200 000 cycles respectively, and at the 65 percent stress level, these values are 200 000 and 1 700 000 cycles respectively. The difference in the fatigue lives of the two concretes at 70 percent of the modulus of rupture is 130 000 cycles, and at 65 percent, it is 1 500 000 cycles. The lower stress ranges are crucial with respect to pavement design, which makes this divergence of critical importance.

CONCLUSIONS

1. The fatigue behavior of plain concrete in flexure is affected by its air content. Fatigue strength decreases as air content increases.
2. The modulus of rupture, the compressive strength, the modulus of elasticity, and the unit weight of concrete all decrease as the air content of the concrete increases.
3. As the air content increases, the failure of concrete subjected to fatigue occurs increasingly at the interface of the aggregate and the cement paste. On a macroscopic level, the fatigue failure surface is similar to the modulus-of-rupture (static) failure surface.

ACKNOWLEDGMENTS

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REFERENCES

1. G. M. Nordby. Fatigue of Concrete: A Review of Research. Journal of the American Concrete Institute (ACI, Proc. Vol. 55), Vol. 30, No. 2 Aug. 1958, pp. 191-219.
2. W. K. Hatt. Fatigue of Concrete. HRB, Proc. Vol. 4, 1924, pp. 47-60.
3. H. F. Clemmer. Fatigue of Concrete. ASTM, Proc. Vol. 22, Pt. 2, 1922, pp. 409-419.
4. C. Older. Highway Research in Illinois. Trans., ASCE, Vol. 87, 1924, pp. 1180-1222.
5. Thickness Design for Concrete Pavements. PCA, Skokie, IL, 1966.
6. G. E. Troxell, H. F. Davis, and J. W. Kelly. Composition and Properties of Concrete. McGraw-Hill, New York, 1968.
7. W. N. Carey and P. E. Irick. Relationships of AASHO Road Test Pavement Performance to Design and Load Factors. HRB, Special Rept. 73, 1962, p. 259.
8. W. R. Hudson and B. F. McCullough. An Extension of Rigid Pavement Design Methods. HRB, Highway Research Record 60, 1964, pp. 1-14.
9. G. K. Ray, E. G. Robbins, and R. G. Packard. Concrete Pavement Design Today. Proc., ASCE Conference on Pavement Design for Practicing Engineers, Atlanta, GA, 1975, pp. 1-2.
10. G. K. Ray. History and Development of Concrete Pavement Design. Journal of the Highway Division, Proc., ASCE, Vol. 90, No. HW1, Jan. 1964, pp. 79-101.
11. A. S. Vesic and S. K. Saxena. Analysis of Structural Behavior of AASHO Road Test Rigid Pavements. NCHRP, Rept. No. 97, 1970.
12. E. J. Yoder and M. W. Witczak. Principles of Pavement Design. Wiley, New York, 1975.
13. W. Lerch. Basic Principles of Air-Entrained Concrete. PCA, Skokie, IL, 1953, p. 36.
14. G. W. Hollen and M. E. Prior. Factors Influencing Proportioning of Air-Entrained Concrete. ACI, Publ. SP-46, 1974.
15. C. E. Wuerpel. Purposeful Entrainment of Air in Concrete. Hercules Powder Company, Wilmington, DE, 1970.
16. L. E. Gregg. Experiments With Air-Entrainment in Cement Concrete. Kentucky Department of Highways, Bull., No. 5, Sept. 1947.
17. J. DeC. Antrim and J. F. McLaughlin. Fatigue Study of Air-Entrained Concrete. Journal of the American Concrete Institute (ACI, Proc. Vol. 55), Vol. 30, No. 11, May 1959, pp. 1173-1182.
18. D. Y. Lee, F. W. Klaiber, and J. W. Coleman. Fatigue Behavior of Air-Entrained Concrete. Engineering Research Institute, Iowa State Univ., Ames; Iowa Department of Transportation, Final Rept., July 1977.

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Pavement-Layer Modular Ratios From Dynaflect Deflections

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Pavement systems and individual layers were evaluated by using the deflections obtained with the Dynaflect device. The pavements were considered to be three-layer systems, and the deflection data were used to estimate ratios of the elastic moduli of the adjacent layers (K1 and K2). These ratios reduce the system from three values of elastic modulus to two values of modular ratio. Certain assumptions were made related to pavement factors that affect deflections and also the elastic modulus of the asphalt concrete layer (E1). A graphical trial-and-error procedure was used to match the surface deflections calculated by using the Chevron program for the Dynaflect load with the actual deflections measured on

the roadway. The results obtained were related to (a) time-of-year effects, (b) range of values of K1 and K2, (c) effects of the assumed value of E1 on the estimated values of the moduli of the base and subbase (E2 and E3 respectively), (d) effects of elevation on E1/E2 (i.e., K1), and (e) suggested modification of the locations of the Dynaflect geophones.

The Highway Division of the Arizona Department of Transportation (ADOT) is developing a design procedure for flexible pavements based on three-layer elastic theory for the control of stress and strain. The basic concepts involved in the procedure have been given elsewhere (1) as have improved definitions of the material characteristics and vehicular loadings used (2). This paper will begin with a discussion of the methods used for the computation of stresses and strains.

The design procedure is based on fatigue considerations and related to the radial tensile stress at the bottom of the asphalt concrete surface course and the vertical compressive strain on the top of the subgrade. It is assumed that there is a singular value—K1—of the ratio of the modulus of the asphalt concrete layer (E1) to the modulus of the base layer (E2) (i.e., K1 = E1/E2) and an analogous ratio—K2—of the modulus of the base layer to the modulus of the subbase layer (E3) (i.e., K2 = E2/E3) and that K1 = 10. This singular-value assumption is based on the concept that the radial stress depends primarily on K1, rather than on the absolute value of E1. Because the surface course is manufactured, it is assigned a constant E1-value of 1.38 GPa (200 000 lbf/in^2). To account for environmental effects, E1 only is modified by a temperature-related factor that varies linearly with the elevation.

The value of E3 can be obtained from physical measurements of the subgrade soil. At present, E3 is obtained by correlation rather than by a direct method. The effects of environment on E3 are included through the use of a factor related to rainfall that also varies linearly with elevation in Arizona.

An opportunity to verify these assumptions and others arose in 1974 when ADOT initiated a research program entitled "Environmental Factor Determination From In-Place Temperature and Moisture Measurements Under Arizona Pavements." At many of the test sites, Dynaflect deflections were made at various times during the year. A portion of these data have been studied to measure the change of layer modulus with time of year and to compare the relative stiffnesses of the pavement layers.

DYNAFLECT SITES AND TEST PROCEDURE

The Dynaflect device was first described by Scrivner and Moore (3) in 1964; in 1966, Scrivner and others (4) described modifications and some results obtained in field measurements. Its recent use for the characterization of pavement systems has been reported by Scrivner and others (5), Peterson and others (6), and Lai (7).

Location of Sites

From a description of the test sites for the ADOT study, 10 locations were selected on the bases that they generally could be treated as three-layer systems and provided a representative range of elevation and rainfall conditions. A description of the test sites and a record of the dates on which the deflection measurements were made are given in Table 1. (Note that the base and subbase will be considered as one layer.)

Testing and Sampling

The pavement loading and the sampling of the surface course were performed by personnel from ADOT. For each location, Dynaflect deflections were obtained at five different places along the length of the test site, pavement temperature was measured, the surface course was sampled, and other information was obtained.

The loading of the pavement was the standard peak load of 2.22 N (500 lbf) on each of two wheels 0.51 m (20 in) apart. The load was applied at 8 Hz and assumed to be over a circle 3.58 cm (1.41 in) in radius and at a contact pressure of 550 kPa (80 lbf/in^2).

The pavement deflections were detected by five geophones spaced 0.30 m (1 ft) apart; the first one (G1) was located midway between the load wheels, and the others (G2-G5) extended parallel to the lane line.

The deflection curve was based on an average for each geophone that was developed by discarding those measurements that deviated from the average by more than 15 percent. In general, each average is based on three to five measurements. There was no attempt to apply a temperature correction to the deflection curves.

CHARACTERISTICS OF DEFLECTION CURVES

The stress criterion on the surface course was selected because it is independent of the modulus of elasticity of the material; rather, it is dependent on K1 (1). The values of E1 and E2 were selected partly on the basis of limiting K2 (E2/E3) to a maximum of about 4.

Burmister's (8) results, which are given as curves for the calculation of surface deflection of two-layer systems, show deflection factors to be dependent on modular ratios. Because the pavement design procedure depends on modular ratios and because Burmister's deflection factors are also dependent (to an appreciable

Table 1. Dynaflect test sites.

Site Identification	Location	Route	Section	Direction	Milepost	Layer Thickness (cm) Asphalt	Base	Subbase	Elevation (m)	Rainfall (cm)	Date Deflection Measured January 1974	May 1974	October 1974
D1	Benson	I-10	5(7)	Westbound	300	7.6	10.2	35.6	1240	30.5	Yes	Yes	Yes
D2	Alpine	US-180	S269(2)	Eastbound	427	17.2	0	17.8	2420	50.8		Yes	
D3	Avondale	US-80	S371(1)	Eastbound	183	12.7	10.2	20.3	303	17.8			Yes
D4	Topock	I-40	1(8)	Westbound	0.43	10.2	10.2	22.9	152	10.2			Yes
D5	Winona	I-40	4(69)	Westbound	212	10.2	7.6	22.9	2140	50.8	Yes	Yes	Yes
D6	Deer Valley	I-17	1(56)	Northbound	223	7.6	10.2	30.5	499	25.4	Yes	Yes	Yes
D7	Casa Grande	I-10	3(59)	Eastbound	196	15.3	10.2	45.8	366	20.3	Yes	Yes	Yes
D8	Sybil Road	I-10	6(27)	Westbound	311	7.6	10.2	61.0	1435	30.5	Yes	E.B.	Yes
D9	Gila Bend	I-8	2(18)	Eastbound	113	19.7	10.2	10.2	221	15.3		Yes	Yes
D10	Globe-Cutter	US-70	FLH13A-1	Eastbound	258	7.6	5.1	40.7	975	40.7		Yes	Yes
D11	Marana	I-10	4(27)	Eastbound	235	7.6	25A[a]	12.7	597	28.0	Yes	Yes	Yes

Note: 1 m = 3.3 ft.

[a]Includes 15.3-cm (6-in) cement-treated base.

extent) on modular ratios, it is now being assumed that Dynaflect deflections are primarily dependent on K1 and K2 for a three-layer system. If K1 and K2 can be estimated from Dynaflect deflections, then E2 and E3 can be obtained for the new design procedure because the value of E1 is fixed.

The values of K1 and K2 were determined through a graphical trial-and-error procedure described below:

By using the Chevron computer program (9), a family of 20 surface deflection curves corresponding to the Dynaflect loading was obtained for each particular pavement cross section. The elastic material properties used are given below (1 GPa = 145 000 lbf/in²):

Property	Value
E1, GPa	1.38
Poisson's ratio	
$\mu 1$	0.35
$\mu 2$	0.45
$\mu 3$	0.50
K1	1-20
K2	1-5

When K1 = 1 or K2 = 1, this does not give a homogeneous or a two-layer system because Poisson's ratio is a variable. In these curves, the logarithm of the vertical deflection of each geophone was plotted against the radial distance of the geophone from one wheel.

The average geophone deflection values were plotted on transparent paper and to the same scale as the family of curves obtained from the calculations. The measured deflection curve was then superimposed on the family of curves to obtain a first estimate of the values of K1 and K2. From these values of K1 and K2, a new deflection curve was calculated and compared with the field curve to obtain a second (and improved) estimate of K1 and K2. The procedure was repeated 3 or 4 times until the calculated and measured deflection curves were in close agreement.

The effects of K1 and K2 on the shapes and positions of the calculated deflection curves are illustrated in Figure 1. The principal effect of K2 is on the slopes of the curves and that of K1 is on the position of the curves. Figure 2 shows the completed solution for K1 and K2 of test site D11.

RESULTS AND DISCUSSION

The values of K1 and K2 obtained for the test sites are shown in Table 2. All deflection curves were calculated by assuming that E1 = 1.38 GPa; however, two sites (D6 and D9) were also investigated by assuming that E1 = 5.52 and 0.345 GPa (800 000 and 50 000 lbf/in²). The data presented in the table indicate the following results.

Figure 1. Effects of K1 and K2 on shape and position of calculated deflection curves.

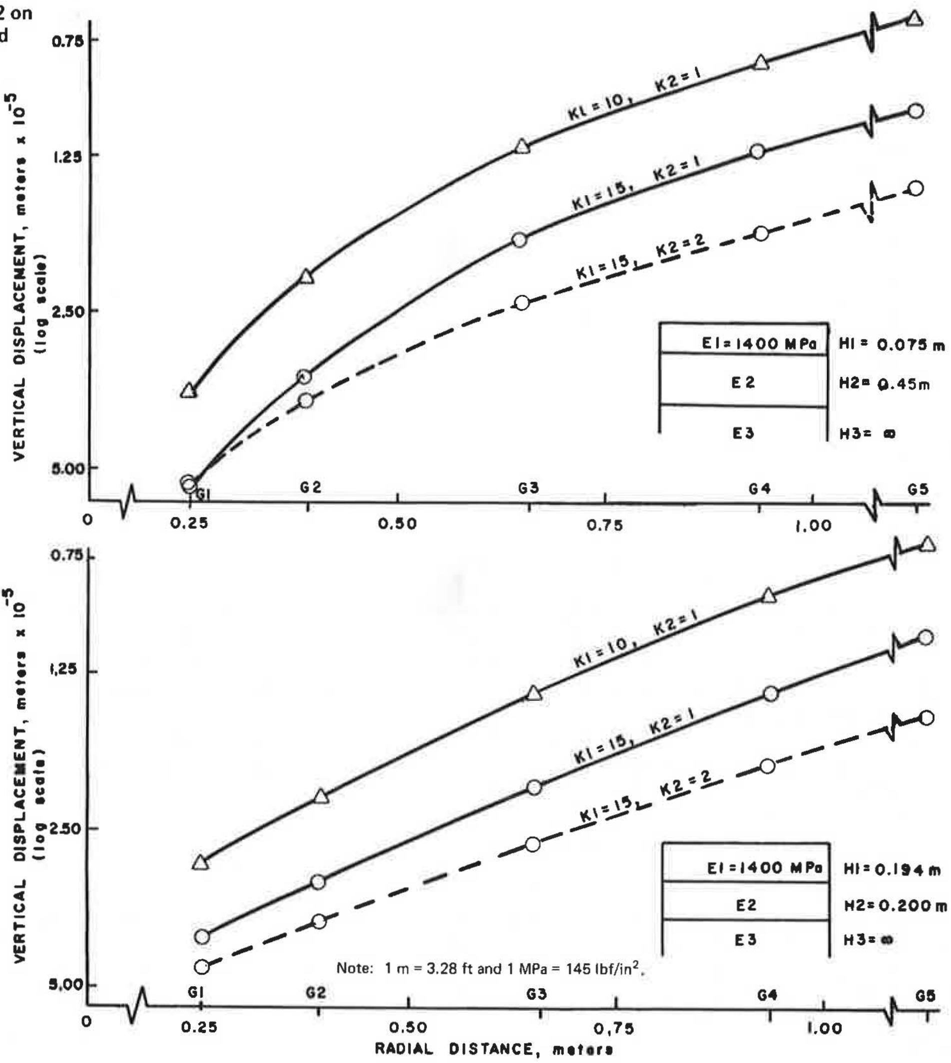


Figure 2. Example: trial-and-error solution for K1 and K2 under Dynaflect loading.

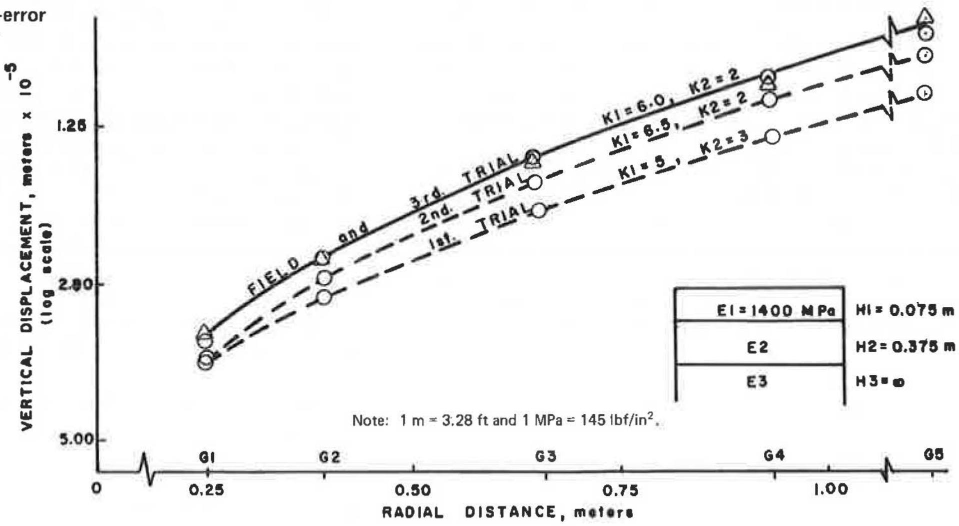


Table 2. Values of K1 and K2 estimated from Dynaflect tests.

Site Identification	Test Date (1974)	K1[a] E1 = 5.52 GPa	K1[a] E1 = 1.38 GPa	K1[a] E1 = 0.345 GPa	K2 E1 = 5.52 GPa	K2 E1 = 1.38 GPa	K2 E1 = 0.345 GPa
D1	January		8.5			1.0	
	May		9.0			0.9	
	October		8.5			1.0	
D2	May		10.5			0.4	
D3	October		5.0			2.0	
D4	October		4.0			1.5	
D5	January		16.0			0.8	
	May		22.0			0.8	
	October		13.5			0.8	
D6	January	69.0	15.0	4.8	0.8	1.0	0.8
	May	64.0	16.5	4.4	1.0	1.0	1.0
	October	59.0	13.0	4.0	0.8	1.0	0.8
D7	January		5.1			2.0	
	May		9.5			1.0	
	October		6.0			1.5	
D8	January		12.0			0.4	
	May		13.0			0.4	
	October		11.0			0.4	
D9	May	-[b]	8.0	2.0	-[b]	0.7	0.7
	October	31.0	4.3	1.5	0.5	1.0	0.7
D10	May		11.8			1.5	
	October		19.0			1.0	
D11	January		6.0			2.0	
	May		3.0			4.0	
	October		4.5			2.0	

Notes: 1 GPa = 145 000 lbf/in^2.
Calculated values of E2 and E3 are relatively independent of assumed value of E1.
[a]K1 = 14.7 - 4.81 K2; R^2 = 0.38; and N = 11. [b]No single-valued solution.

1. The time of year has no apparent effect on K2, which is a direct function of E3.

2. The time of year has an effect on K1, but it is not consistent with the usual assumption that K1 is larger in the winter (January) than in the summer (May). It would seem that the effect of temperature is greater on E2 than on E1. This agrees with the statement of Carpenter and others (10) that "the base course material is much more thermally active than the asphaltic concrete."

3. The relatively low values of K1 and high values of K2 at test site D11, which had a 0.15-m (6-in) thick cement-treated base, indicate that this base performs like a more rigid base.

4. For the fixed value of E1, K1 = 10.2 and K2 = 1.2.

5. In the two cases examined, the choice of E1 did not significantly affect the calculated value of K1, but this was not true for K2. Consequently, the reduction of E1 values to E2 and E3 values by the use of K1 and K2 shows that E2 and E3 are independent of the value assumed for E1.

K2 values of less than 1.0 cannot be simply justified, other than that the procedure used is not very precise. However, such values for K2 have also been reported by Scrivner and others (5) for a two-layered system and by Lai (7) for a five-layer system. Scrivner found modular ratios (K2 for our comparison) ranging from 0.6 to 6.3 and Lai found K1 values of less than 3.0 for a temperature range of 4.4 to 43.3°C (40 to 110°F).

Equation 1, which relates K1 to K2, was derived from the data obtained on all test sites and the stated assumptions.

$$K1 = 14.7 - 4.81\,K2 \qquad (1)$$

The implication of this relationship is that the elastic modulus of a surface course or a base layer is dependent on the modulus of the subgrade. For example, if E2 is held constant, then when E3 is low, E1 will also be low, and when E3 is high, E1 will also be high. The above statements apply to the base-course material if E1 is held constant. Comparable findings have been reported by Ueshita, Yoshikane, and Tamano (11) from Benkleman-beam tests on three-layer pavements.

The K2 values that are less than 1 and the general lack of effect of the time of year on K2 and perhaps also on K1 are cause for a certain amount of concern, although one must accept some variability from experimental errors in the data acquisition and from the graphical reductions. However, there are additional useful data that could be obtained from the Dynaflect measurements. For example, the deflection at the first geophone is not the maximum deflection caused by the loading. Figure 3 shows plots of calculated surface deflections under the Dynaflect loading for two pavement systems. It is readily seen that the deflection at G1 does not correspond to the maximum. If one is to calculate E3 from surface deflections, then one should use the largest value of practical measurement. From Figure 3, it would seem to be advantageous to obtain deflections in a transverse direction and at locations closer to the wheels than are presently obtained.

The Dynaflect deflection data at the geophones are given in Table 3, and those for geophone G1 are plotted against the corresponding values of K1 in Figure 4. (Because the statistical analyses of these data were carried out in U.S. customary units, SI units are not given in Figure 4.) The plot suggests that the deflection at G1 is closely related to K1; a statistical calculation gives an R^2 value of 0.82 when G1 is regressed on K1 (regressions of deflection differences G1, G2, G4, and G5 on K1 give R^2 values of less than 0.23).

To account for environmental effects in the pavement design procedure, E1 was modified by a temperature-correction factor based on elevation. A comparison between the temperature correlation factor for E1 and the K1 values obtained is shown in Figure 5. From the graph, it appears that K1 increases as the elevation of the test site increases. One would wonder whether K1 is somewhat independent of the original material modulus. Does the modulus of elasticity of a base at a higher elevation in Arizona decrease because the rainfall and thermal activity increase with elevation or do asphalt concretes age to a greater degree and become stiffer at higher elevations?

SUMMARY AND CONCLUSIONS

The purposes of this study were to obtain from Dynaflect deflections a measure of time-of-year effects on the elastic moduli of pavement layers and also to compare the relative stiffnesses of the layers.

Figure 3. Calculated Dynaflect deflections.

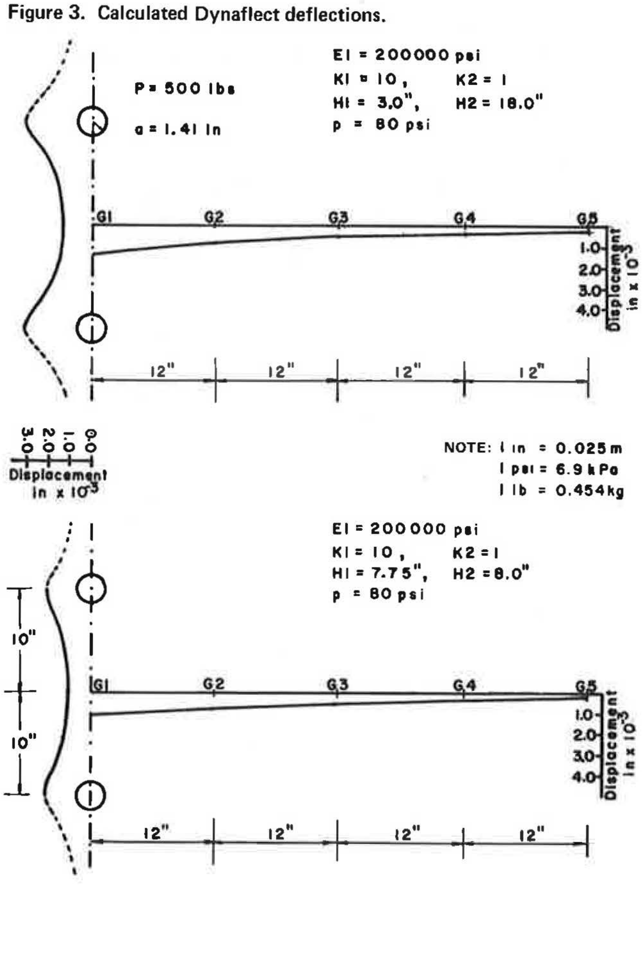


Table 3. Dynaflect deflection data.

Site Identification	Test Date (1974)	Deflection (μm) G1	G1-G2	G4-G5
D1	January	25.9	7.6	1.8
	May	30.2	12.7	2.3
	October	29.4	10.9	1.0
D2	May	18.0	7.1	0.8
D3	October	21.2	2.8	3.0
D4	October	18.5	5.8	0
D5	January	51.0	20.3	3.8
	May	64.0	20.3	5.1
	October	40.9	15.2	1.8
D6	January	53.8	19.8	4.3
	May	58.6	20.6	4.8
	October	46.7	18.3	3.0
D7	January	24.4	4.8	2.5
	May	29.0	6.9	2.3
	October	23.1	4.6	1.3
D8	January	28.2	12.7	1.3
	May	32.8	17.0	1.0
	October	35.0	19.5	0.8
D9	May	19.3	5.6	1.3
	October	12.7	2.8	1.3
D10	May	-	-	-
	October	60.0	9.9	4.3
D11	January	30.8	8.6	2.8
	May	25.4	6.6	2.3
	October	17.5	1.3	1.8

Note: 1 μm = 0.000 04 in.

Figure 4. Comparison of Dynaflect geophone deflection with K1.

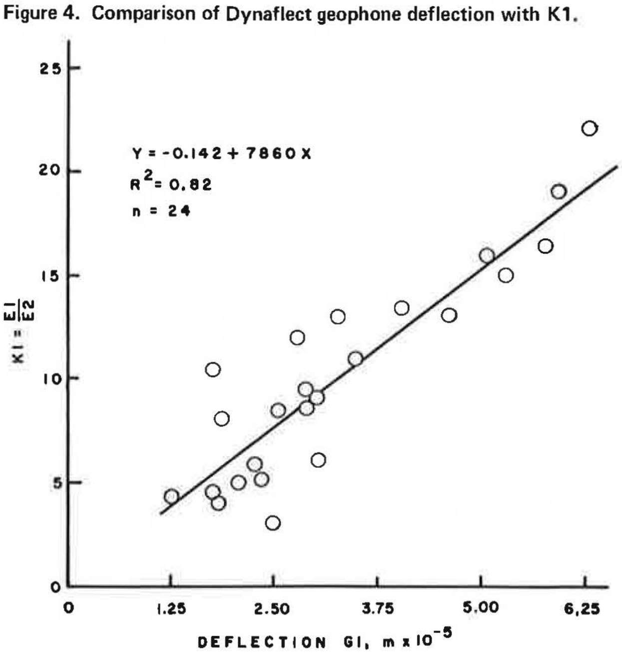
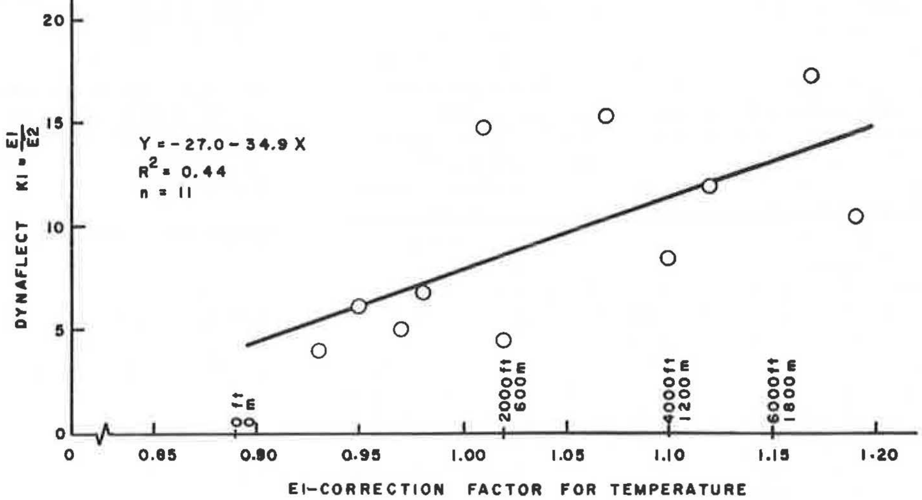


Figure 5. Comparison between temperature correction factors and K1 values.



The following limitations are acknowledged:

1. The amount of data was quite limited,
2. The graphical procedure used to establish K1 and K2 was not precise,
3. The value of E1 was assumed to be constant, and
4. The Dynaflect surface deflections were assumed to depend primarily on K1 and K2.

With these restrictions and limitations, I believe that the following general conclusions are warranted:

1. The values of K1 and K2 are not appreciably affected by the time of year;
2. Although the differences are small, the values of K1 are generally greater in summer (May) than in winter (January);
3. The calculated values of K2 are independent of the value of E1;
4. K1 is affected by the elevation of the test site;
5. The values of K2 (average = 1.2) imply that the deflection characteristics of the pavements are basically those of a two-layer system; and
6. Further work with the Dynaflect device should include measurements of deflection in a transverse direction and closer to the wheels to obtain higher values of surface deflection and curvature.

ACKNOWLEDGMENT

The cooperation received from the Arizona Department of Transportation is greatly appreciated. I sincerely appreciate the sponsorship by ADOT and the Federal Highway Administration of this work because I believe that it is through such efforts that a theoretical design procedure will evolve. The contents of this report reflect my views: I am responsible for reduction of the data presented here. The contents do not necessarily reflect the views or policies of the sponsoring agencies.

REFERENCES

1. R. A. Jimenez. Structural Design of Asphalt Pavements (Arizona): Phase 1. Arizona Highway Department, Oct. 1972.
2. R. A. Jimenez. Structural Design of Asphalt Pavements (Arizona): Phase 2. Arizona Department of Transportation, May 1975.
3. F. H. Scrivner and W. M. Moore. An Electromechanical System for Measuring the Dynamic Deflection of a Road Surface Caused by an Oscillating Load. Texas Transportation Institute, Texas A&M Univ., College Station, Res. Rept. 32-4, Dec. 1964.
4. F. H. Scrivner, G. Swift, and W. M. Moore. A New Research Tool for Measuring Pavement Deflections. HRB, Highway Research Record 129, 1966, pp. 1-11.
5. F. H. Scrivner, C. H. Michalak, and W. M. Moore. Calculation of Elastic Moduli of a Two-Layered Pavement System from Measured Surface Deflections. Texas Transportation Institute, Texas A&M Univ., College Station, Res. Rept. 123-6, 1971.
6. G. Peterson and L. W. Shepherd. Deflection Analysis of Flexible Pavements. Utah State Highway Department, Final Rept., 1972.
7. J. S. Lai. Determination of Resilient Characteristics of Pavement Systems by Using Dynaflect Deflection Measurements. Preprint of paper presented at the 53rd Annual Meeting, HRB, 1974.
8. D. M. Burmister. The Theory of Stresses and Displacements in Layered Systems and Applications to the Design of Airport Runways. Proc., HRB, Vol. 23, 1943, pp. 126-148.
9. H. Warren and W. L. Dickman. Numerical Computations of Stresses and Strains in a Multiple-Layered Asphalt Pavement System. California Research Corporation, Richmond, CA, 1963.
10. S. H. Carpenter, R. L. Lytton, and J. A. Epps. Pavement Cracking in West Texas Due to Freeze-Thaw Cycling. HRB, Highway Research Record 532, 1975, pp. 1-13.
11. K. Ueshita, T. Yoshkane, and T. Tamano. Young's Moduli of Layers in Pavement Structures. Trans., Japan Society of Civil Engineers, Vol. 5, 1974.

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