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16. Abstract
Transverse cracking of asphalt pavements can be the result of temperature changes and it was once thought that temperature induced transverse cracking of asphalt pavements was entirely the result of low temperatures causing the pavement material's tensile strength to be exceeded by tensile stresses--a mechanism now termed "low-temperature cracking". Although models for low temperature cracking have been used with some success in northerly regions, where the temperature drops low enough to cause a pavement to reach its "fracture temperature", in many cases, transverse cracking is quite common even though relatively moderate temperatures prevail. A mechanism that accounts for thermally induced cracking of asphalt pavements in relatively moderate climates is "thermal-fatigue cracking" due to temperature cycling that eventually results in the fatigue resistance of the asphalt concrete being exceeded.

This report describes the development of a design procedure for asphalt pavements to resist thermal fatigue cracking. The first step is the development of a computer model based on fracture mechanics for predicting transverse cracking due to thermal fatigue cracking in asphalt concrete pavements. It uses Shahin's and McCullough's revision of Barber's Equations (Bulletin 168, Highway Research Board, 1957) to compute pavement temperatures but extends upon mechanistic methods of Chang, Lytton, and Carpenter, based on fracture mechanics to predict crack growth and spacing. The effectiveness of the model developed is demonstrated by comparing its results with field data from Michigan. The design equation is developed by regression analysis of the results of 576 separate runs of the computer model for a

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DESIGN OF ASPHALT PAVEMENTS FOR THERMAL FATIGUE CRACKING

by

Robert L. Lytton
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B. D. Garrett

Research Report Number 284-4

Flexible Pavement Data Base and Design
Research Study 2-8-80-284

conducted for the
State Department of Highways
and Public Transportation

in cooperation with the
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by the

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ABSTRACT

Transverse cracking of asphalt pavements is often the result of environmental, non-load associated causes and accounts for many millions of dollars in maintenance cost each year. Such cracking can be the result of temperature stresses. It was once thought that temperature induced transverse cracking of asphalt pavements was entirely the result of low temperatures causing the pavement material's tensile strength to be exceeded by tensile stresses - a mechanism now termed "low-temperature cracking". Although models for low temperature cracking have been used with some success in northerly regions, where the temperature drops low enough to cause a pavement to reach its "fracture temperature", in many cases transverse cracking is quite common even though relatively moderate temperatures prevail. A mechanism that accounts for thermally induced cracking of asphalt pavements in relatively moderate climates is "thermal-fatigue cracking" due to temperature cycling that eventually results in the fatigue resistance of the asphalt concrete being exceeded.

This report describes the development of a design procedure for asphalt pavements to resist thermal fatigue cracking. The first step is the development of a computer model based on fracture mechanics for predicting transverse cracking due to thermal fatigue-cracking in asphalt concrete pavements. It uses Shahin's and McCullough's revision of

Barber's Equations (Bulletin 168, Highway Research Board, 1957) to compute pavement temperatures but extends upon mechanistic methods of Chang, Lytton, and Carpenter, based on fracture mechanics to predict crack growth and spacing. The effectiveness of the model developed is demonstrated by comparing its results with field data from Michigan. The design equation is developed by regression analysis of the results of 576 separate runs of the computer model for eight different climatic conditions. The design procedure is automated, using a computerized pattern search routine to select the best combination of asphalt concrete thickness, bitumen and mix properties to withstand thermal fatigue for a specified period of time in a specified climate.

Thermal fatigue cracking was first described by M. Shahin and B.M. McCullough in Research Report No. 123-14, August, 1972, but their procedure gave no insight into the mechanism itself. H. S. Chang, R. L. Lytton, and S. H. Carpenter in Research Report No. 18-3, 1976 and in Research Report No. 18-4F, October, 1977, developed mechanistic models to predict crack growth and spacing due to cyclic thermal contraction in base materials. This report builds upon both to develop a design procedure for asphalt pavements to resist thermal fatigue cracking.

IMPLEMENTATION STATEMENT

Throughout large portions of Texas, particularly in West Texas and the northern half of the State, extensive amounts of transverse cracking of asphalt pavements is observed. Mechanisms to explain transverse cracking in those pavements due to thermally induced fatigue-cracking have not been adequately developed.

This report describes the development of a design procedure for asphalt pavements to resist thermal fatigue cracking for climatic conditions in north Texas. The design procedure is automated, using a computer to select the best combination of asphalt concrete thickness, bitumen, and mix properties to withstand thermal fatigue for a specified period of time (say 10 years) under specified climatic conditions. Example problems are worked and climatic information is provided in Appendix E so that this design procedure may be readily put to use in the Department. This design procedure does not replace the structural design procedure for flexible pavement in the Flexible Pavement System (FPS) but is intended to be used as an additional check on the final design selected by FPS.

DISCLAIMER

LIST OF REPORTS

Report No. 284-1, "An Investigation of Vehicle Speed and Pavement Roughness Relationships for Texas Highways", by N.F. Rhodes, Jr., J.P. Mahoney, and R.L. Lytton, September, 1979.

Report No. 284-2, "Pavement Roughness on Expansive Clays", by Manuel O. Velasco and R.L. Lytton, October 1980.

Report No. 284-3, "Layer Equivalency Factors and Deformation Characteristics of Flexible Pavements", by J.T. Hung, J-L. Briaud, and R.L. Lytton, January 1982.

Report No. 284-3a, "Layer Equivalency Factors and Deformation Characteristics of Flexible Pavements Test Data", by J.T. Hung, J-L. Briaud, and R.L. Lytton, January, 1982.

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CHAPTER I

INTRODUCTION

The problem of non-load associated cracking of asphalt pavements has been a serious concern for many years. By 1966 this concern had grown to the point that, as a part of the 1966 Annual Meeting of the Association of Asphalt Paving Technologists, a special symposium, "Non-Traffic Load Associated Cracking of Asphalt Pavements," was held to address this problem. In the introductory paper of that symposium (1), V. Marker summarized the known possible contributing causes for this type of cracking.

Non-load associated cracking in flexible pavements generally takes the form of "transverse cracking"; that is, nearly straight cracks across the pavement or perpendicular to the direction of traffic. Transverse cracking, when fully developed, can be seen as a series of cracks across the pavement whose spacings may be as little as a few feet to as much as several hundred feet.

At the time of the symposium mentioned above, the only suitable explanations for temperature induced transverse cracking of flexible pavements involved the exceeding of the pavement material's tensile strength by tensile stresses -- a mechanism now termed "low-temperature cracking." The statement below comes from Marker's 1966 paper at that symposium.

> "It would appear that the only manner in which a more or less straight crack can occur in an asphalt pavement is by a pulling force. In other words, a pull of some type sets up tensile stresses in the pavement which are greater than its resisting capabilities."

Extending from the above assumption, Marker listed a number of possible causes of transverse cracking. Among them are included both shrinkage of the asphalt layer itself and shrinkage of the base or subgrade.

Models for low temperature cracking have been used with varying degrees of success in the more northerly regions of the United States and in Canada. In those areas, the temperature drops low enough that it will reach the pavement material's "fracture temperature," defined as the temperature at which the developed tensile thermal stress exceeds the tensile strength of the asphalt concrete mixture. However, in many cases transverse cracking may be common even though the pavement has not been subjected to such temperature extremes. This is the case in some parts of Texas where a considerable amount of transverse cracking is observed and where relatively moderate temperatures prevail.

A mechanism to account for thermally induced transverse cracking of flexible pavements other than low-temperature cracking, is "thermal-fatigue cracking." It was first described by M. Shahin and B. F. McCullough (2) and is defined to be caused by thermal fatigue distress due to daily temperature cycling, which eventually exceeds the fatigue resistance of the asphalt concrete. They developed a model to predict thermal-fatigue cracking which assumes a fatigue law and obtains necessary constants by requiring the results to match an actual data point. The results of their procedure are not easily applied, particularly as no method of determining the fatigue constants of an asphalt mix was developed and no insight is provided into the mechanism itself.

In "Prediction of Thermal Reflection Cracking in West Texas" (3) and in "Thermal Pavement Cracking in West Texas" (4), computer models were developed to predict crack growth and crack spacing with time, where the cracking was due to volumetric changes in base materials. These mechanistic models use both materials properties and climatic data as inputs and since they do offer insight into the mechanism of thermal-fatigue cracking of flexible pavements, are an improvement over the Shahin-McCullough model.

This report describes the development of a design procedure for asphalt concrete pavements to resist thermal fatigue cracking. The first step in this development is a computer model based on fracture mechanics for predicting the occurrence of transverse cracking in asphalt concrete pavements. This work was motivated by the work of Shahin and McCullough and the later developments described above to develop better understanding of the mechanisms of thermal fatigue cracking. It makes use of Shahin's and McCullough's revisions of Barber's Equations (5) to compute pavement temperatures based on air temperature, wind speed, and solar radiation, calculates pavement temperature as was done in (5) and determines the effective modulus as in (3). The mechanistic method, based on fracture mechanics, used in this development may be expected to have more universal application than previous methods. The effectiveness of this method is demonstrated by comparing its results with observed crack spacings from Michigan which were previously used for evaluation of an empirical model developed by Haas (6, 7). A total of 576 runs of the computer model for four sites in Michigan and four sites in north Texas provided data for the development of a regression equation for thermal fatigue cracking that is the basis for the design procedure which is the objective of this report. The design is carried out using another computer program that selects, for given climatic conditions, the best pavement thickness, asphalt properties, and volumetric concentration of aggregate in the mix. Example problems are worked to show the results that may be expected when using the design procedure.

CHAPTER II

DEVELOPMENT OF FRACTURE MECHANICS COMPUTER PROGRAM

This chapter summarizes the theory of fracture mechanics that was used in developing a computer program that is capable of predicting thermal fatigue cracking. The reader who is more interested in seeing the results of calculations made with the program may turn directly to Chapter 3, which is concerned with verifying the model by comparing calculated results with observed field data. The actual design procedure with example calculations is given in Chapter 4.

The subjects that are covered in this chapter include the basic equation of fracture mechanics, the computation of stress intensity factors, and the set of equations used in the thermal cracking model.

THE BASIC EQUATION OF FRACTURE MECHANICS

In the development of a model to predict the frequency or spacing of transverse cracks in asphalt concrete that are the result of thermal-fatigue cracking, the equation of Paris and Erdogan (8) is used. This equation was originally developed through a fatigue test in metals. As formulated here, cracking of the asphalt concrete surface is assumed to begin at the top and progress downward through the asphalt. The asphalt is said to be "cracked" (or failed) when the calculated "crack length" (or depth in this case) equals at least the thickness of the asphalt layer. Thus we have

$$\frac{dc}{dN} = A(\Delta K)^n \tag{1}$$

where

$\frac{dc}{dN}$ = the rate of growth of the crack length (depth) with respect to the number of thermal loadings, N,

ΔK = the change at the cracked tip of the stress intensity factor, from the time of maximum temperature to the time of minimum temperature,

A and n are fracture properties of the asphalt mix.

Using equation (1), the number of temperature cycles from a temperature maximum to a temperature minimum that are required before the cracking of the asphalt will have developed a crack through the asphalt layer can be found by integration. Rearranging equation (1) we have

$$N_f = 1 + \int_{c_o}^{d} \frac{dc}{A(\Delta K)^n} \tag{2}$$

c_o = the initial crack length that occurs in a new pavement,

d = the thickness of the asphalt layer,

N_f = the number of temperature cycles to failure, and

C, A, and ΔK are as defined before.

In the above Equations, if A, ΔK and n are known, then, for some number ΔN of temperature cycles, which is less than the change in crack depth, ΔC can be found by using the following equation, developed from Equation 1:

$$C = A(\Delta K)^n \Delta N \qquad (3)$$

To successfully apply Equations 1 and 2 toward the development of a method for predicting the frequency (spacing) of transverse cracks in asphalt pavements, the various elements of those equations must be properly described. This requires the following

(1) A methodology for the calculation of the stress intensity factor, K, must be developed which considers that the stress intensity factor is sensitive to the thickness of the pavement surface, the current crack length, the effective modulus of elasticity of asphalt concrete, and the range of temperature to which the pavement has been subjected.

(2) The fatigue parameters A and n need to be determined from asphalt concrete properties that are readily available when a pavement is designed and in such a way that the change in material

properties with time and temperature is accounted for.

The methods used to handle these concerns are detailed in the next two sections of this chapter.

COMPUTATION OF THERMAL STRESS INTENSITY FACTORS

The stress intensity factor at the crack tip within the asphalt concrete can be found using the general expression

$$K_1 = a(Y_c)^b \tag{4}$$

where K_1 = the stress intensity factor at the crack tip

Y_c = the crack depth (in inches), and

the parameters a and b were empirically derived as a function of

(1) modulus of elasticity of the asphalt concrete mix, E, in psi,

(2) change of air temperature, T_R in °F below the assumed stress-free temperature of 75°F, and

(3) the thickness, d, of the asphalt concrete surface course in inches.

The determination of a and b involves the following procedure. A finite element computer program with crack tip element, developed by Chang, Lytton, and Carpenter (3) is used to compute the value of the stress intensity factor at the crack tip which is then corrected in the manner of Barenblatt (9). As was stated before and as is represented in Figure 1, the crack is assumed to be in a transverse direction. For purposes of analysis, the influence of the crack is assumed to be within 45 inches of the crack in either direction, so that the solutions will not be affected by boundaries. The spacing of the transverse cracks usually ranges from 5 feet to several hundreds of feet (2). The details of the pavement cross section used for this analysis are shown in Figure 2 and its material properties are given in Table 1. A typical example of the finite element mesh is shown in Figure 3. The thermal tensile stresses were calculated at both the top of the pavement and at the top of the crack tip element (Figure 4) using Barber's equation as modified by Shahin and McCullough (2). That equation is

$$T = T_m + T_v \frac{He^{-xc}}{[(H+C)^2+C^2]^{\frac{1}{2}}} \text{Sin}(S_i) \qquad (5)$$

where T = temperature of the mass in °F,

T_M = mean effective air temperature in °F,

T_V = maximum variation in temperature from the effective mean temperature in °F,

x = depth below the surface in feet,

H = h/k,

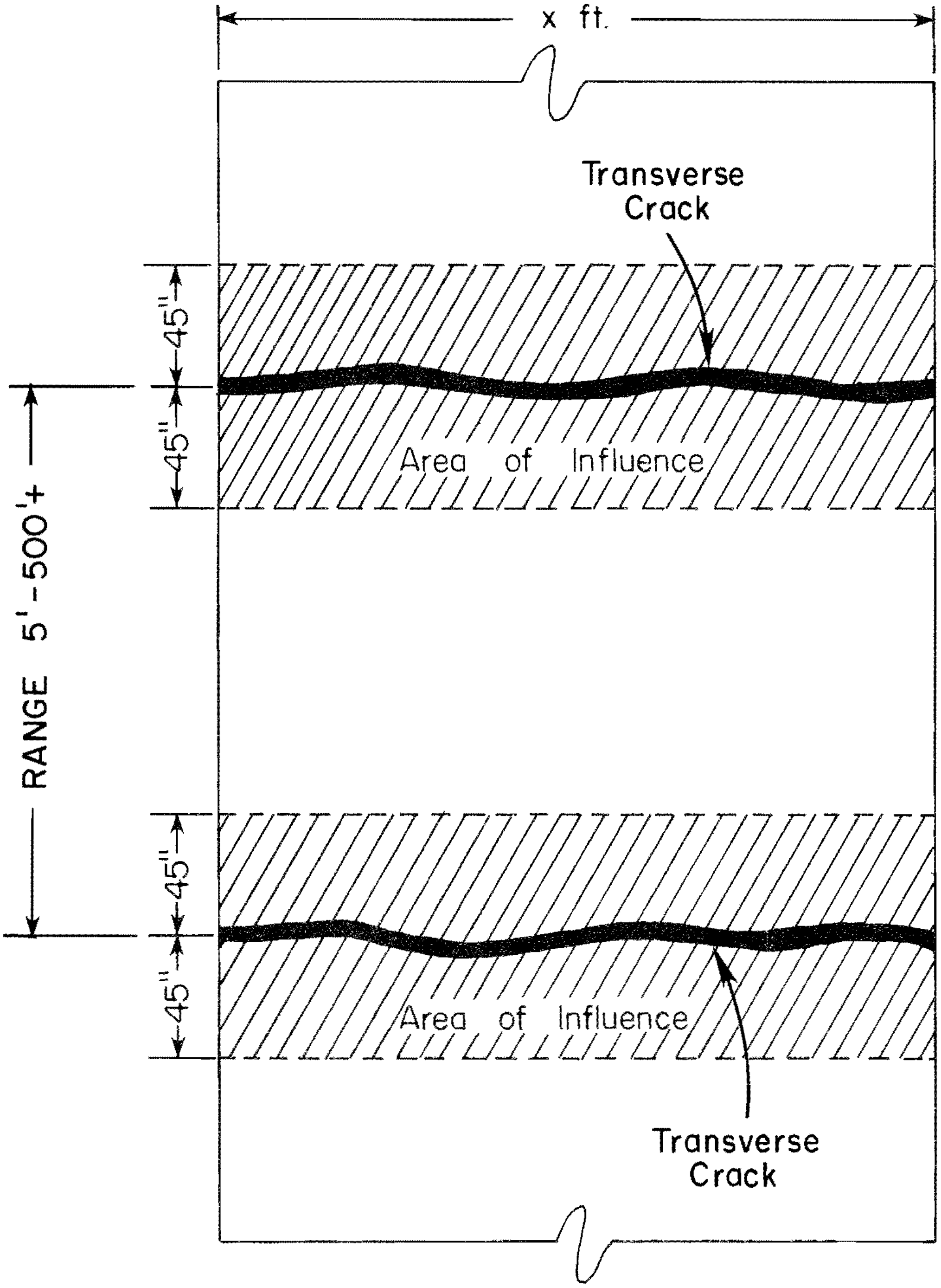

Figure 1. Area of Influence of Transverse Cracks

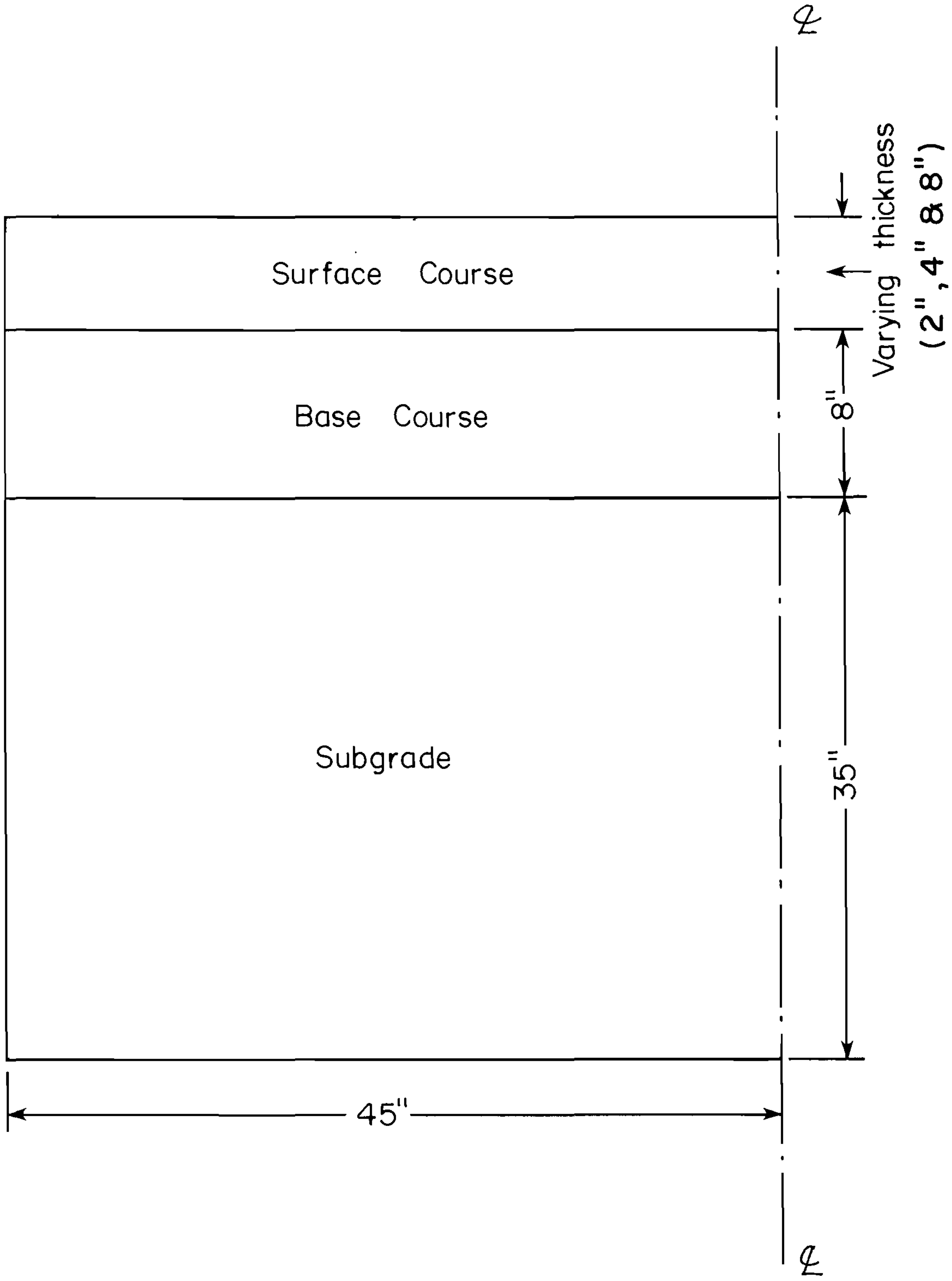

Figure 2. Details of the Pavement Used

TABLE 1. Properties of Pavement Used

	Modulus of Elasticity E (psi)	Poisson's Ratio ν	Density	
			lb/ft.^{3}	lb/in^3
Surface Course	1,000	0.45	146	0.0845
	10,000	0.40	146	0.0845
	100,000	0.30	146	0.0845
Base Course	50,000	0.35	140	0.0810
Subgrade	20,000	0.45	120	0.0694

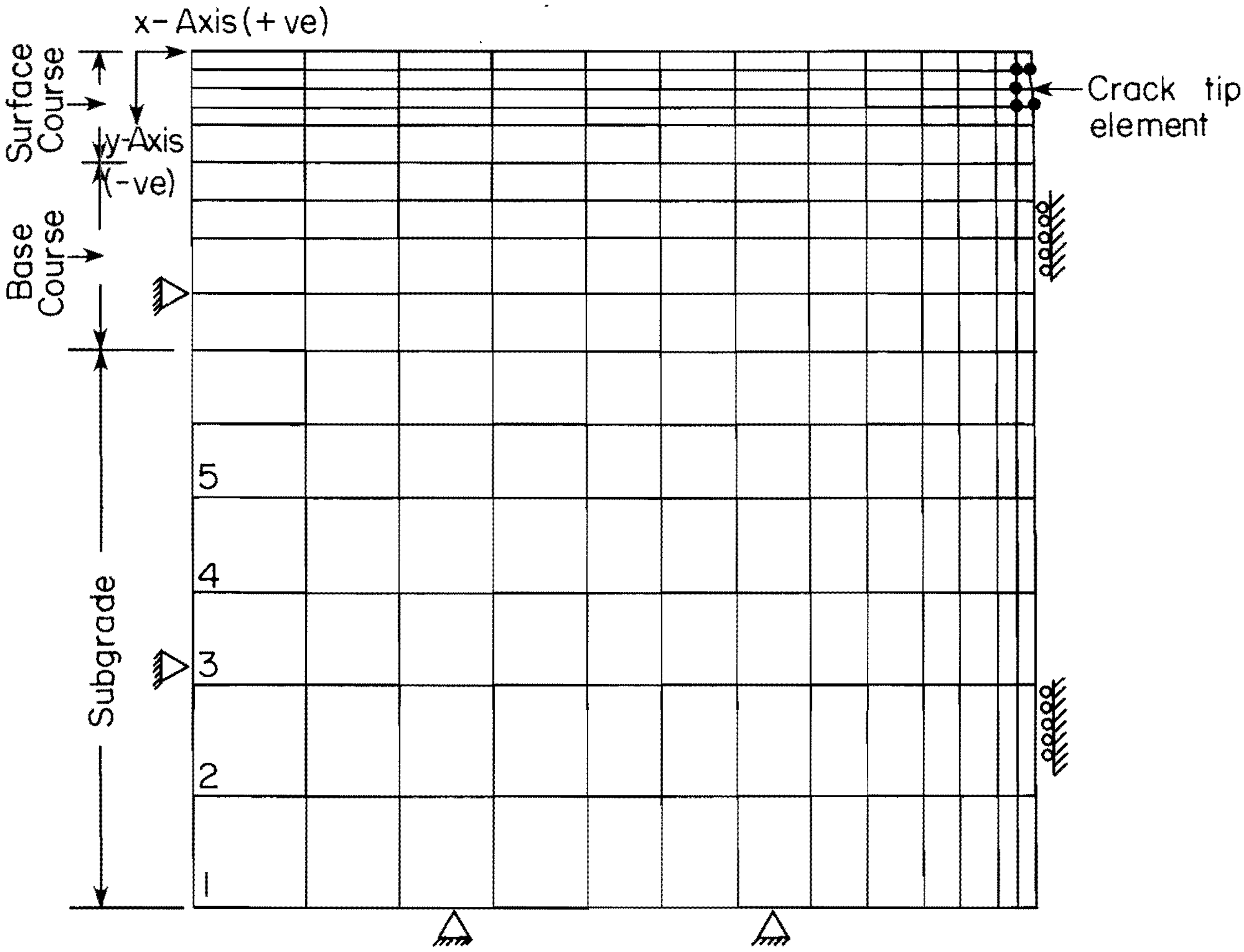

Figure 3. Finite Element Representation of Pavement Structure

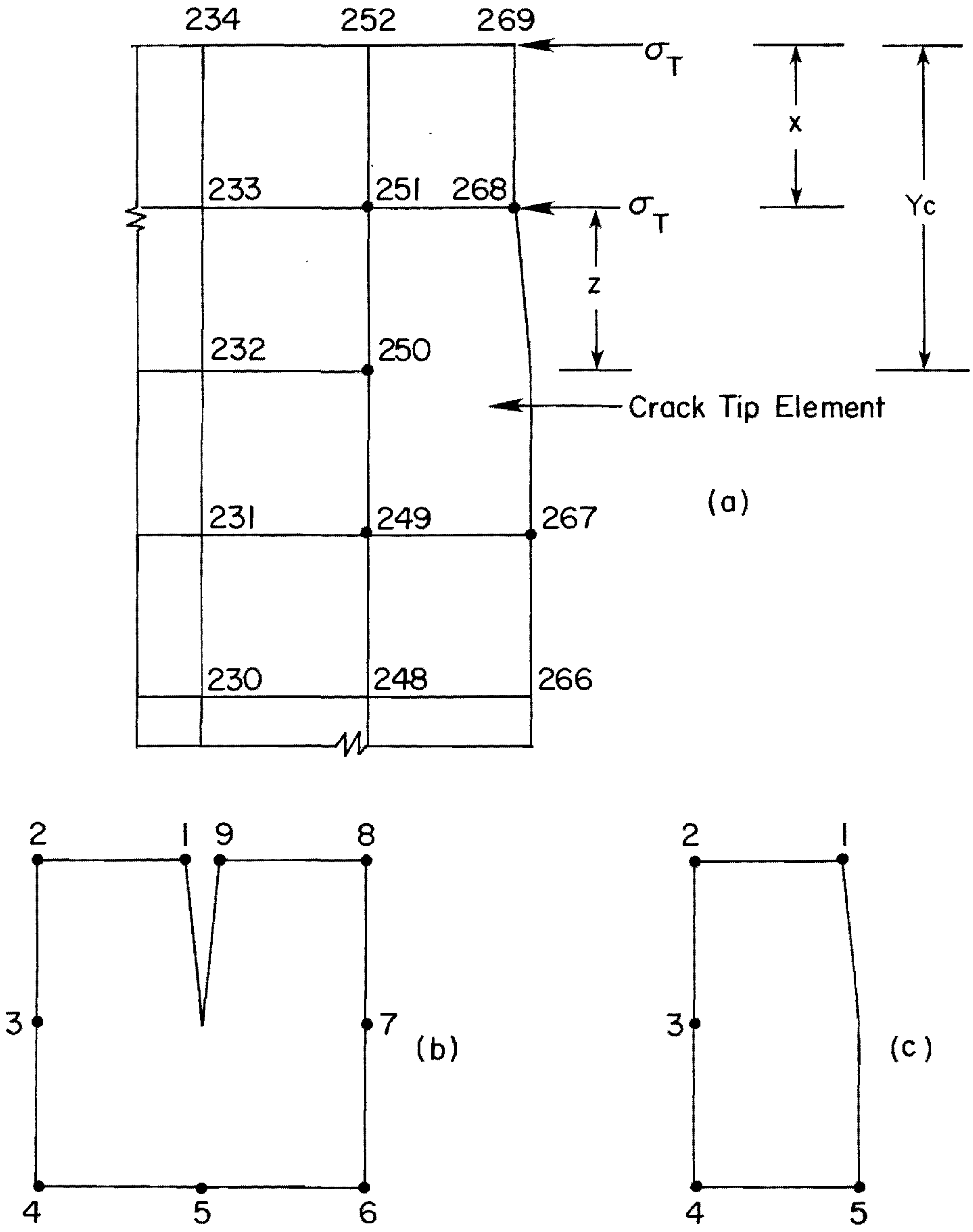

Figure 4. (a) Details of Crack Tip Element, (b) Nine-node Tip Element for Non-Symmetric Case, (c) Five-node Tip Element for Symmetric Case

h = surface coefficient in BTU per square foot per hour, °F,

k = thermal conductivity (the capacity of material for transferring heat) in BTU per square foot per hour, °F per foot,

C = $\left(\frac{0.131}{C}\right)^{\frac{1}{2}}$,

c = diffusivity in square feet per hour, $\frac{K}{SW}$

s = specific heat (amount of heat which must be supplied to a unit mass of material to increase its temperature one degree) in BTU per pound, °F,

w = density in pounds per cubic foot,

S_i = S_1, S_2, or S_3,

S_1 = $6.81768(0.0576t - 0.075xc - 0.288)$, for $t = 2$ to 9 (7:00 a.m. to 2:00 p.m.),

S_2 = $14.7534(0.02057t - 0.075xc - 0.288)$, for $t = 10$ to 14 (3:00 p.m. to 7:00 p.m.),

S_3 = $-6.94274(0.02057t - 0.12xc - 0.288)$, for $t = 15$ to 25 (8:00 p.m. to 6:00 a.m.), and

t = time since the beginning of the current cycle (one cycle = 24 hours) in hours.

The surface coefficient h can be estimated as

$$h = 1.3 + 0.62\ V^{3/4}, \qquad (6)$$

where V = wind velocity in mph.

Figure 5 shows the surface temperature as a function of time without radiation and wind. Solar radiation is the amount of heat from the sun per unit area and time. The average net loss of solar radiation through long wave radiation is about one-third of the total solar radiation. Therefore the average contribution of solar radiation to the effective air temperature can be determined by

$$R = \left(\frac{2}{3}\right) (b) \text{ (solar radiation) } \left(\frac{1}{h}\right) \qquad (7)$$

where b is the surface absorptivity (ability of the surface to absorb heat) from solar radiation. Since solar radiation is usually reported in Langleys per day and one Langley is 3.69 BTU per square foot per day, Equation 7 can be rewritten as

$$R = \left(\frac{2}{3}\right) (b) \left(\frac{3.69L}{24}\right) \frac{1}{h} \qquad (8)$$

where L = solar radiation in Langleys per day.

Figure 6 shows the effect of solar radiation on pavement temperatures.

The maximum or the minimum pavement temperature can be determined using the following equations in conjunction with Equation 7

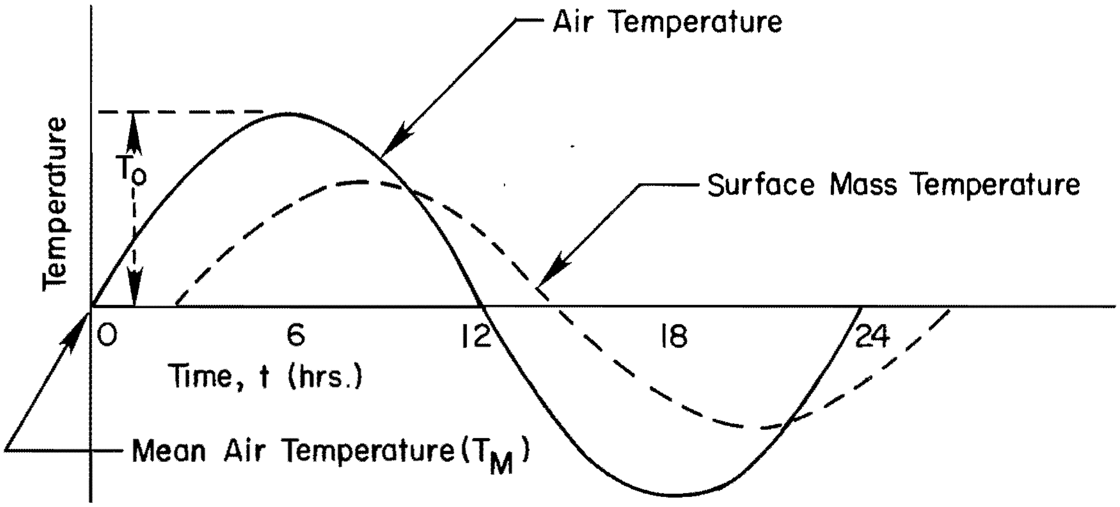

Figure 5. Surface Temperature as a Function of Time Without Radiation and Wind (1)

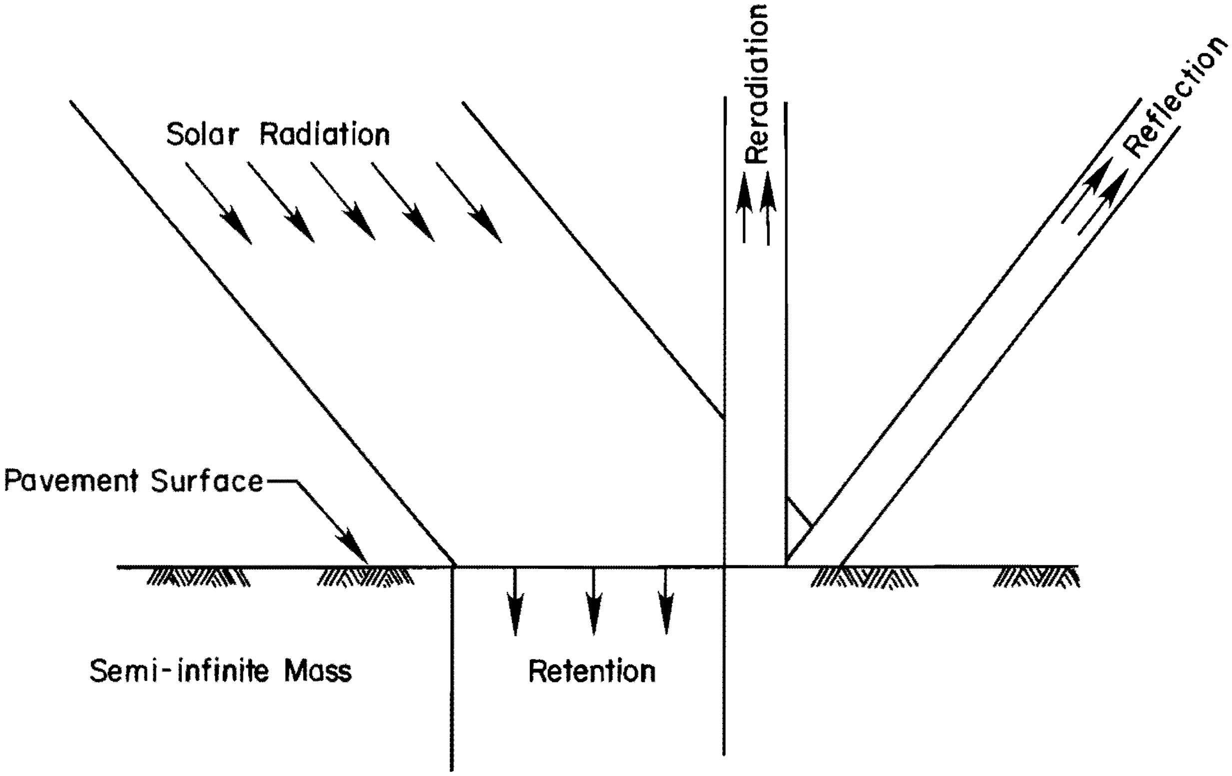

Figure 6. Illustration of the Effect of Solar Radiation on Pavements (1)

$$T_V = 0.5T_R + 3R, \text{ if } \sin (S_i) \geq 0, \tag{9}$$

$$T_M = T_A + R, \quad \text{if } \sin (S_i) \geq 0, \tag{10}$$

$$T_V = 0.5\ T_R, \quad \text{if } \sin (S_i) < 0, \text{ and} \tag{11}$$

$$T_M = T_A + 0.5\ T_R, \text{ if } \sin (S\ ) < 0, \tag{12}$$

where T_R is the daily air temperature range in °F. A comparison between air temperature and effective air temperature is shown in Figure 7.

Sample calculations for determining the change in pavement temperature, ΔT, and thermal tensile stress, are given in Appendix A; the results are summarized in Tables A1 through A4. The stress intensity factors were determined for six crack depths in each of three surface thicknesses (2 inches, 4 inches, and 8 inches), for two different moduli of elasticity (10,000 and 100,000 psi), and for three different temperature ranges, ΔT, (50°F, 100°F, and 150° F). The computed values of stress intensity factors, $\overline{K}_1$ are corrected using a correction factor (9),

$$C_K = (\frac{8}{\pi})^{\frac{1}{2}}\ \sigma_T\ (Z)^{\frac{1}{2}} \tag{13}$$

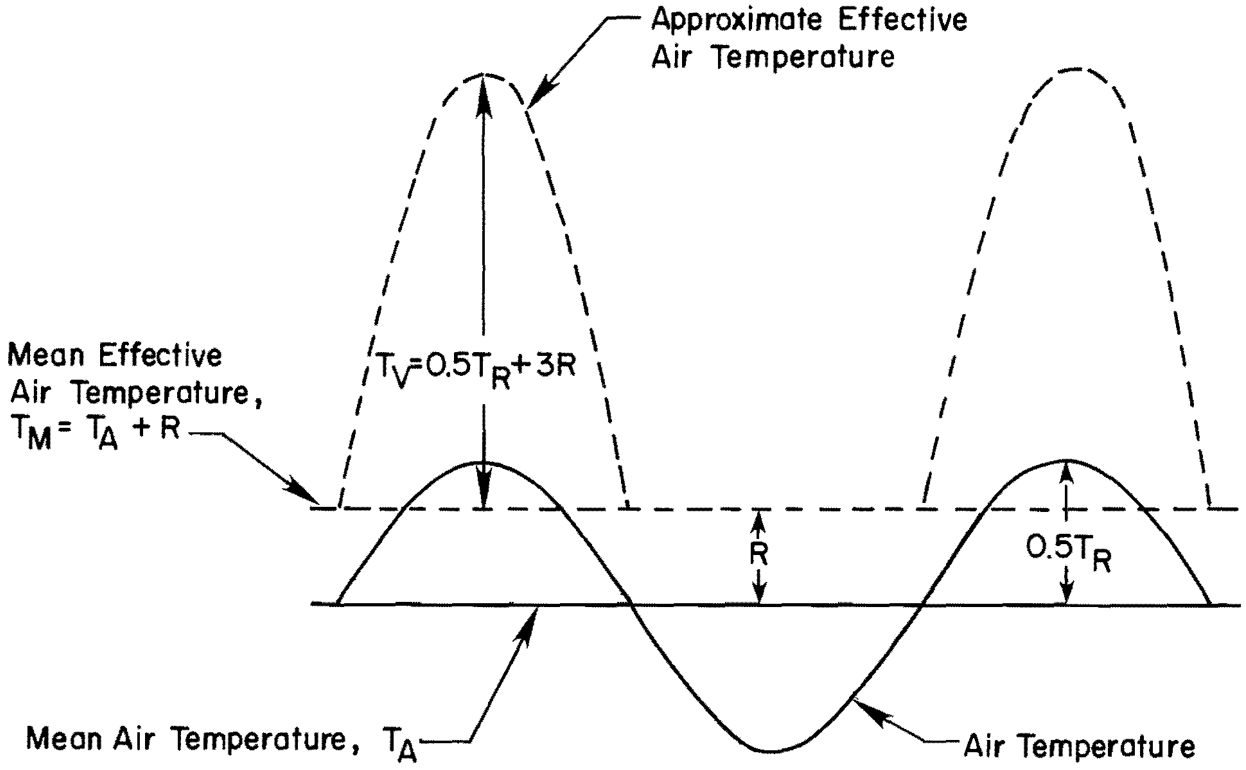

Figure 7. A Comparison Between Air Temperature and Effective Air Temperature

For the definition of Z, see Figure 4a. In this investigation, the value of Z was taken to be 0.25 inches. The corrected stress intensity factor, K_1, is equal to the sum of the computed value of stress intensity factor, $\overline{K}_1$, and the correction factor, C_k,

$$K_1 = \overline{K}_1 + C_K \tag{14}$$

The computed stress intensity factors, correction factors, and the corrected stress intensity factors are given in Tables A5 through A13.

For particular values of the modulus of elasticity, E, daily air temperature range below stress-free temperature, T_R, and depth, d, values of the stress intensity factor, K_1, were plotted against crack length, Y_C, on a full logarithmic graph paper (Figures A1 through A6). From these plots, values of a and b are obtained by linear regression analysis and are summarized in Table A14. If all values of a and b were the same, a general equation for the stress intensity factor, K_1, would result.

Given a value of E, a and b varies with daily air temperature range below the stress-free temperature, T_R. Therefore, a and b are plotted against daily air temperature range below stress-free temperature, T_R (Figures A7 through A14). The resulting linear relationship between a and T_R, and between b and T_R are written as

$$a = (T_R - m_1) m_2 \quad \text{and} \tag{15}$$

$$b = m_3 + m_4 \; T_R \tag{16}$$

The values of m_1, m_2, m_3, and m_4 are given in Table A15.

The values of m_1, m_2, m_3, and m_4 change with a change in the modulus of elasticity, E, or in the depth, d. The relationships of m_1, m_2, m_3, and m_4 with the modulus of elasticity, E, and depth, d, are generated as described below.

The value of m_1 is plotted against d for values of E=100,000, and 10,000 psi. In Figure A15, it can be seen that a linear relation holds between m_1 and d whenever E is in the range 100,000 to 10,000 psi, provided that d is between 0.0 and 29.1063 inches. Thus for 10,000 $\leq$ E $\leq$ 100,000 psi,

$$m_1 = 8.8988 + (29.1063-d)(1.3573-0.01357(\frac{E}{1000})) \tag{17}$$

In Figure A15, it can be seen that a linear relation holds between m_2 and d whenever E is in the range 100,000 to 10,000 psi, with d between 0.0 and 129.3215 inches. Thus for 10,000 $\leq$ E $\leq$ 100,000 psi,

$$m_2 = 2.0599 - (129.3215-d)(0.01687-0.000169(\frac{E}{1000})) \tag{18}$$

In Figure A17, it is seen that, when $d \leq 4$ and $10,000 \leq E \leq 100,000$ psi, then

$$m_3 = 0.8481 + (2.7811-d)(0.002738(\frac{E}{1000})) \tag{19}$$

and when $d \geq 4$ inches and $10,000 \leq E \leq 100,000$ psi, then

$$m_3 = 0.8481 - (6.5835-4)(0.12919-0.0012919(\frac{E}{1000})) \tag{20}$$

The plot of m_4 versus d is shown in Figure A18. As in the case of m_1 and m_2, a linear relation holds between m_4 and d for E in the range of 100,000 to 10,000 psi. Thus for $10,000 \leq E \leq 100,000$ psi,

$$m_4 = -0.00157 + (5.0472-d)(0.001129-0.00001129(\frac{E}{1000})) \tag{21}$$

In summary, the equation for the thermal stress intensity factor is

$$K_1 = a\ (Y_c)^b \tag{22}$$

where $a = (T_R - m_1)m_2$ and (23)

$b = m_3 + m_4\ T_R.$ (24)

which results in the final form given in Equation 25.

$$K_1 = (T_R-m_1)m_2\ (Y_c)^{(m_3+m_4\ T_R)} \tag{25}$$

EQUATIONS USED IN THE MECHANISTIC THERMAL CRACKING MODEL

The equation for the number of thermal cycles to reach failure is

$$N_f = 1 + \int_{c_o}^{d} \frac{dc}{A(\Delta K)^n} \tag{2}$$

The previous section of this chapter showed how the change of stress intensity factor, ΔK, may be calculated as a function of temperature, modulus, and pavement depth. This section will show how the fracture properties A and n may be calculated.

Although these two fatigue parameters can be measured in the laboratory, it is a very time consuming process. Their values are not likely to be available to designers during the preparation of mixes for asphalt concrete pavements and, therefore, not likely to be available for direct use in our model.

The values of the two fatigue parameters, A and n, are found in the model as follows.

(1) The asphalt stiffness is calculated using Van der Poel's nomograph (10) as computerized by de Bats (11).

(2) Given the stiffness of the asphalt cement, the stiffness of the asphalt mix is calculated for various loading times, producing a relaxation modulus curve.

(3) Schapery (12) has shown that the slope, m, for a relaxation modulus curve, at a master temperature of 77°F, of the $\log_{10}$ of the loading time is related to n as follows:

$$n = 2(1 + \frac{1}{m}) \qquad (26)$$

(4) Germann and Lytton (13) attempted to verify Schapery's relation in the laboratory, and found that the values of n from Equation (26) must be divided by 2.5 in order that the calculated values will agree with laboratory observations.

(5) The value of A is found by substitution into

$$n = -0.69 - 0.511 \log_{10}A \qquad (27)$$

which is a relationship found through crack propagation testing of asphalt concrete at the Texas Transportation Institute (14).

The de Bats program has been modified to compute the viscoelastic properties of the asphalt concrete; inputs are the aggregate volume concentration along with sufficient parameters to identify the temperature susceptibility of the bitumen. The model allows several choices of parameters to describe temperature susceptibility. The stiffness of the asphalt cement is used to calculate the stiffness of the mix given various loading times (15):

$$S_{mix} = S_{bit}[1+\frac{2.5}{S_N}\ (\frac{C_V}{1-C_V})]^{S_N} \times 0.000145 \qquad (28)$$

where S_{mix} = stiffness modulus of the asphalt concrete mix in lb/in^2,

S_{bit} = stiffness modulus of bitumen from Van der Poel's nomograph in N/m^2,

C_V = $\frac{\text{volume of aggregate}}{\text{volume of aggregate + volume of bitumen}}$,

S_N = $0.83\ \log_{10}\ [\frac{(4 \times 10^5)}{S_B}]$, and

S_B = stiffness modulus of bitumen from Van der Poel's nomograph in kg/cm^2.

A relaxation modulus curve can be drawn as the log of stiffness modulus of asphalt concrete mix versus the log of loading time as shown in Figure 8. The slope of this curve is designated as m and the intercept of this curve is designated as E_1 at a master temperature, T_M, of 25°C (77° F). From the relaxation curve, a relation between S_{mix}, E_1, m, and t (loading time) is obtained:

$$S_{mix} = E_1\ t^{-m} \qquad (29)$$

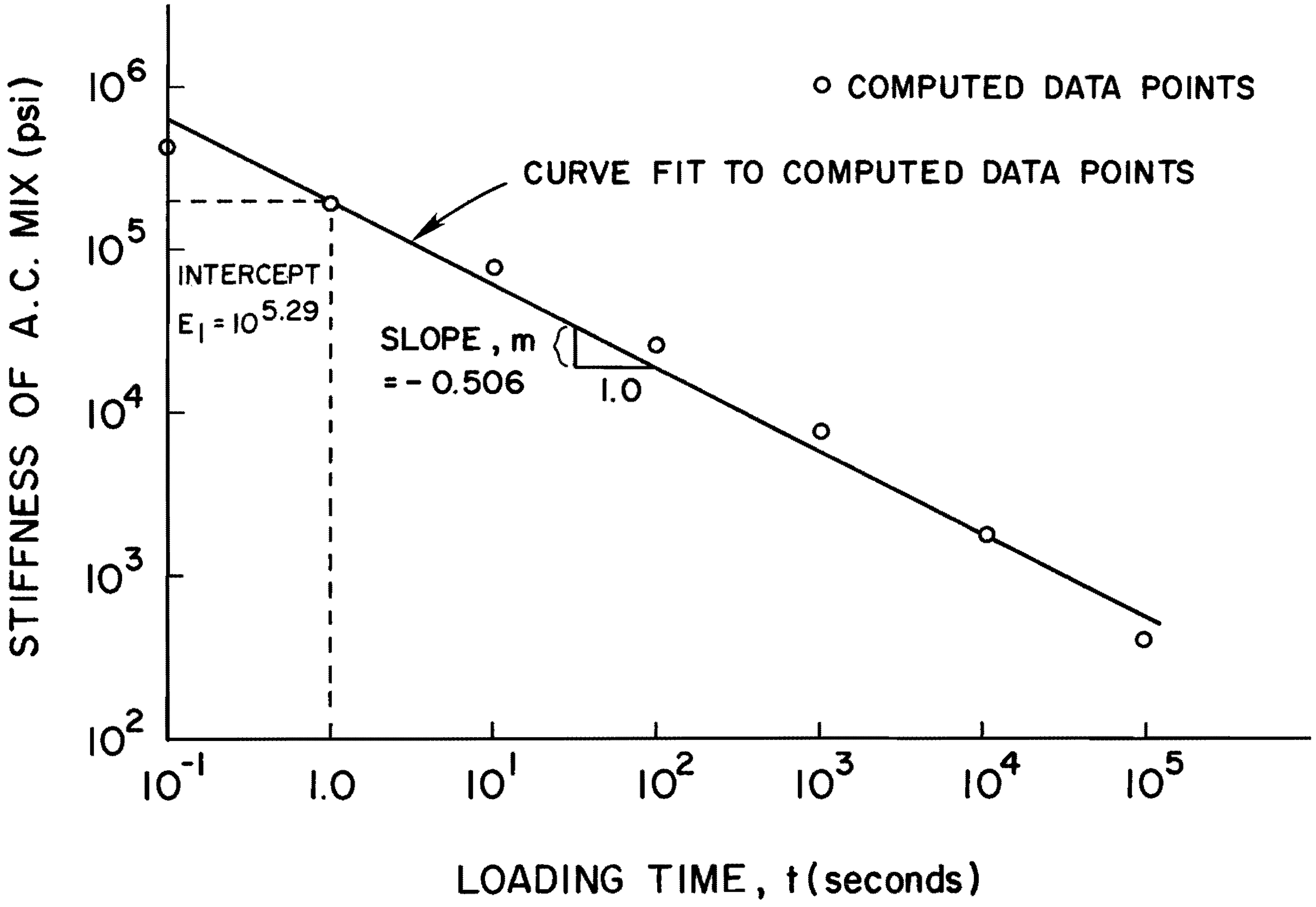

Figure 8. A Typical Relaxation Modulus Curve at Master Temperature of 25°C; Stiffness of A.C. Mix Versus Loading Time.

The above relation is obtained for three temperatures, 0° C, 25°C (master temperature), and 60°C. From Equation 29, the loading times, t, for the three temperatures can be written as follows:

$$t(\text{at } 0°C) = \left(\frac{S_{mix}}{E_1(\text{at } 0°C)}\right)^{-\frac{1}{m}} \quad (\text{at } 0°C),$$

$$t(\text{at } 25°C) = \left(\frac{S_{mix}}{E_1(\text{at } 25°C)}\right)^{-\frac{1}{m}} \quad (\text{at } 25°C) \qquad (30)$$

$$t(\text{at } 60°C) = \left(\frac{S_{mix}}{E_1(\text{at } 60°C)}\right)^{-\frac{1}{m}} \quad (\text{at } 60°C)$$

where S_{mix} is assumed to be constant and its value is calculated by taking 1/2 of the mix stiffness corresponding to a loading time of one second on the log S_{mix} versus log t (Figure 8) curve at the master temperature. Then the time-temperature shift factor, a_T, is defined as the loading time at temperature T divided by loading time at the master temperature, T_M. For the three different temperatures, a_T can be written as follows:

$$a_T \ (\text{at } 0°C) = \frac{t(\text{at } 0°C)}{t(\text{at } 25°C)}$$

$$a_T \ (\text{at } 25°C) = \frac{t(\text{at } 25°C)}{t(\text{at } 25°C)} \quad \text{and} \qquad (31)$$

$$a_T \ (\text{at } 60°C) = \frac{t(\text{at } 60°C)}{t(\text{at } 25°C)}$$

A graph is drawn relating log a_T and log $(T - T_A)$. The value of T_A is chosen by trial and error so that the graph is as close as possible to a straight line. The temperature of the mix, T, and the temperature constant, T_A, are expressed in °C. A typical straight line fit is shown in Figure 9. The slope of the straight line is designated as BETA. The variables Log_{10} E_1, m, T_A, and BETA are viscoelastic properties of the asphalt concrete mix. These viscoelastic properties are used as inputs to the thermal cracking program, THERM.

Some empirical equations were developed by regression analysis of a data set published by Shahin and McCullough (2), which includes observations from four areas of the United States, to predict aging of the asphalt. Those equations are

$$P(t) = 0.4 + 0.716P_o - (0.193P_o - 9.1) \log t, \tag{32}$$

$$T_{RB}(t) = -30.6 + 1.230T_{RB} + 10.5 \log_e t, \tag{33}$$

where

t is the time in months that the asphalt has been in place in the pavement,

P_o and P(t) are respectively, the penetration at 77 ° F of the original and aged asphalt in standard units of 0.1 millimeters penetration, and

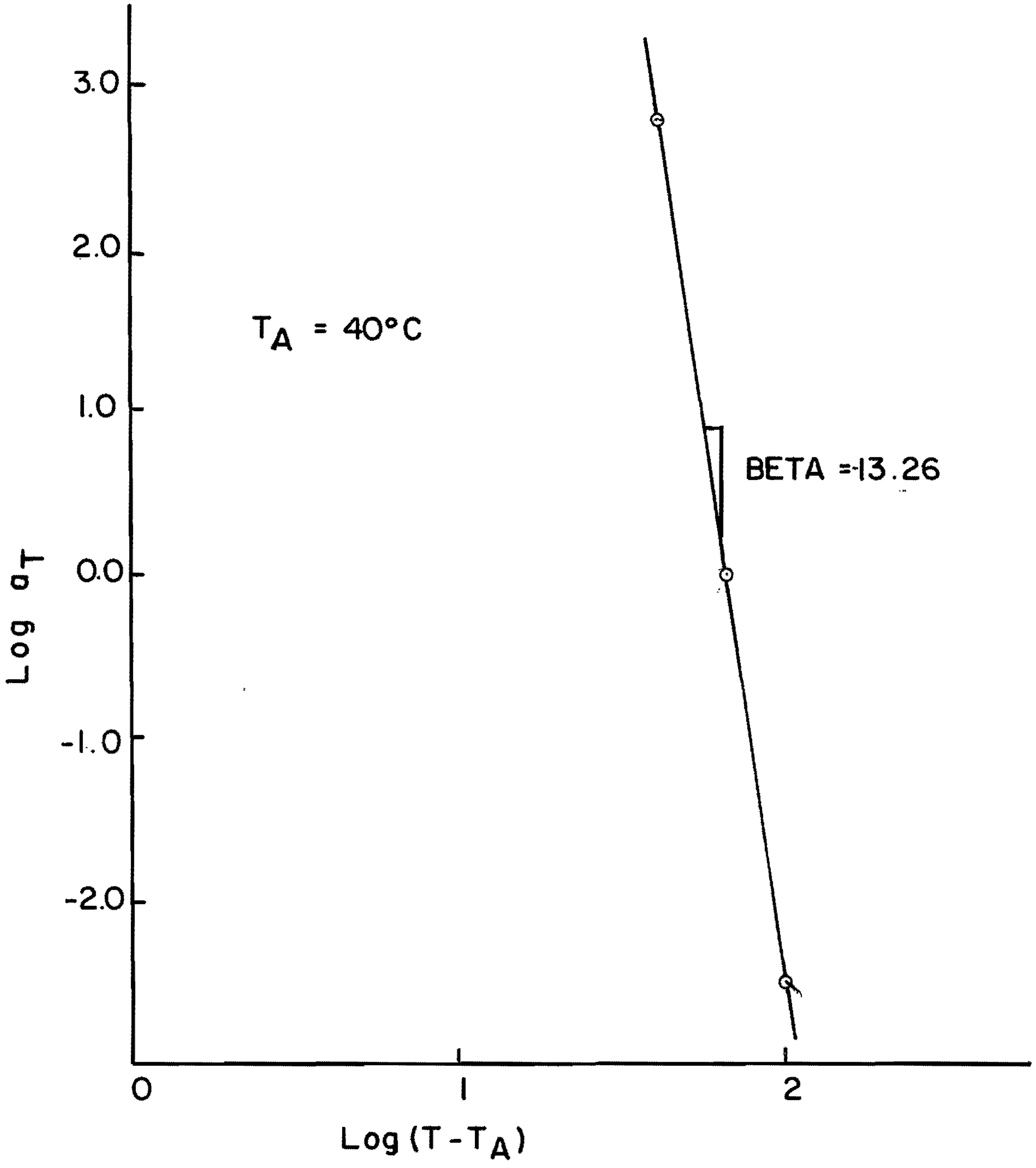

Figure 9. A typical Log a_T versus Log (T - T_A) curve.

T_{RB} and $T_{RB}(t)$, respectively, for original and aged asphalt, are the softening point ring and ball temperatures in °F.

Equations 32 and 33, which predict the aging of the asphalt, are incorporated in the modified de Bats' program. The range of variables on which these equations are based is given in Table 2. Both equations were developed assuming an initial change in properties during mixing and construction placement followed by time dependent changes as described by Benson (16). There is an anomaly in the relation of penetration with time since the long-term penetration is inversely proportioned to the original penetration. Tables 3 and 4 exhibit this peculiarity with two examples of aged asphalt properties, including the fracture properties, A and n. The calculations of viscoelastic properties are repeated for each year of the analysis in order to allow for aging of the bitumen.

Program THERM, which makes up the main part of the thermal cracking model, uses the viscoelastic properties of the asphalt concrete obtained from the modified de Bats' program. The inputs to THERM, apart from viscoelastic properties, are the thickness and other properties of the asphalt layer, daily temperatures, initial crack length, volumetric concentration of aggregate, and others.

The fracture parameter, n, is estimated using Schapery's formula (12), as modified by laboratory

TABLE 2. Range of Variables Used to Develop Aging Equations

	High	Low
Original Penetration	239	61
Softening Point Ring and Ball Temperature, °F	125	100
Time to Age, Months	118	5

TABLE 3. Predicted Aging of a Low Penetration Asphalt

Original Penetration at 77°F: 58
Original Softening Point: 124°F

Age of Pavement Months	Penetration 77°F	Softening Point °F	Fracture Parameters	
			A	n
6	37	140	$2.6x10^{-6}$	2.16
18	35	152	$1.1x10^{-6}$	2.36
30	34	157	$7.1x10^{-7}$	2.45
42	33	161	$2.6x10^{-7}$	2.67
54	33	164	$2.0x10^{-7}$	2.73
66	32	166	$3.4x10^{-7}$	2.62
78	32	167	$2.8x10^{-7}$	2.66
90	32	169	$2.4x10^{-7}$	2.69
102	31	170	$2.1x10^{-7}$	2.72

TABLE 4. Predicted Aging of a High Penetration Asphalt

Original Penetration at 77°F: 172
Original Softening Point: 106°F

Age of Pavement Months	Penetration 77°F	Softening Point °F	Fracture Parameters	
			A	n
6	80	118	6.2×10^{-6}	1.97
18	53	130	4.3×10^{-6}	2.05
30	41	135	3.6×10^{-6}	2.09
42	33	139	3.2×10^{-6}	2.12
54	27	141	3.0×10^{-6}	2.14
66	22	144	2.8×10^{-6}	2.15
78	20	145	2.6×10^{-6}	2.17
90	20	147	2.3×10^{-6}	2.19
102	20	148	2.1×10^{-6}	2.21

observations by Germann and Lytton (13):

$$n = \frac{2}{b}\left(1 + \frac{1}{m}\right) \tag{34}$$

The value of b used in Equation 34 is 2.5 so that calculated values of n match laboratory observations of these values (13, 14).

The parameter A in equation (1) is calculated directly from

$$n = -0.69 - 0.511 \log A \tag{35}$$

Equation 35 was developed from crack propagation testing of asphalt concrete at the Texas Transportation Institute (14). Calculations of fracture parameters are repeated each year to allow aging of the bitumen.

For each day, the maximum and the minimum temperatures of the asphalt concrete layer of the pavement, the change in stress intensity factor, the number of cycles required to extend a crack through the asphalt concrete layer, and the two cumulative damage functions described below are computed in the THERM program. The maximum and the minimum temperatures of the asphalt concrete layer corresponding to the maximum and minimum temperatures of the air are determined using Barber's equations modified by Shahin and McCullough (2), given as the Equations 5 through 11.

The stress intensity factor is calculated using the

Equations 4 and 14 through 20. These equations hold for moduli of elasticity in the range of 10,000 to 100,000 psi. The asphalt concrete is assumed to approach a glassy state whenever the modulus of elasticity is above 100,000 psi; so that the modulus no longer varies with temperature and the calculations for m_1 through m_4 are made using an E value of 100,000 psi. The modulus used in this program is an effective modulus computed from the viscoelastic properties of the mix according to the power law theory developed by Schapery (12) and assuming that the temperature decreases linearly from the maximum to the minimum temperature each day.

In the method developed herein to predict crack frequency, two cumulative damage functions CMDG and CMDG1 are computed:

$$\text{CMDG} = \sum_{j=1} \frac{1}{N_{foj}} \tag{36}$$

$$\text{CMDG1} = \sum_{j=1} N_{fij} \tag{37}$$

where N_{fo} and N_{fi} represent the number of cycles to failure determined each day, j, by different methods.

The first of these, N_{foj}, is calculated as the number of thermal stress cycles such as experienced on day, j, which will cause a crack to propagate from the current crack depth all the way through the rest of the depth of the asphalt concrete. The second of these, N_{fij}, is calculated as the number of thermal stress cycles such as experienced on day, j, which will cause a crack to propagate from its initial crack length through the entire depth of the asphalt surface layer.

This is explained in more detail as follows. The number of cycles to failure is given by Equation 2, for which ways are now developed of determining all of the needed elements:

$$N_f = 1 + \int_{C_o}^{d} \frac{dc}{A(\Delta K)^n} \tag{2}$$

where C_o = the initial crack depth,

d = the thickness of the asphalt concrete surface,

ΔK = the change in the stress intensity factor at the crack tip from the time of maximum temperature to the time of minimum temperature, and

A and n are fracture properties of the asphalt mix.

If, rather than using the initial crack depth, C_o, the current crack depth, C_c, is used then Equation 38 is found:

$$N_f = \int_{C_c}^{d} \frac{dc}{A(\Delta K)} \tag{38}$$

From Equations 2 and 38, N_{fo} and N_{fi} are found and used to calculate CMDG and CMDG1 respectively.

The number of temperature cycles to failure, as N_{fo}, is computed as follows:

(1) For the first day of thermal fatigue cracking, Equation 2 is used so that

$$N_{fo} = 1 + \int_{C_o}^{d} \frac{dc}{A(\Delta K)^n}$$

(2) After the first day of thermal fatigue cracking, Equation 38 is used and

$$N_{fo} = \int_{C_c}^{d} \frac{dc}{A(\Delta K)^n}$$

(3) When the current crack length, C_c, exceeds d, the depth of the pavement, N_{fo} is zero.

With the initial crack length specified, the current crack length, C_c, is determined by adding the change in the crack length to the crack length of the previous day, C_p; thus we have

$$\Delta C = A(\Delta K)^n(\Delta N) \qquad (3)$$

where ΔC is the increase in the crack length and

ΔN is the number of temperature cycles per day (assumed here to be 1.0 per day).

Now C_c can be found with

$$C_c = C_p + \Delta C \tag{39}$$

where C_p is the crack length of the previous day. Obviously, on the first day, $C_p = C_o$.

The number of temperature cycles to failure, N_{fi}, is computed only with the use of Equation 2, i.e.

$$N_{fi} = \int_{C_o}^{d} \frac{dc}{A(\Delta K)^n}$$

which is calculated each day during the period of the analysis.

The calculation of CMDG, which uses N_{foj}, is terminated when the crack breaks through the entire depth of the asphalt surface layer whereas CMDG1, which uses N_{fij}, is computed again each day during the entire period of analysis. A third cumulative damage index, CMDG2, is computed from CMDG1 using its value on the day when the crack length, computed by Equation 39, penetrates through the entire depth of the asphalt surface layer. The equation for CMDG2 is as follows:

$$\text{CMDG2} = \frac{\text{CMDG1}}{[\text{CMDG1}]_{C_c=d}}$$

These three cumulative damage indices are used in verifying the mechanistic thermal cracking model in the next chapter.

CHAPTER III

EMPIRICAL VERIFICATION OF THE MECHANISTIC THERMAL CRACKING MODEL

The mechanistic thermal cracking model that has been described in the previous chapter was run for thirty-two Michigan pavements starting with the year of construction and ending with the year cracking observations were recorded. The data were collected and recorded by Novak (17). The Michigan data were gathered from thirty-two highway segments ranging from 3.0 to 14.8 miles in length. A mean cracking index I, the sum of the number of complete transverse cracks and one-half the number of half transverse cracks per 500 ft. of roadway, was reported for each section. Novak's report included the original asphalt properties, the pavement surface thickness, bitumen stiffness, and the age of the pavement at the time of observations. The stiffness was reported for a loading time of 20,000 seconds at the winter design temperature as defined by Haas (6). The cracking which was reported was observed during the late summer and fall of 1973. Table 5 presents the range of key variables reported by Novak. The asphalt properties were obtained from construction records; however, test results did not indicate locations within each pavement where each particular asphalt was used and equivalent data were not available for all projects. Novak divided the state of Michigan into four environmental areas.

TABLE 5. Range of Important Variables Reported Relating to Transverse Cracks in Michigan (5).

Variable	High	Low
Observed Cracking Index, I	21.20	0.00
Standard Deviation of Observed I at each site	6.70	0.00
Original Penetration at 77°F	243.00	60.00
Penetration Index	+0.09	-0.84
Softening Point Ring and Ball Temperature °C	51.00	37.00
Thickness of Pavement, Inches	4.5	2.1
Age of Pavement, Years	12.00	1.00
Stiffness of Asphalt Concrete at Winter design Temperature and 20,000 seconds loading time (KG/cm^2)	300.00	13.00

The data collected for the Michigan Areas 1, 2, 3, and 4 are shown in the Table 6 and were used to run the model. The ring and ball temperature, penetration index, and pavement thickness were entered into the model for each of the thirty-two Michigan pavements shown in Table 6, while typical asphalt mix heat transfer characteristics, as reported by Shahin (2), and an aggregate volume concentration, C_v, of 0.88, determined to be typical in Michigan (17) were held constant. Table 7 presents the asphalt concrete mix properties used to run this model for analyzing the Michigan pavements. An initial crack length of 0.2 inches is assumed for all of the Michigan cases. The initial crack break-through predicted by the model is very sensitive to the initial crack length selected. It is possible that this initial crack length is related to the size of the larger aggregates in the mix or surface macrotexture.

Representative daily maximum and minimum temperatures for each area were obtained on computer readable magnetic tapes from the National Climatic Center in Asheville, North Carolina. The tapes contained data for approximately fourteen years prior to 1973. Such tapes are readily available for locations throughout the United States; with them, actual air temperatures closely approximating those to which the pavements were subjected during their life could be entered into the thermal cracking model.

TABLE 6. The Data Used to Run the Model for Analyzing the Michigan Pavements

Serial No.	Station I.D.	Area I.D.	Starting Date	* No. of Years to run	Ring and Ball Temperature (°C)	Penetration Index	Pavement Thickness (in.)	Wind Velocity (mph)	Average Solar Radiation for July (Langleys /day)	Yearly Average Solar Radiation (Langleys /day)
1	1	4	680630	5	46	-0.64	2.1	10.3	519	308
2	2	4	670630	6	45	-0.39	2.5	10.3	519	308
3	3	4	690630	4	43	-0.38	2.5	10.3	519	308
4	4	4	690630	4	46	-0.44	2.5	10.3	519	308
5	7	3	700630	3	38	-0.36	3.3	9.0	518	272
6	8	2	670630	6	44	-0.26	2.5	9.6	498	283
7	9	2	690630	4	38	-0.25	2.5	9.6	498	283
8	10	2	670630	6	38	+0.09	2.5	9.6	498	283
9	11	1	710630	2	38	-0.40	2.5	8.3	498	333
10	12	2	720630	1	42	-0.25	2.5	9.6	498	283
11	13	1	670630	6	38	-0.02	2.5	8.3	498	333
12	14	2	690630	4	41	-0.56	2.8	9.6	498	283
13	15	2	640630	9	48	+0.07	3.3	9.6	498	283
14	16	3	680630	5	37	-1.18	2.5	9.0	518	272
15	17	3	650630	8	47	-0.45	2.5	9.0	518	272
16	18	3	680630	5	37	-0.18	2.5	9.0	518	272

* 680630 means June 30, 1968

TABLE 6. The Data Used to Run the Model for Analyzing the Michigan Pavements (Cont'd)

Serial No.	Station I.D.	Area I.D.	Starting Date	No. of Years to run	Ring and Ball Temperature (°C)	Penetration Index	Pavement Thickness (in.)	Wind Velocity (mph)	Average Solar Radiation for July (Langleys /day)	Yearly Average Solar Radiation (Langleys /day)
17	19	3	710630	2	43	-0.09	2.5	9.0	518	272
18	20	3	650630	8	46	-0.40	2.5	9.0	518	272
19	21	3	640630	9	42	-0.32	2.5	9.0	518	272
20	22	3	640630	9	41	-0.27	2.5	9.0	518	272
21	23	3	640630	11	51	-0.59	4.5	9.0	518	272
22	24	3	640630	12	51	-0.73	4.5	9.0	518	272
23	25	4	620630	11	49	-0.84	4.5	10.3	519	308
24	26	4	620630	11	50	-0.60	4.5	10.3	519	308
25	27	4	610630	12	50	-0.61	4.5	10.4	519	308
26	28	4	610630	12	50	-0.60	4.5	10.4	519	308
27	29	4	640630	9	50	-0.53	4.5	10.4	519	308
28	30	3	640630	12	50	-0.61	4.5	9.0	518	272
29	31	3	640630	12	50	-0.56	4.5	9.0	518	272
30	32	3	640630	12	50	-0.56	4.5	9.0	518	272
31	33	3	640630	12	50	-0.56	4.5	9.0	518	272
32	34	3	640630	11	50	-0.53	4.5	9.0	518	272

Table 7. Asphalt Concrete Mix Properties Used to Run the Model for Analyzing Michigan Pavements.

Volumetric Concentration of the Aggregate, cv	0.88
Unit Weight of the Pavement, w, (lbs/cft)	140
Specific Heat, s, (BTU/lb, °F)	0.22
Thermal Conductivity, k, (BTU/ft^2/hr, °F)	0.70
Surface Absorptivity to the Solar Radiation, b	0.95

The model was run for three cases for thirty-two Michigan pavements starting with the year of construction and ending with the year cracking observations were recorded. Temperatures used by the model for each of the pavements were recorded during the actual life of the [illegible] computations of the CMDG2 using the results from the model with aging (Case: 1), the model without aging (Case: 2), and the model with no aging when $Y_c > 1.0$ (Case: 3).

The calculated value of CMDG2 was related to observed cracking through the application of regression analysis. Both linear and log forms were investigated with the best relationship including aging being

$$I = -2.18 + 2.14(\text{CMDG2}), \text{ with } R^2 = 0.17. \tag{40}$$

The standard error in observed cracking index through application of the thermal cracking model and the above equation was 5.2. Analysis on the Michigan data was repeated without using the asphalt aging process in the thermal cracking model; that is, with the initial asphalt properties maintained throughout the analysis period. The resulting relationship without aging considered is

$$I = -2.91 + 2.65(\text{CMDG2}), \text{ with } R^2 = 0.40. \tag{41}$$

TABLE 8. Computation of CMDG2 for Michigan Pavements Using the Results from the Model (Case: 1, with Aging)

(1) Serial No.	(2) Station I.D.	(3) Area I.D.	(4) No. of Years	(5) Observed Cracking Index, I	(6) Time to First Crack Break Through (months)	(7) CDMG at First Crack Break Through	(8) CDMG1 at First Crack Break Through	(9) Ending CDMG1	(10) CDMG2 (9)/(8)
1	1	4	5	0.7	46	7.4	0.890	1.049	1.18
2	2	4	6	3.3	53	7.5	0.879	1.183	1.35
3	3	4	4	0.0	-	-	-	0.829	1.00
4	4	4	4	0.1	-	-	-	0.778	1.00
5	7	3	3	0.0	20	6.9	0.896	1.242	1.39
6	8	2	6	0.1	31	19.6	0.894	2.328	2.60
7	9	2	4	1.0	20	8.5	0.962	1.960	2.04
8	10	2	6	0.3	31	6.3	0.926	2.552	2.76
9	11	1	2	0.0	-	-	-	0.374	1.00
10	12	2	1	0.0	-	-	-	0.329	1.00
11	13	1	6	0.4	55	15.4	0.900	1.167	1.30
12	14	2	4	3.4	20	15.2	0.915	1.784	1.95
13	15	2	9	1.0	31	7.5	0.822	2.736	3.33
14	16	3	5	0.0	30	6.1	0.922	2.182	2.37
15	17	3	8	0.0	31	7.2	0.908	3.212	3.54
16	18	3	5	0.0	30	6.1	0.922	2.182	2.37

TABLE 8. (Continued)

(1) Serial No.	(2) Station I.D.	(3) Area I.D.	(4) No. of Years	(5) Observed Cracking Index, I	(6) Time to First Crack Break Through (months)	(7) CDMG at First Crack Break Through	(8) CDMG1 at First Crack Break Through	(9) Ending CDMG1	(10) CDMG2 (9)/(8)
17	19	3	2	0.0	20	5.4	0.932	0.970	1.04
18	20	3	8	1.9	31	6.8	0.917	3.304	3.60
19	21	3	9	0.0	32	5.5	0.919	3.996	4.35
20	22	3	9	0.0	32	8.8	0.931	4.094	4.40
21	23	3	11	2.6	32	6.1	0.717	2.417	3.37
22	24	3	12	5.4	32	60.3	0.723	2.559	3.54
23	25	4	11	1.0	31	7.4	0.719	2.833	3.94
24	26	4	11	3.1	32	12.8	0.713	2.722	3.82
25	27	4	12	1.5	31	6.7	0.709	2.893	4.08
26	28	4	12	10.7	32	12.8	0.713	2.893	4.06
27	29	4	9	0.2	32	6.4	0.711	2.331	3.28
28	30	3	12	10.4	32	7.0	0.727	2.701	3.72
29	31	3	12	21.2	32	11.6	0.729	2.699	3.70
30	32	3	12	20.3	32	11.6	0.729	2.699	3.70
31	33	3	12	12.5	32	11.6	0.729	2.699	3.70
32	34	3	11	0.2	32	6.4	0.725	2.538	3.50

TABLE 9. Computations of CMDG2 for Michigan Pavements Using the Results from the Model (Case: 2, without Aging)

(1) Serial No.	(2) Station I.D.	(3) Area I.D.	(4) No. of Years	(5) Observed Cracking Index, I	(6) Time to First Crack Break Through (months)	(7) CDMG at First Crack Break Through	(8) CDMG1 at First Crack Break Through	(9) Ending CDMG1	(10) CDMG2 (9)/(8)
1	1	4	5	0.7	-	-	-	0.895	1.00
2	2	4	6	3.3	-	-	-	0.763	1.00
3	3	4	4	0.0	-	-	-	0.423	1.00
4	4	4	4	0.1	-	-	-	0.622	1.00
5	7	3	3	0.0	-	-	-	0.406	1.00
6	8	2	6	0.1	41.30	6.520	0.927	2.012	2.17
7	9	2	4	1.0	-	-	-	0.773	1.00
8	10	2	6	0.3	-	-	-	0.916	1.00
9	11	1	2	0.0	-	-	-	0.082	1.00
10	12	2	1	0.0	-	-	-	0.154	1.00
11	13	1	6	0.4	-	-	-	0.254	1.00
12	14	2	4	3.4	31.00	9.083	0.940	1.371	1.46
13	15	2	9	1.0	32.30	6.588	0.926	2.873	3.10
14	16	3	5	0.0	-	-	-	0.574	1.00
15	17	3	8	0.0	30.20	6.196	0.953	3.227	3.39
16	18	3	5	0.0	-	-	-	0.574	1.00

TABLE 9. (Continued)

(1) Serial No.	(2) Station I.D.	(3) Area I.D.	(4) No. of Years	(5) Observed Cracking Index, I	(6) Time to First Crack Break Through (months)	(7) CDMG at First Crack Break Through	(8) CDMG1 at First Crack Break Through	(9) Ending CDMG1	(10) CDMG2 (9)/(8)
17	19	3	2	0.0	-	-	-	0.499	1.00
18	20	3	8	1.9	30.30	6.139	0.951	2.903	3.05
19	21	3	9	0.0	42.00	5.351	0.932	2.539	2.72
20	22	3	9	0.0	43.50	5.566	0.944	2.264	2.40
21	23	3	11	2.6	31.75	5.130	0.829	3.518	4.24
22	24	3	12	5.4	31.30	6.021	0.823	3.909	4.75
23	25	4	11	1.0	55.50	7.114	0.841	1.954	2.32
24	26	4	11	3.1	56.00	5.332	0.840	1.898	2.26
25	27	4	12	1.5	54.50	13.081	0.821	2.114	2.57
26	28	4	12	10.7	54.50	105.048	0.831	2.109	2.54
27	29	4	9	0.2	66.50	6.229	0.824	1.429	1.73
28	30	3	12	10.4	32.00	6.017	0.834	3.688	4.42
29	31	3	12	21.2	32.30	6.911	0.830	3.665	4.41
30	32	3	12	20.3	32.30	6.911	0.830	3.665	4.41
31	33	3	12	12.5	32.30	6.911	0.830	3.665	4.41
32	34	3	11	0.2	32.30	5.057	0.829	3.378	4.07

TABLE 10. Computations of CMDG2 for Michigan Pavements Using the Results from the Model (Case: 3, Aging up to a Depth of 1.0" i.e. No Aging when Yc > 1.0")

(1) Serial No.	(2) Station I.D.	(3) Area I.D.	(4) No. of Years	(5) Observed Cracking Index, I	(6) Time to First Crack Break Through (months)	(7) CDMG at First Crack Break Through	(8) CDMG1 at First Crack Break Through	(9) Ending CDMG1	(10) CDMG2 (9)/(8)
1	1	4	5	0.7	55.60	8.713	0.970	0.970	1.000
2	2	4	6	3.3	55.40	4.699	0.938	1.040	1.108
3	3	4	4	0.0	-	-	-	0.772	1.000
4	4	4	4	0.1	-	-	-	0.750	1.000
5	7	3	3	0.0	-	-	-	0.797	1.000
6	8	2	6	0.1	31.00	6.507	0.959	2.236	2.332
7	9	2	4	1.0	30.50	5.448	0.938	1.238	1.320
8	10	2	6	0.3	42.90	9.077	0.962	1.323	1.375
9	11	1	2	0.0	-	-	-	0.593	1.000
10	12	2	1	0.0	-	-	-	0.329	1.000
11	13	1	6	0.4	-	-	-	0.780	1.000
12	14	2	4	3.4	19.50	5.361	0.954	1.577	1.653
13	15	2	9	1.0	31.90	8.451	0.911	2.967	3.256
14	16	3	5	0.0	43.30	5.723	0.971	1.127	1.161
15	17	3	8	0.0	31.80	7.627	0.948	2.975	3.140
16	18	3	5	0.0	43.30	5.723	0.971	1.127	1.161

TABLE 10. (Continued)

(1) Serial No.	(2) Station I.D.	(3) Area I.D.	(4) No. of Years	(5) Observed Cracking Index, I	(6) Time to First Crack Break Through (months)	(7) CDMG at First Crack Break Through	(8) CDMG1 at First Crack Break Through	(9) Ending CDMG1	(10) CDMG2 (9)/(8)
17	19	3	2	0.0	-	-	-	0.801	1.000
18	20	3	8	1.9	31.60	4.996	0.952	2.772	2.912
19	21	3	9	0.0	31.60	8.654	0.976	2.678	2.742
20	22	3	9	0.0	31.90	8.443	0.950	2.471	2.601
21	23	3	11	2.6	42.00	12.574	0.831	3.118	3.750
22	24	3	12	5.4	42.00	6.884	0.830	3.444	4.151
23	25	4	11	1.0	55.90	5.145	0.822	1.912	2.327
24	26	4	11	3.1	66.00	17.615	0.836	1.848	2.211
25	27	4	12	1.5	55.80	5.211	0.806	1.975	2.450
26	28	4	12	10.7	55.80	5.071	0.805	1.970	2.446
27	29	4	9	0.2	54.90	17.025	0.819	1.521	1.856
28	30	3	12	10.4	32.30	6.059	0.826	3.266	3.956
29	31	3	12	21.2	32.60	5.941	0.833	3.196	3.838
30	32	3	12	20.3	32.60	5.941	0.833	3.196	3.838
31	33	3	12	12.5	32.60	5.941	0.833	3.196	3.838
32	34	3	11	0.2	32.60	6.148	0.833	2.989	3.590

In this case, the standard error in estimated crack index was 4.4.

Finally, a third analysis was made assuming that the asphalt ages only to a depth of one inch (=2.54 cm), which is consistent with the observations of Jones (18). The regression equations that resulted were

$I = -2.66 + 3.06(\mathrm{CMDG1})$, for which $R^2 = 0.28$ and the standard error was 4.9, and (42)

$I = -4.23 + 3.23(\mathrm{CMDG2})$, with $R^2 = 0.30$ and the standard error was 5.3. (43)

Equations 40, 41, 42, and 43 are reasonable: a greater frequency of cracks is predicted with an increase in the cumulative damage function and at the minimum allowable value of CMDG2 = 1.0, neither of these equations predicts cracking. The onset of cracking is predicted as CMDG2 grows to slightly above 1.0. Standard errors in the predicted crack index are below the standard error of 6.2 reported by Haas in his empirical equation developed from observed cracking on test roads in Canada (6). Haas' empirical equation had a coefficient of determination, $R^2 = 0.82$.

FURTHER ANALYSIS OF MICHIGAN DATA

The Michigan data reported by Novak (17) was run through a regression search program, SELECT; in which the observed cracking index, I, was the dependent variable, and a total of eighteen independent variables were tried. The resulting best equation is as follows:

$$I = 55.6 - 30.2(\log T_{R+B}) - (3.53(\log P_{77})) + (0.906A - 2.61)(\log S-1) \qquad (44)$$

where	I	is the sum of full transverse cracks plus 1/2 of the number of half transverse cracks per 500 feet of roadway.
	T_{R+B}	is the softening point ring and ball temperature in C of the original asphalt,
	P_{77}	is the penetration of the original asphalt at 25 C in units of 0.1 mm,
	A	is the age of the pavement in years, and
	S	is the stiffness of the bitumen at the winter design temperature and with 20,000 seconds loading time in Kg/cm^2.

While the statistics for Equation 44 are remarkable, $R^2 = 0.996$ and a standard error in estimated I of 0.4, some discussion of its applicability is necessary. The coefficient on T_{R+B} indicates that as the original asphalt ring and ball temperature increases, the frequency of cracking will drop. It is known that, for a given value of penetration at 25° C, the asphalt temperature susceptibility decreases when the ring and ball temperature increases, which is consistent with Equation 44. The equation also says that at higher penetrations, cracks will be less frequent, as is expected for a softer asphalt. The older the pavement, the more cracks are expected - again reasonable. However, at ages of less than about three years, the empirical equation says that increasing stiffness gives fewer cracks. To maintain reasonable results, the equation should not be used for pavements which are less than three years old. Only three of the pavements in the Michigan data base were of less than three years in age. The model also fails to behave well when stiffness is below 10 kg/cm^2; such low stiffness is outside the range for which the model is based (see Table 5) and it should not then be applied.

Comparing this empirical equation, Equation 44, with the mechanistic thermal cracking equation described herein, the following conclusions can be drawn.

(1) Both of the equations depend heavily upon the original asphalt rheological properties and its temperature susceptibility.

(2) Both of the equations are highly dependent on the age of the pavement. The mechanistic equation only produces cracking due to temperature cycling but the empirical equation may account for other causes of cracking through the age variable.

(3) The thickness of the pavement is important in the mechanistic model while it did not appear in the empirical equation. It should be noted that, in the Michigan data used, age and thickness correlated highly because the pavements were built thicker with time; the correlation coefficient between these two variables was 0.83. Also, the coefficient of age reported in this empirical model was lower than the coefficient (0.906 vs 1.339) of an identical variable in the Haas empirical equation. Because of these considerations, the age variable may take into account the effects of both the age and the pavement thickness on observed cracking behavior.

(4) Temperature is considered in the empirical model only through the stiffness at the winter design temperature - a low temperature expected to be reached only for a few hours during the coldest winters. The mechanistic model considers daily temperatures, but most of its contribution to the predicted cumulative damage occurs on only a few very

cold days during the year.

(5) The empirical equation has no consideration of the asphalt concrete mix or aggregate. It is only applicable for mixes typical in Michigan. The mechanistic model considers mix and aggregate properties through aggregate volume concentrations and initial crack length.

(6) Both of the models are sensitive to the same inputs. The empirical equation reproduces the data on which it was based better than the mechanistic model reproduces that data. However, the mechanistic model can be used for conditions not necessarily similar to conditions in the Michigan data base as it has a sound theoretical basis.

CHAPTER IV

DESIGN PROCEDURE FOR THERMAL FATIGUE CRACKING

The mechanistic model is not directly applicable to the design of individual roadway segments. It consumes large amounts of computer time and requires very detailed temperature data for its operation. A schematic diagram, Figure 10, indicates the nature of the repetitive detailed calculation necessary for the model. The mechanistic thermal cracking model and the guide to the input data are given in Appendix B. However, the mechanistic model could be used by the individual highway departments to develop an empirical design equation suited to pavements and conditions in their jurisdiction. The following empirical design equation is developed for use in north Texas and is an example of how the model may be used to develop other such design equations for other regions in the United States.

The mechanistic model was run for eight locations, four in Michigan and four in Texas. Quite large differences in climatic conditions prevailed among the eight locations. For each location, several runs (36 in all) were made with variations in layer thickness, bitumen properties, and asphalt concrete mix characteristics. These runs were made using the aging predictions to a depth of 1-inch within the computations of the cumulative damage index and the crack length. The results are given in Tables D-1 through D-8 in

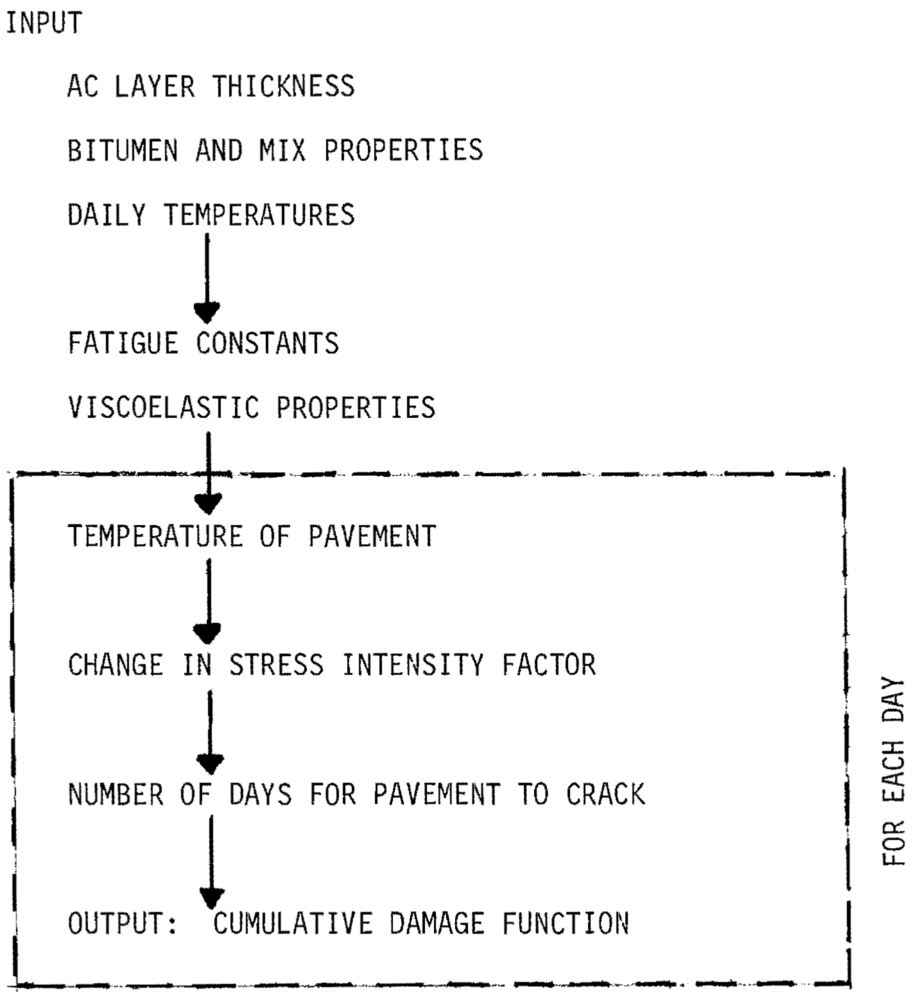

Figure 10. Schematic Diagram of Mechanistic Thermal Cracking Model.

Appendix D.

A regression analysis program, SELECT, was run on the resulting data and an empirical equation for predicting the cumulative damage index, CMDG1, was chosen. For convenience in the regression analysis, all of the variables in the resulting equation, Equation 45, are normalized to be less than or equal to 1.0, as defined below.

$$\mathrm{CMDG1} = 0.519(\mathrm{PI})^{0.257}(\mathrm{SP})^{0.122}(C_v)^{24.5}$$

$$\times\ (D)^{-0.410}(T)^{1.66}(\mathrm{SA})^{1.97}(\mathrm{MT})^{-7.43}$$

$$R^2 = 0.74 \text{ and } n = 576 \tag{45}$$

where, as normalized variables,

CMDG1	is the cumulative damage index,
PI	is 0.25 (penetration index +2),
SP	is the ring and ball softening point temperature in °F / 125.6,
C_v	is the volumetric concentration of the aggregate,
D	is the depth of the asphalt layer in inches / 8,
T	is the age of the pavement in years / 10,
SA	is the average annual amplitude of solar radiation in Langleys per day / 240.0, and
MT	is (the minimum monthly temperature + 20 ° F) / 55.7.

When the cumulative damage index, CMDG1, is 1.0, the first crack appears in the pavement (13). If it is desired to use Equation 45 in the design of a pavement, then the cumulative damage index from Equation 45 can be substituted into Equation 42, and a critical level of the crack index at a specific age may be set. By trial and error, the mix properties and depth of the pavement may be chosen to meet the selected criteria. It is significant that the pavement depth variable has a negative exponent, meaning that thicker pavements will retard crack propagation better than will thinner pavements - a fact that may explain why the Michigan data indicated that pavements were built thicker with time (and with experience). The large exponent of C_v, 24.5, makes it essential that no value of C_v should ever be entered into Equation 45 which is outside the range used in the regression analysis, i.e., 0.85 to 0.90. A similar comment applies to the value of the minimum temperature variable.

A computer program (19) for function optimization, using pattern search and gradient, is modified to find the optimum values of penetration index, PI, softening point ring and ball temperature, SP, depth of asphalt concrete layers, DF, and the volumetric concentration of aggregate, C_v, for given values of the age of pavement, T, the average annual amplitude of solar radiation, SA, and the minimum monthly temperature, MT. The inputs to this program are the initial values of PI, SP, C_v, and DF, and T, SA, and MT. The lower and upper limits of PI, SP, C_v, and DF applicable to this model are

PI = -1.00 to 2.00,
SP = 100.4 F to 125.6 F,
C_v = 0.85 to 0.90, and
DF = 2.00 inches to 8.00 inches.

These limits are set within the program. The limits on the surface course thickness, D_f, are set between 2 and 8 inches so as to span the range of practical thicknesses that are usually built with asphaltic concrete. The equation can be used to extrapolate to other values outside the range, if such is desirable. However, because of the large exponent on the C_v-term, it is usually advisable to remain within the range of 0.85 and 0.90. Using Equation 42 the value of CDMG1 is determined by setting the desired value of the cracking index, I, at the end of a design period. As an example, suppose I = 0.90, i.e.,

$$0.90 = -2.66 + 3.06\ (\text{CMDG1}),$$

$$\text{CMDG1} = 1.163 = C.$$

Substituting the value 1.163 for C in Equation 45, the value of the constant A0 is calculated for the given values of T, SA, and MT. Using T = 10 years, SA = 215 Langleys/day, MT = 6 F for Michigan Area 2, A0 is determined as follows:

$$1.163 = 0.159(PI)^{0.257}(SP)^{0.122}(C_V)^{24.5} \times (P)^{-0.410}(10/10)^{1.66}(215/240)^{1.97} \times [(6+20)/55.7]^{-7.43} \quad \text{or}$$

$$1.163 = 120.09(PI)^{0.257}(SP)^{0.122}(C_V)^{24.5}(D)^{-0.410}$$

thus

$$A0 = 120.09; \text{ i.e.,}$$

$$1.163 = A0(PI)^{0.257}(SP)^{0.122}(C_V)^{24.5}(D)^{-0.410} \tag{46}$$

and

$$A0 = 0.519(T)^{1.66}(SA)^{1.97}(MT)^{-7.43} \tag{47}$$

where PI, SP, C_V, D, T, SA, and MT are as defined following Equation 45. The optimum values of PI, SP, C_V, and D are computed so that a squared error, e^2, is minimized. The error term, e, is defined in Equation 48.

$$e = \frac{1}{1.163} - \frac{(DF)^{0.410}}{A0(PI)^{0.257}(SP)^{0.122}(C_V)^{24.5}} \tag{48}$$

Equations 47 and 48 are used in the program and from the optimum values obtained, the final values of PI, TRB, C_V, and DF are calculated. If the value of cracking index, I, to be used is different from 0.9, the value of CMDG1 must be recomputed and the value of CMDG1 or C (1.163

in Equation 48) must be replaced by the new value.

This program was run for four locations in Michigan and four locations in Texas, setting the value of C_v at either its lower limit of 0.85 or its upper limit of 0.90 to determine the effect of various design inputs such as minimum temperature, pavement age, and solar radiation upon the optimum design thickness, DF, ring and ball softening point, SP, and penetration index, PI. The results of these example problems are given in Table 11.

For convenience in applying this design procedure in Texas, the minimum temperature and solar radiation data for Texas can be taken from maps given in Appendix E.

Table 11 shows that the optimum pavement thickness varies between the limits of 2.0 and 8.0 inches, and that the thickness is very sensitive to the minimum temperature and less so to changes in the design pavement life. This sensitivity could be expected from a review of the exponents in Equation 45. The higher exponents produce the greater sensitivity of the variables, including the pavement thickness and mix design variables in the equation. The following list of variables is ranked in order of decreasing sensitivity.

TABLE 11. Results of Pavement Design Program

Location	Problem No.	Given Values				Optimal Solutions			Error
		C_v	T (years)	SA (Langleys /day)	MT (°F)	PI	T_{RB} (°F)	D_f (inches)	
Michigan	1	0.85	10	240	10	0.8	102	3.74	7.2×10^{-5}
Area 1	2	0.90	10	240	10	-1.0	100	7.72	0.50
Michigan	3	0.85	10	215	6	-1.0	100	7.72	0.21
Area 2	4	0.90	10	215	6	-1.0	100	7.72	0.70
Michigan	5	0.85	10	226	7	-1.0	100	7.72	0.085
Area 3	6	0.90	10	226	7	-1.0	100	7.72	0.67
Michigan	7	0.85	10	223	16	1.5	125	2.00	-1.87
Area 4	8	0.90	10	223	16	0.75	110	3.00	-5.8×10^{-4}
Dallas	9	0.90	10	181	35	2.0	125	2.00	-22.0
	10	0.85	20	181	25	2.0	125	2.00	-5.8
	11	0.90	20	181	25	2.0	125	2.00	-0.77
El Paso	12	0.90	10	212	30	2.0	125	2.00	-7.4
	13	0.85	20	212	18	2.0	125	2.00	-0.52
	14	0.90	20	212	18	-1.0	105	7.71	2.6×10^{-5}
Abilene	15	0.90	10	177	32	2.0	125	2.00	-14.9
	16	0.85	20	177	21	2.0	125	2.00	-2.6
	17	0.90	20	177	21	1.9	124	2.00	2.1×10^{-5}
Amarillo	18	0.90	10	199	23	1.8	125	2.00	-2.2
	19	0.85	20	199	13	0.8	102	4.48	-2.6×10^{-4}
	20	0.85	20	199	12	-0.1	104	6.27	2.4×10^{-4}
	21	0.90	20	199	12	-1.0	100	8.00	0.58

C_v = volumetric concentration of the aggregate

T = age of pavement, years

SA = average annual amplitude of solar radiation, Langleys/day

MT = minimum monthly temperature, °F

PI = penetration index (initially assumed value, 1.0)

T_{RB} = softening point ring and ball temperature (initially assumed value, 110°F)

D_f = depth of asphalt layer (initially assumed value, 3.50 inches)

Sensitivity Rank	Variable	Exponent
1	C_v	24.5
2	DF	0.410
3	PI	0.257
4	SP	0.122

The optimization procedure will change the most sensitive variable first until it reaches its most extreme favorable value. In this case, the most sensitive variable is C_v, which has 0.85 as its lowest and most favorable value. The second most sensitive variable is the depth of the asphaltic concrete, which has an exponent of 0.410. Its largest value is its most favorable value. To understand at a glance how the optimization procedure works, it is helpful to look at Equation 48. The optimization procedure will try to raise the value of the quotient

$$\frac{(DF)^{0.410}}{A0(PI)^{0.257}(SP)^{0.122}(C_v)^{24.5}}$$

to a value that is large enough to be equal to 1/1.163. If the value of C_v is set, the next most profitable variable to change is the depth, DF, because it is the most sensitive variable remaining. An increase of DF strengthens the pavement against thermal cracking and this correponds to increasing the numerator of the quotient toward its maximum value. The next most sensitive variable is the penetration index, PI, which will be reduced toward its smallest value because it is in the denominator. And, of course, a lower penetration index gives a pavement added resistance against thermal cracking. Similarly, the smallest value of the softening point is its most favorable value.

If the climate is relatively mild, the pattern search procedure will force the quotient toward its lowest value, which is reached when DF=2.0 inches, PI=+2.0, and TRB=125°F. But even with these variables at their most unfavorable values, the resulting quotient is a number that is larger in magnitude than 1/1.63. Since the quotient has a negative sign, the error calculated by Equation 48 is a negative number and the error term has a negative sign. This means that even at its lower limits the pavement has an excess capacity to resist thermal cracking.

It is seen in Table 11 that when a negative error is reported, the design quantities are at or close to their least favorable values. In all areas in Michigan and in Amarillo, Texas the climate was severe enough to cause the program to seek a greater pavement depth. Once the design period was changed to 20 years, one of the example problems in El Paso reached a greater pavement thickness without changing the softening point to its most favorable value. In all of the areas where a milder climate prevails, the pavement thickness that was determined by the pattern search procedure was set at its lowest limiting value, and the error term was negative. The larger the magnitude of the negative error, the more resistant the pavement is to thermal cracking. It appears from these runs that pavement thickness begins to be very sensitive to the minimum temperature at around 18°F.

It is also obvious from comparing Example Problem pairs 1 and 2, 7 and 8, 10 and 11, 13 and 14, 20 and 21 that a value of C_v closer to 0.85 is more favorable to pavement durability against thermal fatigue. Changing C_v from 0.85 to 0.90 causes drastic changes in the required thickness of the asphaltic concrete layer.

The sensitivity of the design to small temperature changes below 18°F is illustrated by Example Problems 19 and 20. A change of design temperature by one degree from 13°F to 12°F resulted in an increase in the required pavement thickness of nearly two inches.

The design temperatures that were used in Example Problems 10 and 11 (Dallas), 13 and 14 (El Paso), 16 and 17 (Abilene), and 20 and 21 (Amarillo) are 10°F lower than the values that may be read from the average minimum temperature map that is given in Appendix E.

The amplitude of solar radiation that is used for design is the difference between the mean and the maximum solar radiation, and maps of both of these quantities are also given in Appendix E.

As the example problems in Table 11 illustrate, the design program is very versatile. It can provide an optimum mix design (i.e., C_v, PI, T_{RB}) of the asphalt concrete to resist thermal cracking or it can be used to calculate the depth of the asphalt layer that is required to resist thermal cracking assuming that the mix has already been designed by other means to resist traffic stresses. In fact, Equation 48, as it stands, can be used as a design equation for the depth of the asphalt concrete if the mix has already been designed. Alternatively, if a surface course depth has already been selected, and a choice of asphalt cements is available, Equation 48 can be used to determine which asphalt will provide the best resistance to thermal cracking.

CHAPTER V

CONCLUSIONS

A mechanistic model based on fracture mechanics has been developed to predict temperature cracking of asphalt concrete pavement. The standard errors in the cracking index, I, from the application of the model described herein are smaller than those that were computed in the development of other design equations and models (6). Two real advantages exist for the mechanistically based approach over those that are probabilistic or empirical.

(1) Mechanistic models can be more readily transferred from situation to situation than can empirical models. Empirical models are restricted to situations or conditions close to those from which they were derived.

(2) Mechanistic models can be improved by giving consideration to more or different variables and conditions.

There are four areas of further development which could prove to be valuable in improving the model reported here.

(1) This fracture mechanics based model considers only one mode of crack generation. The crack is assumed to begin at the surface and progress downward through the asphalt concrete. Considerable work has been done on a different mode of failure (3, 4, 20) in which a crack begins

in stiff base course materials and reflects upward through the surface. A model developed to predict such a mode of failure could be combined with the one described here and the prediction of crack frequency would be from the accumulated contributions of both modes of failure.

(2) In its present form, the model described here gives no consideration to residual stresses or to healing. Cracks are predicted to develop as the pavement temperature drops. However, when the temperature returns to a higher level, the cracks will close and may heal due to the residual stresses that develop (21). No authoritative work allowing inclusion of the healing process in a mechanistic model of asphalt concrete is known to be available.

(3) More work is needed on the prediction of aged rheological properties of bitumen.

(4) The current methodology for calculating the fracture parameters A and n from the slope of the relaxation modulus curve can, and should, be developed further. Fracture properties of aged asphalt concrete pavement should be measured in the laboratory to permit confirmation or revision of the aged properties that are predicted by the model.

The pavement thermal cracking model which was developed in this report is based on fracture mechanics and thermal stresses calculated with viscoelastic theory. Despite its sophisticated basis in mechanics, the model is easy to use since it requires very simple input data on the properties of the mix and pavement thickness. It generates all of the required time and temperature dependent properties internally by using a numerical form of Van der Poel's nomograph. The verification that has been done by comparing predictions made with this program with observed thermal cracking data has shown that the program is a reasonably reliable prediction tool and recommends its further use in the analysis of pavements subjected to thermal cracking.

This report has described the use of this model to develop a design procedure for asphaltic concrete pavements to resist thermal cracking, and has presented several design examples which illustrate how the computerized design procedure works, and how sensitive it is to several climatic and material property variables.

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APPENDIX A

Sample Calculations
for
Change of Pavement Temperature

TABLE M.

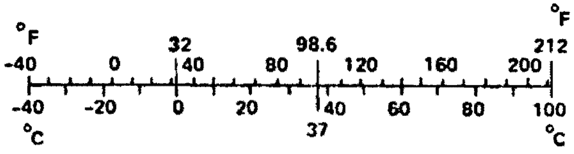
METRIC CONVERSION FACTORS

Approximate Conversions to Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
in	inches	*2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
		AREA		
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
	acres	0.4	hectares	ha
		MASS (weight)		
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2000 lb)	0.9	tonnes	t
		VOLUME		
tsp	teaspoons	5	milliliters	ml
Tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
		AREA		
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares (10,000 m^2)	2.5	acres	
		MASS (weight)		
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	
		VOLUME		
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	35	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3
		TEMPERATURE (exact)		
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



*1 in = 2.54 (exactly). For other exact conversions and more detailed tables, see NBS Misc. Publ. 286, Units of Weights and Measures, Price $2.25, SD Catalog No. C13.10:286.

Sample calculation for determining the change in pavement temperature, ΔT, and thermal tensile stress, σ_T:

Stress-free temperature, $T_0 = 75°F$

Maximum change in air temperature, T_R, below the stress-free temperature $= 150°F$;

Mean air temperature, $T_A = 1/2(75 + (75-150)) = 0°F$

Thickness of surface course (asphalt concrete) = 2"

The following values are used for the investigation:

Thermal conductivity, $k = 0.80$ BTU/ft^2/hr, °F

Specific heat, $s = 0.22$ BTU/lb, °F

Unit weight of surface course, $w = 146$ lbs/cft

Wind velocity, $V = 10$ mph

Maximum solar radiation, $L = 500$ Langleys/day

Minimum solar radiation, $L = 100$ Langleys/day

Surface absorptivity to the solar radiation, $b = 0.95$

Coefficient of thermal activity of the surface course, $\alpha = 1.35\text{x}10^{-5}/°F$

Sample calculation to find maximum pavement temperature, T_{max}, at the surface of the pavement; i.e., at x=0 (Figure 4a)

$$c = \frac{k}{sw} = \frac{0.80}{0.22 \text{ x } 146} = 0.02491 \text{ ft}^2/\text{hr},$$

$$C = \left(\frac{0.131}{c}\right)^{1/2} = 2.29325,$$

$$h - 1.3 + 0.62\, V^{3/4} = 1.3 + 0.62(10)^{3/4} = 4.7865,$$

$$R = \frac{2}{3} \text{ x } b \text{ x } \left(\frac{3.69L}{24}\right) \text{ x } \frac{1}{h} = \frac{2}{3} \text{ x } 0.95 \text{ x } \left(\frac{3.69 \text{ x } 500}{24}\right) \text{ x } \frac{1}{4.7856} = 10.17184, \text{ and}$$

$$H = \frac{h}{k} = \frac{4.7865}{0.80} = 5.983.$$

For calculating maximum pavement temperature, it is assumed that

$$\sin (S_i) = 1 > 0.$$

Therefore, using Equation (9),

$$T_V = 0.5\ T_R + 3R = 0.5 \times 150 + 3 \times 10.17184 = 105.5155\ °F$$

and, using Equation (10),

$$T_M = T_A + R = 0 + 10.17184 = 10.17184\ °F.$$

Then using Equation (5) to calculated T_{max},

$$T_{max} = T_M + T_V \left(\frac{He^{-xC}}{[(H+C)^2 + C^2]^{1/2}} \right) \text{Sin } (S_i),$$

$$T_{max} = 10.17184 + 105.5515 \left(\frac{5.983e^{-(0)(2.29324)}}{[(5.983 + 2.29324)^2 + 2.29324^2]^{1/2}} \right) (1), \text{ or}$$

$$T_{max} = 10.17184 + 105.5155 \left(\frac{5.983}{8.588}\right) = 83.68°F.$$

Sample calculation to find minimum pavement temperature, T_{min}, at the surface ie at x = 0

$$c = \frac{k}{sw} = \frac{0.80}{0.22 \times 146} = 0.02491\ ft^2/hr,$$

$$C = \left(\frac{0.131}{c}\right)^{1/2} = 2.29324,$$

$$h = 1.3 + 0.62\ V^{3/4},$$

$$h = 1.3 + 0.62\ (10)^{3/4},$$

$$h = 4.7865,$$

$$R = \frac{2}{3} \times b \times (\frac{3.69L}{24}) \times \frac{1}{h},$$

$$R = \frac{2}{3} \times 0.95 \times (\frac{3.69 \times 100}{24}) \times \frac{1}{4.7865},$$

$$R = 2.03437,$$

$$H = \frac{h}{k} = \frac{4.7865}{0.80}, \text{ and}$$

$$H = 5.983.$$

For calculating minimum pavement temperature, it is assumed that

$$\sin (S_i) = -1 < 0$$

Therefore using Equation (11),

$$T_V = 0.5\ T_R,$$

$$T_V = 0.5 \times 150, \text{ or}$$

$$T_V = 75°F,$$

and, using Equation (12),

$$T_M = T_A + 0.5\ R,$$

$$T_M = 0 + 0.5 \times 2.03437,$$

$$T_M = 1.01718°F.$$

By using equation (5) for calculating T_{min},

$$T_{min} = T_M + T_V \left(\frac{He^{-xC}}{[(H + C)^2 + C^2]^{1/2}} \right) \sin (S_i),$$

$$T_{min} = 1.01718 + 75 \left(\frac{(5.983e^{-(0)(2.29324)}}{[(5.983 + 2.29324)^2 + (2.2934)^2]^{1/2}} \right) (-1),$$

$$T_{min} = 1.01718 - 52.25, \text{ or}$$

$$T_{min} = -51.23°F.$$

<u>Sample calculation to find ΔT and σ_T at x = 0</u>

$$\Delta T_{at\ x=0} = \min (T_{max} \text{ or stress-free temperature}) - T_{min},$$

$$\Delta T = 75 - (-51.23), \text{ or}$$

$$\Delta T = \underline{126.23°F}$$

$$\sigma_T = \alpha \times E \times \Delta T,$$

$$\sigma_T = 1.35 \times 10^{-5} \times 10000 \times 126.23, \text{ or}$$

$$\sigma_T = \underline{17.04} \text{ psi}.$$

<u>Sample calculation to find ΔT, and σ_T at x = 1/4" below the surface</u>

$$T_{max} = T_M + T_V \left(\frac{He^{-xC}}{[(H + C)^2 + C^2]^{1/2}} \right) \sin (S_i),$$

$$T_{max} = 10.17184 + 105.5155 \left(\frac{5.983 \times e^{-(1/4 \times 1/12)(2.29324)}}{[(5.983 + 2.29324)^2 + (2.29324)^2]^{1/2}} \right) (1),$$

$$T_{max} = 10.17184 + 70.082, \text{ or}$$

$$T_{max} = 80.254°F.$$

$$T_{min} = T_M + T_V\left(\frac{He^{-xC}}{[(H + C)^2 + C^2]^{1/2}}\right) \sin (S_i),$$

$$T_{min} = 1.01718 + 75\left(\frac{(5.983)\ e^{-(1/4 \times 1/12)(2.29324)}}{[(5.983 + 2.29324)^2 + (2.29324)^2]^{1/2}}\right) (-1),$$

$$T_{min} = 1.01718 - 49.814, \text{ or}$$

$$T_{min} = -48.7968°\text{F}.$$

$$\Delta T = (T_{max} \text{ or } 75°\text{F (whichever is smaller)} - T_{min}),$$

$$\Delta T = 75 - (-48.7968),$$

$$\Delta T = 123.7968, \text{ or}$$

$$\Delta T = 123.80°\text{F}.$$

TABLE A1. Calculated Values of σ_T and Δ_T

Depth Below Surface (in)	Daily Air Temperature Range, T_R, below Stress Free Temperature = 50°F		Daily Air Temperature Range, T_R, below Stress Free Temperature = 100°F		Daily Air Temperature Range, T_R, below Stress Free Temperature = 150°F	
	ΔT (°F)	σ_T for E = 10,000 psi (psi)	ΔT (°F)	σ_T for E = 10,000 psi (psi)	ΔT (°F)	σ_T for E = 10,000 psi (psi)
0.00	41.40	5.589	83.82	11.320	126.23	17.040
0.25	40.59	5.480	82.19	11.096	123.80	16.700
0.50	39.81	5.374	80.64	10.890	121.47	16.400
0.75	39.07	5.275	79.17	10.690	118.13	15.947
1.00	38.37	5.180	77.76	10.500	113.04	15.260
1.25	37.70	5.090	76.42	10.320	108.20	14.600
1.50	37.06	5.003	75.13	10.143	103.58	14.000
1.75	36.45	4.921	73.92	9.979	99.17	13.388
2.00	35.87	4.843	71.20	9.613	94.97	12.822
2.25	35.31	4.767	68.31	9.222	90.97	12.280
2.75	34.28	4.628	62.92	8.494	83.51	11.274
3.25	33.34	4.501	58.02	7.833	76.74	10.360
3.50	32.91	4.443	55.74	7.525	73.59	9.935
3.75	32.49	4.386	53.57	7.232	70.59	9.529
4.25	31.72	4.282	49.52	6.686	64.99	8.774
4.75	31.01	4.186	45.84	6.188	59.90	8.086
5.00	30.68	4.143	44.13	5.958	57.53	7.767
5.75	27.85	3.760	39.46	5.327	51.07	6.895
6.75	24.60	3.321	34.19	4.616	43.78	5.910

TABLE A2. Calculated Values of Thermal Tensile Stress, σ_T, for 2" Thickness of Surface Course.

Depth Below Surface (in)	Thermal Tensile Stress, σ_T (psi)					
	Daily Air Temperature Range, T_R, below Stress Free Temperature = 50°F		Daily Air Temperature Range, T_R, below Stress Free Temperature = 100°F		Daily Air Temperature Range, T_R, below Stress Free Temperature = 150°F	
	Modulus of Elasticity, E (psi)		Modulus of Elasticity, E (psi)		Modulus of Elasticity, E (psi)	
	10,000	100,000	10,000	100,000	10,000	100,000
0.0	5.589	55.89	11.320	113.20	17.040	170.40
0.25	5.480	54.80	11.096	110.96	16.700	167.00
0.50	5.374	53.74	10.890	108.90	16.400	164.00
0.75	5.275	52.75	10.690	106.90	15.947	159.47
1.00	5.180	51.80	10.500	105.00	15.260	152.60
1.25	5.090	50.90	10.320	103.20	14.600	146.00
1.50	5.003	50.03	10.143	101.43	14.000	140.00

TABLE A3. Calculated Values of Thermal Tensile Stress, σ_T, for 4" Thickness of Surface Course.

Depth Below Surface (in)	Thermal Tensile Stress, σ_T (psi)					
	Daily Air Temperature Range, T_R, below Stress Free Temperature = 50°F		Daily Air Temperature Range, T_R, below Stress Free Temperature = 100°F		Daily Air Temperature Range, T_R, below Stress Free Temperature = 150°F	
	Modulus of Elasticity, E (psi)		Modulus of Elasticity, E (psi)		Modulus of Elasticity, E (psi)	
	10,000	100,000	10,000	100,000	10,000	100,000
0.00	5.589	55.89	11.320	113.20	17.040	170.40
0.75	5.275	52.75	10.690	106.90	15.947	159.47
1.25	5.090	50.90	10.320	103.20	14.600	146.00
1.75	4.921	49.21	9.979	99.79	13.388	133.88
2.25	4.767	47.67	9.222	92.22	12.280	122.80
2.75	4.628	46.28	8.494	84.94	11.274	112.74
3.25	4.501	45.01	7.833	78.33	10.360	103.60

TABLE A4. Calculated Values of Thermal Tensile Stress, σ_T, for 8" Thickness of Surface Course.

Depth Below Surface (in)	Thermal Tensile Stress, σ_T (psi)					
	Daily Air Temperature Range, T_R, below Stress Free Temperature = 50°F		Daily Air Temperature Range, T_R, below Stress Free Temperature = 100°F		Daily Air Temperature Range, T_R, below Stress Free Temperature = 150°F	
	Modulus of Elasticity, E (psi)		Modulus of Elasticity, E (psi)		Modulus of Elasticity, E (psi)	
	10,000	100,000	10,000	100,000	10,000	100,000
0.00	5.589	55.89	11.320	113.20	17.040	170.40
0.75	5.275	52.75	10.690	106.90	15.947	159.47
1.75	4.921	49.21	9.979	99.79	13.388	133.88
2.75	4.628	46.28	8.494	84.94	11.274	112.74
3.75	4.386	43.86	7.232	72.32	9.529	95.29
4.75	4.186	41.86	6.188	61.88	8.086	80.86
5.75	3.760	37.60	5.327	53.27	6.895	68.95
6.75	3.321	33.21	4.616	46.16	5.910	59.10

TABLE A5. Calculations for the Corrected Stress Intensity Factor, K_1, for d = 2", and T_R = 50°F

Elastic Modulus E (psi)	Crack Length Y_c (inches)	Computed Stress Intensity Factor $\overline{K}_1$ (lb-in$^{-3/2}$)	Correction Factor C_K (lb-in$^{-3/2}$)	Corrected Stress Intensity Factor $K_1=\overline{K}_1+C_K$ (lb-in$^{-3/2}$)
10,000	0.50	-6.4687	4.3720	-2.0937
	0.75	-7.2436	4.2880	-2.9556
	1.00	-6.2624	4.2090	-2.0534
	1.25	-6.6953	4.1320	-2.5633
	1.50	-6.3662	4.0610	-2.3052
	1.75	-2.5938	3.9910	1.3972
100,000	0.50	9.0309	43.7200	52.7509
	0.75	11.0447	42.8800	53.9247
	1.00	41.2181	42.0900	83.3081
	1.25	59.6755	41.3200	100.9955
	1.50	72.2146	40.6100	112.8246
	1.75	84.6702	39.9100	124.5802

TABLE A6. Calculations for the Corrected Stress Intensity Factor, K_1, for d=2", and T_R = 100°F

Elastic Modulus E (psi)	Crack Length Y_c (inches)	Computed Stress Intensity Factor $\overline{K}_1$ (lb-in$^{-3/2}$)	Correction Factor C_K (lb-in$^{-3/2}$)	Corrected Stress Intensity Factor $K_1=\overline{K}_1+C_K$ (lb-in$^{-3/2}$)
10,000	0.50	-4.4071	8.8530	4.4459
	0.75	-5.0805	8.6890	3.6085
	1.00	-2.0683	8.5290	6.4607
	1.25	-1.7716	8.3780	6.6064
	1.50	-0.5403	8.2340	7.6937
	1.75	6.0588	8.0930	14.1518
100,000	0.50	34.0312	88.5300	122.5612
	0.75	37.6344	86.8900	124.5244
	1.00	99.1391	85.2900	184.4291
	1.25	136.1290	83.7800	219.9090
	1.50	161.9470	82.3400	244.2870
	1.75	188.9340	80.9300	269.8640

TABLE A7. Calculations for the Corrected Stress Intensity Factor, K_1, for d = 2", and T_R = 150°F

Elastic Modulus E (psi)	Crack Length Y_c (inches)	Computed Stress Intensity Factor $\overline{K}_1$ (lb-in$^{-3/2}$)	Correction Factor C_K (lb-in$^{-3/2}$)	Corrected Stress Intensity Factor $K_1=\overline{K}_1+C_K$ (lb-in$^{-3/2}$)
10,000	0.50	-2.3497	13.3250	10.9753
	0.75	-2.9206	13.0850	10.1644
	1.00	-2.0684	12.7240	10.6556
	1.25	2.9218	12.1760	10.6556
	1.50	4.8132	11.6490	15.0978
	1.75	13.7054	11.1700	24.8754
100,000	0.50	58.9811	133.2500	192.2311
	0.75	64.1846	130.8500	195.0346
	1.00	156.2400	127.2400	283.4800
	1.25	208.9020	121.7600	330.6620
	1.50	244.3250	116.4900	360.8150
	1.75	281.2120	111.7000	392.9120

TABLE A8. Calculations for the Corrected Stress Intensity Factor, K_1, for d = 4", and T_R = 50°F

Elastic Modulus E (psi)	Crack Length Y_c (inches)	Computed Stress Intensity Factor $\overline{K}_1$ ($lb\text{-}in^{-3/2}$)	Correction Factor C_K ($lb\text{-}in^{-3/2}$)	Corrected Stress Intensity Factor $K_1=\overline{K}_1+C_K$ ($lb\text{-}in^{-3/2}$)
10,000	1.00	-2.1757	4.2090	2.0333
	1.50	-1.1703	4.0610	2.8907
	2.00	-0.8333	3.9260	3.0927
	2.50	-0.1840	3.8040	3.6200
	3.00	-0.5361	3.6930	3.1569
	3.50	0.4871	3.5910	4.0781
100,000	1.00	47.5878	42.0900	89.6778
	1.50	78.6993	40.6100	119.3093
	2.00	102.6050	39.2600	141.8650
	2.50	126.7460	38.0400	164.7860
	3.00	164.5010	36.9300	201.4310
	3.50	185.3530	35.9100	221.2630

TABLE A9. Calculations for the Corrected Stress Intensity Factor, K_1, for d = 4", and T_R = 100°F

Elastic Modulus E (psi)	Crack Length Y_c (inches)	Computed Stress Intensity Factor $\overline{K}_1$ ($lb\text{-}in^{-3/2}$)	Correction Factor C_K ($lb\text{-}in^{-3/2}$)	Corrected Stress Intensity Factor $K_1=\overline{K}_1+C_K$ ($lb\text{-}in^{-3/2}$)
10,000	1.00	3.4685	8.5290	11.9975
	1.50	6.8235	8.2340	15.0575
	2.00	8.6551	7.9620	16.6171
	2.50	10.3244	7.3580	17.6824
	3.00	10.6555	6.7770	17.4325
	3.50	12.8593	6.2500	19.1093
100,000	1.00	115.0340	85.2900	200.3240
	1.50	179.4490	82.3400	261.7890
	2.00	228.8660	79.6200	308.4860
	2.50	271.5680	73.5800	345.1480
	3.00	338.3880	67.7700	406.1580
	3.50	370.2320	62.5000	432.7320

TABLE A10. Calculations for the Corrected Stress Intensity Factor, K_1, for d = 4", and T_R = 150°F

Elastic Modulus E (psi)	Crack Length Y_c (inches)	Computed Stress Intensity Factor $\overline{K}_1$ (lb-in$^{-3/2}$)	Correction Factor C_K (lb-in$^{-3/2}$)	Corrected Stress Intensity Factor $K_1=\overline{K}_1+C_K$ (lb-in$^{-3/2}$)
10,000	1.00	9.0329	12.7240	21.7569
	1.50	14.1421	11.6490	25.7911
	2.00	16.7215	10.6820	27.4035
	2.50	19.4015	9.7980	29.1995
	3.00	20.5725	8.9950	29.5675
	3.50	24.0878	8.2660	32.3538
100,000	1.00	181.5020	127.2400	308.7420
	1.50	271.4310	116.4900	387.9210
	2.00	335.7450	106.8200	442.5650
	2.50	396.4150	97.9800	494.3950
	3.00	492.4270	89.9500	582.3770
	3.50	538.3980	82.6600	621.0580

TABLE A11. Calculations for the Corrected Stress Intensity Factor, K_1, for d = 8", and T_R = 50°F

Elastic Modulus E (psi)	Crack Length Y_c (inches)	Computed Stress Intensity Factor $\overline{K}_1$ ($lb\text{-}in^{-3/2}$)	Correction Factor C_K ($lb\text{-}in^{-3/2}$)	Corrected Stress Intensity Factor $K_1=\overline{K}_1+C_K$ ($lb\text{-}in^{-3/2}$)
10,000	1.00	-1.6714	4.2090	2.5376
	2.00	1.0470	3.9260	4.9260
	3.00	5.6364	3.6930	9.3294
	4.00	7.0390	3.5000	10.5390
	5.00	9.1528	3.3400	12.4928
	6.00	11.2093	3.0000	14.2093
	7.00	8.4651	2.6500	11.1151
100,000	1.00	37.5670	42.0900	79.6570
	2.00	92.2173	39.2600	131.4773
	3.00	165.5830	36.9300	202.5130
	4.00	202.6790	35.0000	237.6790
	5.00	268.7020	33.4000	302.1020
	6.00	332.0150	30.0000	362.0150
	7.00	341.5890	26.5000	368.0890

TABLE A12. Calculations for the Corrected Stress Intensity Factor, K_1, for d = 8", and T_R = 100°F

Elastic Modulus E (psi)	Crack Length Y_c (inches)	Computed Stress Intensity Factor $\overline{K}_1$ (lb-in$^{-3/2}$)	Correction Factor C_K (lb-in$^{-3/2}$)	Corrected Stress Intensity Factor $K_1=\overline{K}_1+C_K$ (lb-in$^{-3/2}$)
10,000	1.00	4.0799	8.5290	12.6089
	2.00	11.4738	7.9620	19.4358
	3.00	19.9371	6.7770	26.7141
	4.00	21.9121	5.7700	27.6821
	5.00	25.5840	4.9370	30.5210
	6.00	29.6863	4.2500	33.9363
	7.00	27.0993	3.6830	30.7823
100,000	1.00	103.5410	85.2900	188.8310
	2.00	217.8810	79.6200	297.5010
	3.00	347.8440	67.7700	415.6140
	4.00	400.5190	57.7000	458.2190
	5.00	503.8990	49.3700	553.2690
	6.00	612.6470	42.5000	655.1470
	7.00	633.6580	36.8300	670.4880

TABLE A13. Calculations for the Corrected Stress Intensity Factor, K_1, for d = 8", and T_R = 150°F

Elastic Modulus E (psi)	Crack Length Y_c (inches)	Computed Stress Intensity Factor $\overline{K}_1$ ($lb\text{-}in^{-3/2}$)	Correction Factor C_K ($lb\text{-}in^{-3/2}$)	Corrected Stress Intensity Factor $K_1=\overline{K}_1+C_K$ ($lb\text{-}in^{-3/2}$)
10,000	1.00	9.7499	12.7240	22.4739
	2.00	20.3509	10.6820	31.0329
	3.00	32.6579	8.9950	41.6529
	4.00	35.8153	7.6030	43.4183
	5.00	41.7676	6.4520	48.2196
	6.00	48.1385	5.5010	53.6395
	7.00	45.7020	4.7150	50.4170
100,000	1.00	168.5560	127.2400	295.7960
	2.00	324.0690	106.8200	430.8890
	3.00	509.0910	89.9500	599.0410
	4.00	585.1860	76.0300	661.2160
	5.00	735.5230	64.5200	800.0430
	6.00	892.9000	55.0100	947.9100
	7.00	925.2310	47.1500	972.3810

TABLE A14. Intercepts and Slopes from the Stress Intensity Factor, K_1, versus Crack Length, Yc, Curves

Elastic Modulus E (psi)	Daily Air Temp. Range below Stress Free Temperature T_R (°F)	Depth of Surface Course d (inches)	Intercept a	Slope b
100,000	150	2	289.0765	0.6270
		4		
		8		
100,000	100	2	191.3016	0.6615
		4		
		8		
100,000	50	2	83.0854	0.7842
		4		
		8		
10,000	150	2	10.5728	1.3991
		4	22.2331	0.2906
		8	23.2550	0.4458
10,000	100	2	5.6456	1.2796
		4	12.5750	0.3430
		8	13.6505	0.4904
10,000	50	2	---	---
		4	2.1846	0.4703
		8	2.8700	0.8599

TABLE A15. Intercepts and Slopes from a versus T_R, and b versus T_R Curves

Elastic Modulus E (psi)	Depth of Surface Course d (inches)	a versus T_R curve		b versus T_R curve	
		Intercept on x-axis m_1	Slope m_2	Intercept m_3	Slope m_4
100,000	2	8.8988	2.0599	0.8481	-0.00157
100,000	4	8.8988	2.0599	0.8481	-0.00157
100,000	8	8.8988	2.0599	0.8481	-0.00157
10,000	2	42.7099	0.0985	1.0406	0.00239
10,000	4	38.5220	0.2005	0.5477	-0.00180
10,000	8	35.0316	0.2039	1.0128	-0.00414

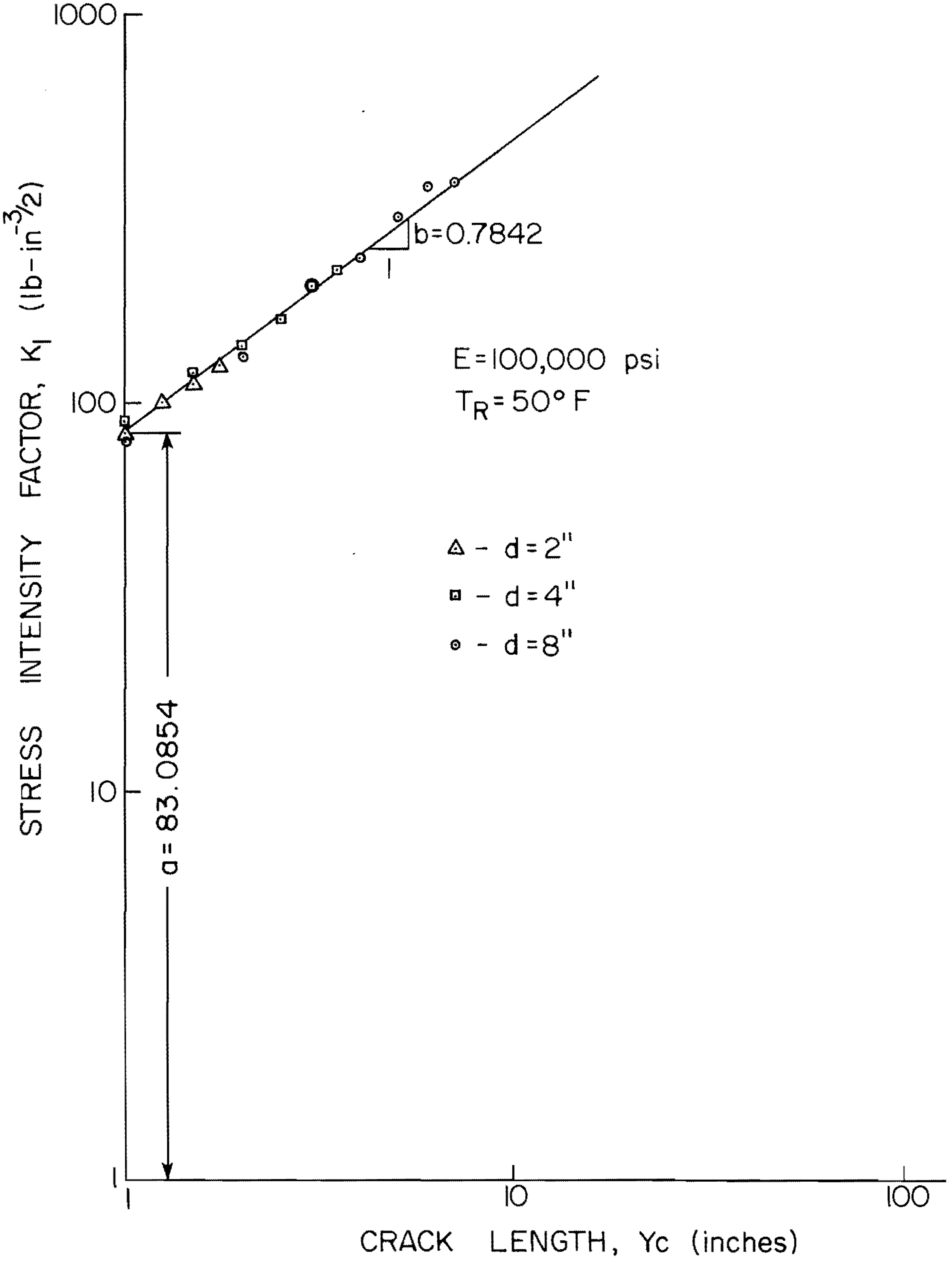


Figure A1. Stress Intensity Factor Versus Crack Length

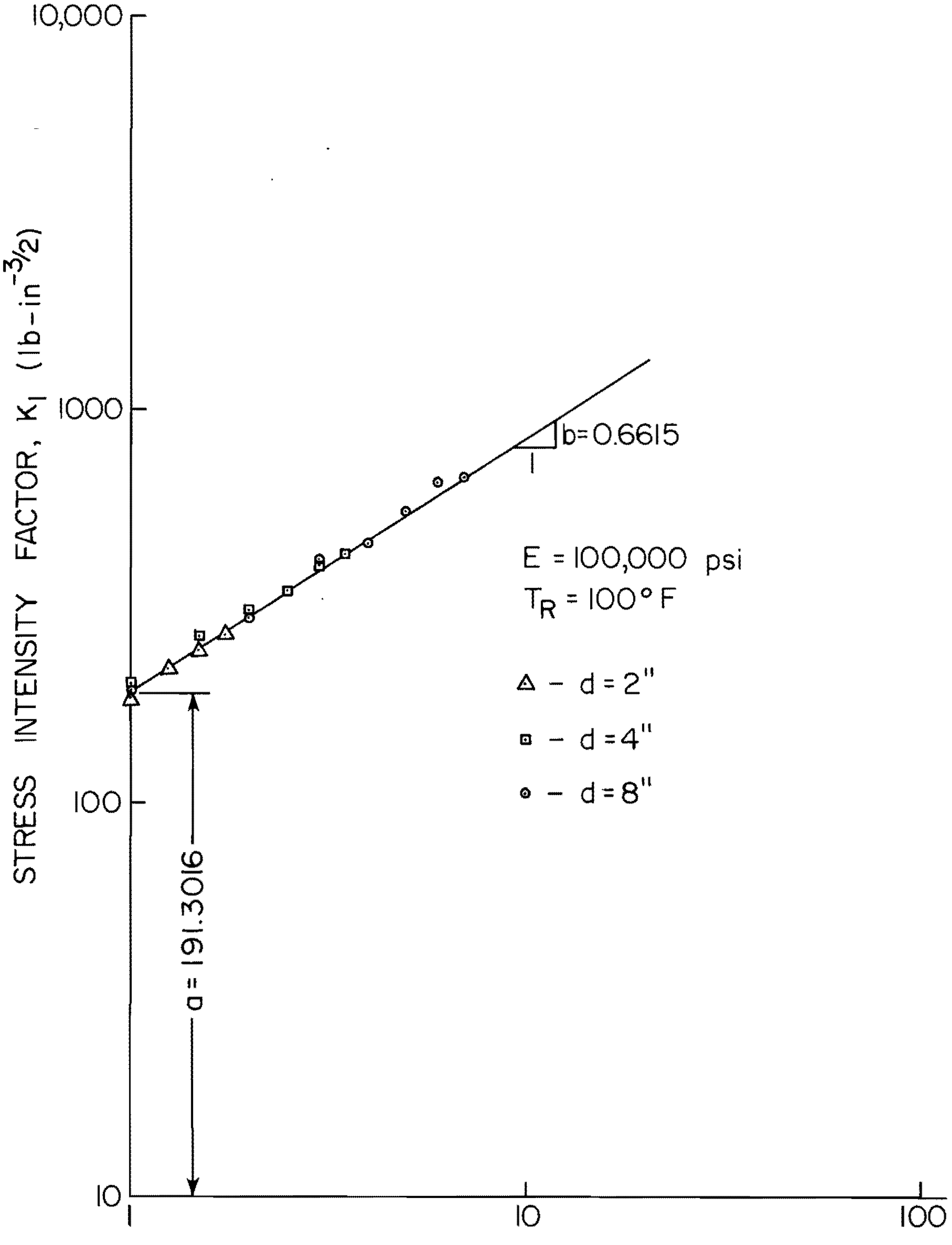


Figure A2. Stress Intensity Factor Versus Crack Length

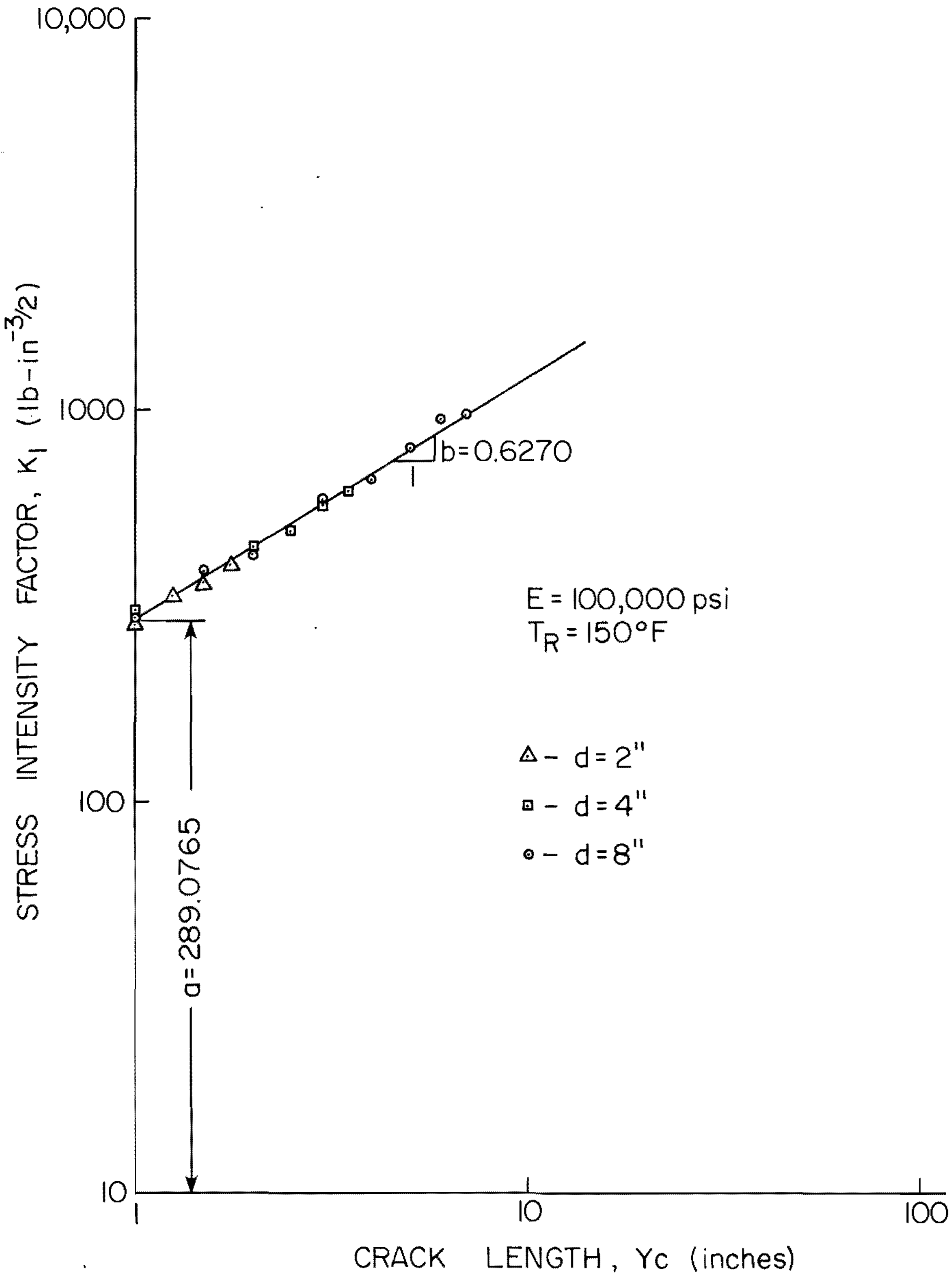


Figure A3. Stress Intensity Factor Versus Crack Length

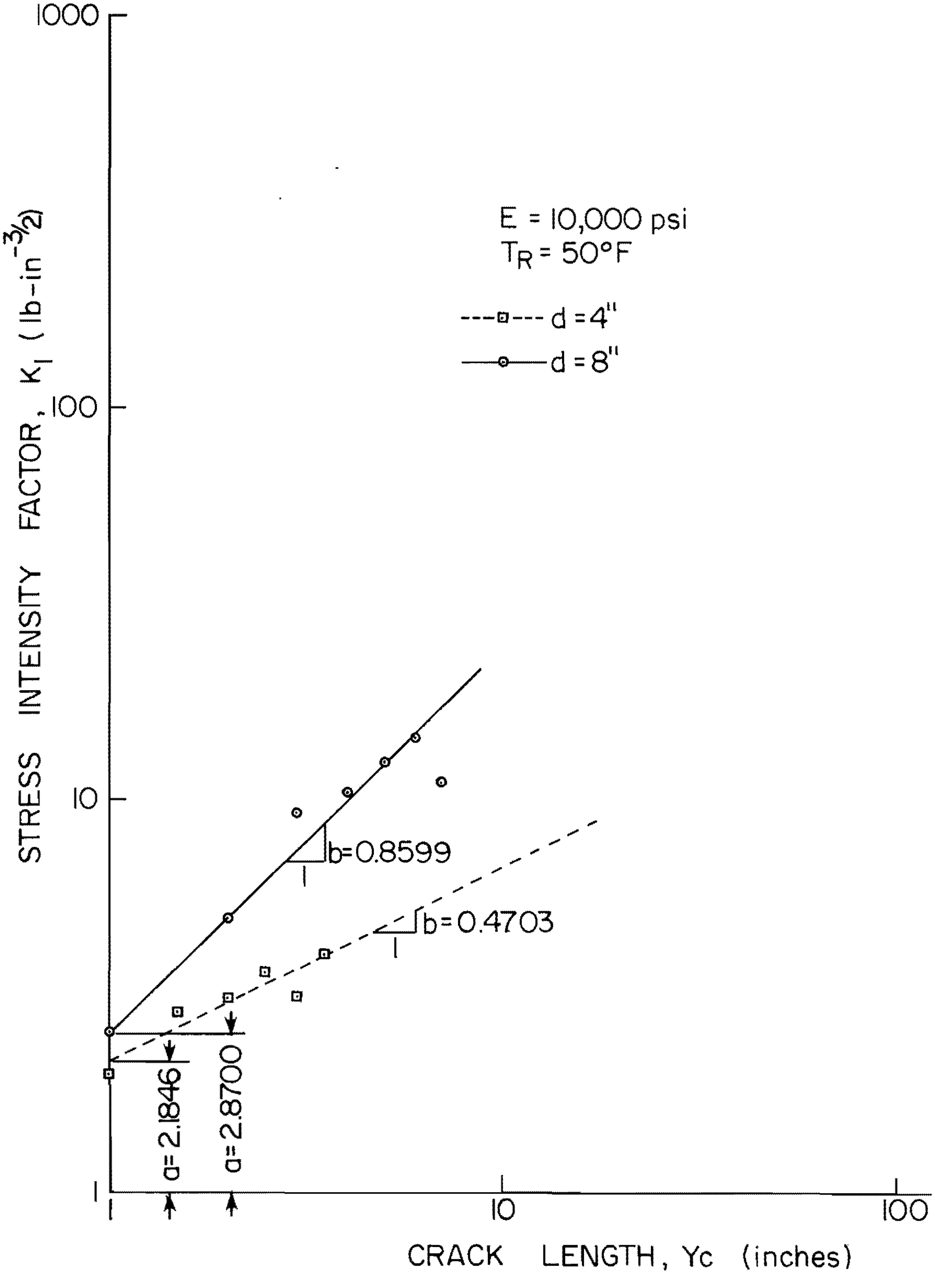


Figure A4. Stress Intensity Factor Versus Crack Length

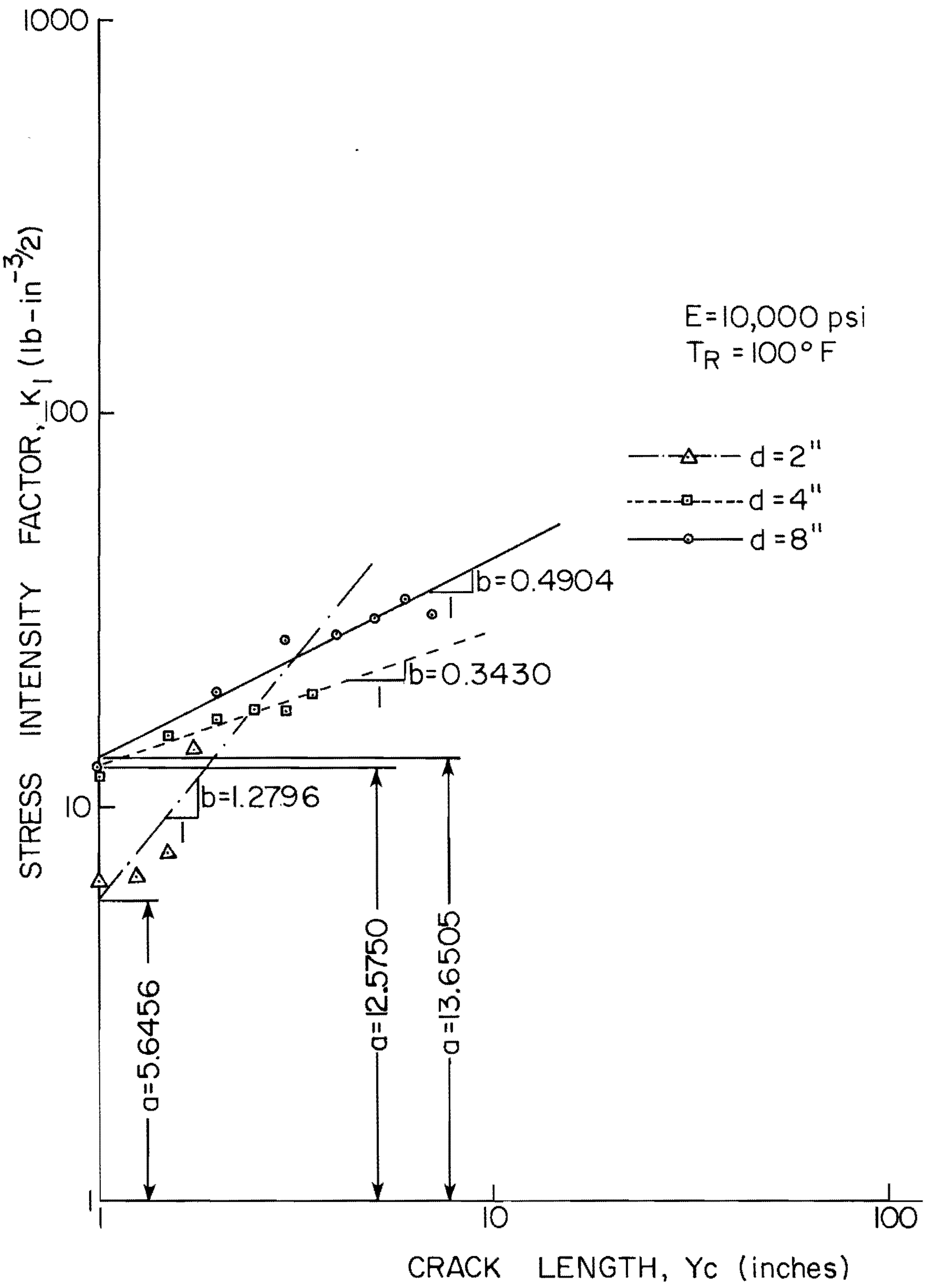


Figure A-5. Stress Intensity Factor Versus Crack Length

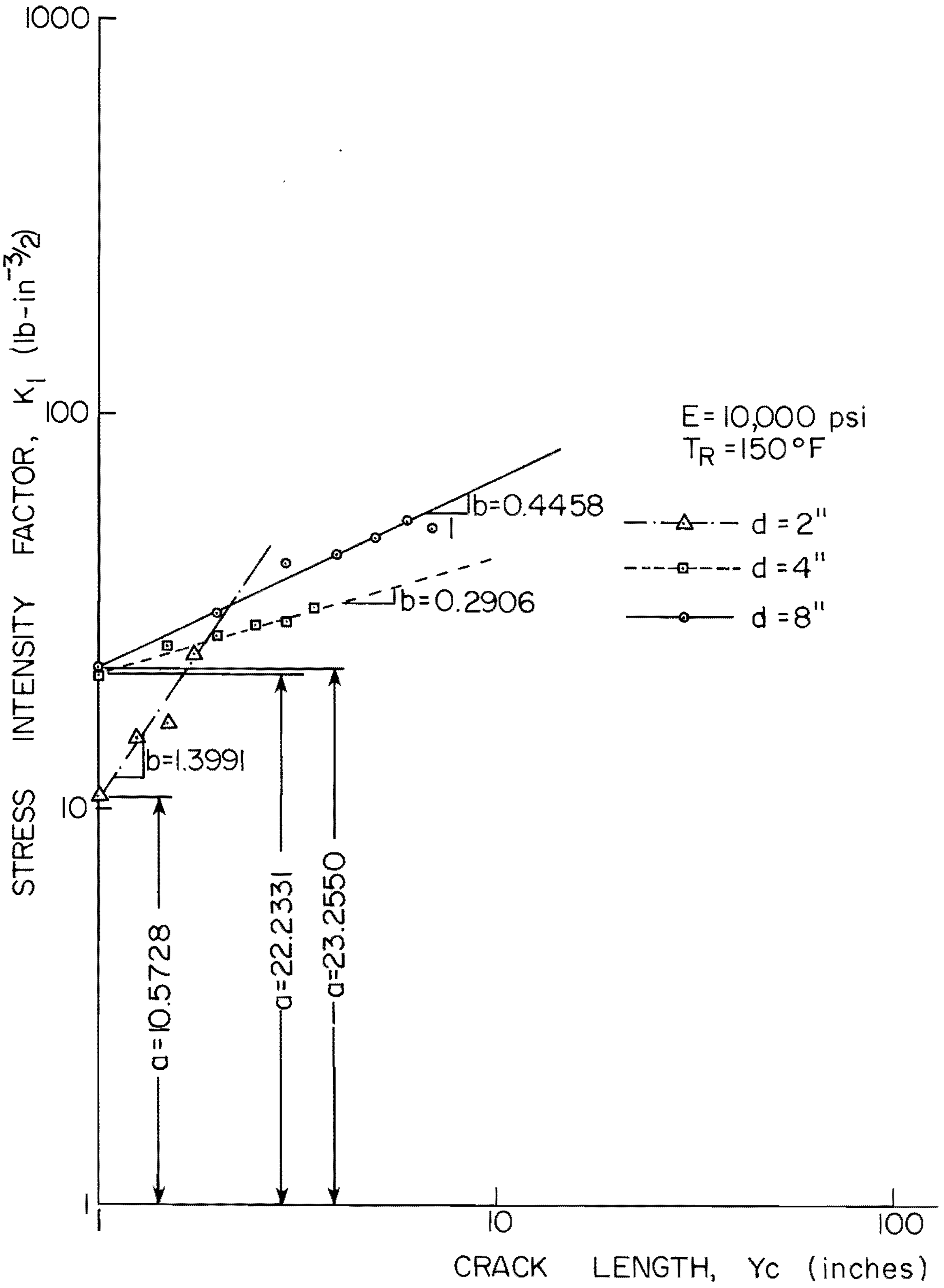


Figure A6. Stress Intensity Factor Versus Crack Length

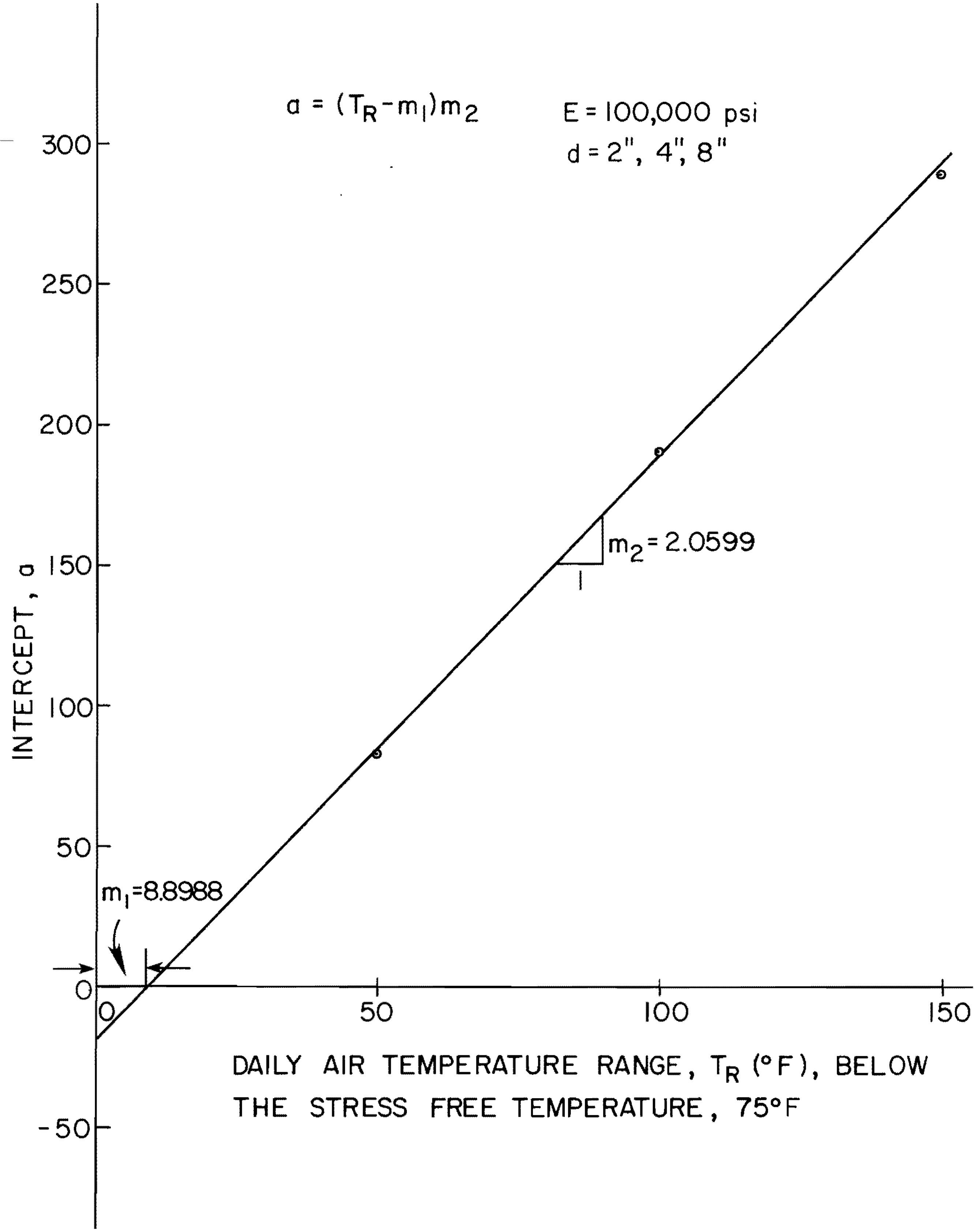


Figure A7. Intercept, a, Versus Daily Air Temperature Range Below the Stress Free Temperature

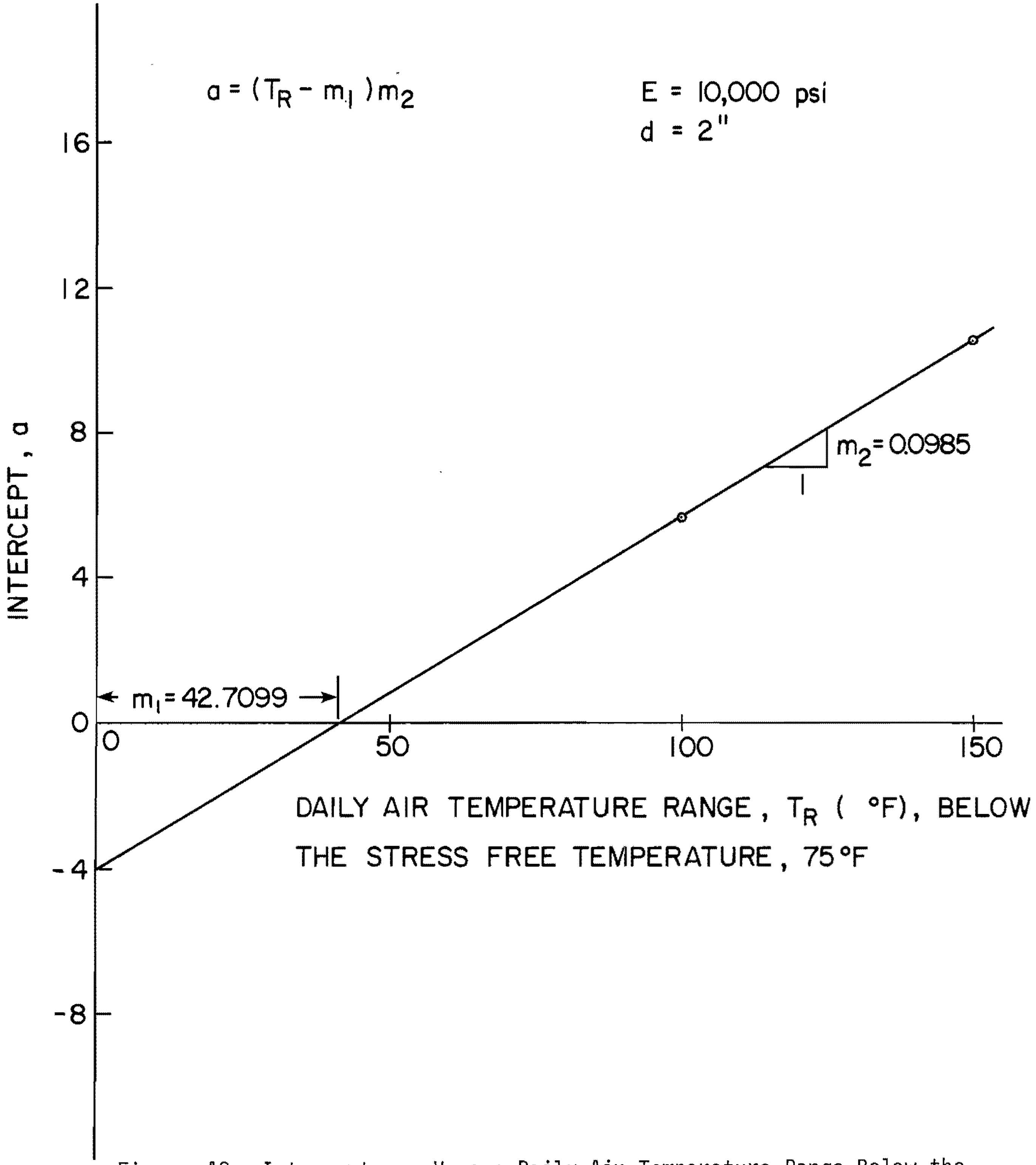


Figure A8. Intercept, a, Versus Daily Air Temperature Range Below the Stress Free Temperature

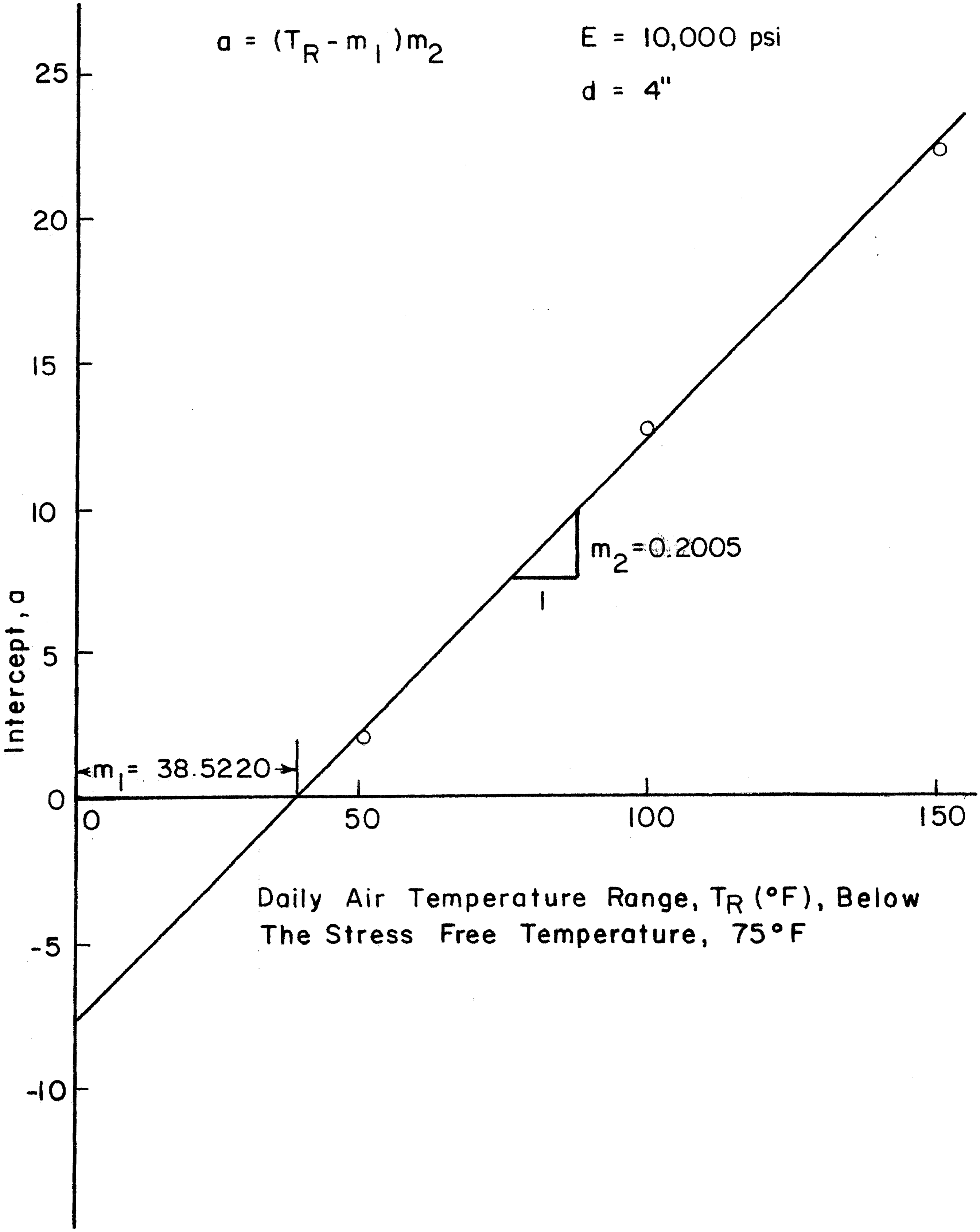


Figure A9. Intercept, a, Versus Daily Air Temperature Range Below the Stress Free Temperature.

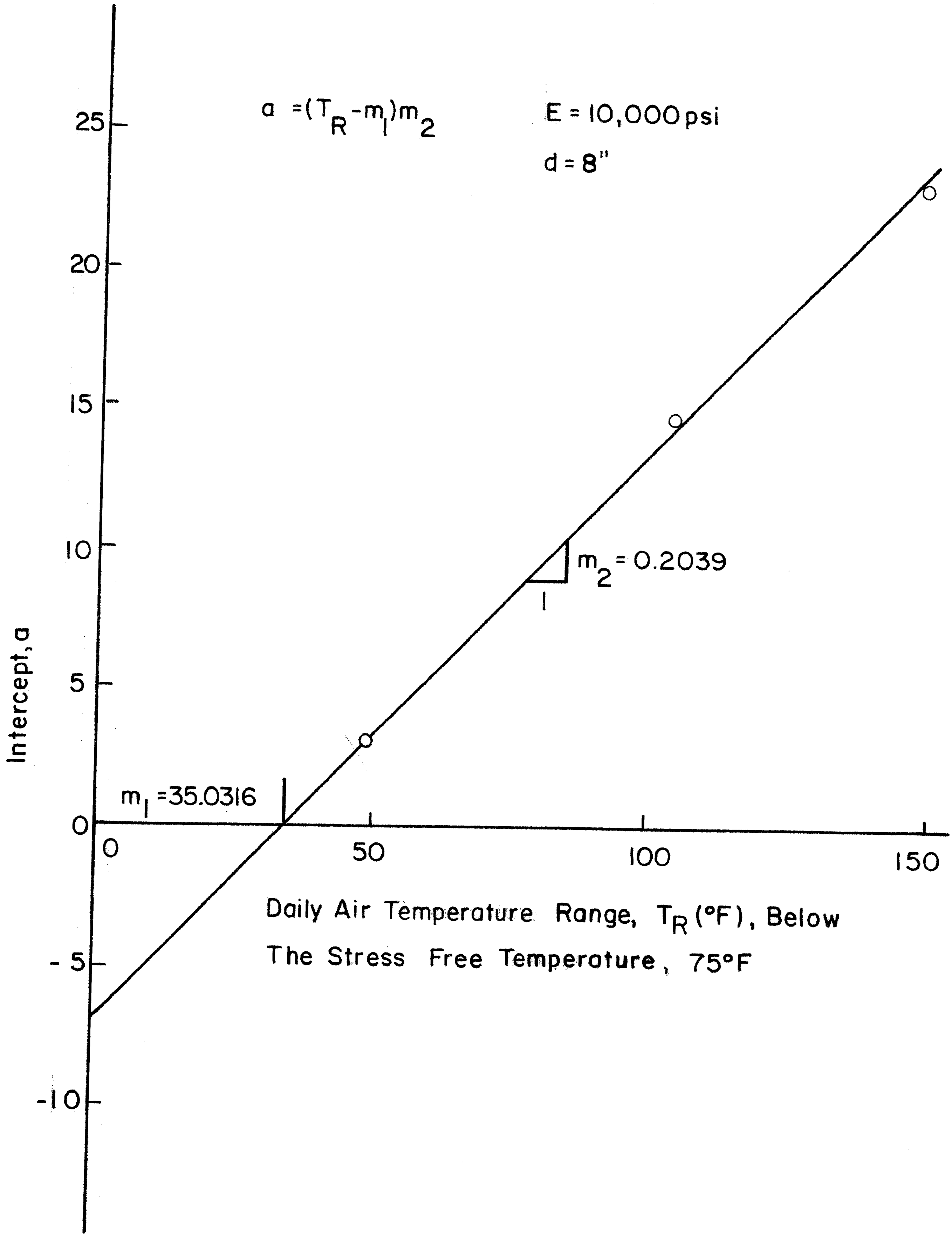


Figure A10. Intercept, a, Versus Daily Air Temperature Range Below the Stress Free Temperature.

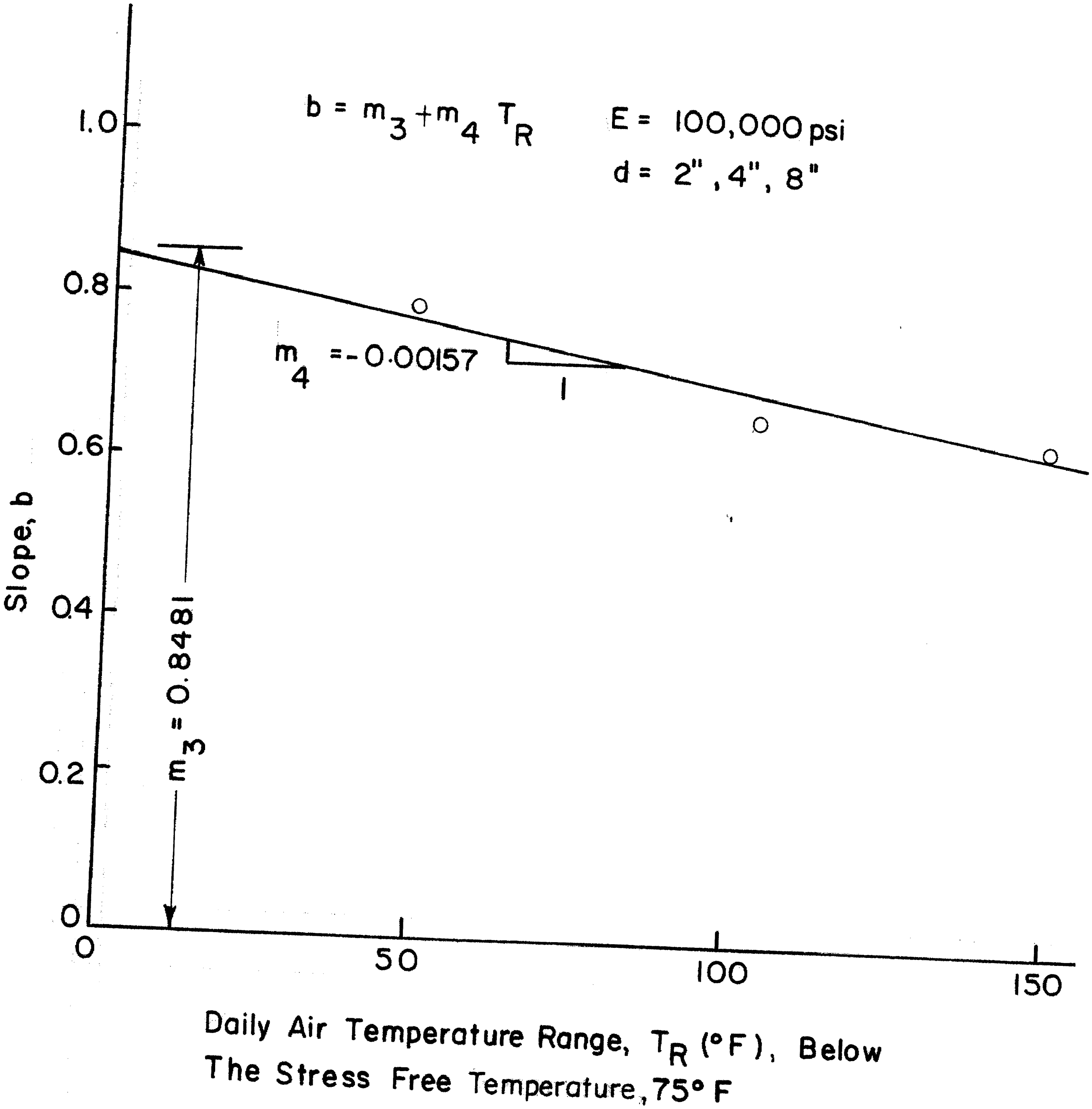


Figure A11. Slope, b, Versus Daily Air Temperature Range Below the Stress Free Temperature.

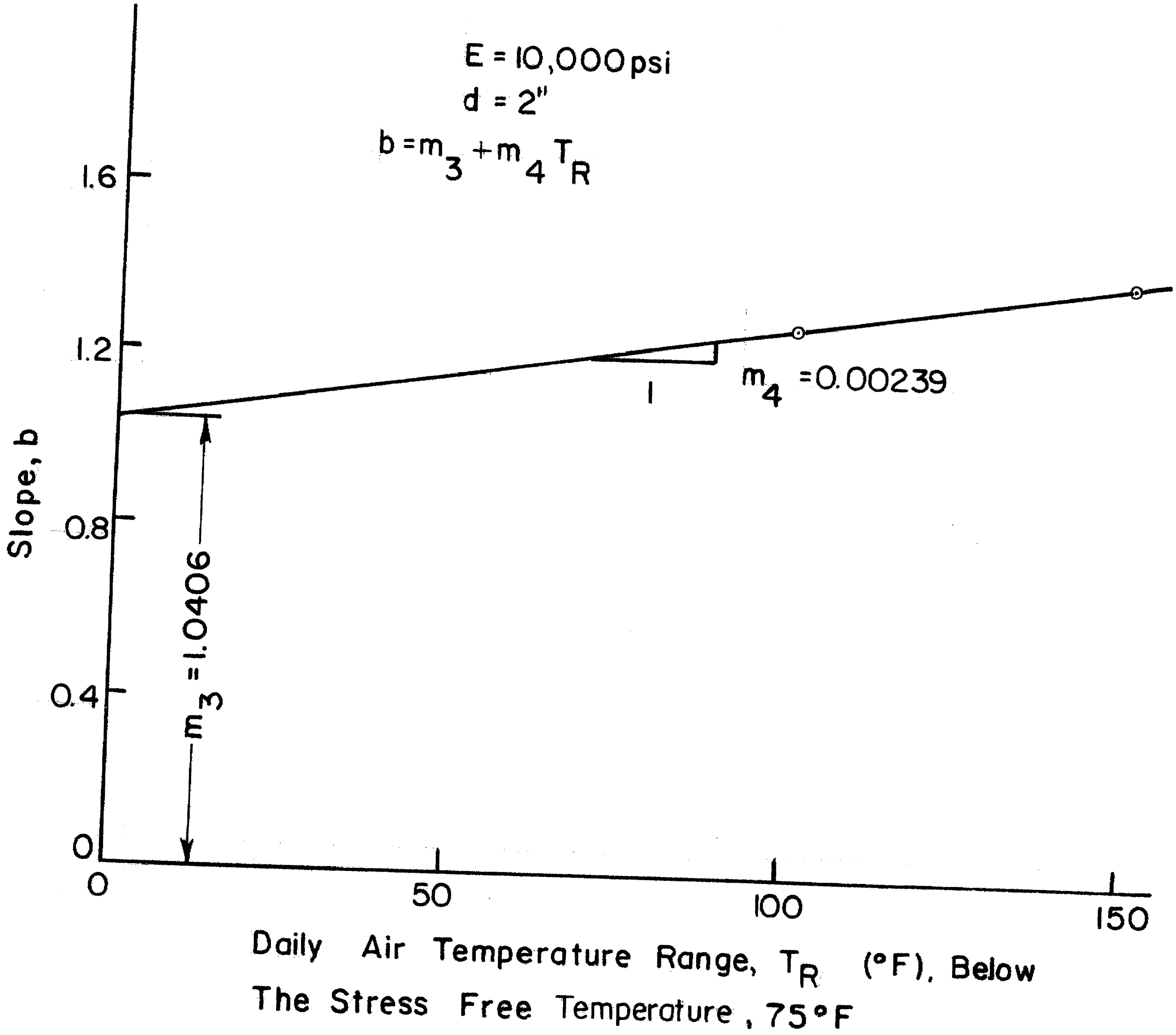


Figure A12. Slope, b, Versus Daily Air Temperature Range Below the Stress Free Temperature.

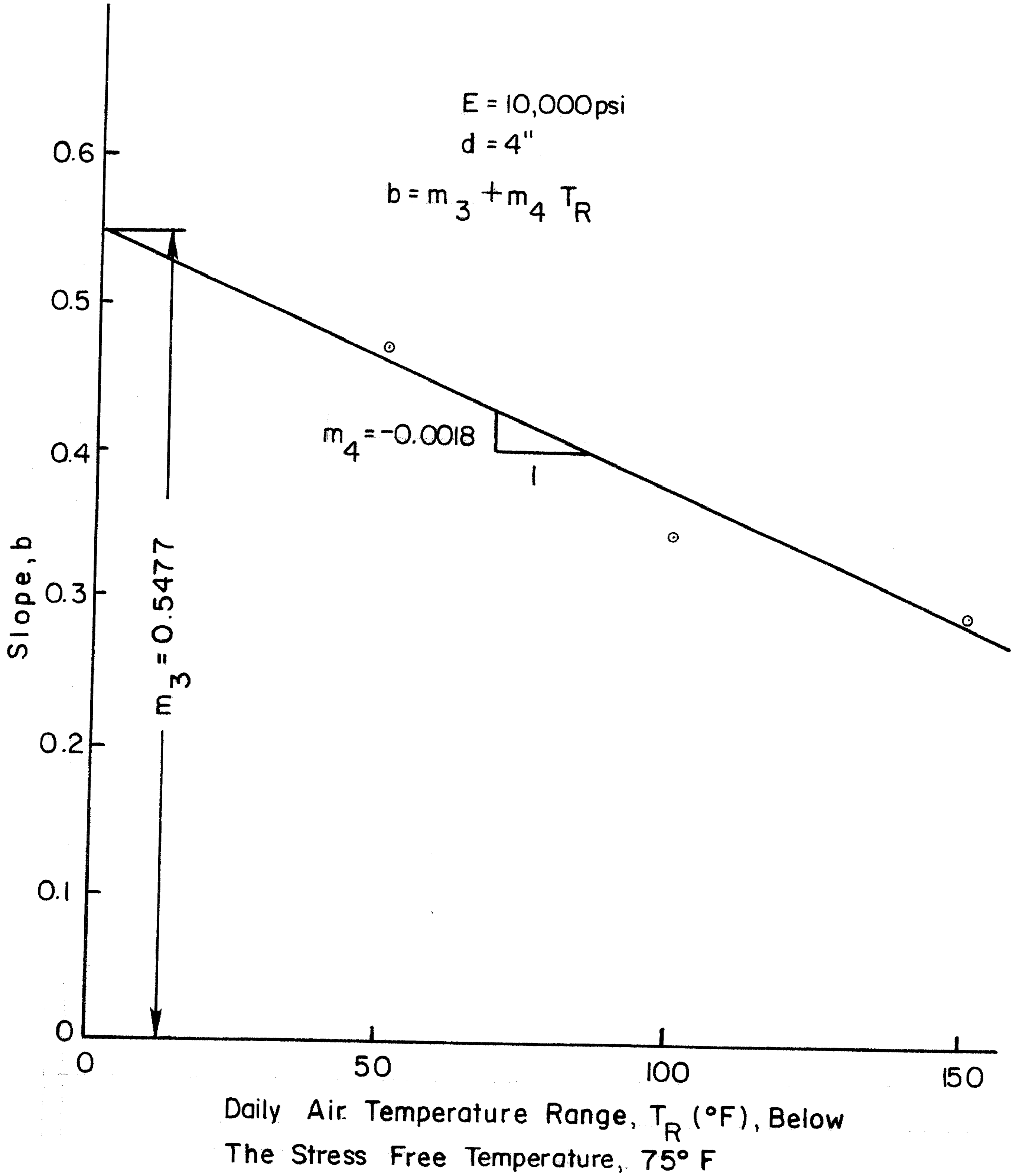


Figure A13. Slope, b, Versus Daily Air Temperature Range Below the Stress Free Temperature.

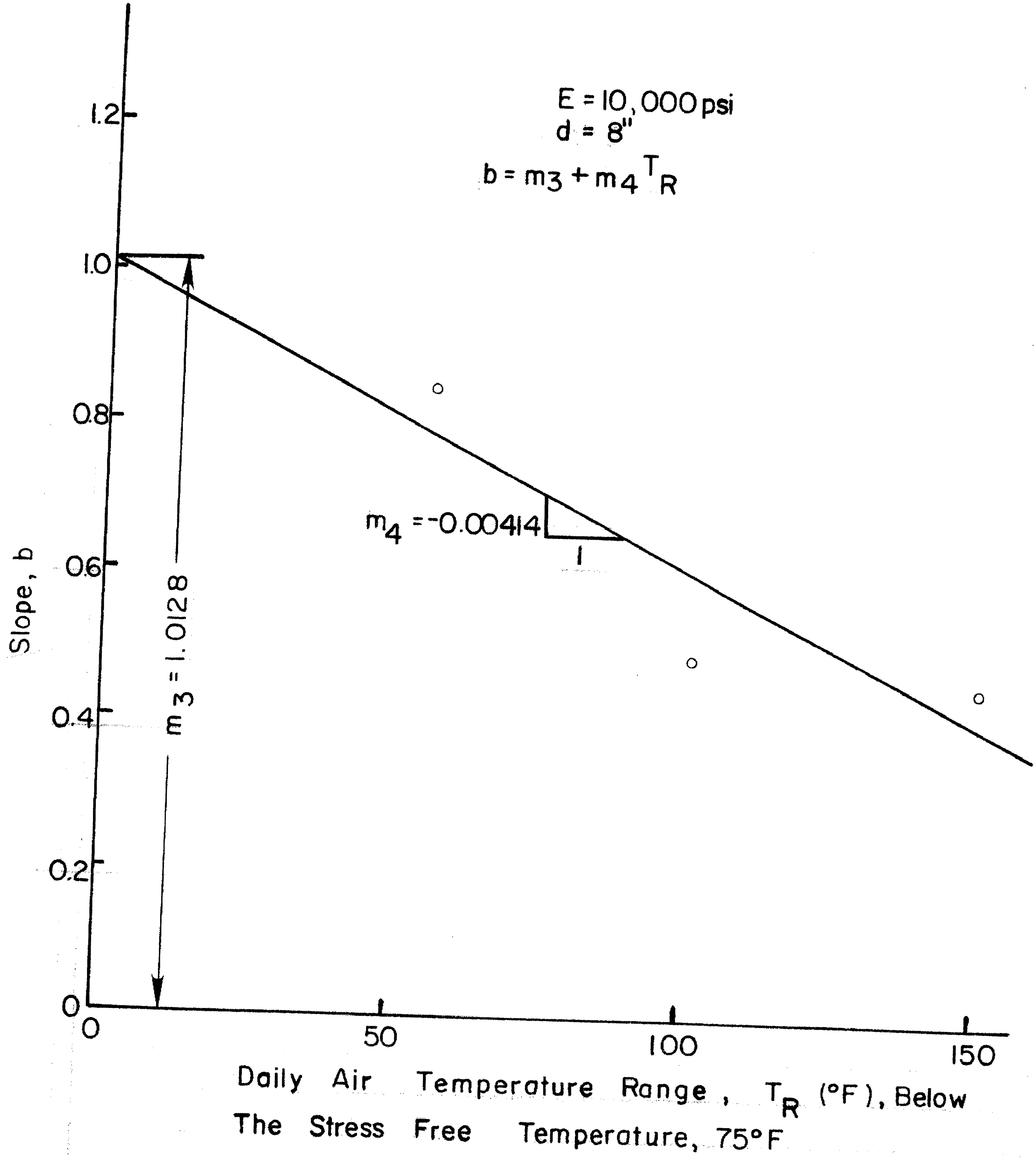


Figure A14. Slope, b, Versus Daily Air Temperature Range Below the Stress Free Temperature.

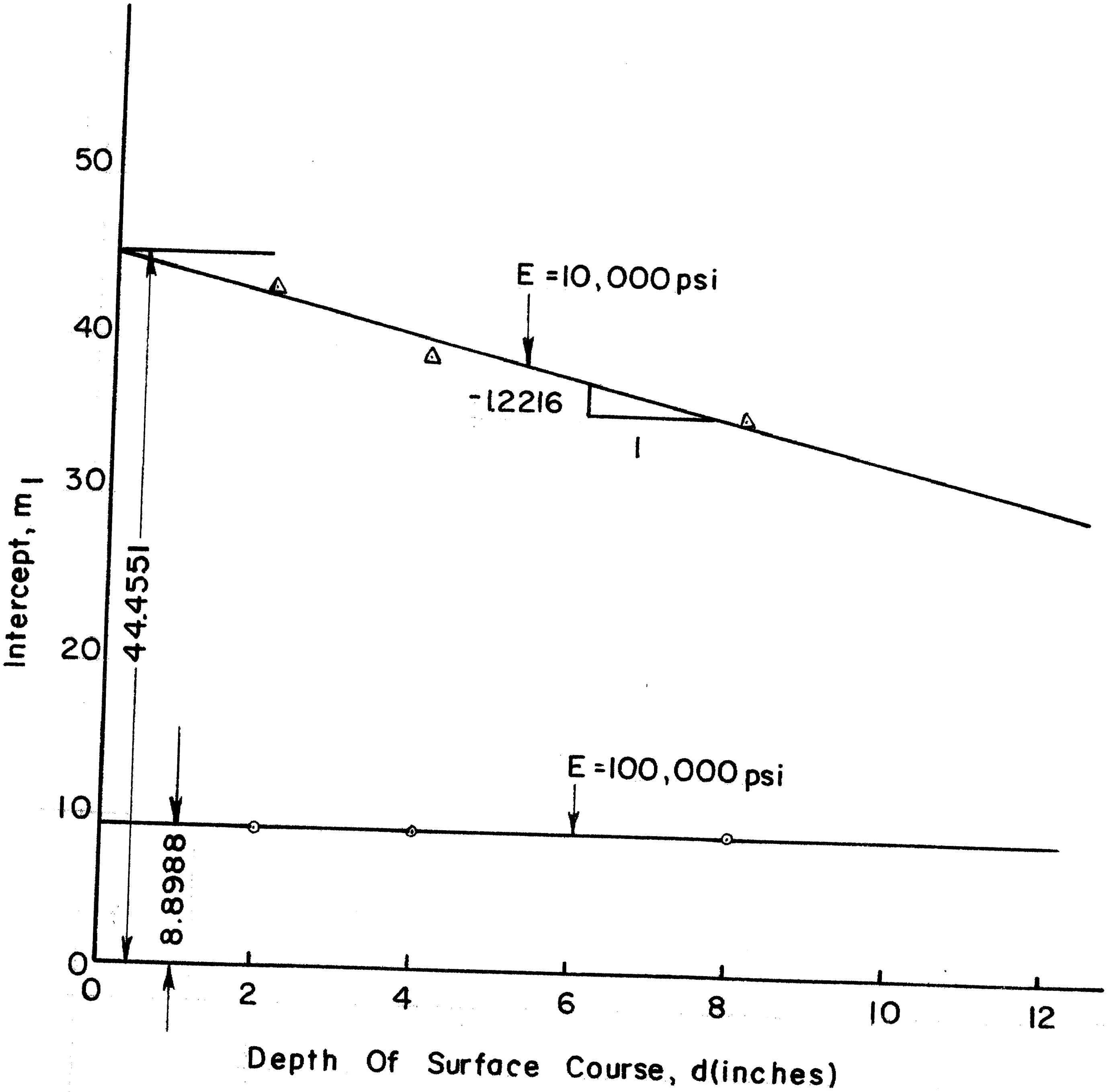


Figure A15. Intercept, m_1, Versus Depth of Surface Course.

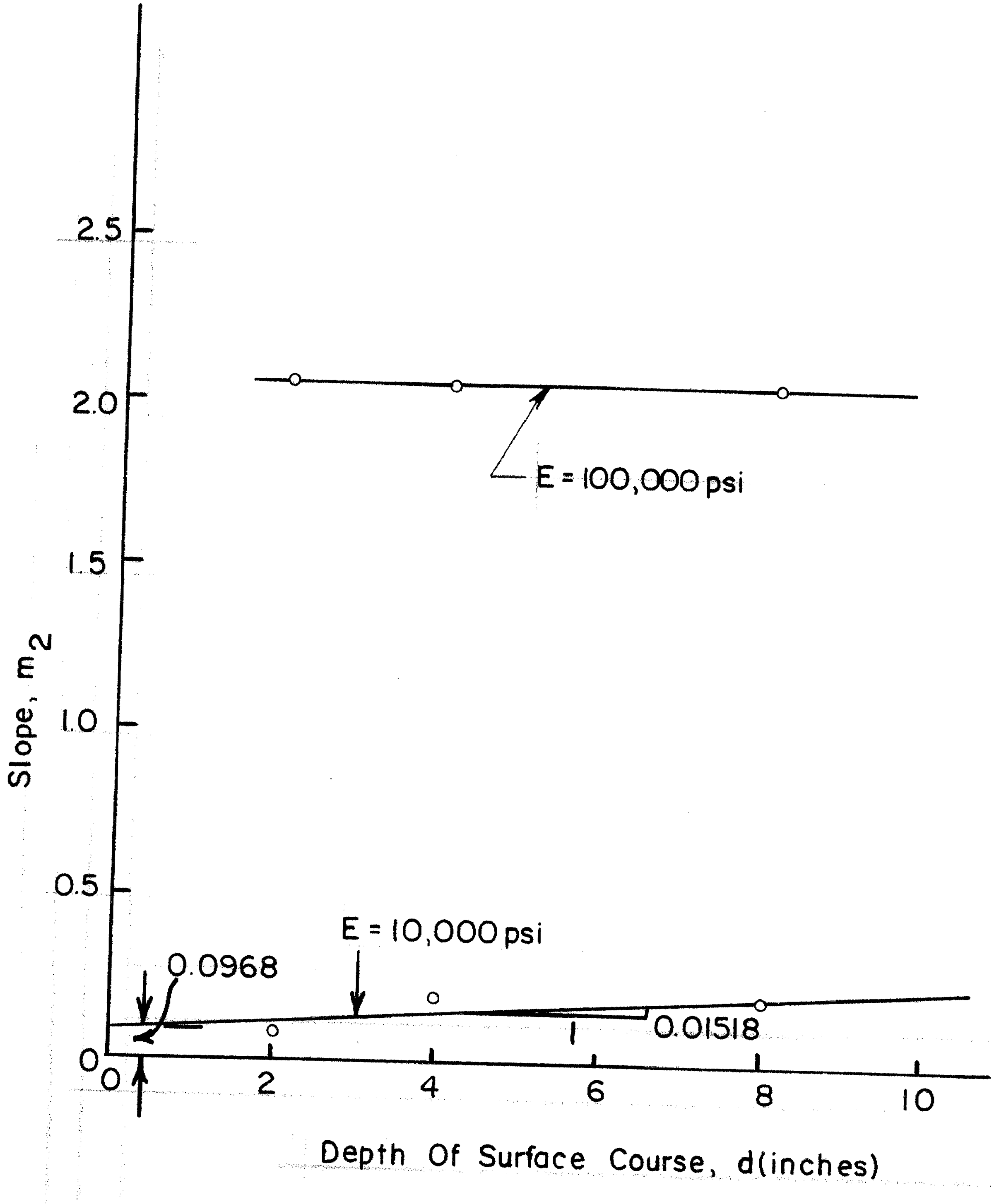


Figure A16. Slope, m_2, Versus Depth of Surface Course.

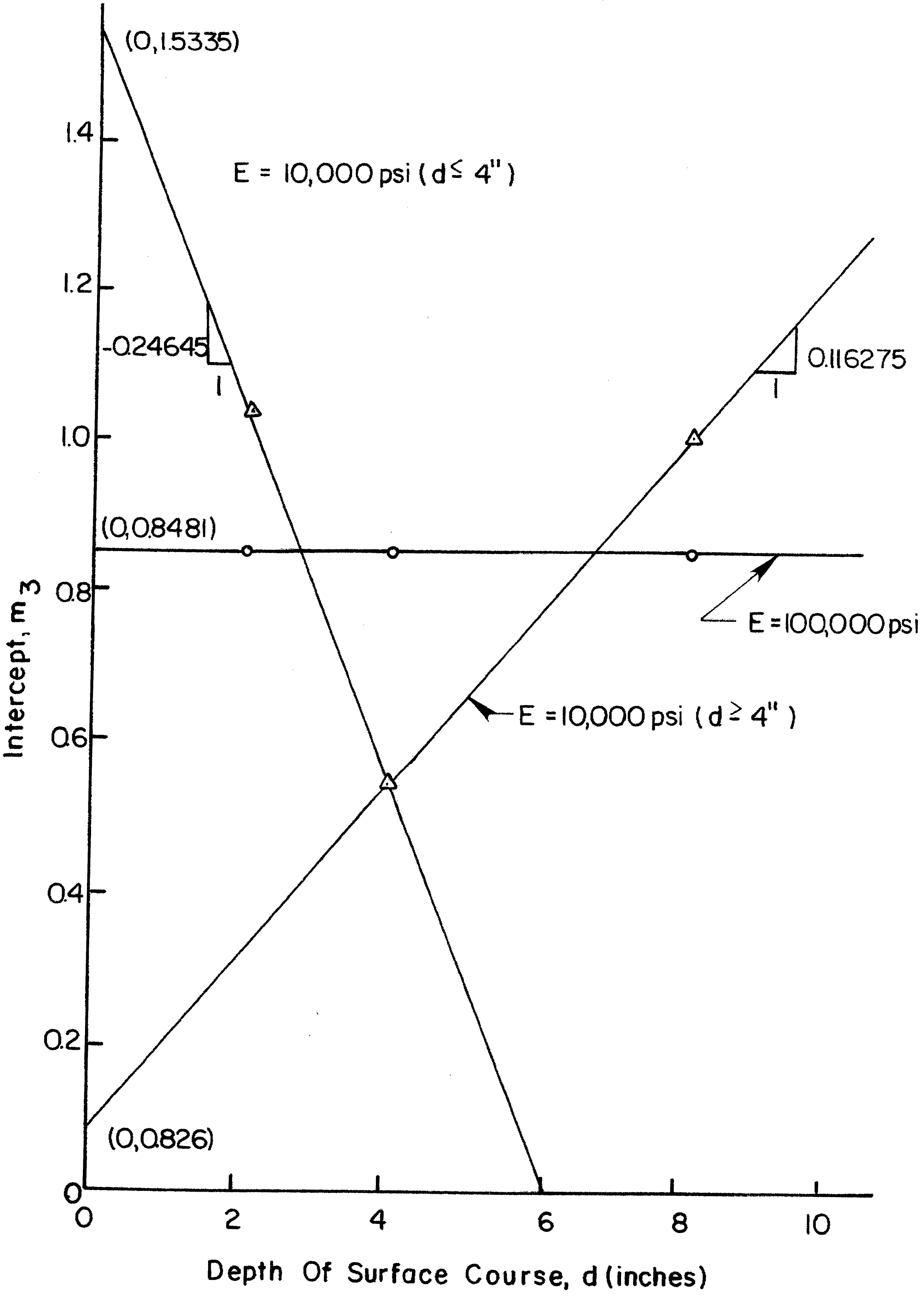


Figure A17. Intercept, m_3, Versus Depth of Surface Course.

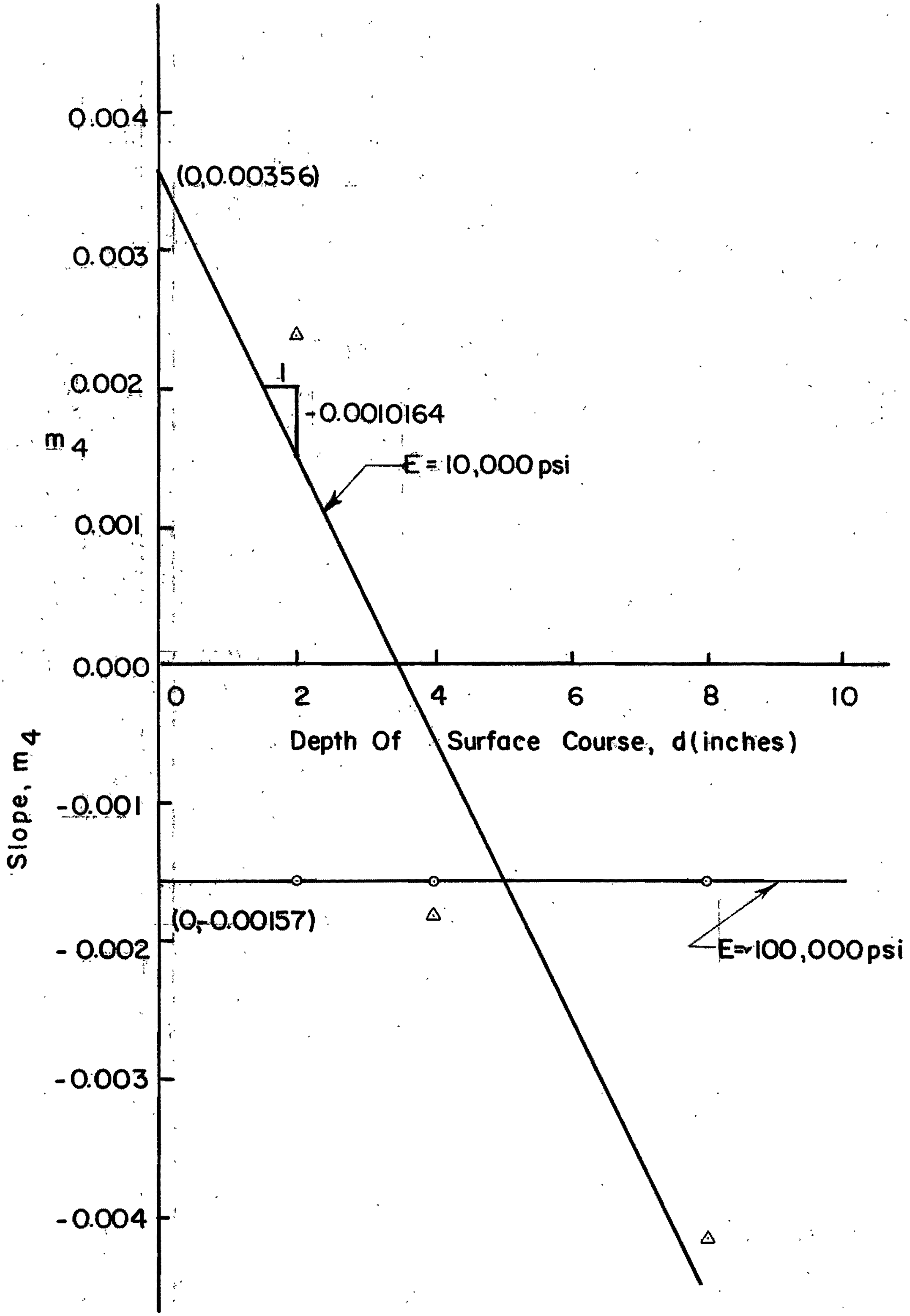


Figure A18. Slope, m_4, Versus Depth of Surface Course.

APPENDIX B

Computer Model To Predict Thermal Cracking

APPENDIX B

COMPUTER MODEL TO PREDICT THERMAL CRACKING

This model, based on fracture mechanics, has been developed to predict the occurrence of transverse cracking in asphalt concrete pavements due to temperature changes. Cracks are assumed to begin at the surface of the pavement and propagate downward as temperature cycling occurs. There are two programs, VISCO and THERM, in the thermal cracking model. Program VISCO makes use of Van der Poel's nomograph (10) as computerized by de Bats' (11) to calculate stiffness of the asphalt, which is used to compute the stiffness of the mix, given various loading times. The viscoelastic properties of the asphalt concrete mix are computed in the VISCO program for every year, assuming that the asphalt ages with time. In this program, the asphalt can be aged up to 10 years. Program THERM, uses viscoelastic properties, thermal properties, and material properties of the asphalt concrete mix, air temperature, wind velocity, and solar radiation. The thermal cracking program computes the cumulative damage indices, CMDG and CMDG1. The computations of CMDG and CMDG1 are shown in the Flow Chart, pages B-3 through B-10.

Other versions of Programs VISCO and THERM, in which the asphalt does not age, compute the cumulative damage indices, CMDG and CMDG1 when the crack length, $Y_c > 1.0$ inches, i.e., when $Y_c > 1.0$ inches (the original properties of the asphalt are used); these versions of the programs are called VISCO1 and THERM1. A Flow Chart for them is on pages B-11 through B-19. The input data guide for VISCO, THERM, VISCO1, and THERM1 are given on pages B-20 through B-26. Listings of each of these programs are given and sample runs with both input and output data follow.

FLOW CHART OF THERMAL CRACKING PROGRAM
WITH AGING, THERM,
WHICH MAKES USE OF VISCO

INPUT TAPE 05

W = DENSITY OF THE ASPHALT CONCRETE, PCF.

S = SPECIFIC HEAT OF THE ASPHALT CONCRETE, BTU/LB, °F.

AK = THERMAL CONDUCTIVITY OF THE ASPHALT CONCRETE, BTU/FT^{2}/HR, °F/FT.

B = THE ABSORBTIVITY OF THE ASPHALT CONCRETE.

DO = INITIAL CRACK LENGTH, INCHES.

DF = DEPTH OF THE ASPHALT CONCRETE, INCHES.

VMPH = AVERAGE WIND VELOCITY, MPH.

NSEL = STARTING DATE: YR/MO/DY.

SR1 = THE AVERAGE SOLAR RADIATION FOR JULY, LANGLEYS PER DAY.

SRM = THE YEARLY AVERAGE SOLAR RADIATION, LANGLEYS PER DAY.

INPUT TAPE 02 (FROM VISCO)

IMODE = MODES 1, 2, & 3.

IAGE = NUMBER OF YEARS TO BE RUN.

CV = (AGGREGATE VOLUME)/(AGGREGATE VOLUME + ASPHALT VOLUME).

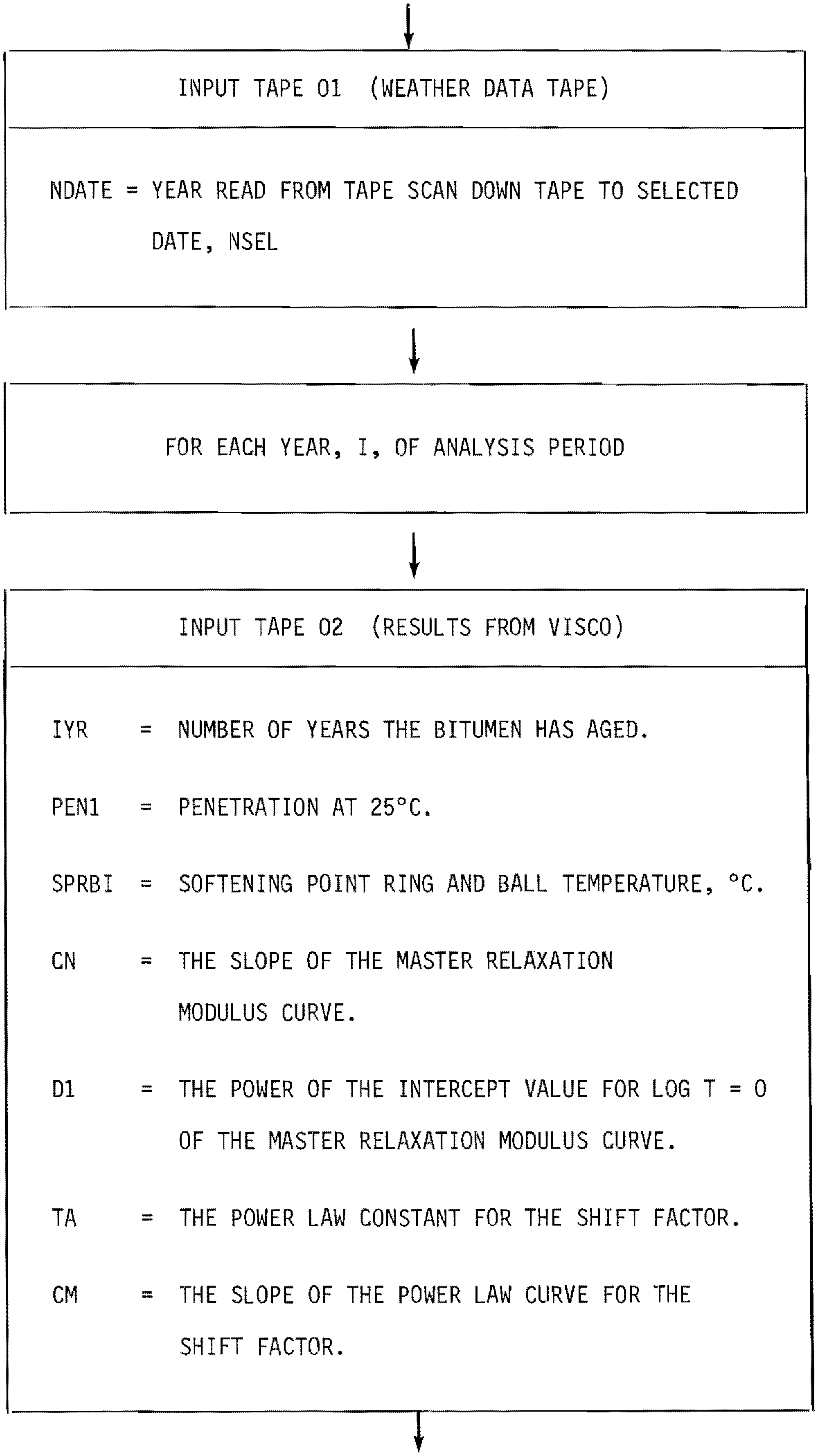
SPRB = ORIGINAL SOFTENING POINT RING AND BALL TEMPERATURE, °C. (IMODE = 1 OR 2)

PI = ORIGINAL PENETRATION INDEX. (IMODE = 1)

TPEN2 = ORIGINAL TEMPERATURE OF REFERENCE PENETRATION, °C. (IMODE = 3)

PEN1 = ORIGINAL PENETRATION AT 25°C. (IMODE = 2 OR 3)

PEN2 = ORIGINAL REFERENCE PENETRATION AT TPEN2. (IMODE = 3)



INPUT TAPE 01 (WEATHER DATA TAPE)

NDATE = YEAR READ FROM TAPE SCAN DOWN TAPE TO SELECTED DATE, NSEL

FOR EACH YEAR, I, OF ANALYSIS PERIOD

INPUT TAPE 02 (RESULTS FROM VISCO)

IYR = NUMBER OF YEARS THE BITUMEN HAS AGED.

PEN1 = PENETRATION AT 25°C.

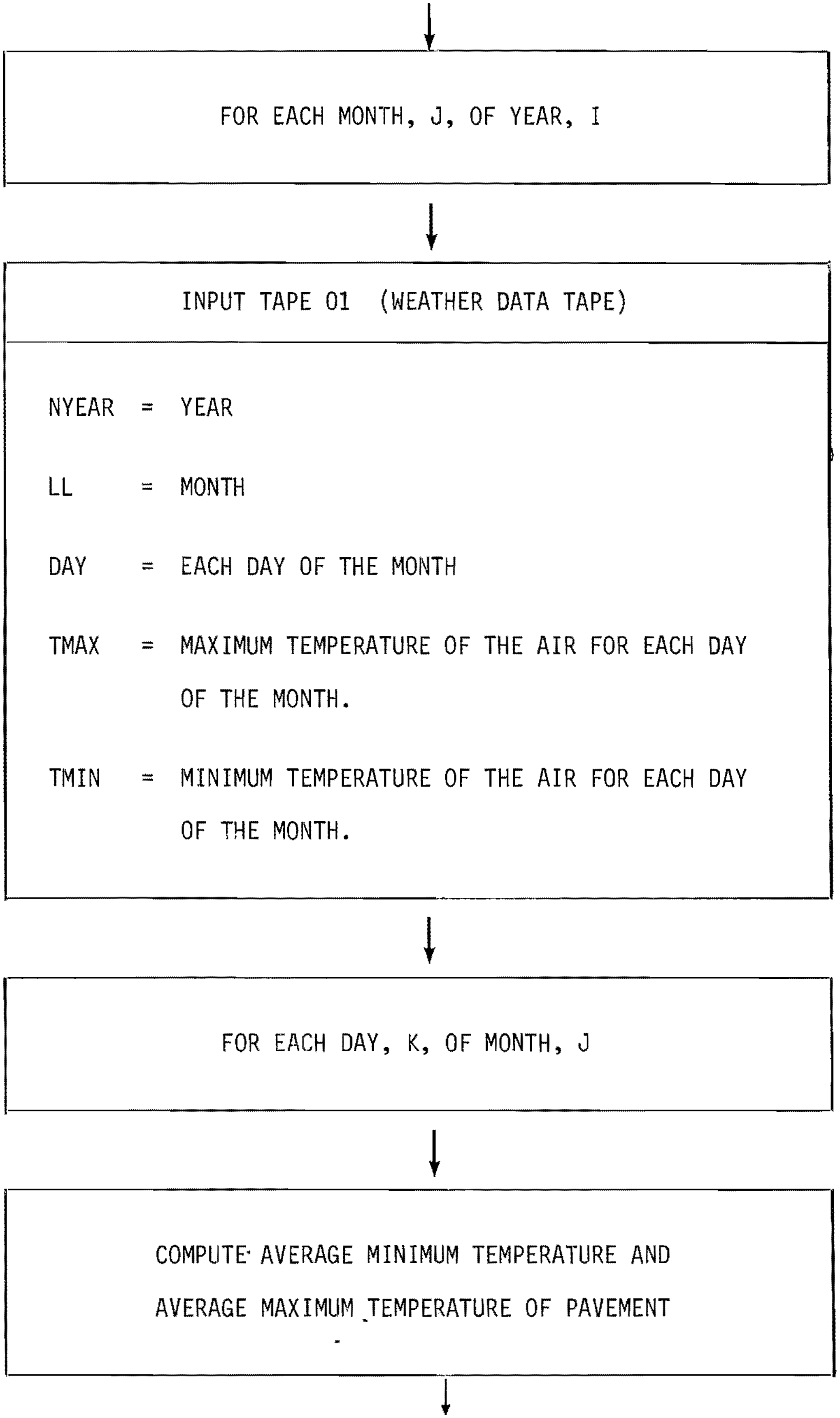
SPRBI = SOFTENING POINT RING AND BALL TEMPERATURE, °C.

CN = THE SLOPE OF THE MASTER RELAXATION MODULUS CURVE.

D1 = THE POWER OF THE INTERCEPT VALUE FOR LOG T = 0 OF THE MASTER RELAXATION MODULUS CURVE.

TA = THE POWER LAW CONSTANT FOR THE SHIFT FACTOR.

CM = THE SLOPE OF THE POWER LAW CURVE FOR THE SHIFT FACTOR.


FOR EACH MONTH, J, OF YEAR, I
INPUT TAPE 01 (WEATHER DATA TAPE)
NYEAR = YEAR
LL = MONTH
DAY = EACH DAY OF THE MONTH
TMAX = MAXIMUM TEMPERATURE OF THE AIR FOR EACH DAY OF THE MONTH.
TMIN = MINIMUM TEMPERATURE OF THE AIR FOR EACH DAY OF THE MONTH.
FOR EACH DAY, K, OF MONTH, J
COMPUTE AVERAGE MINIMUM TEMPERATURE AND AVERAGE MAXIMUM TEMPERATURE OF PAVEMENT

↓

COMPUTE EFFECTIVE MODULUS OF ELASTICITY AT AVERAGE MINIMUM AND MAXIMUM TEMPERATURES OF THE PAVEMENT USING SUBROUTINES CURVE, COOL, HEAT, INTGRT, AND FACTOR.

↓

COMPUTE STRESS INTENSITY FACTOR AT MAXIMUM TEMPERATURE (KTMX) AND AT MINIMUM TEMPERATURE (KTMN) OF THE PAVEMENT USING SUBROUTINE, FACTOR.

↓

COMPUTE THE DIFFERENCE OF STRESS INTENSITY FACTOR (ΔK) BETWEEN MAXIMUM AND MINIMUM TEMPERATURES. COMPUTE THE CHANGE IN CRACK LENGTH AND THE TOTAL CRACK LENGTH, YC.

↓

COMPUTE NUMBER OF TEMPERATURE CYCLES TO FAILURE

METHOD 1

$$NFO = 1 + \int_{DO}^{DF} \frac{dc}{A(\Delta K)^n}$$

FOR THE FIRST DAY WHEN THE TEMPERATURE CYCLE OCCURS

$$NF = \int_{YC(ID)}^{DF} \frac{dc}{A(\Delta K)^n}$$

FOR THE SUCCESSIVE DAYS WHEN THE TEMPERATURE CYCLE OCCURS

METHOD 2

$$NF1 = \int_{DO}^{DF} \frac{dc}{A(\Delta K)^n}$$

COMPUTE CUMULATIVE DAMAGE INDEX

METHOD 1

$$CMDG = \frac{1}{NFO} + \sum_{L} \frac{1}{NF}$$

METHOD 2

$$CMDG1 = \sum_{L} \frac{1}{NF1}$$

WHERE L = SET OF DAYS WHEN TEMPERATURE CYCLING OCCURS

AT THE END OF THE MONTH, J, PRINT OUT THE CURRENT RESULTS.

FLOW CHART OF THERMAL CRACKING PROGRAM WITH NO AGING WHEN CRACK LENGTH, YC, IS GREATER THAN 1.00 INCH (THERM1) WHICH MAKES USE OF VISCO1

INPUT TAPE 05

W = DENSITY OF THE ASPHALT CONCRETE, PCF.

S = SPECIFIC HEAT OF THE ASPHALT CONCRETE, BTU/LB, °F.

AK = THERMAL CONDUCTIVITY OF THE ASPHALT CONCRETE, BTU/FT^2/HR, °F/FT.

B = THE ABSORBTIVITY OF THE ASPHALT CONCRETE.

DO = INITIAL CRACK LENGTH, INCHES.

DF = DEPTH OF THE ASPHALT CONCRETE, INCHES.

VMPH = AVERAGE WIND VELOCITY, MPH.

NSEL = STARTING DATE: YR/MO/DY.

SR1 = THE AVERAGE SOLAR RADIATION FOR JULY, LANGLEYS PER DAY.

SRM = THE YEARLY AVERAGE SOLAR RADIATION, LANGLEYS PER DAY.

INPUT TAPE 02 (FROM VISCO)

IMODE = MODES 1, 2, & 3.

IAGE = NUMBER OF YEARS TO BE RUN.

CV = (AGGREGATE VOLUME)/(AGGREGATE VOLUME + ASPHALT VOLUME)

SPRB = ORIGINAL SOFTENING POINT RING AND BALL TEMPERATURE, °C. (IMODE = 1 OR 2)

PI = ORIGINAL PENETRATION INDEX. (IMODE = 1)

TPEN2 = ORIGINAL TEMPERATURE OF REFERENCE PENETRATION, °C. (IMODE = 3)

PEN1 = ORIGINAL PENETRATION AT 25°C. (IMODE = 2 OR 3)

PEN2 = ORIGINAL REFERENCE PENETRATION AT TPEN2. (IMODE = 3)

INPUT TAPE 01 (WEATHER DATA TAPE)

NDATE = YEAR READ FROM TAPE. SCAN DOWN TAPE TO SELECTED DATE, NSEL.

INPUT TAPE 02 (RESULTS FROM VISCO1)
(VARIABLES OF BITUMEN WITHOUT AGING)

IYR = NUMBER OF YEARS THE BITUMEN HAS AGED (IN THIS CASE IYR = -1, ie NO AGING)

DUM1 = PEN1

DUM2 = SPRB

DUM3 = CN, THE SLOPE OF THE MASTER RELAXATION MODULUS CURVE.

DUM4 = D1, THE POWER OF THE INTERCEPT VALUE FOR LOG T = 0 OF THE MASTER RELAXATION MODULUS CURVE.

DUM5 = TA, THE POWER LAW CONSTANT FOR THE SHIFT FACTOR.

DUM6 = CM, THE SLOPE OF THE POWER LAW CURVE FOR THE SHIFT FACTOR.

FOR EACH YEAR, I, OF ANALYSIS PERIOD

INPUT TAPE 02 (RESULTS FROM VISCO)

IYR = NUMBER OF YEARS THE BITUMEN HAS AGED.

PEN1 = PENETRATION AT 25°C.

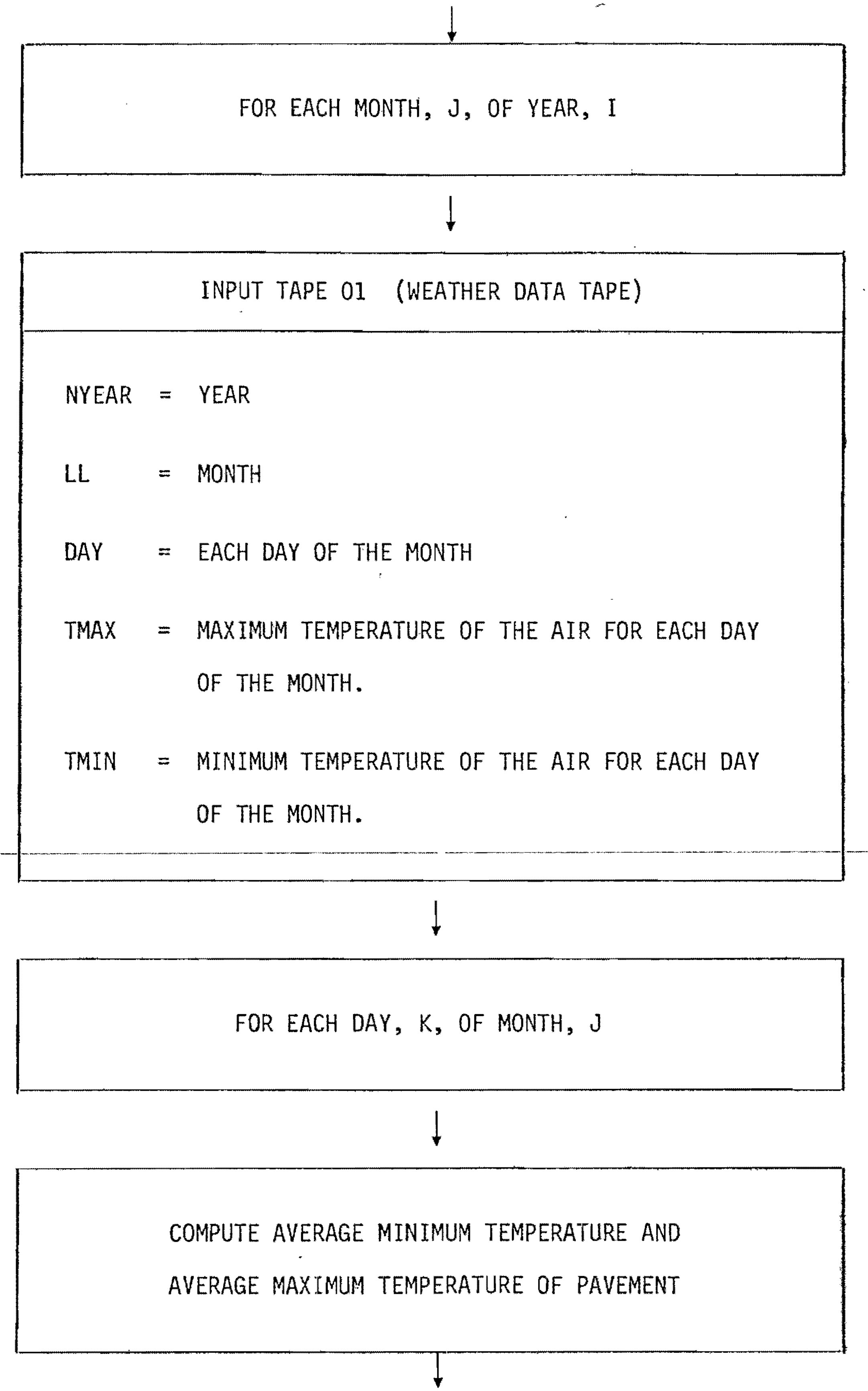
SPRBI = SOFTENING POINT RING AND BALL TEMPERATURE, °C.

CN = THE SLOPE OF THE MASTER RELAXATION MODULUS CURVE.

D1 = THE POWER OF THE INTERCEPT VALUE FOR LOG T = 0 OF THE MASTER RELAXATION MODULUS CURVE.

TA = THE POWER LAW CONSTANT FOR THE SHIFT FACTOR.

CM = THE SLOPE OF THE POWER LAW CURVE FOR THE SHIFT FACTOR.



FOR EACH MONTH, J, OF YEAR, I

INPUT TAPE 01 (WEATHER DATA TAPE)

NYEAR = YEAR

LL = MONTH

DAY = EACH DAY OF THE MONTH

TMAX = MAXIMUM TEMPERATURE OF THE AIR FOR EACH DAY OF THE MONTH.

TMIN = MINIMUM TEMPERATURE OF THE AIR FOR EACH DAY OF THE MONTH.

FOR EACH DAY, K, OF MONTH, J

COMPUTE AVERAGE MINIMUM TEMPERATURE AND AVERAGE MAXIMUM TEMPERATURE OF PAVEMENT

COMPUTE EFFECTIVE MODULUS OF ELASTICITY AT AVERAGE MINIMUM AND MAXIMUM TEMPERATURES OF THE PAVEMENT USING SUBROUTINES CURVE, COOL, HEAT, INTGRT, AND FACTOR.

COMPUTE STRESS INTENSITY FACTOR AT MAXIMUM TEMPERATURE (KTMX) AND AT MINIMUM TEMPERATURE (KTMN) OF THE PAVEMENT USING SUBROUTINE, FACTOR.

COMPUTE THE DIFFERENCE OF STRESS INTENSITY FACTOR (ΔK) BETWEEN MAXIMUM AND MINIMUM TEMPERATURES. COMPUTE THE CHANGE IN CRACK LENGTH AND THE TOTAL CRACK LENGTH, YC. IF YC > 1.00" THE PROGRAM USES THE ORIGINAL PROPERTIES OF BITUMEN.

COMPUTE NUMBER OF TEMPERATURE CYCLES TO FAILURE

METHOD 1

$$NFO = 1 + \int_{DO}^{DF} \frac{dc}{A(\Delta K)^n}$$

FOR THE FIRST DAY WHEN THE TEMPERATURE CYCLE OCCURS

$$NF = \int_{YC(ID)}^{DF} \frac{dc}{A(\Delta K)^n}$$

FOR THE SUCCESSIVE DAYS WHEN THE TEMPERATURE CYCLE OCCURS

METHOD 2

$$NF1 = 1 + \int_{DO}^{DF} \frac{dc}{A(\Delta K)^n}$$

COMPUTE CUMULATIVE DAMAGE INDEX

METHOD 1

$$CMDG = \frac{1}{NFO} + \sum_{L} \frac{1}{NF}$$

METHOD 2

$$CMDG1 = \sum_{L} \frac{1}{NF1}$$

WHERE L = SET OF DAYS WHEN TEMPERATURE CYCLING OCCURS

AT THE END OF THE MONTH, J, PRINT OUT THE CURRENT RESULTS.

DESCRIPTION OF INPUT DATA: VISCO, VISCO1, THERM, AND THERM1

The inputs for VISCO, VISCO1, THERM, AND THERM1 must be coded according to the following for proper execution. Inputs for VISCO and VISCO1 are the same but THERM and THERM1 do not have identical sets of input data.

Input to VISCO and VISCO1

CARD 01: (I1)

Column	Variable	Description
01	MODE	1, 2, or 3.

CARD 02: Card 02 is different for MODE 1, 2, and 3. All the input variables are for the original bitumen.

MODE 1: (3F10.2,I5)

Column	Variable	Description
01-10	PINIT	Penetration index.
11-20	SPINIT	Softening point ring and ball temperature, °C.
21-30	CV	(Aggregate volume)/(aggregate volume + ashpalt volume).
31-35	IYRS	Number of years asphalt is to be aged.

MODE 2: (3F10.2,I5)

Column	Variable	Description
01-10	P1INIT	Penetration at 25°C.
11-20	SPINIT	Same as for MODE 1.
21-30	CV	Same as for MODE 1.
31-35	IYRS	Same as for MODE 1.

MODE 3: (4F10.2,I5)

Column	Variable	Description
01-10	P1INIT	Same as for MODE 2.
11-20	P2INIT	Reference penetration at TPEN2.
21-30	TPEN2	Temperature of reference penetration, °C.
31-40	CV	Same as for MODE 1 and 2.
41-45	IYRS	Same as for MODE 1 and 2.

NOTE: A blank card should be inserted at the end of the data cards.

Input to THERM

DATA from TAPE 05

CARD 01: (15A4)

Column	Variable	Description
01-60	TITL	Title of the problem (Alpha-numeric).

CARD 02: (8F10.0)

Column	Variable	Description
01-10	W	Unit weight of the asphalt concrete, PCF.
11-20	S	Specific heat of the asphalt concrete, BTU/lb, °F.
21-30	AK	Thermal conductivity of the asphalt concrete, BTU/sq.ft/hr, °F/ft.
31-40	B	The absorbtivity of the asphalt concrete.

CARD 03: (8F10.0)

Column	Variable	Description
01-10	DO	Initial crack lengths, in. (Crack is propagating downwards).
11-20	DF	Depth of the asphalt concrete, in.
21-30	VMPH	Average wind velocity, mph.

CARD 04: (8I10)

Column	Variable	Description
01-10	NSEL	Starting date, YR/MO/DY.

CARD 05: (8F10.0)

Column	Variable	Description
01-10	SR1	The average solar radiation for July, Langleys/day.
11-20	SRM	The yearly average solar radiation, Langleys/day.

DATA from TAPE 02 (Variables from VISCO program)

CARD 01: (2I2,4F10.3)

Column	Variable	Description
01-02	IMODE	MODES 1, 2, or 3.
03-04	IAGE	(Number of years to be run) or (The number of years the bitumen is to be aged), usually both are the same.
05-14	CV	(Aggregate volume)/(aggregate volume + asphalt volume).
15-24	SPRB	Original softening point ring and ball temperature, °C (For IMODE = 1 or 2).
	or	
	TPEN2	Temperature of reference penetration, °C (For IMODE = 3).
25-34	PI	Original penetration index (IMODE = 1).
	or	
	PEN1	Original penetration at 25°C (IMODE = 2, 3).
35-44	PEN2	Reference penetration at TPEN2 (Only for IMODE = 3).

CARD 02: (I2,2F10.3)

Card 02 to 04 are for the current year.

Column	Variable	Description
01-02	IYR	The number of years the bitumen has aged [IYR = 0 (Aged 6 months, for the first year), IYR = 1 (Aged 18 months, for the second year), etc.].
03-12	PEN1	Penetration at 25°C.
13-22	SPRBI	Softening point ring and ball temperature, °C.

CARD 03: (2F10.5)

Column	Variable	Description
01-10	CN	The slope of the master relaxation modulus curve.
11-20	D1	The power of the intercept value for Log T = 0 of the master relaxation modulus curve.

CARD 04: (2F10.5)

Column	Variable	Description
01-10	TA	The power law constant for the shift factor.
11-20	CM	The slope of the power law curve for the shift factor.

DATA from TAPE 01 (Weather Tape)

CARD 01: (11X,I6)

Column	Variable	Description
12-17	NDATE	Date, YR/MO/DY, in the weather data tape (Scan down tape to selected date, NSEL).

CARD 02: (11X,3I2,2X,2F3.0)

Column	Variable	Description
12-13	NYEAR	Year (2 digits).
14-15	LL	Month (2 digits).
16-17	DAY(1)	Day (2 digits).
20-22	TMAX(1)	Maximum temperature during DAY(1), °F.
23-25	TMIN(1)	Minimum temperature during DAY(1), °F.

CARD 03: (11X,I2,2X,I2,2X,2F3.0)

Column	Variable	Description
12-13	NYEAR	Year (2 digits).
16-17	DAY(I)	Day (2 digits).
20-22	TMAX(I)	Maximum temperature during DAY(I), °F.
23-25	TMIN(I)	Minimum temperature during DAY(I), °F.

NOTE: CARD 03 must be repeated for each day of the analysis period. Format of the CARDS 01, 02, and 03 must be changed according to the format of weather data tape.

INPUT TO THERM1 (No Aging When Crack Length, Yc, > 1.0")

DATA from TAPE 05

Same as for THERM program.

DATA from TAPE 02 (Variables from VISCO1 program)

CARD 01:

Same as for THERM program.

CARD 02: (I2,210.3)

[CARD 02 to 04 are the variables of asphalt without aging (original properties of asphalt)]

Column	Variable	Description
01-02	IYR	Number of years the bitumen has aged [In this case, IYR = -1 (No aging)].
03-12	DUM1	Penetration at 25°C.
13-22	DUM2	Original softening point ring and ball temperature, °C.

CARD 03: (2F10.5)

Column	Variable	Description
01-10	DUM3	The slope of the master relaxation modulus curve, CN.
11-20	DUM4	The power of the intercept value for Log T = 0 of the master relaxation modulus curve, D1.

CARD 04: (2F10.5)

Column	Variable	Description
01-10	DUM5	The power law constant for the shift factor, TA.
11-20	DUM6	The slope of the power law curve for the shift factor, CM.

CARD 05: (I2,2F10.3)

(CARD 05 to 07 are the variables of ashpalt with aging for the current year)

Column	Variable	Description
01-02	IYR	The number of years the bitumen has aged [IYR = -1 (No aging), IYR = 0 (Aged 6 months, for the first year), IYR = 1 (Aged 18 months, for the second year), etc.].

CARD 05 (Continued):

Column	Variable	Description
03-12	PEN1	Penetration at 25°C.
13-22	SPRBI	Softening point ring and ball temperature, °C.

CARD 06: (2F10.5)

Column	Variable	Description
01-10	CN	The slope of the master relaxation modulus curve.
11-20	D1	The power of the intercept value for Log T = 0 of the master relaxation modulus curve.

CARD 07: (2F10.5)

Column	Variable	Description
01-10	TA	The power law constant for the shift factor.
11-20	CM	The slope of the power law curve for the shift factor.

DATA from TAPE 01 (Weather Tape)

Same as for THERM program.

```
C*****************************************************************
C*                                                               *
C*                 COMPUTER PROGRAM ( VISCO )                    *
C*                        TO DETERMINE                           *
C*          VISCOELASTIC PROPERTIES OF ASPHALT CONCRETE          *
C*                                                               *
C*****************************************************************
C*          EXPLANATION OF INPUT VARIABLES                       *
C*          ------------------------------                       *
C*                                                               *
C*   PINIT     PENETRATION INDEX, (PII)                          *
C*                                                               *
C*   SPINIT    SOFTENING POINT RING & BALL, DEGREES C, (SPRBI)   *
C*                                                               *
C*   P1INIT    PENETRATION AT 25 DEGREES C, (PEN1)               *
C*                                                               *
C*   P2INIT    REFERENCE PENETRATION AT TPEN2, (PEN2)            *
C*                                                               *
C*   TPEN2     TEMPERATURE OF REF. PENETRATION, DEGREES C        *
C*                                                               *
C*   CV        [AGGREGATE VOL]/([AGGREGATE VOL]+[ASPHALT VOL])   *
C*                                                               *
C*   IYRS      NUMBER OF YEARS ASPHALT IS TO BE AGED             *
C*                                                               *
C*                                                               *
C*                                                               *
C*     THIS PROGRAM CAN OPERATE IN THREE DIFFERENT MODES, SELECTED *
C* BY THE INPUT VARIABLE MODE.  INPUT REQUIRED FOR EACH MODE IS AS *
C* FOLLOWS:                                                      *
C*                                                               *
C*    CARD 01                                                    *
C*    -------                                                    *
C*                                                               *
C*              DATA ENTERED                 INPUT FORMAT        *
C*              ------------                 ------------        *
C*                                                               *
C*              MODE                         (I1)                *
C*                                                               *
C*                                                               *
C*    CARD 02                                                    *
C*    -------                                                    *
C*                                                               *
C*    MODE      DATA ENTERED                 INPUT FORMAT        *
C*    ----      ------------                 ------------        *
C*                                                               *
C*      1       PINIT,SPINIT,CV,IYRS         (3F10.2,I5)         *
C*      2       P1INIT,SPINIT,CV,IYRS        (3F10.2,I5)         *
C*      3       P1INIT,P2INIT,TPEN2,CV,IYRS  (4F10.2,I5)         *
C*                                                               *
C*                                                               *
C*                                                               *
C*    NOTE: A BLANK CARD SHOULD BE INSERTED AT THE END OF ALL    *
C*    ----  DATA CARDS                                           *
C*                                                               *
C*                                                               *
C*  SEE COMMENTS IN FUNCTION POEL FOR FURTHER INFORMATION.       *
C*                                                               *
C*****************************************************************
      DIMENSION X(20),Y(20),E1(20),E2(20),E3(20)
      REAL TEMPS(3)/0.0,25.,60./
```

```
C**********  DEFINE INPUT AND OUTPUT UNITS  **********
      NTT = 5
      NTO = 6
C**********  INITIALIZE CONSTANTS  **********
      KPI=1
      KSPRB=1
      KTEMP=1
      TIMOLI=1.0E+05
      KTIMOL=7
      FTIMOL=.1
      KPEN1=1
      TPEN1=25.
    1 CONTINUE
      NN = 0
C**********  INPUT MODE 1,2, OR 3  **********
   10 READ(NTT,9010,END=9999)MODE
C**********  WRITE PAGE HEADER  **********
C**********  PERFORM SELECTED MODE CALCULATIONS **********
      GO TO(100,200,300),MODE
      WRITE(NTO,9050)
      STOP 1
C***************  M O D E   1    *****************************
C*                                                           *
C*  PII AND SPRBI ARE READ IN DIRECTLY                       *
C*                                                           *
C*************************************************************
  100 READ(NTT,9210)PINIT,SPINIT,CV,IYRS
      WRITE (1,1001) MODE, IYRS, CV, SPINIT, PINIT
 1001 FORMAT ( 2I2, 3F10.3, 10X, '<-- MODE, YRS, CV, SPRB, PI' )
      DO 102 IY=1,IYRS
      IYR=IY-1
      PII=PINIT
      SPRBI=SPINIT
      NN=0
C*****  AGE ASPHALT  *****
      CALL CONV(MODE,IYR,PII,SPRBI,TPEN1,0.)
C**********  LOOP FOR 3 TEMPERATURES  **********
      DO 101 I101=1,3
      TEMPI=TEMPS(I101)
      IWRITE=0
      WRITE(NTO,9030)
      WRITE(NTO,9040)MODE
C**********  WRITE OUT INPUTS  **********
      WRITE(NTO,9070)PINIT,IYR,PII
      WRITE(NTO,9090)SPINIT,IYR,SPRBI
      WRITE(NTO,9110)TEMPI,KTEMP
      WRITE(NTO,9140)TIMOLI,KTIMOL
      WRITE(NTO,9150)FTIMOL
      PI=PII
      SPRB=SPRBI
      TEMP=TEMPI
      TIMOL=TIMOLI
      CALL CALC(NP,PI,SPRB,TEMP,TIMOL,X,Y,MODE,IWRITE,FTIMOL,NN,
     +          E1,E2,E3,KTIMOL,CV)
  101 CONTINUE
  102 CALL FINDTA(NN,E1,E2,E3)
      GO TO 1
C***************  M O D E   2    *****************************
C*                                                           *
C*  PII CALCULATED FROM PENETRATION VALUE AND SPRBI          *
```

```
C*                                                           *
C*************************************************************
  200 READ(NTT,9210)P1INIT,SPINIT,CV,IYRS
      WRITE (1,1002) MODE, IYRS, CV, SPINIT, P1INIT
 1002 FORMAT ( 2I2, 3F10.3, 10X, '<-- MODE, YRS, CV, SPRB, PEN1' )
C***  AGE ASPHALT  ***
      DO 202 I202=1,IYRS
      IYR=I202-1
      PEN1I=P1INIT
      SPRBI=SPINIT
      NN=0
      CALL AGE(IYR,PEN1I,TPEN1,SPRBI)
C**********  LOOP FOR 3 TEMPERATURES  **********
      DO 201 I201=1,3
      TEMPI=TEMPS(I201)
      IWRITE=0
      WRITE(NTO,9030)
      WRITE(NTO,9040)MODE
      WRITE(NTO,9160)P1INIT,IYR,PEN1I
      WRITE(NTO,9180)TPEN1
      WRITE(NTO,9090)SPINIT,IYR,SPRBI
      WRITE(NTO,9110)TEMPI,KTEMP
      WRITE(NTO,9140)TIMOLI,KTIMOL
      WRITE(NTO,9150)FTIMOL
      PEN1=PEN1I
      SPRB=SPRBI
      A=(ALOG10(800.)-ALOG10(PEN1))/(SPRB-TPEN1)
      PI=(20.-500.*A)/(1.+50.*A)
      TEMP=TEMPI
      TIMOL=TIMOLI
      CALL CALC(NP,PI,SPRB,TEMP,TIMOL,X,Y,1,IWRITE,FTIMOL,NN,
     +          E1,E2,E3,KTIMOL,CV)
  201 CONTINUE
  202 CALL FINDTA(NN,E1,E2,E3)
      GO TO 1
C*************  M O D E  3  ***************************************
C                                                                     *
C     PI AND SOFTENING POINT RING & BALL ARE CALCULATED FROM THE TWO*
C     GIVEN PENETRATION VALUES AND CORRESPONDING TEMPERATURES.        *
C                                                                     *
C**********************************************************************
  300 READ(NTT,9211)P1INIT,P2INIT,TPEN2,CV,IYRS
      WRITE (1,1003) MODE, IYRS, CV, TPEN2, P1INIT, P2INIT
 1003 FORMAT ( 2I2, 4F10.3, '<-- MODE, YRS, CV, TPEN2, PEN1, PEN2' )
C***  AGE ASPHALT  ***
      DO 302 I302=1,IYRS
      IYR=I302-1
      PEN1=P1INIT
      PEN2=P2INIT
      NN=0
      CALL CONV(MODE,IYR,PEN1,PEN2,TPEN1,TPEN2)
      SPRB=PEN2
      A=(ALOG10(800.)-ALOG10(PEN1))/(SPRB-TPEN1)
      PI=(20.-500.*A)/(1.+50.*A)
C**********  LOOP FOR 3 TEMPERATURES  **********
      DO 301 I301=1,3
      TEMPI=TEMPS(I301)
      IWRITE=0
      WRITE(NTO,9030)
      WRITE(NTO,9040)MODE
```

```
      WRITE(NTO,9160)P1INIT,IYR,PEN1
      WRITE(NTO,9180)TPEN1
      WRITE(NTO,9200)P2INIT,TPEN2
      WRITE(NTO,9205)IYR,SPRB
      WRITE(NTO,9110)TEMPI,KTEMP
      WRITE(NTO,9140)TIMOLI,KTIMOL
      WRITE(NTO,9150)FTIMOL
      TEMP=TEMPI
      TIMOL=TIMOLI
      CALL CALC(NP,PI,SPRB,TEMP,TIMOL,X,Y,1,IWRITE,FTIMOL,NN,
     +          E1,E2,E3,KTIMOL,CV)
  301 CONTINUE
  302 CALL FINDTA ( NN, E1, E2, E3 )
      GO TO 1
 9999 CONTINUE
      STOP
C**********   FORMATS FOR MAIN PROGRAM   **************
 9010 FORMAT(I1)
 9030 FORMAT('OSTIFFNESS OF MIX USING VAN DER POELS NOMOGRAPH')
 9040 FORMAT(1X,'INPUT DATA:',22X,'MODE  =  ',I4)
 9050 FORMAT('1MODE MUST BE INTEGER 1 OR 2 OR 3  STOP.')
 9070 FORMAT(/28X,'INITIAL PI  =  ',1X,F5.2/26X,
     -'AGED ',I2,' YEAR(S) TO',F5.2)
 9090 FORMAT(/1X,'INITIAL SOFTENING POINT RING AND BALL  =  ',F6.1/1X,
     -23X,'AGED ',I2,' YEAR(S) TO ',F6.1)
 9110 FORMAT(/19X,'INITIAL TEMPERATURE  =  ',F6.1/8X,'NUMBER OF STEPS IN
     - TEMPERATURE  =  ',I4)
 9140 FORMAT(/18X,'INITIAL LOADING TIME  =  ',1PE10.1/7X,'NUMBER OF STEP
     -S IN LOADING TIME  =  ',I4)
 9150 FORMAT(4X,'MULTIPLYING FACTOR IN LOADING TIME  =  ',F6.1)
 9160 FORMAT(/19X,'INITIAL PENETRATION  =  ',F6.1/25X,
     -'AGED ',I2,' YEAR(S) TO', F6.1)
 9180 FORMAT(15X,'PENETRATION TEMPERATURE  =  ',F6.1)
 9200 FORMAT(17X,'REFERENCE PENETRATION  =  ',F6.1/5X,'REFERENCE PENETRA
     -TION TEMPERATURE  =  ',F6.1)
 9205 FORMAT( 17X, 'AGED ',I2,' YEAR(S),  SPRB =',F8.1)
 9210 FORMAT(3F10.2,I5)
 9211 FORMAT(4F10.2,I5)
      END
```

```
      SUBROUTINE CALC(NP,PI,SPRB,TEMP,TIMOL,X,Y,MODE,IWRITE,
     +           FTIMOL,NN,E1,E2,E3,KTIMOL,CV)
C*** USE NOMOGRAPH AND SET UP VARS FOR REGRESSION  ***
      DIMENSION X(20),Y(20),E1(20),E2(20),E3(20)
      NP = 0
      DO70 LTIMOL=1,KTIMOL
      ALGS=POEL(PI,SPRB,TEMP,TIMOL)
      IF ( ALGS.LT.-20.0) GO TO 65
      NP = NP+1
      X(NP) = ALOG10(TIMOL)
      SB = 10**ALGS*1.450E-04*0.0703
      SN = 0.83*ALOG10((4.0E+05)/SB)
      CONST = ( 1.0 +(2.5/SN) * (CV/(1.0-CV)))**SN * 0.000145
      SMIX  = 10.0 ** ALGS * CONST
      Y(NP) = ALOG10(SMIX)
   65 CONTINUE
      CALL TYPES(1,IWRITE,PI,SPRB,TEMP,TIMOL,PEN1,TPEN1,
```

```
     +           PEN2,TPEN2,ALGS,CONST)
      TIMOL=TIMOL*FTIMOL
   70 CONTINUE
      CALL LINEAR(NP,X,Y,EA,EB)
      NN = NN + 1
      E1(NN) = EB
      E2(NN) = EA
      E3(NN) = TEMP
      WRITE (6,666) NN, E3(NN), E2(NN), E1(NN)
C**** SAVE CN AND D1 AT MASTER TEMPERATURE  ******
      IF(TEMP.NE.25.)RETURN
      WRITE (1,100)E2(NN),E1(NN)
  100 FORMAT(2F10.5,' <---- CN, D1')
      RETURN
  666 FORMAT ( '  NN ', I5, '  TEMP ', E14.7, '  SLOPE, M ', E14.7,
     1         '  INTERCEPT,E1', E14.7 )
      END



      SUBROUTINE CONV(MODE,IYR,VAR1,VAR2,VAR3,VAR4)
C**** CONVERT TO MODE 2 TO USE AGE ROUTINE  *****
      IF(MODE.EQ.3)GOTO2
C**** CONVERT FROM MODE 1 TO MODE 2 AND AGE *****
      PII=VAR1
      SPRBI=VAR2
      TPEN1=VAR3
      A=(20.-PII)/(500.+50.*PII)
      DELTA=A*(SPRBI-25.)
      PEN1I=10.**(ALOG10(800.)-DELTA)
C***** NOW AGE *****
      CALL AGE(IYR,PEN1I,TPEN1,SPRBI)
C***** CONVERT BACK TO MODE 1 AFTER AGING *****
      A=(ALOG10(800.)-ALOG10(PEN1I))/(SPRBI-TPEN1)
      PII=(20.-500.*A)/(1.+50.*A)
      VAR1=PII
      VAR2=SPRBI
      RETURN
C**********  CONVERT FROM MODE 3 TO MODE 2  **********
    2 PEN1=VAR1
      PEN2=VAR2
      TPEN1=VAR3
      TPEN2=VAR4
      A=(ALOG10(PEN1)-ALOG10(PEN2))/(TPEN1-TPEN2)
      DPEN=ALOG10(800.)-ALOG10(PEN2)
      SPRB=TPEN2+DPEN/A
C*** NOW AGE ***
      CALL AGE(IYR,PEN1,TPEN1,SPRB)
C*** PASS BACK RESULTS TO MAIN IN MODE 2 FORM ***
      VAR1=PEN1
      VAR2=SPRB
      RETURN
      END



      SUBROUTINE AGE(IYR,PEN1I,TPEN1,SPRBI)
C**********  AGES PAVEMENT USING MODE 2 VARIABLES **********
```

```
      WRITE(6,600)PEN1I,TPEN1,SPRBI,IYR
  600 FORMAT('0*** AGE CALLED: PEN1I=',F10.4,' TPEN1=',F10.4,
     +       'SPRBI=',F10.4,' IYR=',I2)
C**** ABORT IF ASKED TO AGE MORE THAN 10 YEARS  ***
      IYR2=IYR
      IF(IYR.LT.10)GO TO 5
      WRITE(6,610)
  610 FORMAT('0*** WARNING ***  PAVEMENT CAN ONLY BE AGED',
     +  ' 10 YEARS.  10 YEARS ASSUMED.')
      IYR=10.
C*** T IS MONTHS TO AGE AND RUNS 6, 18, 30.... ***
C*** STARTS AT 6 MONTHS TO BE AS CLOSE AS POSSIBLE ***
    5 T=6.+12.*FLOAT(IYR)
      SPRB1=-16.2+1.230*(SPRBI*9./5.+32.)
      SPRBT=SPRB1-14.4+10.5*ALOG(T)
      SPRBI=5.*(SPRBT-32.)/9.
      PEN1I=(-.4+.716*PEN1I)-(.193*PEN1I-9.1)*ALOG(T)
      IF(PEN1I.LT.20.)PEN1I=20.
      IYR=IYR2
      WRITE(6,601)IYR,PEN1I,TPEN1,SPRBI
  601 FORMAT(' *** AFTER AGING --> IYR=',I2,' PEN1=',F8.3,
     -' TPEN1=',F8.3,' SPRBI=',F8.3)
      WRITE (1,100)IYR,PEN1I,SPRBI
  100 FORMAT(I2,2F10.3,'<-- YR, PEN1, SPRBI')
      RETURN
      END
```

```
      FUNCTION POEL(PI,SPRB,TEMP,TIMOL)
C     THE FUNCTION SUBPROGRAM POEL PROVIDES THE LOGARITHM (BASE TEN)
C     OF THE STIFFNESS MODULUS OF A BITUMEN FROM GIVEN PENETRATION
C     INDEX, SOFTENING POINT RING AND BALL, TEMPERATURE AND TIME OF
C     LOADING. THE PROGRAM POEL IS A COMPUTERIZED VERSION OF VAN DER
C     POEL'S NOMOGRAPH EDITION AUGUST 1953, 2ND EDITION 1969.
C     REFERENCE: ''JOURNAL OF APPLIED CHEMISTRY'', VOLUME 4, PART5,
C     MAY 1954. KSLA DRAWING NUMBER 69.12.1164A.
C     THE PROGRAM POEL USES ONLY GEOMETRIC INFORMATION TAKEN FROM THE
C     NOMOGRAPH. A GRID OF X,Y COORDINATES, WITH ORIGIN IN THE POINT
C     TEMPERATURE EQUALS SOFTENING POINT RING AND BALL, IS LAID
C     OVER THE NOMOGRAPH. TEMPERATURE DIFFERENCES ARE FOUND ON THE
C     LINE (X,Y=0); LOADING TIMES ON THE LINE (X,Y=-11). THE UNIT OF
C     LENGTH IS CENTIMETRE. THE LINES OF CONSTANT PI ARE THE HORIZONTAL
C     LINES (X,Y=0.545*(PI+10)). THE LINES OF CONSTANT STIFFNESS FORM
C     A BUNDLE OF CURVED LINES INTERSECTING THE PI LINES. EACH POINT
C     OF INTERSECTION ASSIGNS AN X VALUE TO EACH LOG. STIFFNESS VALUE
C     ON A GIVEN PI LINE.
C     THE ASSEMBLY OF INTERSECTION POINTS COVERS AN AREA ON THE
C     NOMOGRAPH, WHICH IS CALLED THE ADMITTED AREA.
C     LET XT BE THE X COORDINATE OF A POINT ON THE TEMPERATURE LINE
C     AND XL BE THE X COORDINATE OF A POINT ON THE LOADING TIME LINE,
C     THEN A STRAIGHT LINE CAN BE DRAWN THROUGH THESE TWO POINTS.
C     THE EQUATION OF THIS LINE IS X = XT + (XT - XL)*(Y/11).
C     SUBSTITUTING INTO THIS EQUATION THE Y VALUE CORRESPONDING TO
C     THE PENETRATION INDEX, THE X COORDINATE OF THE INTERSECTION
C     POINT OF THIS LINE WITH THE PI LINE IS OBTAINED. BY INTERPOLATION
C     BETWEEN THE LOG. STIFFNESS VALUES CORRESPONDING WITH THE TWO NEXT
C     CONTINUE
C     NEIGHBOUR POINTS OF THE ASSEMBLY ON THE SAME PI LINE, THE PROGRAM
```

```
C     YIELDS THE REQUIRED LOG. STIFFNESS VALUE.
C     TO KEEP THE AMOUNT OF STORED DATA LIMITED, ONLY THE INTERSECTIONS
C     OF THE STIFFNESS LINES WITH INTEGER VALUE  PI LINES ARE READ OUT.
C
C     PI LINES ARE COUNTED FROM PI = -3 UP TO PI = +7, WITH VARIABLE I
C     RUNNING FROM 1 UP TO 11.
C     EQUI-STIFFNESS LINES ARE COUNTED FROM RIGHT TO LEFT, WITH VARIABLE
C     J RUNNING FROM 1 UP TO 46.
C     KSTIF(I) IS NUMBER OF INTERSECTION POINTS OF EQUI-STIFFNESS LINES
C     WITH NUMBER I PI LINE.
C     XSTIF(I,J) IS X COORDINATE OF INTERSECTION POINT OF NUMBER I PI
C     LINE WITH NUMBER J EQUI-STIFFNESS LINE.
C     THE ARRAY XTEMP CONTAINS THE X-COORDINATES OF THE 10-DEGREE
C     CALIBRATION  MARKS ON THE TEMPERATURE LINE.
C     SMIN(I) IS SMALLEST LOG. STIFFNESS VALUE INTERSECTING NUMBER I
C     PI LINE.
C     TO KEEP STATEMENT LENGTH LIMITED TO 20 CARDS, THE X-COORDINATES
C     OF THE INTERSECTION POINTS OF EQUI-STIFFNESS LINES WITH PI LINES
C     ARE STORED IN THE ARRAYS XDUM1 AND XDUM2. THE EQUIVALENCE
C     STATEMENT IDENTIFIES THESE ARRAYS WITH THE ARRAY XSTIF(I,J). THE
C     VARIABLE I RUNNING FIRST, THE DATA SHOULD BE READ IN GROUPS OF
C     11 NUMBERS.
      POEL=-20.
      IF(PI.GT.7.)  POEL=-21.
      IF(PI.LT.-3.)  POEL=-22.
      IF(TIMOL.GT.1.E+10) POEL=-23.
      IF(TIMOL.LT.1.E-06) POEL=-24.
      IF(POEL.LT.-20.5.AND.POEL.GT.-24.5)  GO TO20
C     XL IS X COORDINATE OF LOADING TIME;
C     XT IS X COORDINATE OF SPRB MINUS TEMP.
      XL=(ALOG10(TIMOL)+3.953)*1.693
      PI4=PI+4.
      IP=PI4
      Y1=0.545*FLOAT(IP+6)
      XT=XDRT(SPRB,TEMP)
C     XT=66. MEANS TEMPERATURE TOO LOW, WITH RESPECT TO S.P. RING & BALL
C     XT=67. MEANS TEMPERATURE TOO HIGH,WITH RESPECT TO S.P. RING & BALL
      IF(XT.EQ.66.)  POEL=-25.
      IF(XT.EQ.67.)  POEL=-26.
      IF(XT.LT.68..AND.XT.GT.65.)  GO TO20
      X=XT-(Y1/11.)*(XL-XT)
      SLOG1=SLOG(IP,X)
C     SLOG=50. MEANS GLASSY STATE
C     SLOG=56. MEANS WHITE AREA
      IF(SLOG1.EQ.50.)  POEL=-27.
      IF(SLOG1.EQ.56.)  POEL=-28.
      IF(SLOG1.LT.57..AND.SLOG1.GT.49.)  GO TO20
      AIP=IP
      IF(PI4.EQ.AIP)  GO TO10
      IP=IP+1
      Y2=0.545*FLOAT(IP+6)
      X=XT-(Y2/11.)*(XL-XT)
      SLOG2=SLOG(IP,X)
      IF(SLOG2.EQ.50.)  POEL=-27.
      IF(SLOG2.EQ.56.)  POEL=-28.
      IF(SLOG2.LT.57..AND.SLOG2.GT.49.)  GO TO20
      Y=0.545*(PI+10.)
      SLOG3=SLOG1+(SLOG2-SLOG1)*((Y-Y1)/(Y2-Y1))
      SLOG1=SLOG3
   10 POEL=SLOG1
```

```
   20 CONTINUE
      RETURN
      END




      BLOCK DATA
      COMMON/BLOCKT/XTEMP
      COMMON/BLOCKS/KSTIF,XSTIF,SMIN
      INTEGER KSTIF(11)
      REAL XSTIF(11,46),XTEMP(34),SMIN(11),XDUM1(209),XDUM2(297)
C     EQUIVALENCE (XDUM1,XSTIF(1,1)),(XDUM2,XSTIF(1,20))
      EQUIVALENCE (XDUM1(1),XSTIF(1,1)),(XDUM2(1),XSTIF(1,20))
      DATA XTEMP/-2.47,-2.37,-2.26,-2.14,-2.04,-1.89,-1.74,
     --1.6,-1.42,-1.2,-.95,-.69,-.38,0.,.44,.97,1.55,2.21,
     -2.88,3.61,4.42,5.23,6.09,6.98,7.98,8.81,9.72,10.62,
     -11.53,12.44,13.34,14.25,15.15,16.06/
      DATA KSTIF/46,44,42,41,40,27,21,15,12,12,9/
      DATA XDUM1/3.32,4.8,6.48,8.19,10.1,12.,13.99,16.3,18.98,21.
     -81,25.12,2.15,3.49,5.1,6.71,8.6,10.42,12.42,14.68,17.13,19.
     -81,22.87,1.21,2.,3.38,4.94,6.65,8.4,10.26,12.21,14.5,17.21,
     -20.21,.91,1.49,2.52,3.75,5.3,6.9,8.61,10.62,12.98,15.54,18.
     -52,.61,1.,1.71,2.75,3.98,5.33,6.8,8.7,10.91,13.43,16.38,
     -.41,.7,1.29,2.01,2.99,4.13,5.48,7.24,9.49,11.9,14.72,
     -.18,.42,.8,1.4,2.26,3.23,4.44,5.99,7.81,10.13,13.08,
     --.1,.03,.29,.72,1.35,2.17,3.18,4.48,6.11,8.27,10.86,
     --.29,-.21,-.01,.31,.81,1.49,2.3,3.4,4.81,6.7,9.17,
     --.48,-.42,-.3,-.08,.3,.8,1.41,2.31,3.51,5.2,0.,
     --.7,-.7,-.65,-.53,-.31,0.,.45,1.11,2.09,3.41,0.,
     --.86,-.9,-.92,-.89,-.77,-.58,-.26,.27,1.03,2.16,0.,
     --1.04,-1.13,-1.2,-1.2,-1.18,-1.08,-.88,-.53,3*0.,
     --1.3,-1.42,-1.54,-1.65,-1.71,-1.72,-1.65,-1.5,3*0.,
     --1.46,-1.63,-1.82,-1.98,-2.09,-2.18,-2.2,-2.12,3*0.,
     --1.66,-1.88,-2.07,-2.24,-2.43,-2.58,-2.69,4*0.,
     --1.9,-2.15,-2.4,-2.62,-2.88,-3.1,-3.3,4*0.,
     --2.03,-2.31,-2.61,-2.91,-3.21,-3.5,-3.78,4*0.,
     --2.2,-2.52,-2.88,-3.19,-3.57,-3.91,-4.24,4*0./
      DATA XDUM2/-2.45,-2.79,-3.16,-3.52,-3.95,-4.37,-4.78,4*0.,
     --2.63,-3.03,-3.45,-3.85,-4.3,-4.71,-5.18,4*0.,
     --2.83,-3.26,-3.69,-4.12,-4.6,-5.04,5*0.,
     --3.06,-3.5,-3.98,-4.46,-5.01,-5.51,5*0.,
     --3.24,-3.71,-4.21,-4.72,-5.3,-5.89,5*0.,
     --3.42,-3.95,-4.48,-5.02,-5.62,-6.2,5*0.,
     --3.64,-4.2,-4.79,-5.38,-6.04,-6.7,5*0.,
     --3.81,-4.4,-5.02,-5.61,-6.3,-7.03,5*0.,
     --4.02,-4.6,-5.27,-5.9,-6.61,6*0.,-4.24,-4.89,-5.52,-6.20,
     --6.9,6*0.,-4.41,-5.08,-5.77,-6.46,-7.21,6*0.,
     --4.65,-5.31,-6.,-6.7,-7.48,6*0.,-4.85,-5.55,-6.31,-7.04,
     --7.79,6*0.,-5.03,-5.75,-6.53,-7.3,-8.15,6*0.,
     --5.27,-6.,-6.81,-7.6,-8.43,6*0.,-5.49,-6.25,-7.09,-7.88,
     --8.72,6*0.,-5.65,-6.46,-7.28,-8.13,-9.06,6*0.,
     --5.88,-6.67,-7.53,-8.4,-9.34,6*0.,-6.09,-6.92,-7.83,
     --8.71,-9.68,6*0.,-6.24,-7.18,-8.1,-9.,-10.,6*0.,
     --6.88,-7.81,-8.8,-9.81,-10.91,6*0.,-7.49,-8.47,-9.57,
     --10.7,7*0.,-8.05,-9.14,-10.3,8*0.,-8.61,-9.77,9*0.,
     --9.24,-10.38,9*0.,-9.8,10*0.,-10.41,10*0./
      DATA SMIN/-10.,-8.,-6.,-5.,-4.,1.,3.,5.,6.,6.,7./
      END
```

```
C
C
      FUNCTION SLOG(IP,X)
C     RESULT IS LOG STIFFNESS (SLOG) FROM PI AND X. THE INTEGER VALUE
C     IP OF PI + 4. IS USED INSTEAD OF PI.
      INTEGER KSTIF(11)
      REAL XSTIF(11,46),SMIN(11)
      COMMON/BLOCKS/KSTIF,XSTIF, SMIN
      IF(X-XSTIF(IP,1))  30,20,10
   10 SLOG=50.
      GO TO140
   20 SLOG=9.+ALOG10(2.5)
      GO TO140
   30 IF(X-XSTIF(IP,KSTIF(IP)))  40,50,60
   40 SLOG=56.
      GO TO140
   50 SLOG=SMIN(IP)
      GO TO140
   60 KSTAF=KSTIF(IP)
      DO70 I5=1,KSTAF
      M=I5
      IF(X.GT.XSTIF(IP,I5))  GO TO80
   70 CONTINUE
   80 M1=M/3
      M2=M-3*M1
      AM1=M1
      FRACT=(X-XSTIF(IP,M))/(XSTIF(IP,M-1)-XSTIF(IP,M))
      IF(M.EQ.2)  GO TO130
      IF(M.GT.39)  GO TO120
      IF(M2.EQ.0)  GO TO90
      IF(M2.EQ.1)  GO TO100
      IF(M2.EQ.2)  GO TO110
   90 SLOG=10.-AM1+ALOG10(2.)*FRACT
      GO TO140
  100 SLOG=9.-AM1+ALOG10(5.)+(1.-ALOG10(5.))*FRACT
      GO TO140
  110 SLOG=9.-AM1+ALOG10(2.)+(ALOG10(5.)-ALOG10(2.))*FRACT
      GO TO140
  120 M3=M-39
      AM3=M3
      SLOG=-3.-AM3+FRACT
      GO TO140
  130 SLOG=9.+ALOG10(2.)+(ALOG10(2.5)-ALOG10(2.))*FRACT
  140 CONTINUE
      RETURN
      END
```

```
C
C
      FUNCTION XDRT(SPRB,TEMP)
C     RESULT IS HORIZONTAL COORDINATE XT CORRESPONDING TO TEMPERATURE
C     DIFFERENCE SPRB - TEMP.
      REAL XTEMP(34)
      COMMON/BLOCKT/XTEMP
      DRT=SPRB-TEMP
C     ADMITTED RANGE FOR DRT IS (-130,+200)
      Z=DRT+130.
```

```
      IF(Z-330.)  30,20,10
   10 X=66.
      GO TO70
   20 X=XTEMP(34)
      GO TO70
   30 IF(Z)  40,50,60
   40 X=67.
      GO TO70
   50 X=XTEMP(1)
      GO TO70
   60 N=INT(Z)/10
      R=AMOD(Z,10.)
      X=XTEMP(N+1)+(XTEMP(N+2)-XTEMP(N+1))*R/10.
   70 XDRT=X
      RETURN
      END
```

```
C
      SUBROUTINE TYPES(MODE,IWRITE,PI,SPRB,TEMP,TIMOL,PEN1,TPEN1,PEN2,
     - TPEN2,ALGS,CONST)
C*****  SUBROUTINE TO PRODUCE OUTPUT DETAIL LINES   *****
      INTEGER NOTE(6,8),LIST(6)
      DATA NOTE/' *  ', 'PI >', ' +7 ', '    ', '    ', '    ',
     1          ' *  ', 'PI <', ' -3 ', '    ', '    ', '    ',
     2          ' *  ', 'LOAD', 'ING ', 'TIME', ' > 1', 'E+10',
     3          ' *  ', 'LOAD', 'ING ', 'TIME', ' < 1', 'E-06',
     4          ' *  ', 'TEMP', 'ERAT', 'URE ', 'TOO ', 'LOW ',
     5          ' *  ', 'TEMP', 'ERAT', 'URE ', 'TOO ', 'HIGH',
     6          ' *  ', 'GLAS', 'SY S', 'TATE', '    ', '    ',
     7          ' *  ', 'WHIT', 'E AR', 'EA  ', '    ', '    '/
      NTO        = 6
 9000 FORMAT(1HO)
 9010 FORMAT(1H )
      IF(IWRITE.GT.O) GO TO10
      ALG800=ALOG10(800.)
   10 CONTINUE
      IF(MOD(IWRITE,35).EQ.O) GO TO20
      GO TO60
   20 CONTINUE
      WRITE(NTO,9000)
C     WRITE TREE HEADLINES OF TABLE
      GO TO ( 30, 40, 50 ), MODE
   30 WRITE(NTO,9020)
 9020 FORMAT('    PI    SOFTENING    TEMP.    LOADING   PEN.25       SMI
     -X ' )
      WRITE(NTO,9030)
 9030 FORMAT('          POINT R&B              TIME ' )
      WRITE(NTO,9040)
 9040 FORMAT('           (DEG. C)   (DEG. C)   ( S )            (LB/IN**
     -2) ' )
      GO TO 60
C
   40 WRITE(NTO,9050)
 9050 FORMAT('    PI    SOFTENING    TEMP.    LOADING   PEN.   PEN.
     -   LOG.   STIFFNESS  COMPUTED ')
      WRITE(NTO,9060)
 9060 FORMAT('          POINT R&B              TIME              TEMP.
```

```
     -STIFFNESS           VISCOSITY')
      WRITE(NTO,9070)
 9070 FORMAT('           (DEG. C)   (DEG. C)   ( S )         (DEG. C)
     -(N/M**2)  (N/M**2)   (NS/M**2)')
      GO TO 60
C
   50 WRITE(NTO,9080)
 9080 FORMAT('    PI     EPT 800     TEMP.    LOADING   PEN.   PEN.   RE
     -FERENCE  TEMP. OF  PEN.RATIO    LOG.   STIFFNESS  COMPUTED ')
      WRITE(NTO,9090)
 9090 FORMAT('                                   TIME            TEMP.
     -PEN.     REF.PEN.  (T+15)/T   STIFFNESS             VISCOSITY')
      WRITE(NTO,9100)
 9100 FORMAT('           (DEG. C)   (DEG. C)   ( S )         (DEG. C)
     -          (DEG. C)            (N/M**2)  (N/M**2)   (NS/M**2)')
   60 CONTINUE
      ETA=S*TIMOL/3.
      ALGPR=(20.-PI)/((50./15.)*(10.+PI))
      PENRAT=10.**ALGPR
      IF(MOD(IWRITE, 5).EQ.0) WRITE(NTO,9010)
      IF(ALGS.GT.-20.) GO TO70
      GO TO110
   70 CONTINUE
      SMIX  = 10.0 ** ALGS * CONST
C     WRITE NUMERIC OUTPUT WITHOUT NOTE.
      GO TO ( 80, 90, 100 ), MODE
C     CALCULATE IN CASE MODE = 1 PEN.25 FROM PI AND S.P. RING & BALL.
   80 ALGP25=ALG800+((20.-PI)/(500.+50.*PI))*(25.-SPRB)
      PEN25=10.**ALGP25
      WRITE(NTO,9110)PI,SPRB,TEMP,TIMOL,PEN25,SMIX
 9110 FORMAT(2X,F5.2,4X,F6.1,5X,F6.1,3X,1PE8.1,2X,0PF6.1,5X,1PE9.2,1X,
     - 1PE9.2,2X,1PE9.2)
      GO TO160
   90 WRITE(NTO,9120)PI,SPRB,TEMP,TIMOL,PEN1,TPEN1,ALGS,S,ETA
 9120 FORMAT(2X,F5.2,4X,F6.1,5X,F6.1,3X,1PE8.1,1X,0PF6.1,2X,F5.1,5X,
     - 1PE9.2,1X,1PE9.2,2X,1PE9.2)
      GO TO160
  100 WRITE(NTO,9130)PI,SPRB,TEMP,TIMOL,PEN1,TPEN1,PEN2,TPEN2,PENRAT,
     -  ALGS,S,ETA
 9130 FORMAT(2X,F5.2,4X,F6.1,5X,F6.1,3X,1PE8.1,1X,0PF6.1,2X,F5.1,4X,
     - F6.1,5X,F5.1,5X,F6.2,4X,1PE9.2,1X,1PE9.2,2X,1PE9.2)
      GO TO160
C
  110 CONTINUE
C     WRITE NUMERIC OUTPUT WITH NOTE, DEPENDING ON (DUMMY) VALUE OF ALGS
      L=IABS(INT(ALGS-0.001))-20
C     L HAS VALUE 1 UP TO 8 IF ALGS HAS VALUE -21. DOWN TO -28.
      DO120 I=1,6
      LIST(I)=NOTE(I,L)
  120 CONTINUE
      GO TO ( 130, 140, 150 ), MODE
  130 ALGP25=ALG800+((20.-PI)/(500.+50.*PI))*(25.-SPRB)
      PEN25=10.**ALGP25
      WRITE(NTO,9140)PI,SPRB,TEMP,TIMOL,PEN25,(LIST(I),I=1,6)
 9140 FORMAT(2X,F5.2,4X,F6.1,5X,F6.1,3X,1PE8.1,2X,0PF6.1,2X,6A4)
      GO TO160
  140 WRITE(NTO,9150)PI,SPRB,TEMP,TIMOL,PEN1,TPEN1,(LIST(I),I=1,6)
 9150 FORMAT(2X,F5.2,4X,F6.1,5X,F6.1,3X,1PE8.1,1X,0PF6.1,2X,F5.1,2X,6A4)
      GO TO160
  150 WRITE(NTO,9160)PI,SPRB,TEMP,TIMOL,PEN1,TPEN1,PEN2,TPEN2,PENRAT,
```

```
     - (LIST(I),I=1,6)
 9160 FORMAT(2X,F5.2,4X,F6.1,5X,F6.1,3X,1PE8.1,1X,0PF6.1,2X,F5.1,4X,
     - F6.1,5X,F5.1,5X,F6.2,1X,6A4)
  160 CONTINUE
      IWRITE=IWRITE+1
      RETURN
      END




      SUBROUTINE  LINEAR ( N, X, Y, A, B )
C*****  DO A SIMPLE LINEAR REGRESSION ON X & Y ******
      DIMENSION   X(N), Y(N)
      SUMN       = N
      SUMX       = 0.0
      SUMY       = 0.0
      SMX2       = 0.0
      SMXY       = 0.0
      DO 1100 I = 1, N
      SUMX       = SUMX + X(I)
      SUMY       = SUMY + Y(I)
      SMX2       = SMX2 + X(I) * X(I)
      SMXY       = SMXY + X(I) * Y(I)
 1100 CONTINUE
      DETR       = ( SUMN * SMX2 - SUMX * SUMX )
      A          = ( SUMN * SMXY - SUMX * SUMY ) / DETR
      B          = ( SUMY * SMX2 - SUMX * SMXY ) / DETR
      RETURN
      END



      SUBROUTINE FINDTA ( NN, E1, E2, T )
C***** FIT LINE TO LOGLOG PLOT OF TEMP SHIFT VS TEMP DIFF *****
C*****  TEMPERATURE IS VARIED TO PRODUCE BEST FIT *****
      DIMENSION    E1(20), E2(20), T(20)
      DIMENSION   X(20), Y(20), AT(20), TL(20)
  500 FORMAT ( 3F10.0 )
  510 FORMAT ( E14.7 )
  600 FORMAT ( '  SMIX ', E14.7, '   TA ', F10.3, '    BETA  ',
     1 E14.7, '   INTERCEPT, B   ', E14.7, '   SOE2 ', E14.7 )
C**********  INITIALIZE SELECTION VARIABLES  **********
      ERRMIN=999.
      TASEL=999.
      ASEL=999.
      TM=25.
      TA=-75.
      TINC=5.
      TAS        = TA
 1000 CONTINUE
      SMIX       = 10.000 ** E1(2) / 2.0
      IF ( SMIX .LE. 0.0E+00 ) GO TO 1700
      TA         = TAS
      DO 1200 I = 1, NN
      TL(I)      = ( SMIX /10.0E+00 ** E1(I) ) ** ( 1.0E+00 / E2(I) )
 1200 CONTINUE
      TLMC       = TL(2)
      DO 1300 I = 1, NN
```

```
      AT(I)      = TL(I) / TLMC
 1300 CONTINUE
 1400 CONTINUE
      TA         = TA + TINC
      DO 1500 I = 1, NN
      X(I)       = ALOG10 ( T(I) - TA )
      Y(I)       = ALOG10 ( AT(I) )
 1500 CONTINUE
      CALL LINEAR ( NN, X, Y, A, B )
      SOE2       = 0.0E+00
      DO 1600 I = 1, NN
      Z          = A * X(I) + B
      DIFF       = Z - Y(I)
      SOE2       = SOE2 + DIFF * DIFF
 1600 CONTINUE
C**********  SELECT TA AND B AT MINIMUM SOE2  **********
      IF(ERRMIN.LT.SOE2)GOTO2
      ERRMIN=SOE2
      TASEL=TA
      ASEL=A
      WRITE (6,600) SMIX, TA, A, B, SOE2
    2 IF ( TA .LE. -20.00E+00 ) GO TO 1400
 1700 CONTINUE
C***** WRITE SELECTED TA AND BETA TO DISK FILE  *******
      WRITE (1,100)TASEL,ASEL
  100 FORMAT(2F10.5,' <---- TA, CM')
      RETURN
      END
```

```
C
C     *************************************************************
C
C          COMPUTER PROGRAM FOR THERMAL CRACKING MODEL (THERM)
C                    (USING THE RESULTS FROM VISCO)
C
C     *************************************************************
C
C                      THE BITUMEN AGES WITH TIME.
C
C     *************************************************************
C
C                AUTHORS    :  DR. ROBERT L. LYTTON
C                              MS. ULPALA L. SHANMUGHAM
C
C                              TEXAS TRANSPORTATION INSTITUTE
C                              TEXAS A&M UNIVERSITY
C                              COLLEGE STATION, TEXAS 77843
C
C     *************************************************************
C
C     RESULTS PRINTED EVERY MONTH
C
C     *************************************************************
C
C     DESCRIPTION OF INPUT VARIABLES
C
C     *************************************************************
C
C     TITL    = TITLE OF THE PROBLEM.
C     W       = DENSITY OF THE ASPHALT CONCRETE,PCF.
C     S       = SPECIFIC HEAT OF THE ASPHALT CONCRETE,BTU/LB,
C               DEGREE FAHRENHEIT.
C     AK      = THERMAL CONDUCTIVITY OF THE ASPHALT CONCRETE,
C               BTU/SQUARE FOOT/HR, DEGREE FAHRENHEIT PER FOOT.
C     B       = THE ABSORBTIVITY OF THE ASPHALT CONCRETE.
C     DO      = INITIAL CRACK LENGTH, INCHES (CRACK IS PROPAGATING
C               DOWNWARDS).
C     DF      = DEPTH OF THE ASPHALT CONRETE, INCHES.
C     VMPH    = AVERAGE WIND VELOCITY, MPH.
C     NSEL    = STARTING DATE: YR/MO/DY
C     SR1     = THE AVERAGE SOLAR RADIATION FOR JULY,LANGLEYS PER DAY.
C     SRM     = THE YEARLY AVERAGE SOLAR RADIATION,LANGLEYS PER DAY.
C     IMODE   = MODES, 1, 2,& 3
C     IAGE    = (NUMBER OF YEARS TO BE RUN) OR (THE NUMBER OF YEARS
C               THE BITUMEN TO BE AGED), USUALLY BOTH ARE SAME.
C     CV      = AGGREGATE VOLUME / ( AGGREGATE VOL + ASPHALT VOL )
C     SPRB    = ORIGINAL SOFTENING POINT RING AND BALL TEMPERATURE,
C               DEGREES C. ( IMODE = 1 OR 2 )
C     TPEN2   = TEMPERATURE OF REFERENCE PENETRATION, DEGREES C.
C               ( IMODE = 3 ).
C     PI      = ORIGINAL PENETRATION INDEX.( IMODE = 1 )
C     PEN1    = PENETRATION AT 25 DEGREES C. ( IMODE = 2 OR 3 )
C     PEN2    = REFERENCE PENETRATION AT TPEN2. ( IMODE = 3 )
C     IYR     = THE NUMBER OF YEARS THE BITUMEN HAS AGED.
C               ( IYR = 0 ( AGED 6 MONTHS, FOR FIRST YEAR ),
C               IYR = 1 (AGED 18 MONTHS, FOR SECOND YEAR ), ETC )
C     SPRBI   = SOFTENING POINT RING & BALL TEMPERATURE FOR THE
C               CURRENT YEAR, DEGREES C.
C     CN      = THE SLOPE OF THE MASTER RELAXATION MODULUS CURVE.
```

```
C     D1       = THE POWER OF THE INTERCEPT VALUE FOR LOG T=0 OF THE
C                MASTER RELAXATION MODULUS CURVE.
C     TA       = THE POWER LAW CONSTANT FOR THE SHIFT FACTOR.
C     CM       = THE SLOPE OF THE POWER LAW CURVE FOR THE SHIFT FACTOR.
C     NDATE    = DATE, YR/MO/DY, IN THE WEATHER DATA TAPE.
C                (SCAN DOWN TAPE TO SELECTED DATE)
C     NYEAR    = YEAR.(2 DIGITS)
C     LL       = MONTH.(2 DIGITS)
C     DAY(I)   = DAY.(2 DIGITS)
C     TMAX(I)  = MAXIMUM TEMPERATURE DURING DAY(I),DEGREE FAHRENHEIT.
C     TMIN(I)  = MINIMUM TEMPERATURE DURING DAY(I),DEGREE FAHRENHEIT.
C
C     ***********************************************************
C
C     INPUT DATA INFORMATION:
C     -----------------------
C
C     DATA FROM TAPE05
C     ----------------
C
C     CARD     COLUMNS/FORMAT      VARIABLE
C     NO.                          NAME
C
C     01       01-60    (15A4)     TITL
C
C     02       01-10     F10.0     W
C     02       11-20     F10.0     S
C     02       21-30     F10.0     AK
C     02       31-40     F10.0     B
C
C     03       01-10     F10.0     DO
C     03       11-20     F10.0     DF
C     03       21-30     F10.0     VMPH
C
C     04       01-10     I10       NSEL
C
C     05       01-10     F10.0     SR1
C     05       11-20     F10.0     SRM
C
C
C     DATA FROM TAPE02 (RESULTS FROM VISCO PROGRAM)
C     ---------------------------------------------
C
C     CARD     COLUMNS/FORMAT      VARIABLE
C     NO.                          NAME
C
C     01       01-02    I2         IMODE
C     01       03-04    I2         IAGE
C     01       05-14    F10.3      CV
C     01       15-24    F10.3      SPRB (IMODE=1,2) OR TPEN2 (IMODE=3)
C     01       25-34    F10.3      PI (IMODE=1) OR PEN1 (IMODE=2,3)
C     01       35-44    F10.3      PEN2 ( FOR IMODE=3 ONLY )
C
C     02       01-02    I2         IYR
C     02       03-12    F10.3      PEN1
C     02       13-22    F10.3      SPRBI
C
C     03       01-10    F10.5      CN
C     03       11-20    F10.5      D1
C
```

```
C     04      01-10   F10.5      TA
C     04      11-20   F10.5      CM
C
C
C     NOTE:  CARDS 02-04 MUST BE REPEATED FOR EACH YEAR I,
C            I = 1, ..., IAGE
C
C     DATA FROM TAPE01 (WEATHER TAPE)
C     -------------------------------
C
C     CARD    COLUMNS/FORMAT      VARIABLE
C     NO.                         NAME
C
C     01      12-17   I6          NDATE
C
C     02      12-13   I2          NYEAR
C     02      14-15   I2          LL
C     02      16-17   I2          DAY(1)
C     02      20-22   F3.0        TMAX(1)
C     02      23-25   F3.0        TMIN(1)
C
C     03      12-13   I2          NYEAR
C     03      16-17   I2          DAY(I)
C     03      20-22   F3.0        TMAX(I)
C     03      23-25   F3.0        TMIN(I)
C
C     NOTE:  CARD 03 MUST BE REPEATED FOR EACH DAY OF THE
C            ANALYSIS PERIOD.
C            FORMAT OF THE CARDS 1, 2, & 3 MUST BE CHANGED
C            ACCORDING TO THE FORMAT OF WEATHER DATA TAPE.
C
C     ***************************************************************
C
      IMPLICIT REAL*8 (A-H, O-Z)
      DIMENSION   XX(3),TE(3,24),TI(3,24)
      DIMENSION   TMAX(31),TMIN(31),AL(372),N(12)
      DIMENSION   DAY(31)
      DIMENSION   YC(2500), DYC(2500), K1(2500)
      DIMENSION   NF(2500), DN(2500), TITL(15), NF1(2500)
      COMMON /A1/ CN, CM, TM, TR, TA, E1, EE
      COMMON /A2/ SA1, SA2, SB1, SB2
      COMMON /A3/ M1, M2, M3, M4
      COMMON /A4/ TC(12), TH(12)
      INTEGER     DAY
      INTEGER MOS(12)/'JAN','FEB','MAR','APR','MAY','JUN',
     1               'JUL','AUG','SEP','OCT','NOV','DEC'/
      REAL*8      M1, M2, M3, M4, K1, NF, KTMX, KTMN, NF1
  500 FORMAT ( 15A4 )
  520 FORMAT ( 8F10.0 )
  530 FORMAT ( 8I10 )
C**********  INPUT DATA FOR NEW PROBLEM  *********
    8 READ(5,500,END=999)TITL
      READ  (5,520) W, S, AK, B
      READ  (5,520) DO, DF, VMPH
      READ  (5,530)NSEL
      READ  (5,520) SR1, SRM
C*************************************
C       TM IS THE REFERENCE TEMPERATURE OF THE MASTER
C       RELAXATION CURVE, DEGREE FAHRENHEIT.
C       TR IS THE TEMPERATURE OF THE STRESS FREE STATE,
```

```
C        DEGREE FAHRENHEIT.
C****************************************
      TM=77.
      TR=75.
      DZ=1.0
C
C*****READ ORIGINAL PROPERTIES OF BITUMEN FROM VISCO FOR
C*****DIFFERENT MODES 1, 2, OR 3.
C
      READ  (2,208) IMODE, IAGE, CV, SPRB, PI, PEN2
      SPRB=(SPRB*9./5.)+32.
      TPEN2 = SPRB
  208 FORMAT ( 2I2, 4F10.3 )
      WRITE(6,600)TITL
  600 FORMAT('1', 10(/), 10X, 'THERMAL CRACKING ANALYSIS FOR ',15A4)
      WRITE(6,601)NSEL,IAGE
  601 FORMAT(/,10X,'THIS ANALYSIS BEGINS AFTER ',I6,' AND RUNS FOR ',I2,
     +         ' YEARS.')
      WRITE(6,602)
  602 FORMAT(/,10X,'THE BITUMEN USED HAS THE FOLLOWING ORIGINAL ',
     1 'PROPERTIES:' )
      IF(IMODE.EQ.1)WRITE(6,603)PI
  603 FORMAT( 15X, 'PENETRATION INDEX           = ',F10.3)
      IF(IMODE.EQ.2)WRITE(6,605)PI
  605 FORMAT( 15X, 'PENETRATION AT 77 DEG F     = ',F10.3)
      IF ( IMODE .EQ. 3 ) WRITE (6,6051) PI, TPEN2, PEN2
 6051 FORMAT (15X, 'PENETRATION AT  77.0 DEG F = ', F10.3, /,
     1         15X, 'PENETRATION AT', F6.1, ' DEG F = ', F10.3 )
      IF ( IMODE .LT. 3 ) WRITE(6,606)SPRB
  606 FORMAT(15X,'SOFTENING POINT RING & BALL TEMP = ',F10.3,' DEG F')
      IF ( IMODE .EQ. 3 ) WRITE (6,6065) TPEN2
 6065 FORMAT ( 15X, 'TEMPERATURE OF REFERENCE PENETRATION = ', F10.3,
     1 ' DEG F' )
      WRITE(6,607)DF,DO
  607 FORMAT(10X,'THE ASPHALT CONCRETE LAYER IS ',F10.3,' INCHES THICK'
     + /, 10X, 'AND IS ASSUMED TO HAVE AN INITIAL CRACK OF ',F10.3,
     + /10X, 'INCHES EXTENDING FROM THE SURFACE.')
      WRITE(6,608)
  608 FORMAT(10X,'THE ASPHALT CONCRETE HAS THE FOLLOWING MIX ',
     1 'PROPERTIES:' )
      WRITE(6,609)CV,W,S,AK,B
  609 FORMAT(15X, 'AGGREGATE VOLUME CONCENTRATION = ',F10.3,
     +/, 15X, 'DENSITY = ',F10.3,' LBS/FT**3'
     +/, 15X, 'SPECIFIC HEAT = ',F10.3,' BTU/LB DEG F'
     +/, 15X,'THERMAL CONDUCTIVITY = ',F10.3,' BTU/FT**2/HR,DEG F/FT'
     +/, 15X,'ABSORPTIVITY = ',F10.3)
      WRITE(6,610)VMPH,SRM,SR1
  610 FORMAT(/, 10X, 'THE PAVEMENT IS ASSUMED TO BE SUBJECTED TO THE'
     +/, 10X, 'FOLLOWING AVERAGE ENVIRONMENTAL CONDITIONS:'
     +/, 15X,'WIND VELOCITY = ',F10.3,' MILES PER HOUR'
     +/, 15X,'AVERAGE ANNUAL SOLAR RADIATION = ',F10.3,' LANGLEYS/DAY'
     +/, 15X,'AVERAGE JULY SOLAR RADIATION = ',F10.3,' LANGLEYS/DAY')
C**********  INITIALIZE CONSTANTS  **********
      ACON=1.0D0
      ID         = 0
      YC(1)      = DO
      CDMG       = 0.0D0
      CDMG1      = 0.0D0
      IKOUNT     = 1
C**********  DAYS IN THE MONTH  **********
```

```
      N(1)=31
      N(2)=28
      N(3)=31
      N(4)=30
      N(5)=31
      N(6)=30
      N(7)=31
      N(8)=31
      N(9)=30
      N(10)=31
      N(11)=30
      N(12)=31
      XYZTIM=14.0
      XYZTEM=80.0D0
      DZ=10.D0**DZ
      EE=DZ
   18 CONTINUE
      DO 109 IJK=1,360
      F=IJK/57.2958
      AL(IJK) = SRM + (SR1-SRM) * DCOS( F )/0.966
  109 CONTINUE
      DO 108 IJK=361,366
      AL(IJK)=AL(360)
  108 CONTINUE
  138 CONTINUE
C****** THE UPPER LIMIT ON THE RELAXATION MODULUS CURVE IS SPECIFIED
      SBTMAX = 3.625D+05
      ESSM   = SBTMAX * (1.0D0 + 2.52D0 * (CV/(1.0-CV))) ** 0.9923D0
C********** SCAN DOWN TAPE TO SELECTED DATE ************
    9 READ(1,101)NDATE
  101 FORMAT(11X,I6)
      IF(NDATE.LT.NSEL)GOTO9
C********** TAPE NOW IS AT STARTING POINT **************
C**********  DO ONE YEAR AT A TIME  **********
      DO 3 I3=1,IAGE
C**********  READ VARIABLES FROM VISCO  *********
      READ(2,201)IYR,PEN1,SPRBI
      SPRBI=(SPRBI*9./5.)+32
  201 FORMAT(I2,2F10.3)
      READ(2,200)CN,D1
      READ(2,200)TA,CM
  200 FORMAT(2F10.5)
      CN=-CN
      CM=-CM
      D1=10.0D0**D1
   16 E1=D1
      I3M1=I3-1
C****** FATIGUE PARAMETERS, CA & FN, ARE CALCULATED  *****
C SCFT IS THE SCALING FACTOR TO CALCULATE FN
C AFAT AND BFAT ARE EMPIRICAL CONSTANTS THAT
C RELATE CA AND FN.
C*********************************************
      SCFT=2.5
      FN=(1.+1./CN)*(2./SCFT)
      AFAT=0.69
      BFAT=-0.511
      CA=10.**((AFAT+FN)/BFAT)
      WRITE (6,667)
  667 FORMAT ( // )
      IF ( MOD(IYR,2) .EQ. 0 ) WRITE (6,666)
```

```
  666 FORMAT ( 1H1, //// )
      WRITE(6,604)IYR,PEN1,SPRBI,CA,FN
  604 FORMAT( 10X, ' *** YEAR ',I2,' ***'/,
     1 10X, ' IN PLACE BITUMIN PROPERTIES:',
     +     /, 15X, 'PENETRATION AT 77 DEG F    = ',F10.3
     +  /,15X,'SOFTENING POINT RING & BALL TEMP = ',F10.3,' DEG F',
     +  //, 10X, ' FATIGUE PARAMETERS OF THE MIX:',
     +  /, 15X, 'A = ', E10.3, '     N = ', F8.3, // )
      WRITE (6,3457)
      CALL CURVE(TH,TC)
      TC(12) = TC(11)
      TH(12) = TH(11)
C**********  DO ONE MONTH AT A TIME **********
      DO   1 LJ = 1, 12
  997 READ  (1,1233) NYEAR, LL, DAY(1), TMAX(1), TMIN(1)
 1233 FORMAT (11X,3I2,2X,2F3.0)
      IF(TMAX(1).EQ.999)GOTO997
      M         = MOD(NYEAR,4)
      N(2)      = 28
      IF ( M .EQ. 0 ) N(2) = 29
      JYR       = N(LL)
      DO 3333 I = 2,JYR
      READ (1,1234) NYEAR, DAY(I), TMAX(I), TMIN(I)
 1234 FORMAT(11X,I2,2X,I2,2X,2F3.0)
 3333 CONTINUE
C**********  ADD A DAY IF LEAP YEAR  **********
      MAXDAY    = 365 + N(2) - 28
C**********  TEMPORARY DEBUG OUTPUT  **********
C**********  DO ONCE FOR EACH DAY IN MONTH  **********
      DO 2 NI=1,JYR
      TRANG     = 0.0D0
      IF ( TMIN(NI) .GE. TR ) GO TO 2
      TAVG=0.5*(DMIN1(TR,TMAX(NI))+DMIN1(TR,TMIN(NI)))
      TRANG     = DMIN1( TR,TMAX(NI) ) - DMIN1(TR,TMIN(NI))
      AH=1.3+0.62*(VMPH/24.)**0.75
      H=AH/AK
      AC=AK/(S*W)
      C=(0.131/AC)**0.5
      R=0.67*B*3.69*AL(IKOUNT)/(24.*AH)
C****************************************************
C SET UP TO CALCULATE TEMPERATURE OF TOP, MIDDLE, AND
C BOTTOM OF PAVEMENT.
C    XX(1)= BOTTOM TEMPERATURE
C    XX(2)= MIDDLE TEMPERATURE
C    XX(3)= TOP TEMPERATURE
C TEMPERATURE CALCULATED EACH HOUR FOR A COMPLETE DAY
C****************************************************
      DO 10 ITHCK=1,3
      XX(ITHCK)=DF/ITHCK
      IF(ITHCK.EQ.3)XX(3)=0.0D0
      Z2=(-XX(ITHCK))*C/12.0
      Z3 = DEXP(Z2) * H/(( H+C)**2. + C**2.) ** 0.5
      DO 10 J=2,25
      TIM=J
      IF(J.GT.9) GO TO 31
      Z4=6.8176*(.0576*TIM+0.144*Z2-0.288)
      GO TO 35
   31 IF(J.GT.14) GO TO 32
      Z4=+14.7534*(0.02057*TIM+0.075*Z2-0.288)
      GO TO 35
```

```
   32 Z4=-6.94274*(0.02057*TIM+0.12*Z2-0.288)
   35 Z5 = DSIN(Z4)
      IF(Z5) 21,22,22
   21 TMEAN=TAVG+0.5*R
      TV=.5*TRANG
      GO TO 23
   22 TV=.5*TRANG+3.*R
      TMEAN=TAVG+R
   23 TEMP=TMEAN+TV*Z3*Z5
      IF(J.GT.19) TIM=TIM-24
      ITM = TIM + 5
      TE(ITHCK,ITM)=TEMP
      TI(ITHCK,ITM)=ITM
   10 CONTINUE
C**********  1 DAYS CALCULATIONS COMPLETE   **********
   20 IKOUNT=IKOUNT+1
      IF(IKOUNT.EQ.MAXDAY) IKOUNT=1
      DO 110 L1=1,3
      DO 110 L=2,23
      IF(TE(L1,L).LE.TE(L1,L-1).AND.TE(L1,L).LE.TE(L1,L+1)) GO TO 112
      GO TO 118
  112 CONTINUE
C**********  MINIMUM TEMPERATURES HAVE BEEN CALCULATED   **********
      IF(L1.EQ.1)TEMP1=TE(1,L)
      IF(L1.EQ.2)TEMP2=TE(2,L)
      IF(L1.EQ.3)TEMP3=TE(3,L)
C**********  TIME FOR MINIMUM TEMPERATURES   **********
      IF(L1.EQ.1)TIM1=TI(1,L)
      IF(L1.EQ.2)TIM2=TI(2,L)
      IF(L1.EQ.3)TIM3=TI(3,L)
  118 CONTINUE
C**********  NOW CALCULATE MAX TEMPERATURES   **********
      IF(TE(L1,L).GT.TE(L1,L-1).AND.TE(L1,L).GT.TE(L1,L+1)) GO TO 113
      GO TO 110
  113 CONTINUE
      IF(L1.EQ.1)TEMP4=TE(L1,L)
      IF(L1.EQ.2)TEMP5=TE(L1,L)
      IF(L1.EQ.3)TEMP6=TE(L1,L)
      IF(L1.EQ.1)TEMP7=TE(L1,L+1)
      IF(L1.EQ.2)TEMP8=TE(L1,L+1)
      IF(L1.EQ.3)TEMP9=TE(L1,L+1)
C**********  TIME FOR MAXIMUM TEMPERATURES   **********
      IF(L1.EQ.1)TIM4=TI(L1,L)
      IF(L1.EQ.2)TIM5=TI(L1,L)
      IF(L1.EQ.3)TIM6=TI(L1,L)
  110 CONTINUE
C*****************************************************
C IF THE MAX TEMPERATURE IS ABOVE 75 F, FIND TIME AT WHICH
C 75 F OCCURS.  DEL IS TEMP DROP PER HOUR
C*****************************************************
      DEL1=(TEMP4-TEMP1)/(-TIM4+TIM1)
      DEL2=(TEMP5-TEMP2)/(-TIM5+TIM2)
      DEL3=(TEMP6-TEMP3)/(-TIM6+TIM3)
      IF(TEMP4.GT.TR) TIM4=TIM4+(TEMP4-TR)/DEL1
      IF(TEMP5.GT.TR) TIM5=TIM5+(TEMP5-TR)/DEL2
      IF(TEMP6.GT.TR) TIM6=TIM6+(TEMP6-TR)/DEL3
C***** CALCULATE AVG MIN TEMP OF PAVEMENT******
      TMEN=(1./3.)*(TEMP1+TEMP2+TEMP3)
      IF ( TMEN .LT. TR ) GO TO 231
      TRANG     = 0.0D0
```

```
      GO TO 2
  231 CONTINUE
      ID      = ID + 1
      DN(ID) = 1.ODO
C****  CALCULATE AVG MAX TEMP OF PAVEMENT  ******
      TMEX=(1./3.)*(TEMP4+TEMP5+TEMP6)
      IF(TMEX.GT.TR) TMEX=TR
C****  CALCULATE AVG TIME FOR MIN TEMP AND MAX TEMP  *******
      TIMMIN=(TIM1+TIM2+TIM3)/3.O
      TIMMAX=(TIM4+TIM5+TIM6)/3.
      PERIOD=24.O-XYZTIM+TIMMIN
      XYZTIM=TIMMAX
      DLTN=TMEN-TR
      DLTX=TMEX-TR
      XYZTEM=TMEX
 1000 CONTINUE
      KTMX        = O.ODO
      KTMN        = O.ODO
      TRMX        = DMAX1 ( O.ODO, TR-TMAX(NI) )
      TRMN        = TR - TMIN(NI)
C*** CALCULATE STRESS INTENSITY FACTOR FOR MIN & MAX TEMP  ****
      CALL FACTOR ( DF, DLTX, PERIOD, TRMX, ID, YC, SA1, SB1, KTMX,
     *               NYEAR, LJ, ESSM )
      CALL FACTOR ( DF, DLTN, PERIOD, TRMN, ID, YC, SA2, SB2, KTMN,
     *               NYEAR, LJ, ESSM )
      K1(ID)      = KTMN - KTMX
      DYC(ID)     = O.ODO
      IF (K1(ID) .GT. O.ODO) GO TO 875
      ID = ID-1
      GO TO 2
  875 CONTINUE
      ZO          = YC(ID)
      Z1          = DF
      ZO1         = O.ODO
      IF ( ZO .LT. Z1 ) CALL SIMPSN ( CA, FN, ZO, Z1, ZO1 )
      NF(ID)      = ACON + ZO1
      ACON=O.ODO
      IF ( NF(ID) .GT. O.ODO ) CDMG = CDMG + DN(ID)/NF(ID)
      DYC(ID)     = DN(ID) * CA * (K1(ID) ** FN)
      IF(NF(ID).LE.O.ODO)DYC(ID)=O.
  876 YC(ID+1)    = YC(ID) + DYC(ID)
      ZO1         = O.ODO
      CALL SIMPSN ( CA, FN, DO, DF, ZO1 )
      NF1(ID)     = 1.OO + ZO1
      CDMG1       = CDMG1 + DN(ID)/NF1(ID)
      IF ( YC(ID+1) .LE. DF ) GO TO 9880
      WRITE (6,3456) IYR, MOS(LL), DAY(NI), NYEAR,
     1                ID, NF(ID), NF1(ID), YC(ID), CDMG, CDMG1
      IF ( YC(ID+1) .LE. DF ) GO TO 9880
      YC(ID+1)     = DF
 9880 CONTINUE
    2 CONTINUE
      YCID = YC(ID)
      IF ( ID .EQ. O ) YCID = DO
      WRITE (6,3456) IYR, MOS(LL), JYR,     NYEAR,
     1                ID, NF(ID), NF1(ID), YCID, CDMG, CDMG1
 3456 FORMAT ( 11X, I2, 2X, A4, I2, ', 19', I2,
     1          1X, I5, 5E13.6 )
 3457 FORMAT ( 11X, 'NO', 6X, 'DATE',
     1          8X, 'ID', 6X, 'NF', 10X, 'NF1', 11X,
```

```
     2          'YC', 10X, 'CDMG',  9X, 'CDMG1', / )
    1 CONTINUE
    3 CONTINUE
C********** REWIND FILE AND PROCESS NEXT PROBLEM **********
      REWIND 1
      GOTO 8
  999 STOP
      END
```

```
      SUBROUTINE CURVE(TH,TC)
C*** CURVE CALCULATES TH AND TC, HEATING AND COOLING TEMPS   ***
      IMPLICIT REAL*8 (A-H,O-Z)
      DIMENSION TH(11),TC(11)
      COMMON /A1/ CN,CM,TM,TR,TA,E1,EE
      COMMON /GT/ GAB1
      DIMENSION F(50)
      COMMON      HH(11),ZZ
      COMMON /KK/ I
  100 CONTINUE
      INT=40
      A=CM/(CM+1.0)+CN-2.0
      B=-CN
      DM=(1.0-CN)/(CM+1.0)**(1.0-CN)
      GA=DGAMMA(A+1.0)
      GB1=DGAMMA(B+1.0)
      GAB1=GA*GB1/DGAMMA(A+B+2.0)
      TH(1)=1.0
      TC(1)=1.0
      TC(11)=0.0D0
      DO 40 INDEX=1,2
      HH(1)=1.0
      AREA=0.0D0
      ZZ=0.0D0
      DTN=0.0D0
      DO 10 I=1,10
      DTN=DTN+0.1
      DTR=DABS(DTN)
      IF(INDEX.EQ.1) GO TO 21
      H=(DTN+1.0)**(CM+1.0)
      HH(I+1)=H
      HS=(HH(I+1)-HH(I))/(INT-1)
      CALL HEAT(A,B,H,INT,F,AREA,HS)
      CONS=DM*(1.0+1.0/DTN)**(1.0-CN)
      TII=CONS*AREA
      TH(I+1)=TII
      GO TO 25
   21 CONTINUE
      IF(I.EQ.10) GO TO 10
      RR=-DTR
      H=(1.0+RR)**(CM+1.0)
      HH(I+1)=H
      HS=(HH(I)-HH(I+1))/(INT-1)
      CALL COOL(A,B,H,AREA)
      CONS=DM*(-1.0-1.0/RR)**(1.0-CN)
      TII=CONS*AREA
      TC(I+1)=TII
   25 CONTINUE
```

```
10 CONTINUE
40 CONTINUE
   RETURN
   END




   SUBROUTINE HEAT(A,B,H,INT,F,AREA,HS)
   IMPLICIT REAL*8 (A-H,O-Z)
   DIMENSION F(INT)
   COMMON      HH(11),ZZ
   COMMON /KK/ I
   DA=H**(A+1.0)*(-1.0+H)**(B+1.0)/(B+1.0)
   DB=-(A+B+2.0)/(B+1.0)
   DO 10 J=1,INT
   XX=HH(I)+HS*(J-1)
10 F(J)=XX**A*(-1.0+XX)**(B+1.0)
   CALL INTGRT(INT,F,HS,AR)
   ZZ=ZZ+AR
   AREA=DA+ZZ*DB
   RETURN
   END




   SUBROUTINE INTGRT(N,F,H,AREA)
   IMPLICIT REAL*8 (A-H,O-Z)
   DIMENSION F(N)
   AREA=0.0D0
   S=0.5*H
   DO 10 I=2,N
   AREA=AREA+S*(F(I-1)+F(I))
10 CONTINUE
   RETURN
   END




   SUBROUTINE COOL (A,B,H,AREA)
   IMPLICIT REAL*8 (A-H,O-Z)
   REAL*4 SH,SA1,SB2,SP
   REAL*4 SNGL
   COMMON /GT/ GAB1
   A1=A+1.0
   B1=B+1.0
   P=0.0D0
   SH=SNGL(H)
   SA1 = SNGL(A1)
   SB2=SNGL(B1)
   SP=SNGL(P)
10 CONTINUE
   P=DBLE(SP)
   H=DBLE(SH)
   A1=DBLE(SA1)
   B2=DBLE(SB2)
   AREA=GAB1*(1.D0-P)
   RETURN
```

```
      END



      SUBROUTINE FACTOR ( DF, DELT, PERIOD, TRG, ID, YC, SA, SB, XXX,
     *                    NYEAR, LJ, ESSM )
C***************************************************************
C* CALCULATES STRESS INTENSITY FACTOR FOR A GIVEN PAVEMENT     *
C*                                                             *
C*   DF    = DEPTH OF ASPHALT LAYER                            *
C*   DELT = PAVEMENT TEMP - STRESS FREE TEMP                   *
C*   PERIOD LOADING TIME                                       *
C*   TRG   = STRESS FREE TEMP - MAX AIR TEMP                   *
C*   ID    = DAY COUNTER                                       *
C*   YC    = CRACK LENGTH                                      *
C*   SA,SB= CONSTANTS TO CALCULATE STRESS INTENSITY FACTOR     *
C*   XXX   = STRESS INTENSITY FACTOR                           *
C***************************************************************
      IMPLICIT REAL*8 (A-H,O-Z)
      REAL*8       M1, M2, M3, M4
      DIMENSION    YC(2500)
      COMMON /A1/ CN, CM, TM, TR, TA, E1, EE
      COMMON /A3/ M1, M2, M3, M4
      COMMON /A4/ TC(12), TH(12)
      SA          = 0.0D0
      SB          = 0.0D0
      XXX         = 0.0D0
      DT=DELT
      IF (PERIOD.LT.1.0) PERIOD=1.0
      TIME=PERIOD*3600.
      TTN=TIME**(-CN)
      T=TR+DT
      AT=((TM-TA)/(T-TA))**CM
      ATN=AT**CN
      DTN=OT/(TR-TA)
      DTR=DABS(DTN*10.0)
      NN=IDINT(DTR)
      DIF=DTR-NN
      NG = NN + 1
      IF ( NG .LE. 11 ) GO TO 99
      WRITE (6,654)
  654 FORMAT ( 5X, 'NG IS GREATER THAN 11. SET NG = 11', // )
      NG = 11
   99 CONTINUE
C** CALCULATION OF EFF MODULUS. SEE P. 17, REPORT 18-3 ***
      IF(DELT) 90,29,30
   90 RATIO = (TC(NG+1) - TC(NG)) * DIF + TC(NG)
      J=1
      GO TO 120
   29 RATIO=1.D0
      J=3
      GO TO 120
   30 RATIO = (TH(NG+1) - TH(NG)) * DIF + TH(NG)
      J=2
  120 CONTINUE
      ESS=ATN*E1*TTN/(1.D0-CN)
      IF (ESS .GT. ESSM) ESS = ESSM
      EEF        = EE + RATIO * ( ESS - EE )
      M1         = 8.8988D+00
```

```
      M2        = 2.0599D+00
      M3        = 0.8481D+00
      M4        =-0.00157D+00
      IF ( EEF .GE. 1.000D+05 ) GO TO 978
      M1        = M1 + ( 29.1063D+00 - DF ) * ( 1.3573D+00
     1          - 0.013573D+00 * ( EEF / 1000.0D0) )
      M2        = M2 - ( 129.3215D+00 - DF ) * ( 0.01687+00
     1          - 0.0001687D+00 * ( EEF / 1000.0D0) )
      IF ( DF .GT. 4.0D0 ) GO TO 988
      M3        = M3 + ( 2.7811D+00 - DF ) * ( 0.2738D+00
     1          - 0.002738D+00 * ( EEF / 1000.0D0) )
      GO TO 987
  988 CONTINUE
      M3        = M3 - ( 6.5835D+00 - DF ) * ( 0.12919D+00
     1          -0.0012919D+00 * ( EEF / 1000.0D0))
  987 CONTINUE
      M4        = M4 + ( 5.0472D+00 - DF ) * ( 0.001129D+00
     1          - 0.00001129D+00 * ( EEF / 1000.0D0) )
  978 IF ( TRG .LE. M1 ) RETURN
      SA        = M2 * ( TRG - M1 )
      SB        = M3 + M4 * TRG
      XXX       = SA * YC(ID) ** SB
      RETURN
      END



      SUBROUTINE SIMPSN ( CA, FN, XF, XL, AREA )
      IMPLICIT REAL*8 (A-H,O-Z)
      REAL*8      KMIN, KMAX
      DIMENSION   Y(7)
      COMMON /A2/ SA1, SA2, SB1, SB2
      NS        = 6
      NP        = 7
      XINC      = ( XL - XF ) / 6.000D+00
      X         = XF
      DO 1100 I = 1, NP
      F         =  SA2 * X ** SB2 - SA1 * X ** SB1
      YI        = CA * DABS(F) ** FN
      Y(I)      = 1.000D+00 / YI
      X         = X + XINC
 1100 CONTINUE
      AREA      = 0.0D0
      DO 1200 I = 1, NS, 2
      A         = Y(I) + 4.000D+00 * Y(I+1) + Y(I+2)
      A         = A * XINC / 3.000D+00
      AREA      = AREA + A
 1200 CONTINUE
      RETURN
      END
```

```
C*******************************************************************
C*                                                                 *
C*                  COMPUTER PROGRAM ( VISCO1 )                    *
C*                         TO DETERMINE                            *
C*         VISCOELASTIC PROPERTIES OF ASPHALT CONCRETE             *
C*                                                                 *
C*******************************************************************
C*          EXPLANATION OF INPUT VARIABLES                         *
C*          ------------------------------                         *
C*                                                                 *
C*   PINIT    PENETRATION INDEX, (PII)                             *
C*                                                                 *
C*   SPINIT   SOFTENING POINT RING & BALL, DEGREES C, (SPRBI)      *
C*                                                                 *
C*   P1INIT   PENETRATION AT 25 DEGREES C, (PEN1)                  *
C*                                                                 *
C*   P2INIT   REFERENCE PENETRATION AT TPEN2, (PEN2)               *
C*                                                                 *
C*   TPEN2    TEMPERATURE OF REF. PENETRATION, DEGREES C           *
C*                                                                 *
C*   CV       [AGGREGATE VOL]/([AGGREGATE VOL]+[ASPHALT VOL])      *
C*                                                                 *
C*   IYRS     NUMBER OF YEARS ASPHALT IS TO BE AGED                *
C*                                                                 *
C*                                                                 *
C*                                                                 *
C*     THIS PROGRAM CAN OPERATE IN THREE DIFFERENT MODES, SELECTED *
C* BY THE INPUT VARIABLE MODE.  INPUT REQUIRED FOR EACH MODE IS AS *
C* FOLLOWS:                                                        *
C*                                                                 *
C*    CARD 01                                                      *
C*    -------                                                      *
C*                                                                 *
C*              DATA ENTERED                 INPUT FORMAT          *
C*              ------------                 ------------          *
C*                                                                 *
C*              MODE                         (I1)                  *
C*                                                                 *
C*                                                                 *
C*    CARD 02                                                      *
C*    -------                                                      *
C*                                                                 *
C*    MODE      DATA ENTERED                 INPUT FORMAT          *
C*    ----      ------------                 ------------          *
C*                                                                 *
C*      1       PINIT,SPINIT,CV,IYRS         (3F10.2,I5)           *
C*      2       P1INIT,SPINIT,CV,IYRS        (3F10.2,I5)           *
C*      3       P1INIT,P2INIT,TPEN2,CV,IYRS  (4F10.2,I5)           *
C*                                                                 *
C*                                                                 *
C*                                                                 *
C*    NOTE: A BLANK CARD SHOULD BE INSERTED AT THE END OF ALL      *
C*    ----  DATA CARDS                                             *
C*                                                                 *
C*                                                                 *
C*  SEE COMMENTS IN FUNCTION POEL FOR FURTHER INFORMATION.         *
C*                                                                 *
C*******************************************************************
      DIMENSION X(20),Y(20),E1(20),E2(20),E3(20)
      REAL TEMPS(3)/0.0,25.,60./
```

```
C**********  DEFINE INPUT AND OUTPUT UNITS  **********
      NTT = 5
      NTO = 6
C**********  INITIALIZE CONSTANTS  **********
      KPI=1
      KSPRB=1
      KTEMP=1
      TIMOLI=1.0E+05
      KTIMOL=7
      FTIMOL=.1
      KPEN1=1
      TPEN1=25.
    1 CONTINUE
      NN = 0
C**********  INPUT MODE 1,2, OR 3  **********
   10 READ(NTT,9010,END=9999)MODE
C**********  WRITE PAGE HEADER  **********
C**********  PERFORM SELECTED MODE CALCULATIONS **********
      GO TO(100,200,300),MODE
      WRITE(NTO,9050)
      STOP 1
C***************   M O D E   1     ******************************
C*                                                            *
C*  PII AND SPRBI ARE READ IN DIRECTLY                        *
C*                                                            *
C*************************************************************
  100 READ(NTT,9210)PINIT,SPINIT,CV,IYRS
      WRITE (1,1001) MODE, IYRS, CV, SPINIT, PINIT
 1001 FORMAT ( 2I2, 3F10.3, 10X, '<-- MODE, YRS, CV, SPRB, PI' )
      IYRT  = IYRS + 1
      DO 102 IY=1,IYRT
      IYR=IY-2
      PII=PINIT
      SPRBI=SPINIT
      NN=0
C*****  AGE ASPHALT  *****
      CALL CONV(MODE,IYR,PII,SPRBI,TPEN1,0.)
C**********  LOOP FOR 3 TEMPERATURES  **********
      DO 101 I101=1,3
      TEMPI=TEMPS(I101)
      IWRITE=0
      WRITE(NTO,9030)
      WRITE(NTO,9040)MODE
C**********  WRITE OUT INPUTS  **********
      WRITE(NTO,9070)PINIT,IYR,PII
      WRITE(NTO,9090)SPINIT,IYR,SPRBI
      WRITE(NTO,9110)TEMPI,KTEMP
      WRITE(NTO,9140)TIMOLI,KTIMOL
      WRITE(NTO,9150)FTIMOL
      PI=PII
      SPRB=SPRBI
      TEMP=TEMPI
      TIMOL=TIMOLI
      CALL CALC(NP,PI,SPRB,TEMP,TIMOL,X,Y,MODE,IWRITE,FTIMOL,NN,
     +          E1,E2,E3,KTIMOL,CV)
  101 CONTINUE
  102 CALL FINDTA(NN,E1,E2,E3)
      GO TO 1
C***************   M O D E   2     ******************************
C*                                                            *
```

```
C*  PII CALCULATED FROM PENETRATION VALUE AND SPRBI                   *
C*                                                                    *
C*********************************************************************
  200 READ(NTT,9210)P1INIT,SPINIT,CV,IYRS
      WRITE (1,1002) MODE, IYRS, CV, SPINIT, P1INIT
 1002 FORMAT ( 2I2, 3F10.3, 10X, '<-- MODE, YRS, CV, SPRB, PEN1' )
C***  AGE ASPHALT  ***
      IYRT = IYRS + 1
      DO 202 I202=1,IYRT
      IYR=I202-2
      PEN1I=P1INIT
      SPRBI=SPINIT
      NN=0
      CALL AGE(IYR,PEN1I,TPEN1,SPRBI)
C**********  LOOP FOR 3 TEMPERATURES  **********
      DO 201 I201=1,3
      TEMPI=TEMPS(I201)
      IWRITE=0
      WRITE(NTO,9030)
      WRITE(NTO,9040)MODE
      WRITE(NTO,9160)P1INIT,IYR,PEN1I
      WRITE(NTO,9180)TPEN1
      WRITE(NTO,9090)SPINIT,IYR,SPRBI
      WRITE(NTO,9110)TEMPI,KTEMP
      WRITE(NTO,9140)TIMOLI,KTIMOL
      WRITE(NTO,9150)FTIMOL
      PEN1=PEN1I
      SPRB=SPRBI
      A=(ALOG10(800.)-ALOG10(PEN1))/(SPRB-TPEN1)
      PI=(20.-500.*A)/(1.+50.*A)
      TEMP=TEMPI
      TIMOL=TIMOLI
      CALL CALC(NP,PI,SPRB,TEMP,TIMOL,X,Y,1,IWRITE,FTIMOL,NN,
     +          E1,E2,E3,KTIMOL,CV)
  201 CONTINUE
  202 CALL FINDTA(NN,E1,E2,E3)
      GO TO 1
C*************  M O D E  3  ***************************************
C                                                                    *
C     PI AND SOFTENING POINT RING & BALL ARE CALCULATED FROM THE TWO*
C     GIVEN PENETRATION VALUES AND CORRESPONDING TEMPERATURES.       *
C                                                                    *
C*********************************************************************
  300 READ(NTT,9211)P1INIT,P2INIT,TPEN2,CV,IYRS
      WRITE (1,1003) MODE, IYRS, CV, TPEN2, P1INIT, P2INIT
 1003 FORMAT ( 2I2, 4F10.3, '<-- MODE, YRS, CV, TPEN2, PEN1, PEN2' )
C***  AGE ASPHALT  ***
      IYRT = IYRS + 1
      DO 302 I302=1,IYRT
      IYR=I302-2
      PEN1=P1INIT
      PEN2=P2INIT
      NN=0
      CALL CONV(MODE,IYR,PEN1,PEN2,TPEN1,TPEN2)
      SPRB=PEN2
      A=(ALOG10(800.)-ALOG10(PEN1))/(SPRB-TPEN1)
      PI=(20.-500.*A)/(1.+50.*A)
C**********  LOOP FOR 3 TEMPERATURES  **********
      DO 301 I301=1,3
      TEMPI=TEMPS(I301)
```

```
      IWRITE=0
      WRITE(NTO,9030)
      WRITE(NTO,9040)MODE
      WRITE(NTO,9160)P1INIT,IYR,PEN1
      WRITE(NTO,9180)TPEN1
      WRITE(NTO,9200)P2INIT,TPEN2
      WRITE(NTO,9205)IYR,SPRB
      WRITE(NTO,9110)TEMPI,KTEMP
      WRITE(NTO,9140)TIMOLI,KTIMOL
      WRITE(NTO,9150)FTIMOL
      TEMP=TEMPI
      TIMOL=TIMOLI
      CALL CALC(NP,PI,SPRB,TEMP,TIMOL,X,Y,1,IWRITE,FTIMOL,NN,
     +          E1,E2,E3,KTIMOL,CV)
  301 CONTINUE
  302 CALL FINDTA ( NN, E1, E2, E3 )
      GO TO 1
 9999 CONTINUE
      STOP
C**********    FORMATS FOR MAIN PROGRAM    **************
 9010 FORMAT(I1)
 9030 FORMAT('0STIFFNESS OF MIX USING VAN DER POELS NOMOGRAPH')
 9040 FORMAT(1X,'INPUT DATA:',22X,'MODE  =  ',I4)
 9050 FORMAT('1MODE MUST BE INTEGER 1 OR 2 OR 3  STOP.')
 9070 FORMAT(/28X,'INITIAL PI  =  ',1X,F5.2/26X,
     -'AGED ',I2,' YEAR(S) TO',F5.2)
 9090 FORMAT(/1X,'INITIAL SOFTENING POINT RING AND BALL  =  ',F6.1/1X,
     -23X,'AGED ',I2,' YEAR(S) TO ',F6.1)
 9110 FORMAT(/19X,'INITIAL TEMPERATURE  =  ',F6.1/8X,'NUMBER OF STEPS IN
     - TEMPERATURE  =  ',I4)
 9140 FORMAT(/18X,'INITIAL LOADING TIME  =  ',1PE10.1/7X,'NUMBER OF STEP
     -S IN LOADING TIME  =  ',I4)
 9150 FORMAT(4X,'MULTIPLYING FACTOR IN LOADING TIME  =  ',F6.1)
 9160 FORMAT(/19X,'INITIAL PENETRATION  =  ',F6.1/25X,
     -'AGED ',I2,' YEAR(S) TO', F6.1 )
 9180 FORMAT(15X,'PENETRATION TEMPERATURE  =  ',F6.1)
 9200 FORMAT(17X,'REFERENCE PENETRATION  =  ',F6.1/5X,'REFERENCE PENETRA
     -TION TEMPERATURE  =  ',F6.1)
 9205 FORMAT( 17X, 'AGED ',I2,' YEAR(S),  SPRB =',F8.1)
 9210 FORMAT(3F10.2,I5)
 9211 FORMAT(4F10.2,I5)
      END




      SUBROUTINE CALC(NP,PI,SPRB,TEMP,TIMOL,X,Y,MODE,IWRITE,
     +          FTIMOL,NN,E1,E2,E3,KTIMOL,CV)
C*** USE NOMOGRAPH AND SET UP VARS FOR REGRESSION  ***
      DIMENSION X(20),Y(20),E1(20),E2(20),E3(20)
      NP = 0
      DO70 LTIMOL=1,KTIMOL
      ALGS=POEL(PI,SPRB,TEMP,TIMOL)
      IF ( ALGS.LT.-20.0) GO TO 65
      NP = NP+1
      X(NP) = ALOG10(TIMOL)
      SB = 10**ALGS*1.450E-04*0.0703
      SN = 0.83*ALOG10((4.0E+05)/SB)
      CONST = ( 1.0 +(2.5/SN) * (CV/(1.0-CV)))**SN * 0.000145
      SMIX  = 10.0 ** ALGS * CONST
```

```
      Y(NP) = ALOG10(SMIX)
   65 CONTINUE
      CALL TYPES(1,IWRITE,PI,SPRB,TEMP,TIMOL,PEN1,TPEN1,
     +           PEN2,TPEN2,ALGS,CONST)
      TIMOL=TIMOL*FTIMOL
   70 CONTINUE
      CALL LINEAR(NP,X,Y,EA,EB)
      NN = NN + 1
      E1(NN) = EB
      E2(NN) = EA
      E3(NN) = TEMP
      WRITE (6,666) NN, E3(NN), E2(NN), E1(NN)
C**** SAVE CN AND D1 AT MASTER TEMPERATURE  ******
      IF(TEMP.NE.25.)RETURN
      WRITE (1,100)E2(NN),E1(NN)
  100 FORMAT(2F10.5,' <---- CN, D1')
      RETURN
  666 FORMAT ( '  NN ', I5, '  TEMP ', E14.7, '  SLOPE, M ', E14.7,
     1         '  INTERCEPT,E1', E14.7 )
      END
```

```
      SUBROUTINE CONV(MODE,IYR,VAR1,VAR2,VAR3,VAR4)
C**** CONVERT TO MODE 2 TO USE AGE ROUTINE  *****
      IF(MODE.EQ.3)GOTO2
C**** CONVERT FROM MODE 1 TO MODE 2 AND AGE *****
      PII=VAR1
      SPRBI=VAR2
      TPEN1=VAR3
      A=(20.-PII)/(500.+50.*PII)
      DELTA=A*(SPRBI-25.)
      PEN1I=10.**(ALOG10(800.)-DELTA)
C***** NOW AGE *****
      CALL AGE(IYR,PEN1I,TPEN1,SPRBI)
C***** CONVERT BACK TO MODE 1 AFTER AGING *****
      A=(ALOG10(800.)-ALOG10(PEN1I))/(SPRBI-TPEN1)
      PII=(20.-500.*A)/(1.+50.*A)
      VAR1=PII
      VAR2=SPRBI
      RETURN
C**********  CONVERT FROM MODE 3 TO MODE 2  **********
    2 PEN1=VAR1
      PEN2=VAR2
      TPEN1=VAR3
      TPEN2=VAR4
      A=(ALOG10(PEN1)-ALOG10(PEN2))/(TPEN1-TPEN2)
      DPEN=ALOG10(800.)-ALOG10(PEN2)
      SPRB=TPEN2+DPEN/A
C*** NOW AGE ***
      CALL AGE(IYR,PEN1,TPEN1,SPRB)
C*** PASS BACK RESULTS TO MAIN IN MODE 2 FORM ***
      VAR1=PEN1
      VAR2=SPRB
      RETURN
      END
```

```
      SUBROUTINE AGE(IYR,PEN1I,TPEN1,SPRBI)
      IF ( IYR .GE. 0 ) GO TO 1234
      WRITE (6,200)
  200 FORMAT ( '0USING ORIGINAL PROPERIES OF BITUMEN (WITHOUT AGING)')
      WRITE (1,100) IYR, PEN1I, SPRBI
      RETURN
 1234 CONTINUE
C**********  AGES PAVEMENT USING MODE 2 VARIABLES **********
      WRITE(6,600)PEN1I,TPEN1,SPRBI,IYR
  600 FORMAT('0*** AGE CALLED: PEN1I=',F10.4,' TPEN1=',F10.4,
     +       'SPRBI=',F10.4,' IYR=',I2)
C**** ABORT IF ASKED TO AGE MORE THAN 10 YEARS  ***
      IYR2=IYR
      IF(IYR.LT.10)GO TO 5
      WRITE(6,610)
  610 FORMAT('0*** WARNING ***  PAVEMENT CAN ONLY BE AGED',
     +  '  10 YEARS.  10 YEARS ASSUMED.')
      IYR=10.
C*** T IS MONTHS TO AGE AND RUNS 6, 18, 30.... ***
C*** STARTS AT 6 MONTHS TO BE AS CLOSE AS POSSIBLE ***
    5 T=6.+12.*FLOAT(IYR)
      SPRB1=-16.2+1.230*(SPRBI*9./5.+32.)
      SPRBT=SPRB1-14.4+10.5*ALOG(T)
      SPRBI=5.*(SPRBT-32.)/9.
      PEN1I=(-.4+.716*PEN1I)-(.193*PEN1I-9.1)*ALOG(T)
      IF(PEN1I.LT.20.)PEN1I=20.
      IYR=IYR2
      WRITE(6,601)IYR,PEN1I,TPEN1,SPRBI
  601 FORMAT(' *** AFTER AGING --> IYR=',I2,' PEN1=',F8.3,
     -' TPEN1=',F8.3,' SPRBI=',F8.3)
      WRITE (1,100)IYR,PEN1I,SPRBI
  100 FORMAT(I2,2F10.3,'<-- YR, PEN1, SPRBI')
      RETURN
      END


      FUNCTION POEL(PI,SPRB,TEMP,TIMOL)
C     THE FUNCTION SUBPROGRAM POEL PROVIDES THE LOGARITHM (BASE TEN)
C     OF THE STIFFNESS MODULUS OF A BITUMEN FROM GIVEN PENETRATION
C     INDEX, SOFTENING POINT RING AND BALL, TEMPERATURE AND TIME OF
C     LOADING. THE PROGRAM POEL IS A COMPUTERIZED VERSION OF VAN DER
C     POEL'S NOMOGRAPH EDITION AUGUST 1953, 2ND EDITION 1969.
C     REFERENCE: ''JOURNAL OF APPLIED CHEMISTRY'', VOLUME 4, PART5,
C     MAY 1954. KSLA DRAWING NUMBER 69.12.1164A.
C     THE PROGRAM POEL USES ONLY GEOMETRIC INFORMATION TAKEN FROM THE
C     NOMOGRAPH. A GRID OF X,Y COORDINATES, WITH ORIGIN IN THE POINT
C     TEMPERATURE EQUALS SOFTENING POINT RING AND BALL, IS LAID
C     OVER THE NOMOGRAPH. TEMPERATURE DIFFERENCES ARE FOUND ON THE
C     LINE (X,Y=0); LOADING TIMES ON THE LINE (X,Y=-11). THE UNIT OF
C     LENGTH IS CENTIMETRE. THE LINES OF CONSTANT PI ARE THE HORIZONTAL
C     LINES (X,Y=0.545*(PI+10)). THE LINES OF CONSTANT STIFFNESS FORM
C     A BUNDLE OF CURVED LINES INTERSECTING THE PI LINES. EACH POINT
C     OF INTERSECTION ASSIGNS AN X VALUE TO EACH LOG. STIFFNESS VALUE
C     ON A GIVEN PI LINE.
C     THE ASSEMBLY OF INTERSECTION POINTS COVERS AN AREA ON THE
C     NOMOGRAPH, WHICH IS CALLED THE ADMITTED AREA.
C     LET XT BE THE X COORDINATE OF A POINT ON THE TEMPERATURE LINE
C     AND XL BE THE X COORDINATE OF A POINT ON THE LOADING TIME LINE,
```

```
C     THEN A STRAIGHT LINE CAN BE DRAWN THROUGH THESE TWO POINTS.
C     THE EQUATION OF THIS LINE IS X = XT + (XT - XL)*(Y/11).
C     SUBSTITUTING INTO THIS EQUATION THE Y VALUE CORRESPONDING TO
C     THE PENETRATION INDEX, THE X COORDINATE OF THE INTERSECTION
C     POINT OF THIS LINE WITH THE PI LINE IS OBTAINED. BY INTERPOLATION
C     BETWEEN THE LOG. STIFFNESS VALUES CORRESPONDING WITH THE TWO NEXT
C     CONTINUE
C     NEIGHBOUR POINTS OF THE ASSEMBLY ON THE SAME PI LINE, THE PROGRAM
C     YIELDS THE REQUIRED LOG. STIFFNESS VALUE.
C     TO KEEP THE AMOUNT OF STORED DATA LIMITED, ONLY THE INTERSECTIONS
C     OF THE STIFFNESS LINES WITH INTEGER VALUE  PI LINES ARE READ OUT.
C
C     PI LINES ARE COUNTED FROM PI = -3 UP TO PI = +7, WITH VARIABLE I
C     RUNNING FROM 1 UP TO 11.
C     EQUI-STIFFNESS LINES ARE COUNTED FROM RIGHT TO LEFT, WITH VARIABLE
C     J RUNNING FROM 1 UP TO 46.
C     KSTIF(I) IS NUMBER OF INTERSECTION POINTS OF EQUI-STIFFNESS LINES
C     WITH NUMBER I PI LINE.
C     XSTIF(I,J) IS X COORDINATE OF INTERSECTION POINT OF NUMBER I PI
C     LINE WITH NUMBER J EQUI-STIFFNESS LINE.
C     THE ARRAY XTEMP CONTAINS THE X-COORDINATES OF THE 10-DEGREE
C     CALIBRATION  MARKS ON THE TEMPERATURE LINE.
C     SMIN(I) IS SMALLEST LOG. STIFFNESS VALUE INTERSECTING NUMBER I
C     PI LINE.
C     TO KEEP STATEMENT LENGTH LIMITED TO 20 CARDS, THE X-COORDINATES
C     OF THE INTERSECTION POINTS OF EQUI-STIFFNESS LINES WITH PI LINES
C     ARE STORED IN THE ARRAYS XDUM1 AND XDUM2. THE EQUIVALENCE
C     STATEMENT IDENTIFIES THESE ARRAYS WITH THE ARRAY XSTIF(I,J). THE
C     VARIABLE I RUNNING FIRST, THE DATA SHOULD BE READ IN GROUPS OF
C     11 NUMBERS.
      POEL=-20.
      IF(PI.GT.7.)  POEL=-21.
      IF(PI.LT.-3.)  POEL=-22.
      IF(TIMOL.GT.1.E+10) POEL=-23.
      IF(TIMOL.LT.1.E-06) POEL=-24.
      IF(POEL.LT.-20.5.AND.POEL.GT.-24.5)  GO TO20
C     XL IS X COORDINATE OF LOADING TIME;
C     XT IS X COORDINATE OF SPRB MINUS TEMP.
      XL=(ALOG10(TIMOL)+3.953)*1.693
      PI4=PI+4.
      IP=PI4
      Y1=0.545*FLOAT(IP+6)
      XT=XDRT(SPRB,TEMP)
C     XT=66. MEANS TEMPERATURE TOO LOW, WITH RESPECT TO S.P. RING & BALL
C     XT=67. MEANS TEMPERATURE TOO HIGH,WITH RESPECT TO S.P. RING & BALL
      IF(XT.EQ.66.)  POEL=-25.
      IF(XT.EQ.67.)  POEL=-26.
      IF(XT.LT.68..AND.XT.GT.65.)  GO TO20
      X=XT-(Y1/11.)*(XL-XT)
      SLOG1=SLOG(IP,X)
C     SLOG=50. MEANS GLASSY STATE
C     SLOG=56. MEANS WHITE AREA
      IF(SLOG1.EQ.50.)  POEL=-27.
      IF(SLOG1.EQ.56.)  POEL=-28.
      IF(SLOG1.LT.57..AND.SLOG1.GT.49.)  GO TO20
      AIP=IP
      IF(PI4.EQ.AIP)  GO TO10
      IP=IP+1
      Y2=0.545*FLOAT(IP+6)
      X=XT-(Y2/11.)*(XL-XT)
```

```
      SLOG2=SLOG(IP,X)
      IF(SLOG2.EQ.50.)  POEL=-27.
      IF(SLOG2.EQ.56.)  POEL=-28.
      IF(SLOG2.LT.57..AND.SLOG2.GT.49.)  GO TO20
      Y=0.545*(PI+10.)
      SLOG3=SLOG1+(SLOG2-SLOG1)*((Y-Y1)/(Y2-Y1))
      SLOG1=SLOG3
   10 POEL=SLOG1
   20 CONTINUE
      RETURN
      END
```

```
      BLOCK DATA
      COMMON/BLOCKT/XTEMP
      COMMON/BLOCKS/KSTIF,XSTIF,SMIN
      INTEGER KSTIF(11)
      REAL XSTIF(11,46),XTEMP(34),SMIN(11),XDUM1(209),XDUM2(297)
C     EQUIVALENCE (XDUM1,XSTIF(1,1)),(XDUM2,XSTIF(1,20))
      EQUIVALENCE (XDUM1(1),XSTIF(1,1)),(XDUM2(1),XSTIF(1,20))
      DATA XTEMP/-2.47,-2.37,-2.26,-2.14,-2.04,-1.89,-1.74,
     --1.6,-1.42,-1.2,-.95,-.69,-.38,0.,.44,.97,1.55,2.21,
     -2.88,3.61,4.42,5.23,6.09,6.98,7.98,8.81,9.72,10.62,
     -11.53,12.44,13.34,14.25,15.15,16.06/
      DATA KSTIF/46,44,42,41,40,27,21,15,12,12,9/
      DATA XDUM1/3.32,4.8,6.48,8.19,10.1,12.,13.99,16.3,18.98,21.
     -81,25.12,2.15,3.49,5.1,6.71,8.6,10.42,12.42,14.68,17.13,19.
     -81,22.87,1.21,2.,3.38,4.94,6.65,8.4,10.26,12.21,14.5,17.21,
     -20.21,.91,1.49,2.52,3.75,5.3,6.9,8.61,10.62,12.98,15.54,18.
     -52,.61,1.,1.71,2.75,3.98,5.33,6.8,8.7,10.91,13.43,16.38,
     -.41,.7,1.29,2.01,2.99,4.13,5.48,7.24,9.49,11.9,14.72,
     -.18,.42,.8,1.4,2.26,3.23,4.44,5.99,7.81,10.13,13.08,
     --.1,.03,.29,.72,1.35,2.17,3.18,4.48,6.11,8.27,10.86,
     --.29,-.21,-.01,.31,.81,1.49,2.3,3.4,4.81,6.7,9.17,
     --.48,-.42,-.3,-.08,.3,.8,1.41,2.31,3.51,5.2,0.,
     --.7,-.7,-.65,-.53,-.31,0.,.45,1.11,2.09,3.41,0.,
     --.86,-.9,-.92,-.89,-.77,-.58,-.26,.27,1.03,2.16,0.,
     --1.04,-1.13,-1.2,-1.2,-1.18,-1.08,-.88,-.53,3*0.,
     --1.3,-1.42,-1.54,-1.65,-1.71,-1.72,-1.65,-1.5,3*0.,
     --1.46,-1.63,-1.82,-1.98,-2.09,-2.18,-2.2,-2.12,3*0.,
     --1.66,-1.88,-2.07,-2.24,-2.43,-2.58,-2.69,4*0.,
     --1.9,-2.15,-2.4,-2.62,-2.88,-3.1,-3.3,4*0.,
     --2.03,-2.31,-2.61,-2.91,-3.21,-3.5,-3.78,4*0.,
     --2.2,-2.52,-2.88,-3.19,-3.57,-3.91,-4.24,4*0./
      DATA XDUM2/-2.45,-2.79,-3.16,-3.52,-3.95,-4.37,-4.78,4*0.,
     --2.63,-3.03,-3.45,-3.85,-4.3,-4.71,-5.18,4*0.,
     --2.83,-3.26,-3.69,-4.12,-4.6,-5.04,5*0.,
     --3.06,-3.5,-3.98,-4.46,-5.01,-5.51,5*0.,
     --3.24,-3.71,-4.21,-4.72,-5.3,-5.89,5*0.,
     --3.42,-3.95,-4.48,-5.02,-5.62,-6.2,5*0.,
     --3.64,-4.2,-4.79,-5.38,-6.04,-6.7,5*0.,
     --3.81,-4.4,-5.02,-5.61,-6.3,-7.03,5*0.,
     --4.02,-4.6,-5.27,-5.9,-6.61,6*0.,-4.24,-4.89,-5.52,-6.20,
     --6.9,6*0.,-4.41,-5.08,-5.77,-6.46,-7.21,6*0.,
     --4.65,-5.31,-6.,-6.7,-7.48,6*0.,-4.85,-5.55,-6.31,-7.04,
     --7.79,6*0.,-5.03,-5.75,-6.53,-7.3,-8.15,6*0.,
     --5.27,-6.,-6.81,-7.6,-8.43,6*0.,-5.49,-6.25,-7.09,-7.88,
     --8.72,6*0.,-5.65,-6.46,-7.28,-8.13,-9.06,6*0.,
```

```
     --5.88,-6.67,-7.53,-8.4,-9.34,6*0.,-6.09,-6.92,-7.83,
     --8.71,-9.68,6*0.,-6.24,-7.18,-8.1,-9.,-10.,6*0.,
     --6.88,-7.81,-8.8,-9.81,-10.91,6*0.,-7.49,-8.47,-9.57,
     --10.7,7*0.,-8.05,-9.14,-10.3,8*0.,-8.61,-9.77,9*0.,
     --9.24,-10.38,9*0.,-9.8,10*0.,-10.41,10*0./
      DATA SMIN/-10.,-8.,-6.,-5.,-4.,1.,3.,5.,6.,6.,7./
      END




C
C
      FUNCTION SLOG(IP,X)
C     RESULT IS LOG STIFFNESS (SLOG) FROM PI AND X. THE INTEGER VALUE
C     IP OF PI + 4. IS USED INSTEAD OF PI.
      INTEGER KSTIF(11)
      REAL XSTIF(11,46),SMIN(11)
      COMMON/BLOCKS/KSTIF,XSTIF, SMIN
      IF(X-XSTIF(IP,1))  30,20,10
   10 SLOG=50.
      GO TO140
   20 SLOG=9.+ALOG10(2.5)
      GO TO140
   30 IF(X-XSTIF(IP,KSTIF(IP)))  40,50,60
   40 SLOG=56.
      GO TO140
   50 SLOG=SMIN(IP)
      GO TO140
   60 KSTAF=KSTIF(IP)
      DO70 I5=1,KSTAF
      M=I5
      IF(X.GT.XSTIF(IP,I5))  GO TO80
   70 CONTINUE
   80 M1=M/3
      M2=M-3*M1
      AM1=M1
      FRACT=(X-XSTIF(IP,M))/(XSTIF(IP,M-1)-XSTIF(IP,M))
      IF(M.EQ.2)  GO TO130
      IF(M.GT.39)  GO TO120
      IF(M2.EQ.0)  GO TO90
      IF(M2.EQ.1)  GO TO100
      IF(M2.EQ.2)  GO TO110
   90 SLOG=10.-AM1+ALOG10(2.)*FRACT
      GO TO140
  100 SLOG=9.-AM1+ALOG10(5.)+(1.-ALOG10(5.))*FRACT
      GO TO140
  110 SLOG=9.-AM1+ALOG10(2.)+(ALOG10(5.)-ALOG10(2.))*FRACT
      GO TO140
  120 M3=M-39
      AM3=M3
      SLOG=-3.-AM3+FRACT
      GO TO140
  130 SLOG=9.+ALOG10(2.)+(ALOG10(2.5)-ALOG10(2.))*FRACT
  140 CONTINUE
      RETURN
      END
```

```
C
C
      FUNCTION XDRT(SPRB,TEMP)
C     RESULT IS HORIZONTAL COORDINATE XT CORRESPONDING TO TEMPERATURE
C     DIFFERENCE SPRB - TEMP.
      REAL XTEMP(34)
      COMMON/BLOCKT/XTEMP
      DRT=SPRB-TEMP
C     ADMITTED RANGE FOR DRT IS (-130,+200)
      Z=DRT+130.
      IF(Z-330.)  30,20,10
   10 X=66.
      GO TO70
   20 X=XTEMP(34)
      GO TO70
   30 IF(Z)  40,50,60
   40 X=67.
      GO TO70
   50 X=XTEMP(1)
      GO TO70
   60 N=INT(Z)/10
      R=AMOD(Z,10.)
      X=XTEMP(N+1)+(XTEMP(N+2)-XTEMP(N+1))*R/10.
   70 XDRT=X
      RETURN
      END




C
      SUBROUTINE TYPES(MODE,IWRITE,PI,SPRB,TEMP,TIMOL,PEN1,TPEN1,PEN2,
     - TPEN2,ALGS,CONST)
C*****  SUBROUTINE TO PRODUCE OUTPUT DETAIL LINES  *****
      INTEGER NOTE(6,8),LIST(6)
      DATA NOTE/' *  ', 'PI >', ' +7 ', '    ', '    ', '    ',
     1          ' *  ', 'PI <', ' -3 ', '    ', '    ', '    ',
     2          ' *  ', 'LOAD', 'ING ', 'TIME', ' > 1', 'E+10',
     3          ' *  ', 'LOAD', 'ING ', 'TIME', ' < 1', 'E-06',
     4          ' *  ', 'TEMP', 'ERAT', 'URE ', 'TOO ', 'LOW ',
     5          ' *  ', 'TEMP', 'ERAT', 'URE ', 'TOO ', 'HIGH',
     6          ' *  ', 'GLAS', 'SY S', 'TATE', '    ', '    ',
     7          ' *  ', 'WHIT', 'E AR', 'EA  ', '    ', '    '/
      NTO        = 6
 9000 FORMAT(1HO)
 9010 FORMAT(1H )
      IF(IWRITE.GT.O) GO TO10
      ALG800=ALOG10(800.)
   10 CONTINUE
      IF(MOD(IWRITE,35).EQ.O) GO TO20
      GO TO60
   20 CONTINUE
      WRITE(NTO,9000)
C     WRITE TREE HEADLINES OF TABLE
      GO TO ( 30, 40, 50 ), MODE
   30 WRITE(NTO,9020)
 9020 FORMAT('    PI    SOFTENING    TEMP.    LOADING   PEN.25       SMI
     -X ' )
      WRITE(NTO,9030)
 9030 FORMAT('          POINT R&B              TIME ' )
```

```
      WRITE(NTO,9040)
 9040 FORMAT('           (DEG. C)    (DEG. C)   ( S )            (LB/IN**
     -2) ' )
      GO TO 60
C
   40 WRITE(NTO,9050)
 9050 FORMAT('    PI    SOFTENING    TEMP.    LOADING   PEN.   PEN.
     -   LOG.   STIFFNESS  COMPUTED ')
      WRITE(NTO,9060)
 9060 FORMAT('          POINT R&B               TIME            TEMP.
     -STIFFNESS            VISCOSITY')
      WRITE(NTO,9070)
 9070 FORMAT('           (DEG. C)    (DEG. C)   ( S )         (DEG. C)
     -(N/M**2)   (N/M**2)  (NS/M**2)')
      GO TO 60
C
   50 WRITE(NTO,9080)
 9080 FORMAT('    PI     EPT 800      TEMP.    LOADING   PEN.   PEN.   RE
     -FERENCE  TEMP. OF  PEN.RATIO      LOG.   STIFFNESS  COMPUTED ')
      WRITE(NTO,9090)
 9090 FORMAT('                                  TIME            TEMP.
     -PEN.     REF.PEN.  (T+15)/T    STIFFNESS            VISCOSITY')
      WRITE(NTO,9100)
 9100 FORMAT('           (DEG. C)    (DEG. C)   ( S )         (DEG. C)
     -         (DEG. C)              (N/M**2)  (N/M**2)   (NS/M**2)')
   60 CONTINUE
      ETA=S*TIMOL/3.
      ALGPR=(20.-PI)/((50./15.)*(10.+PI))
      PENRAT=10.**ALGPR
      IF(MOD(IWRITE, 5).EQ.0) WRITE(NTO,9010)
      IF(ALGS.GT.-20.) GO TO70
      GO TO110
   70 CONTINUE
      SMIX  = 10.0 ** ALGS * CONST
C     WRITE NUMERIC OUTPUT WITHOUT NOTE.
      GO TO ( 80, 90, 100 ), MODE
C     CALCULATE IN CASE MODE = 1 PEN.25 FROM PI AND S.P. RING & BALL.
   80 ALGP25=ALG800+((20.-PI)/(500.+50.*PI))*(25.-SPRB)
      PEN25=10.**ALGP25
      WRITE(NTO,9110)PI,SPRB,TEMP,TIMOL,PEN25,SMIX
 9110 FORMAT(2X,F5.2,4X,F6.1,5X,F6.1,3X,1PE8.1,2X,0PF6.1,5X,1PE9.2,1X,
     - 1PE9.2,2X,1PE9.2)
      GO TO160
   90 WRITE(NTO,9120)PI,SPRB,TEMP,TIMOL,PEN1,TPEN1,ALGS,S,ETA
 9120 FORMAT(2X,F5.2,4X,F6.1,5X,F6.1,3X,1PE8.1,1X,0PF6.1,2X,F5.1,5X,
     - 1PE9.2,1X,1PE9.2,2X,1PE9.2)
      GO TO160
  100 WRITE(NTO,9130)PI,SPRB,TEMP,TIMOL,PEN1,TPEN1,PEN2,TPEN2,PENRAT,
     -  ALGS,S,ETA
 9130 FORMAT(2X,F5.2,4X,F6.1,5X,F6.1,3X,1PE8.1,1X,0PF6.1,2X,F5.1,4X,
     - F6.1,5X,F5.1,5X,F6.2,4X,1PE9.2,1X,1PE9.2,2X,1PE9.2)
      GO TO160
C
  110 CONTINUE
C     WRITE NUMERIC OUTPUT WITH NOTE, DEPENDING ON (DUMMY) VALUE OF ALGS
      L=IABS(INT(ALGS-0.001))-20
C     L HAS VALUE 1 UP TO 8 IF ALGS HAS VALUE -21. DOWN TO -28.
      DO120 I=1,6
      LIST(I)=NOTE(I,L)
  120 CONTINUE
```

```
      GO TO ( 130, 140, 150 ), MODE
  130 ALGP25=ALG800+((20.-PI)/(500.+50.*PI))*(25.-SPRB)
      PEN25=10.**ALGP25
      WRITE(NTO,9140)PI,SPRB,TEMP,TIMOL,PEN25,(LIST(I),I=1,6)
 9140 FORMAT(2X,F5.2,4X,F6.1,5X,F6.1,3X,1PE8.1,2X,0PF6.1,2X,6A4)
      GO TO160
  140 WRITE(NTO,9150)PI,SPRB,TEMP,TIMOL,PEN1,TPEN1,(LIST(I),I=1,6)
 9150 FORMAT(2X,F5.2,4X,F6.1,5X,F6.1,3X,1PE8.1,1X,0PF6.1,2X,F5.1,2X,6A4)
      GO TO160
  150 WRITE(NTO,9160)PI,SPRB,TEMP,TIMOL,PEN1,TPEN1,PEN2,TPEN2,PENRAT,
     - (LIST(I),I=1,6)
 9160 FORMAT(2X,F5.2,4X,F6.1,5X,F6.1,3X,1PE8.1,1X,0PF6.1,2X,F5.1,4X,
     - F6.1,5X,F5.1,5X,F6.2,1X,6A4)
  160 CONTINUE
      IWRITE=IWRITE+1
      RETURN
      END
```

```
      SUBROUTINE  LINEAR ( N, X, Y, A, B )
C*****  DO A SIMPLE LINEAR REGRESSION ON X & Y ******
      DIMENSION   X(N), Y(N)
      SUMN        = N
      SUMX        = 0.0
      SUMY        = 0.0
      SMX2        = 0.0
      SMXY        = 0.0
      DO 1100 I = 1, N
      SUMX        = SUMX + X(I)
      SUMY        = SUMY + Y(I)
      SMX2        = SMX2 + X(I) * X(I)
      SMXY        = SMXY + X(I) * Y(I)
 1100 CONTINUE
      DETR        = ( SUMN * SMX2 - SUMX * SUMX )
      A           = ( SUMN * SMXY - SUMX * SUMY ) / DETR
      B           = ( SUMY * SMX2 - SUMX * SMXY ) / DETR
      RETURN
      END
```

```
      SUBROUTINE FINDTA ( NN, E1, E2, T )
C***** FIT LINE TO LOGLOG PLOT OF TEMP SHIFT VS TEMP DIFF *****
C*****  TEMPERATURE IS VARIED TO PRODUCE BEST FIT *****
      DIMENSION    E1(20), E2(20), T(20)
      DIMENSION   X(20), Y(20), AT(20), TL(20)
  500 FORMAT ( 3F10.0 )
  510 FORMAT ( E14.7 )
  600 FORMAT ( '  SMIX ', E14.7, '   TA ', F10.3, '     BETA  ',
     1 E14.7, '  INTERCEPT, B   ', E14.7, '   SOE2 ', E14.7 )
C**********  INITIALIZE SELECTION VARIABLES  **********
      ERRMIN=999.
      TASEL=999.
      ASEL=999.
      TM=25.
      TA=-75.
      TINC=5.
```

```
      TAS        = TA
 1000 CONTINUE
      SMIX       = 10.000 ** E1(2) / 2.0
      IF ( SMIX .LE. 0.0E+00 ) GO TO 1700
      TA         = TAS
      DO 1200 I = 1, NN
      TL(I)      = ( SMIX /10.0E+00 ** E1(I) ) ** ( 1.0E+00 / E2(I) )
 1200 CONTINUE
      TLMC       = TL(2)
      DO 1300 I = 1, NN
      AT(I)      = TL(I) / TLMC
 1300 CONTINUE
 1400 CONTINUE
      TA         = TA + TINC
      DO 1500 I = 1, NN
      X(I)       = ALOG10 ( T(I) - TA )
      Y(I)       = ALOG10 ( AT(I) )
 1500 CONTINUE
      CALL LINEAR ( NN, X, Y, A, B )
      SOE2       = 0.0E+00
      DO 1600 I = 1, NN
      Z          = A * X(I) + B
      DIFF       = Z - Y(I)
      SOE2       = SOE2 + DIFF * DIFF
 1600 CONTINUE
C**********  SELECT TA AND B AT MINIMUM SOE2  **********
      IF(ERRMIN.LT.SOE2)GOTO2
      ERRMIN=SOE2
      TASEL=TA
      ASEL=A
      WRITE (6,600) SMIX, TA, A, B, SOE2
    2 IF ( TA .LE. -20.00E+00 ) GO TO 1400
 1700 CONTINUE
C***** WRITE SELECTED TA AND BETA TO DISK FILE  *******
      WRITE (1,100)TASEL,ASEL
  100 FORMAT(2F10.5,' <---- TA, CM')
      RETURN
      END
```

```
C
C     *********************************************************
C
C          COMPUTER PROGRAM FOR THERMAL CRACKING MODEL (THERM1)
C                 (USING THE RESULTS FROM VISCO1)
C
C     *********************************************************
C
C             NO AGING WHEN CRACK LENGTH, YC, IS GREATER
C             THAN 1.0 IN.
C
C     *********************************************************
C
C             AUTHORS    :  DR. ROBERT L. LYTTON
C                           MS. ULPALA L. SHANMUGHAM
C
C                           TEXAS TRANSPORTATION INSTITUTE
C                           TEXAS A&M UNIVERSITY
C                           COLLEGE STATION, TEXAS 77843
C
C     *********************************************************
C
C     RESULTS PRINTED EVERY MONTH
C
C     *********************************************************
C
C     DESCRIPTION OF INPUT VARIABLES
C
C     *********************************************************
C
C     TITL     = TITLE OF THE PROBLEM.
C     W        = DENSITY OF THE ASPHALT CONCRETE,PCF.
C     S        = SPECIFIC HEAT OF THE ASPHALT CONCRETE,BTU/LB,
C                DEGREE FAHRENHEIT.
C     AK       = THERMAL CONDUCTIVITY OF THE ASPHALT CONCRETE,
C                BTU/SQUARE FOOT/HR, DEGREE FAHRENHEIT PER FOOT.
C     B        = THE ABSORBTIVITY OF THE ASPHALT CONCRETE.
C     DO       = INITIAL CRACK LENGTH, INCHES (CRACK IS PROPAGATING
C                DOWNWARDS).
C     DF       = DEPTH OF THE ASPHALT CONRETE, INCHES.
C     VMPH     = AVERAGE WIND VELOCITY, MPH.
C     NSEL     = STARTING DATE: YR/MO/DY
C     SR1      = THE AVERAGE SOLAR RADIATION FOR JULY,LANGLEYS PER DAY.
C     SRM      = THE YEARLY AVERAGE SOLAR RADIATION,LANGLEYS PER DAY.
C     IMODE    = MODES, 1, 2,& 3
C     IAGE     = (NUMBER OF YEARS TO BE RUN) OR (THE NUMBER OF YEARS
C                THE BITUMEN TO BE AGED), USUALLY BOTH ARE SAME.
C     CV       = AGGREGATE VOLUME / ( AGGREGATE VOL + ASPHALT VOL )
C     SPRB     = ORIGINAL SOFTENING POINT RING AND BALL TEMPERATURE,
C                DEGREES C. ( IMODE = 1 OR 2 )
C     TPEN2    = TEMPERATURE OF REFERENCE PENETRATION, DEGREES C.
C                ( IMODE = 3 )
C     PI       = ORIGINAL PENETRATION INDEX. ( IMODE = 1 )
C     PEN1     = PENETRATION AT 25 DEGREES C. ( IMODE = 2 OR 3 )
C     PEN2     = REFERENCE PENETRATION AT TPEN2. ( IMODE = 3 )
C     IYR      = NUMBER OF YEARS THE BITUMEN HAS AGED.
C                ( IYR = -1 ( NO AGING ), IYR = 0 ( AGED 6 MONTHS,
C                FOR FIRST YEAR ), IYR = 1 ( AGED 18 MONTHS, FOR
C                SECOND YEAR ), ETC )
C     CN       = THE SLOPE OF THE MASTER RELAXATION MODULUS CURVE.
```

```
C      D1       = THE POWER OF THE INTERCEPT VALUE FOR LOG T=0 OF THE
C                 MASTER RELAXATION MODULUS CURVE.
C      TA       = THE POWER LAW CONSTANT FOR THE SHIFT FACTOR.
C      CM       = THE SLOPE OF THE POWER LAW CURVE FOR THE SHIFT FACTOR.
C      SPRBI    = SOFTENING POINT RING & BALL TEMPERATURE FOR THE
C                 CURRENT YEAR, DEGREES C.
C      DUM1     = PEN1
C      DUM2     = SPRB
C      DUM3     = CN
C      DUM4     = D1
C      DUM5     = TA
C      DUM6     = CM
C      NDATE    = DATE, YR/MO/DY, IN THE WEATHER DATA TAPE.
C                 ( SCAN DOWN TAPE TO SELECTED DATE )
C      NYEAR    = YEAR.( 2 DIGITS )
C      LL       = MONTH. ( 2 OIGITS )
C      DAY(I)   = DAY.( 2 DIGITS )
C      TMAX(I) = MAXIMUM TEMPERATURE DURING DAY(I),DEGREE FAHRENHEIT.
C      TMIN(I) = MINIMUM TEMPERATURE DURING DAY(I),DEGREE FAHRENHEIT.
C
C      ************************************************************
C
C      INPUT DATA INFORMATION:
C      -----------------------
C
C      DATA FROM TAPE05
C      ----------------
C
C      CARD   COLUMNS/FORMAT      VARIABLE
C      NO.                        NAME
C
C      01     01-60   (15A4)      TITL
C
C      02     01-10    F10.0      W
C      02     11-20    F10.0      S
C      02     21-30    F10.0      AK
C      02     31-40    F10.0      B
C
C      03     01-10    F10.0      D0
C      03     11-20    F10.0      DF
C      03     21-30    F10.0      VMPH
C
C      04     01-10    I10        NSEL
C
C      05     01-10    F10.0      SR1
C      05     11-20    F10.0      SRM
C
C
C      DATA FROM TAPE02 (RESULTS FROM VISCO1 PROGRAM)
C      ----------------------------------------------
C
C      CARD   COLUMNS/FORMAT      VARIABLE
C      NO.                        NAME
C
C      01     01-02   I2          IMODE
C      01     03-04   I2          IAGE
C
C*****ORIGINAL PROPERTIES OF BITUMEN
C
C      01     05-14   F10.3       CV
```

```
C      01      15-24    F10.3      SPRB (IMODE=1,2) OR TPEN2 (IMODE=3)
C      01      25-34    F10.3      PI (IMODE = 1) OR PEN1 (IMODE =.2, 3)
C      01      35-44    F10.3      PEN2 ( FOR IMODE=3 ONLY )
C
C*****VARIABLES OF BITUMEN WITHOUT AGING
C
C      02      01-02    I2         IYR
C      02      03-12    F10.3      DUM1(PEN1)
C      02      13-22    F10.3      DUM2(SPRB)
C
C      03      01-10    F10.5      DUM3(CN)
C      03      11-20    F10.5      DUM4(D1)
C
C      04      01-10    F10.5      DUM5(TA)
C      04      11-20    F10.5      DUM6(CM)
C
C*****VARIABLES OF BITUMEN FOR THE CURRENT YEAR
C
C      05      01-02    I2         IYR
C      05      03-12    F10.3      PEN1
C      05      13-22    F10.3      SPRBI
C
C      06      01-10    F10.5      CN
C      06      11-20    F10.5      D1
C
C      07      01-10    F10.5      TA
C      07      11-20    F10.5      CM
C
C
C      NOTE:   CARDS 05-07 MUST BE REPEATED FOR EACH YEAR I,
C              I = 1, ..., IAGE
C
C      DATA FROM TAPE01 (WEATHER TAPE)
C      -------------------------------
C
C      CARD    COLUMNS/FORMAT      VARIABLE
C      NO.                         NAME
C
C      01      12-17    I6         NDATE
C
C      02      12-13    I2         NYEAR
C      02      14-15    I2         LL
C      02      16-17    I2         DAY(1)
C      02      20-22    F3.0       TMAX(1)
C      02      23-25    F3.0       TMIN(1)
C
C      03      12-13    I2         NYEAR
C      03      16-17    I2         DAY(I)
C      03      20-22    F3.0       TMAX(I)
C      03      23-25    F3.0       TMIN(I)
C
C      NOTE:   CARD 03 MUST BE REPEATED FOR EACH DAY OF THE
C              ANALYSIS PERIOD.
C              FORMAT OF THE CARDS 1, 2, & 3 MUST BE CHANGED
C              ACCORDING TO THE FORMAT OF WEATHER DATA TAPE.
C
C      ***********************************************************
C
       IMPLICIT REAL*8 (A-H, O-Z)
       LOGICAL  FLAG, FLG1
```

```
      DIMENSION   XX(3),TE(3,24),TI(3,24)
      DIMENSION   TMAX(31),TMIN(31),AL(372),N(12)
      DIMENSION   DAY(31)
      DIMENSION   YC(2500), DYC(2500), K1(2500)
      DIMENSION   NF(2500), DN(2500), TITL(15), NF1(2500)
      COMMON /A1/ CN, CM, TM, TR, TA, E1, EE
      COMMON /A2/ SA1, SA2, SB1, SB2
      COMMON /A3/ M1, M2, M3, M4
      COMMON /A4/ TC(12), TH(12)
      INTEGER     DAY
      INTEGER MOS(12)/'JAN','FEB','MAR','APR','MAY','JUN',
     1               'JUL','AUG','SEP','OCT','NOV','DEC'/
      REAL*8      M1, M2, M3, M4, K1, NF, KTMX, KTMN, NF1
  500 FORMAT ( 15A4 )
  520 FORMAT ( 8F10.0 )
  530 FORMAT ( 8I10 )
C**********  INPUT DATA FOR NEW PROBLEM  **********
    8 READ(5,500,END=999)TITL
      READ  (5,520) W, S, AK, B
      READ  (5,520) DO, DF, VMPH
      READ  (5,530)NSEL
      READ  (5,520) SR1, SRM
C****************************************
C       TM IS THE REFERENCE TEMPERATURE OF THE MASTER
C       RELAXATION CURVE, DEGREE FAHRENHEIT.
C       TR IS THE TEMPERATURE OF THE STRESS FREE STATE,
C       DEGREE FAHRENHEIT.
C****************************************
      TM=77.
      TR=75.
      DZ=1.0
C
C*****READ ORIGINAL PROPERTIES OF BITUMEN FROM VISCO1 FOR
C*****DIFFERENT CASES OF MODES 1, 2, AND 3
C
      READ  (2,208) IMODE, IAGE, CV, SPRB, PI, PEN2
      SPRB=(SPRB*9./5.)+32.
      TPEN2 = SPRB
  208 FORMAT ( 2I2, 4F10.3 )
      WRITE(6,600)TITL
  600 FORMAT('1', 10(/), 10X, 'THERMAL CRACKING ANALYSIS FOR ',15A4)
      WRITE(6,601)NSEL,IAGE
  601 FORMAT(/,10X,'THIS ANALYSIS BEGINS AFTER ',I6,' AND RUNS FOR ',I2,
     +         ' YEARS.')
      WRITE(6,602)
  602 FORMAT(/,10X,'THE BITUMEN USED HAS THE FOLLOWING ORIGINAL ',
     1 'PROPERTIES:' )
      IF(IMODE.EQ.1)WRITE(6,603)PI
  603 FORMAT( 15X, 'PENETRATION INDEX            = ',F10.3)
      IF(IMODE.EQ.2)WRITE(6,605)PI
  605 FORMAT( 15X, 'PENETRATION AT 77 DEG F     = ',F10.3)
      IF ( IMODE .EQ. 3 ) WRITE (6,6051) PI, TPEN2, PEN2
 6051 FORMAT (15X, 'PENETRATION AT  77.0 DEG F = ', F10.3, /,
     1        15X, 'PENETRATION AT', F6.1, ' DEG F = ', F10.3 )
      IF ( IMODE .LT. 3 ) WRITE(6,606)SPRB
  606 FORMAT(15X,'SOFTENING POINT RING & BALL TEMP = ',F10.3,' DEG F')
      IF ( IMODE .EQ. 3 ) WRITE (6,6065) TPEN2
 6065 FORMAT ( 15X, 'TEMPERATURE OF REFERENCE PENETRATION = ', F10.3,
     1 ' DEG F' )
      WRITE(6,607)DF,DO
```

```
  607 FORMAT(10X,'THE ASPHALT CONCRETE LAYER IS ',F10.3,' INCHES THICK'
     + /, 10X, 'AND IS ASSUMED TO HAVE AN INITIAL CRACK OF ',F10.3,
     + /10X, 'INCHES EXTENDING FROM THE SURFACE.')
      WRITE(6,608)
  608 FORMAT(10X,'THE ASPHALT CONCRETE HAS THE FOLLOWING MIX ',
     1 'PROPERTIES:' )
      WRITE(6,609)CV,W,S,AK,B
  609 FORMAT(15X, 'AGGREGATE VOLUME CONCENTRATION = ',F10.3,
     +/, 15X, 'DENSITY = ',F10.3,' LBS/FT**3'
     +/, 15X, 'SPECIFIC HEAT = ',F10.3,' BTU/LB DEG F'
     +/, 15X, 'THERMAL CONDUCTIVITY = ',F10.3,' BTU/FT**2/HR,DEG F/FT'
     +/, 15X, 'ABSORPTIVITY = ',F10.3)
      WRITE(6,610)VMPH,SRM,SR1
  610 FORMAT(/, 10X, 'THE PAVEMENT IS ASSUMED TO BE SUBJECTED TO THE'
     +/, 10X, 'FOLLOWING AVERAGE ENVIRONMENTAL CONDITIONS:'
     +/, 15X,'WIND VELOCITY = ',F10.3,' MILES PER HOUR'
     +/, 15X,'AVERAGE ANNUAL SOLAR RADIATION = ',F10.3,' LANGLEYS/DAY'
     +/, 15X,'AVERAGE JULY SOLAR RADIATION = ',F10.3,' LANGLEYS/DAY')
C**********  INITIALIZE CONSTANTS  **********
      ACON=1.0D0
      ID         = 0
      YC(1)      = D0
      YC1        = D0
      CDMG       = 0.0D0
      CDMG1      = 0.0D0
      IKOUNT     = 1
C**********  DAYS IN THE MONTH  **********
      N(1)=31
      N(2)=28
      N(3)=31
      N(4)=30
      N(5)=31
      N(6)=30
      N(7)=31
      N(8)=31
      N(9)=30
      N(10)=31
      N(11)=30
      N(12)=31
      XYZTIM=14.0
      XYZTEM=80.0D0
      DZ=10.D0**DZ
      EE=DZ
   18 CONTINUE
      DO 109 IJK=1,360
      F=IJK/57.2958
      AL(IJK) = SRM + (SR1-SRM) * DCOS( F )/0.966
  109 CONTINUE
      DO 108 IJK=361,366
      AL(IJK)=AL(360)
  108 CONTINUE
  138 CONTINUE
C****** THE UPPER LIMIT ON THE RELAXATION MODULUS CURVE IS SPECIFIED
      SBTMAX = 3.625D+05
      ESSM   = SBTMAX * (1.0D0 + 2.52D0 * (CV/(1.0-CV))) ** 0.9923D0
C********** SCAN DOWN TAPE TO SELECTED DATE ************
    9 READ(1,101)NDATE
  101 FORMAT(11X,I6)
      IF(NDATE.LT.NSEL)GOTO9
C********** TAPE NOW IS AT STARTING POINT **************
```

```
      READ  (2,201) IYR, DUM1, DUM2
      DUM2        = (DUM2 * 9.0 / 5.0) + 32.0
      READ   (2,200) DUM3, DUM4
      READ   (2,200) DUM5, DUM6
      FLAG = .FALSE.
      FLG1 = .FALSE.
C**********  DO ONE YEAR AT A TIME   **********
      DO 3 I3=1,IAGE
C**********  READ VARIABLES FROM VISCO1 *********
      READ(2,201)IYR,PEN1,SPRBI
      SPRBI=(SPRBI*9./5.)+32
  201 FORMAT(I2,2F10.3)
      READ(2,200)CN,D1
      READ(2,200)TA,CM
  200 FORMAT(2F10.5)
C
C*****USE ORIGINAL PROPERTIES OF BITUMEN WHEN CRACK LENGTH,
C*****YC, IS GREATER THAN 1.0 IN.
C
      IF (YC1 .LE. 1.0D0) GO TO 1701
      PEN1    = DUM1
      SPRBI   = DUM2
      CN      = DUM3
      D1      = DUM4
      TA      = DUM5
      CM      = DUM6
 1701 CONTINUE
      CN=-CN
      CM=-CM
      D1=10.0D0**D1
   16 E1=D1
      I3M1=I3-1
C****** FATIGUE PARAMETERS, CA & FN, ARE CALCULATED  *****
C SCFT IS THE SCALING FACTOR TO CALCULATE FN
C AFAT AND BFAT ARE EMPIRICAL CONSTANTS THAT
C RELATE CA AND FN.
C**********************************************
      SCFT=2.5
      FN=(1.+1./CN)*(2./SCFT)
      AFAT=0.69
      BFAT=-0.511
      CA=10.**((AFAT+FN)/BFAT)
      IF ( FLG1 ) GO TO 1702
      CAO = CA
      FNO = FN
      FLG1 = .TRUE.
 1702 CONTINUE
      WRITE (6,667)
  667 FORMAT ( // )
      IF ( MOD(IYR,2) .EQ. 0 ) WRITE (6,666)
  666 FORMAT ( 1H1, //// )
      WRITE(6,604)IYR,PEN1,SPRBI,CA,FN, CAO, FNO
  604 FORMAT( 10X, ' *** YEAR ',I2,' ***'/,
     1 10X, ' IN PLACE BITUMIN PROPERTIES:',
     +     /, 15X, 'PENETRATION AT 77 DEG F     = ',F10.3
     +  /,15X,'SOFTENING POINT RING & BALL TEMP = ',F10.3,' DEG F',
     +  //, 10X, ' FATIGUE PARAMETERS OF THE MIX:',
     +  2(/, 15X, 'A = ', E10.3, '      N = ', F8.3),
     +  4X, '(VALUES USED WHEN YC IS GREATER THAN 1.0 INCH)', // )
      WRITE (6,3457)
```

```
      CALL CURVE(TH,TC)
      TC(12) = TC(11)
      TH(12) = TH(11)
C**********  DO ONE MONTH AT A TIME **********
      DO    1 LJ = 1, 12
  997 READ  (1,1233) NYEAR, LL, DAY(1), TMAX(1), TMIN(1)
 1233 FORMAT (11X,3I2,2X,2F3.0)
      IF(TMAX(1).EQ.999)GOTO997
      M          = MOD(NYEAR,4)
      N(2)       = 28
      IF ( M .EQ. 0 ) N(2) = 29
      JYR        = N(LL)
      DO 3333 I = 2,JYR
      READ (1,1234) NYEAR, DAY(I), TMAX(I), TMIN(I)
 1234 FORMAT(11X,I2,2X,I2,2X,2F3.0)
 3333 CONTINUE
C**********  ADD A DAY IF LEAP YEAR   **********
      MAXDAY     = 365 + N(2) - 28
C**********  TEMPORARY DEBUG OUTPUT   **********
C**********  DO ONCE FOR EACH DAY IN MONTH  **********
      DO 2 NI=1,JYR
      TRANG      = 0.0D0
      IF ( TMIN(NI) .GE. TR ) GO TO 2
      TAVG=0.5*(DMIN1(TR,TMAX(NI))+DMIN1(TR,TMIN(NI)))
      TRANG      = DMIN1( TR,TMAX(NI) ) - DMIN1(TR,TMIN(NI))
      AH=1.3+0.62*(VMPH/24.)**0.75
      H=AH/AK
      AC=AK/(S*W)
      C=(0.131/AC)**0.5
      R=0.67*B*3.69*AL(IKOUNT)/(24.*AH)
C**************************************************************
C SET UP TO CALCULATE TEMPERATURE OF TOP, MIDDLE, AND
C BOTTOM OF PAVEMENT.
C    XX(1)= BOTTOM TEMPERATURE
C    XX(2)= MIDDLE TEMPERATURE
C    XX(3)= TOP TEMPERATURE
C TEMPERATURE CALCULATED EACH HOUR FOR A COMPLETE DAY
C**************************************************************
      DO 10 ITHCK=1,3
      XX(ITHCK)=DF/ITHCK
      IF(ITHCK.EQ.3)XX(3)=0.0D0
      Z2=(-XX(ITHCK))*C/12.0
      Z3 = DEXP(Z2) * H/(( H+C)**2. + C**2.) ** 0.5
      DO 10 J=2,25
      TIM=J
      IF(J.GT.9) GO TO 31
      Z4=6.8176*(.0576*TIM+0.144*Z2-0.288)
      GO TO 35
   31 IF(J.GT.14) GO TO 32
      Z4=+14.7534*(0.02057*TIM+0.075*Z2-0.288)
      GO TO 35
   32 Z4=-6.94274*(0.02057*TIM+0.12*Z2-0.288)
   35 Z5 = DSIN(Z4)
      IF(Z5) 21,22,22
   21 TMEAN=TAVG+0.5*R
      TV=.5*TRANG
      GO TO 23
   22 TV=.5*TRANG+3.*R
      TMEAN=TAVG+R
   23 TEMP=TMEAN+TV*Z3*Z5
```

```
      IF(J.GT.19) TIM=TIM-24
      ITM = TIM + 5
      TE(ITHCK,ITM)=TEMP
      TI(ITHCK,ITM)=ITM
   10 CONTINUE
C**********  1 DAYS CALCULATIONS COMPLETE  **********
   20 IKOUNT=IKOUNT+1
      IF(IKOUNT.EQ.MAXDAY) IKOUNT=1
      DO 110 L1=1,3
      DO 110 L=2,23
      IF(TE(L1,L).LE.TE(L1,L-1).AND.TE(L1,L).LE.TE(L1,L+1)) GO TO 112
      GO TO 118
  112 CONTINUE
C**********  MINIMUM TEMPERATURES HAVE BEEN CALCULATED  **********
      IF(L1.EQ.1)TEMP1=TE(1,L)
      IF(L1.EQ.2)TEMP2=TE(2,L)
      IF(L1.EQ.3)TEMP3=TE(3,L)
C**********  TIME FOR MINIMUM TEMPERATURES  **********
      IF(L1.EQ.1)TIM1=TI(1,L)
      IF(L1.EQ.2)TIM2=TI(2,L)
      IF(L1.EQ.3)TIM3=TI(3,L)
  118 CONTINUE
C**********  NOW CALCULATE MAX TEMPERATURES  **********
      IF(TE(L1,L).GT.TE(L1,L-1).AND.TE(L1,L).GT.TE(L1,L+1)) GO TO 113
      GO TO 110
  113 CONTINUE
      IF(L1.EQ.1)TEMP4=TE(L1,L)
      IF(L1.EQ.2)TEMP5=TE(L1,L)
      IF(L1.EQ.3)TEMP6=TE(L1,L)
      IF(L1.EQ.1)TEMP7=TE(L1,L+1)
      IF(L1.EQ.2)TEMP8=TE(L1,L+1)
      IF(L1.EQ.3)TEMP9=TE(L1,L+1)
C**********  TIME FOR MAXIMUM TEMPERATURES  **********
      IF(L1.EQ.1)TIM4=TI(L1,L)
      IF(L1.EQ.2)TIM5=TI(L1,L)
      IF(L1.EQ.3)TIM6=TI(L1,L)
  110 CONTINUE
C*******************************************************
C IF THE MAX TEMPERATURE IS ABOVE 75 F, FIND TIME AT WHICH
C 75 F OCCURS.  DEL IS TEMP DROP PER HOUR
C*******************************************************
      DEL1=(TEMP4-TEMP1)/(-TIM4+TIM1)
      DEL2=(TEMP5-TEMP2)/(-TIM5+TIM2)
      DEL3=(TEMP6-TEMP3)/(-TIM6+TIM3)
      IF(TEMP4.GT.TR) TIM4=TIM4+(TEMP4-TR)/DEL1
      IF(TEMP5.GT.TR) TIM5=TIM5+(TEMP5-TR)/DEL2
      IF(TEMP6.GT.TR) TIM6=TIM6+(TEMP6-TR)/DEL3
C***** CALCULATE AVG MIN TEMP OF PAVEMENT******
      TMEN=(1./3.)*(TEMP1+TEMP2+TEMP3)
      IF ( TMEN .LT. TR ) GO TO 231
      TRANG     = 0.0D0
      GO TO 2
  231 CONTINUE
      ID     = ID + 1
      DN(ID) = 1.0D0
C****  CALCULATE AVG MAX TEMP OF PAVEMENT  ******
      TMEX=(1./3.)*(TEMP4+TEMP5+TEMP6)
      IF(TMEX.GT.TR) TMEX=TR
C****  CALCULATE AVG TIME FOR MIN TEMP AND MAX TEMP  *******
      TIMMIN=(TIM1+TIM2+TIM3)/3.0
```

```
      TIMMAX=(TIM4+TIM5+TIM6)/3.
      PERIOD=24.0-XYZTIM+TIMMIN
      XYZTIM=TIMMAX
      DLTN=TMEN-TR
      DLTX=TMEX-TR
      XYZTEM=TMEX
 1000 CONTINUE
      KTMX      = 0.0D0
      KTMN      = 0.0D0
      TRMX      = DMAX1 ( 0.0D0, TR-TMAX(NI) )
      TRMN      = TR - TMIN(NI)
C*** CALCULATE STRESS INTENSITY FACTOR FOR MIN & MAX TEMP   ****
      CALL FACTOR ( DF, DLTX, PERIOD, TRMX, ID, YC, SA1, SB1, KTMX,
     *             NYEAR, LJ, ESSM )
      CALL FACTOR ( DF, DLTN, PERIOD, TRMN, ID, YC, SA2, SB2, KTMN,
     *             NYEAR, LJ, ESSM )
      K1(ID)    = KTMN - KTMX
      DYC(ID)   = 0.0D0
      IF (K1(ID) .GT. 0.0D0) GO TO 875
      ID = ID-1
      GO TO 2
  875 CONTINUE
      Z0        = YC(ID)
      Z1        = DF
      Z01       = 0.0D0
      IF ( Z0 .LT. Z1 ) CALL SIMPSN ( CA, FN, Z0, Z1, Z01 )
      NF(ID)    = ACON + Z01
      ACON=0.0D0
      IF ( NF(ID) .GT. 0.0D0 ) CDMG = CDMG + DN(ID)/NF(ID)
      DYC(ID)   = DN(ID) * CA * (K1(ID) ** FN)
      IF(NF(ID).LE.0.0D0)DYC(ID)=0.
  876 YC(ID+1)  = YC(ID) + DYC(ID)
      YC1       = YC(ID+1)
      IF(YC(ID).LE.1.0D0)GOTO 877
      IF(FLAG)GOTO 877
      FLAG   = .TRUE.
      PEN1   = DUM1
      SPRBI  = DUM2
      CN     = DUM3
      D1     = DUM4
      TA     = DUM5
      CM     = DUM6
      CN     = -CN
      CM     = -CM
      D1     = 10.0D0**D1
      E1     = D1
C****** FATIGUE PARAMETERS, CA & FN, ARE CALCULATED  *****
C SCFT IS THE SCALING FACTOR TO CALCULATE FN
C AFAT AND BFAT ARE EMPIRICAL CONSTANTS THAT
C RELATE CA AND FN.
C*********************************************
      SCFT=2.5
      FN=(1.+1./CN)*(2./SCFT)
      AFAT=0.69
      BFAT=-0.511
      CA=10.**((AFAT+FN)/BFAT)
      CALL CURVE(TH,TC)
      TC(12) = TC(11)
      TH(12) = TH(11)
  877 CONTINUE
```

```
      Z01         = 0.0D0
      CALL SIMPSN ( CA, FN, D0, DF, Z01 )
      NF1(ID)     = 1.00 + Z01
      CDMG1       = CDMG1 + DN(ID)/NF1(ID)
      IF ( YC(ID+1) .LE. DF ) GO TO 9880
      WRITE (6,3456) IYR, MOS(LL), DAY(NI), NYEAR,
     1                ID, NF(ID), NF1(ID), YC(ID), CDMG, CDMG1
      IF ( YC(ID+1) .LE. DF ) GO TO 9880
      YC(ID+1)    = DF
 9880 CONTINUE
    2 CONTINUE
      YCID = YC(ID)
      IF ( ID .EQ. 0 ) YCID = D0
      WRITE (6,3456) IYR, MOS(LL), JYR,     NYEAR,
     1                ID, NF(ID), NF1(ID), YCID, CDMG, CDMG1
 3456 FORMAT ( 11X, I2, 2X, A4, I2, ', 19', I2,
     1          1X, I5, 5E13.6 )
 3457 FORMAT ( 11X, 'NO', 6X, 'DATE',
     1          8X, 'ID', 6X, 'NF', 10X, 'NF1', 11X,
     2          'YC', 10X, 'CDMG',  9X, 'CDMG1', / )
    1 CONTINUE
    3 CONTINUE
C********** REWIND FILE AND PROCESS NEXT PROBLEM **********
      REWIND 1
      GOTO 8
  999 STOP
      END
```

```
      SUBROUTINE CURVE(TH,TC)
C*** CURVE CALCULATES TH AND TC, HEATING AND COOLING TEMPS   ***
      IMPLICIT REAL*8 (A-H,O-Z)
      DIMENSION TH(11),TC(11)
      COMMON /A1/ CN,CM,TM,TR,TA,E1,EE
      COMMON /GT/ GAB1
      DIMENSION F(50)
      COMMON       HH(11),ZZ
      COMMON /KK/ I
  100 CONTINUE
      INT=40
      A=CM/(CM+1.0)+CN-2.0
      B=-CN
      DM=(1.0-CN)/(CM+1.0)**(1.0-CN)
      GA=DGAMMA(A+1.0)
      GB1=DGAMMA(B+1.0)
      GAB1=GA*GB1/DGAMMA(A+B+2.0)
      TH(1)=1.0
      TC(1)=1.0
      TC(11)=0.0D0
      DO 40 INDEX=1,2
      HH(1)=1.0
      AREA=0.0D0
      ZZ=0.0D0
      DTN=0.0D0
      DO 10 I=1,10
      DTN=DTN+0.1
      DTR=DABS(DTN)
      IF(INDEX.EQ.1) GO TO 21
```

```
      H=(DTN+1.0)**(CM+1.0)
      HH(I+1)=H
      HS=(HH(I+1)-HH(I))/(INT-1)
      CALL HEAT(A,B,H,INT,F,AREA,HS)
      CONS=DM*(1.0+1.0/DTN)**(1.0-CN)
      TII=CONS*AREA
      TH(I+1)=TII
      GO TO 25
   21 CONTINUE
      IF(I.EQ.10) GO TO 10
      RR=-DTR
      H=(1.0+RR)**(CM+1.0)
      HH(I+1)=H
      HS=(HH(I)-HH(I+1))/(INT-1)
      CALL COOL(A,B,H,AREA)
      CONS=DM*(-1.0-1.0/RR)**(1.0-CN)
      TII=CONS*AREA
      TC(I+1)=TII
   25 CONTINUE
   10 CONTINUE
   40 CONTINUE
      RETURN
      END
```

```
      SUBROUTINE HEAT(A,B,H,INT,F,AREA,HS)
      IMPLICIT REAL*8 (A-H,O-Z)
      DIMENSION F(INT)
      COMMON       HH(11),ZZ
      COMMON /KK/ I
      DA=H**(A+1.0)*(-1.0+H)**(B+1.0)/(B+1.0)
      DB=-(A+B+2.0)/(B+1.0)
      DO 10 J=1,INT
      XX=HH(I)+HS*(J-1)
   10 F(J)=XX**A*(-1.0+XX)**(B+1.0)
      CALL INTGRT(INT,F,HS,AR)
      ZZ=ZZ+AR
      AREA=DA+ZZ*DB
      RETURN
      END
```

```
      SUBROUTINE INTGRT(N,F,H,AREA)
      IMPLICIT REAL*8 (A-H,O-Z)
      DIMENSION F(N)
      AREA=0.0D0
      S=0.5*H
      DO 10 I=2,N
      AREA=AREA+S*(F(I-1)+F(I))
   10 CONTINUE
      RETURN
      END
```

```
      SUBROUTINE COOL (A,B,H,AREA)
      IMPLICIT REAL*8 (A-H,O-Z)
      REAL*4 SH,SA1,SB2,SP
      REAL*4 SNGL
      COMMON /GT/ GAB1
      A1=A+1.0
      B1=B+1.0
      P=0.0D0
      SH=SNGL(H)
      SA1 = SNGL(A1)
      SB2=SNGL(B1)
      SP=SNGL(P)
   10 CONTINUE
      P=DBLE(SP)
      H=DBLE(SH)
      A1=DBLE(SA1)
      B2=DBLE(SB2)
      AREA=GAB1*(1.D0-P)
      RETURN
      END
```

```
      SUBROUTINE FACTOR ( DF, DELT, PERIOD, TRG, ID, YC, SA, SB, XXX,
     *              NYEAR, LJ, ESSM )
C***************************************************************
C* CALCULATES STRESS INTENSITY FACTOR FOR A GIVEN PAVEMENT     *
C*                                                             *
C*   DF    = DEPTH OF ASPHALT LAYER                            *
C*   DELT = PAVEMENT TEMP - STRESS FREE TEMP                   *
C*   PERIOD LOADING TIME                                       *
C*   TRG  = STRESS FREE TEMP - MAX AIR TEMP                    *
C*   ID   = DAY COUNTER                                        *
C*   YC   = CRACK LENGTH                                       *
C*   SA,SB= CONSTANTS TO CALCULATE STRESS INTENSITY FACTOR     *
C*   XXX  = STRESS INTENSITY FACTOR                            *
C***************************************************************
      IMPLICIT REAL*8 (A-H,O-Z)
      REAL*8      M1, M2, M3, M4
      DIMENSION   YC(2500)
      COMMON /A1/ CN, CM, TM, TR, TA, E1, EE
      COMMON /A3/ M1, M2, M3, M4
      COMMON /A4/ TC(12), TH(12)
      SA         = 0.0D0
      SB         = 0.0D0
      XXX        = 0.0D0
      DT=DELT
      IF (PERIOD.LT.1.0) PERIOD=1.0
      TIME=PERIOD*3600.
      TTN=TIME**(-CN)
      T=TR+DT
      AT=((TM-TA)/(T-TA))**CM
      ATN=AT**CN
      DTN=DT/(TR-TA)
      DTR=DABS(DTN*10.0)
      NN=IDINT(DTR)
      DIF=DTR-NN
      NG = NN + 1
      IF ( NG .LE. 11 ) GO TO 99
```

```
      WRITE (6,654)
  654 FORMAT ( 5X, 'NG IS GREATER THAN 11. SET NG = 11', // )
      NG = 11
   99 CONTINUE
C** CALCULATION OF EFF MODULUS. SEE P. 17, REPORT 18-3 ***
      IF(DELT) 90,29,30
   90 RATIO = (TC(NG+1) - TC(NG)) * DIF + TC(NG)
      J=1
      GO TO 120
   29 RATIO=1.D0
      J=3
      GO TO 120
   30 RATIO = (TH(NG+1) - TH(NG)) * DIF + TH(NG)
      J=2
  120 CONTINUE
      ESS=ATN*E1*TTN/(1.D0-CN)
      IF (ESS .GT. ESSM) ESS = ESSM
      EEF        = EE + RATIO * ( ESS - EE )
      M1         = 8.8988D+00
      M2         = 2.0599D+00
      M3         = 0.8481D+00
      M4         =-0.00157D+00
      IF ( EEF .GE. 1.000D+05 ) GO TO 978
      M1         = M1 + ( 29.1063D+00 - DF ) * ( 1.3573D+00
     1          - 0.013573D+00 * ( EEF / 1000.0D0) )
      M2         = M2 - ( 129.3215D+00 - DF ) * ( 0.01687+00
     1          - 0.0001687D+00 * ( EEF / 1000.0D0) )
      IF ( DF .GT. 4.0D0 ) GO TO 988
      M3         = M3 + ( 2.7811D+00 - DF ) * ( 0.2738D+00
     1          - 0.002738D+00 * ( EEF / 1000.0D0) )
      GO TO 987
  988 CONTINUE
      M3         = M3 - ( 6.5835D+00 - DF ) * ( 0.12919D+00
     1          -0.0012919D+00 * ( EEF / 1000.0D0))
  987 CONTINUE
      M4         = M4 + ( 5.0472D+00 - DF ) * ( 0.001129D+00
     1          - 0.00001129D+00 * ( EEF / 1000.0D0) )
  978 IF ( TRG .LE. M1 ) RETURN
      SA         = M2 * ( TRG - M1 )
      SB         = M3 + M4 * TRG
      XXX        = SA * YC(ID) ** SB
      RETURN
      END



      SUBROUTINE SIMPSN ( CA, FN, XF, XL, AREA )
      IMPLICIT REAL*8 (A-H,O-Z)
      REAL*8      KMIN, KMAX
      DIMENSION   Y(7)
      COMMON /A2/ SA1, SA2, SB1, SB2
      NS         = 6
      NP         = 7
      XINC       = ( XL - XF ) / 6.000D+00
      X          = XF
      DO 1100 I  = 1, NP
      F          =  SA2 * X ** SB2 - SA1 * X ** SB1
      YI         = CA * DABS(F) ** FN
      Y(I)       = 1.000D+00 / YI
```

```
      X          = X + XINC
 1100 CONTINUE
      AREA       = 0.0D0
      DO 1200 I  = 1, NS, 2
      A          = Y(I) + 4.000D+00 * Y(I+1) + Y(I+2)
      A          = A * XINC / 3.000D+00
      AREA       = AREA + A
 1200 CONTINUE
      RETURN
      END
```

```
*** AGE CALLED: PEN1I=  149.0325 TPEN1=   25.0000SPRBI=   43.0000 IYR= 0
*** AFTER AGING --> IYR= 0 PEN1=  71.075 TPEN1=  25.000 SPRBI=  50.431
STIFFNESS OF MIX USING VAN DER POELS NOMOGRAPH
INPUT DATA:                        MODE  =      1

                             INITIAL PI  =    -0.09
                           AGED  0 YEAR(S) TO-0.22

INITIAL SOFTENING POINT RING AND BALL  =    43.0
                         AGED  0 YEAR(S) TO   50.4

                  INITIAL TEMPERATURE  =     0.0
       NUMBER OF STEPS IN TEMPERATURE  =      1

                 INITIAL LOADING TIME  =      1.0E+05
      NUMBER OF STEPS IN LOADING TIME  =      7
   MULTIPLYING FACTOR IN LOADING TIME  =      0.1

   PI     SOFTENING    TEMP.     LOADING   PEN.25       SMIX
          POINT R&B               TIME
           (DEG. C)   (DEG. C)   ( S )             (LB/IN**2)

 -0.22       50.4       0.0      1.0E+05    71.1       3.27E+03
 -0.22       50.4       0.0      1.0E+04    71.1       1.50E+04
 -0.22       50.4       0.0      1.0E+03    71.1       5.84E+04
 -0.22       50.4       0.0      1.0E+02    71.1       1.92E+05
 -0.22       50.4       0.0      1.0E+01    71.1       5.33E+05

 -0.22       50.4       0.0      1.0E+00    71.1       1.12E+06
 -0.22       50.4       0.0      1.0E-01    71.1       1.95E+06
 NN      1  TEMP  0.0          SLOPE, M -0.4654609E+00  INTERCEPT,E1 0.6046534E+01
STIFFNESS OF MIX USING VAN DER POELS NOMOGRAPH
INPUT DATA:                        MODE  =      1

                             INITIAL PI  =    -0.09
                           AGED  0 YEAR(S) TO-0.22

INITIAL SOFTENING POINT RING AND BALL  =    43.0
                         AGED  0 YEAR(S) TO   50.4

                  INITIAL TEMPERATURE  =    25.0
       NUMBER OF STEPS IN TEMPERATURE  =      1

                 INITIAL LOADING TIME  =      1.0E+05
      NUMBER OF STEPS IN LOADING TIME  =      7
   MULTIPLYING FACTOR IN LOADING TIME  =      0.1
```

```
   PI    SOFTENING    TEMP.    LOADING   PEN.25       SMIX
         POINT R&B              TIME
          (DEG. C)   (DEG. C)   ( S )            (LB/IN**2)

 -0.22      50.4       25.0    1.0E+05    71.1      2.18E+01
 -0.22      50.4       25.0    1.0E+04    71.1      1.26E+02
 -0.22      50.4       25.0    1.0E+03    71.1      7.28E+02
 -0.22      50.4       25.0    1.0E+02    71.1      3.54E+03
 -0.22      50.4       25.0    1.0E+01    71.1      1.62E+04

 -0.22      50.4       25.0    1.0E+00    71.1      6.20E+04
 -0.22      50.4       25.0    1.0E-01    71.1      2.02E+05
 NN     2  TEMP  0.2500000E+02  SLOPE, M -0.6655233E+00  INTERCEPT,E1 0.4782354E+01
STIFFNESS OF MIX USING VAN DER POELS NOMOGRAPH
INPUT DATA:                      MODE  =     1

                           INITIAL PI  =   -0.09
                         AGED  O YEAR(S) TO-0.22

INITIAL SOFTENING POINT RING AND BALL  =    43.0
                       AGED  O YEAR(S) TO   50.4

                  INITIAL TEMPERATURE  =    60.0
       NUMBER OF STEPS IN TEMPERATURE  =     1

                 INITIAL LOADING TIME  =     1.0E+05
      NUMBER OF STEPS IN LOADING TIME  =     7
   MULTIPLYING FACTOR IN LOADING TIME  =     0.1

   PI    SOFTENING    TEMP.    LOADING   PEN.25       SMIX
         POINT R&B              TIME
          (DEG. C)   (DEG. C)   ( S )            (LB/IN**2)

 -0.22      50.4       60.0    1.0E+05    71.1      6.62E-02
 -0.22      50.4       60.0    1.0E+04    71.1      4.83E-01
 -0.22      50.4       60.0    1.0E+03    71.1      3.36E+00
 -0.22      50.4       60.0    1.0E+02    71.1      2.26E+01
 -0.22      50.4       60.0    1.0E+01    71.1      1.28E+02

 -0.22      50.4       60.0    1.0E+00    71.1      7.47E+02
 -0.22      50.4       60.0    1.0E-01    71.1      3.63E+03
 NN     3  TEMP  0.6000000E+02  SLOPE, M -0.7920183E+00  INTERCEPT,E1 0.2859218E+01
 SMIX  0.3029166E+05   TA    -70.000    BETA  -0.2011975E+02   INTERCEPT, B    0.3995209E+02   SOE2  0.3877208E-01
 SMIX  0.3029166E+05   TA    -65.000    BETA  -0.1904903E+02   INTERCEPT, B    0.3737157E+02   SOE2  0.3161228E-01
 SMIX  0.3029166E+05   TA    -60.000    BETA  -0.1797690E+02   INTERCEPT, B    0.3481262E+02   SOE2  0.2443966E-01
 SMIX  0.3029166E+05   TA    -55.000    BETA  -0.1689684E+02   INTERCEPT, B    0.3226402E+02   SOE2  0.1744193E-01
 SMIX  0.3029166E+05   TA    -50.000    BETA  -0.1580934E+02   INTERCEPT, B    0.2972871E+02   SOE2  0.1090100E-01
 SMIX  0.3029166E+05   TA    -45.000    BETA  -0.1471123E+02   INTERCEPT, B    0.2720287E+02   SOE2  0.5263560E-02
 SMIX  0.3029166E+05   TA    -40.000    BETA  -0.1360094E+02   INTERCEPT, B    0.2468622E+02   SOE2  0.1255732E-02
 SMIX  0.3029166E+05   TA    -35.000    BETA  -0.1247640E+02   INTERCEPT, B    0.2217807E+02   SOE2  0.7058751E-04
```

```
*** AGE CALLED: PEN1I=  149.0325 TPEN1=   25.0000SPRBI=   43.0000 IYR= 1
*** AFTER AGING --> IYR= 1 PEN1=  49.473 TPEN1=  25.000 SPRBI=  56.839
STIFFNESS OF MIX USING VAN DER POELS NOMOGRAPH
INPUT DATA:                       MODE   =      1

                               INITIAL PI   =   -0.09
                             AGED  1 YEAR(S) TO 0.35

INITIAL SOFTENING POINT RING AND BALL   =    43.0
                           AGED  1 YEAR(S) TO   56.8

                       INITIAL TEMPERATURE   =     0.0
              NUMBER OF STEPS IN TEMPERATURE   =     1

                      INITIAL LOADING TIME   =     1.0E+05
             NUMBER OF STEPS IN LOADING TIME   =     7
         MULTIPLYING FACTOR IN LOADING TIME   =     0.1

   PI     SOFTENING    TEMP.     LOADING   PEN.25       SMIX
          POINT R&B               TIME
           (DEG. C)   (DEG. C)    ( S )             (LB/IN**2)

  0.35       56.8         0.0     1.0E+05    49.5      8.38E+03
  0.35       56.8         0.0     1.0E+04    49.5      3.40E+04
  0.35       56.8         0.0     1.0E+03    49.5      1.10E+05
  0.35       56.8         0.0     1.0E+02    49.5      3.07E+05
  0.35       56.8         0.0     1.0E+01    49.5      7.00E+05

  0.35       56.8         0.0     1.0E+00    49.5      1.29E+06
  0.35       56.8         0.0     1.0E-01    49.5      2.03E+06
 NN     1  TEMP  0.0            SLOPE, M -0.3969445E+00  INTERCEPT,E1 0.6114758E+01
STIFFNESS OF MIX USING VAN DER POELS NOMOGRAPH
INPUT DATA:                       MODE   =      1

                               INITIAL PI   =   -0.09
                             AGED  1 YEAR(S) TO 0.35

INITIAL SOFTENING POINT RING AND BALL   =    43.0
                           AGED  1 YEAR(S) TO   56.8

                       INITIAL TEMPERATURE   =    25.0
              NUMBER OF STEPS IN TEMPERATURE   =     1

                      INITIAL LOADING TIME   =     1.0E+05
             NUMBER OF STEPS IN LOADING TIME   =     7
         MULTIPLYING FACTOR IN LOADING TIME   =     0.1
```

```
   PI     SOFTENING    TEMP.     LOADING   PEN.25        SMIX
          POINT R&B              TIME
           (DEG. C)   (DEG. C)    ( S )              (LB/IN**2)

  0.35       56.8        25.0     1.0E+05    49.5       7.10E+01
  0.35       56.8        25.0     1.0E+04    49.5       3.85E+02
  0.35       56.8        25.0     1.0E+03    49.5       1.86E+03
  0.35       56.8        25.0     1.0E+02    49.5       8.61E+03
  0.35       56.8        25.0     1.0E+01    49.5       3.48E+04

  0.35       56.8        25.0     1.0E+00    49.5       1.12E+05
  0.35       56.8        25.0     1.0E-01    49.5       3.12E+05
 NN      2  TEMP  0.2500000E+02  SLOPE, M -0.6117365E+00  INTERCEPT,E1 0.5041730E+01
STIFFNESS OF MIX USING VAN DER POELS NOMOGRAPH
INPUT DATA:                         MODE  =     1

                              INITIAL PI  =   -0.09
                            AGED  1 YEAR(S) TO 0.35

INITIAL SOFTENING POINT RING AND BALL  =    43.0
                          AGED  1 YEAR(S) TO   56.8

                    INITIAL TEMPERATURE  =    60.0
       NUMBER OF STEPS IN TEMPERATURE  =     1

                   INITIAL LOADING TIME  =     1.0E+05
      NUMBER OF STEPS IN LOADING TIME  =     7
   MULTIPLYING FACTOR IN LOADING TIME  =     0.1

   PI     SOFTENING    TEMP.     LOADING   PEN.25        SMIX
          POINT R&B              TIME
           (DEG. C)   (DEG. C)    ( S )              (LB/IN**2)

  0.35       56.8        60.0     1.0E+05    49.5       1.92E-01
  0.35       56.8        60.0     1.0E+04    49.5       1.25E+00
  0.35       56.8        60.0     1.0E+03    49.5       9.29E+00
  0.35       56.8        60.0     1.0E+02    49.5       5.72E+01
  0.35       56.8        60.0     1.0E+01    49.5       3.08E+02

  0.35       56.8        60.0     1.0E+00    49.5       1.49E+03
  0.35       56.8        60.0     1.0E-01    49.5       7.14E+03
 NN      3  TEMP  0.6000000E+02  SLOPE, M -0.7636267E+00  INTERCEPT,E1 0.3187518E+01
 SMIX  0.5504259E+05   TA    -70.000   BETA  -0.2043449E+02   INTERCEPT, B   0.4058609E+02   SOE2  0.4453669E-01
 SMIX  0.5504259E+05   TA    -65.000   BETA  -0.1934731E+02   INTERCEPT, B   0.3796574E+02   SOE2  0.3671252E-01
 SMIX  0.5504259E+05   TA    -60.000   BETA  -0.1825867E+02   INTERCEPT, B   0.3536728E+02   SOE2  0.2883490E-01
 SMIX  0.5504259E+05   TA    -55.000   BETA  -0.1716200E+02   INTERCEPT, B   0.3277936E+02   SOE2  0.2107830E-01
 SMIX  0.5504259E+05   TA    -50.000   BETA  -0.1605775E+02   INTERCEPT, B   0.3020485E+02   SOE2  0.1370536E-01
 SMIX  0.5504259E+05   TA    -45.000   BETA  -0.1494275E+02   INTERCEPT, B   0.2763997E+02   SOE2  0.7176872E-02
 SMIX  0.5504259E+05   TA    -40.000   BETA  -0.1381536E+02   INTERCEPT, B   0.2508441E+02   SOE2  0.2211459E-02
 SMIX  0.5504259E+05   TA    -35.000   BETA  -0.1267351E+02   INTERCEPT, B   0.2253745E+02   SOE2  0.6232895E-05
```

```
THERMAL CRACKING ANALYSIS FOR    1     HOUGHTON ( MICHIGAN AREA 3 )

THIS ANALYSIS BEGINS AFTER 710630 AND RUNS FOR  2 YEARS.

THE BITUMEN USED HAS THE FOLLOWING ORIGINAL PROPERTIES:
     PENETRATION INDEX            =     -0.090
     SOFTENING POINT RING & BALL TEMP =    109.400 DEG F
THE ASPHALT CONCRETE LAYER IS      2.500 INCHES THICK
AND IS ASSUMED TO HAVE AN INITIAL CRACK OF      0.200
INCHES EXTENDING FROM THE SURFACE.
THE ASPHALT CONCRETE HAS THE FOLLOWING MIX PROPERTIES:
     AGGREGATE VOLUME CONCENTRATION =      0.880
     DENSITY =    140.000 LBS/FT**3
     SPECIFIC HEAT =      0.220 BTU/LB DEG F
     THERMAL CONDUCTIVITY =      0.700 BTU/FT**2/HR,DEG F/FT
     ABSORPTIVITY =      0.950

THE PAVEMENT IS ASSUMED TO BE SUBJECTED TO THE
FOLLOWING AVERAGE ENVIRONMENTAL CONDITIONS:
     WIND VELOCITY =      9.000 MILES PER HOUR
     AVERAGE ANNUAL SOLAR RADIATION =    294.000 LANGLEYS/DAY
     AVERAGE JULY SOLAR RADIATION =    518.000 LANGLEYS/DAY
```

Sample Run of Program THERM

```
*** YEAR  0 ***
IN PLACE BITUMIN PROPERTIES:
    PENETRATION AT 77 DEG F     =      71.075
    SOFTENING POINT RING & BALL TEMP =     122.776 DEG F

FATIGUE PARAMETERS OF THE MIX:
    A =  0.539D-05     N =    2.002


NO       DATE          ID      NF            NF1            YC            CDMG           CDMG1

 0   JUL 31, 1971     0 0.0          0.0           0.200000D+00 0.0           0.0
 0   AUG 31, 1971     0 0.0          0.0           0.200000D+00 0.0           0.0
 0   SEP 30, 1971     0 0.0          0.0           0.200000D+00 0.0           0.0
 0   OCT 31, 1971     0 0.0          0.0           0.200000D+00 0.0           0.0
 0   NOV 30, 1971    10 0.134348D+05 0.136053D+05 0.201928D+00 0.728313D-02 0.723763D-02
 0   DEC 31, 1971    34 0.344179D+02 0.362104D+02 0.205877D+00 0.499727D-01 0.482049D-01
 0   JAN 31, 1972    65 0.479800D+03 0.729414D+03 0.292415D+00 0.246260D+00 0.212314D+00
 0   FEB 29, 1972    93 0.449788D+07 0.123669D+08 0.434560D+00 0.532214D+00 0.395368D+00
 0   MAR 31, 1972   113 0.543942D+07 0.335512D+08 0.790139D+00 0.108925D+01 0.630121D+00
 0   APR 30, 1972   119 0.609798D+05 0.381244D+06 0.790286D+00 0.108953D+01 0.630167D+00
 0   MAY 31, 1972   119 0.609798D+05 0.381244D+06 0.790286D+00 0.108953D+01 0.630167D+00
 0   JUN 30, 1972   119 0.609798D+05 0.381244D+06 0.790286D+00 0.108953D+01 0.630167D+00
```

```
*** YEAR  1 ***
IN PLACE BITUMIN PROPERTIES:
    PENETRATION AT 77 DEG F     =     49.473
    SOFTENING POINT RING & BALL TEMP =     134.310 DEG F

FATIGUE PARAMETERS OF THE MIX:
    A =  0.335D-05     N =    2.108

NO      DATE          ID       NF            NF1             YC            CDMG           CDMG1

 1  JUL 31,  1972    119 0.609798D+05 0.381244D+06 0.790286D+00 0.108953D+01 0.630167D+00
 1  AUG 31,  1972    119 0.609798D+05 0.381244D+06 0.790286D+00 0.108953D+01 0.630167D+00
 1  SEP 30,  1972    119 0.609798D+05 0.381244D+06 0.790286D+00 0.108953D+01 0.630167D+00
 1  OCT 31,  1972    132 0.405106D+08 0.271952D+09 0.790324D+00 0.108959D+01 0.630175D+00
 1  NOV 30,  1972    151 0.403932D+05 0.266600D+06 0.791011D+00 0.109088D+01 0.630380D+00
 1  DEC 31,  1972    182 0.510105D+06 0.555364D+07 0.106758D+01 0.148144D+01 0.719484D+00
 1  JAN 31,  1973    211 0.142292D+02 0.110614D+03 0.129400D+01 0.185549D+01 0.780760D+00
 1  FEB 26,  1973    237 0.583243D+00 0.306006D+02 0.225834D+01 0.537436D+01 0.932423D+00
 1  FEB 28,  1973    239 0.0          0.501101D+07 0.250000D+01 0.537436D+01 0.970300D+00
 1  MAR 31,  1973    250 0.0          0.338285D+09 0.250000D+01 0.537436D+01 0.970305D+00
 1  APR 30,  1973    256 0.0          0.371983D+07 0.250000D+01 0.537436D+01 0.970306D+00
 1  MAY 31,  1973    256 0.0          0.371983D+07 0.250000D+01 0.537436D+01 0.970306D+00
 1  JUN 30,  1973    256 0.0          0.371983D+07 0.250000D+01 0.537436D+01 0.970306D+00
```

```
USING ORIGINAL PROPERIES OF BITUMEN (WITHOUT AGING)
STIFFNESS OF MIX USING VAN DER POELS NOMOGRAPH
INPUT DATA:                           MODE  =      1

                                INITIAL PI  =   -0.09
                              AGED -1 YEAR(S) TO-0.09

INITIAL SOFTENING POINT RING AND BALL  =    43.0
                            AGED -1 YEAR(S) TO   43.0

                     INITIAL TEMPERATURE  =     0.0
       NUMBER OF STEPS IN TEMPERATURE  =      1

                    INITIAL LOADING TIME  =     1.0E+05
      NUMBER OF STEPS IN LOADING TIME  =      7
   MULTIPLYING FACTOR IN LOADING TIME  =      0.1

   PI     SOFTENING    TEMP.    LOADING   PEN.25       SMIX
          POINT R&B              TIME
           (DEG. C)   (DEG. C)   ( S )             (LB/IN**2)

 -0.09       43.0        0.0     1.0E+05   149.0      7.29E+02
 -0.09       43.0        0.0     1.0E+04   149.0      3.55E+03
 -0.09       43.0        0.0     1.0E+03   149.0      1.60E+04
 -0.09       43.0        0.0     1.0E+02   149.0      6.05E+04
 -0.09       43.0        0.0     1.0E+01   149.0      1.94E+05

 -0.09       43.0        0.0     1.0E+00   149.0      5.32E+05
 -0.09       43.0        0.0     1.0E-01   149.0      1.11E+06
 NN      1  TEMP  0.0           SLOPE, M -0.5349426E+00  INTERCEPT,E1 0.5706578E+01
STIFFNESS OF MIX USING VAN DER POELS NOMOGRAPH
INPUT DATA:                           MODE  =      1

                                INITIAL PI  =   -0.09
                              AGED -1 YEAR(S) TO-0.09

INITIAL SOFTENING POINT RING AND BALL  =    43.0
                            AGED -1 YEAR(S) TO   43.0

                     INITIAL TEMPERATURE  =    25.0
       NUMBER OF STEPS IN TEMPERATURE  =      1

                    INITIAL LOADING TIME  =     1.0E+05
      NUMBER OF STEPS IN LOADING TIME  =      7
   MULTIPLYING FACTOR IN LOADING TIME  =      0.1
```

```
  PI    SOFTENING    TEMP.    LOADING   PEN.25       SMIX
        POINT R&B               TIME
         (DEG. C)   (DEG. C)   ( S )              (LB/IN**2)

 -0.09      43.0       25.0    1.0E+05   149.0      5.02E+00
 -0.09      43.0       25.0    1.0E+04   149.0      3.49E+01
 -0.09      43.0       25.0    1.0E+03   149.0      1.88E+02
 -0.09      43.0       25.0    1.0E+02   149.0      1.01E+03
 -0.09      43.0       25.0    1.0E+01   149.0      5.02E+03

 -0.09      43.0       25.0    1.0E+00   149.0      2.28E+04
 -0.09      43.0       25.0    1.0E-01   149.0      7.87E+04
NN     2  TEMP  0.2500000E+02  SLOPE, M -0.7015494E+00  INTERCEPT,E1 0.4328370E+01
STIFFNESS OF MIX USING VAN DER POELS NOMOGRAPH
INPUT DATA:                       MODE  =      1

                            INITIAL PI  =   -0.09
                          AGED -1 YEAR(S) TO-0.09

INITIAL SOFTENING POINT RING AND BALL  =    43.0
                        AGED -1 YEAR(S) TO   43.0

                   INITIAL TEMPERATURE  =    60.0
       NUMBER OF STEPS IN TEMPERATURE  =     1

                  INITIAL LOADING TIME  =     1.0E+05
      NUMBER OF STEPS IN LOADING TIME  =     7
   MULTIPLYING FACTOR IN LOADING TIME  =     0.1

  PI    SOFTENING    TEMP.    LOADING   PEN.25       SMIX
        POINT R&B               TIME
         (DEG. C)   (DEG. C)   ( S )              (LB/IN**2)

 -0.09      43.0       60.0    1.0E+05   149.0      3.07E-02
 -0.09      43.0       60.0    1.0E+04   149.0      2.42E-01
 -0.09      43.0       60.0    1.0E+03   149.0      1.50E+00
 -0.09      43.0       60.0    1.0E+02   149.0      1.11E+01
 -0.09      43.0       60.0    1.0E+01   149.0      6.73E+01

 -0.09      43.0       60.0    1.0E+00   149.0      3.70E+02
 -0.09      43.0       60.0    1.0E-01   149.0      1.81E+03
NN     3  TEMP  0.6000000E+02  SLOPE, M -0.7976673E+00  INTERCEPT,E1 0.2559314E+01
 SMIX  0.1064974E+05   TA    -70.000   BETA  -0.1851500E+02   INTERCEPT, B    0.3678659E+02   SOE2  0.4285266E-01
 SMIX  0.1064974E+05   TA    -65.000   BETA  -0.1753035E+02   INTERCEPT, B    0.3441319E+02   SOE2  0.3588247E-01
 SMIX  0.1064974E+05   TA    -60.000   BETA  -0.1654437E+02   INTERCEPT, B    0.3205956E+02   SOE2  0.2878901E-01
 SMIX  0.1064974E+05   TA    -55.000   BETA  -0.1555110E+02   INTERCEPT, B    0.2971542E+02   SOE2  0.2171302E-01
 SMIX  0.1064974E+05   TA    -50.000   BETA  -0.1455097E+02   INTERCEPT, B    0.2738347E+02   SOE2  0.1485654E-01
 SMIX  0.1064974E+05   TA    -45.000   BETA  -0.1354111E+02   INTERCEPT, B    0.2506020E+02   SOE2  0.8567978E-02
 SMIX  0.1064974E+05   TA    -40.000   BETA  -0.1252001E+02   INTERCEPT, B    0.2274533E+02   SOE2  0.3409549E-02
 SMIX  0.1064974E+05   TA    -35.000   BETA  -0.1148581E+02   INTERCEPT, B    0.2043820E+02   SOE2  0.3256090E-03
```

```
*** AGE CALLED: PEN1I=  149.0325 TPEN1=   25.0000SPRBI=   43.0000 IYR= 0
*** AFTER AGING --> IYR= 0 PEN1=  71.075 TPEN1=  25.000 SPRBI=  50.431
STIFFNESS OF MIX USING VAN DER POELS NOMOGRAPH
INPUT DATA:                      MODE  =     1

                           INITIAL PI  =   -0.09
                         AGED  0 YEAR(S) TO-0.22

INITIAL SOFTENING POINT RING AND BALL  =    43.0
                       AGED  0 YEAR(S) TO   50.4

                  INITIAL TEMPERATURE  =     0.0
       NUMBER OF STEPS IN TEMPERATURE  =     1

                 INITIAL LOADING TIME  =     1.0E+05
      NUMBER OF STEPS IN LOADING TIME  =     7
   MULTIPLYING FACTOR IN LOADING TIME  =     0.1

   PI     SOFTENING    TEMP.    LOADING   PEN.25       SMIX
          POINT R&B              TIME
           (DEG. C)   (DEG. C)   ( S )             (LB/IN**2)

 -0.22       50.4         0.0    1.0E+05    71.1      3.27E+03
 -0.22       50.4         0.0    1.0E+04    71.1      1.50E+04
 -0.22       50.4         0.0    1.0E+03    71.1      5.84E+04
 -0.22       50.4         0.0    1.0E+02    71.1      1.92E+05
 -0.22       50.4         0.0    1.0E+01    71.1      5.33E+05

 -0.22       50.4         0.0    1.0E+00    71.1      1.12E+06
 -0.22       50.4         0.0    1.0E-01    71.1      1.95E+06
 NN     1  TEMP  0.0            SLOPE, M -0.4654609E+00  INTERCEPT,E1 0.6046534E+01
STIFFNESS OF MIX USING VAN DER POELS NOMOGRAPH
INPUT DATA:                      MODE  =     1

                           INITIAL PI  =   -0.09
                         AGED  0 YEAR(S) TO-0.22

INITIAL SOFTENING POINT RING AND BALL  =    43.0
                       AGED  0 YEAR(S) TO   50.4

                  INITIAL TEMPERATURE  =    25.0
       NUMBER OF STEPS IN TEMPERATURE  =     1

                 INITIAL LOADING TIME  =     1.0E+05
      NUMBER OF STEPS IN LOADING TIME  =     7
   MULTIPLYING FACTOR IN LOADING TIME  =     0.1
```

```
   PI     SOFTENING     TEMP.     LOADING   PEN.25        SMIX
          POINT R&B                TIME
           (DEG. C)   (DEG. C)    ( S )              (LB/IN**2)

 -0.22       50.4        25.0     1.0E+05    71.1       2.18E+01
 -0.22       50.4        25.0     1.0E+04    71.1       1.26E+02
 -0.22       50.4        25.0     1.0E+03    71.1       7.28E+02
 -0.22       50.4        25.0     1.0E+02    71.1       3.54E+03
 -0.22       50.4        25.0     1.0E+01    71.1       1.62E+04

 -0.22       50.4        25.0     1.0E+00    71.1       6.20E+04
 -0.22       50.4        25.0     1.0E-01    71.1       2.02E+05
 NN      2  TEMP  0.2500000E+02  SLOPE, M -0.6655233E+00  INTERCEPT,E1 0.4782354E+01
STIFFNESS OF MIX USING VAN DER POELS NOMOGRAPH
INPUT DATA:                        MODE  =     1

                               INITIAL PI  =   -0.09
                             AGED  0 YEAR(S) TO-0.22

INITIAL SOFTENING POINT RING AND BALL  =     43.0
                           AGED  0 YEAR(S) TO   50.4

                    INITIAL TEMPERATURE  =     60.0
       NUMBER OF STEPS IN TEMPERATURE  =      1

                   INITIAL LOADING TIME  =     1.0E+05
      NUMBER OF STEPS IN LOADING TIME  =     7
   MULTIPLYING FACTOR IN LOADING TIME  =     0.1

   PI     SOFTENING     TEMP.     LOADING   PEN.25        SMIX
          POINT R&B                TIME
           (DEG. C)   (DEG. C)    ( S )              (LB/IN**2)

 -0.22       50.4        60.0     1.0E+05    71.1       6.62E-02
 -0.22       50.4        60.0     1.0E+04    71.1       4.83E-01
 -0.22       50.4        60.0     1.0E+03    71.1       3.36E+00
 -0.22       50.4        60.0     1.0E+02    71.1       2.26E+01
 -0.22       50.4        60.0     1.0E+01    71.1       1.28E+02

 -0.22       50.4        60.0     1.0E+00    71.1       7.47E+02
 -0.22       50.4        60.0     1.0E-01    71.1       3.63E+03
 NN      3  TEMP  0.6000000E+02  SLOPE, M -0.7920183E+00  INTERCEPT,E1 0.2859218E+01
```

```
 SMIX  0.3029166E+05   TA    -70.000    BETA  -0.2011975E+02   INTERCEPT, B    0.3995209E+02   SOE2  0.3877208E-01
 SMIX  0.3029166E+05   TA    -65.000    BETA  -0.1904903E+02   INTERCEPT, B    0.3737157E+02   SOE2  0.3161228E-01
 SMIX  0.3029166E+05   TA    -60.000    BETA  -0.1797690E+02   INTERCEPT, B    0.3481262E+02   SOE2  0.2443966E-01
 SMIX  0.3029166E+05   TA    -55.000    BETA  -0.1689684E+02   INTERCEPT, B    0.3226402E+02   SOE2  0.1744193E-01
 SMIX  0.3029166E+05   TA    -50.000    BETA  -0.1580934E+02   INTERCEPT, B    0.2972871E+02   SOE2  0.1090100E-01
 SMIX  0.3029166E+05   TA    -45.000    BETA  -0.1471123E+02   INTERCEPT, B    0.2720287E+02   SOE2  0.5263560E-02
 SMIX  0.3029166E+05   TA    -40.000    BETA  -0.1360094E+02   INTERCEPT, B    0.2468622E+02   SOE2  0.1255732E-02
 SMIX  0.3029166E+05   TA    -35.000    BETA  -0.1247640E+02   INTERCEPT, B    0.2217807E+02   SOE2  0.7058751E-04
*** AGE CALLED: PEN1I=  149.0325 TPEN1=   25.0000SPRBI=   43.0000 IYR= 1
*** AFTER AGING --> IYR= 1 PEN1=  49.473 TPEN1=  25.000 SPRBI=  56.839
STIFFNESS OF MIX USING VAN DER POELS NOMOGRAPH
INPUT DATA:                          MODE   =     1

                                 INITIAL PI   =   -0.09
                               AGED  1 YEAR(S) TO 0.35

INITIAL SOFTENING POINT RING AND BALL   =    43.0
                             AGED  1 YEAR(S) TO   56.8

                         INITIAL TEMPERATURE  =     0.0
       NUMBER OF STEPS IN TEMPERATURE  =     1

                        INITIAL LOADING TIME  =     1.0E+05
      NUMBER OF STEPS IN LOADING TIME  =     7
   MULTIPLYING FACTOR IN LOADING TIME  =     0.1

   PI     SOFTENING    TEMP.     LOADING   PEN.25       SMIX
          POINT R&B               TIME
           (DEG. C)   (DEG. C)    ( S )              (LB/IN**2)

  0.35       56.8         0.0     1.0E+05    49.5       8.38E+03
  0.35       56.8         0.0     1.0E+04    49.5       3.40E+04
  0.35       56.8         0.0     1.0E+03    49.5       1.10E+05
  0.35       56.8         0.0     1.0E+02    49.5       3.07E+05
  0.35       56.8         0.0     1.0E+01    49.5       7.00E+05

  0.35       56.8         0.0     1.0E+00    49.5       1.29E+06
  0.35       56.8         0.0     1.0E-01    49.5       2.03E+06
 NN      1  TEMP  0.0             SLOPE, M -0.3969445E+00  INTERCEPT,E1 0.6114758E+01
```

```
STIFFNESS OF MIX USING VAN DER POELS NOMOGRAPH
INPUT DATA:                        MODE  =     1

                             INITIAL PI  =   -0.09
                           AGED  1 YEAR(S) TO 0.35

INITIAL SOFTENING POINT RING AND BALL  =    43.0
                         AGED  1 YEAR(S) TO   56.8

                  INITIAL TEMPERATURE  =    25.0
       NUMBER OF STEPS IN TEMPERATURE  =     1

                 INITIAL LOADING TIME  =     1.0E+05
      NUMBER OF STEPS IN LOADING TIME  =     7
   MULTIPLYING FACTOR IN LOADING TIME  =     0.1

   PI     SOFTENING    TEMP.    LOADING   PEN.25       SMIX
          POINT R&B              TIME
           (DEG. C)   (DEG. C)   ( S )             (LB/IN**2)

  0.35       56.8        25.0    1.0E+05    49.5      7.10E+01
  0.35       56.8        25.0    1.0E+04    49.5      3.85E+02
  0.35       56.8        25.0    1.0E+03    49.5      1.86E+03
  0.35       56.8        25.0    1.0E+02    49.5      8.61E+03
  0.35       56.8        25.0    1.0E+01    49.5      3.48E+04

  0.35       56.8        25.0    1.0E+00    49.5      1.12E+05
  0.35       56.8        25.0    1.0E-01    49.5      3.12E+05
 NN     2  TEMP  0.2500000E+02  SLOPE, M -0.6117365E+00  INTERCEPT,E1 0.5041730E+01
```

```
STIFFNESS OF MIX USING VAN DER POELS NOMOGRAPH
INPUT DATA:                           MODE  =      1

                               INITIAL PI  =   -0.09
                             AGED  1 YEAR(S) TO 0.35

INITIAL SOFTENING POINT RING AND BALL  =    43.0
                           AGED  1 YEAR(S) TO   56.8

                     INITIAL TEMPERATURE  =    60.0
       NUMBER OF STEPS IN TEMPERATURE  =     1

                    INITIAL LOADING TIME  =     1.0E+05
      NUMBER OF STEPS IN LOADING TIME  =     7
   MULTIPLYING FACTOR IN LOADING TIME  =     0.1

   PI     SOFTENING    TEMP.     LOADING   PEN.25        SMIX
          POINT R&B              TIME
           (DEG. C)   (DEG. C)   ( S )               (LB/IN**2)

  0.35       56.8       60.0    1.0E+05    49.5       1.92E-01
  0.35       56.8       60.0    1.0E+04    49.5       1.25E+00
  0.35       56.8       60.0    1.0E+03    49.5       9.29E+00
  0.35       56.8       60.0    1.0E+02    49.5       5.72E+01
  0.35       56.8       60.0    1.0E+01    49.5       3.08E+02

  0.35       56.8       60.0    1.0E+00    49.5       1.49E+03
  0.35       56.8       60.0    1.0E-01    49.5       7.14E+03
 NN     3  TEMP  0.6000000E+02  SLOPE, M -0.7636267E+00  INTERCEPT,E1 0.3187518E+01
  SMIX  0.5504259E+05   TA     -70.000    BETA  -0.2043449E+02   INTERCEPT, B     0.4058609E+02   SOE2  0.4453669E-01
  SMIX  0.5504259E+05   TA     -65.000    BETA  -0.1934731E+02   INTERCEPT, B     0.3796574E+02   SOE2  0.3671252E-01
  SMIX  0.5504259E+05   TA     -60.000    BETA  -0.1825867E+02   INTERCEPT, B     0.3536728E+02   SOE2  0.2883490E-01
  SMIX  0.5504259E+05   TA     -55.000    BETA  -0.1716200E+02   INTERCEPT, B     0.3277936E+02   SOE2  0.2107830E-01
  SMIX  0.5504259E+05   TA     -50.000    BETA  -0.1605775E+02   INTERCEPT, B     0.3020485E+02   SOE2  0.1370536E-01
  SMIX  0.5504259E+05   TA     -45.000    BETA  -0.1494275E+02   INTERCEPT, B     0.2763997E+02   SOE2  0.7176872E-02
  SMIX  0.5504259E+05   TA     -40.000    BETA  -0.1381536E+02   INTERCEPT, B     0.2508441E+02   SOE2  0.2211459E-02
  SMIX  0.5504259E+05   TA     -35.000    BETA  -0.1267351E+02   INTERCEPT, B     0.2253745E+02   SOE2  0.6232895E-05
```

```
THERMAL CRACKING ANALYSIS FOR   1     HOUGHTON ( MICHIGAN AREA 3 )

THIS ANALYSIS BEGINS AFTER 710630 AND RUNS FOR  2 YEARS.

THE BITUMEN USED HAS THE FOLLOWING ORIGINAL PROPERTIES:
     PENETRATION INDEX           =     -0.090
     SOFTENING POINT RING & BALL TEMP =    109.400 DEG F
THE ASPHALT CONCRETE LAYER IS      2.500 INCHES THICK
AND IS ASSUMED TO HAVE AN INITIAL CRACK OF      0.200
INCHES EXTENDING FROM THE SURFACE.
THE ASPHALT CONCRETE HAS THE FOLLOWING MIX PROPERTIES:
     AGGREGATE VOLUME CONCENTRATION =      0.880
     DENSITY =    140.000 LBS/FT**3
     SPECIFIC HEAT =      0.220 BTU/LB DEG F
     THERMAL CONDUCTIVITY =      0.700 BTU/FT**2/HR,DEG F/FT
     ABSORPTIVITY =      0.950

THE PAVEMENT IS ASSUMED TO BE SUBJECTED TO THE
FOLLOWING AVERAGE ENVIRONMENTAL CONDITIONS:
     WIND VELOCITY =      9.000 MILES PER HOUR
     AVERAGE ANNUAL SOLAR RADIATION =    294.000 LANGLEYS/DAY
     AVERAGE JULY SOLAR RADIATION =    518.000 LANGLEYS/DAY
```

```
*** YEAR  0 ***
IN PLACE BITUMIN PROPERTIES:
    PENETRATION AT 77 DEG F     =      71.075
    SOFTENING POINT RING & BALL TEMP =     122.776 DEG F

FATIGUE PARAMETERS OF THE MIX:
    A =  0.539D-05     N =     2.002
    A =  0.539D-05     N =     2.002    (VALUES USED WHEN YC IS GREATER THAN 1.0 INCH)


NO       DATE         ID       NF            NF1           YC            CDMG          CDMG1

 0  JUL 31, 1971     0 0.0           0.0           0.200000D+00 0.0           0.0
 0  AUG 31, 1971     0 0.0           0.0           0.200000D+00 0.0           0.0
 0  SEP 30, 1971     0 0.0           0.0           0.200000D+00 0.0           0.0
 0  OCT 31, 1971     0 0.0           0.0           0.200000D+00 0.0           0.0
 0  NOV 30, 1971    10 0.134348D+05 0.136053D+05 0.201928D+00 0.728313D-02 0.723763D-02
 0  DEC 31, 1971    34 0.344179D+02 0.362104D+02 0.205877D+00 0.499727D-01 0.482049D-01
 0  JAN 31, 1972    65 0.479800D+03 0.729414D+03 0.292415D+00 0.246260D+00 0.212314D+00
 0  FEB 29, 1972    93 0.449788D+07 0.123669D+08 0.434560D+00 0.532214D+00 0.395368D+00
 0  MAR 31, 1972   113 0.543942D+07 0.335512D+08 0.790139D+00 0.108925D+01 0.630121D+00
 0  APR 30, 1972   119 0.609798D+05 0.381244D+06 0.790286D+00 0.108953D+01 0.630167D+00
 0  MAY 31, 1972   119 0.609798D+05 0.381244D+06 0.790286D+00 0.108953D+01 0.630167D+00
 0  JUN 30, 1972   119 0.609798D+05 0.381244D+06 0.790286D+00 0.108953D+01 0.630167D+00
```

```
*** YEAR  1 ***
IN PLACE BITUMIN PROPERTIES:
    PENETRATION AT 77 DEG F     =     49.473
    SOFTENING POINT RING & BALL TEMP =     134.310 DEG F

FATIGUE PARAMETERS OF THE MIX:
    A =  0.335D-05      N =     2.108
    A =  0.539D-05      N =     2.002    (VALUES USED WHEN YC IS GREATER THAN 1.0 INCH)

NO       DATE         ID       NF            NF1            YC            CDMG           CDMG1

 1   JUL 31,  1972    119 0.609798D+05 0.381244D+06 0.790286D+00 0.108953D+01 0.630167D+00
 1   AUG 31,  1972    119 0.609798D+05 0.381244D+06 0.790286D+00 0.108953D+01 0.630167D+00
 1   SEP 30,  1972    119 0.609798D+05 0.381244D+06 0.790286D+00 0.108953D+01 0.630167D+00
 1   OCT 31,  1972    132 0.405106D+08 0.271952D+09 0.790324D+00 0.108959D+01 0.630175D+00
 1   NOV 30,  1972    151 0.403932D+05 0.266600D+06 0.791011D+00 0.109088D+01 0.630380D+00
 1   DEC 31,  1972    168 0.192820D+03 0.141784D+04 0.104614D+01 0.145790D+01 0.715554D+00
 1   JAN 31,  1973    184 0.253701D+04 0.355671D+05 0.136106D+01 0.185215D+01 0.797254D+00
 1   FEB 28,  1973    201 0.326472D+02 0.130484D+04 0.198523D+01 0.282292D+01 0.903870D+00
 1   MAR 31,  1973    201 0.326472D+02 0.130484D+04 0.198523D+01 0.282292D+01 0.903870D+00
 1   APR 30,  1973    201 0.326472D+02 0.130484D+04 0.198523D+01 0.282292D+01 0.903870D+00
 1   MAY 31,  1973    201 0.326472D+02 0.130484D+04 0.198523D+01 0.282292D+01 0.903870D+00
 1   JUN 30,  1973    201 0.326472D+02 0.130484D+04 0.198523D+01 0.282292D+01 0.903870D+00
```

APPENDIX C

Pattern Search Program To Find Optimum Pavement Design Quantities

APPENDIX C

Pattern Search Program to Find Optimum Values

A computer program for function optimization using pattern search and gradient is modified to find the optimum values of penetration index, PI, softening point ring and ball temperature, TRB, depth of asphalt concrete layer, DF, and the volumetric concentration of aggregate, CV, for given values of the age of pavement, T, the average annual amplitude of solar radiation, SA, and the minimum monthly temperature, TM. The inputs to this program are the initial values of PI, TRB, CV, and DF, and T, SA, and TM. The lower and upper limits of PI, TRB, CV, and DF applicable to this model are:

PI = -1.00 to 2.00,
TRB = 100.4°F to 125.6°F,
CV = 0.85 to 0.90, and
DF = 2.00" to 8.00".

These values are set in the program.

THE GUIDE FOR INPUT DATA

CARD 01: (4F10.0)

Column	Variable	Description
01-10	PI	Penetration index.
11-20	TRB	Softening point ring and ball temperature, °F.
21-30	CV	(Aggregate volume)/(aggregate volume + asphalt volume).
31-40	DF	Depth of the asphalt concrete layer, in.

The values of PI, TRB, CV, and DF are the initial values assumed.

CARD 02: (3F10.0)

Column	Variable	Description
01-10	T	The age of the pavement.
11-20	SA	The average annual amplitude of solar radiation, Langleys/day.
21-30	TM	The minimum monthly temperature, °F.

```
C*************************************************************
C
C     PATTERN SEARCH PROGRAM TO DETERMINE OPTIMAL VALUES OF
C
C                    PI, TRB, CV, AND DF
C
C*************************************************************
      IMPLICIT REAL*8 (A-H, O-Z)
      DIMENSION X(11),XBASE(11),XTEMP(11),XTEST(11),PARTZ(11),PARTH(11)
      COMMON KC, IFEAS, C(10), ISTOP, LACT, CFSC, CASS, ADAF, M, N
      COMMON /VALUES/ VLO(5),VHI(5),A(4),AO, NC
C
C
C
      LAST = 0
C
   20 CONTINUE
      ZTEST = 0.0
      ZBASE = 0.0
      ZP    = 0.0
      ZM    = 0.0
      Z     = 0.0
      ISW = 0
      CALL INPUT (LAST)
      IF ( LAST .EQ. 1 ) GO TO 9999
C
   22 CONTINUE
C
      M = NC
      N = NC
C
      DO 10 I = 1, N
   10 X(I) = A(I)
      D = 0.05
      ADAF = 1.0
      CFSC = 0.03
      CASS = CFSC
      ISTOP = 2
      IFEAS = 1
      KC = 0
      LACT = 0
C
C
C     X = 1
      X(11) = 1.0
C
      CALL SUMS(X, ZBASE)
      ZTEMP = ZBASE
      DO 110 I = 1, N
      XTEMP(I) = X(I)
  110 XBASE(I) = X(I)
      IF (IFEAS .EQ. 1) GO TO 111
C
C     X = 2
      X(11) = 2.0
C
      CALL SUMC(X, CBASE)
      CTEMP = CBASE
      CFSCI = CFSC
C**** THIS IS POINT A WHICH APPEARS IN FLOWCHART, FIG. 8.
```

```
 5111 DO 5112 I = 1,N
 5112 XTEST(I) = XBASE(I)
 5114 DO 5115 I = 1, N
      XTEST(I) = XTEMP(I) + CFSCI
C
C     X = 3
      XTEST(11) = 3.0
C
      CALL SUMC (XTEST, CTEST)
      IF (CTEST .GT. CTEMP) GO TO 5135
      XTEST(I) = XTEMP(I) - CFSCI
C
C     X = 4
      XTEST(11) = 4.0
C
      CALL SUMC (XTEST, CTEST)
      IF (CTEST .LE. CTEMP) GO TO 5115
 5135 CTEMP = CTEST
      XTEMP(I) = XTEST(I)
 5115 CONTINUE
C
C     X = 5
      XTEMP(11) = 5.0
C
      CALL SUMC (XTEMP, CTEST)
 5145 IF (IFEAS .EQ. 1) GO TO 5146
C**** THIS IS POINT C WHICH APPEARS IN FLOWCHART, FIG. 9
 5150 IF (CTEST .LE. CBASE) GO TO 5210
      CTEMP = CTEST
      DO 5160 I = 1,N
 5160 XTEST(I) = XTEMP(I)*2.0 -X(I)
C
C     X = 6
      XTEST(11) = 6.0
C
      CALL SUMC (XTEST, CTEST)
 5170 IF (CTEST .LE. CTEMP) GO TO 5172
 5171 IF (IFEAS.EQ. 1) GO TO 5173
C**** THIS IS POINT E WHICH APPEARS IN FLOWCHART, FIG. 10.
      CBASE = CTEST
      CTEMP = CTEST
      DO 5180 I = 1,N
      X(I) = XTEMP(I)
      XBASE(I) = XTEST(I)
 5180 XTEMP(I) = XTEST(I)
      GO TO 5111
 5173 DO 5174 I = 1,N
      X(I) = XTEST(I)
      XTEMP(I) = XTEST(I)
 5174 XBASE(I) = XTEST(I)
      GO TO 5176
C**** THIS IS POINT B WHICH APPEARS IN FLOWCHART, FIG. 10.
 5146 DO 5147 I = 1,N
      X(I) = XTEMP(I)
 5147 XBASE(I) = XTEMP(I)
C**** THIS IS POINT F WHICH APPEARS IN FLOWCHART, FIG. 10.
 5176 CONTINUE
C
C     X = 7
      X(11) = 7.0
```

```
C
      CALL VAL (X, ZBASE)
      ZTEMP = ZBASE
      GO TO 111
 5210 CONTINUE
      CTEMP = CBASE
      DO 5216 I = 1,N
 5216 XTEMP(I) = XBASE(I)
      CFSCI = CFSCI/3.0
      IF(CFSCI .GE. 10.**(-6)) GO TO 5111
      WRITE(6,5270)
 5270 FORMAT( 10X, 'NO FEASIBLE SOLUTION FOUND.  PROBLEM ENDED.'   )
      GO TO 8888
C**** THIS IS POINT D WHICH APPEARS IN FLOWCHART, FIG. 10.
 5172 CONTINUE
      CBASE = CTEMP
      DO 5195 I = 1,N
      X(I) = XTEMP(I)
 5195 XBASE(I) = XTEMP(I)
      GO TO 5111
C**** THIS IS POINT 111 WHICH APPEARS IN FLOWCHART, FIG. 11.
  111 DO 112 I = 1, N
      XTEMP(I) = XBASE(I)
  112 XTEST(I) = XBASE(I)
      ZTEMP = ZBASE
  114 DO 115 I = 1, N
      XTEST(I) = XTEMP(I) + CFSC
C
C     X = 8
      XTEST(11) = 8.0
C
      CALL SUMS(XTEST, ZTEST)
      IF (ZTEST .GT. ZTEMP) GO TO 135
      XTEST(I) = XTEMP(I) - CFSC
C
C     X = 9
      XTEST(11) = 9.0
C
      CALL SUMS (XTEST, ZTEST)
      IF (ZTEST .LE. ZTEMP) GO TO 115
  135 ZTEMP = ZTEST
      XTEMP(I) = XTEST(I)
  115 CONTINUE
C**** THIS IS POINT G WHICH APPEARS IN FLOWCHART, FIG. 12.
C
C     X = 10
      XTEMP(11) = 10.0
C
      CALL SUMS(XTEMP, ZTEST)
  145 IF (IFEAS .EQ. 2) GO TO 146
  150 IF( ZTEST .LE. ZBASE + 10.0 ** (-20)) GO TO 149
      ZTEMP = ZTEST
      CASS = CFSC
      ISTOP = 2
      ADAF = 1.0
      DO 160 I = 1,N
  160 XTEST(I) = XTEMP(I)*2. -X(I)
C
C     X = 11
      XTEST(11) = 11.0
```

```
C
       CALL SUMS (XTEST, ZTEST)
   170 IF( ZTEST .LE. ZTEMP + 10.0 ** (-20)) GO TO 172
   171 IF (IFEAS .EQ. 2) GO TO 173
       ZBASE = ZTEST
       ZTEMP = ZTEST
       ADAF = 1.0
       DO 180 I = 1,N
       X(I) = XTEMP(I)
   180 XBASE(I) = XTEST(I)
       GO TO 111
   173 CONTINUE
       GO TO 190
C**** THIS IS POINT K WHICH APPEARS IN FLOWCHART, FIG. 13.
   172 CONTINUE
C**** THIS IS POINT L WHICH APPEARS IN FLOWCHART, FIG. 13.
   190 ZBASE = ZTEMP
       DO 195 I = 1, N
       X(I) = XTEMP(I)
   195 XBASE(I) = XTEMP(I)
       GO TO 111
   151 CONTINUE
       GO TO 220
C**** THIS IS POINT H WHICH APPEARS IN FLOWCHART, FIG. 13.
   146 ZTEMP = ZBASE
       DO 147 I = 1,N
   147 XTEMP(I) = XBASE(I)
       IF (KC .NE. 1) GO TO 151
   148 CONTINUE
C**** THIS IS POINT 210 WHICH APPEARS IN FLOWCHART, FIG. 14.
   210 IF (ISTOP .EQ. 2) GO TO 409
C**** THIS IS POINT M WHICH APPEARS IN FLOWCHART, FIG. 14.
   220 CFSC = CFSC/3.0
       IF (CFSC .GE. 10.**(-6)) GO TO 231
C
C      X = 12
       XTEMP(11) = 12.0
C
       CALL SUMS (XTEMP, ZTEMP)
C
       ISW = ISW + 1
       GO TO ( 40, 50, 60 ), ISW
       GO TO 8888
C
    40 DO 42 ICX = 1, NC
    42 A(ICX) = XTEMP(ICX)
       CALL OUTPUT( XTEMP, ZTEMP, ISW )
       GO TO 20
C
    50 DO 52 ICX = 1, NC
    52 A(ICX) = XTEMP(ICX)
       CALL OUTPUT( XTEMP, ZTEMP, ISW )
       GO TO 22
C
    60 CALL OUTPUT( XTEMP, ZTEMP, ISW )
       GO TO 22
C
C**** THIS IS POINT N WHICH APPEARS IN FLOWCHART, FIG. 13.
   149 CONTINUE
C**** THIS IS POINT J WHICH APPEARS IN FLOWCHART, FIG. 13.
```

```
  215 ZTEMP = ZBASE
      DO 216 I = 1,N
  216 XTEMP(I) = XBASE(I)
      GO TO 220
  231 CONTINUE
      GO TO 111
C**** THIS IS POINT 310 WHICH APPEARS IN FLOWCHART, FIG. 17.
  310 CONTINUE
  329 DO 330 I = 1, N
  330 XTEST(I) = XBASE(I) + ADAF*CASS*PARTH(I)
C
C     X = 13
      XTEST(11) = 13.0
C
      CALL SUMS (XTEST, ZTEST)
  350 GO TO (355, 380),IFEAS
  355 CONTINUE
  360 IF (ZTEST .GT. ZBASE) GO TO 370
      IF (ADAF .LE. 1.1) GO TO 362
      ADAF = 1.0
      GO TO 329
  362 CONTINUE
      GO TO 381
  380 CONTINUE
      ADAF = 1.0
  381 CASS = CASS/3.0
  385 IF (CASS .GT. 10.**(-6)) GO TO 310
  390 ISTOP = 1
      GO TO 215
  370 ADAF = ADAF + 1.0
      ZBASE = ZTEST
      ZTEMP = ZTEST
      DO 375 I = 1, N
      X(I) = XTEST(I)
      XBASE(I) = XTEST(I)
  375 XTEMP(I) = XBASE(I)
      GO TO 111
C**** THIS IS POINT P WHICH APPEARS IN FLOWCHART, FIG. 15.
  409 DO 410 I = 1, N
  410 X(I) = XBASE(I)
      CASS = CFSC
      DO 426 I = 1,N
      X(I) = X(I) + D
C
C     X = 14
      X(11) = 14.0
C
      CALL VAL(X, ZP)
      CP = C(LACT)
      X(I) = X(I) - 2.0 * D
C
C     X = 15
      X(11) = 15.0
C
      CALL VAL(X, ZM)
      CM = C(LACT)
  422 PARTZ(I) = (ZP-ZM)
      PARTH(I) = (CP-CM)
      X(I) = XBASE(I)
  426 CONTINUE
```

```
      DENOM = 0.0
      DO 430 I = 1, N
  430 DENOM = DENOM + PARTZ(I)**2
      DENOM = DSQRT(DENOM)
      IF (DENOM .LT. 10.**(-6)) DENOM = 10.**(-6)
      IF( DENOM .EQ. 0.0 ) DENOM = 10.0 ** (-6)
      DO 440 I = 1,N
      PARTZ(I) = PARTZ(I)/DENOM
  440 CONTINUE
C**** THIS IS POINT Q WHICH APPEARS IN FLOWCHART, FIG. 16.
      DENOM = 0.0
      DO 460 I = 1, N
  460 DENOM = DENOM + PARTH(I)**2
      DENOM =DSQRT(DENOM)
      IF( DENOM .EQ. 0.0 ) DENOM = 10.0 ** (-6)
      DO 470 I = 1, N
  470 PARTH(I) = PARTH(I)/DENOM
      DENOM = 0.0
      DO 480 I = 1, N
      PARTH(I) = PARTH(I) + PARTZ(I)
  480 DENOM = DENOM + PARTH(I)**2
      DENOM =DSQRT(DENOM)
      IF (DENOM .LT. 10.**(-6)) DENOM = 10.**(-6)
      IF( DENOM .EQ. 0.0 ) DENOM = 10.0 ** (-6)
      DO 490 I = 1, N
  490 PARTH(I) = PARTH(I)/DENOM
      IF (DENOM .GT. 0.03) GO TO 310
      ISTOP = 1
      GO TO 111
 8888 CONTINUE
      GO TO 20
 9999 CONTINUE
      RETURN
      END



      SUBROUTINE SUMS(X, Z)
      IMPLICIT REAL*8 (A-H, O-Z)
C**** THIS SUBROUTINE APPEARS IN FLOWCHART, FIG. 4.
      DIMENSION X(11)
      COMMON KC, IFEAS, C(10), ISTOP, LACT, CFSC,CASS,ADAF, M, N
      CALL VAL(X, Z)
      KC = 0
      IFEAS = 1
      IF (M .LT. 1) GO TO 11
      DO 10 I = 1, M
      IF (C(I) .GE. 0.0) GO TO 10
   40 IFEAS = 2
      LACT = I
   50 KC = KC + 1
   10 CONTINUE
   11 CONTINUE
      RETURN
      END
```

```
      SUBROUTINE SUMC(X, CON)
      IMPLICIT REAL*8 (A-H, O-Z)
C**** THIS SUBROUTINE APPEARS IN FLOWCHART, FIG. 5.
      DIMENSION X(11)
      COMMON KC, IFEAS, C(10), ISTOP, LACT, CFSC, CASS, ADAF, M, N
      CALL VAL (X, Z)
      CON = 0.0
      IFEAS = 1
      DO 10 I = 1,M
      IF(C(I) .GE. 0.0) GO TO 9
      IFEAS = 2
      CON = CON + C(I)
    9 CONTINUE
   10 CONTINUE
   11 CONTINUE
      RETURN
      END




      SUBROUTINE OUTPUT ( X, Z, ISW )
      IMPLICIT REAL*8 (A-H, O-Z)
C**** THIS SUBROUTINE APPEARS IN FLOWCHART, FIG. 6.
      COMMON /VALUES/ VLO(5), VHI(5), A(4), AO, NC
      COMMON /ERR/ ER
      COMMON KC, IFEAS, C(10), ISTOP, LACT, CFSC, CASS, ADAF, M, N
      DIMENSION X(11), EX(11)
C
      EX(1)      = 4.0 * X(1) - 2.0
      EX(2)      = 125.6 * X(2)
      EX(3)      = X(3)
      EX(4)      = 8.0 * X(4)
      WRITE (6,600)
  600 FORMAT ( //, 10X, 'SOLUTION', // )
      WRITE (6,700) (EX(I), I = 1,NC)
  700 FORMAT ( 10X, 'FINAL VALUES', /, 10X, 'PI     ', F10.6, 3X,
     1 'TRB    ', F10.6, 3X, 'CV     ', F10.6, 3X, 'DF     ', F10.6, / )
C
      WRITE (6,720) ER
  720 FORMAT ( /, 10X, 'ERROR        ',F10.6, 5(/) )
      RETURN
      END




      SUBROUTINE VAL(X, Z)
      IMPLICIT REAL*8 (A-H, O-Z)
      COMMON KC, IFEAS, C(10), ISTOP, LACT, CFSC, CASS, ADAF, M, N
      COMMON /VALUES/ VLO(5), VHI(5), A(4), AO, NC
      COMMON /ERR/ ER
      DIMENSION X(11), EX(4)
      EX(1)      = 4.0 * X(1) - 2.0
      EX(2)      = 125.6 * X(2)
      EX(3)      = X(3)
      EX(4)      = 8.0 * X(4)
      JSW = 0
C
      DO 200 I = 1, M
```

```
      C(I) = 0.01
      IF(EX(I) .LT. VLO(I) ) C(I) = -1.0
      IF(EX(I) .GT. VHI(I) ) C(I) = -1.0
      IF (C(I).LT.0.0) JSW = 1
  200 CONTINUE
      IF (JSW.EQ.1) RETURN
      ER = -1.163 + ( AO * X(1) ** 0.257 * X(2) ** 0.122 *
     1      X(3) ** 24.50 * X(4) ** (-0.410) )
      Z = ER * ER
      Z = -Z
      RETURN
      END
```

```
      SUBROUTINE INPUT (LAST)
      IMPLICIT REAL*8 (A-H, O-Z)
      COMMON /VALUES/ VLO(5), VHI(5), A(4), AO, NC
      NC = 4
      READ (5,500,END=50) PI,TRB,CV,DF
  500 FORMAT (4F10.0)
      A(1) = 0.25 * (PI + 2.0)
      A(2) = TRB/125.6
      A(3) = CV
      A(4) = DF/8.0
      VLO(1) = -1.00
      VHI(1) =  2.00
      VLO(2) =  100.40
      VHI(2) =  125.60
      VLO(3) =  0.85
      VHI(3) =  0.90
      VLO(4) =  2.00
      VHI(4) =  8.00
      WRITE (6,600)
  600 FORMAT ( 1H1, 14(/), 10X, 'PATTERN SEARCH PROGRAM', 3(/),
     1          10X, 'INPUT DATA', //  )
      READ (5,520) T, SA, TM
  520 FORMAT (3F10.0)
      WRITE (6,620) T, SA, TM
  620 FORMAT (  10X, 'T     ', F10.6, 3X, 'SA    ', F10.6,
     1 3X, 'TM    ', F10.6, // )
      T1  = T / 10.0
      SA1 = SA / 240.0
      TM1 = (TM + 20.0) / 55.70
      AO  = 0.519 * T1 ** 1.66 * SA1 ** 1.97 * TM1 ** (-7.43)
      WRITE (6,800) PI,TRB,CV,DF
  800 FORMAT ( 10X, 'INITIAL VALUES', /,
     1 10X, 'PI    ', F10.6, 3X, 'TRB   ', F10.6,
     2 3X, 'CV    ', F10.6, 3X, 'DF    ', F10.6)
      WRITE (6,700)
  700 FORMAT ( //, 10X, 'BOUNDS ON PI, TRB, CV, AND DF', // )
      WRITE (6,810) ( VLO(I), I = 1, NC )
  810 FORMAT ( 10X, 'LOWER LIMITS', /,
     1 10X, 'PI    ', F10.6, 3X, 'TRB   ', F10.6,
     2 3X, 'CV    ', F10.6, 3X, 'DF    ', F10.6 )
      WRITE (6,820) ( VHI(I), I = 1, NC )
  820 FORMAT ( /,10X, 'HIGHER LIMITS', /,
     1 10X, 'PI    ', F10.6, 3X, 'TRB   ', F10.6,
     2 3X, 'CV    ', F10.6, 3X, 'DF    ', F10.6, / )
```

```
   RETURN
50 LAST = 1
   RETURN
   END
```

APPENDIX D

Results of Computations
in Michigan and Texas
Using Program THERM1

TABLE D-1. Computation of CMDG1 Using Thermal Cracking Program for Michigan - Area 1 (Marquette).

The Average Annual Solar Radiation, SR = 330.0 Langleys/day.
The Average Annual Amplitude of Solar Radiation, SA = 240.0 Langleys/day.
The Minimum Monthly Temperature, MMT = 9.8 ° F.

Penetration Index P.I.	Softening Point Ring & Ball Temperature T_{R+B} (°F)	Volumetric Concentration of the Aggregate C_v	Pavement Thickness DF (in)	Number of Years	Crack Length Y_c (in)	CMDG1
2.00	125.6	0.85	2.0	4.000	0.4550	0.4863
				8.000	1.4045	0.8528
		0.90		5.581	2.00	0.9275
				8.000	-	1.2127
	100.4	0.85		4.000	0.9931	0.7409
				8.000	1.0315	0.7525
		0.90		4.000	1.0170	0.7495
				8.000	1.0645	0.7585
	125.6	0.85	5.0	4.000	0.4822	0.3475
				8.000	1.4208	0.5814
		0.90		6.573	5.00	0.6803
				8.000	-	0.7765
	100.4	0.85		4.000	0.9655	0.5146
				8.000	1.0296	0.5150
		0.90		4.000	1.0039	0.5176
				8.000	1.0410	0.5265
	125.6	0.85	8.0	4.000	0.4668	0.2437
				8.000	1.3116	0.4098
		0.90		7.435	8.0	0.5260
				8.000	-	0.5360

TABLE D-1. Computation of CMDG1 Using Thermal Cracking Program for Michigan - Area 1 (Marquette) - continued.

The Average Annual Solar Radiation, SR = 330.0 Langleys/day.
The Average Annual Amplitude of Solar Radiation, SA = 240.0 Langleys/day.
The Minimum Monthly Temperature, MMT = 9.8 ° F.

Penetration Index P.I.	Softening Point Ring & Ball Temperature T_{R+B} (°F)	Volumetric Concentration of the Aggregate C_v	Pavement Thickness DF (in)	Number of Years	Crack Length Y_c (in)	CMDG1
	100.4	0.85		4.000	0.8775	0.3673
				8.000	1.0024	0.3900
		0.90		4.000	1.0122	0.3892
				8.000	1.0456	0.3951
-1.0	125.6	0.85	2.0	5.473	2.00	0.9369
				8.000	-	2.0199
		0.90		3.595	2.00	0.9455
				8.000	-	2.7909
	100.4	0.85		7.435	2.00	0.9528
				8.000	-	0.9532
		0.90		4.622	2.00	0.9499
				8.000	-	1.2422
	125.6	0.85	5.0	5.565	5.00	0.7902
				8.000	-	1.4827
		0.90		4.511	5.00	0.7287
				8.000	-	1.9238
	100.4	0.85		4.000	1.0207	0.5175
				8.000	1.9673	0.6709
		0.90		6.598	5.00	0.8059
				8.000	-	0.8488

TABLE D-1. Computation of CMDG1 Using Thermal Cracking Program for Michigan - Area 1 (Marquette) - continued.

The Average Annual Solar Radiation, SR = 330.0 Langleys/day.
The Average Annual Amplitude of Solar Radiation, SA = 240.0 Langleys/day.
The Minimum Monthly Temperature, MMT = 9.8 ° F.

Penetration Index P.I.	Softening Point Ring & Ball Temperature T_{R+B} (°F)	Volumetric Concentration of the Aggregate C_v	Pavement Thickness DF (in)	Number of Years	Crack Length Y_c (in)	CMDG1
	125.6	0.85	8.0	6.513	8.000	0.6360
				8.000	-	1.0200
		0.90		4.559	8.000	0.5541
				8.000	-	1.3416
	100.4	0.85		4.000	1.0028	0.3933
				8.000	1.8109	0.5021
		0.90		4.000	1,1897	0.4185
				8.000	4.4956	0.6043
0.0	125.6	0.85	2.0	6.573	2.0	0.9507
				8.000	-	1.1963
		0.90		4.589	2.0	0.9256
				8.000	-	1.8873
	100.4	0.85		4.00	1.0020	0.7332
				8.000	1.2056	0.7929
		0.90		4.00	1,0074	0.7554
				8.000	1.8687	0.9280
	125.6	0.85	5.0	7.435	5.0	0.8016
				8.000	-	0.8329
		0.90		4.658	5.0	0.7157
				8.00	-	1.3300

TABLE D-1. Computation of CMDG1 Using Thermal Cracking Program for Michigan - Area 1 (Marquette) - continued .

The Average Annual Solar Radiation, SR = 330.0 Langleys/day.
The Average Annual Amplitude of Solar Radiation, SA = 240.0 Langleys/day.
The Minimum Monthly Temperature, MMT = 9.8 ° F .

Penetration Index P.I.	Softening Point Ring & Ball Temperature T_{R+B} (°F)	Volumetric Concentration of the Aggregate C_v	Pavement Thickness DF (in)	Number of Years	Crack Length Y_c (in)	CMDG1
	100.4	0.85		4.00	1.0329	0.5233
				8.00	1.2339	0.5681
		0.90		4.00	1.0820	0.5296
				8.00	1.9438	0.6538
	125.6	0.85	8.0	4.00	0.5999	0.2883
				8.00	5.0709	0.5887
		0.90		5.604	8.0	0.5496
				8.00	-	0.8990
	100.4	0.85		.00	1.0390	0.4008
				8.00	1.2322	0.4340
		0.90		4.00	1.0308	0.3934
				8.00	1.7453	0.4812

TABLE D-2. Computation of CMDG1 Using Thermal Cracking Program for Michigan - Area 2 (Sault Ste. Marie).

The Average Annual Solar Radiation, SR = 283.0 Langleys/day.
The Average Annual Amplitude of Solar Radiation, SA = 215.2 Langleys/day.
THe Minimum Monthly Temperature, MMT = 6.40 ° F.

Penetration Index P.I.	Softening Point Ring & Ball Temperature T_{R+B} (°F)	Volumetric Concentration of the Aggregate C_v	Pavement Thickness DF (in)	Number of Years	Crack Length Y_c (in)	CMDG1
2.00	125.6	0.85	2.0	3.573	2.0	0.9512
				8.00	-	1.6622
		0.90		4.565	2.0	0.9467
				8.00	-	2.1009
	100.4	0.85		4.00	1.0832	0.7663
				8.00	1.4089	0.8429
		0.90		4.622	2.0	0.9659
				8.00	-	1.0582
	125.6	0.85	5.0	5.532	5.0	0.7846
				8.00	-	1.1020
		0.90		4.640	5.0	0.6970
				8.00	-	1.3891
	100.4	0.85		4.00	1.1297	0.5410
				8.00	1.2940	0.5745
		0.90		4.00	1.2814	0.5736
				8.00	3.2350	0.7290
	125.6	0.85	8.0	6.641	8.0	0.6324
				8.00	-	0.7244
		0.90		5.519	8.0	0.5395
				8.00	-	0.9572

TABLE D-2. Computation of CMDG1 Using Thermal Cracking Program for Michigan - Area 2 (Sault Ste. Marie) - continued .

The Average Annual Solar Radiation, SR = 283.0 Langleys/day.
The Average Annual Amplitude of Solar Radiation, SA = 215.2 Langleys/day.
THe Minimum Monthly Temperature, MMT = 6.40 ° F .

Penetration Index P.I.	Softening Point Ring & Ball Temperature T_{R+B} (°F)	Volumetric Concentration of the Aggregate C_v	Pavement Thickness DF (in)	Number of Years	Crack Length Y_c (in)	CMDG1
	100.4	0.85		4.00	1.0443	0.4018
				8.00	1.1449	0.4200
		0.90		4.00	1.3040	0.4357
				8.00	2.8706	0.5405
-1.0	125.6	0.85	2.0	2.638	2.00	0.9891
				8.000	-	3.9194
		0.90		2.683	2.00	0.9630
				8.000		3.6364
	100.4	0.85		2.522	2.00	0.9623
				8.000	-	2.3853
		0.90		2.632	2.00	0.9858
				8.000	-	2.7921
	125.6	0.85	5.0	2.699	5.00	0.8146
				8.00	-	2.7352
		0.90		3.417	5.00	0.7366
				8.00	-	2.4913
	100.4	0.85		3.573	5.00	0.8530
				8.00	-	1.5576
		0.90		3.522	5.00	0.8063
				8.00	-	1.8744

TABLE D-2. Computation of CMDG1 Using Thermal Cracking Program for Michigan - Area 2 (Sault Ste. Marie) - continued.

The Average Annual Solar Radiation, SR = 283.0 Langleys/day.
The Average Annual Amplitude of Solar Radiation, SA = 215.2 Langleys/day.
THe Minimum Monthly Temperature, MMT = 6.40 °F.

Penetration Index P.I.	Softening Point Ring & Ball Temperature T_{R+B} (°F)	Volumetric Concentration of the Aggregate C_v	Pavement Thickness DF (in)	Number of Years	Crack Length Y_c (in)	CMDG1
	125.6	0.85	8.0	3.575	8.00	0.6649
				8.00	-	1.9439
		0.90		3.613	8.00	0.5832
				8.00	-	1.7334
	100.4	0.85		4.622	8.00	0.7235
				8.00	-	1.1052
		0.90		4.522	8.00	0.6645
				8.00	-	1.3550
0.0	125.6	0.85	2.0	2.609	2.0	0.9870
				8.00	-	3.1955
		0.90		3.604	2.0	0.9424
				8.00	-	2.9520
	100.4	0.85		2.618	2.0	0.9671
				8.00	-	1.5526
		0.90		2.644	2.0	0.9779
				8.00	-	1.9637
	125.6	0.85	5.0	3.527	5.0	0.8003
				8.00	-	2.0923
		0.90		3.696	5.0	0.7263
				8.00	-	2.0072

TABLE D-2. Computation of CMDG1 Using Thermal Cracking Program for Michigan - Area 2 (Sault Ste. Marie) - continued.

The Average Annual Solar Radiation, SR = 283.0 Langleys/day.
The Average Annual Amplitude of Solar Radiation, SA = 215.2 Langleys/day.
THe Minimum Monthly Temperature, MMT = 6.40 °F.

Penetration Index P.I.	Softening Point Ring & Ball Temperature $T_{R + B}$ (°F)	Volumetric Concentration of the Aggregate C_v	Pavement Thickness DF (in)	Number of Years	Crack Length Y_c (in)	CMDG1
	100.4	0.85		4.622	5.0	0.8612
				8.00	-	1.0427
		0.90		4.562	5.0	0.8123
				8.00	-	1.3376
	125.6	0.85	8.0	4.524	8.0	0.6496
				8.00	-	1.4470
		0.90		4.505	8.0	0.5575
				8.00	-	1.4326
	100.4	0.85		6.641	8.0	0.7178
				8.00	-	0.7446
		0.90		5.532	8.0	0.6798
				8.00	-	0.9459

TABLE D-3. Computation of CMDG1 Using Thermal Cracking Program for Michigan - Area 3 (Honghton).

The Average Annual Solar Radiation, SR = 272.0 Langleys/day.
The Average Annual Amplitude of Solar Radiation, SA = 226.2 Langleys/day.
THe Minimum Monthly Temperature, MMT = 7.1 °F.

Penetration Index P.I.	Softening Point Ring & Ball Temperature T_{R+B} (°F)	Volumetric Concentration of the Aggregate C_v	Pavement Thickness DF (in)	Number of Years	Crack Length Y_c (in)	CMDG1
2.0	125.6	0.85	2.0	4.5565	2.00	0.9354
				8.00	-	1.6041
		0.90		4.5215	2.00	0.9071
				8.00	-	1.9566
	100.4	0.85		4.00	1.022	0.7580
				8.00	1.033	0.7596
		0.90		6.6034	2.00	0.8931
				8.00	-	0.9008
	125.6	0.85	5.0	5.5806	5.00	0.8006
				8.00	-	1.0358
		0.90		5.4866	5.00	0.7213
				8.00	-	1.230
	100.4	0.85		4.00	1.0253	0.5234
				8.00	1.0339	0.5258
		0.90		4.00	1.280	0.5716
				8.00	1.6237	0.6236
	125.6	0.85	8.0	6.6063	8.00	0.6357
				8.00	-	0.7035
		0.90		5.5511	8.00	0.5576
				8.00	-	0.8321

TABLE D-3. Computation of CMDG1 Using Thermal Cracking Program for Michigan - Area 3 (Honghton) - continued.

The Average Annual Solar Radiation, SR = 272.0 Langleys/day.
The Average Annual Amplitude of Solar Radiation, SA = 226.2 Langleys/day.
THe Minimum Monthly Temperature, MMT = 7.1 °F.

Penetration Index P.I.	Softening Point Ring & Ball Temperature T_{R+B} (°F)	Volumetric Concentration of the Aggregate C_v	Pavement Thickness DF (in)	Number of Years	Crack Length Y_c (in)	CMDG1
	100.4	0.85		4.00	1.006	0.3967
				8.00	1.016	0.3987
		0.90		4.00	1.1564	0.4166
				8.00	1.3768	0.4467
-1.0	125.6	0.85	2.0	2.652	2.0	0.9867
				8.00	-	3.6729
		0.90		2.669	2.0	0.9628
				8.00	-	3.8025
	100.4	0.85		3.481	2.0	0.9561
				8.00	-	2.1605
		0.90		2.615	2.0	0.9616
				8.00	-	2.4048
	125.6	0.85	5.0	3.462	5.0	0.8047
				8.00	-	2.5164
		0.90		3.497	5.0	0.7412
				8.00	-	2.4883
	100.4	0.85		4.565	5.0	0.8695
				8.00	-	1.3628
		0.90		4.479	5.0	0.8155
				8.00	-	1.5946

TABLE D-3. Computation of CMDG1 Using Thermal Cracking Program for Michigan - Area 3 (Honghton) - continued.

The Average Annual Solar Radiation, SR = 272.0 Langleys/day.
The Average Annual Amplitude of Solar Radiation, SA = 226.2 Langleys/day.
THe Minimum Monthly Temperature, MMT = 7.1 °F.

Penetration Index P.I.	Softening Point Ring & Ball Temperature T_{R+B} (°F)	Volumetric Concentration of the Aggregate C_v	Pavement Thickness DF (in)	Number of Years	Crack Length Y_c (in)	CMDG1
	125.6	0.85	8.0	2.586	8.00	0.6600
				8.00	-	1.8020
		0.90		2.619	8.0	0.5923
				8.00	-	1.7377
	100.4	0.85		5.548	8.00	0.7242
				8.00	-	0.9431
		0.90		4.565	8.00	0.6764
				8.00	-	1.1114
0.0	125.6	0.85	2.0	2.655	2.0	0.9593
				8.00	-	2.9224
		0.90		3.565	2.0	0.9430
				8.00	-	2.9239
	100.4	0.85		4.595	2.0	0.9894
				8.00	-	1.2864
		0.90		4.478	2.0	0.9360
				8.00	-	1.8922
	125.6	0.85	5.0	3.601	5.0	0.8133
				8.00	-	1.8463
		0.90		3.625	5.0	0.7254
				8.00	-	1.9614

TABLE D-3. Computation of CMDG1 Using Thermal Cracking Program for Michigan - Area 3 (Honghton) - continued.

The Average Annual Solar Radiation, SR = 272.0 Langleys/day.
The Average Annual Amplitude of Solar Radiation, SA = 226.2 Langleys/day.
THe Minimum Monthly Temperature, MMT = 7.1 °F.

Penetration Index P.I.	Softening Point Ring & Ball Temperature T_{R+B} (°F)	Volumetric Concentration of the Aggregate C_v	Pavement Thickness DF (in)	Number of Years	Crack Length Y_c (in)	CMDG1
	100.4	0.85		4.00	1.3267	0.5811
				8.00	4.0279	0.8251
		0.90		4.622	5.0	0.8287
				8.00	-	1.2100
	125.6	0.85	8.0	4.559	8.0	0.6558
				8.00	-	1.2469
		0.90		4.408	8.0	0.5685
				8.00	-	1.3776
	100.4	0.85		4.00	1.2818	0.4406
				8.00	3.1911	0.6003
		0.90		5.589	8.0	0.6821
				8.00	-	0.8369

TABLE D-4. Computation of CMDG1 Using Thermal Cracking Program for Michigan - Area 4 (Grand Rapids).

The Average Annual Solar Radiation, SR = 308.0 Langleys/day.
The Average Annual Amplitude of Solar Radiation, SA = 222.8 Langleys/day.
THe Minimum Monthly Temperature, MMT = 16.0 °F.

Penetration Index P.I.	Softening Point Ring & Ball Temperature T_{R+B} (°F)	Volumetric Concentration of the Aggregate C_v	Pavement Thickness DF (in)	Number of Years	Crack Length Y_c (in)	CMDG1
2.0	125.6	0.85	2.0	4.00	0.5271	0.5512
				8.00	1.3285	0.8503
		0.90		4.625	2.0	0.9259
				8.00	-	1.2265
	100.4	0.85		4.00	0.9348	0.7250
				8.00	1.0016	0.7467
		0.90		4.00	1.0218	0.7636
				8.00	1.0592	0.7714
	125.6	0.85	5.0	4.00	0.5120	0.3586
				8.00	1.3074	0.5639
		0.90		6.609	5.0	0.6874
				8.00	-	0.7678
	100.4	0.85		4.00	0.9486	0.4998
				8.00	1.0147	0.5147
		0.90		4.00	1.0027	0.5108
				8.00	1.0337	0.5181
	125.6	0.85	8.0	4.00	0.4701	0.2432
				8.00	1.2262	0.3996
		0.90		4.00	0.7510	0.2987
				8.00	6.0045	0.5095

TABLE D-4. Computation of CMDG1 Using Thermal Cracking Program for Michigan - Area 4 (Grand Rapids) - continued.

The Average Annual Solar Radiation, SR = 308.0 Langleys/day.
The Average Annual Amplitude of Solar Radiation, SA = 222.8 Langleys/day.
THe Minimum Monthly Temperature, MMT = 16.0 °F.

Penetration Index P.I.	Softening Point Ring & Ball Temperature $T_{R + B}$ (°F)	Volumetric Concentration of the Aggregate C_v	Pavement Thickness DF (in)	Number of Years	Crack Length Y_c (in)	CMDG1
	100.4	0.85		4.00	0.8188	0.3556
				8.00	1.0093	0.3925
		0.90		4.00	1.0015	0.3835
				8.00	1.0290	0.3884
-1.0	125.6	0.85	2.0	4.562	2.0	0.9528
				8.00	-	1.8039
		0.90		4.508	2.0	0.9133
				8.00	-	1.9596
	100.4	0.85		4.00	1.0091	0.7424
				8.00	1.7023	0.9533
		0.90		5.551	2.0	0.9538
				8.00	-	1.1858
	125.6	0.85	5.0	5.546	5.0	0.7876
				8.00	-	1.1839
		0.90		4.667	5.0	0.7257
				8.00	-	1.3075
	100.4	0.85		4.00	1.0132	0.5110
				8.00	1.5052	0.6277
		0.90		4.00	1.0553	0.5251
				8.00	4.1327	0.7867

TABLE D-4. Computation of CMDG1 Using Thermal Cracking Program for Michigan - Area 4 (Grand Rapids) - continued.

The Average Annual Solar Radiation, SR = 308.0 Langleys/day.
The Average Annual Amplitude of Solar Radiation, SA = 222.8 Langleys/day.
THe Minimum Monthly Temperature, MMT = 16.0 °F.

Penetration Index P.I.	Softening Point Ring & Ball Temperature T_{R+B} (°F)	Volumetric Concentration of the Aggregate C_v	Pavement Thickness DF (in)	Number of Years	Crack Length Y_c (in)	CMDG1
	125.6	0.85	8.0	6.601	8.0	0.6365
				8.00	-	0.7772
		0.90		5.487	8.0	0.5563
				8.00	-	0.9072
	100.4	0.85		4.00	1.0079	0.3913
				8.00	1.4940	0.4670
		0.90		4.00	1.0597	0.3966
				8.00	3.3128	0.5705
0.0	125.6	0.85	2.0	6.513	2.0	0.9480
				8.00	-	1.2034
		0.90		4.595	2.0	0.9439
				8.00	-	1.5558
	100.4	0.85		4.00	1.0005	0.7441
				8.00	1.1323	0.7855
		0.90		4.00	1.0110	0.7486
				8.00	1.5786	0.9069
	125.6	0.85	5.0	7.634	5.0	0.7935
				8.00	-	0.7936
		0.90		5.524	5.0	0.7182
				8.00	-	1.0462

TABLE D-4. Computation of CMDG1 Using Thermal Cracking Program for Michigan - Area 4 (Grand Rapids) - continued.

The Average Annual Solar Radiation, SR = 308.0 Langleys/day.
The Average Annual Amplitude of Solar Radiation, SA = 222.8 Langleys/day.
THe Minimum Monthly Temperature, MMT = 16.0 °F.

Penetration Index P.I.	Softening Point Ring & Ball Temperature T_{R+B} (°F)	Volumetric Concentration of the Aggregate C_v	Pavement Thickness DF (in)	Number of Years	Crack Length Y_c (in)	CMDG1
	100.4	0.85		4.00	1.0108	0.5110
				8.00	1.1347	0.5408
		0.90		4.00	1.0172	0.5181
				8.00	1.5147	0.6104
	125.6	0.85	8.0	4.00	0.5511	0.2708
				8.00	3.6576	0.5549
		0.90		5.573	8.0	0.5434
				8.00	-	0.7516
	100.4	0.85		4.00	1.0014	0.3900
				8.00	1.1203	0.4118
		0.90		4.00	1.0120	0.3878
				8.00	1.3998	0.4459

TABLE D-5. Computation of CMDG1 Using Thermal Cracking Program for Amarillo.

The Average Annual Solar Radiation, SR = 450.0 Langleys/day.
The Average Annual Amplitude of Solar Radiation, SA = 199.1 Langleys/day.
THe Minimum Monthly Temperature, MMT = 22.5 °F.

Penetration Index P.I.	Softening Point Ring & Ball Temperature T_{R+B} (°F)	Volumetric Concentration of the Aggregate C_v	Pavement Thickness DF (in)	Number of Years	Crack Length Y_c (in)	CMDG1
2.0	125.6	0.85	2.0	4.00	0.2197	0.0774
				8.00	0.2583	0.2053
		0.90		4.00	0.2954	0.3338
				8.00	1.0243	0.7981
	100.4	0.85		4.00	0.2382	0.1097
				8.00	0.5233	0.5242
		0.90		4.00	0.3133	0.2889
				8.00	1.0195	0.7784
	125.6	0.85	5.0	4.00	0.2206	0.05284
				8.00	0.2661	0.1431
		0.90		4.00	0.3125	0.2165
				8.00	1.0305	0.4886
	100.4	0.85		4.00	0.2420	0.07878
				8.00	0.5428	0.3592
		0.90		4.00	0.3155	0.1950
				8.00	1.0240	0.5229
	125.6	0.85	8.0	4.00	0.2193	0.0357
				8.00	0.2587	0.0938
		0.90		4.00	0.2873	0.1270
				8.00	1.0094	0.3271

TABLE D-5. Computation of CMDG1 Using Thermal Cracking Program for Amarillo - continued.

The Average Annual Solar Radiation, SR = 450.0 Langleys/day.
The Average Annual Amplitude of Solar Radiation, SA = 199.1 Langleys/day.
THe Minimum Monthly Temperature, MMT = 22.5 °F.

Penetration Index P.I.	Softening Point Ring & Ball Temperature $T_{R + B}$ (°F)	Volumetric Concentration of the Aggregate C_v	Pavement Thickness DF (in)	Number of Years	Crack Length Y_c (in)	CMDG1
	100.4	0.85	2.0	4.00	0.2392	0.0578
				8.00	0.4943	0.2550
		0.90		4.00	0.2959	0.1275
				8.00	1.0008	0.3849
-1.0	125.6	0.85		4.00	0.2281	0.1026
				8.00	0.2453	0.1620
		0.90		4.00	0.4405	0.5079
				8.00	1.9580	0.9143
	100.4	0.85	5.0	4.00	0.2513	0.1402
				8.00	0.5473	0.5400
		0.90		4.00	0.3225	0.3066
				8.00	1.0314	0.7841
	125.6	0.85		4.00	0.2325	0.0731
				8.00	0.2534	0.1143
		0.90		4.00	0.4574	0.3274
				8.00	2.0223	0.6017
	100.4	0.85		4.00	0.2514	0.09216
				8.00	0.5469	0.3605
		0.90		4.00	0.3318	0.2108
				8.00	1.0117	0.5189

TABLE D-5. Computation of CMDG1 Using Thermal Cracking Program for Amarillo - continued.

The Average Annual Solar Radiation, SR = 450.0 Langleys/day.
The Average Annual Amplitude of Solar Radiation, SA = 199.1 Langleys/day.
THe Minimum Monthly Temperature, MMT = 22.5 °F.

Penetration Index P.I.	Softening Point Ring & Ball Temperature $T_{R + B}$ (°F)	Volumetric Concentration of the Aggregate C_v	Pavement Thickness DF (in)	Number of Years	Crack Length Y_c (in)	CMDG1
	125.6	0.85	8.0	4.00	0.2291	0.04967
				8.00	0.2446	0.07279
		0.90		4.00	0.3908	0.2003
				8.00	1.4096	0.3752
	100.4	0.85		4.00	0.2447	0.0639
				8.00	0.4792	0.2468
		0.90		4.00	0.3152	0.1452
				8.00	1.0042	0.3851
0.0	125.6	0.85	2.0	4.00	0.2215	0.0848
				8.00	0.2432	0.1620
		0.90		4.00	0.3375	0.4031
				8.00	1.0909	0.7917
	100.4	0.85		4.00	0.2431	0.1220
				8.00	0.5245	0.5241
		0.90		4.00	0.3174	0.2973
				8.00	1.0559	0.7917
	125.6	0.85	5.0	4.00	0.2239	0.05882
				8.00	0.2496	0.1121
		0.90		4.00	0.3593	0.2601
				8.00	1.2751	0.5233

TABLE D-5. Computation of CMDG1 Using Thermal Cracking Program for Amarillo - continued.

The Average Annual Solar Radiation, SR = 450.0 Langleys/day.
The Average Annual Amplitude of Solar Radiation, SA = 199.1 Langleys/day.
THe Minimum Monthly Temperature, MMT = 22.5 °F.

Penetration Index P.I.	Softening Point Ring & Ball Temperature T_{R+B} (°F)	Volumetric Concentration of the Aggregate C_v	Pavement Thickness DF (in)	Number of Years	Crack Length Y_c (in)	CMDG1
	100.4	0.85		4.00	0.2461	0.08437
				8.00	0.5374	0.3557
		0.90		4.00	0.3225	0.2019
				8.00	1.010	0.5202
	125.6	0.85	8.0	4.00	0.2218	0.03946
				8.00	0.2422	0.07112
		0.90		4.00	0.3166	0.1517
				8.00	0.9426	0.3177
	100.4	0.85		4.00	0.2415	0.0602
				8.00	0.4890	0.2520
		0.90		4.00	0.3079	0.1390
				8.00	1.0138	0.3879

TABLE D-6. Computation of CMDG1 Using Thermal Cracking Program for Abilene.

The Average Annual Solar Radiation, SR = 422.0 Langleys/day.
The Average Annual Amplitude of Solar Radiation, SA = 177.5 Langleys/day.
THe Minimum Monthly Temperature, MMT = 31.7 °F.

Penetration Index P.I.	Softening Point Ring & Ball Temperature T_{R+B} (°F)	Volumetric Concentration of the Aggregate C_v	Pavement Thickness DF (in)	Number of Years	Crack Length Y_c (in)	CMDG1
2.0	125.6	0.85	2.0	6.0	0.2005	0.0028
				12.0	0.2008	0.0047
		0.90		6.0	0.2409	0.1801
				12.0	0.3630	0.4698
	100.4	0.85		6.0	0.2103	0.0345
				12.0	0.2122	0.0421
		0.90		6.0	0.2492	0.1576
				12.0	0.2966	0.2748
	125.6	0.85	5.0	6.0	0.2016	0.0040
				12.0	0.2031	0.0078
		0.90		6.0	0.2461	0.1154
				12.0	0.4314	0.3250
	100.4	0.85		6.0	0.2128	0.0258
				12.0	0.2172	0.0334
		0.90		6.0	0.2520	0.1043
				12.0	0.3092	0.1871
	125.6	0.85	8.0	6.0	0.2012	0.0024
				12.0	0.2023	0.0046
		0.90		6.0	0.2374	0.0669
				12.0	0.3667	0.1873

TABLE D-6. Computation of CMDG1 Using Thermal Cracking Program for Abilene - continued.

The Average Annual Solar Radiation, SR = 422.0 Langleys/day.
The Average Annual Amplitude of Solar Radiation, SA = 177.5 Langleys/day.
THe Minimum Monthly Temperature, MMT = 31.7 °F.

Penetration Index P.I.	Softening Point Ring & Ball Temperature T_{R+B} (°F)	Volumetric Concentration of the Aggregate C_v	Pavement Thickness DF (in)	Number of Years	Crack Length Y_c (in)	CMDG1
	100.4	0.85	2.0	6.0	0.2112	0.0182
				12.0	0.2145	0.0234
		0.90		6.0	0.2400	0.0633
				12.0	0.2816	0.1146
-1.0	125.6	0.85		4.0	0.2000	0.0002
				8.0	0.2000	0.0002
		0.90		4.0	0.2050	0.0261
				8.0	0.2102	0.0549
	100.4	0.85	5.0	4.0	0.2000	0.0002
				8.0	0.2002	0.0012
		0.90		4.0	0.2018	0.0079
				8.0	0.2144	0.0590
	125.6	0.85		4.0	0.2002	0.0004
				8.0	0.2003	0.0006
		0.90		4.0	0.2098	0.0259
				8.0	0.2204	0.0534
	100.4	0.85		4.0	0.2002	0.0004
				8.0	0.2012	0.0021
		0.90		4.0	0.2032	0.0068
				8.0	0.2204	0.0431

TABLE D-6. Computation of CMDG1 Using Thermal Cracking Program for Abilene - continued.

The Average Annual Solar Radiation, SR = 422.0 Langleys/day.
The Average Annual Amplitude of Solar Radiation, SA = 177.5 Langleys/day.
THe Minimum Monthly Temperature, MMT = 31.7 °F.

Penetration Index P.I.	Softening Point Ring & Ball Temperature T_{R+B} (°F)	Volumetric Concentration of the Aggregate C_v	Pavement Thickness DF (in)	Number of Years	Crack Length Y_c (in)	CMDG1
	125.6	0.85	8.0	4.0	0.2002	0.00039
				8.0	0.2003	0.0006
		0.90		4.0	0.2075	0.0149
				8.0	0.2150	0.0293
	100.4	0.85		4.0	0.2003	0.0004
				8.0	0.2011	0.0018
		0.90		4.0	0.2025	0.0045
				8.0	0.2147	0.0256
0.0	125.6	0.85	2.0	4.0	0.2000	0.0002
				8.0	0.2000	0.0002
		0.90		4.0	0.2051	0.0283
				8.0	0.2150	0.0799
	100.4	0.85		4.0	0.2000	0.0002
				8.0	0.2002	0.0012
		0.90		4.0	0.2011	0.0050
				8.0	0.2145	0.0595
	125.6	0.85	5.0	4.0	0.2002	0.0004
				8.0	0.2003	0.0007
		0.90		4.0	0.2093	0.0259
				8.0	0.2248	0.0658

TABLE D-6. Computation of CMDG1 Using Thermal Cracking Program for Abilene - continued.

The Average Annual Solar Radiation, SR = 422.0 Langleys/day.
The Average Annual Amplitude of Solar Radiation, SA = 177.5 Langleys/day.
THe Minimum Monthly Temperature, MMT = 31.7 °F.

Penetration Index P.I.	Softening Point Ring & Ball Temperature T_{R+B} (°F)	Volumetric Concentration of the Aggregate C_v	Pavement Thickness DF (in)	Number of Years	Crack Length Y_c (in)	CMDG1
	100.4	0.85		4.0	0.2002	0.0003
				8.0	0.2012	0.0021
		0.90		4.0	0.2024	0.0050
				8.0	0.2206	0.0436
	125.6	0.85		4.0	0.2002	0.0003
				8.0	0.2003	0.0006
		0.90		4.0	0.2069	0.0141
				8.0	0.2180	0.0351
	100.4	0.85		4.0	0.2002	0.0003
				8.0	0.2011	0.0018
		0.90		4.0	0.2019	0.0033
				8.0	0.2148	0.0259

TABLE D-7. Computation of CMDG1 Using Thermal Cracking Program for El Paso.

The Average Annual Solar Radiation, SR = 516.0 Langleys/day.
The Average Annual Amplitude of Solar Radiation, SA = 212.3 Langleys/day.
THe Minimum Monthly Temperature, MMT = 30.2 °F.

Penetration Index P.I.	Softening Point Ring & Ball Temperature $T_{R + B}$ (°F)	Volumetric Concentration of the Aggregate C_v	Pavement Thickness DF (in)	Number of Years	Crack Length Y_c (in)	CMDG1
2.0	125.6	0.85	2.0	6.0	0.2062	0.02743
				12.0	0.2064	0.0289
		0.90		6.0	0.2208	0.1282
				12.0	0.3338	0.4315
	100.4	0.85		6.0	0.2130	0.0409
				12.0	0.2135	0.0431
		0.90		6.0	0.2305	0.1042
				12.0	0.2714	0.2196
	125.6	0.85	5.0	6.0	0.2054	0.0142
				12.0	0.2066	0.01707
		0.90		6.0	0.2366	0.0939
				12.0	0.4251	0.3201
	100.4	0.85		6.0	0.2102	0.01945
				12.0	0.2120	0.02261
		0.90		6.0	0.2370	0.07550
				12.0	0.2807	0.1474
	125.6	0.85	8.0	6.0	0.204	0.0077
				12.0	0.2049	0.00947
		0.90		6.0	0.2282	0.0524
				12.0	0.3445	0.1731

TABLE D-7. Computation of CMDG1 Using Thermal Cracking Program for El Paso - continued.

The Average Annual Solar Radiation, SR = 516.0 Langleys/day.
The Average Annual Amplitude of Solar Radiation, SA = 212.3 Langleys/day.
THe Minimum Monthly Temperature, MMT = 30.2 °F.

Penetration Index P.I.	Softening Point Ring & Ball Temperature T_{R+B} (°F)	Volumetric Concentration of the Aggregate C_v	Pavement Thickness DF (in)	Number of Years	Crack Length Y_c (in)	CMDG1
	100.4	0.85		6.0	0.2072	0.01131
				12.0	0.2087	0.01377
		0.90		6.0	0.2294	0.04784
				12.0	0.2606	0.09037
-1.0	125.6	0.85	2.0	4.0	0.2000	0.0001
				8.0	0.2001	0.0001
		0.90		4.0	0.2029	0.0181
				8.0	0.2159	0.0822
	100.4	0.85		4.0	0.2000	0.0001
				8.0	0.2014	0.0066
		0.90		4.0	0.2002	0.0011
				8.0	0.2314	0.1077
	125.6	0.85	5.0	4.0	0.2001	0.0002
				8.0	0.2002	0.0005
		0.90		4.0	0.2079	0.0210
				8.0	0.2231	0.0614
	100.4	0.85		4.0	0.2000	0.0001
				8.0	0.2035	0.0065
		0.90		4.0	0.2010	0.0019
				8.0	0.2346	0.0765

TABLE D-7. Computation of CMDG1 Using Thermal Cracking Program for El Paso - continued.

The Average Annual Solar Radiation, SR = 516.0 Langleys/day.
The Average Annual Amplitude of Solar Radiation, SA = 212.3 Langleys/day.
THe Minimum Monthly Temperature, MMT = 30.2 °F.

Penetration Index P.I.	Softening Point Ring & Ball Temperature T_{R+B} (°F)	Volumetric Concentration of the Aggregate C_v	Pavement Thickness DF (in)	Number of Years	Crack Length Y_c (in)	CMDG1
	125.6	0.85	8.0	4.0	0.2001	0.0002
				8.0	0.2003	0.0005
		0.90		4.0	0.2054	0.0111
				8.0	0.2168	0.0330
	100.4	0.85		4.0	0.2001	0.0002
				8.0	0.2026	0.0043
		0.90		4.0	0.2008	0.0015
				8.0	0.2319	0.0533
0.0	125.6	0.85	2.0	4.0	0.2	0.0001
				8.0	0.2	0.0002
		0.90		4.0	0.2028	0.0176
				8.0	0.2167	0.0861
	100.4	0.85		4.0	0.2	0.0001
				8.0	0.2014	0.0066
		0.90		4.0	0.2002	0.0012
				8.0	0.2315	0.1079
	125.6	0.85	5.0	4.0	0.2	0.0001
				8.0	0.2002	0.0006
		0.90		4.0	0.2073	0.0202
				8.0	0.2267	0.0712

TABLE D-7. Computation of CMDG1 Using Thermal Cracking Program for El Paso - continued.

The Average Annual Solar Radiation, SR = 516.0 Langleys/day.
The Average Annual Amplitude of Solar Radiation, SA = 212.3 Langleys/day.
THe Minimum Monthly Temperature, MMT = 30.2 °F.

Penetration Index P.I.	Softening Point Ring & Ball Temperature T_{R+B} (°F)	Volumetric Concentration of the Aggregate C_v	Pavement Thickness DF (in)	Number of Years	Crack Length Y_c (in)	CMDG1
	100.4	0.85		4.0	0.2	0.0001
				8.0	0.2035	0.0065
		0.90		4.0	0.201	0.0018
				8.0	0.2348	0.0769
	125.6	0.85	8.0	4.0	0.2	0.0001
				8.0	0.2002	0.0005
		0.90		4.0	0.2050	0.0104
				8.0	0.2211	0.0409
	100.4	0.85		4.0	0.2	0.0001
				8.0	0.2026	0.0043
		0.90		4.0	0.2008	0.0015
				8.0	0.2320	0.0535

TABLE D-8. Computation of CMDG1 Using Thermal Cracking Program for Dallas.

The Average Annual Solar Radiation, SR = 399.0 Langleys/day.
The Average Annual Amplitude of Solar Radiation, SA = 181.0 Langleys/day.
THe Minimum Monthly Temperature, MMT = 35.70°F.

Penetration Index P.I.	Softening Point Ring & Ball Temperature T_{R+B} (°F)	Volumetric Concentration of the Aggregate C_v	Pavement Thickness DF (in)	Number of Years	Crack Length Y_c (in)	CMDG1
2.0	125.6	0.85	2.0	6.0	0.2	0.0002
				12.0	0.2007	0.004
		0.90		6.0	0.2149	0.0746
				12.0	0.2584	0.2459
	100.4	0.85		6.0	0.2003	0.00142
				12.0	0.2094	0.0330
		0.90		6.0	0.2074	0.0304
				12.0	0.2275	0.09977
	125.6	0.85	5.0	6.0	0.2003	0.0006
				12.0	0.2018	0.00465
		0.90		6.0	0.219	0.0530
				12.0	0.2767	0.1706
	100.4	0.85		6.0	0.2011	0.00194
				12.0	0.2112	0.02327
		0.90		6.0	0.2122	0.02643
				12.0	0.2396	0.08270
	125.6	0.85	8.0	6.0	0.2002	0.00044
				12.0	0.2014	0.00272
		0.90		6.0	0.2149	0.0295
				12.0	0.2569	0.0935

TABLE D-8. Computation of CMDG1 Using Thermal Cracking Program for Dallas - continued.

The Average Annual Solar Radiation, SR = 399.0 Langleys/day.
The Average Annual Amplitude of Solar Radiation, SA = 181.0 Langleys/day.
THe Minimum Monthly Temperature, MMT = 35.70°F.

Penetration Index P.I.	Softening Point Ring & Ball Temperature T_{R+B} (°F)	Volumetric Concentration of the Aggregate C_v	Pavement Thickness DF (in)	Number of Years	Crack Length Y_c (in)	CMDG1
	100.4	0.85		6.0	0.2009	0.00151
				12.0	0.2095	0.01594
		0.90		6.0	0.21	0.01764
				12.0	0.2347	0.05704
-1.0	125.6	0.85	2.0	4.0	0.2000	0.0001
				8.0	0.2000	0.0002
		0.90		4.0	0.2021	0.0112
				8.0	0.2093	0.0484
	100.4	0.85		4.0	0.2000	0.0001
				8.0	0.2005	0.0023
		0.90		4.0	0.2001	0.0004
				8.0	0.2195	0.0735
	125.6	0.85	5.0	4.0	0.2002	0.0003
				8.0	0.2003	0.0005
		0.90		4.0	0.2051	0.0125
				8.0	0.2143	0.0383
	100.4	0.85		4.0	0.2000	0.0001
				8.0	0.2016	0.0030
		0.90		4.0	0.2004	0.0008
				8.0	0.2232	0.0518

TABLE D-8. Computation of CMDG1 Using Thermal Cracking Program for Dallas - continued.

The Average Annual Solar Radiation, SR = 399.0 Langleys/day.
The Average Annual Amplitude of Solar Radiation, SA = 181.0 Langleys/day.
THe Minimum Monthly Temperature, MMT = 35.70°F.

Penetration Index P.I.	Softening Point Ring & Ball Temperature $T_{R + B}$ (°F)	Volumetric Concentration of the Aggregate C_v	Pavement Thickness DF (in)	Number of Years	Crack Length Y_c (in)	CMDG1
	125.6	0.85	8.0	4.0	0.2001	0.0003
				8.0	0.2002	0.0004
		0.90		4.0	0.2036	0.0070
				8.0	0.2105	0.0208
	100.4	0.85		4.0	0.2000	0.0001
				8.0	0.2012	0.0021
		0.90		4.0	0.2004	0.0007
				8.0	0.2178	0.0313
0.0	125.6	0.85	2.0	4.0	0.2	0.0001
				8.0	0.2	0.0001
		0.90		4.0	0.2013	0.0079
				8.0	0.2108	0.0566
	100.4	0.85		4.0	0.20	0.0004
				8.0	0.2005	0.0025
		0.90		4.0	0.2	0.0002
				8.0	0.2223	0.0816
	125.6	0.85	5.0	4.0	0.2	0.0001
				8.0	0.2002	0.0004
		0.90		4.0	0.2035	0.0094
				8.0	0.2155	0.0433

TABLE D-8. Computation of CMDG1 Using Thermal Cracking Program for Dallas - continued.

The Average Annual Solar Radiation, SR = 399.0 Langleys/day.
The Average Annual Amplitude of Solar Radiation, SA = 181.0 Langleys/day.
THe Minimum Monthly Temperature, MMT = 35.70°F.

Penetration Index P.I.	Softening Point Ring & Ball Temperature T_{R+B} (°F)	Volumetric Concentration of the Aggregate C_v	Pavement Thickness DF (in)	Number of Years	Crack Length Y_c (in)	CMDG1
	100.4	0.85		4.0	0.2	0.0001
				8.0	0.2017	0.0032
		0.90		4.0	0.2003	0.0005
				8.0	0.2247	0.0552
	125.6	0.85	8.0	4.0	0.2001	0.0001
				8.0	0.2002	0.0003
		0.90		4.0	0.2026	0.0052
				8.0	0.2121	0.02434
	100.4	0.85		4.0	0.2	0.0001
				8.0	0.2013	0.0023
		0.90		4.0	0.2003	0.0005
				8.0	0.2191	0.03326

APPENDIX E

Solar Radiation and Minimum Temperature Maps for Texas

APPENDIX E

Thermal fatigue of asphalt concrete pavement occurs because of daily variations in temperature and annual variations of solar radiation. The pavement design equation that was developed in this report represents these two effects with a minimum temperature and an "amplitude" of solar radiation.

The amplitude of solar radiation is the difference between the maximum and the mean solar radiation. In order to help in estimating this quantity for design purposes, two solar radiation maps are presented. Figure E1 gives the mean annual solar radiation and Figure E2 gives the maximum solar radiation which occurs in June in Texas. Both figures were taken from Reference E1.

For some areas of Texas, temperature data are not readily available and, at the present time, normal monthly minimum temperatures have not been compiled for many of the weather stations in the State that do collect temperature data. However, in (Ref. E2) normal monthly minimum temperatures are recorded for weather stations in 144 of Texas' counties. Those 144 counties are scattered generally over the State and offer a reasonable representation of the monthly minimum temperatures throughout the State. In each of those 144 counties, the lowest normal monthly minimum temperature is for January. Thus a map of January normal monthly minimum temperatures for Texas would serve as a map

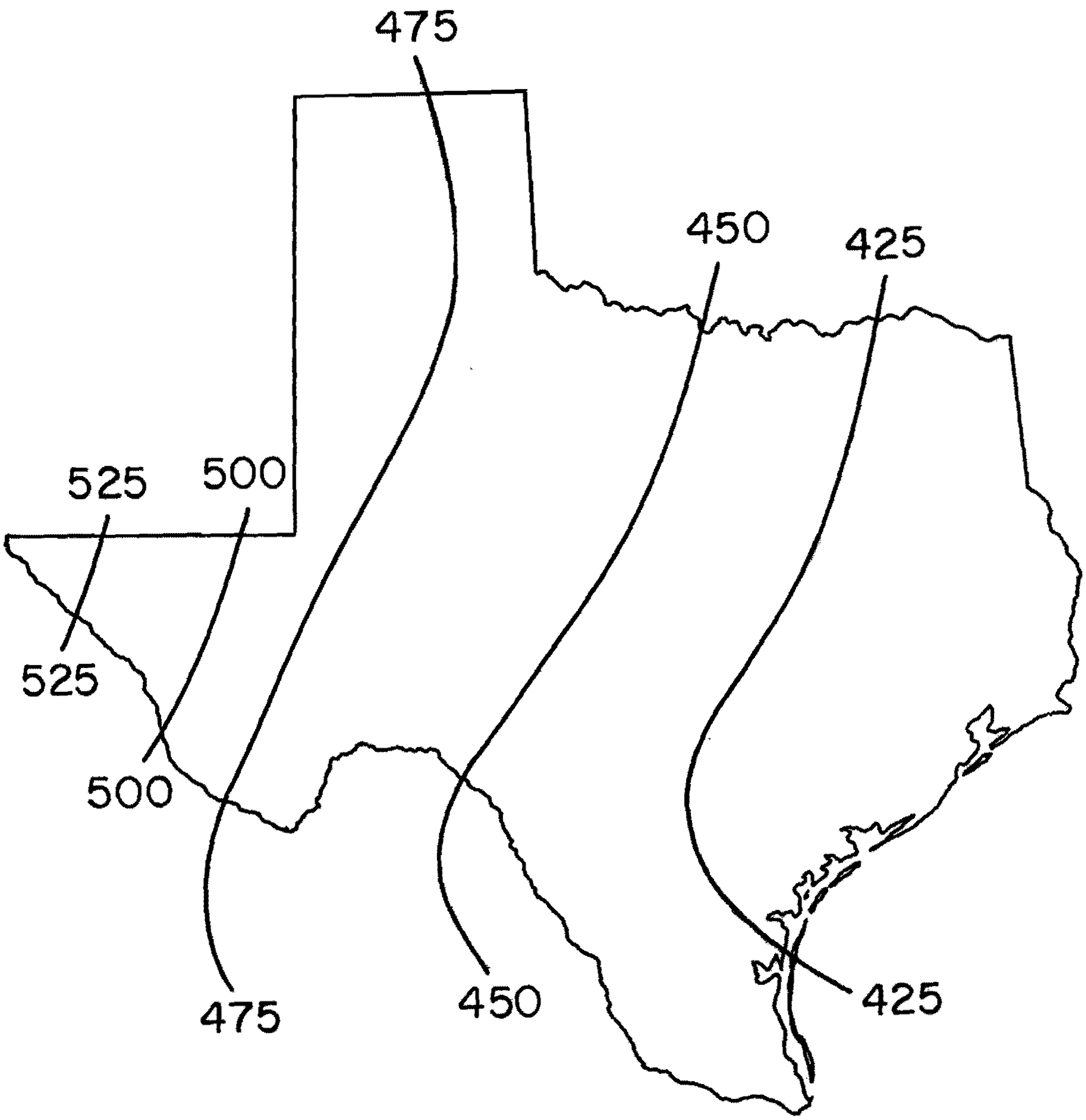


FIGURE E1. Average Annual Solar Radiation in Texas (Langleys/Day)

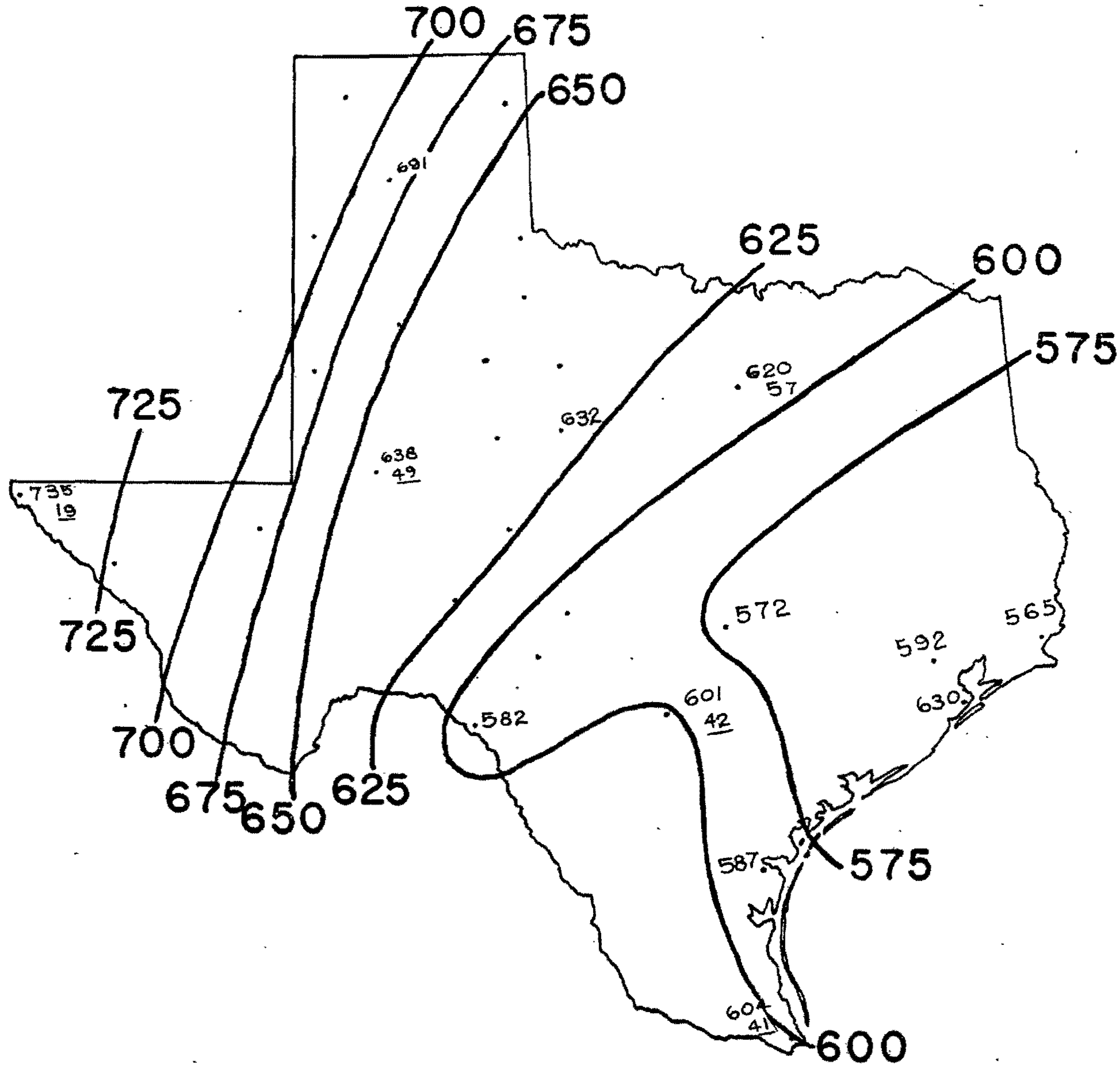


FIGURE E2. Mean Daily Solar Radiation For June in Langleys per Day.

of lowest monthly minimum temperatures. The map in Figure E3 was developed from a map (Ref. E3) of January mean minimum monthly temperatures based on data in the period 1931-1952.

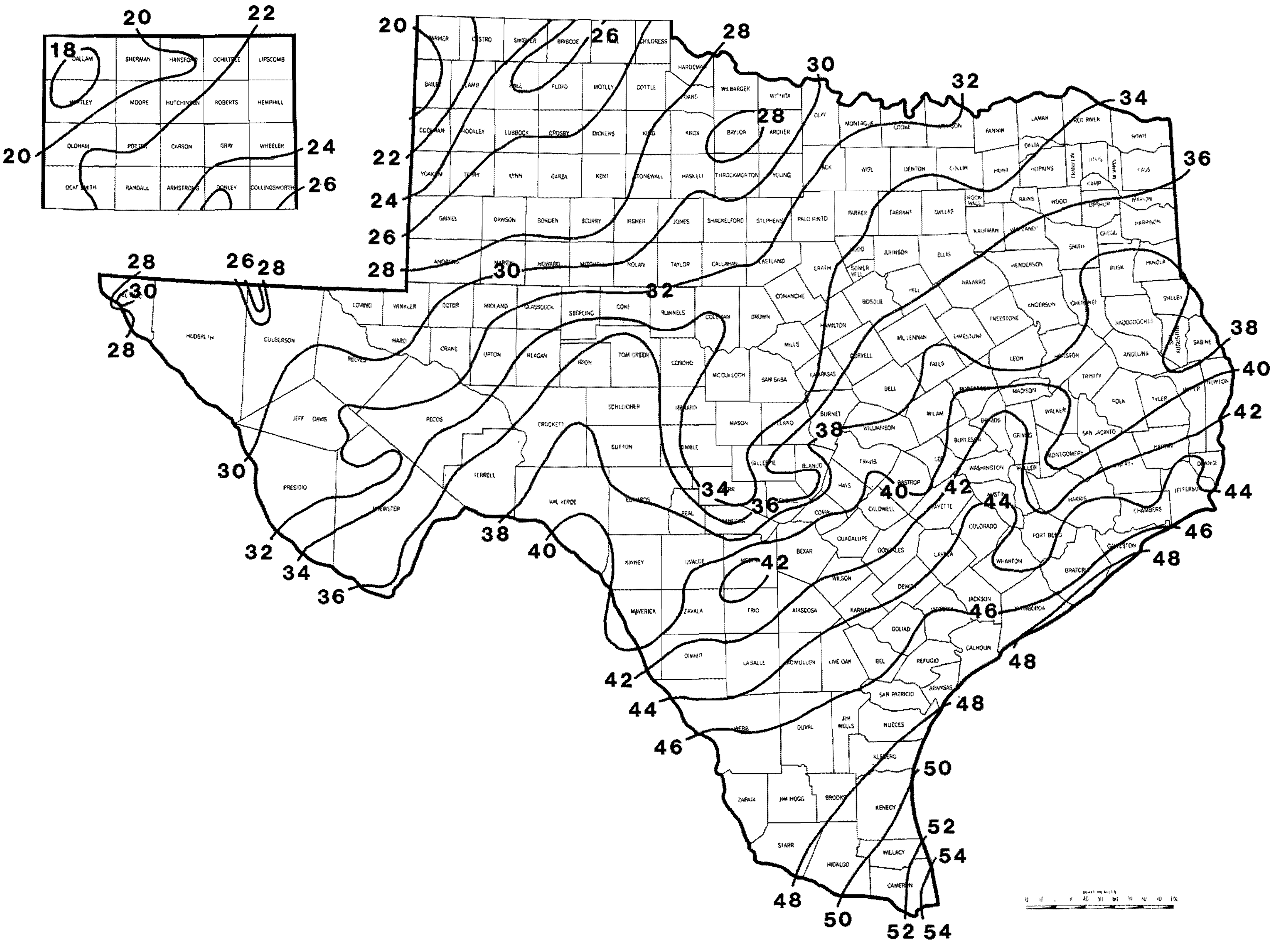


FIGURE E3. Lowest Normal Monthly Minimum Temperatures in Texas

REFERENCES

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