Pavement Temperatures and Their Engineering Significance in Australia

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This paper describes the results of an Australia-wide investigation of seasonal temperatures in and beneath highway pavements. Outside the limited alpine areas, pavement temperatures varied from about 5 C to over 60 C. Thus frost action can be neglected in Australia, but the advantages and disadvantages of high temperatures should be considered in pavement design.

Only poor correlations were found between pavement and air temperatures and the results suggest that net radiation is not only important but extremely variable over the lateral dimensions of the roadway. Net radiation also caused significantly higher temperatures under the bituminous seal than the natural surface.

The temperature gradients were of insufficient magnitude and duration to cause a significant thermal transfer of moisture through the subgrade. This observation is also in agreement with conclusions based on the observed moisture conditions. It is suggested that any thermal transfer of moisture that does take place is more likely to lead to safer conditions than the reverse.

The results suggest that pavement subgrade temperatures observed in Australia have a significant effect on pavement performance, but only insofar as they affect the load-spreading properties of bituminous layers or cement- or lime-treated bases.

•THE INFLUENCE of temperature on pavement performance is now reasonably well documented, indicating that temperature is an important factor in pavement design. For example, if temperatures fall below freezing for sufficiently long periods, frost heave and the reduction of stability during the spring thaw can cause serious damage to road pavements.

In Australia frost action need not be considered, except in the limited and sparsely populated alpine areas. Aitchison and Richards (1) and Richards (2, 3) have shown how, in frost-free areas, the influence of environment (including climate) on subgrade stability and pavement performance can be included in practical design techniques. These techniques have followed the development of new soil suction instrumentation (4). This work suggests that moisture movement under temperature gradients is insignificant in the wide range of soil types and climatic zones investigated and that it is safe to assume isothermal conditions in predicting moisture changes and equilibria beneath sealed pavements.

The Australian investigation (1), undertaken by the Division of Soil Mechanics, Commonwealth Scientific and Industrial Research Organization (CSIRO), with the assistance of the National Association of Australian State Road Authorities, was primarily concerned with the observation of soil suction values under sealed pavements throughout Australia. However, to permit temperature corrections to be made to the gypsum block suction readings, and to provide data on temperature gradients should thermal transfer

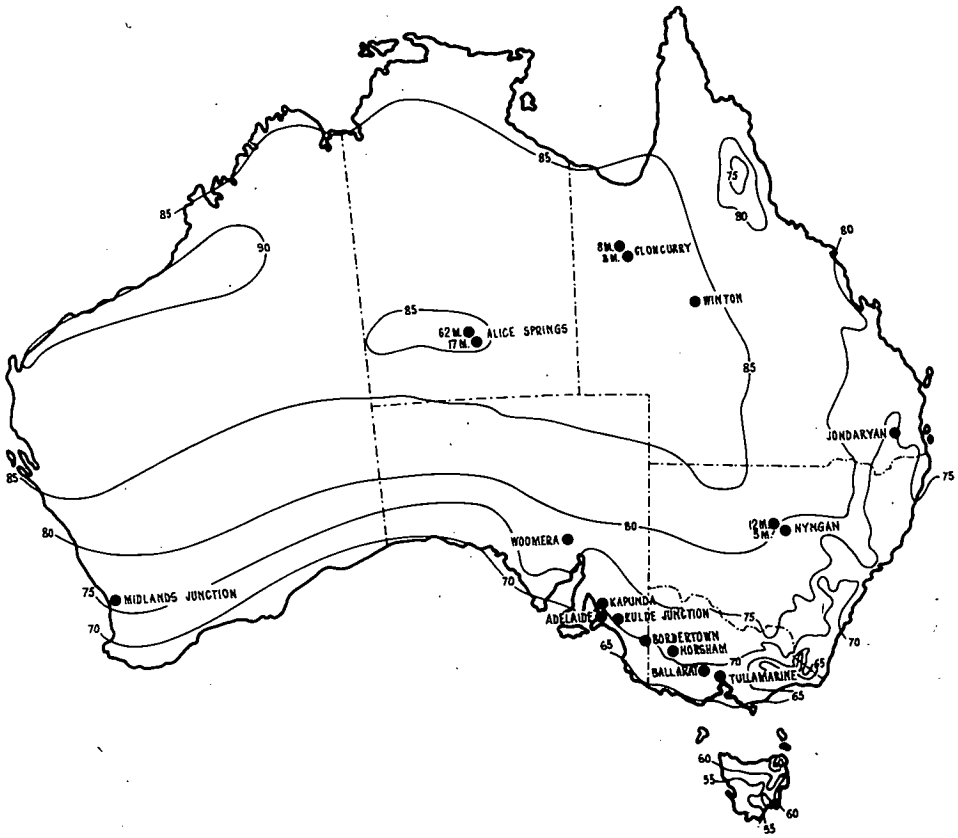

Figure 1. Maximum temperature isotherms (deg F) and location of field sites.

of moisture be evident, temperature measurements were also made. Consequently a large volume of temperature data under typical sealed pavements was amassed. No attempt was made initially to investigate pavement temperatures specifically, and the temperature instrumentation was not ideal, being chosen for convenience. In spite of this, the data do provide useful and interesting information. For instance, the temperature gradients measured permitted the assumption that thermal moisture transfer beneath sealed pavements is negligible under Australian conditions to be analyzed more critically.

In warm areas, such as in Australia, it is the high temperatures and the duration of these temperatures that are most important. The higher the temperature, the lower is the effective elastic modulus of bituminous layers, causing reduced time-dependent, load-spreading properties and lower stability of the pavement as a whole. High temperatures also increase loss of volatiles and oxidation, resulting in increased brittle behavior of bituminous materials and reduced fatigue life. The development of strength and elastic properties of cement- and lime-treated materials is also dependent on temperature and this has important practical significance in warmer areas.

SELECTION OF FIELD SITES

The 18 field sites were chosen to be representative of the wide range of soil and climatic conditions existing throughout Australia (1). The Great Soil Groups (5) provided a convenient and practical level of pedological classification of Australian Soils, in that the number of units was workable, while the morphological attributes of each Great Soil Group were sufficiently distinct to permit ready recognition with the as-

sistance of Soil Map of Australia (6). Furthermore, the chemical characteristics of representative profiles from each Great Soil Group have been defined (7). Another important characteristic of this classification is that most of the dominant soils are not unrelated to the current climate. Thus, frequently the selection of a site to represent a given soil meant that a specific climatic zone was studied. The range of climate covering the Australian continent is summarized in Figures 1 and 2.

The sites were therefore chosen on the basis of Great Soil Group and climate. No attempt was made to study all the major soils or climates, but a reasonable coverage of those conditions of interest to the moisture investigation was achieved. Attention was concentrated primarily on soils with a significant clay content occurring in environments such that some seasonal moisture deficiency of long duration might be expected. Consequently, sites were not selected in abnormally humid environments or on desert sand soils, which is unfortunately a limitation on the temperature data.

CHARACTERISTICS OF REPRESENTATIVE SITES

In order to ensure that each site was acceptable as representative of its region, several factors other than soil and climate were established as basic requirements. These defined the need for the installation site to reflect a modal or dominant soil in its characteristic environment with a pavement of standard form constructed in a manner least likely to introduce any local effects, particularly on moisture conditions (1).

When more than one site was chosen on the same Soil Group, climatic conditions were considered. Where possible an attempt was made to obtain the extremes of climatic conditions occurring in the mapped areas of the Group, e.g., summer rainfall and winter rainfall

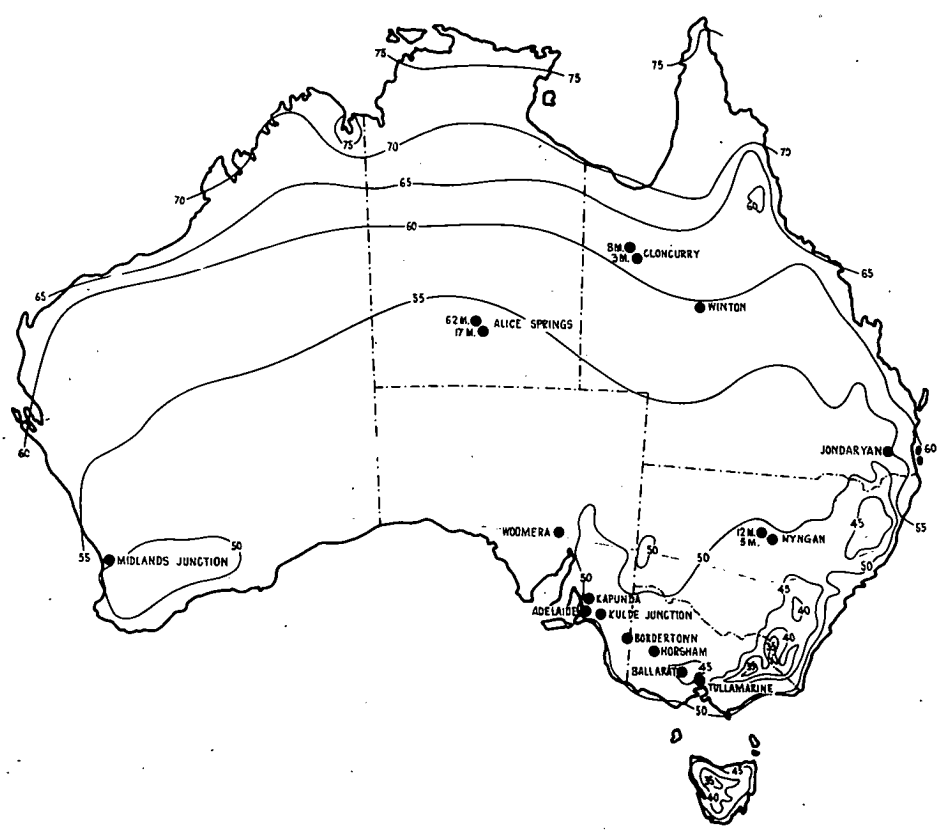

Figure 2. Minimum temperature isotherms (deg F) and location of field sites.

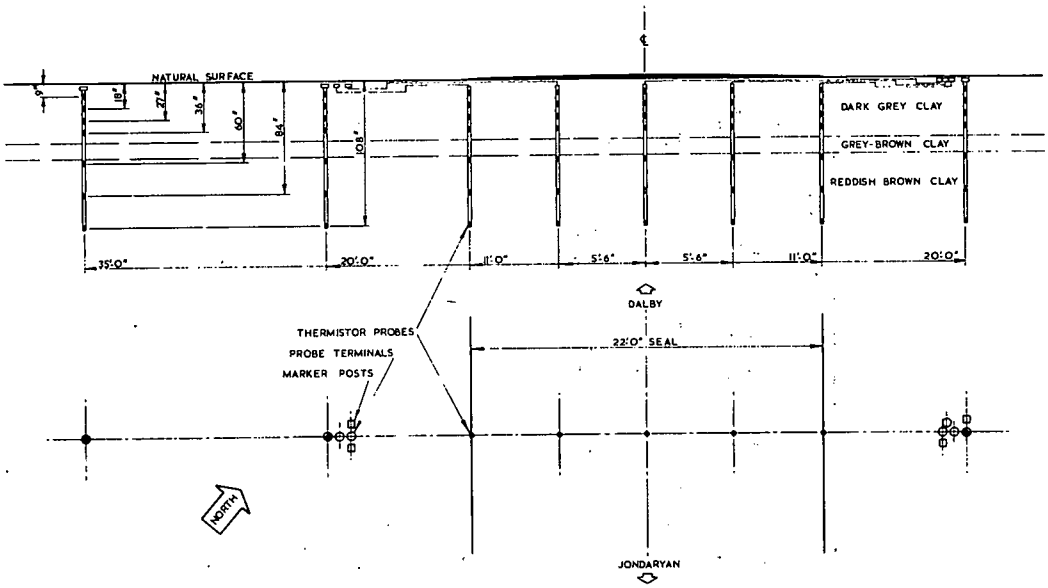

Figure 3. A typical field site.

or most arid and most humid. By the choice of such extremes it was planned not only to investigate the influence of rainfall on moisture conditions, but also to try and isolate any thermal influences on moisture transfer.

The details of each site have been described in detail elsewhere (1). The cross-sectional layout of the instrumentation was the same at each site as far as was practical, and a typical installation is shown in Figure 3. A brief summary of the climatic conditions at each site is given in Table 1, and the location of the sites is set out in Figures 1 and 2. Because the sites were identical in all respects, particularly in the seal type and width, with the exception of the soil type and climatic conditions, the differences in temperature should be strongly dependent on the soil and climatic conditions.

INSTRUMENTATION

The instrumentation and techniques employed in these installations have been described elsewhere (1) and a brief description of the temperature instrumentation is all that is considered necessary here.

The soil temperature was measured by means of thermistors incorporated in thermistor blocks (Fig. 4). These blocks were identical externally to the gypsum blocks for soil suction measurements and the "dummy" spacer blocks. The design of these blocks was chosen to overcome certain limitations in gypsum block design as well as for convenience in installation. These blocks could be mounted together axially in the form of a 2-in. diameter probe, the correct spacing of the gypsum and thermistor blocks being achieved by the insertion of "dummy" blocks. The spacing selected for temperature measurements was 6, 15, 24, 33, 57, 81, and 105 in. depth.

The thermistors used were STC type K5221. Considerable variation was found between thermistors, but it was such that the calibration curves remained parallel, as shown in Figure 5. This meant that the thermistors could be grouped into batches with an accuracy of ± 0.25 C by checking the resistance in a water bath at a set temperature (25 C). Each probe used thermistors of the same nominal resistance (at 25 C), which was noted so that the appropriate calibration curve could be used later. However, it cannot be claimed that the accuracy of reading is ± 0.25 C because long-term drift and insulation breakdown was apparent in a few cases. In general, an accuracy of ± 1.0 C is probably more correct, providing care is taken in disregarding those installations that develop spurious readings.

TABLE 1

SOILS AND CLIMATIC FACTORS AT INSTALLATION SITES

Great Soil Group	Area of Australia Dominated by Soils of Chosen Great Soil Group	Location of Installation	Climatic Factors[a]					Climatic Indices		
			Annual Rainfall P (in.)	Mean Temp. (deg F)	Evap. From Water Surface Ep (in.)	Drainage D (in.)	Deficit d (in.)	After Gentilli[b]	After Prescott[a] K	Thornthwaite Moisture Index[b] T
Red brown earth	2-3%	Adelaide, S. A.	25.3	61.3	31.8	2.0	8.5	CB'd'c	2.24	-18.2
		12 mi NW of Nyngan, N.S.W.	14.9	64.8	39.6	0	24.6	DB'd	1.16	-37.7
Grey and brown soils of heavy texture	5-10%	Horsham, Vic.	17.6	58.9	27.8	0	10.2	CB'dc	1.71	-22.1
		Bordertown, S. A.	18.8	58.8	23.8	0.6	5.6	CB'dc	2.04	- 9.7
		Tullamarine, Vic.	19.5	58.0	24.1	0	4.6	CB'dc	2.10	+ 5.3
		8 mi W of Cloncurry, Qld.	16.9	77.9	66.1	0	49.2	DA'd	0.90	-44.4
Desert sand plain soil	5%	62 mi N of Alice Springs, N. T.	9.9	69.1	54.3	0	44.3	EB'	0.60	-49.6
Arid red earth	5%	17 mi N of Alice Springs, N. T.	9.9	69.1	54.3	0	44.3	EB'	0.60	-49.6
Stony desert tableland soil	3-5%	Roadway at Woomera, S. A.	6.1	65.6	42.7	0	36.6	EB'	0.44	-51.6
		Aerodrome at Woomera, S. A.	6.1	65.6	42.7	0	36.6	EB'	0.44	-51.6
Meadow podzolic soil	<5%	2½ mi N of Midlands Junction, W. A.	34.5	65.0	44.5	12.5	22.5	BB's	2.42	+34.5
Black earth	1-2%	4½ mi NW of Jondaryan, Qld.	25.1	66.3	35.3	0	10.2	CB'dh	2.08	- 4.2
Kraznozem	<1%	2½ mi W of Gordon, Vic.	27.4	53.9	20.5	6.9	0	CB'r	3.31	+10.0
Brown soil of light texture	2-3%	5½ mi NW of Nyngan, N.S.W.	14.9	64.8	39.6	0	24.6	DB'd	1.16	-37.7
Lateritic red earth	1%	3½ mi W of Cloncurry, Qld.	16.9	77.9	66.1	0	49.2	DA'd	0.90	-44.4

[a]At nearest station. [b]From map.

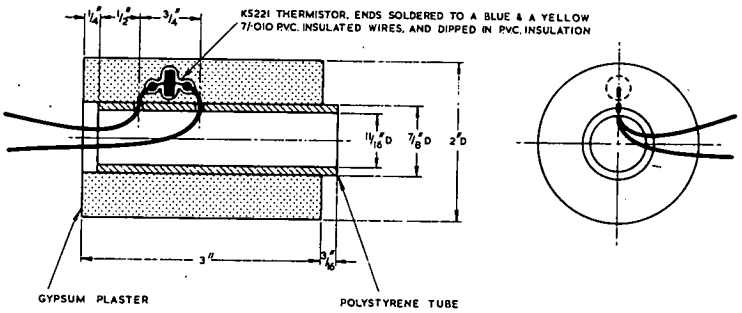

Figure 4. Thermistor block.

RESULTS

The data were produced from periodic observations (usually monthly) at the field installations in the form of resistance measurements at 56 points on a transverse section across the roadway, as shown in Figure 3. From each set of resistances from the thermistor readings, a temperature section across the roadway was produced such as in Figure 6. Because of the large volume of data, only a brief summary can be presented in this paper.

At those installations that gave good sets of data over a 2- to 4-year period, two sets of data were produced, viz., the mean temperatures at each depth beneath (a) the natural surface and (b) the bituminous seal.

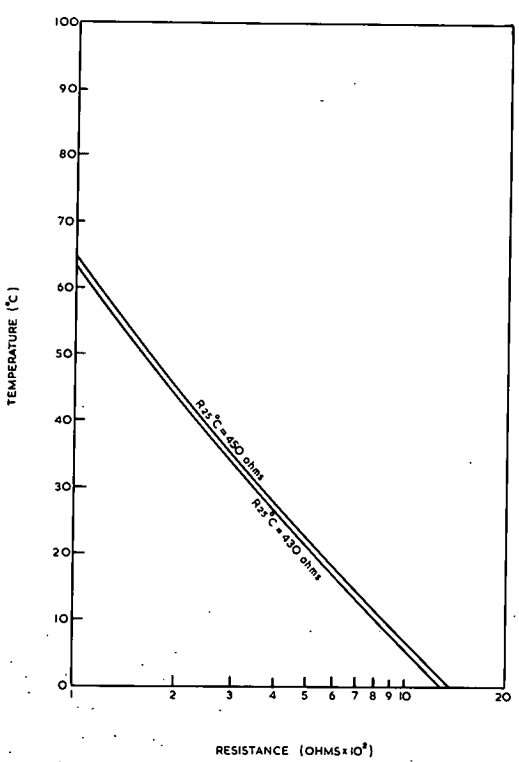

Figure 5. Calibration curves for STC type K5221 thermistors.

For those beneath the natural surface, the arithmetic mean of the temperatures at each depth was taken from the 3 probes away from the bituminous seal and for the corresponding month of the year during the period of observation. Similarly, for the temperatures beneath the bituminous seal, the readings from the 3 probes beneath the interior of the seal were used. This permitted plotting of annual variations in monthly mean temperatures, as shown in Figures 7 and 8. Also included in Figure 8 are the maximum and minimum temperatures that were observed at each depth.

Diurnal variations in temperature could not be investigated because of the nature of the research. Diurnal variations can be extremely high at the upper surface of bituminous layers in warmer areas (8, 9, 10). However, bituminous layers provide good thermal insulation and cause rapid decreases in diurnal temperature variations over depths of only a few inches below the exposed surface (10). This agrees with the theoretical results of the solution to the equation of heat conduction that describes the diurnal temperature variations in bituminous materials and soil (11). However, any influence of diurnal tempera-

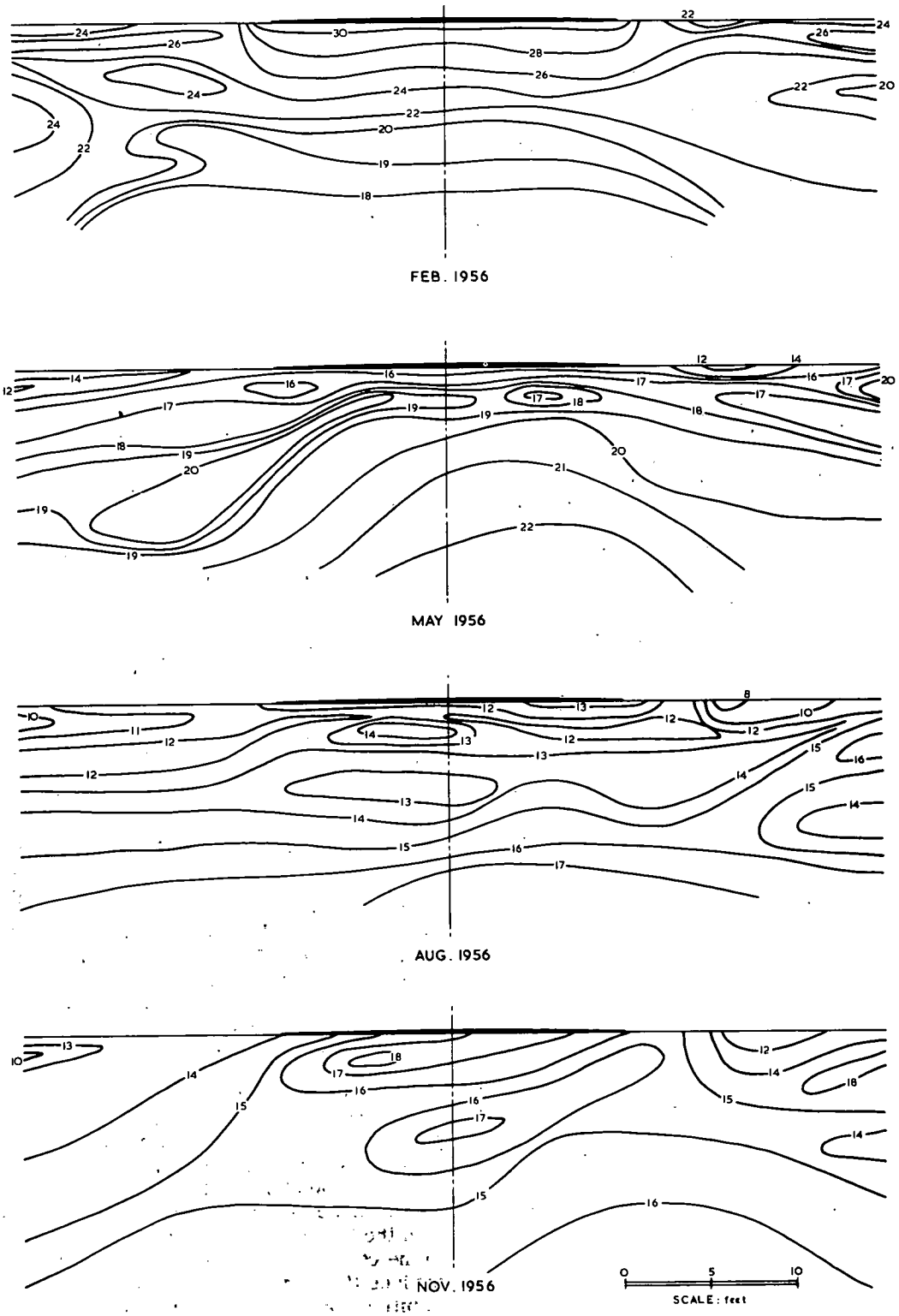

Figure 6. Typical temperature contours (°C) at the Horsham site.

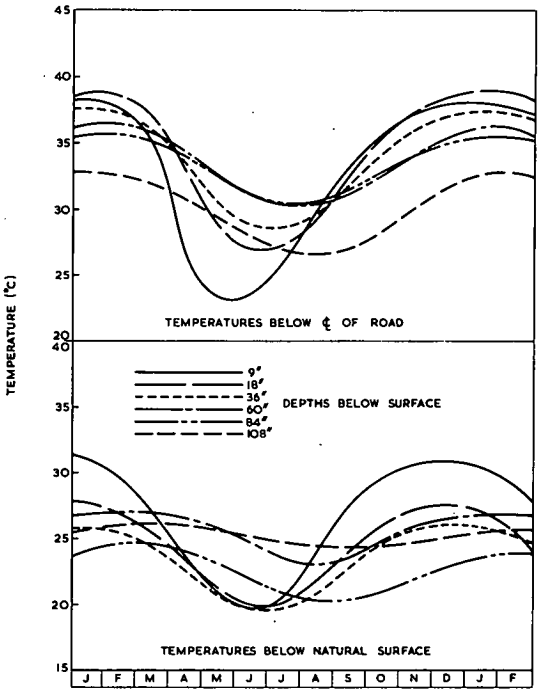

Figure 7. Typical seasonal temperature variations at various depths below centerline of road and natural surface (Jondaryan site).

ture was avoided as far as possible by making the observations at approximately the same time of day.

DISCUSSION OF RESULTS

An examination of all the temperature observations indicates that pavement temperatures over most of the Australian continent range from about 5 C to well over 60 C. The only possible exception to this would be in the limited alpine areas where temperatures below 0 C could be expected. This means that, in general, frost action need not be considered in pavement design (which is the practice of the Australian road authorities). However, the high temperatures observed are very widespread and can have considerable effect on pavement performance, as will be discussed below. These high temperatures are not always considered in pavement design under present Australian design practices.

The individual temperature readings often showed large variations laterally (of the order of ± 5 C near the surface) under the same surface and at the same depth and time. The nature of these variations suggested that they were due more to variations in heat gain or loss (e.g., net radiation) at the surface, rather than difference in the thermal diffusivity of the material. This means, therefore, that actual soil temperatures at the installations can vary considerably from the mean values shown in Figures 7 and 8 and that the mean values themselves are probably not very precise. This is one reason why a large scatter was obtained in the figures that follow. However, the results do show definite trends, which, because of the foregoing arguments, are probably as useful as could be obtained for practical purposes without carrying out a large-scale statistical investigation.

Climatic Trends

The climatic data available in the vicinity of each site included the 30-year averages for the average daily maximum, minimum, and mean temperatures for each month and the whole year. Because this information is available for more than 600 stations throughout Australia, it was considered that any trends between observed soil temperatures and available climatic data could be useful for practical purposes. Consequently, three relationships were examined:

1. Absolute maximum observed temperature at 6 in. depth vs the maximum average daily temperature (Fig. 9);
2. Mean maximum observed temperature at 6 in. depth vs the maximum average daily mean temperature (Fig. 10); and
3. Mean observed temperature at 9 ft depth vs yearly average daily mean temperature (Fig. 11).

These relationships are not considered to be necessarily the best, but they are suggested as possibilities by examination of the theoretical equation for heat conduction in soils.

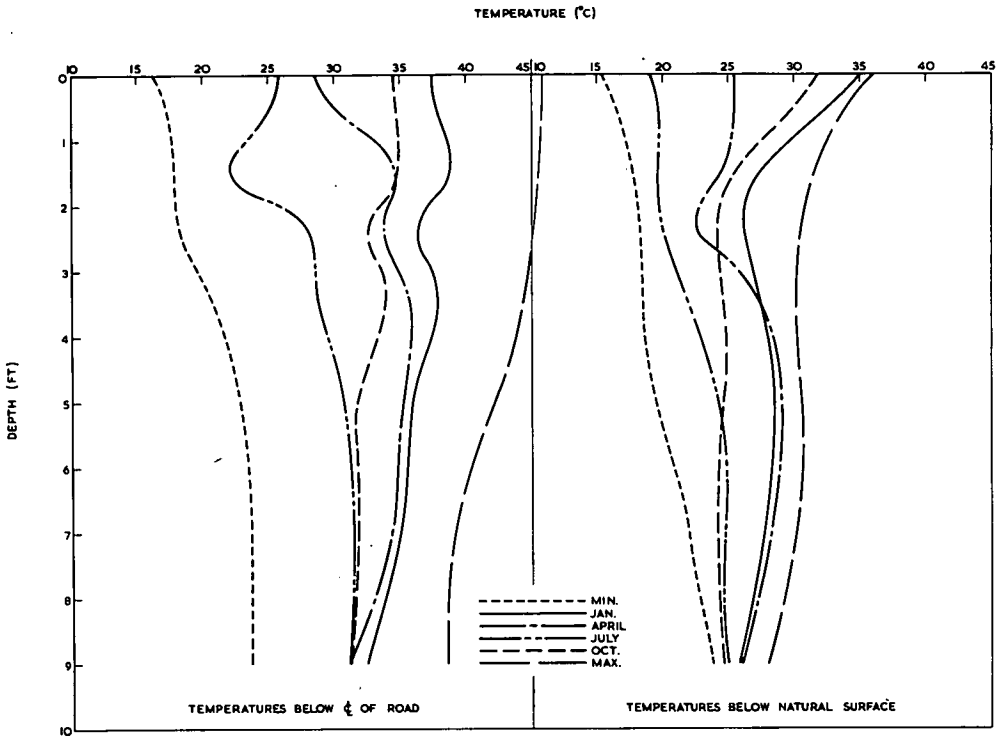

Figure 8. Typical temperature profiles at various months below centerline of road and natural surface (Jondaryan site).

Furthermore, the straight-line correlations shown in Figures 9, 10, and 11 are not very significant and are only shown to indicate trends.

These statistical trends, however, clearly indicate that the soil temperatures are strongly dependent on climate, as could be expected. Furthermore, the summer temperatures and the mean temperatures at all depths are significantly greater under the bituminous seal than under the natural surfaces. The winter temperatures (not shown because of very poor correlations) tend to be slightly higher under the bituminous seal in most cases, although not significantly. These results could again be expected due to the increased thermal absorption characteristics or the increased net radiation taking place at the black bituminous surface.

Thermal Gradients Likely To Cause Moisture Transfer

There is now considerable theoretical and experimental evidence that moisture flow can be set up in soil under temperature gradients (12, 13, 14, 15, 16). This flow, which occurs mainly in the vapor phase in the direction of decreasing temperature, can cause appreciable moisture transfer under certain conditions.

More information has become available on moisture flow under thermal gradients (17, 18). Cary (16), working with Columbia loam soil, obtained thermal moisture fluxes under thermal gradients, which suggest a coefficient of moisture transfer under thermal gradients of 1.4×10^{-6} cm^2/sec deg C at relatively low suctions. Rollins, Spangler, and Kirkham (13) obtained data for a silt loam giving coefficients of the order of 3×10^{-7} cm^2/sec deg C at unknown suctions, but relatively high air voids. Clays with low air voids, even at quite high suctions, should have coefficients no higher, and probably much less, than these, except perhaps in very dry areas. In dry areas, however, thermal moisture transfer is unlikely to have any significant effect on pavement thicknesses.

From the temperature profiles such as Figure 7, the maximum temperature gradient is only of the order of 0.3 C/cm over short distances (of the order of 10-15 cm). This

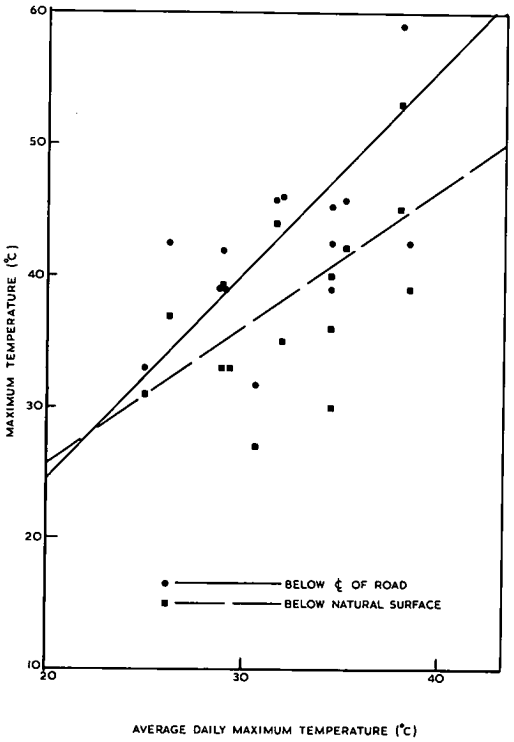

Figure 9. Absolute maximum temperature at 6 in. depth vs the maximum average daily maximum temperature.

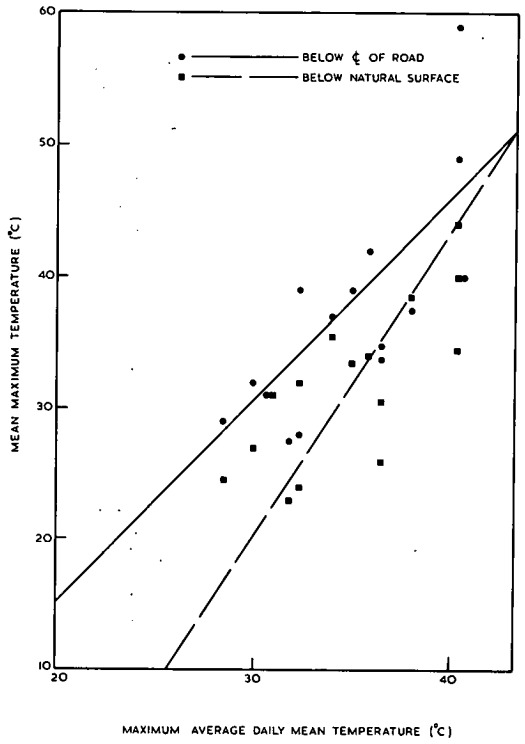

Figure 10. Mean maximum observed temperature at 6 in. depth vs the maximum average daily mean temperature.

gradient is unlikely to cause moisture flow in excess of 10^{-7} cm/sec. Not only does this flow take place over a very short distance, but the temperature gradient exists at any given depth for only a short time as the temperature wave moves vertically down the soil profile. Furthermore, the temperature gradients reverse seasonally, causing a reversal of thermal moisture transfer. However, as pointed out by Croney and Coleman (11), temperature variations are not sinusoidal, so that seasonal flows do not balance, resulting in a net vertical moisture transfer.

The largest average temperature gradient over the whole soil profile occurred at the Woomera road installation, where the gradient was 0.07 C/cm in January, decreasing with depth. Again, this gradient occurs only for a short duration, and to some extent reverses in the winter months. At all other sites the average temperatures were considerably less than this value. Consequently, thermal moisture flow will probably never exceed 2×10^{-8} cm/sec even for short periods.

Aitchison and Holmes (19) have analyzed the effect of vertical flow on suction profiles due to a net evaporative loss at the surface. These results for Waite loam, plus similar calculations by the author using permeability data for Syndal and Horsham clay (20), suggest that only small variations from isothermal conditions can occur due to permanent thermal moisture flow of this order and even smaller variations for the actual flow, which would occur over a short period.

It is also interesting to note that, in every case, the generally high temperatures immediately under the pavement resulted in small gradients in mean temperature with temperatures decreasing both vertically down the profile and laterally away from the centerline at all depths. Thus, if net thermal moisture flow has any effect at all, it would be to increase the subgrade suction, which would result in increased stability and safer conditions than predicted.

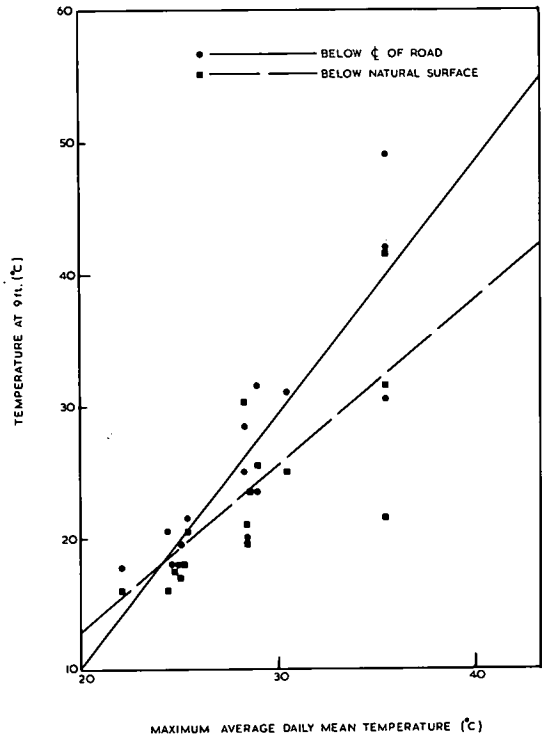

Figure 11. Mean observed temperature at 9 ft depth vs yearly average daily mean temperature.

Temperatures at the Surface of the Bituminous Layer

While no temperatures were measured at the surface, temperatures in excess of 60 C obviously occur in central and northern Australia, as seen from Figure 9. Whiffin and Lister (21) have clearly demonstrated that the load-spreading properties of bituminous roads deteriorate markedly with rise in temperature. The increased stresses and strains at high temperatures must therefore lead to higher pavement deflections and reduced life, apart from the deterioration of the bituminous materials themselves.

Temperatures in the Base Course

Temperatures were also very high in the pavement at a depth of 6 in. The mean maximum temperature probably exceeds 50 C, with localized temperatures probably exceeding 60 C. Maclean and Clare (22), Dumbleton (23), and Metcalf (24) have all demonstrated the increased rate of gain of strength of both lime- and cement-stabilized soils with increase in temperature. These results therefore indicate the fallacy of curing laboratory samples at, say, 25 C in those cases where the in situ temperatures may exceed 50 C for long periods.

CONCLUSIONS

The results of the Australian-wide investigation described are not very conclusive, but they indicate that, in normal areas, soil and pavement temperatures vary from about 5 C to over 60 C. Freezing conditions do not occur, and frost action is not a problem. However, very high temperatures do occur that can have a very significant effect on pavement performance.

There is a significant, but rather poor, correlation between soil and pavement temperatures and recorded air temperatures. The results suggest that net radiation is not only important, but extremely variable even over the lateral dimensions of the roadway. Net radiation is also the reason for the significantly higher temperatures under the bituminous seal than the natural surface.

The temperature gradients are of insufficient magnitude and duration to be likely to cause significant thermal transfer of moisture. This observation is in agreement with conclusions based on the observed moisture conditions. In fact, any thermal transfer of moisture that does take place is probably more likely to lead to safer conditions than the reverse.

Thus, in general, the soil and pavement temperatures observed in Australia have a significant effect on pavement performance, but only insofar as they affect the load-spreading properties of bituminous layers or cement- or lime-treated bases.

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