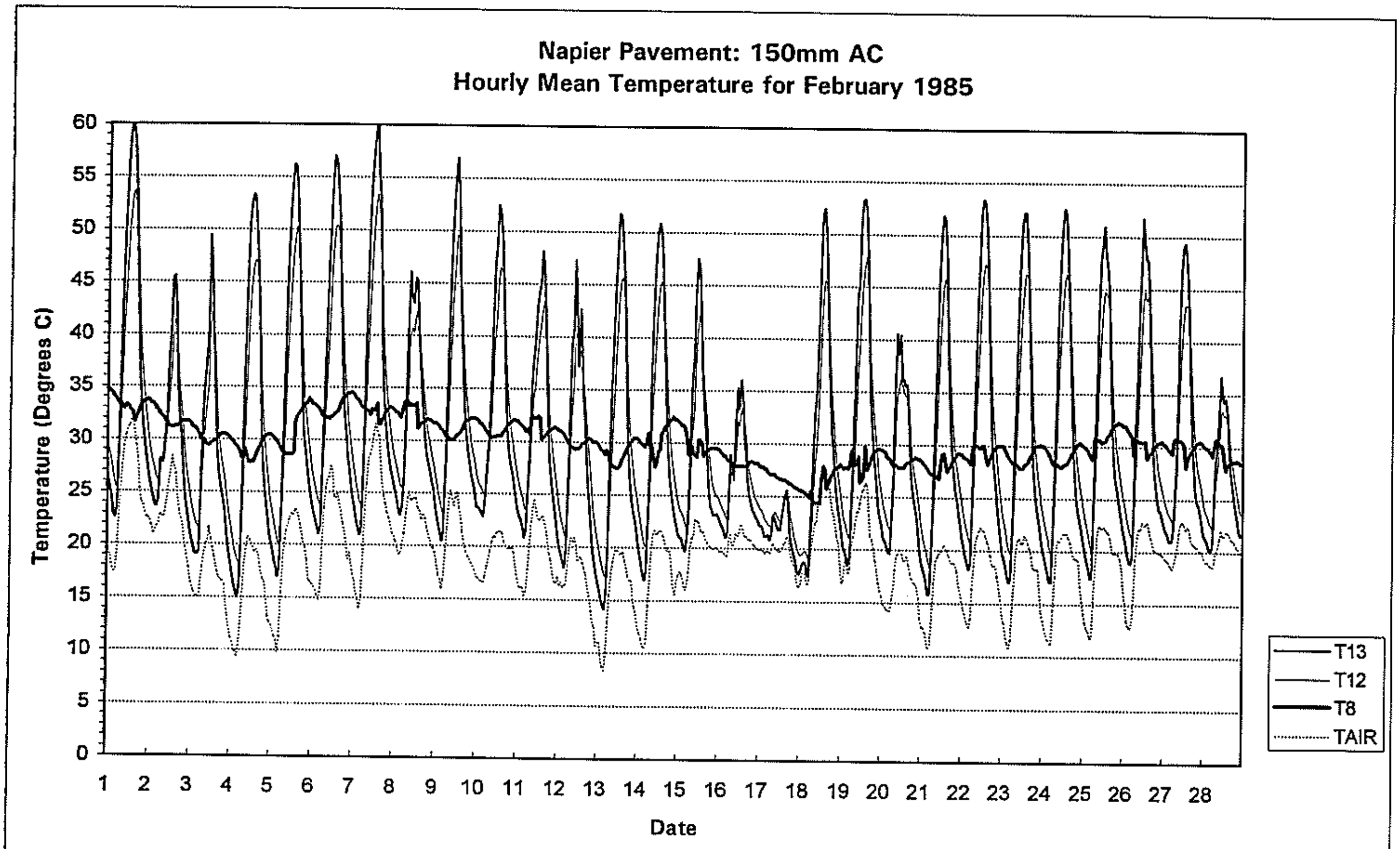


Figure D.16

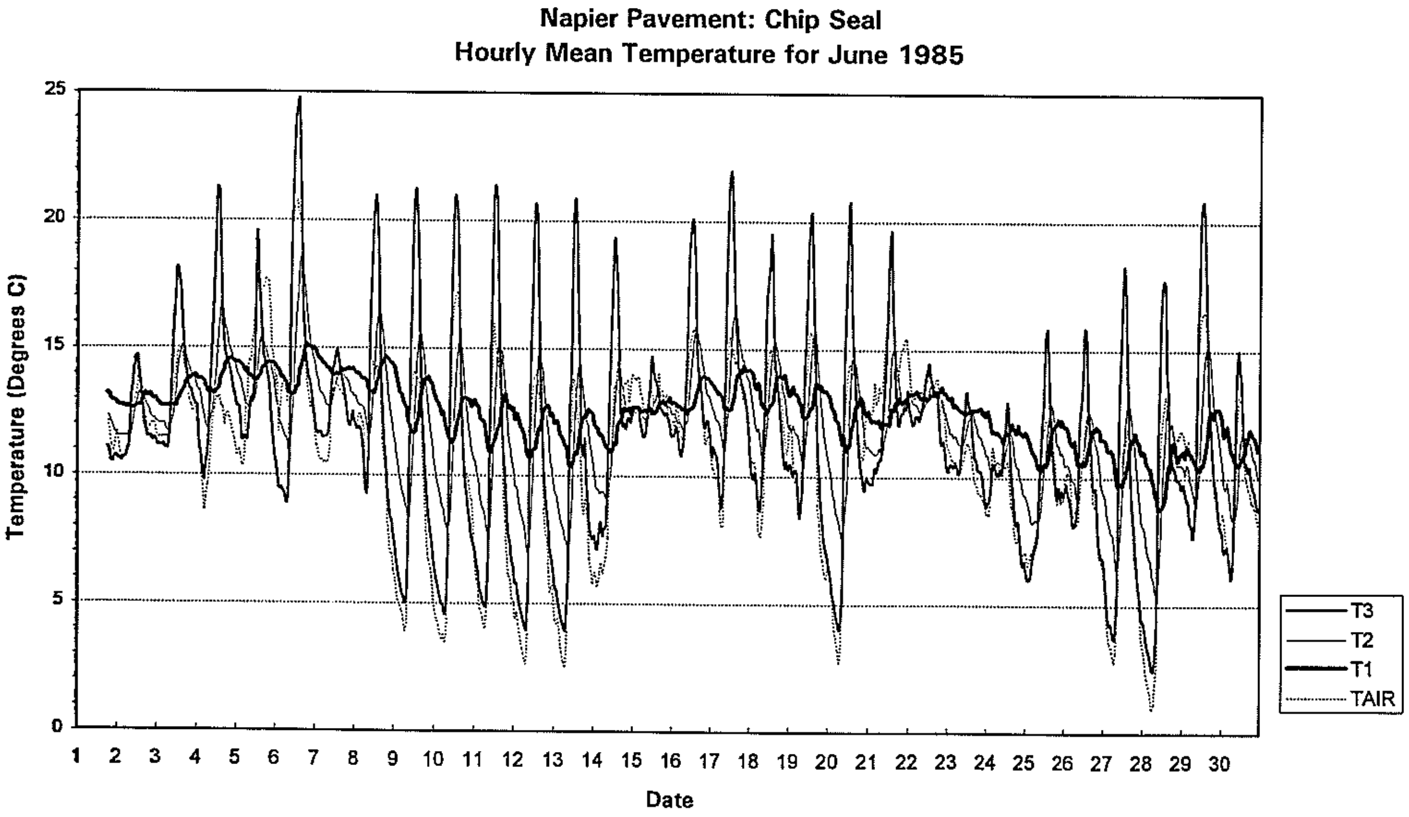


Figure D.17

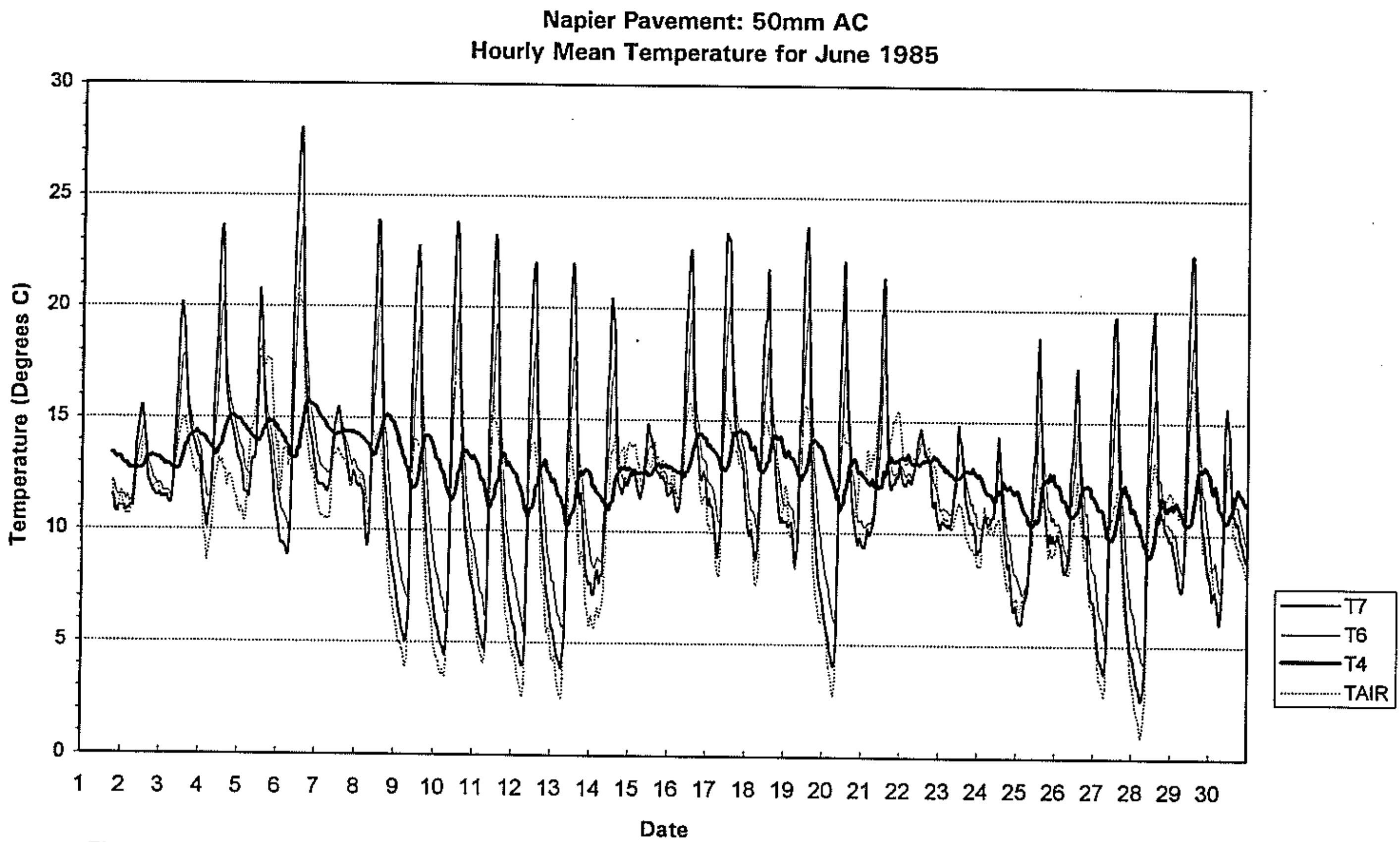


Figure D.18

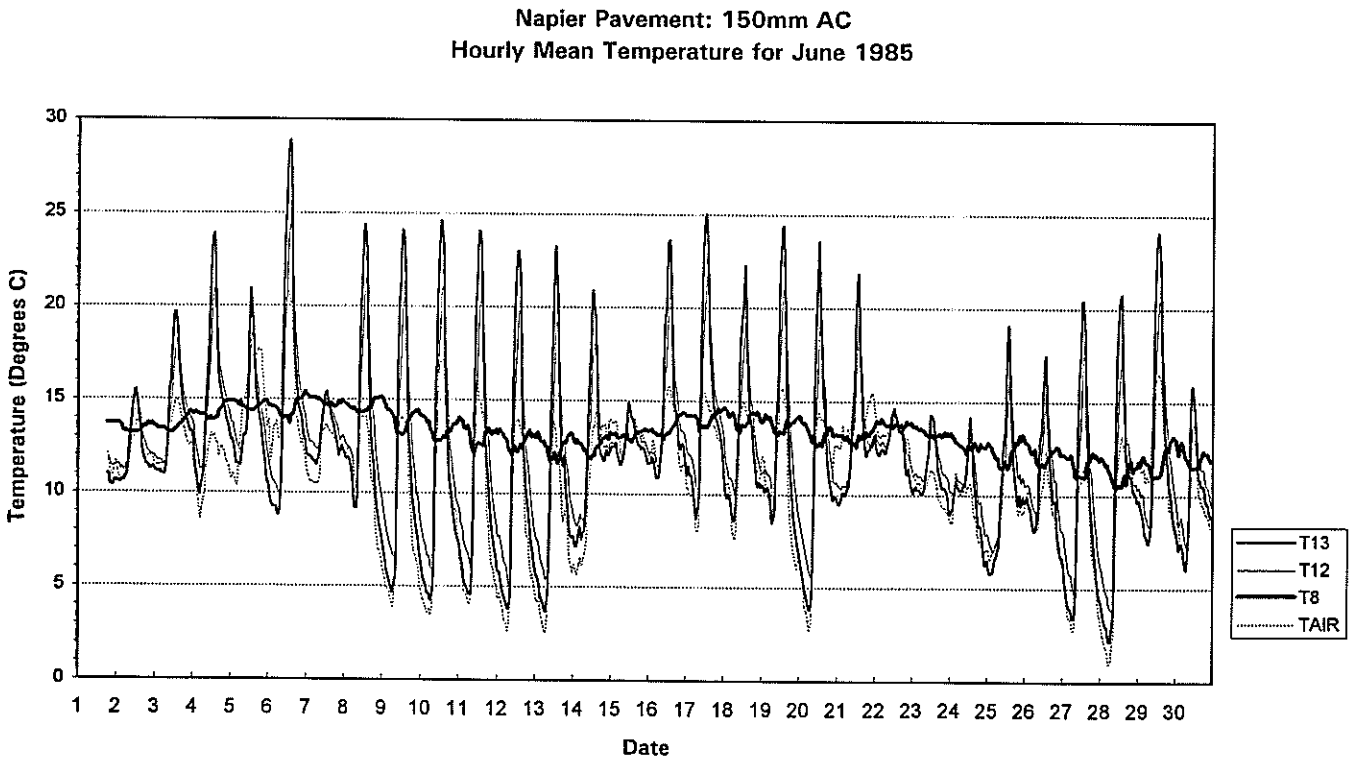


Figure D.19

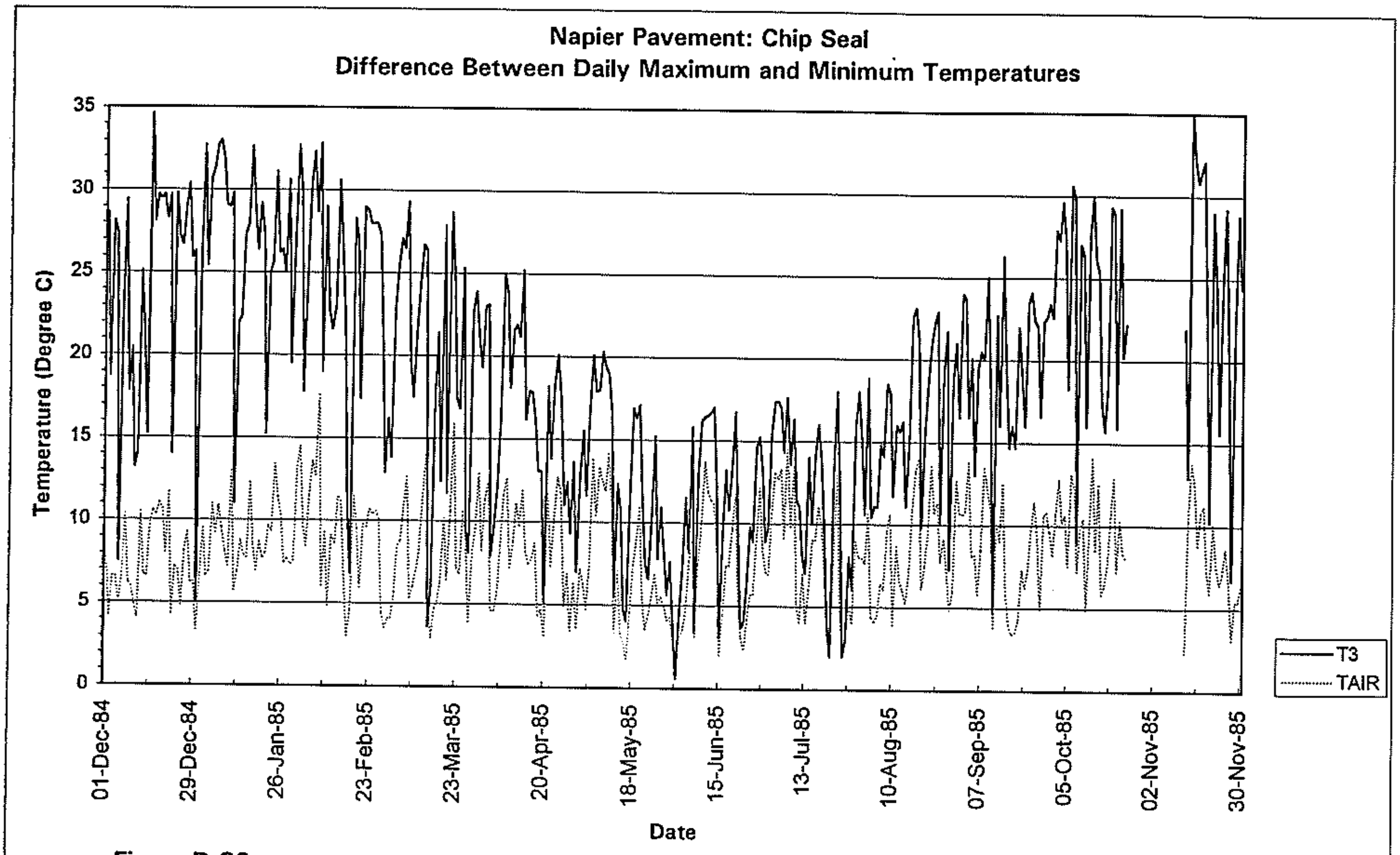


Figure D.20

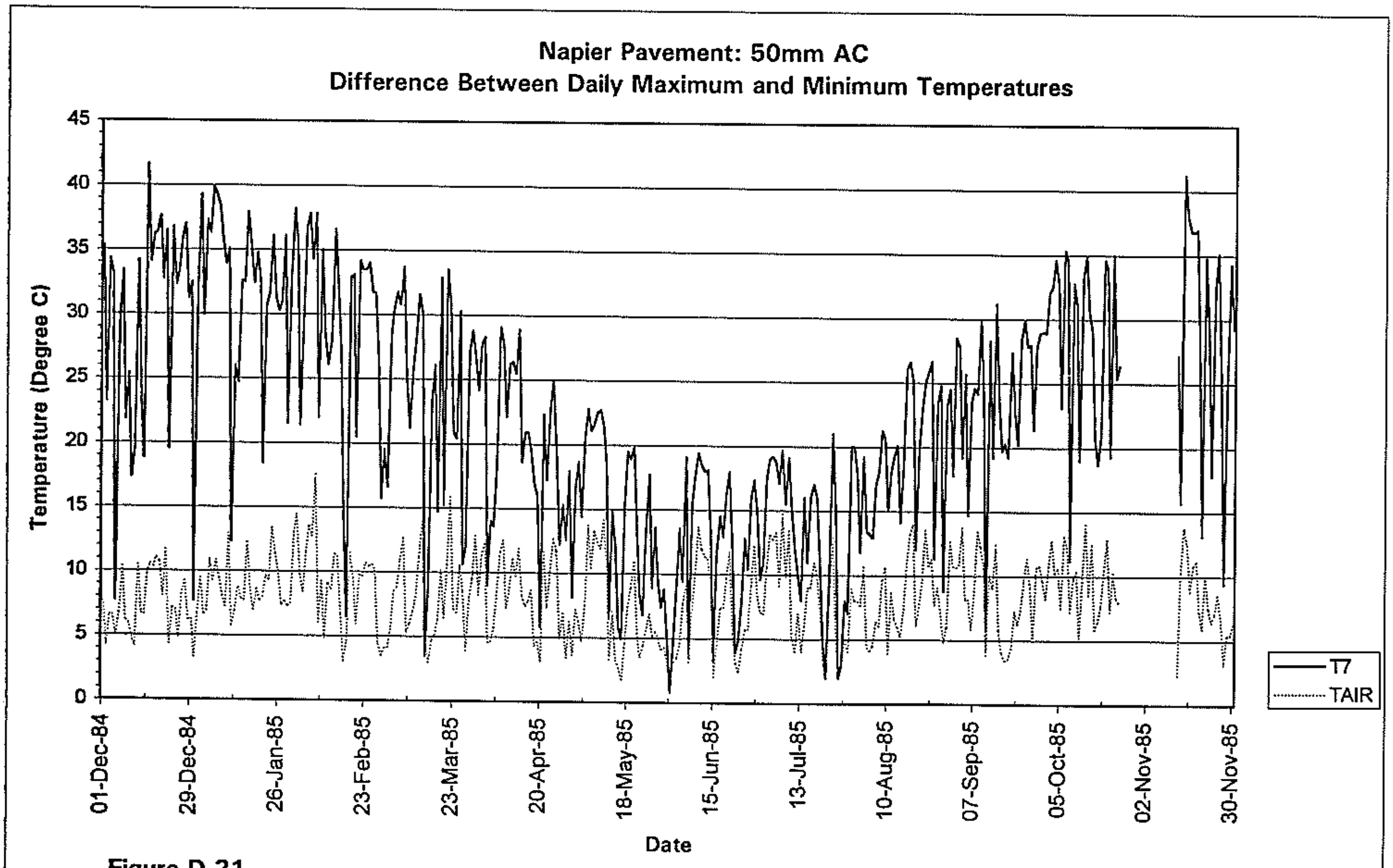


Figure D.21

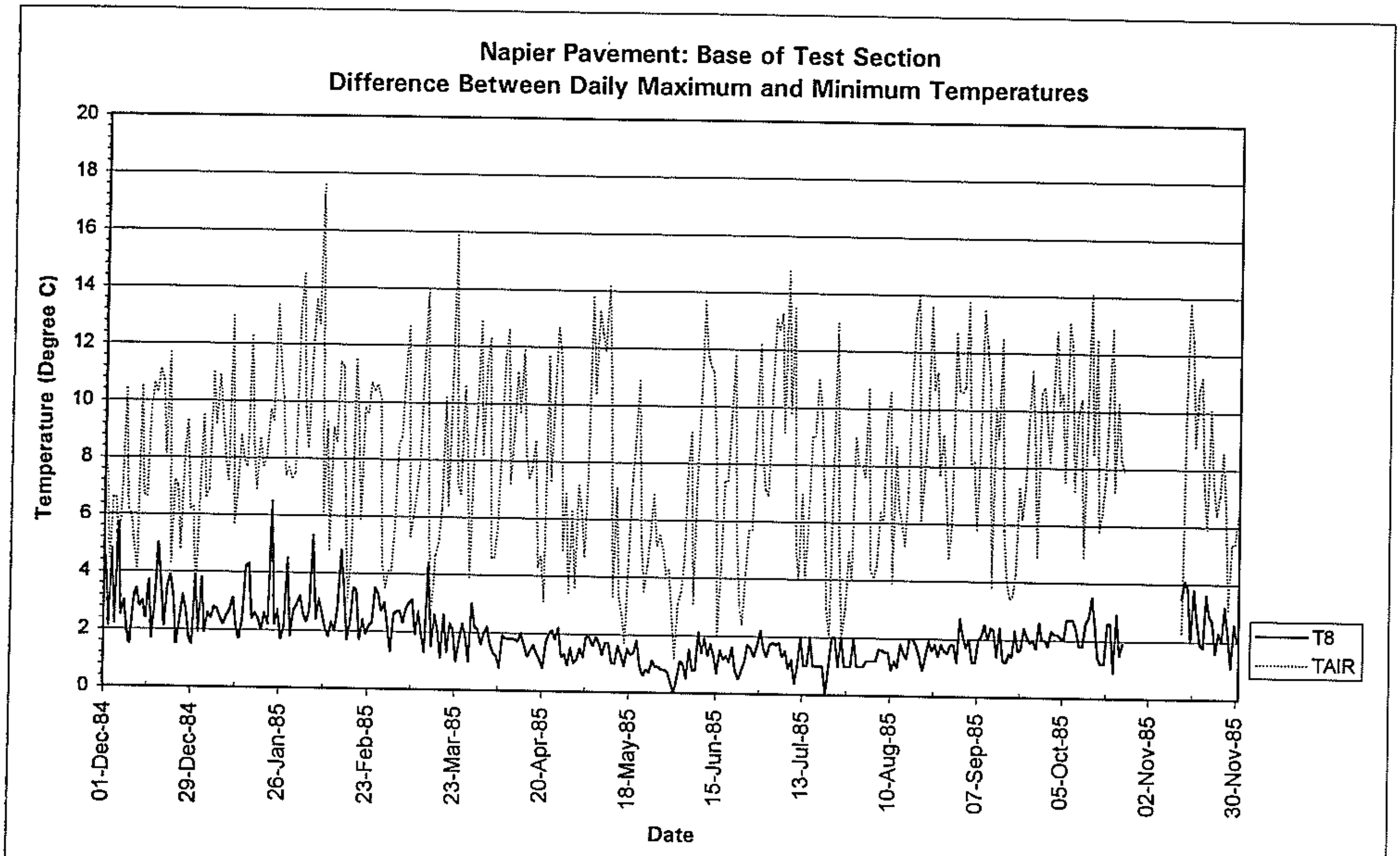
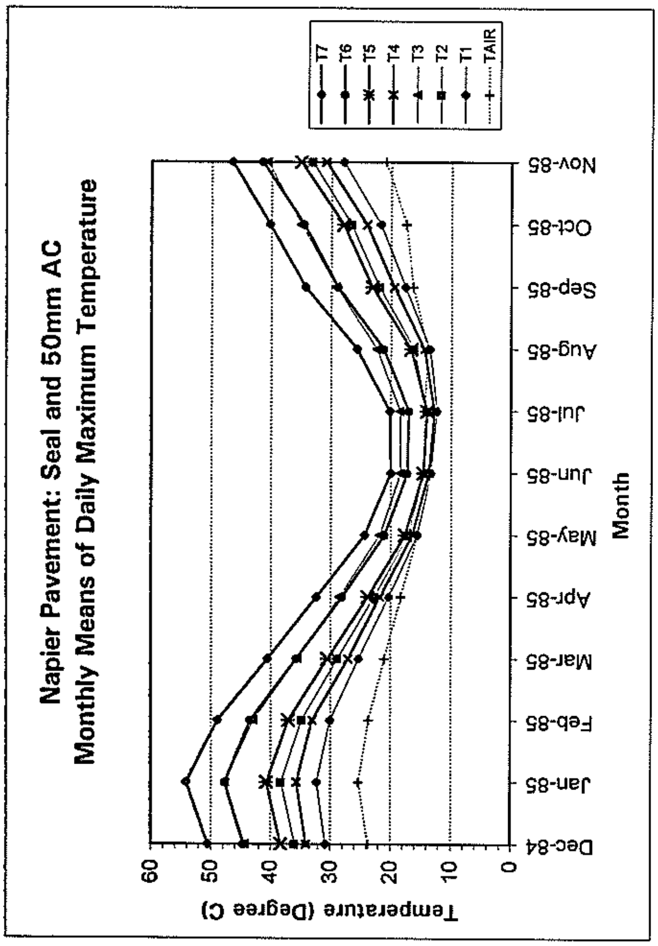


Figure D.22



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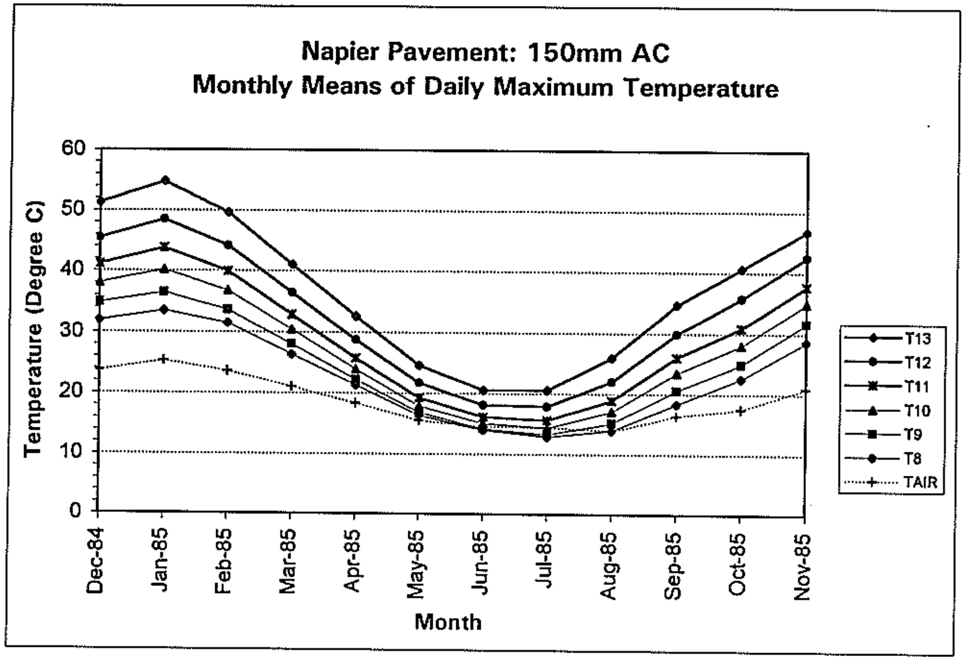

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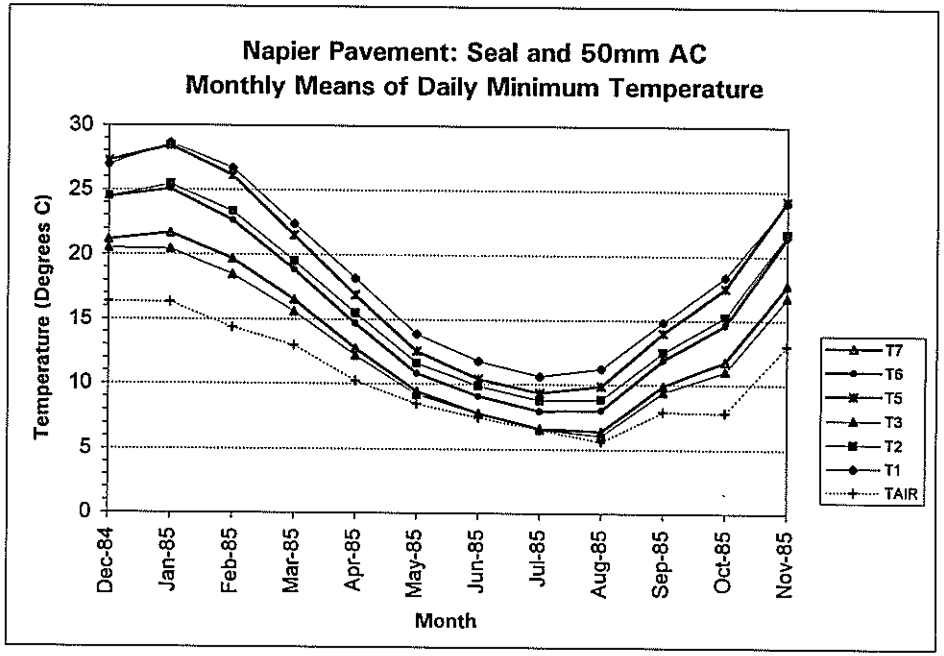


Figure D.25

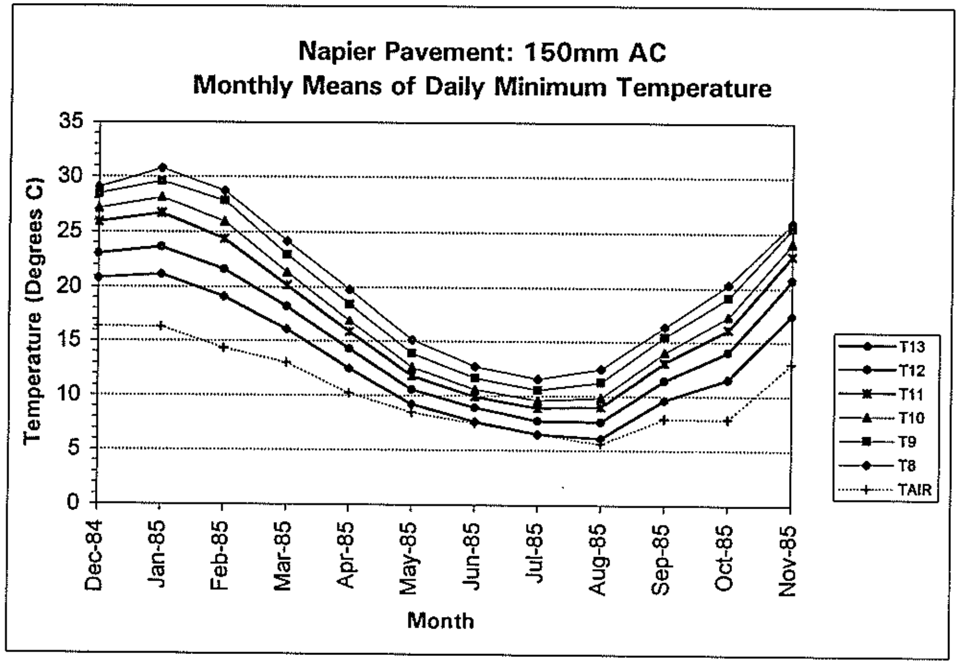


Figure D.26

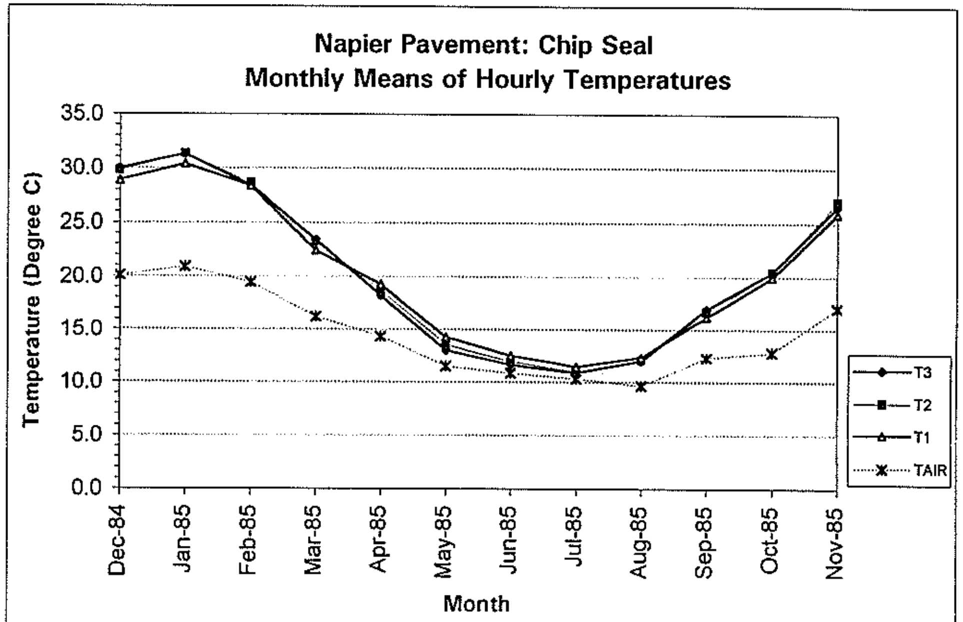


Figure D.27

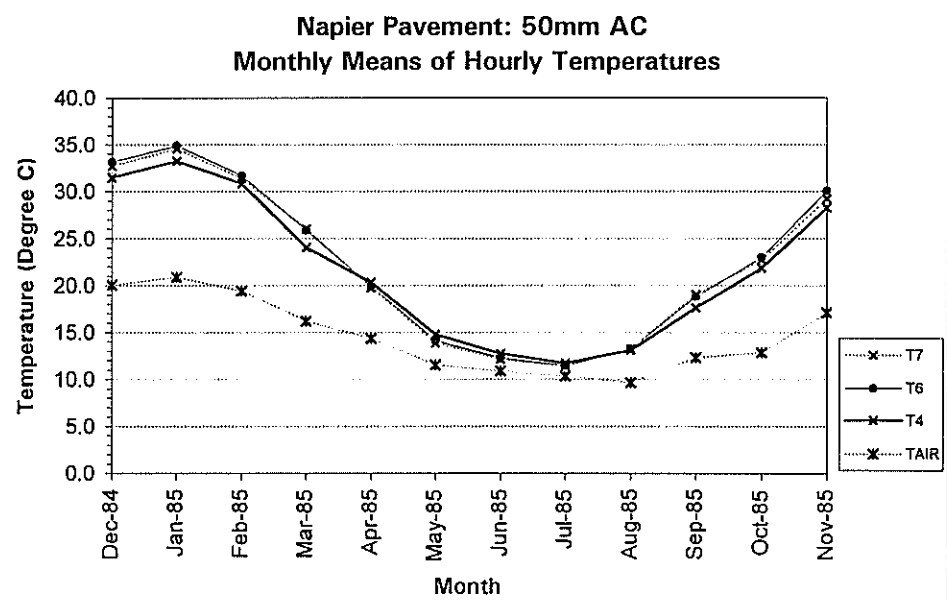


Figure D.28

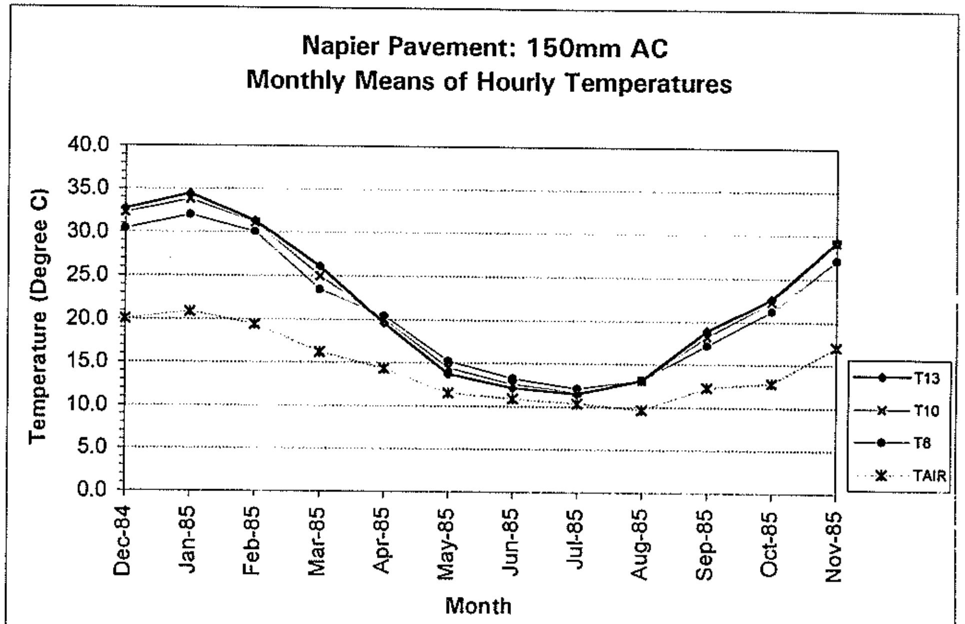


Figure D.29

Napier Pavement: Surface of Chip Seal
Monthly Mean Temperature for Each Hour of Day

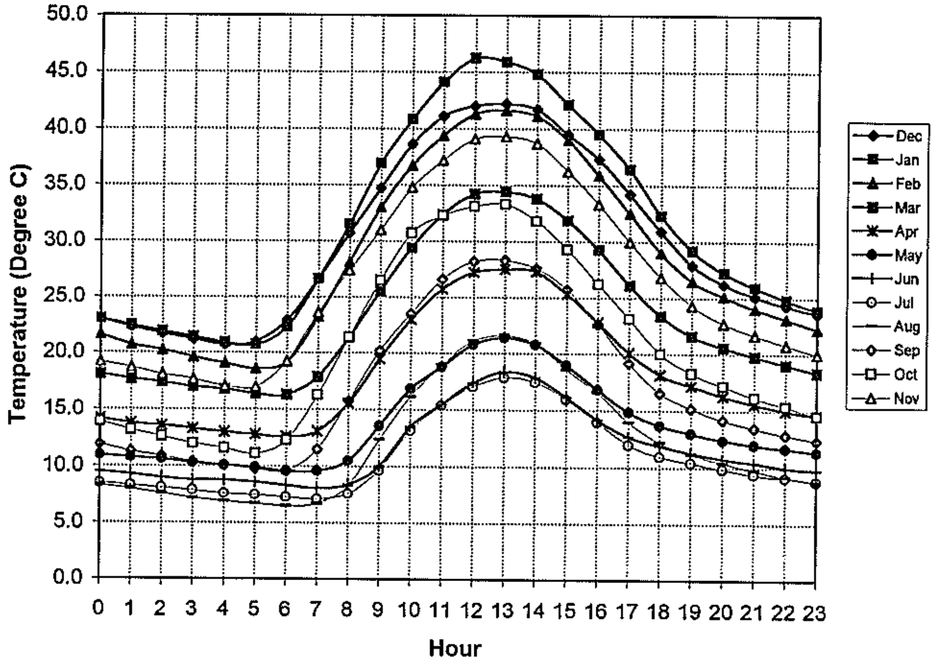


Figure D.30

Napier Pavement: 50 mm Deep in 150 mm AC
Monthly Mean Temperature for Each Hour of Day

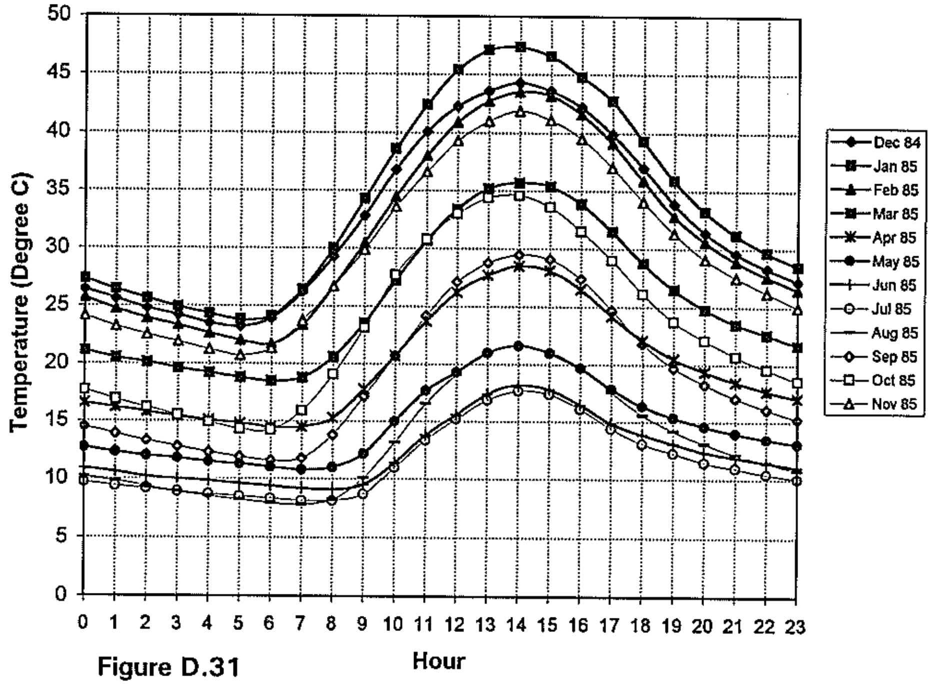


Figure D.31

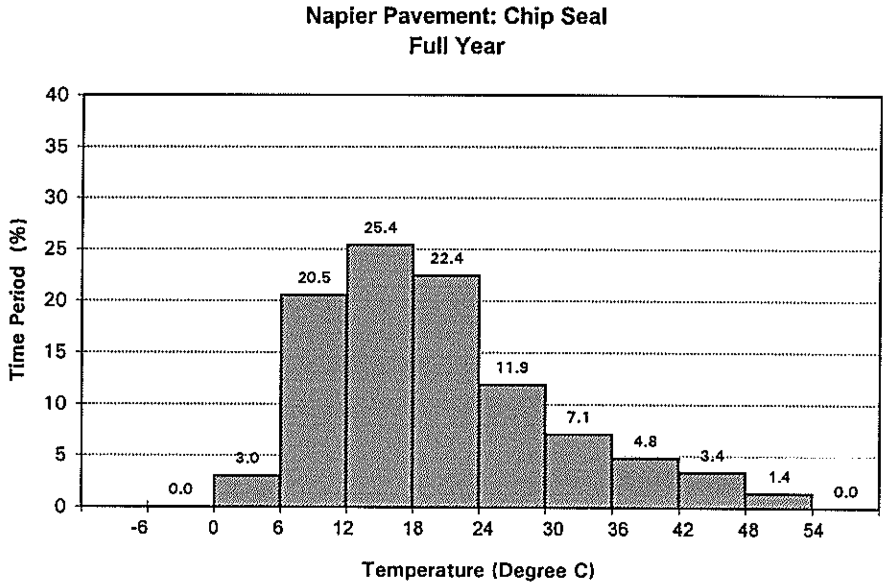


Figure D.32

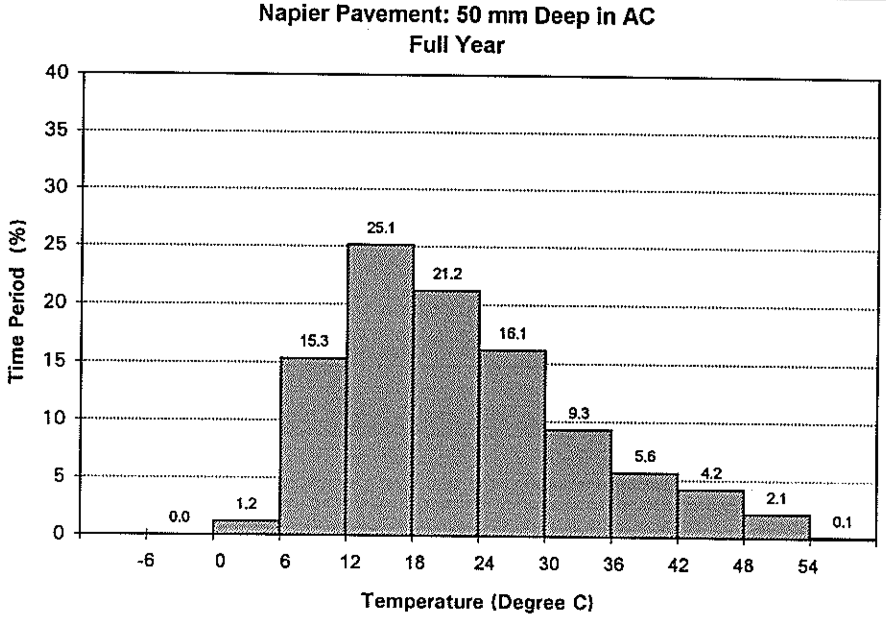


Figure D.33

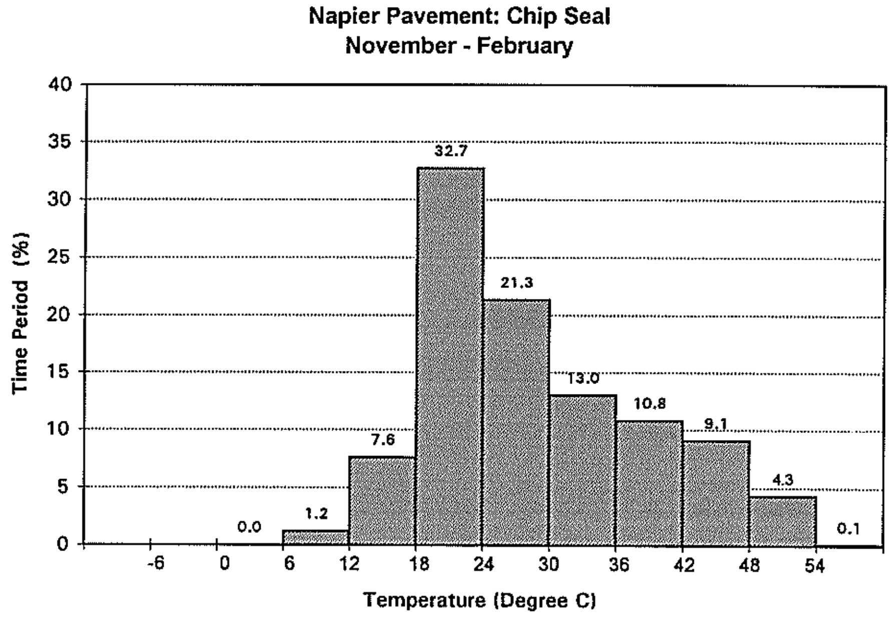


Figure D.34

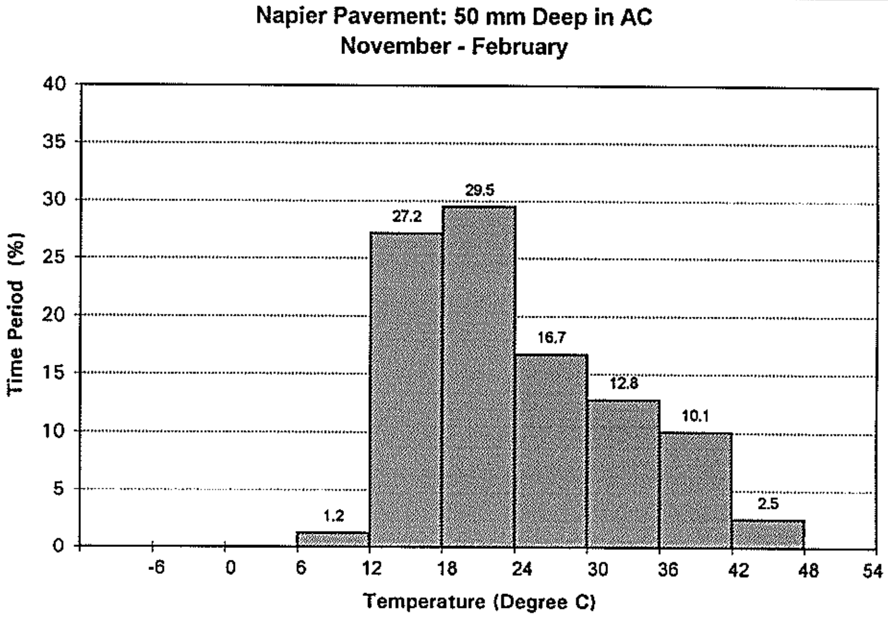
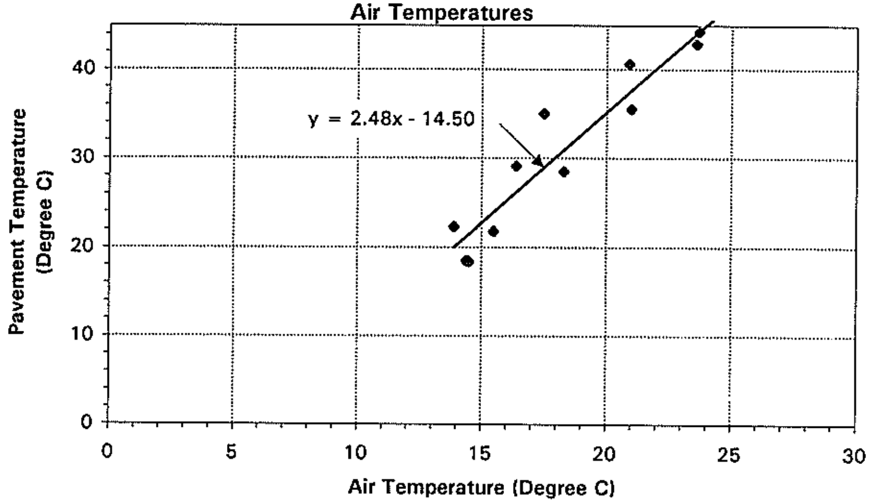
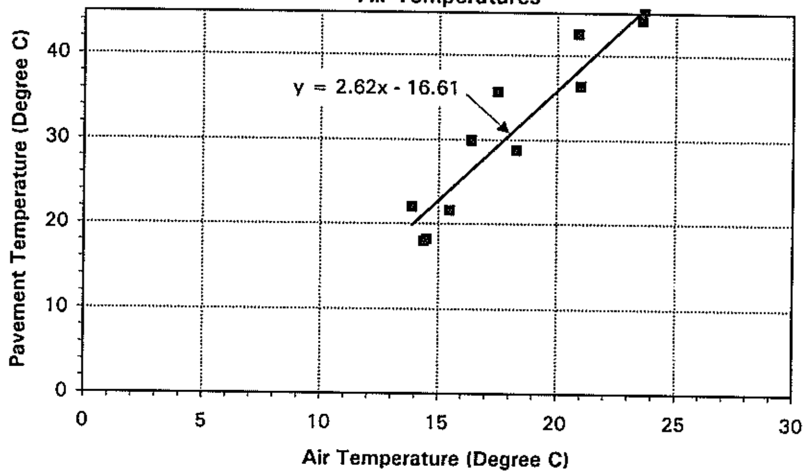


Figure D.35



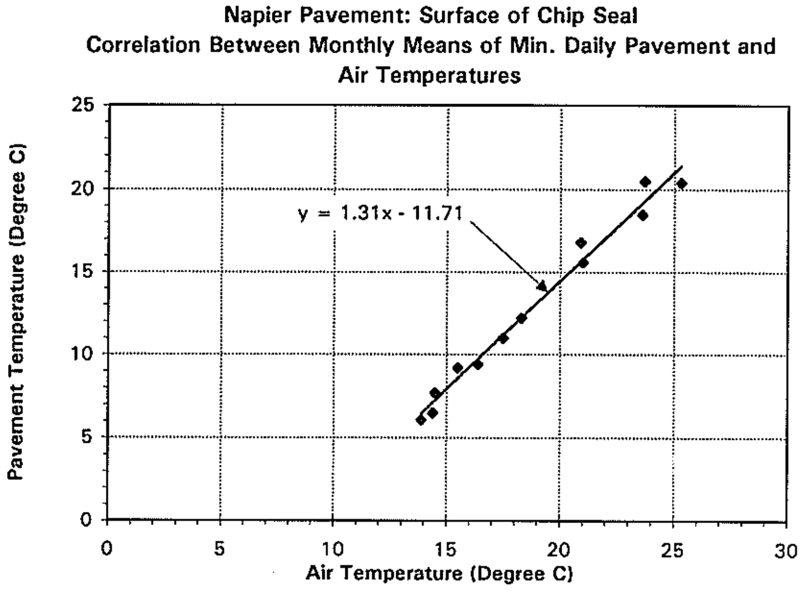
Napier Pavement: Surface of Chip Seal
Correlation Between Monthly Means of Max. Daily Pavement and Air Temperatures

Figure D.36



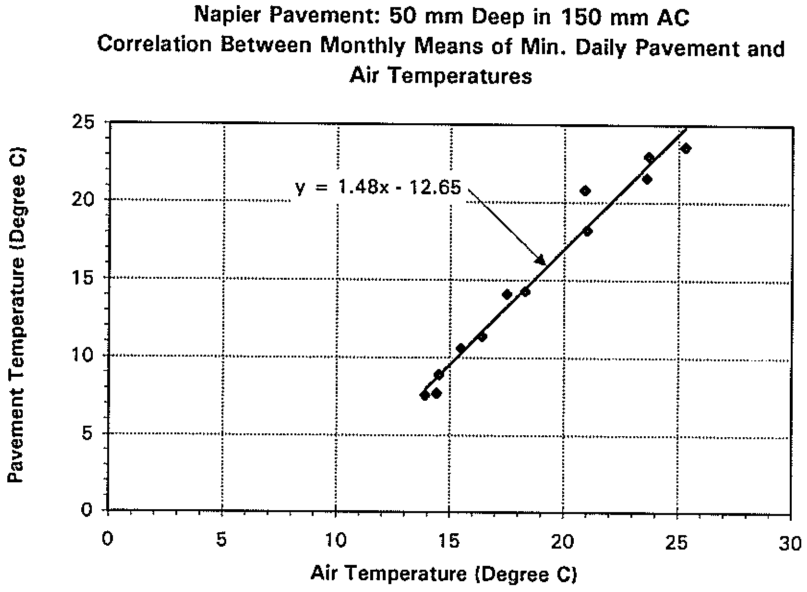
Napier Pavement: 50 mm Deep in 150 mm AC
Correlation Between Monthly Means of Max. Daily Pavement and Air Temperatures

Figure D.37



Napier Pavement: Surface of Chip Seal
Correlation Between Monthly Means of Min. Daily Pavement and Air Temperatures

Figure D.38



Napier Pavement: 50 mm Deep in 150 mm AC
Correlation Between Monthly Means of Min. Daily Pavement and Air Temperatures

Figure D.39

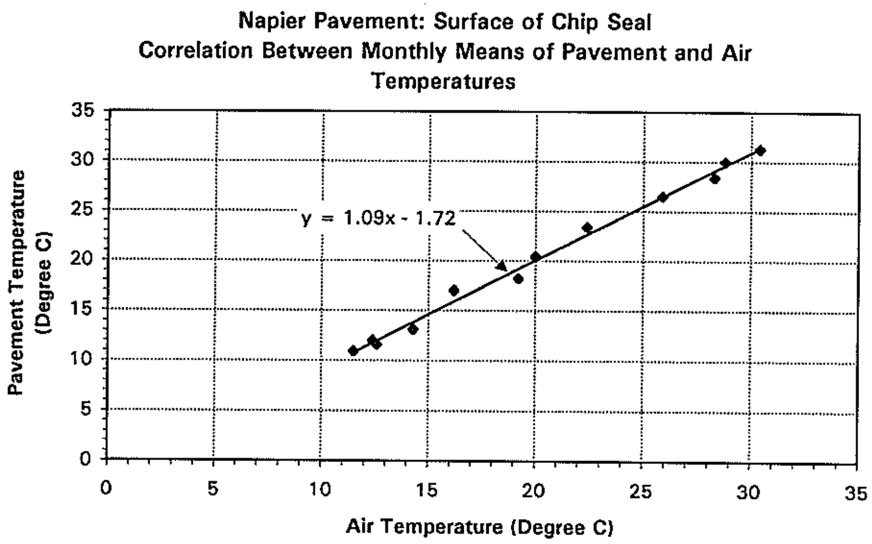


Figure D.40

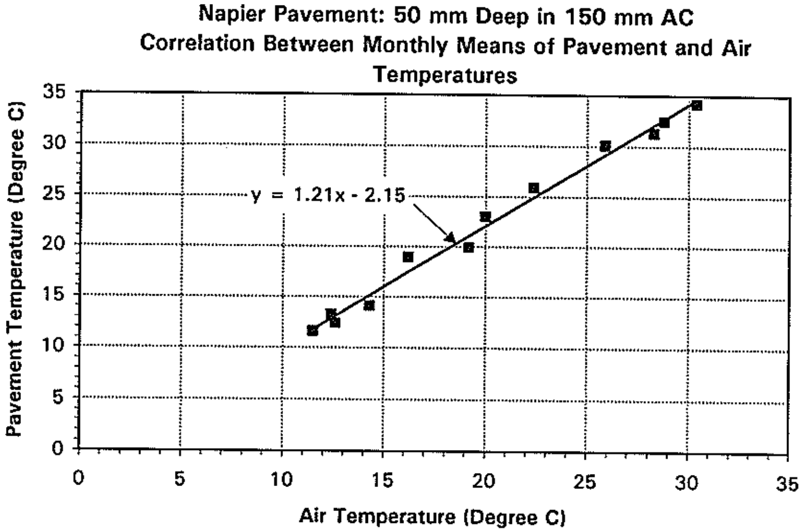


Figure D.41

APPENDIX E

Dunedin Temperature Records

Table E.1 Monthly Means of Daily Maximum Temperatures (Deg C)

	Probe Number													
Month	T1	T2	T3	T4	T5	T6	T7	T8	T9	T10	T11	T12	T13	TAIR
Oct-81	13.9	19.8	27.5	15.0	18.6	25.3	32.9	13.4	16.4	19.6	21.8	27.4	32.3	14.7
Nov-81	16.4	22.4	31.2	17.8	21.5	28.1	37.1	16.0	19.2	22.5	24.6	30.6	36.0	17.4
Dec-81	19.5	24.6	32.2	21.0	24.3	30.3	38.3	19.1	22.3	25.1	27.0	32.5	35.5	18.7
Jan-82	18.9	23.2	30.9	20.0	23.0	28.7	35.5	18.4	21.0	23.7	25.8	31.7	33.9	18.4
Feb-82	19.8	24.7	33.4	20.9	24.1	30.2	39.3	19.2	22.1	25.0	26.9	32.5	37.1	20.7
Mar-82	17.7	21.3	29.5	18.0	20.5	25.6	32.4	17.2	18.9	21.2	22.8	27.4	32.5	18.4
Apr-82	12.9	14.4	20.8	12.6	13.6	17.4	22.9	12.4	12.7	14.0	15.1	18.7	23.8	13.8
May-82	9.9	10.3	14.6	8.9	9.2	11.7	15.3	8.9	8.8	9.5	10.1	12.5	16.1	11.9
Jun-82	7.4	6.6	10.0	6.2	6.0	7.6	10.3	6.5	6.0	6.2	6.6	8.3	11.0	8.2
Jul-82	5.2	5.5	11.1	4.3	4.8	7.8	11.7	4.3	4.3	5.3	6.1	8.7	12.9	
Aug-82	7.3	9.4	15.2	6.4	7.7	11.4	16.1	6.0	6.7	8.3	9.3	12.5	17.0	11.6
Sep-82	10.0	13.8	22.6	9.8	12.3	17.6	24.4	8.9	10.8	13.0	14.6	19.1	24.4	12.3

Table E.2 Monthly Means of Daily Minimum Temperatures (Degree C)

	Probe Number													
Month	T1	T2	T3	T4	T5	T6	T7	T8	T9	T10	T11	T12	T13	TAIR
Oct-81	12.6	9.2	5.1	13.1	12.3	8.9	5.8	12.7	12.9	11.7	10.7	8.1	5.1	3.2
Nov-81	15.1	12.2	8.2	15.9	15.2	12.1	9.0	15.4	15.8	14.7	13.8	11.3	8.3	6.0
Dec-81	18.1	15.2	11.2	18.9	18.1	15.2	11.7	18.3	18.7	17.6	16.8	14.5	11.4	9.0
Jan-82	17.5	13.6	8.7	18.0	16.7	13.2	9.5	17.6	17.5	16.2	14.9	12.4	8.9	6.9
Feb-82	18.4	14.7	9.7	18.9	17.6	14.1	10.5	18.5	18.5	17.0	16.0	10.5	7.4	4.5
Mar-82	16.4	12.2	7.8	16.4	14.7	11.3	8.3	16.4	15.7	14.1	13.1	10.2	7.3	5.5
Apr-82	11.9	6.6	1.7	11.4	9.1	5.1	1.8	11.9	10.4	8.3	7.2	4.4	1.3	0.3
May-82	9.0	5.2	1.9	8.0	6.4	3.8	1.6	8.3	7.2	5.9	5.1	3.3	1.2	1.9
Jun-82	6.6	2.8	0.0	5.4	3.8	1.5	-0.4	5.9	4.6	3.3	2.6	1.0	-0.8	-0.1
Jul-82	4.5	0.8	-2.4	3.5	1.9	-0.5	-2.8	3.9	2.6	1.3	0.5	-1.3	-3.4	
Aug-82	6.5	2.8	-1.1	5.1	4.0	1.3	-1.3	5.5	4.8	3.5	2.7	0.7	-1.7	-0.7
Sep-82	8.9	5.4	1.3	8.4	7.2	4.3	1.5	8.3	8.0	6.7	5.9	3.7	1.2	0.5

Table E.3 Monthly Means of Hourly Temperatures (Deg C)

Month	Probe Number														No. hrs. Record
	T1	T2	T3	T4	T5	T6	T7	T8	T9	T10	T11	T12	T13	TAIR	
Oct-81	13.2	14.0	14.1	14.0	15.2	16.1	16.6	13.0	14.5	15.4	15.7	16.3	15.8	9.0	537
Nov-81	15.7	16.9	17.3	16.7	18.1	19.2	20.0	15.7	17.3	18.3	18.8	19.5	19.1	11.7	720
Dec-81	18.7	19.5	19.4	19.7	20.9	21.8	22.0	18.7	20.3	21.1	21.4	22.0	20.7	13.7	744
Jan-82	18.0	18.1	17.8	18.8	19.6	20.2	19.1	17.9	19.0	19.6	19.9	20.4	19.2	12.6	698
Feb-82	19.0	19.4	19.2	19.7	20.7	21.3	21.7	18.8	20.1	20.8	21.0	21.5	20.7	13.9	672
Mar-82	16.9	16.2	15.9	17.0	17.2	17.3	17.4	16.8	17.1	17.2	17.3	17.3	16.9	11.6	744
Apr-82	12.3	10.2	9.4	11.8	11.1	10.5	10.1	12.1	11.4	10.9	10.7	10.4	10.1	7.1	720
May-82	9.4	7.5	6.8	8.4	7.7	7.1	6.8	8.6	7.9	7.5	7.4	7.1	6.8	6.6	744
Jun-82	6.9	4.5	3.9	5.8	4.9	4.1	3.7	6.2	5.2	4.6	4.4	4.0	3.6	3.7	720
Jul-82	4.8	2.8	2.7	3.8	3.2	2.8	2.6	4.1	3.4	3.1	3.0	2.8	2.6	8.4	742
Aug-82	6.8	5.9	5.6	5.8	5.8	5.7	5.7	5.7	5.7	5.7	5.7	5.7	5.6	5.4	744
Sep-82	9.4	9.3	9.6	9.0	9.6	10.1	10.4	8.5	9.2	9.6	9.8	10.2	10.1	6.4	715
Year Mean	12.6	12.0	11.8	12.5	12.8	13.0	13.0	12.1	12.6	12.8	12.9	13.1	12.6	9.1	8500
Summer Mean	17.8	18.5	18.4	18.7	19.8	20.6	20.7	17.8	19.2	19.9	20.3	20.8	19.9	13.0	

Note:

Year Mean	= sum of (monthly mean x days in month)/(days in year)
Summer Mean	= sum of (monthly mean x days in month for Nov, Dec, Jan, Feb)/(sum of days in months

Table E.4 Monthly Means of Temperature (Deg C) for each Hour of Day: Surface of Chip Seal

Hour	Oct 81	Nov 81	Dec 81	Jan 82	Feb 82	Mar 82	Apr 82	May 82	Jun 82	Jul 82	Aug 82	Sep 82	Mean For Yr
0	8.5	11.0	13.2	11.3	13.0	10.3	5.6	4.8	2.1	-0.1	2.4	4.5	7.1
1	7.8	10.5	13.0	10.5	12.7	9.7	5.0	4.5	2.1	-0.2	2.2	4.0	7.0
2	7.3	10.0	12.8	9.9	12.2	9.3	4.5	4.1	1.8	-0.3	1.8	3.8	6.6
3	6.7	9.7	12.4	9.7	11.8	9.1	4.2	3.9	1.5	-0.4	1.5	3.2	6.3
4	6.1	9.2	12.0	9.3	11.3	8.9	3.9	3.6	1.5	-0.7	1.3	2.7	5.9
5	5.7	8.9	12.2	9.4	10.8	8.6	3.4	3.4	1.5	-0.6	1.2	2.3	5.7
6	6.3	10.0	13.6	11.1	11.1	8.4	2.9	3.3	1.5	-0.9	1.3	1.9	6.1
7	9.1	12.7	16.1	14.0	13.6	9.4	2.7	2.9	1.5	-1.2	1.4	3.3	7.3
8	12.8	16.0	19.2	17.6	17.1	12.4	4.7	3.5	1.5	-1.1	2.6	7.5	9.6
9	16.5	20.0	22.7	21.2	21.3	16.6	9.3	5.8	3.0	1.1	5.4	12.2	13.0
10	19.4	23.5	25.6	23.8	25.1	21.0	13.7	8.5	5.5	4.6	8.6	16.5	16.4
11	22.4	26.0	28.0	26.2	28.2	24.5	17.2	11.1	7.5	7.7	11.3	19.5	19.2
12	25.3	28.2	29.4	27.8	29.8	27.0	19.3	13.0	9.0	9.7	13.3	20.6	21.1
13	26.4	29.1	30.5	28.6	30.8	27.8	20.1	13.9	9.6	10.6	14.1	20.9	22.0
14	25.7	27.9	29.5	28.7	30.0	27.0	19.7	13.5	9.2	10.5	14.1	19.8	21.4
15	23.9	25.9	27.8	27.8	29.3	25.7	17.9	12.4	8.0	8.9	12.6	18.0	20.0
16	21.2	24.3	25.7	25.6	27.5	23.4	15.4	10.2	5.9	6.5	10.4	15.3	17.8
17	18.1	21.8	23.4	22.6	24.6	20.4	12.3	7.9	4.4	3.8	7.4	12.2	15.1
18	15.4	19.6	21.1	20.1	21.8	17.7	9.8	6.7	3.8	2.6	5.4	9.3	13.0
19	12.9	16.9	18.6	17.5	18.7	15.1	8.4	5.9	3.2	1.9	4.3	7.6	11.1
20	11.4	14.9	16.7	15.5	16.5	13.6	7.4	5.5	3.0	1.4	3.5	6.9	9.9
21	10.5	13.6	15.2	14.0	15.3	12.7	6.7	5.4	2.5	1.0	3.0	6.3	9.0
22	9.8	12.7	14.3	12.9	14.2	11.8	6.4	5.2	2.3	0.7	2.8	5.7	8.4
23	9.0	12.0	13.7	12.1	13.4	11.0	6.1	4.9	2.0	0.3	2.5	5.1	7.8
Mean for Mth	14.1	17.3	19.4	17.8	19.2	15.9	9.4	6.8	3.9	2.7	5.6	9.6	12.0

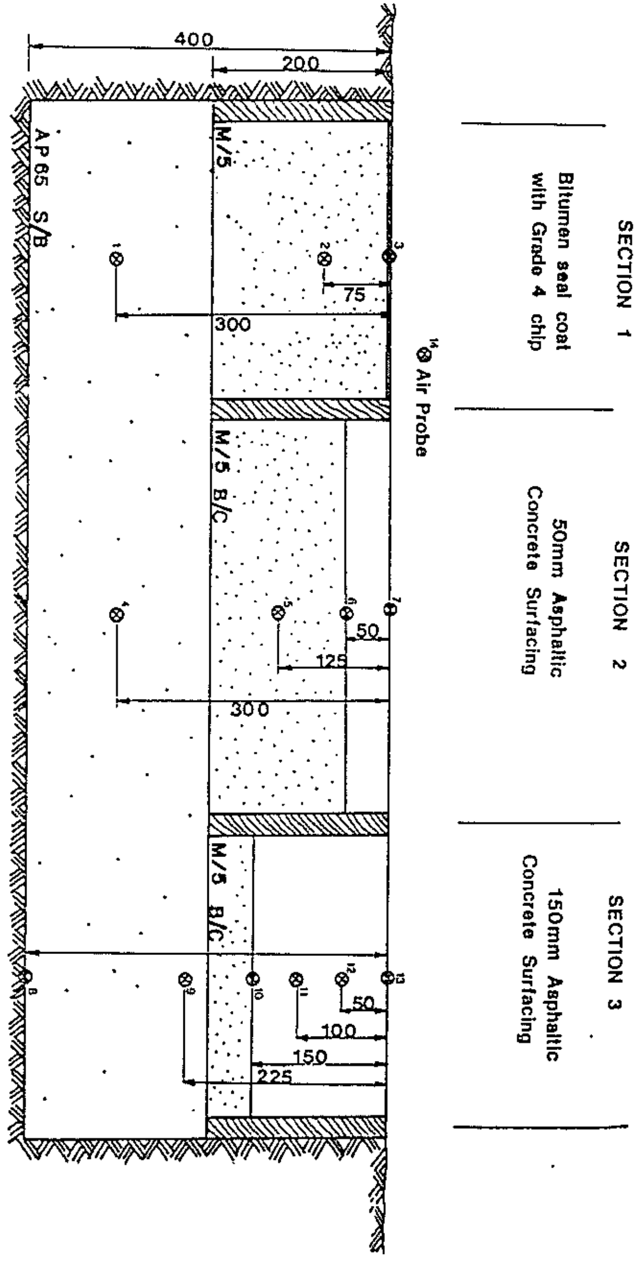


Figure E.1 Test Site Pavement Sections and Probe Locations

Table E.5 Monthly Means of Temp (Deg C) for each Hour of Day:
50mm Deep in 150 mm Thick AC

Hour	Oct 81	Nov 81	Dec 81	Jan 82	Feb 82	Mar 82	Apr 82	May 82	Jun 82	Jul 82	Aug 82	Sep 82	Mean For Yr
0	11.8	14.7	17.2	15.5	17.0	13.8	7.9	5.8	2.8	0.9	3.6	6.8	9.7
1	11.0	13.9	16.5	14.6	16.4	13.0	7.3	5.5	2.7	0.6	3.2	6.2	9.4
2	10.4	13.3	16.1	13.8	15.8	12.4	6.8	5.2	2.5	0.4	2.9	5.8	9.0
3	9.8	12.8	15.6	13.2	15.4	11.9	6.4	4.9	2.2	0.3	2.6	5.3	8.5
4	9.2	12.2	15.1	12.7	14.6	11.6	6.0	4.6	2.1	0.0	2.3	4.8	8.1
5	8.7	11.7	14.8	12.4	14.0	11.2	5.6	4.4	2.0	-0.1	2.1	4.4	7.8
6	8.5	11.8	15.2	12.7	13.6	10.9	5.2	4.2	1.9	-0.4	1.9	3.9	7.6
7	9.6	13.1	16.5	14.1	14.4	11.0	4.9	3.9	1.9	-0.6	1.8	4.0	8.1
8	12.0	15.2	18.5	16.5	16.3	12.2	5.2	3.8	1.8	-0.7	2.0	5.6	9.2
9	15.1	18.3	21.3	19.5	19.3	14.5	7.3	4.6	2.1	-0.2	3.3	8.3	11.3
10	18.0	21.7	24.3	22.4	22.8	17.6	10.2	6.2	3.3	1.5	5.2	11.4	13.9
11	20.9	24.5	26.9	24.9	25.9	20.9	13.1	8.0	4.9	3.8	7.5	14.4	16.5
12	23.9	27.2	29.4	27.0	28.0	23.7	15.6	10.0	6.4	6.0	9.6	16.6	18.8
13	26.1	28.8	31.0	28.9	29.8	25.5	17.4	11.4	7.6	7.7	11.2	18.0	20.5
14	27.0	29.5	31.4	29.6	30.5	26.3	18.3	12.2	8.1	8.5	12.1	18.5	21.2
15	26.4	29.0	30.7	30.0	30.4	26.3	18.2	12.1	8.0	8.3	12.1	18.3	21.0
16	25.1	27.9	29.5	29.2	29.8	25.5	17.3	11.3	7.1	7.4	11.2	17.1	20.1
17	22.8	26.2	28.0	27.5	28.5	23.9	15.4	9.9	5.9	5.8	9.6	15.3	18.4
18	20.4	24.2	26.1	25.4	27.0	21.9	13.3	8.6	5.1	4.3	7.9	13.1	16.7
19	17.9	22.1	24.0	23.1	24.5	19.2	11.7	7.6	4.4	3.5	6.6	11.2	14.9
20	15.9	19.9	22.0	21.0	22.0	17.8	10.5	7.0	4.1	2.8	5.6	9.9	13.4
21	14.5	18.2	20.2	19.2	20.2	16.5	9.5	6.5	3.5	2.2	4.8	9.0	12.2
22	13.5	16.9	18.9	17.7	19.0	15.5	8.8	6.2	3.2	1.8	4.2	8.3	11.4
23	12.5	15.9	17.8	16.6	17.7	14.6	8.3	5.9	2.9	1.4	3.9	7.6	10.6
Mean for Mth	16.3	19.5	22.0	20.4	21.4	17.4	10.4	7.1	4.0	2.8	5.7	10.2	13.3

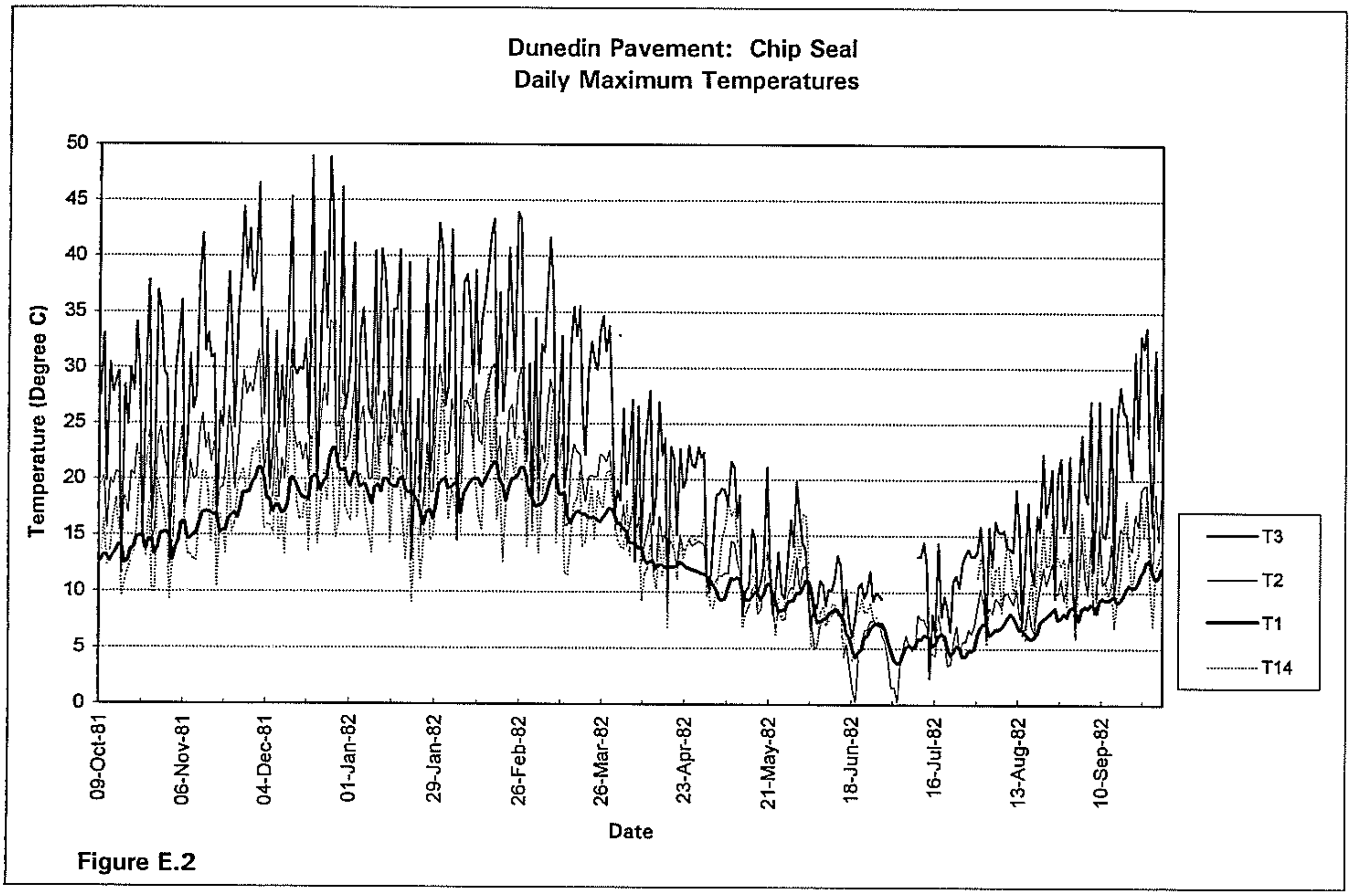
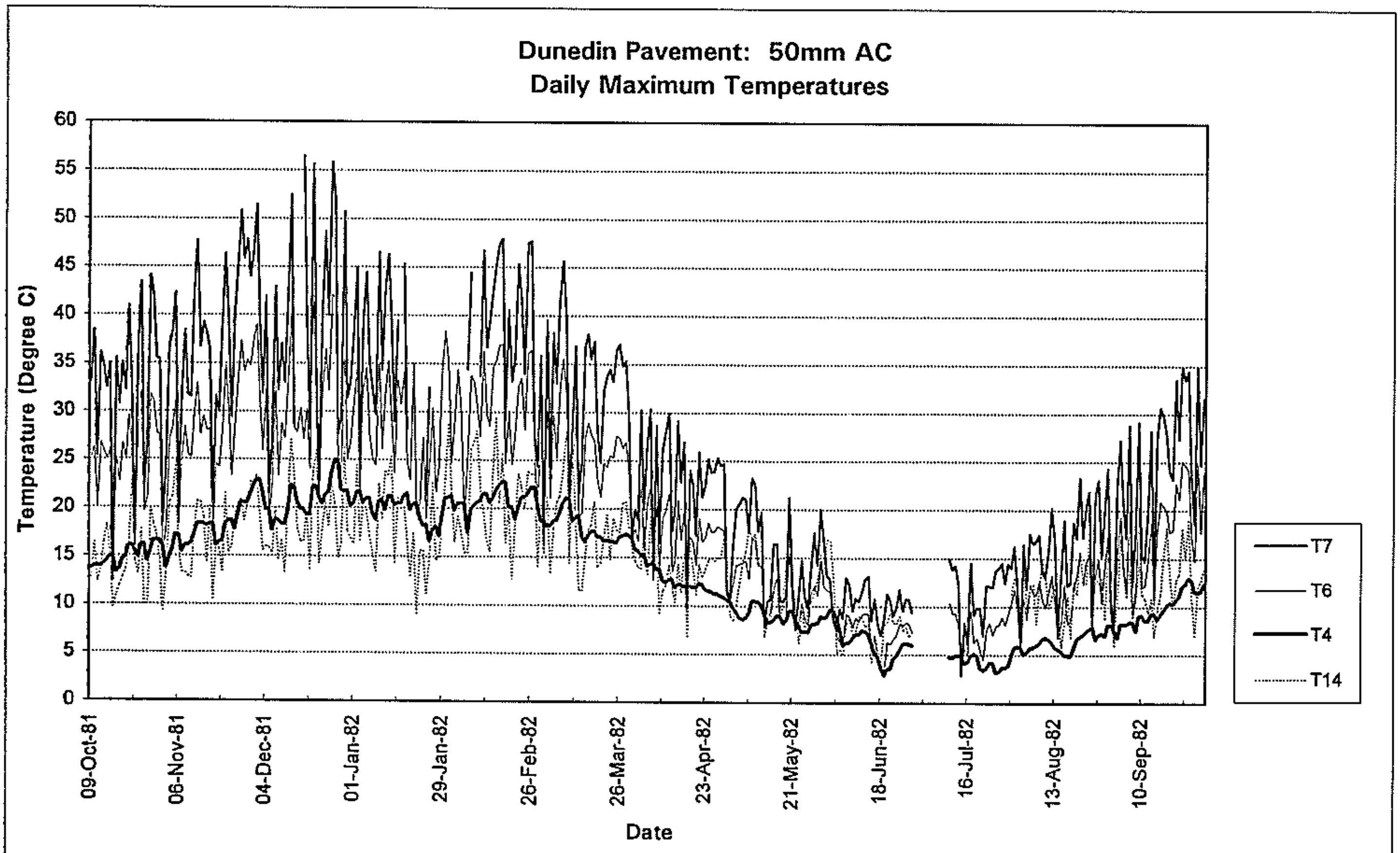


Figure E.2



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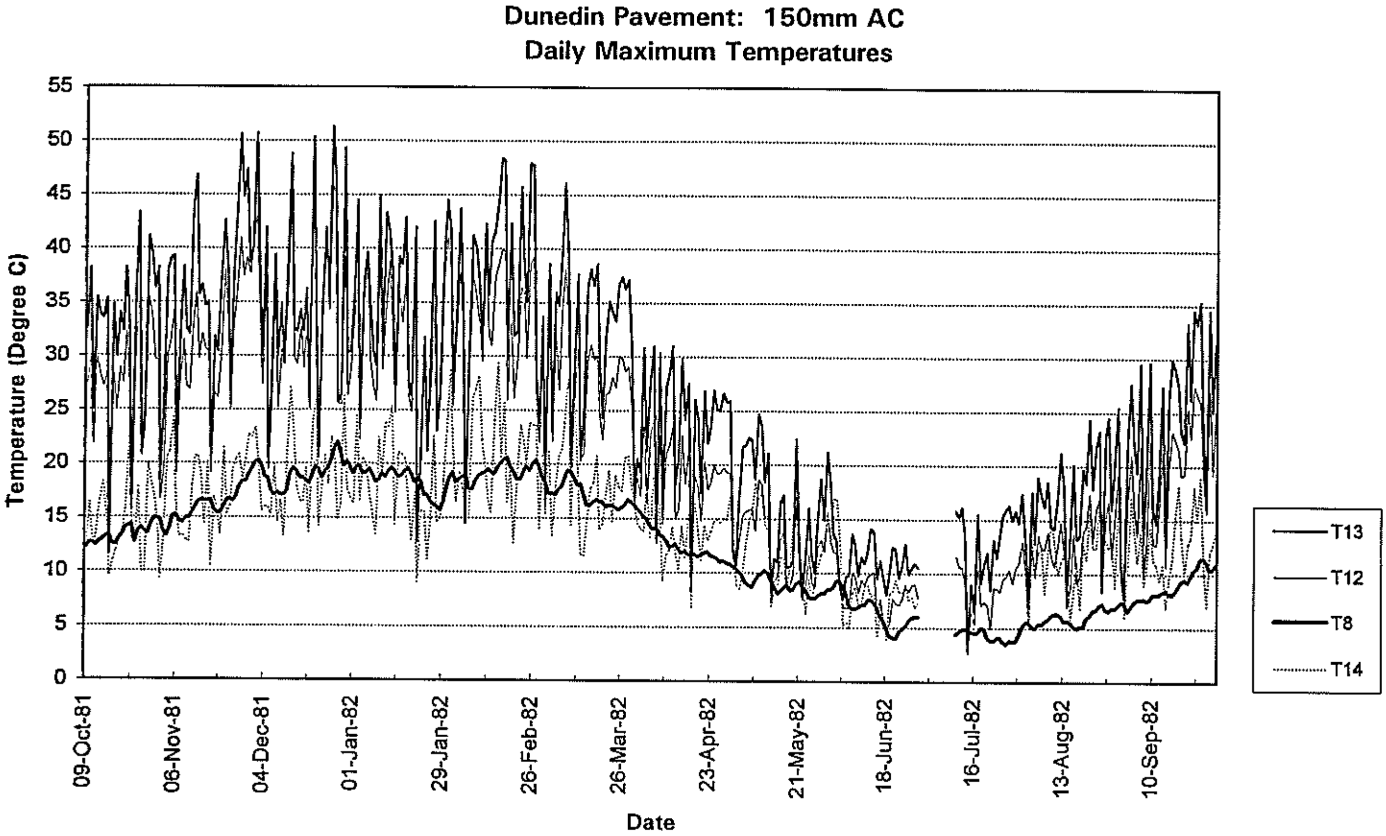

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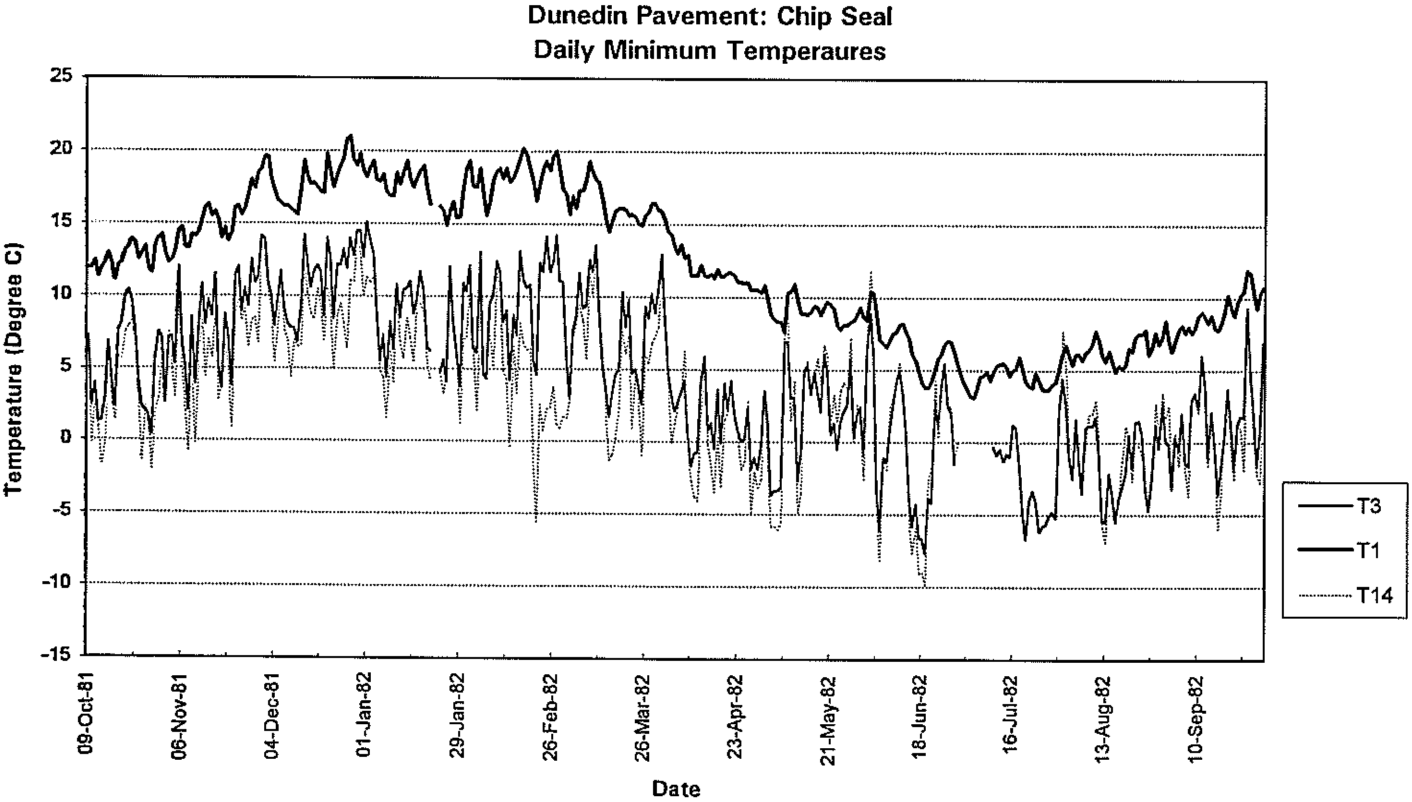
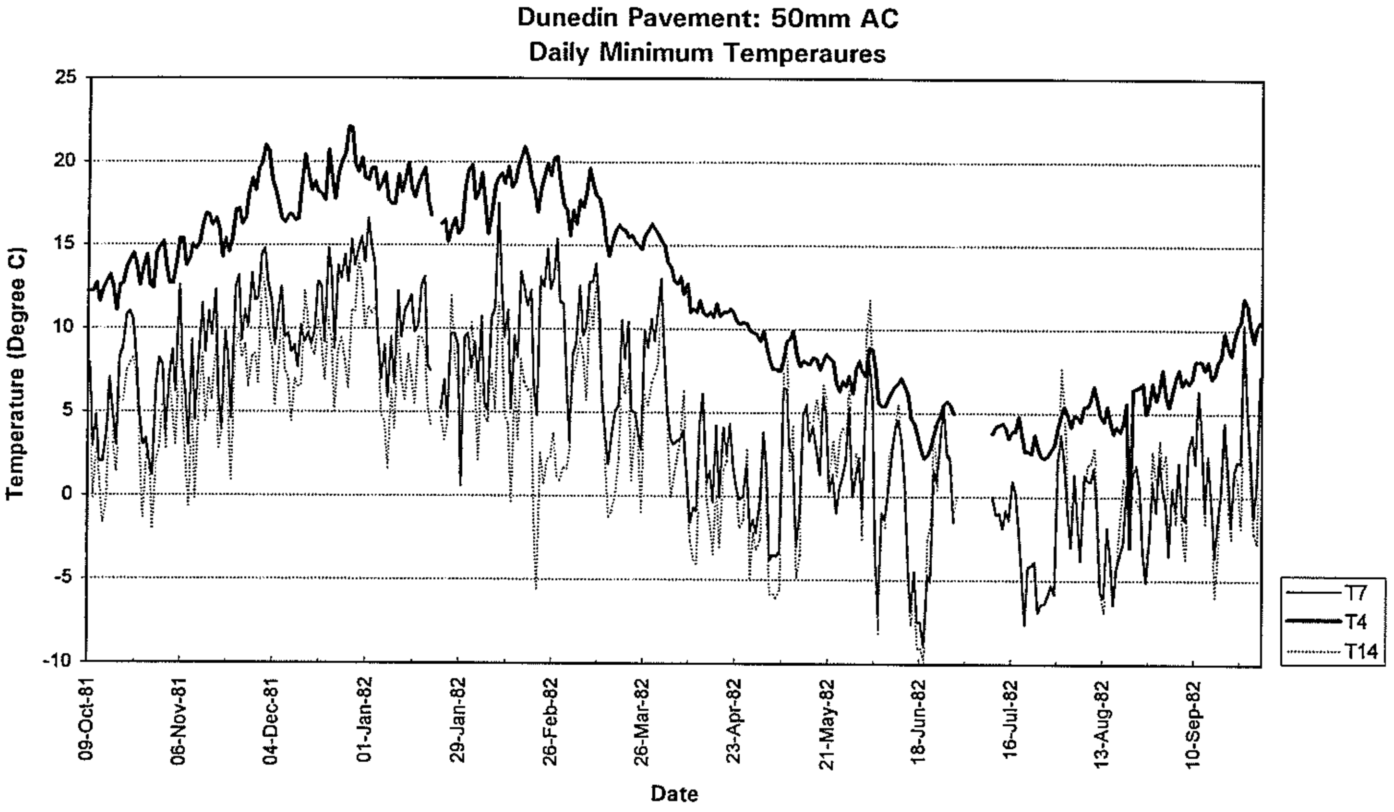


Figure E.5



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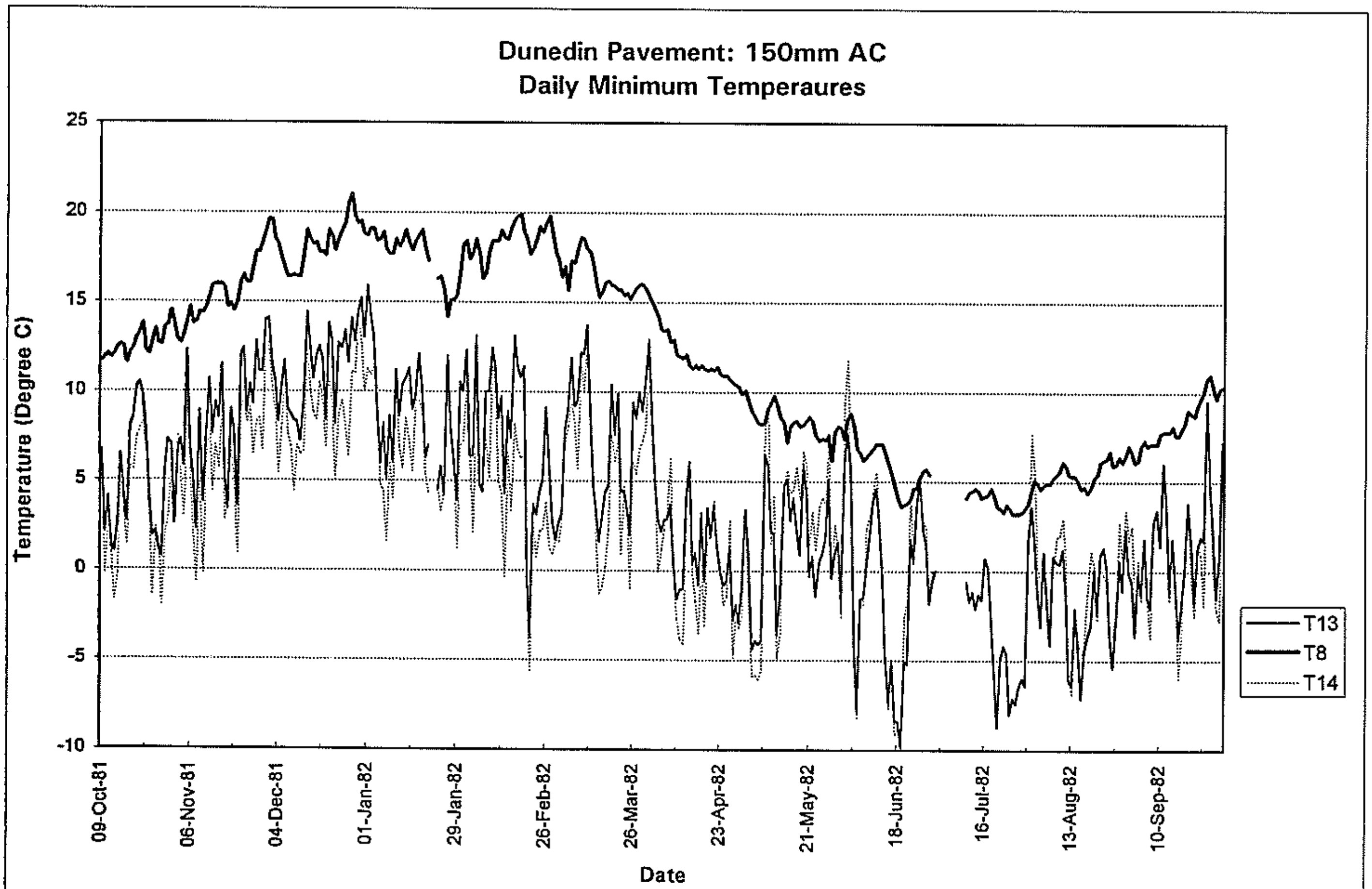


Figure E.7

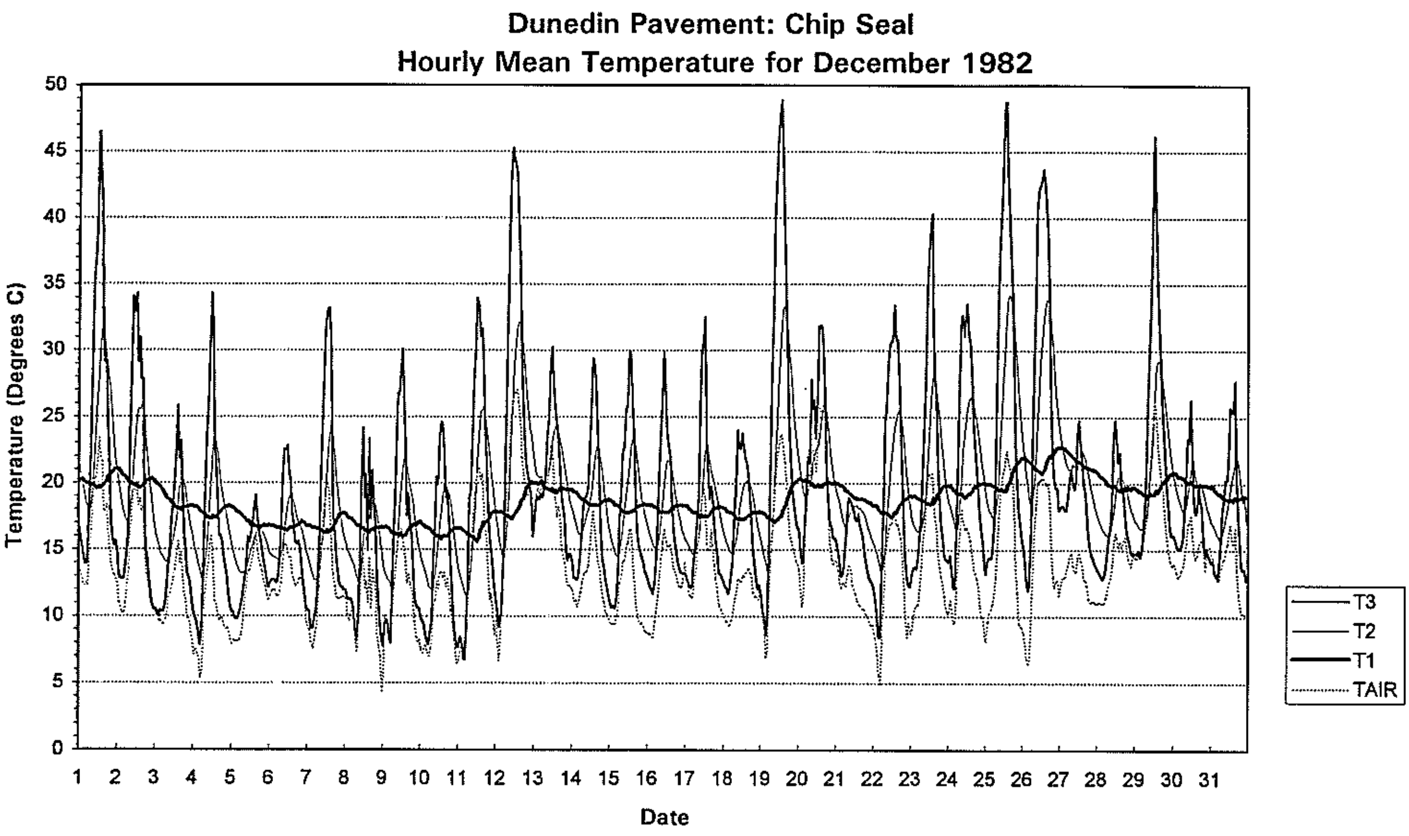

Dunedin Pavement: Chip Seal
Hourly Mean Temperature for December 1982

Figure E.8

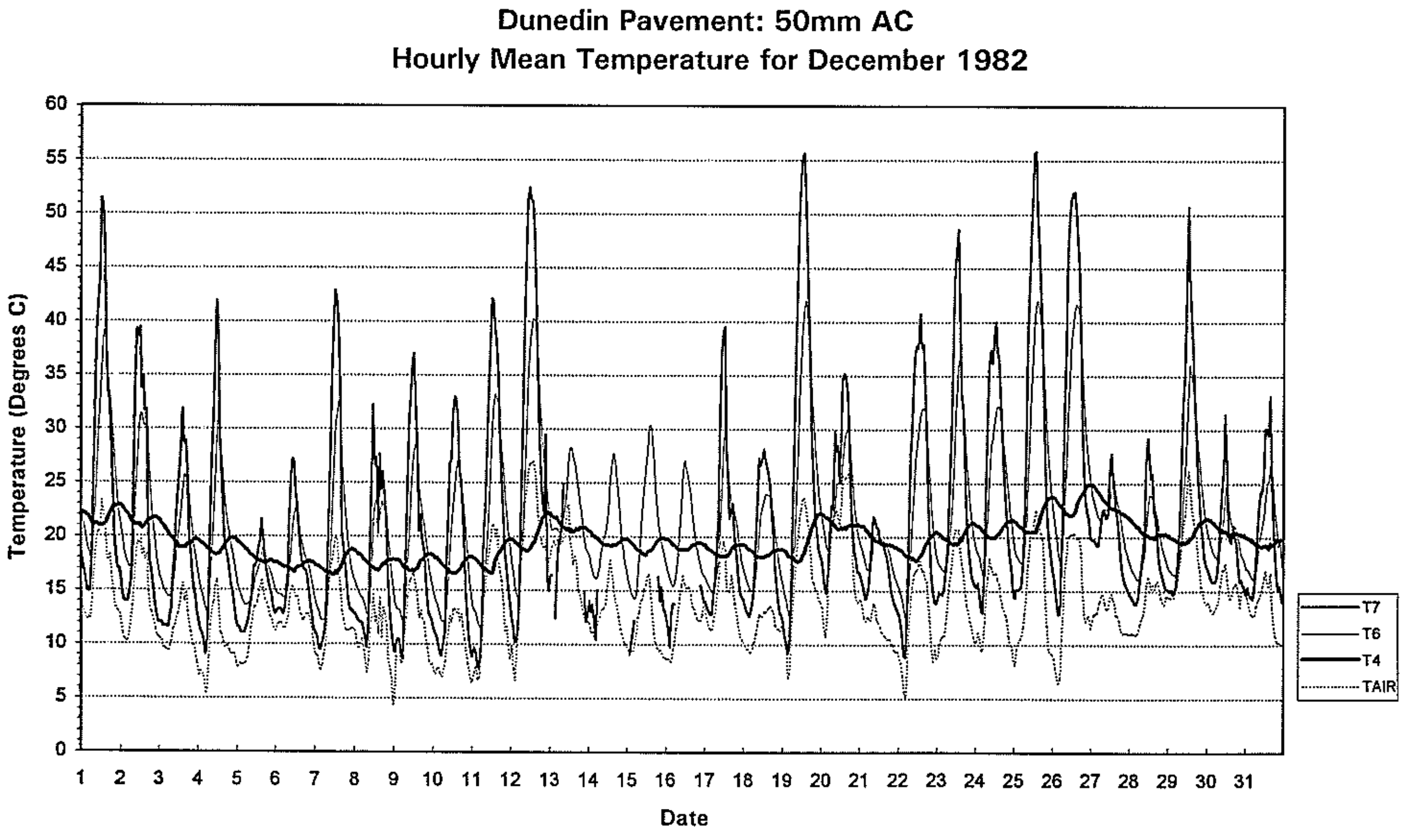

Dunedin Pavement: 50mm AC
Hourly Mean Temperature for December 1982

Figure E.9

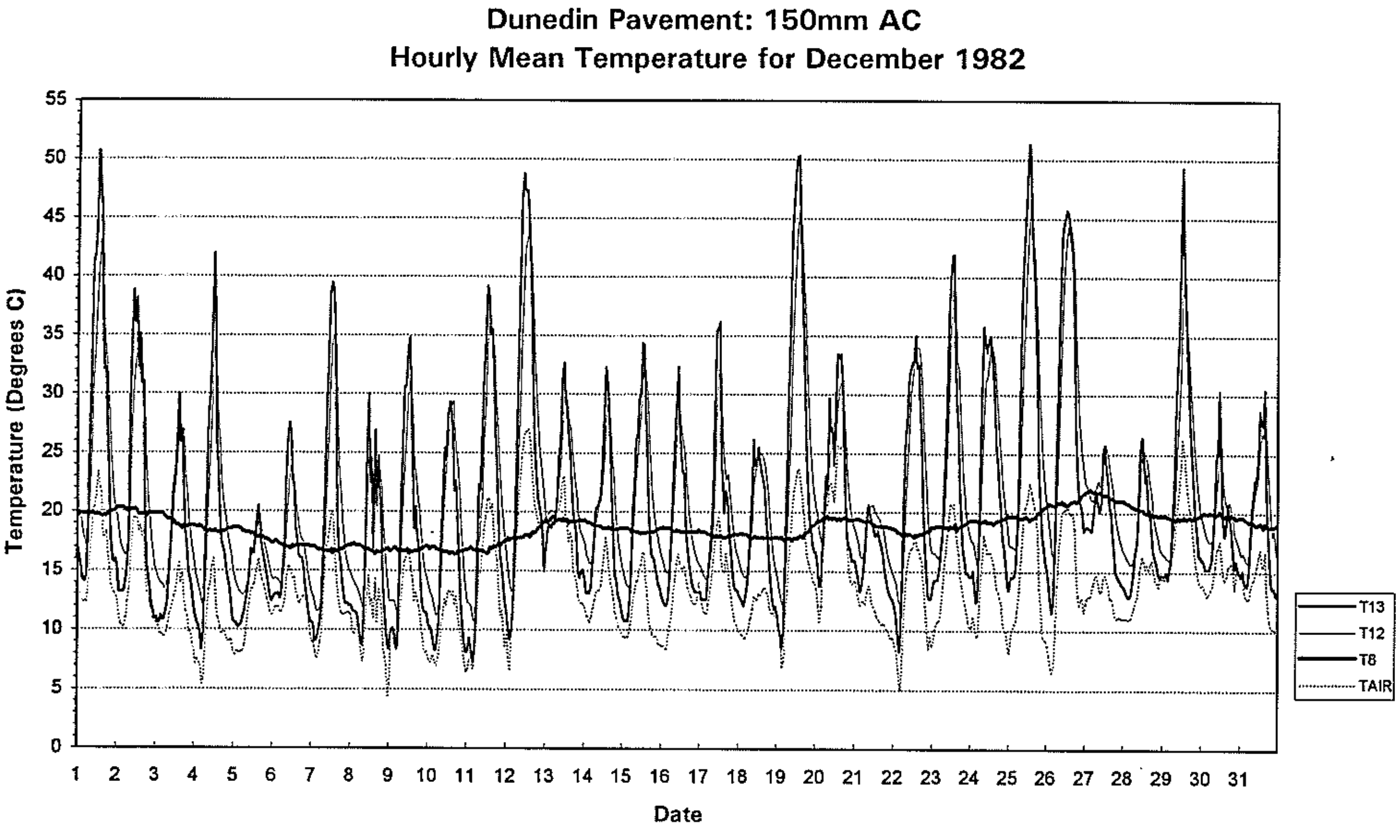


Figure E.10

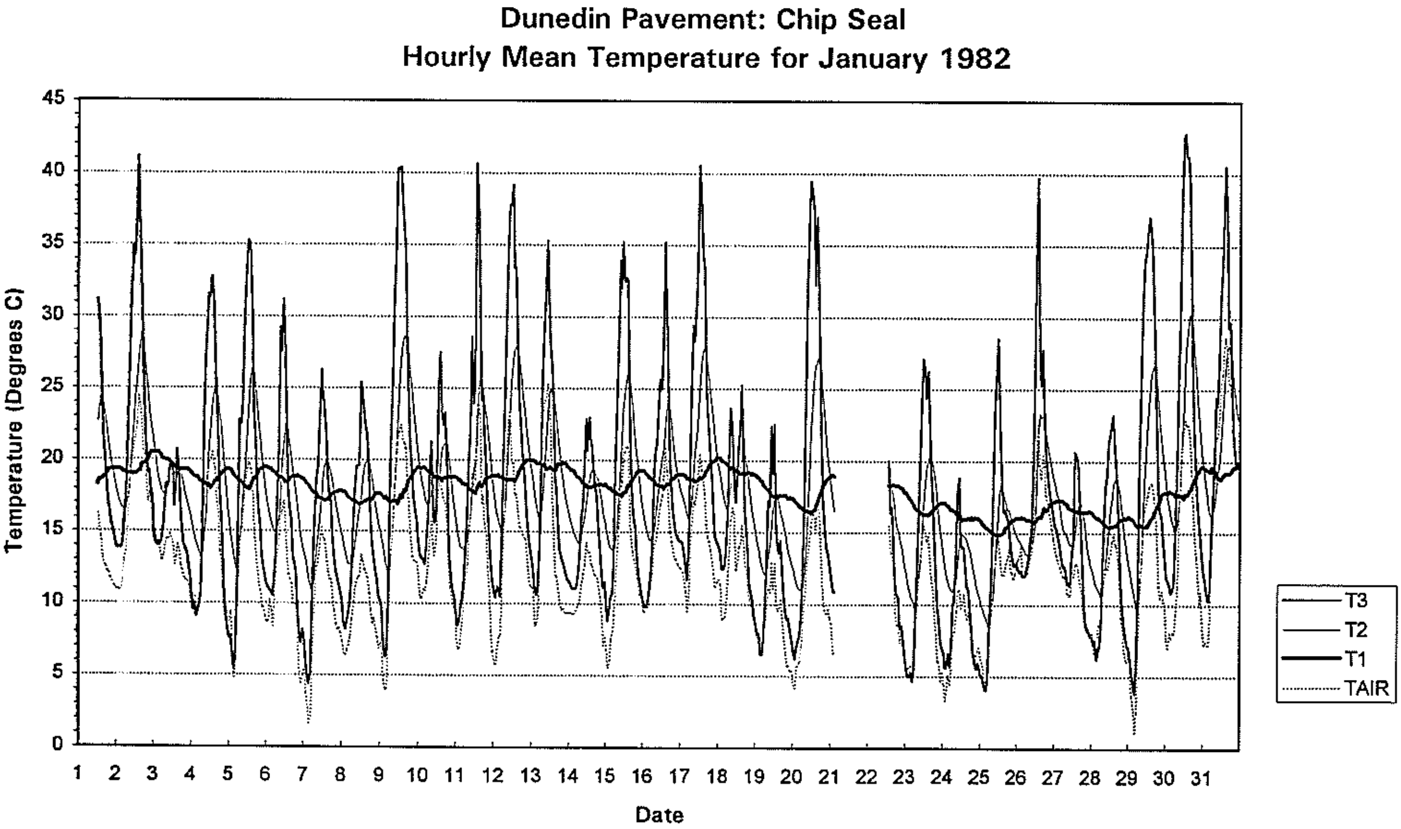
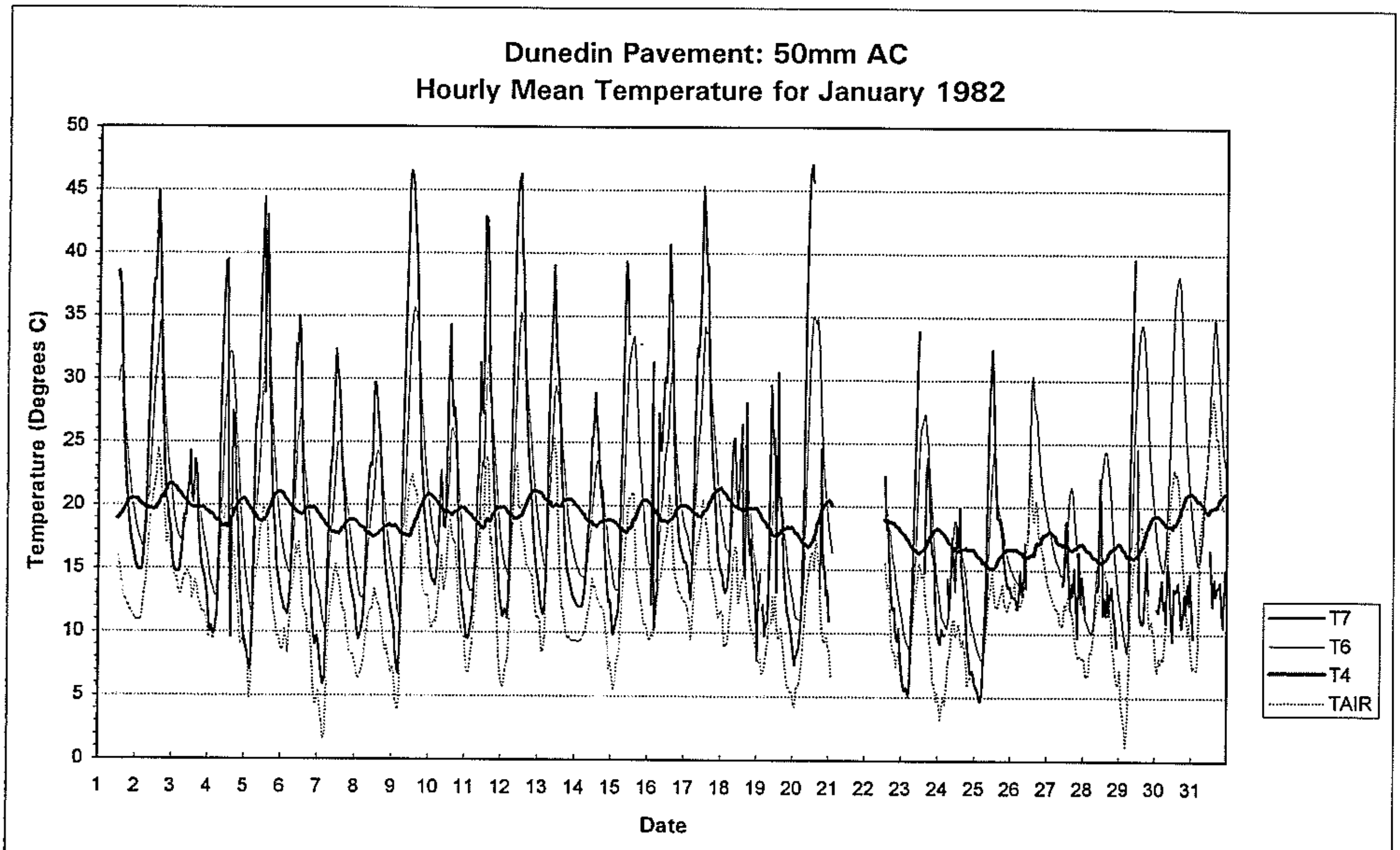


Figure E.11



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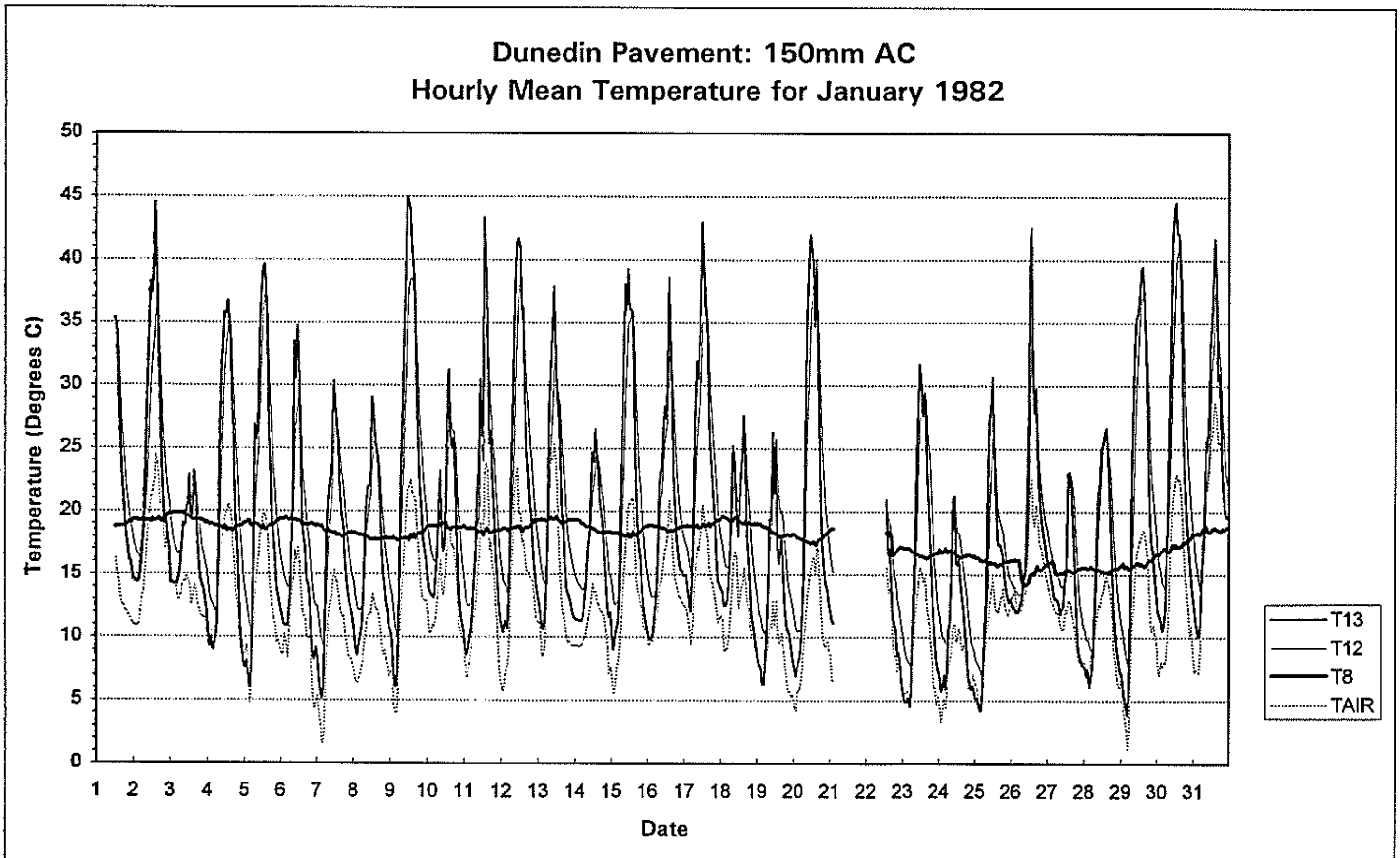

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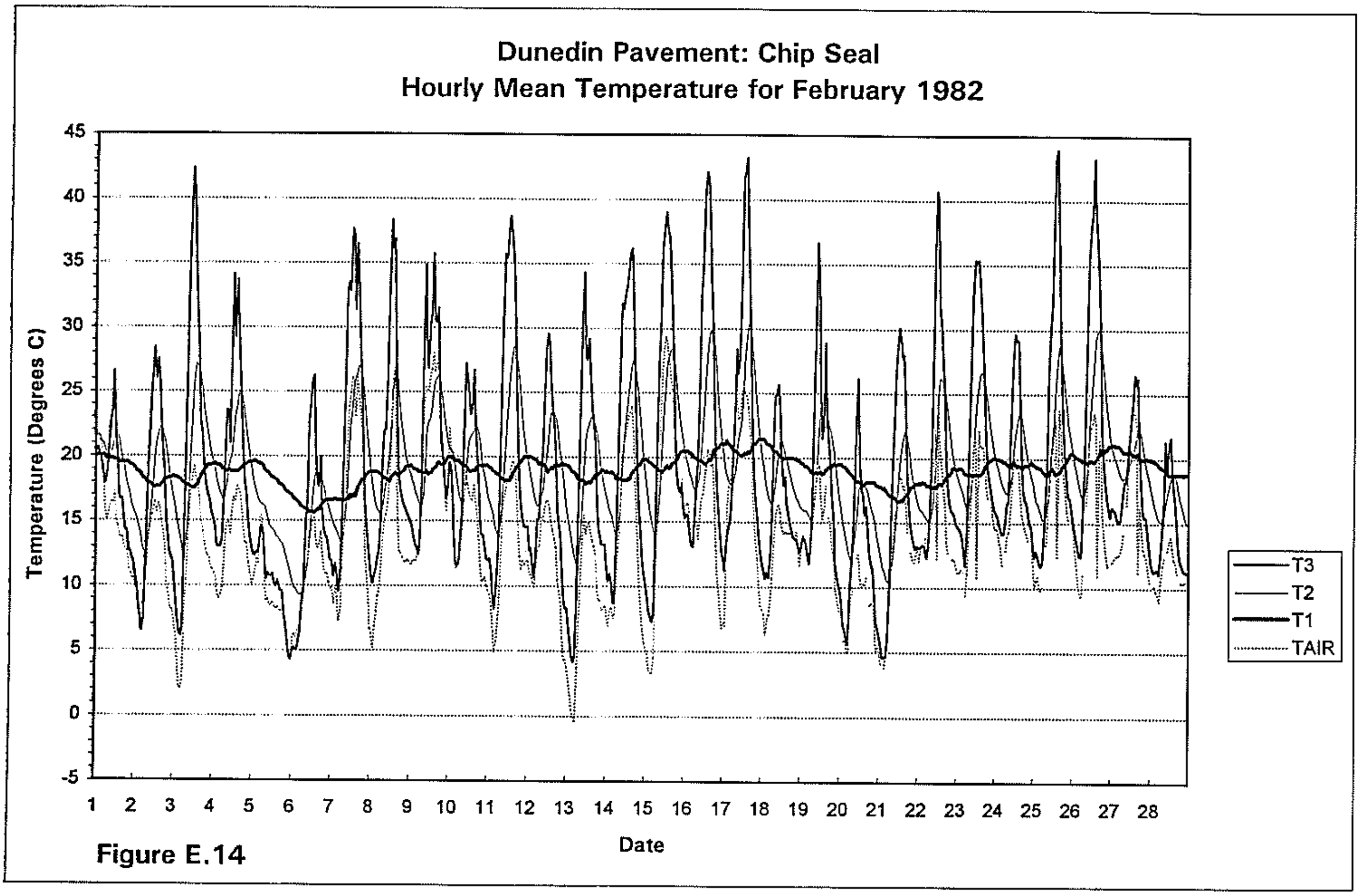

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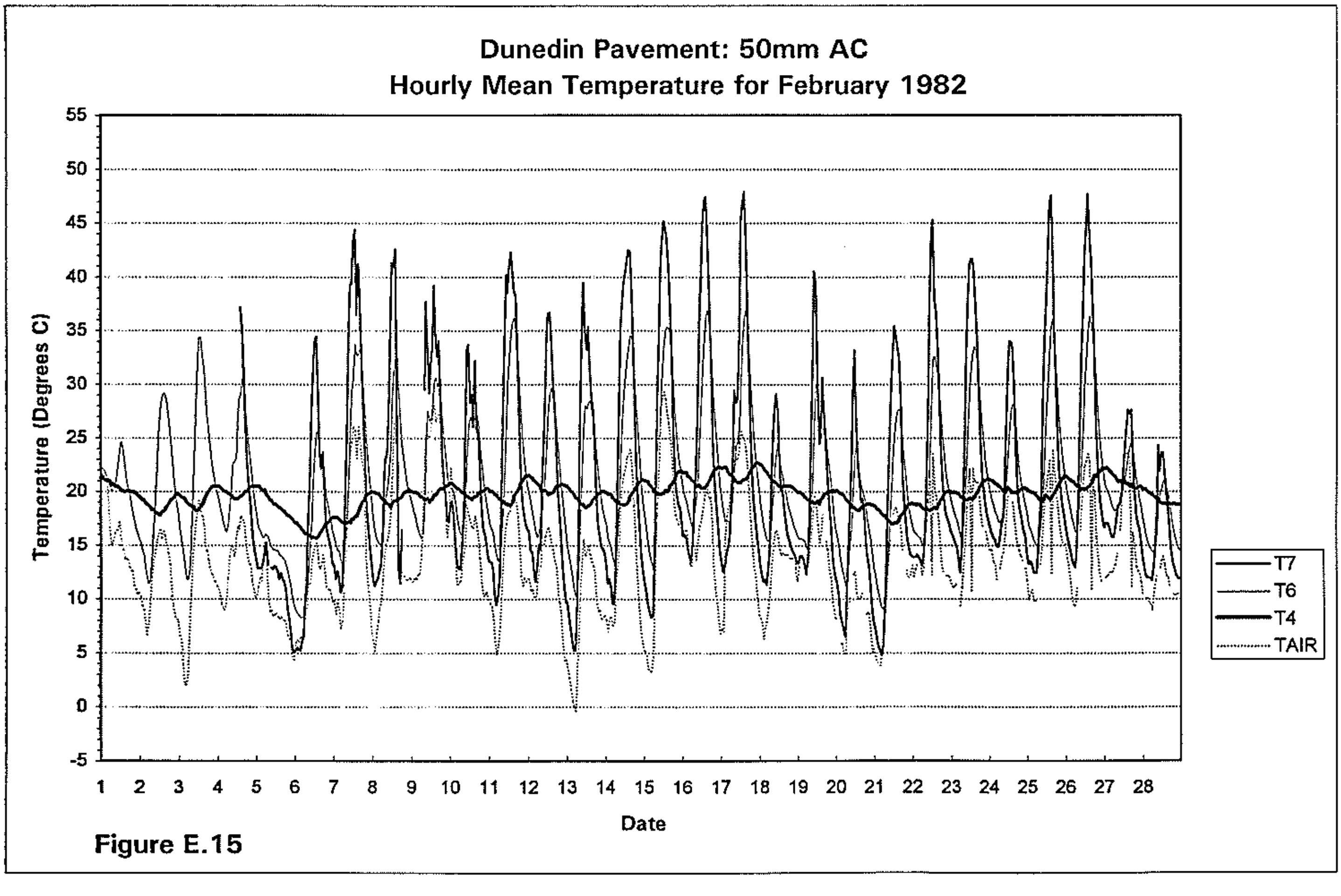

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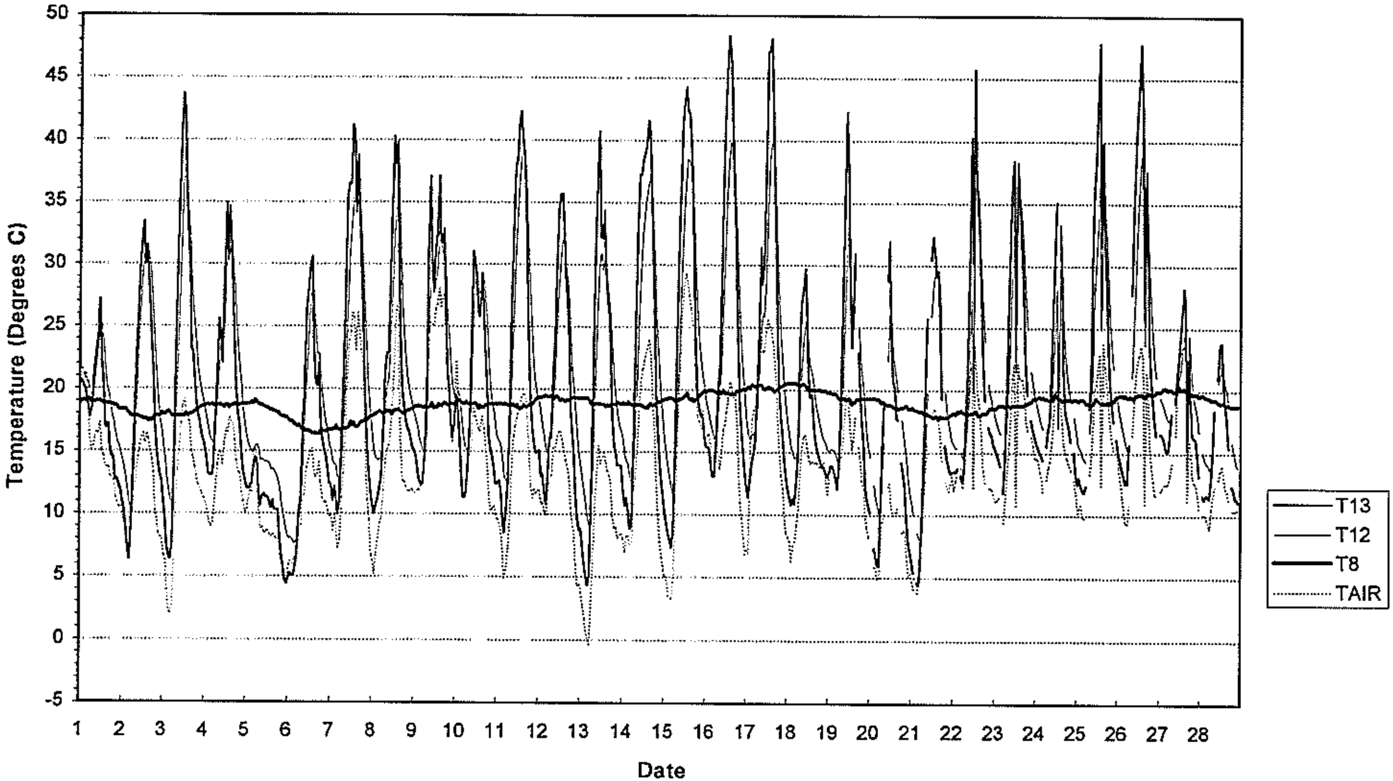
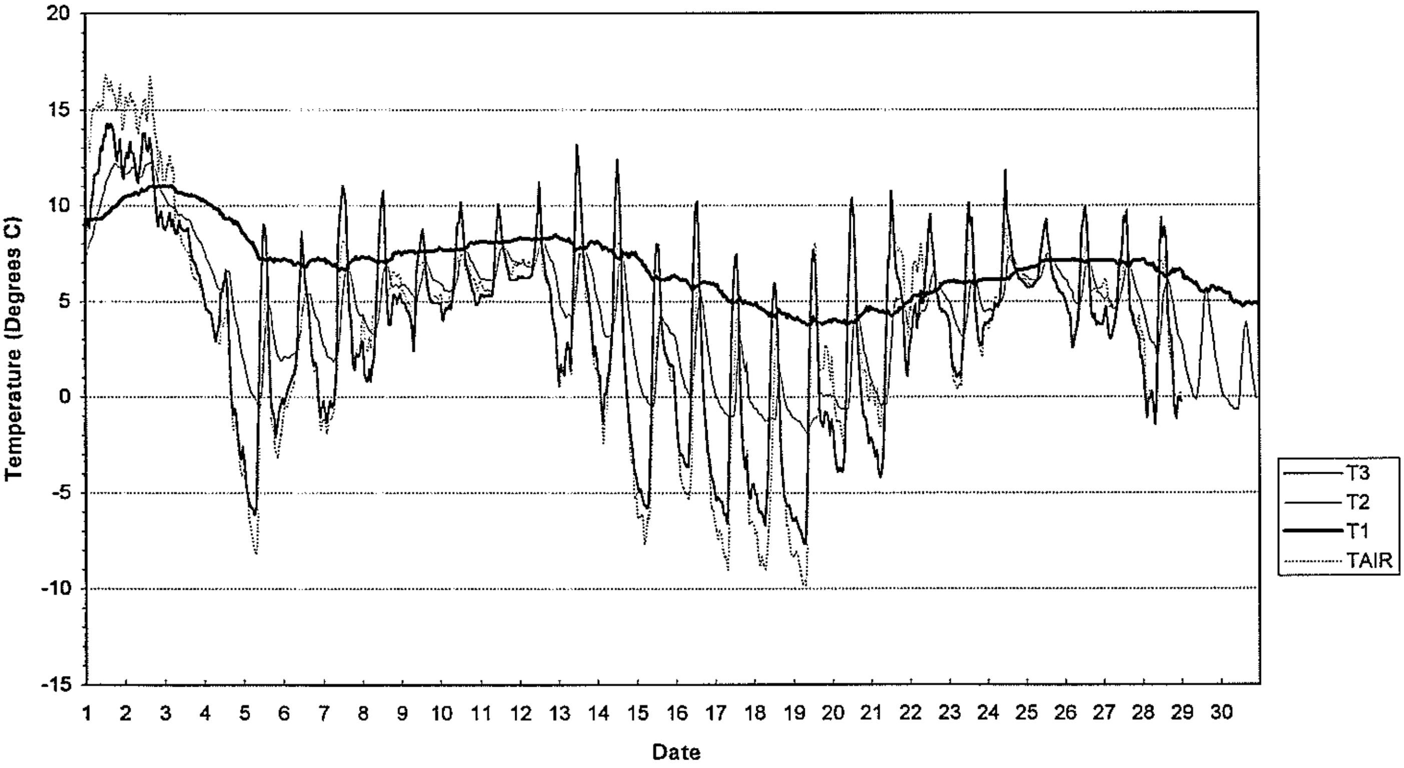


Dunedin Pavement: 150mm AC
Hourly Mean Temperature for February 1982

Figure E.16



Dunedin Pavement: Chip Seal
Hourly Mean Temperature for June 1982

Figure E.17

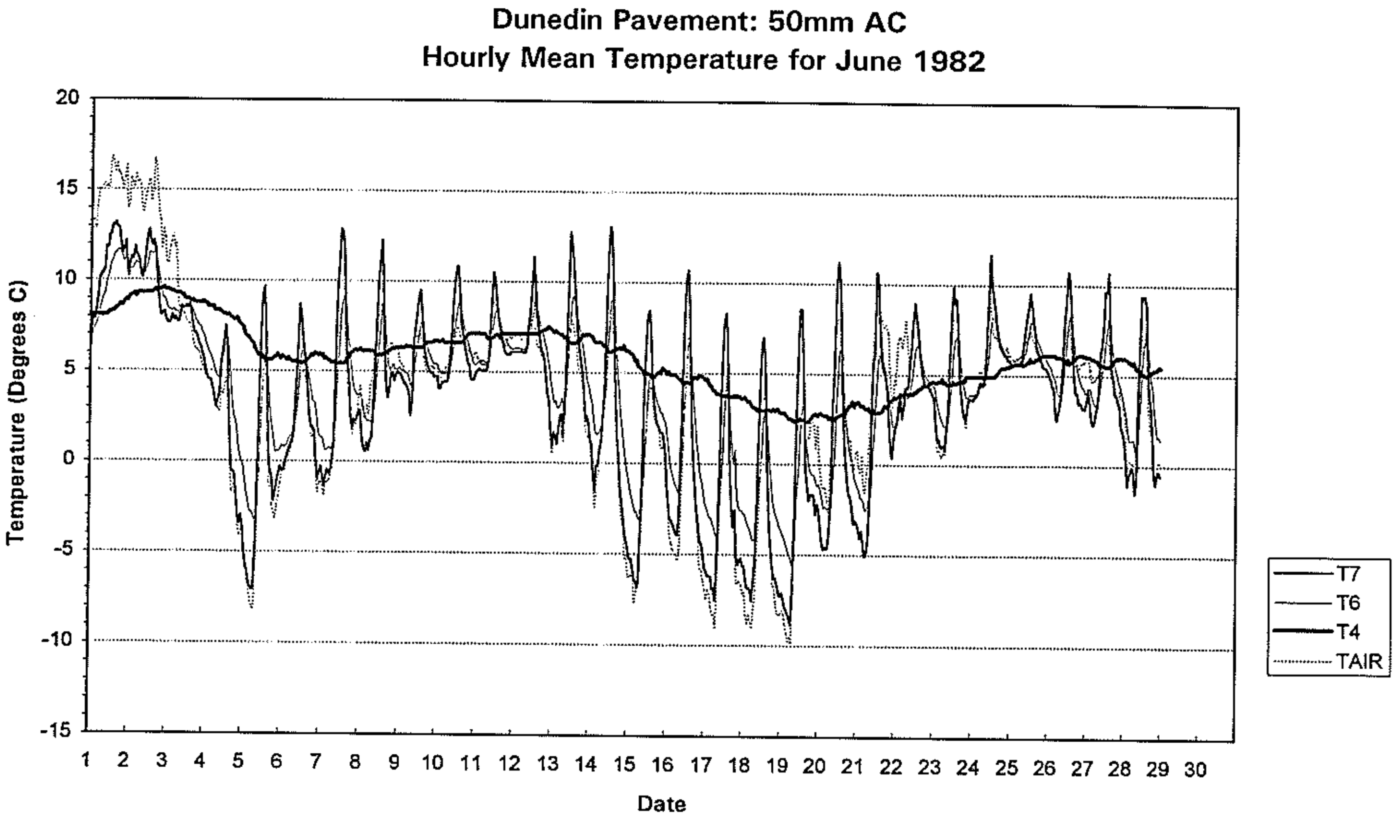


Figure E.18

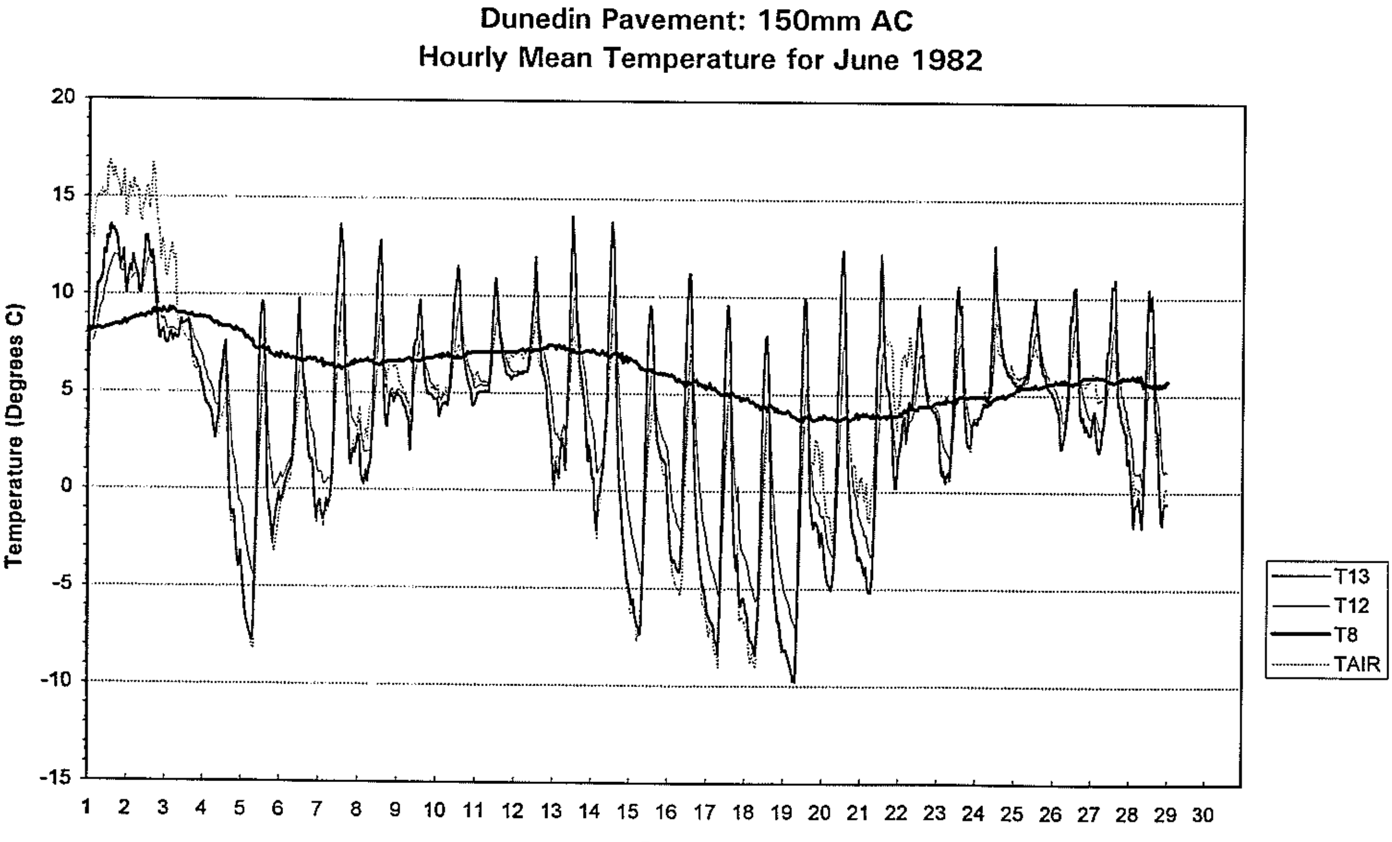


Figure E.19

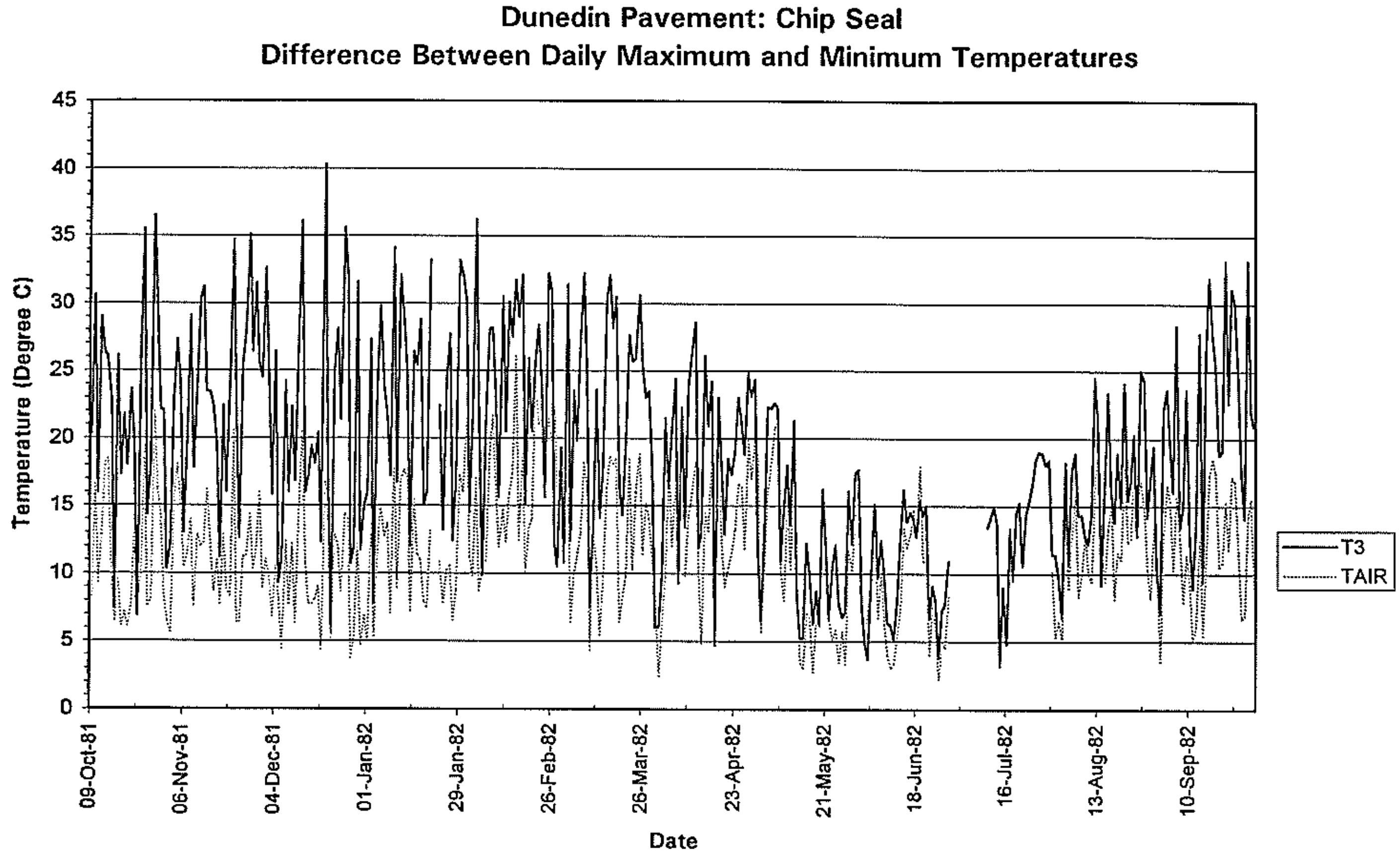

Dunedin Pavement: Chip Seal
Difference Between Daily Maximum and Minimum Temperatures

Figure E.20

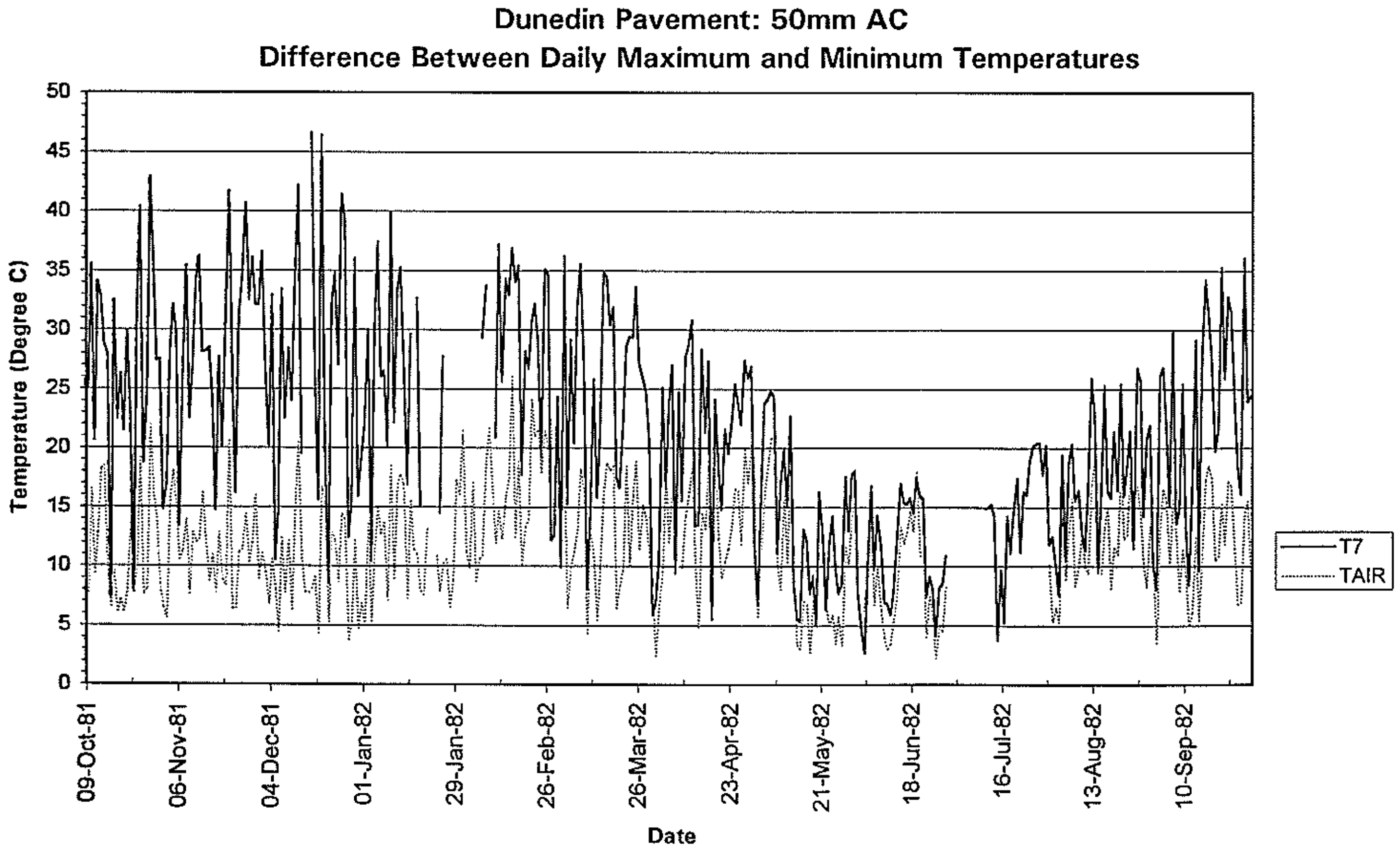

Dunedin Pavement: 50mm AC
Difference Between Daily Maximum and Minimum Temperatures

Figure E.21

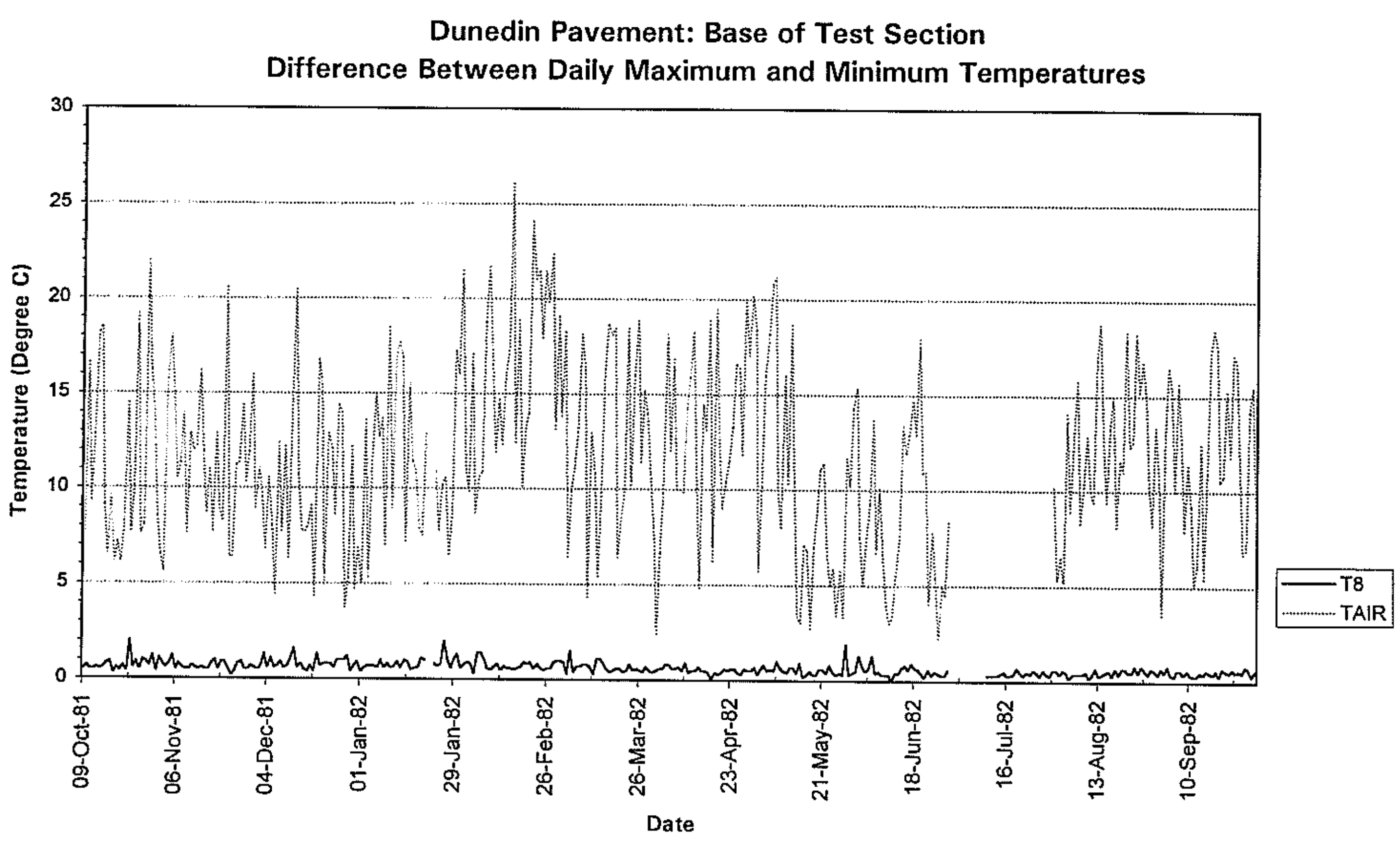
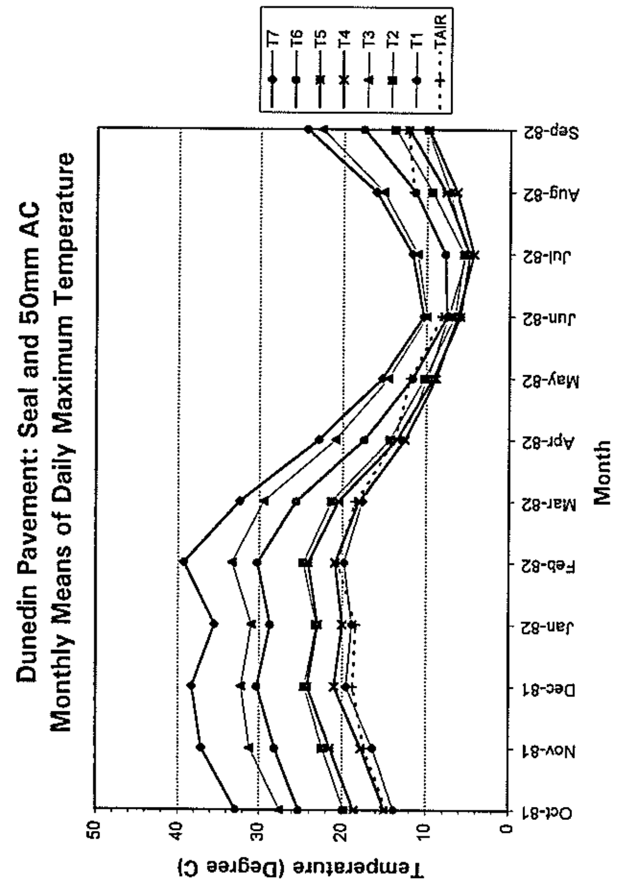


Figure E.22



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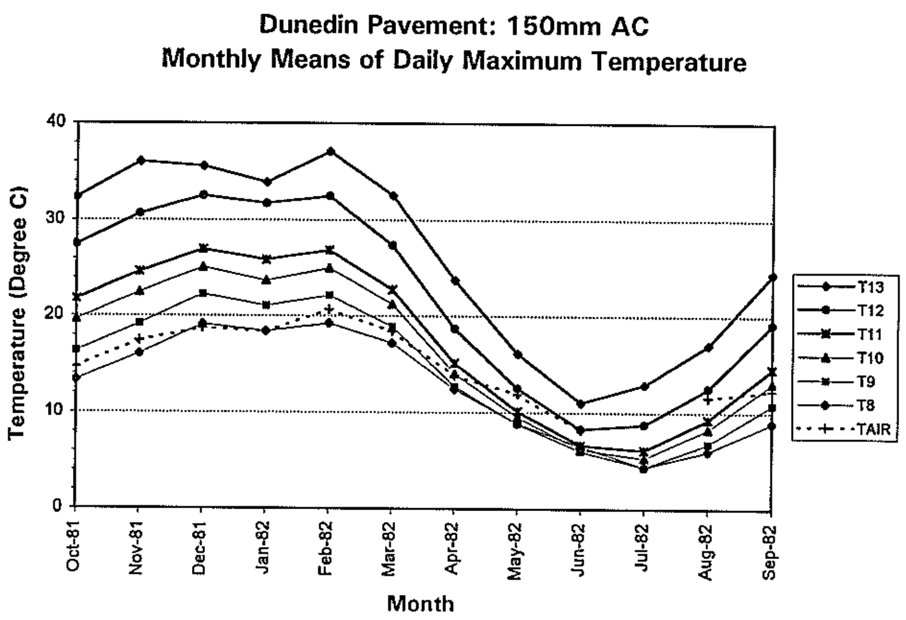

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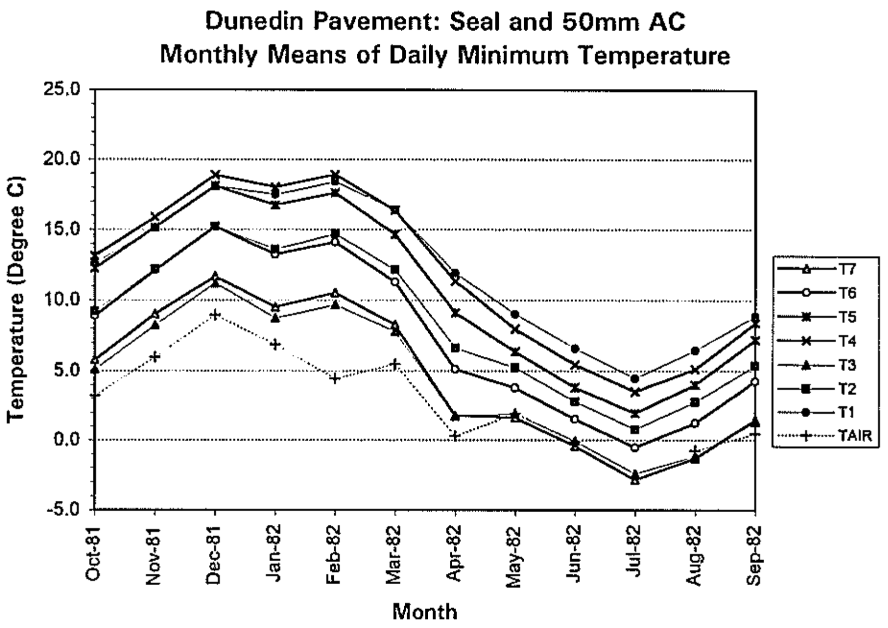

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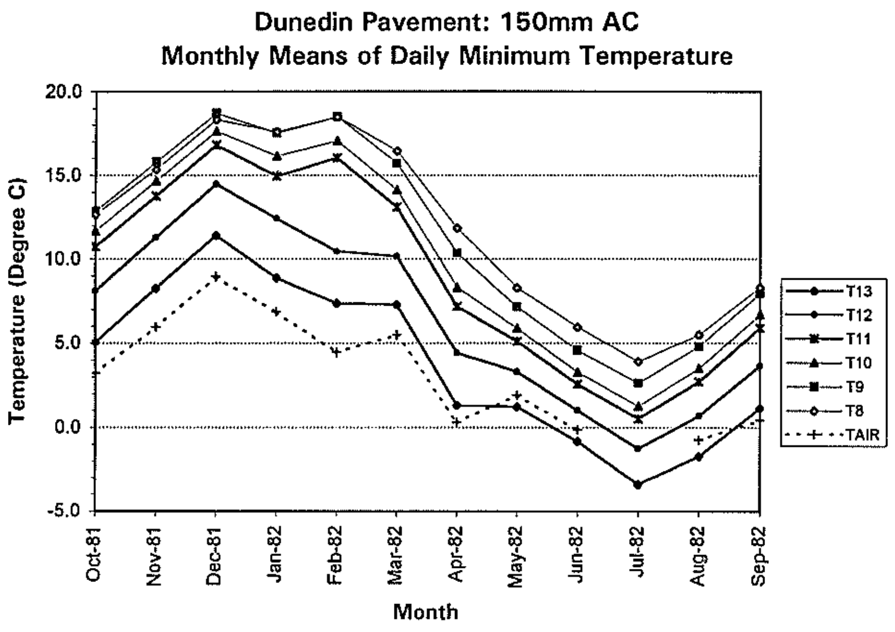


Figure E.26

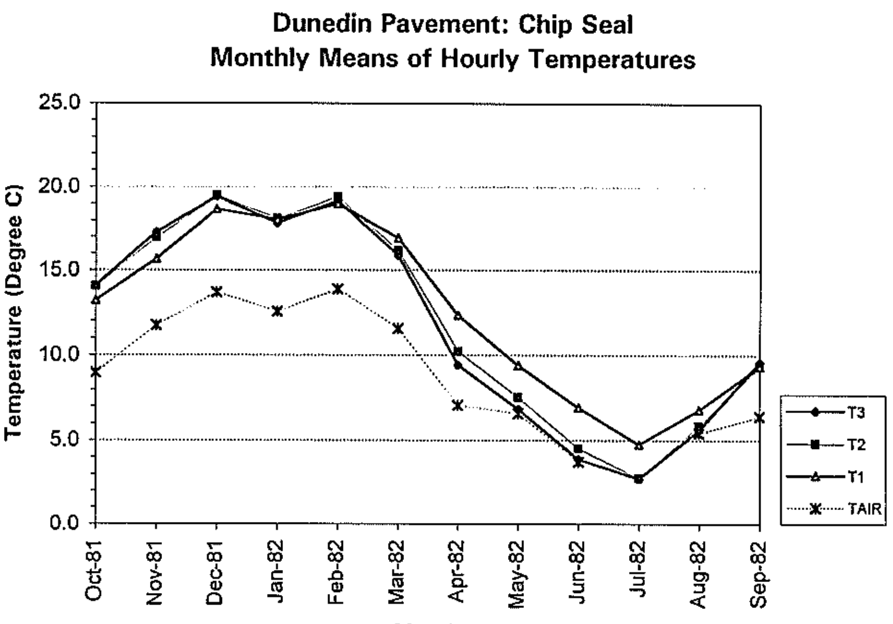


Figure E.27

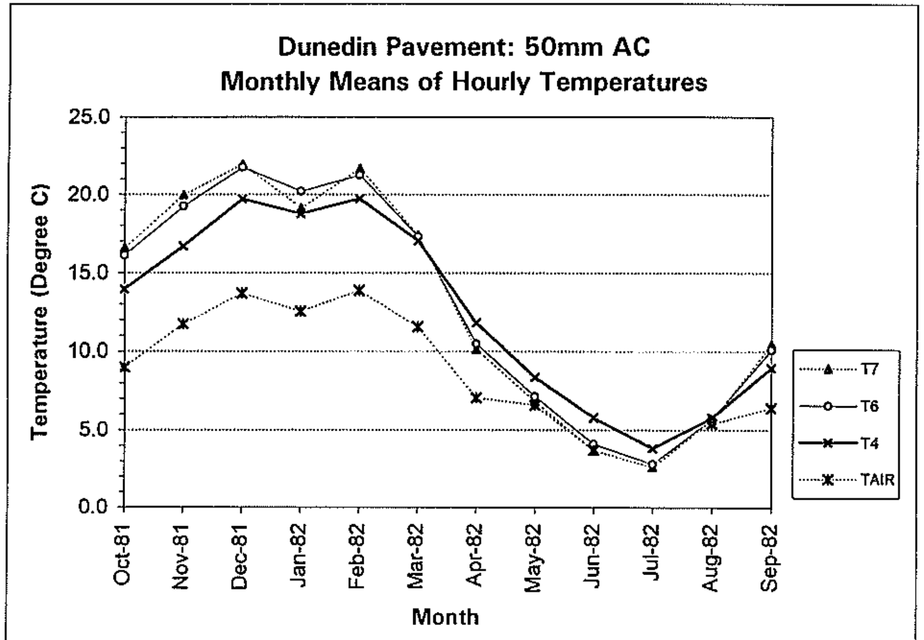

Dunedin Pavement: 50mm AC
Monthly Means of Hourly Temperatures

Figure E.28

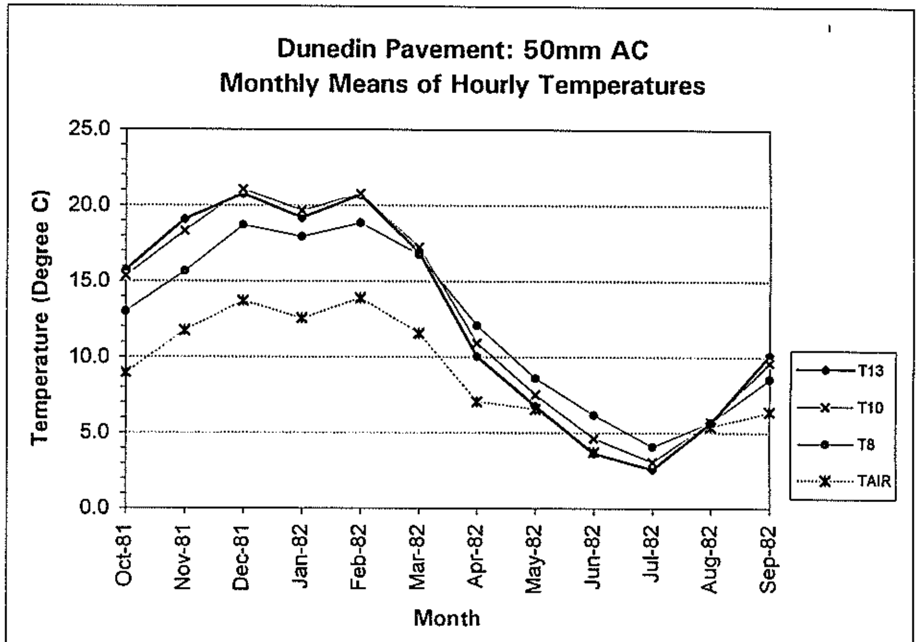

Dunedin Pavement: 50mm AC
Monthly Means of Hourly Temperatures

Figure E.29

Dunedin Pavement: Surface of Chip Seal
Monthly Mean Temperature for Each Hour of Day

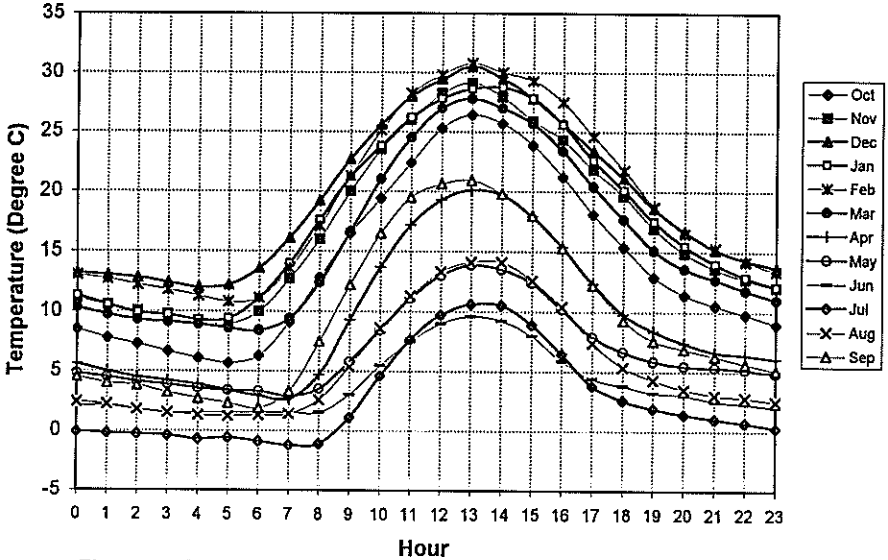


Figure E.30

Dunedin Pavement: 50 mm Deep in 150 mm AC
Monthly Mean Temperature for Each Hour of Day

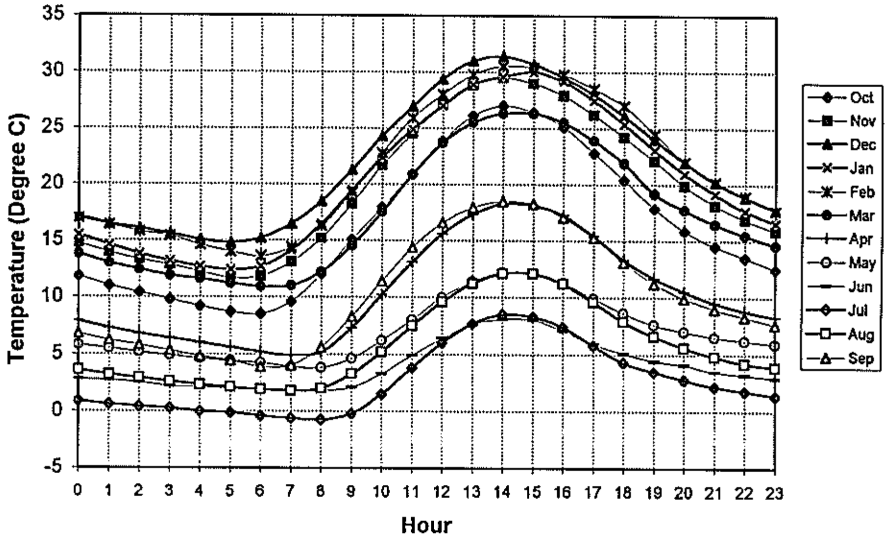
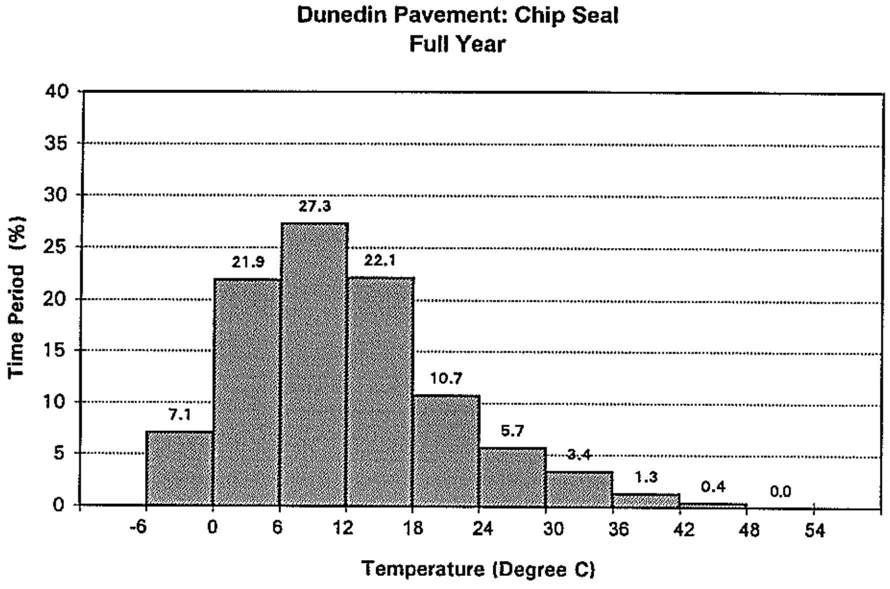


Figure E.31



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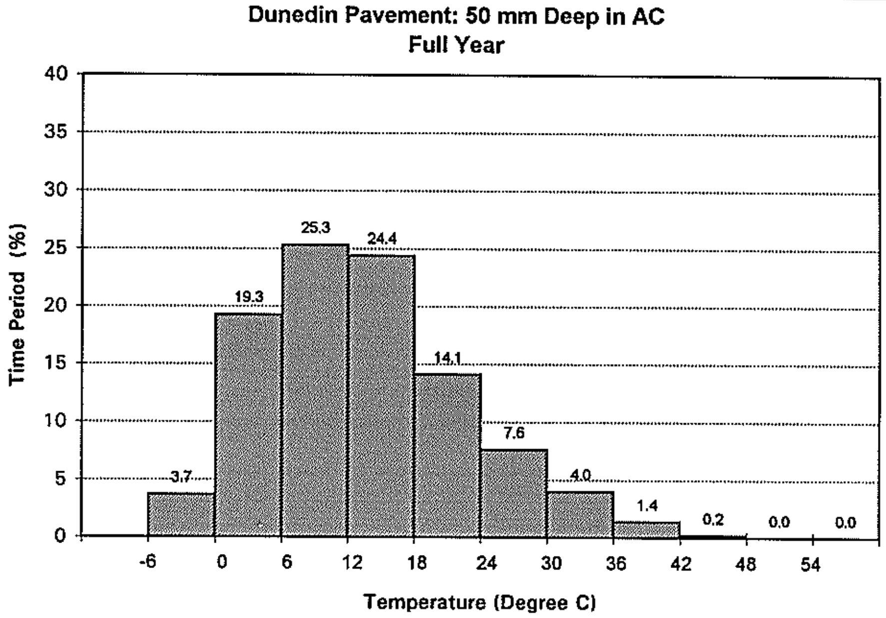

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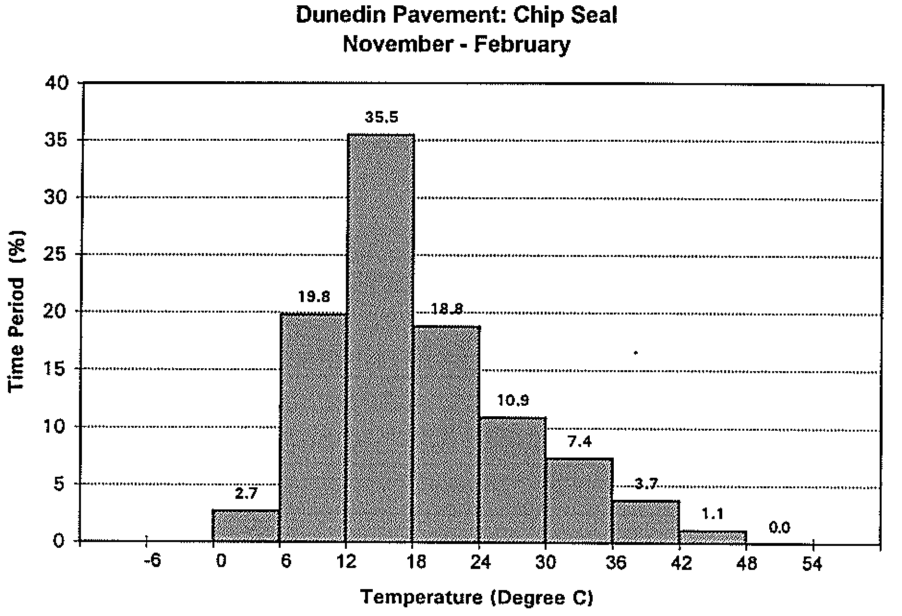


Figure E.34

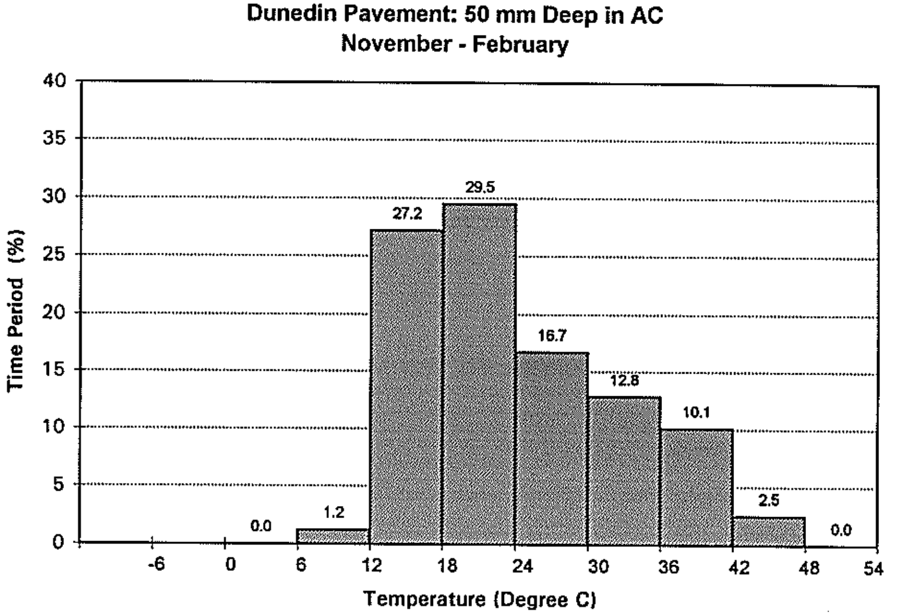
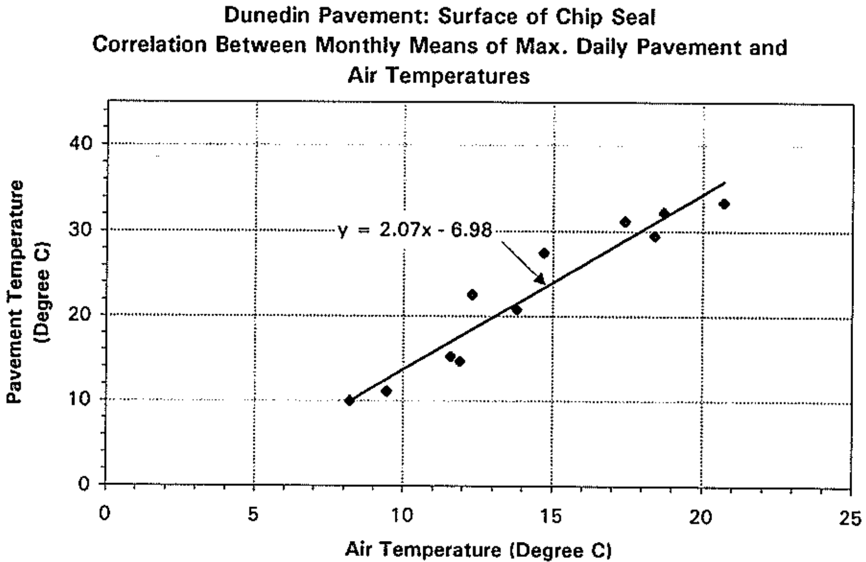


Figure E.35



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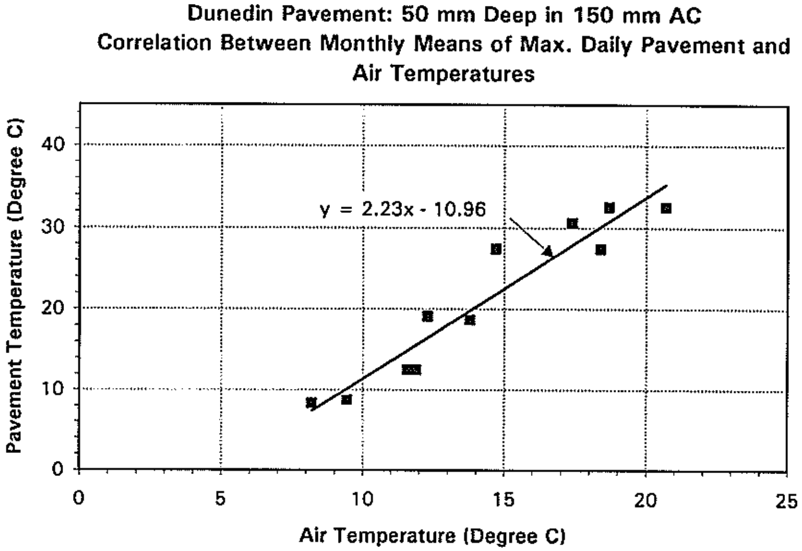

Figure E.37

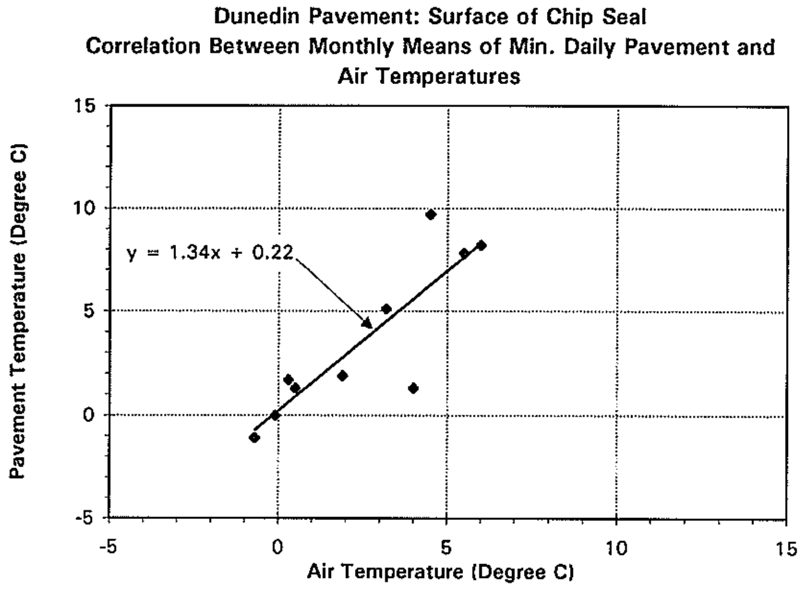
Dunedin Pavement: Surface of Chip Seal
Correlation Between Monthly Means of Min. Daily Pavement and Air Temperatures

Figure E.38

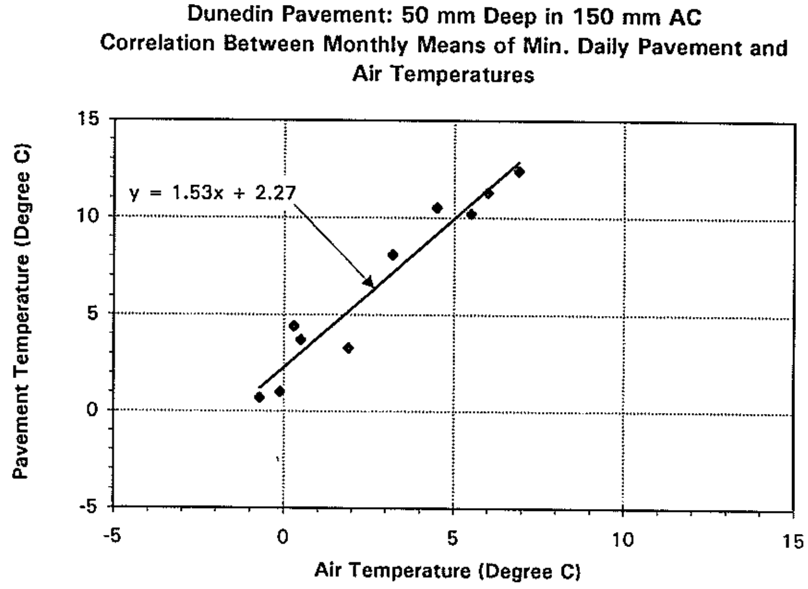
Dunedin Pavement: 50 mm Deep in 150 mm AC
Correlation Between Monthly Means of Min. Daily Pavement and Air Temperatures

Figure E.39

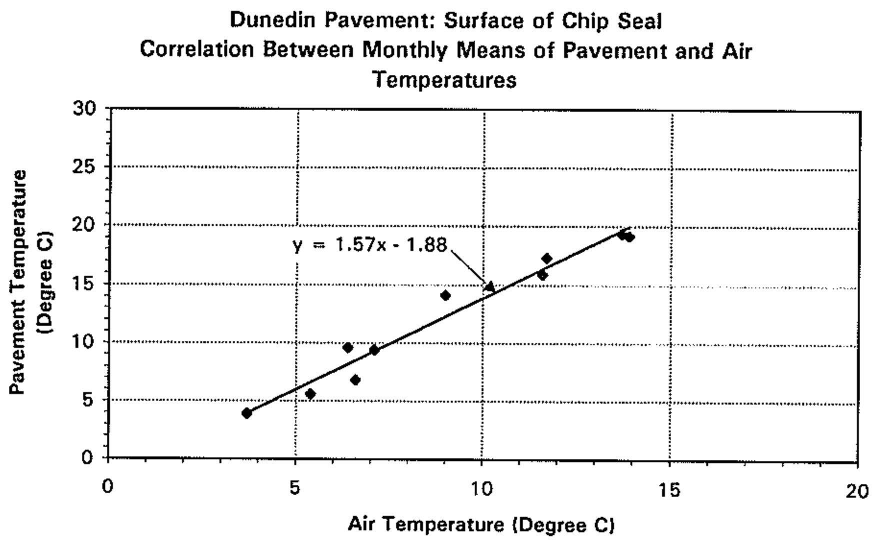

Figure E.40

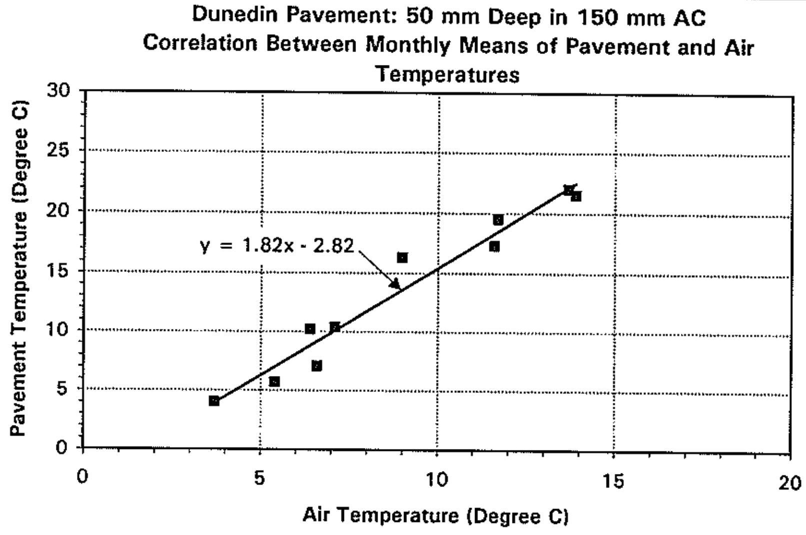

Figure E.41