EFFECT OF TEMPERATURE ON THE ELASTIC RESPONSE OF ASPHALT TREATED BASE MATERIAL

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EFFECT OF TEMPERATURE ON THE ELASTIC RESPONSE OF ASPHALT TREATED BASE MATERIAL

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INTRODUCTION

This is the second report in the research project to determine equivalency factors of asphalt treated bases. It concerns the development of a parameter describing the mechanical behavior of asphalt treated base material for a specified range of stresses and temperatures. The first report was concerned with the development of such a parameter for a granular base material.

In order to establish equivalency factors for a black base (asphalt treated aggregate), it was proposed that the available solution of elastic three-layer systems be used (1). The justification for using an elastic solution was discussed in the Proposal for Research Project 68 E-42. To use this solution, the elastic parameters of pavement materials must be evaluated. A procedure to evaluate the elastic modulus of granular base material, using conventional triaxial apparatus, has been established and the measured quasi-elastic moduli of various types of granular base material (Michigan 22A) have been evaluated (2).

"The rheological or stiffness properties of asphalt and asphaltic concrete have been thoroughly investigated both in the United States and Europe. Although these investigations have shown that asphalt and asphaltic concrete are both time-of-loading and temperature dependent, they can be expected to act elastically for specific conditions. Thus, it is possible to analyze asphaltic mixtures according to the theory of elasticity for a given situation as represented by the modulus of elasticity or stiffness modulus" (3). Since the mechanical properties of asphaltic mixtures are temperature dependent, the temperature effect was investigated by measuring the elastic modulus of a bituminous mixture through a wide range of field temperatures. To indicate temperature dependency, the quasi-elastic modulus of a black base material will be denoted by E_t^*.

TESTING PROCEDURE

The testing procedure used to evaluate the quasi-elastic modulus of asphalt treated material, E_t^*, is similar to that used to evaluate the quasi-elastic modulus, E^*, of granular base material (2) with two main exceptions; 1) the stress level under which the test was conducted is different since stresses in a black base are considerably different from those developed in a granular base, 2) the test was conducted at various temperatures since the stiffness of asphalt treated material is temperature dependent.

Standard triaxial compression equipment was used in this study. The confining pressure and the axial load applied to test specimen were at levels which would induce stresses in the specimen similar and equal to the lateral stress and principal stress difference developed in the material under field loading conditions.

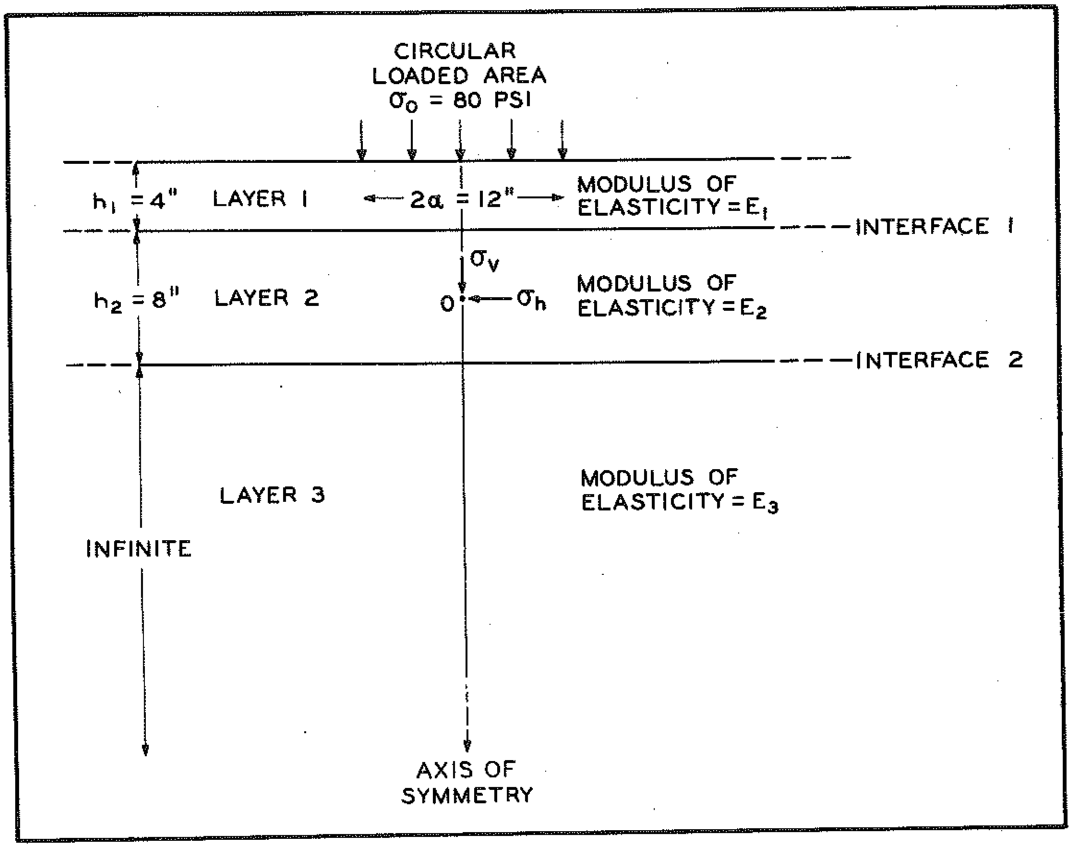

Figure 1. A model of pavement section.

Stresses In A Black Base

It is possible to estimate stresses in a black base layer by assuming that Burmister's analysis (4) is valid in this case and by using Jones' tables (5) of stresses in three-layer elastic systems. To determine the vertical and horizontal stresses at mid-height of a base layer in a typical pavement section (Fig. 1), values of the elastic moduli of the three layers must be assumed. The vertical and lateral stresses at mid-height of a black base layer due to 18 kip axle load (9 kip wheel load distributed over a 6-in. radius circular area at 80 psi pressure), and for different combinations of elastic moduli, are listed in Table 1.

To determine the total stresses in the base layer, the stresses due to the overburden material must be added to the vertical and lateral stresses given in Table 1. The vertical stress at mid-height of the base layer due to the overburden material is approximately 0.5 psi and the lateral stress is 0.25 psi (assuming that the lateral earth pressure at rest, K, is 0.5).

TABLE 1
STRESSES IN A BLACK BASE LAYER (FIGURE 1)
(σ_1 = vertical stress, σ_3 = lateral stress)

	E_2 = 30,000 Psi		E_2 = 59,000 Psi	
	σ_1, psi	σ_3, psi	σ_1, psi	σ_3, psi
E_1 = 200,000 psi E_3 = 10,000 psi	24.72	9.2	24.24	21.2
E_1 = 150,000 psi E_3 = 10,000 psi	27.36	10.08	26.56	22.03

According to Burmister's analysis, the stress in a pavement is a function of the thicknesses, moduli, and Poisson's ratios of the layers of the pavement. In order to simplify the procedure and to establish a standard testing method, stress levels for our tests were selected within the range of calculated field stresses. The tests were conducted at a confining pressure of 10 psi and an axial stress of 30 psi. Thus, the maximum principal stress difference is approximately 20 psi. The test was started with a hydrostatic stress of 1 psi, then the axial stress was increased, at a constant strain rate, to 30 psi, and the confining pressure to 10 psi, in such manner that both stresses reached their maximum values at the same time. The load was then released rapidly. The loading sequence was repeated through fifty cycles to include the effect of load repetition on modulus value. Test loading sequence simulated field loading conditions except for load duration and frequency which could not be simulated because of limitation in the capability of the laboratory equipment.

Test Temperatures

To determine temperature effect, the quasi-elastic modulus of asphalt treated aggregates, E_t^*, was measured through a wide range of temperatures, from subfreezing to a high of 120 F. The testing program, as far as temperature is concerned, can be categorized in three groups:

1. Lowered Temperature Testing: Tests at lowered temperatures were conducted by placing the triaxial apparatus and sample in a Cold Room for 24 hours to insure uniform temperature throughout the specimen, and the entire test conducted at low temperatures. The temperature in the Cold Room could be controlled within ±0.5 F. Thus, it was possible to conduct tests, at a constant temperature, in a range between 30 and 55 F. For tests conducted at temperatures lower than 32 F, the water in the triaxial cell and in the constant pressure system was replaced by ethylene glycol solution. A total of 18 tests were conducted at the lower temperatures.

2. Room Temperature Testing: A total of 14 tests were conducted at room temperatures ranging from 74 to 78 F.

3. Elevated Temperature Testing: Tests were conducted at higher than room temperatures by circulating heated water (at the desired test temperature) around the test specimen until the temperature at the center reached the required test value. At that stage the confining pressure was applied and the test conducted according to established procedure. Temperature variations during the entire test were limited to ± 1 F. A total of six tests were conducted in this range.

Sample Preparation

Samples tested in this study were obtained from the six-mile black base test section located on the northbound lane of I 75 near Roscommon. The bituminous mixture consisted of a "modified" 23A aggregate with 4-6 percent asphalt content (120-150 penetration asphalt).[1] Mixture samples were obtained directly from the paver. Temperature of the asphaltic mix was approximately 375 F at the plant and about 300 F at the paver. Test samples were compacted, at the field site, in a heated 4 by 8-in. cylinderical mold in five layers, using 56 blows of a 10-lb compaction hammer per layer. The number of layers and the required blows per layer were predetermined in the laboratory in order to obtain samples with densities approximating those attained in the field. All sampling equipment, including mold, plate, hammer, and spoons, was heated prior to and during the sampling operation. Table 2 compares the densities obtained in the mold with corresponding densities of core samples removed from the finished base.

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[1] The 23A Modified meets the present 23A specifications requirements, also it has a maximum of 2 Plasticity Index, and the sum of the Loss-by-Washing and Shale Material does not exceed 15 percent.

TABLE 2
DENSITIES OF COMPACTED SAMPLES AND CORE SAMPLES

Sample Location (Sta.)	Compacted Sample, lb/cu ft	Core Sample, lb/cu ft	Percent Field Density lb. cu ft
704 G	145.5	146.5	99.3
738 C	145.6	147.5	98.7
755 G	146.5	146.1	100.3
775 C	146.2	146.2	100.0
814 C	145.9	145.2	100.0
814 F	147.5	149.5	98.6
864 F	147.2	148.2	99.3
942 B	146.8	141.0	104.1
942 E	146.8	141.0	104.1
925 D	147.9	155.4	95.2
977 A	147.0	143.1	102.7
977 B	147.2	143.1	102.9
992 A	148.3	146.2	101.4
992 D	147.3	146.2	100.8

TEST RESULTS

A total of 38 tests were conducted on asphalt treated samples (black base) at various temperatures. The test temperatures included were within a range of the more dominant field temperatures. The test results are placed into three groups based on the range of test temperatures used:

1. Tests at Lowered Temperatures: A total of 18 tests were conducted at temperatures between 30 and 55 F. The quasi-elastic moduli of black base specimens in this range of temperatures are summarized in Table 3. The highest modulus value was approximately 170 x 10^3 psi at 30 F while the average modulus value at 55 F was approximately 60 x 10^3 psi.

2. Tests at Room Temperature: A total of 14 tests were conducted at room temperature. Test temperatures in this category ranged between 74

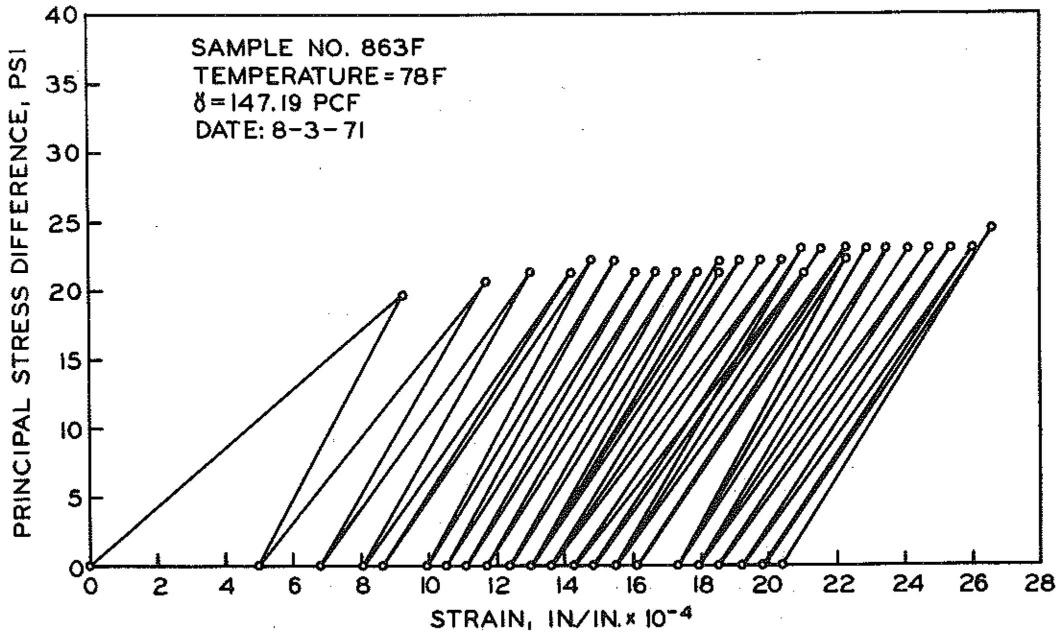

Figure 2. Typical stress-strain curve of test to evaluate E_t^*.

and 78 F. A typical stress-strain curve of a test conducted at room temperature is shown in Figure 2, and the corresponding calculated E_t^* for each load cycle is given in Table 4. The measured E_t^* for all tests conducted at room temperature ranged between 30 x 10^3 psi and 44 x 10^3 psi. Table 5 lists a summary of the measured moduli and the corresponding test temperatures for this group.

3. Tests at Elevated Temperatures: A total of six tests were conducted at elevated temperatures between 100 and 120 F. A summary of the E_t^* moduli, measured at the higher temperatures, is given in Table 6. The lowest modulus value was approximately 25 x 10^3 psi at 120 F.

A plot of E_t^* versus temperature for all tests is shown in Figure 3.

The curve that best fits these points represents an exponential function of the following form:

$$E_t^* = e^{aT+b} \tag{1}$$

where E_t^* is the quasi-elastic modulus in psi, at temperature T, and T is the temperature in deg F. The parameters a and b for this type of black base (23A + 6 percent asphalt), and for these specific test conditions (range

TABLE 3
QUASI-ELASTIC MODULUS OF BLACK BASE MATERIAL AT LOWERED TEMPERATURES

Sample Location (Sta.)	Density, lb/cu ft	Asphalt Content, percent	E_t^*, psi	Test Temp., F
704 G	145.5	4.7	85,365	40
755 G	146.5	4.5	87,643	40
738 C	145.6	4.9	78,608	40
775 C	146.2	4.7	94,456	40
814 C	145.9	4.7	80,887	40
814 F	147.5	4.7	86,901	40
863 F	147.2	4.6	84,128	40
942 B	146.8	4.7	92,356	38
942 E	146.8	4.7	68,808	40
925 D	147.9	4.8	87,301	40
977 A	147.0	4.7	87,990	40
977 B	147.2	4.7	93,107	40
992 A	148.3	4.7	85,617	40
992 D	147.3	4.7	70,265	40
755 G	146.5	4.5	168,952	30
863 F	147.2	4.6	56,920	55
977 A	147.0	4.7	64,787	55
925 D	147.9	4.8	61,092	55

TABLE 4
TYPICAL TEST RESULTS (TEST NO. 863 F at T = 78 F)

Cycle	E_t^*, psi	Cycle	E_t^*, psi	Cycle	E_t^*, psi
1	45,851	18	39,899	35	33,794
2	41,714	19	32,643	36	37,173
3	43,313	20	35,905	37	37,173
4	38,496	21	34,622	38	35,891
5	44,909	22	37,187	39	34,609
6	44,906	23	37,185	40	37,173
7	38,488	24	37,185	41	33,792
8	38,486	25	37,182	42	32,626
9	43,297	26	37,182	43	37,171
10	38,484	27	37,182	44	37,168
11	38,481	28	37,182	45	37,168
12	35,914	29	35,900	46	37,168
13	38,479	30	41,311	47	37,168
14	39,904	31	37,178	48	37,168
15	39,901	32	35,896	49	36,118
16	35,909	33	33,796	50	38,448
17	35,909	34	35,893	Avg. cycle 46 to 50 = 37,214 psi	

TABLE 5
QUASI-ELASTIC MODULUS OF BLACK BASE MATERIAL AT ROOM TEMPERATURE

Sample Location (Sta.)	Density, lb/cu ft	Asphalt Content, percent	E_t^*, psi	Test Temp., F
942 B	146.8	4.7	35,985	74
977 A	147.0	4.7	42,687	76
992 D	147.3	4.7	36,160	76
977 B	147.2	4.7	32,563	76
814 C	145.9	4.7	43,841	75
925 D	147.9	4.8	42,837	74
755 G	146.5	4.5	44,323	77
814 F	147.5	4.7	41,144	78
863 F	147.2	4.6	37,215	78
704 G	145.5	4.7	40,403	77
775 C	146.2	4.7	30,886	76
992 A	148.3	4.7	40,486	76
738 C	145.6	4.9	35,718	77
942 E	146.8	4.7	34,262	76

TABLE 6
QUASI-ELASTIC MODULUS OF BLACK BASE MATERIAL AT ELEVATED TEMPERATURES

Sample Location (Sta.)	Density, lb/cu ft	Asphalt Content, percent	E_t^*, psi	Test Temp., F
814 C	145.9	4.7	27,883	100
977 A	147.0	4.7	27,799	100
863 F	147.2	4.6	26,565	100
755 G	146.5	4.5	25.612	120
942 B	146.8	4.7	25,013	120
992 A	148.3	4.7	24,829	120

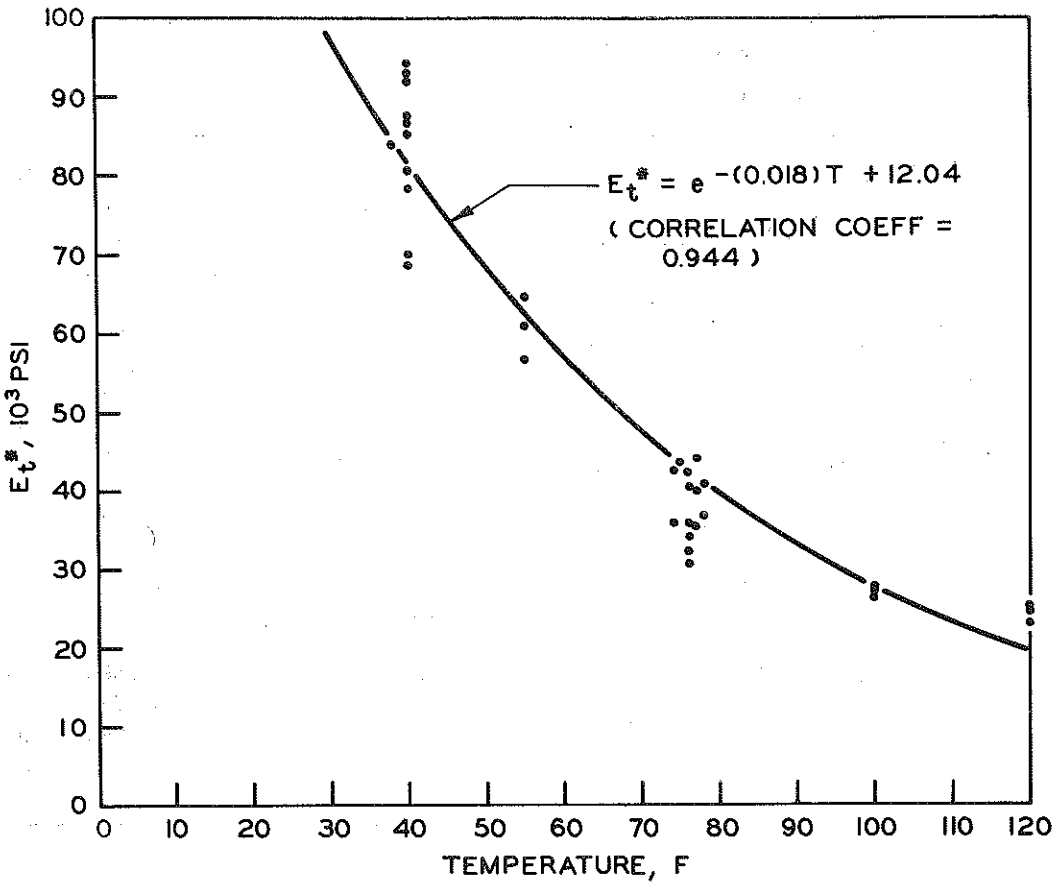

Figure 3. Quasi-elastic modulus of black base material versus temperature.

of density, stress level, and temperature range) are (-0.018) and (12.04), respectively, for which values equation (1) becomes:

$$E_t^* = e^{-(0.018)T + 12.04} \tag{2}$$

Equation (2) is valid for 30 F $\leq$ T $\leq$ 120 F.

PAVEMENT TEMPERATURE

The mechanical properties of bituminous paving mixtures are temperature dependent. Temperature distribution in a flexible pavement depends on the thermal conductivity of the asphalt mixture, time, and the surface temperature. The surface temperature of a pavement is dependent on climatic parameters such as air temperature and solar energy (6). Solar energy varies seasonally and according to atmospheric conditions, so that such energy received by the pavement is a function of solar radiation and the characteristics of the pavement surface, i.e., color, texture, etc.

There is no available record of the amount of monthly solar radiation. In this study air temperature is considered to be the main factor affecting surface temperature of a pavement. Typical maximum temperature-depth relationships for asphalt-bound materials, for various air temperatures, were published by Dorman and Metcalf (7) and are shown in Figure 4.

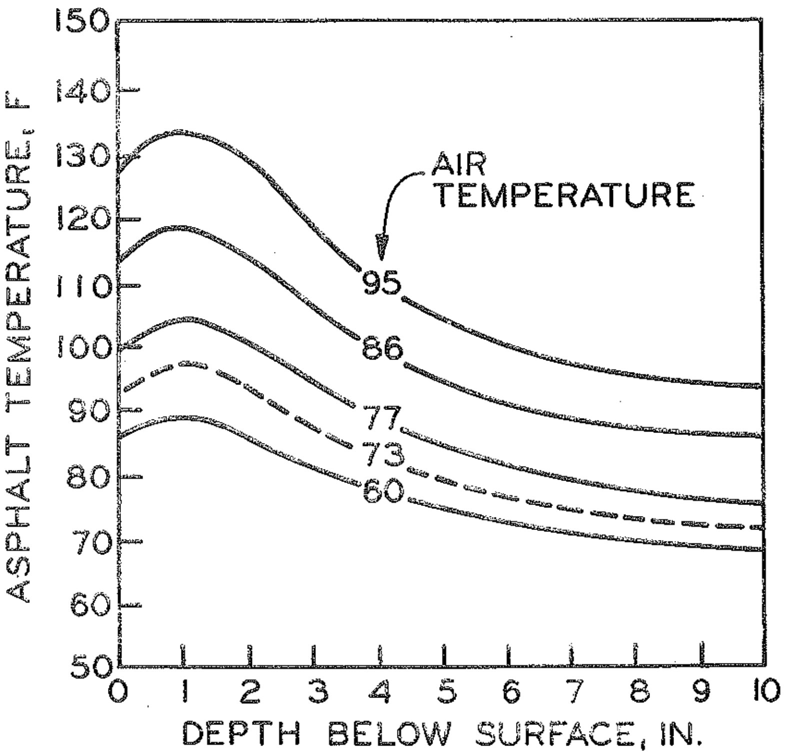

Figure 4. Relation of temperature of asphalt surface to depth below surface. (After Dormon and Metcalf (7)).

Actual pavement temperature profile of a 19-in. asphalt pavement (Bishop Airport, Flint, Michigan (8)) for a twenty-four hour period, is shown in Figure 5. These field data agree closely with the generalized temperature-depth curves proposed by Dormon and Metcalf, and in this study these temperature-depth relationships are assumed valid for the range of air temperature considered.

Although the deformation of a bituminous mixture is temperature dependent, the added consideration of temperature as a variable in the analysis of a pavement structure makes the analysis problem too complex. Thus,

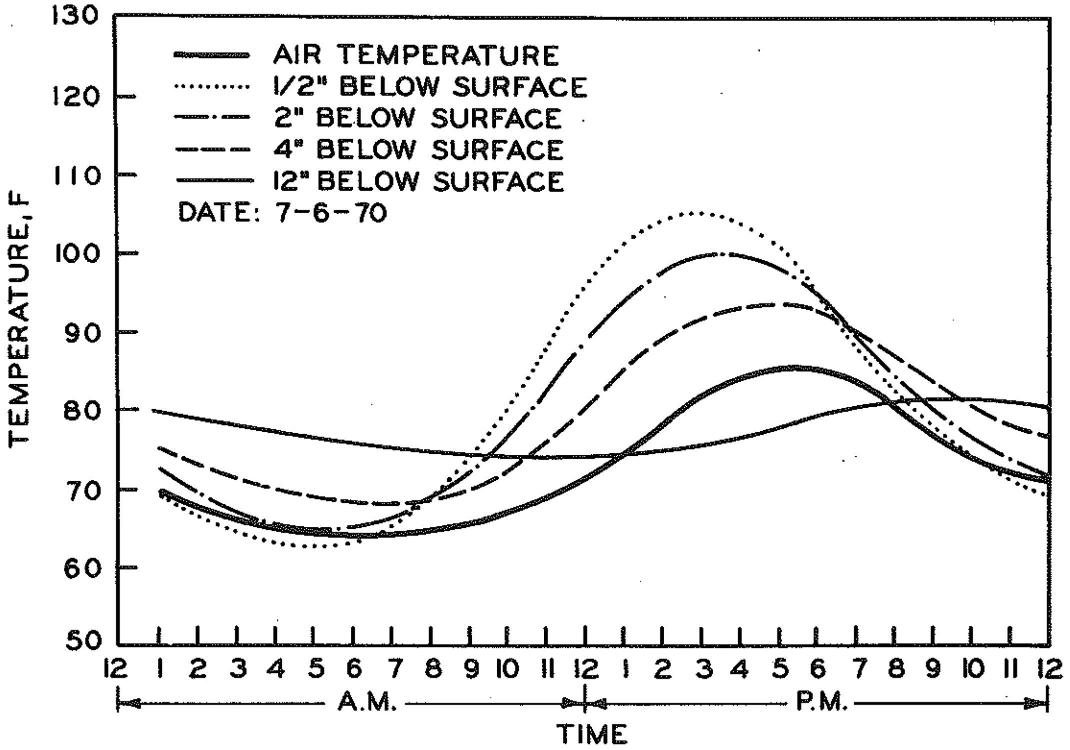

Figure 5. Pavement temperature profile for 24 hour period.

there is a need to establish a "most appropriate" design temperature for asphaltic mixtures. This temperature would have a regional dependence. The test sections for Research Project 68 E-42 are located between Roscommon and Grayling on I 75. Table 7 summarizes the monthly climatological data for the Grayling area during the last ten years (1962-1971). These data are presented in terms of the Average Minimum, Average, and Average Maximum monthly temperatures. Table 7 indicates that, in general, the average monthly temperatures of May through October are higher than the average annual temperature. Figure 5 shows that pavement temperature reaches its maximum value late in the afternoon when the air temperature also reaches a maximum. Actually, there is a lag between the two maximums due to absorbed solar energy. Thus, the average maximum temperature of the warmer months of the year are of critical value in evaluating the stiffness of the bituminous pavements. The average maximum temperature for the warmer months (May through October) for a ten-year period (1962-1971) is 72.7 F for the vicinity of Grayling. It seems reasonable to consider this temperature, approximately 73 F, as the most appropriate air temperature to be used in evaluating the modulus of black base in the Grayling area.

TABLE 7
CLIMATOLOGICAL DATA - (Grayling, Michigan)

Year	Temp, F	Month												Avg Annual	Avg Max May-Oct
		Jan	Feb	March	April	May	June	July	Aug	Sept	Oct	Nov	Dec		
1962	Avg Min	9.1	5.2	18.4	31.0	47.4	50.0	52.0	53.5	44.5	40.0	26.6	14.4	43.5	72.0
	Average	16.5	15.1	29.1	43.0	60.0	63.5	65.0	66.1	55.7	49.5	35.1	22.7		
	Avg Max	23.8	25.0	39.8	54.9	72.6	77.0	77.9	78.7	66.9	58.9	43.6	30.9		
1963	Avg Min	3.5	-0.2	17.7	31.8	38.4	51.9	56.0	51.2	44.4	44.2	33.0	10.9	43.4	73.8
	Average	11.3	10.8	29.4	45.8	52.1	66.2	68.8	62.8	57.4	57.3	40.4	18.6		
	Avg Max	19.0	21.7	41.1	59.8	65.7	80.5	81.5	74.3	70.3	70.3	47.8	26.2		
1964	Avg Min	14.8	11.8	17.7	32.4	45.8	49.6	55.8	50.9	46.0	34.3	30.5	14.0	45.0	72.7
	Average	23.5	22.2	28.2	44.9	59.3	64.0	69.4	63.3	57.4	46.0	39.8	21.8		
	Avg Max	32.1	32.5	38.6	57.3	72.8	78.4	82.9	75.6	68.8	57.7	49.1	29.5		
1965	Avg Min	8.3	10.1	13.9	28.1	45.0	48.9	52.1	54.1	48.3	37.7	29.0	23.0	43.4	70.9
	Average	17.0	19.2	23.6	39.4	59.0	62.2	64.7	64.9	58.0	47.3	36.1	29.0		
	Avg Max	25.7	28.2	33.3	50.7	72.9	75.4	77.2	75.6	67.6	56.8	43.2	34.9		
1966	Avg Min	5.4	13.9	24.3	29.7	36.5	53.0	58.0	55.4	46.3	37.5	28.5	16.6	44.1	71.5
	Average	14.8	22.3	33.8	40.1	49.0	66.5	71.9	66.5	57.8	46.4	35.5	23.7		
	Avg Max														
1967	Avg Min	16.1	4.8	17.0	31.6	36.0	54.6	53.1	49.9	42.0	36.4	25.2	18.1	43.0	70.7
	Average	23.3	15.4	28.8	43.8	49.1	66.9	65.6	62.9	57.6	46.2	30.9	25.3		
	Avg Max	30.4	26.0	40.6	55.9	62.1	79.1	78.1	75.8	73.1	56.0	36.5	32.5		
1968	Avg Min	8.9	1.3	21.5	33.8	38.1	50.3	54.8	53.9	50.4	40.1	28.5	14.4	43.9	71.8
	Average	17.5	13.5	33.3	46.4	50.8	62.7	67.4	67.5	61.3	49.7	35.4	21.8		
	Avg Max	26.0	25.6	45.0	59.0	63.5	75.0	79.9	81.0	72.2	59.3	42.2	29.1		
1969	Avg Min	13.2	8.8	13.4	31.1	39.6	45.6	53.7	53.2		35.7		13.9	42.8	71.3
	Average	19.9	20.1	25.3	43.8	53.7	58.4	67.5	68.1		44.5		20.9		
	Avg Max														
1970	Avg Min	3.7	4.8	12.4	30.2	42.9	49.7	57.6	53.4			28.3	16.4	41.3	78.1
	Average	12.2	15.7	23.9	43.2	55.7	64.4	70.6	67.3			35.8	24.2		
	Avg Max	20.6	26.5	35.3	56.1	68.4	79.0	83.6	81.2			43.3	31.9		
1971	Avg Min	6.7	8.4	12.6	26.7	36.8	53.2	51.6	50.6	50.6	44.7	26.9	19.4	43.8	74.5
	Average	15.2	18.3	24.3	38.9	52.1	67.8	65.4	64.5	61.8	55.7	35.0	26.6		
	Avg Max	23.7	28.1	35.9	51.0	67.4	82.4	79.2	78.4	73.0	66.7	43.0	33.7		

Avg Max 1962-1971 72.7 May-Oct

DISCUSSION

The temperature distribution in a black base pavement, corresponding to an air temperature of 73 F, is shown in Figure 6. This figure also shows the quasi-elastic modulus of black base material versus depth, corresponding to the indicated temperature profile. The quasi-elastic modulus for the various temperatures was established according to Equation 2 (or Fig. 3). The quasi-elastic modulus of black base material ranged between 38×10^3 psi at the top of the base layer to a value of 44×10^3 psi at the bottom of the base (average E^* for the base layer is 41×10^3 psi), while the modulus at mid-height is 42×10^3 psi.

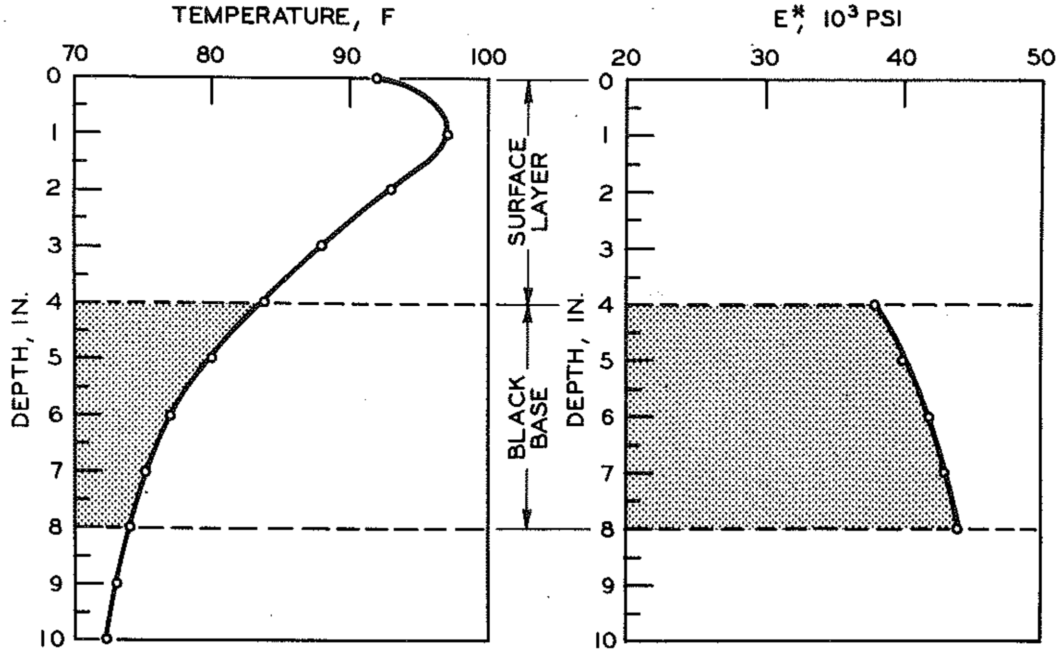

Figure 6. Temperature profile and E_t^* versus depth in a black base section.

There is no analytical solution available of heat transfer in a pavement so reliance must be placed on field measurements. The assumption that pavement temperature is a function of air temperature is a simplifying approach. In addition to temperature, another major factor that influences the value of the elastic modulus of bituminous mixtures is the stress level at which the modulus was measured. Evaluating the elastic modulus as a function of stress would give a rather complicated function that could not be implemented until a new solution considering such functions is found. Since stress changes with depth, the elastic modulus is also a function of depth. Therefore, determining the modulus at a stress level comparable to the level developed in the field at a specific depth, such as mid-height of the base layer, puts a limitation on the applicability of such a value. The developed value of the modulus should be considered valid for the range of stress under which the recoverable strain was measured, since the modulus is developed on the incremental elastic component of strain. The restrictions on the applicability of the values of the developed modulus are also true for the range of temperatures considered. The two major assumptions, concerning stress level and temperature profile in a base layer, were primarily used in this study to simplify the problem to an extent that the use of an available solution of an elastic-layered system is possible. The developed modulus values should not be generalized to a wider range of stresses or temperatures without further study and evaluation.

CONCLUSIONS

1. The procedure developed in this study to determine the quasi-elastic modulus of a bituminous mixture is valid for the range of stresses and temperatures to which the material is exposed in the field.

2. Values of the quasi-elastic modulus developed are applicable to the type of black base mixture used in the field portion of this project (23A + 4-6 percent asphalt, 120-150 penetration). The same procedure can be used to evaluate the quasi-elastic modulus of other types of bituminous mixtures as the need arises.

3. The quasi-elastic modulus of a black base material is represented by the following equation:

$$E_t^* = e^{aT+b} \text{ - - - - - - - - - - - - - - - - - - } \text{for } 30 \text{ F} \leq T \leq 120 \text{ F}$$

where the parameters a and b are (-0.018) and (12.04), respectively, for a mix of modified 23A and 4-6 percent of 120-150 penetration asphalt.

4. For an average maximum air temperature of 73 F, the temperature at mid-height of a black base layer is approximately 77 F, which corresponds to a quasi-elastic modulus of 42 x 10^3 psi.

5. Equation 2 may be used to evaluate E_t^* for any type of black base mixture and any region as long as the parameters a and b are evaluated for the specific type of mix used, and the most appropriate temperature for the region is determined.

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