ARIZONA DEPARTMENT OF TRANSPORTATION

STRUCTURAL DESIGN OF ASPHALT PAVEMENTS

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16. Abstract

The report presents findings to supplement the previous report on a new asphalt pavement design concept for Arizona. Laboratory studies of flexural fatigue showed the eleven field paving mixtures could be separated into four distinct groups. Examination of data obtained from a questionnaire and loadometer reports produce a simple procedure for estimating the load and number for each of 5 "design axles". The study indicated a need to obtain tire inflation pressure and a separation of front axles from single axles in the standard "W4" table. Dynaflect pavement deflection data showed their great dependence on the surface and base courses (K1) and much less dependence on subgrade (E3). A new procedure for determining compression fatigue and E3 for subgrade soils under repetitive loadings is suggested. The design procedure is illustrated with the new data obtained from the research.

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STRUCTURAL DESIGN OF ASPHALT PAVEMENTS (ARIZONA)

by

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May, 1975

Final Report - Phase II

STRUCTURAL DESIGN OF ASPHALT PAVEMENTS (ARIZONA)

SYNOPSIS

This report is a continuation of the development of a pavement design procedure for the State of Arizona. The concepts of the method have been presented in an earlier report which also identified areas for further study. The current report presents findings related to three areas of study enumerated as follows; 1. characterizing the flexural fatigue and tensile strength of actual asphalt paving mixtures, 2. description of wheel loads for use in the proposed pavement design method, and 3. calculation of relative stiffness of pavement layers from dynaflect deflection values. Modifications to the computer program for pavement design are described.

INTRODUCTION

The first phase of the study and reported earlier (1) was concerned with the basic concepts for a design procedure for asphalt pavements. The criteria for design are based on control of cracking of the surface course due to flexural fatigue failure and of rutting of the pavement due to the excessive repetition of vertical strains at the subgrade interface. The stresses at the bottom of the surface course and the vertical strains on top of the subgrade are computed using Burmister's theory for 3-layered elastic systems.

In order to demonstrate the design procedure for obtaining numerical answers for thicknesses of the surface course and the base course certain assumptions had to be made. Some of the most important assumptions were related to the mechanical properties of the materials, to the load and inflation pressure of various truck wheels, and to the effects of the environment on the modulus of elasticity of the pavement materials.

The description and results of the work performed in this phase will be reported in the principal sections entitled (a) Materials, (b) Wheel Loads, (c) Dynaflect Study, and (d) Modifications to the Pavement Design Computer Program.

MATERIALS

The work associated with material properties was confined largely to establishing the flexural fatigue property of asphaltic concrete mixtures used in actual construction. Additionally, a limited amount of work was done towards developing a simple test procedure for defining a strain-load repetition relationship for fine grained soils.

Asphaltic Concrete

The two main physical characteristics of asphaltic concrete required for the pavement design procedure are modulus of elasticity and flexural fatigue. In demonstrating the proposed pavement design concept it was assumed that the fatigue property of all asphaltic concrete was expressed by equation 1 as follows:

$$\sigma_t = I_o N^{-b} = 1800 N^{-0.2} \qquad 1.$$

where: σ_t is the radial tensile stress, psi

N is the number of repetitions of stress S for failure.

The constant values of the coefficient I_o and the exponent were chosen from prior work done out-of-state and for their similarity in values for those proposed by Shell (2). In recognition that asphaltic concrete mixtures are different for most states and also because of newer technology and usage of drum-mixer asphaltic concrete, it was felt necessary to obtain experimental data on actual Arizona paving mixtures for establishing their flexural fatigue and dynamic modulus of elasticity characterization.

Special procedures, as described later, are used for determining the flexural fatigue property of asphaltic concrete. Since the fatigue testing required special equipment, there was a warrant for seeking some correlations between it and standard or relatively simple tests.

The selection of asphaltic concrete mixtures for the study was based upon the availability of on-going construction. As a consequence, the location of the construction sites are near the three main centers of population represented by Phoenix, Tucson, and Flagstaff.

The eleven mixtures sampled and the data related to location, composition, and test results are listed in Appendix B. The following paragraphs summarize test procedures and test results.

Sampling and Testing

The asphaltic concrete was sampled from the lay-down machine by construction personnel and placed in 5-gallon (18.9×10^{-3} m^3) metal containers with lids. The filled can held about 70 pounds (31.7 kg). The sealed containers were then sent to the University's asphalt laboratory. All mixtures remained in the containers and at room temperature of about 77°F (25.0°C) for a minimum of seven days prior to compaction.

A special effort was made to minimize a change in viscosity of the asphalt in the mixture and also segregation of aggregate in the sample sizing procedure. The sealed metal cans were placed in a 140°F (60.0°C) forced draft oven for a period of approximately 2-1/2 hours. This treatment was sufficient to bring the mixture to a low consistency for separating and weighing the mixture for proper specimen sizes. No one can of mixture was heated in this manner for more than two times. The loose mixture was then placed in other metal containers with lids and placed in appropriate ovens to bring the material to the desired compaction temperature. These containers contained from 2.65 pounds (1.2 kg) to 33.0 pounds (15.0 kg) of mixture for specimens of 4 inches (1.02×10^{-1} m) or 18 inches (4.57×10^{-1} m) in diameter.

The larger specimens were used for fatigue testing and formed by vibratory kneading compaction at about 285°F (141°C). This procedure has been previously described in citation 3 for specimens to be tested for fatigue in the device called a deflectometer. (The compactor and deflectometer are shown in Figures 1 and 2.) The 4-inch (1.02×10^{-1} m) diameter specimens were compacted at 250°F (121°C) by vibratory kneading and also with a triaxial institute (T.I.) compactor according to the general procedure of Arizona Test No. 803 (4).

A sufficient amount of mixture was held back for determinations of maximum specific gravity of the loose material by Arizona Test No. 806 and also for asphalt extraction by Arizona Test No. 402 (4).

General descriptions of the tests which were used are given in the following sections.

Deflectometer (Fatigue). The deflectometer test for developing the fatigue equation (No. 1) has been described in citation 3; however, a brief description will be given here. The circular specimen of approximately 18 inches (4.57×10^{-1} m) in diameter is fixed at its periphery, given a uniform pressure fluid support, and is centrally loaded on the top surface with a repeated sinusoidal load. It has been demonstrated that the crack pattern developed is identical to the "alligatoring" that identifies fatigue failures of asphaltic concrete. The loading system is of a constant load so variable tensile flexural stress is obtained by varying specimen thickness and/or the area of the

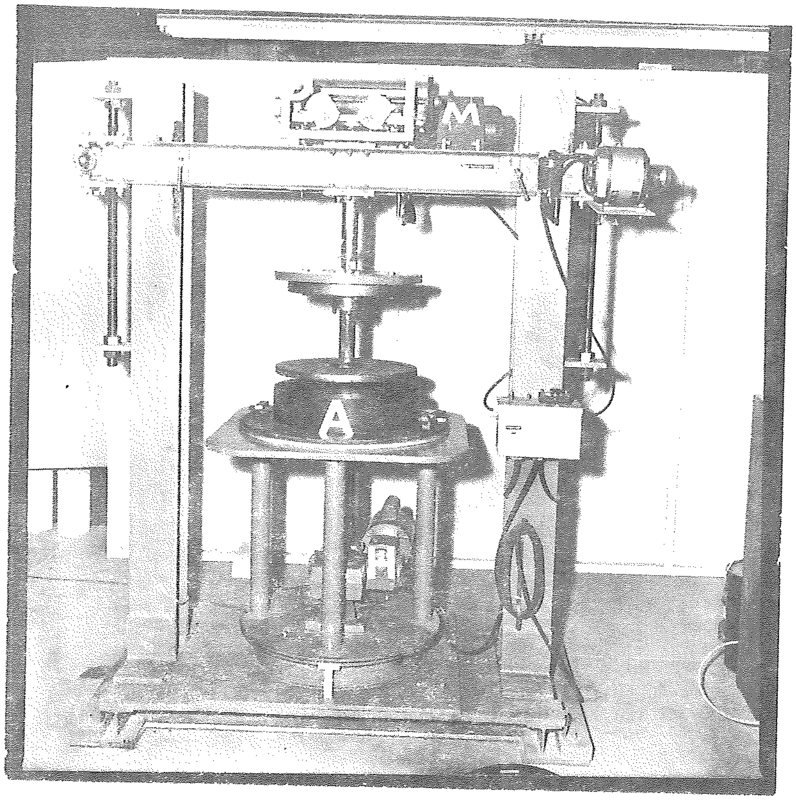

Figure 1. Vibratory Kneading Compactor

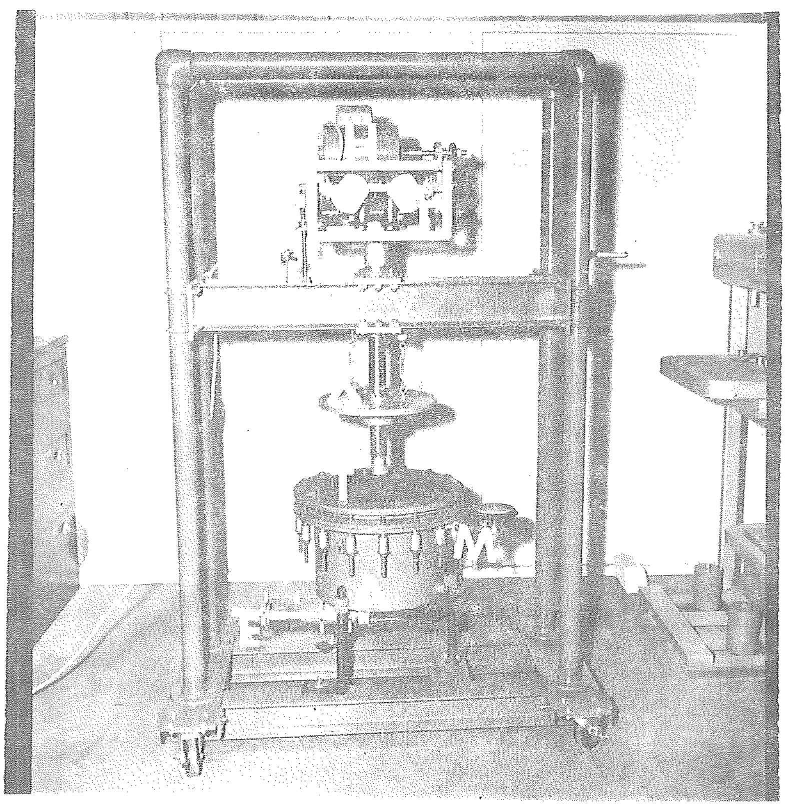

Figure 2. Deflectometer-Flexural Fatigue Tester

repeated-load disc. The fatigue life equation is obtained from testing with three different tensile stresses and obtaining the corresponding number of load repetitions to cause failure. Failrue is defined as the number of repetitions to develop a minimum but detectable number of cracks at the points of maximum tensile stress. The system is assumed to be linearly elastic for the computation of stress and a dynamic modulus of elasticity.

Double Punch Tensile Test. A measure of tensile strength of asphaltic concrete was obtained using a double punch procedure suggested by Fang and Chen (5) and investigated for usage on asphaltic concrete by Jimenez (6). In this test, load is applied to the specimen through two aligned 1-inch (2.54×10^{-2} m) diameter steel punches to the center of the flat surfaces. The maximum force applied corresponds to the failure stress. The test was performed on specimens formed to 4-inch (1.02×10^{-1} m) diameter by T.I. compaction and vibratory kneading compaction and also on 4-inch (1.02×10^{-1} m) diameter cores taken from deflectometer specimens after testing for fatigue.

The use of the double punch test on 4-inch (1.02×10^{-1} m) diameter specimen was expanded in order to obtain a value for modulus of elasticity if it is assumed that asphaltic concrete under rapid and repeated loading behaves as a linear elastic material. In this test load was applied with the loading system of the deflectometer at a frequency of 690 cycles per minute and the amplitude of force varied sinusoidally from 40 to 300 pounds (178 to 1335 N). The repeated radial expansion was measured at mid-height and at three points spaced 120 degrees (2.1 rad) apart with a dial indicator extensometer. Also the repeated vertical deflection of the upper punch was noted. The photograph in

Figure 3 illustrates the set-up. The photograph shows three extensometers for measuring radial displacement but in actual testing only one was used and four measurements were made to insure that the first and fourth readings at the same location were identical. The dial extensometer for the radial measurements was graduated in ten thousandths of an inch (2.54 μm) and the extensometer for the vertical displacement was graduated in thousandths of an inch (25.4 μm).

A discussion on the modulus of elasticity by the double punch procedure is given by D. A. DaDeppo of The University of Arizona and presented in Appendix A. Table A1 in Appendix A shows a listing of coefficients to be used with specimens of various heights and diameters.

Hveem Stability. Specimens were prepared for testing in general accordance with Arizona Test No. 803 (4). Exception to the procedure was that some specimens were compacted by vibratory kneading as noted earlier and also that specimens were removed from the compaction mold after the application of the leveling load. Density of specimens was obtained by weighing in air and also submerged in water.

Results and Discussion

Results of the testing on the field paving mixtures are tabulated in Appendix B. Since it would be convenient and desirable to have some correlation between standard laboratory specimens and those compacted by vibratory kneading (V.K.) compaction such comparisons were made.

Vibratory Kneading vs Triaxial Institute Compactor. Figure 4 shows plots of specimen properties compacted by both T.I. and V.K. procedures. It is noticed that essentially identical densities were obtained by

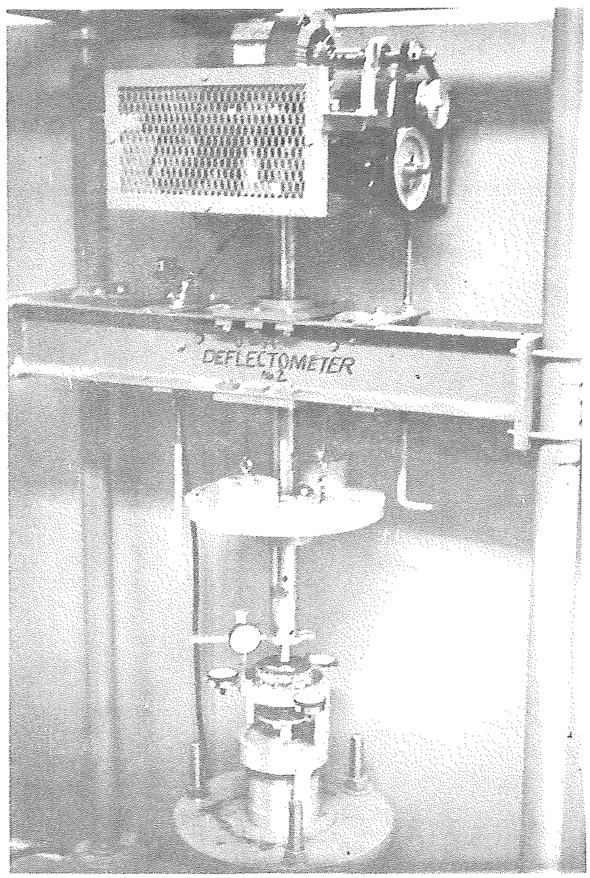

Figure 3. Set-up for Dynamic Modulus of Elasticity by Double Punch Procedure

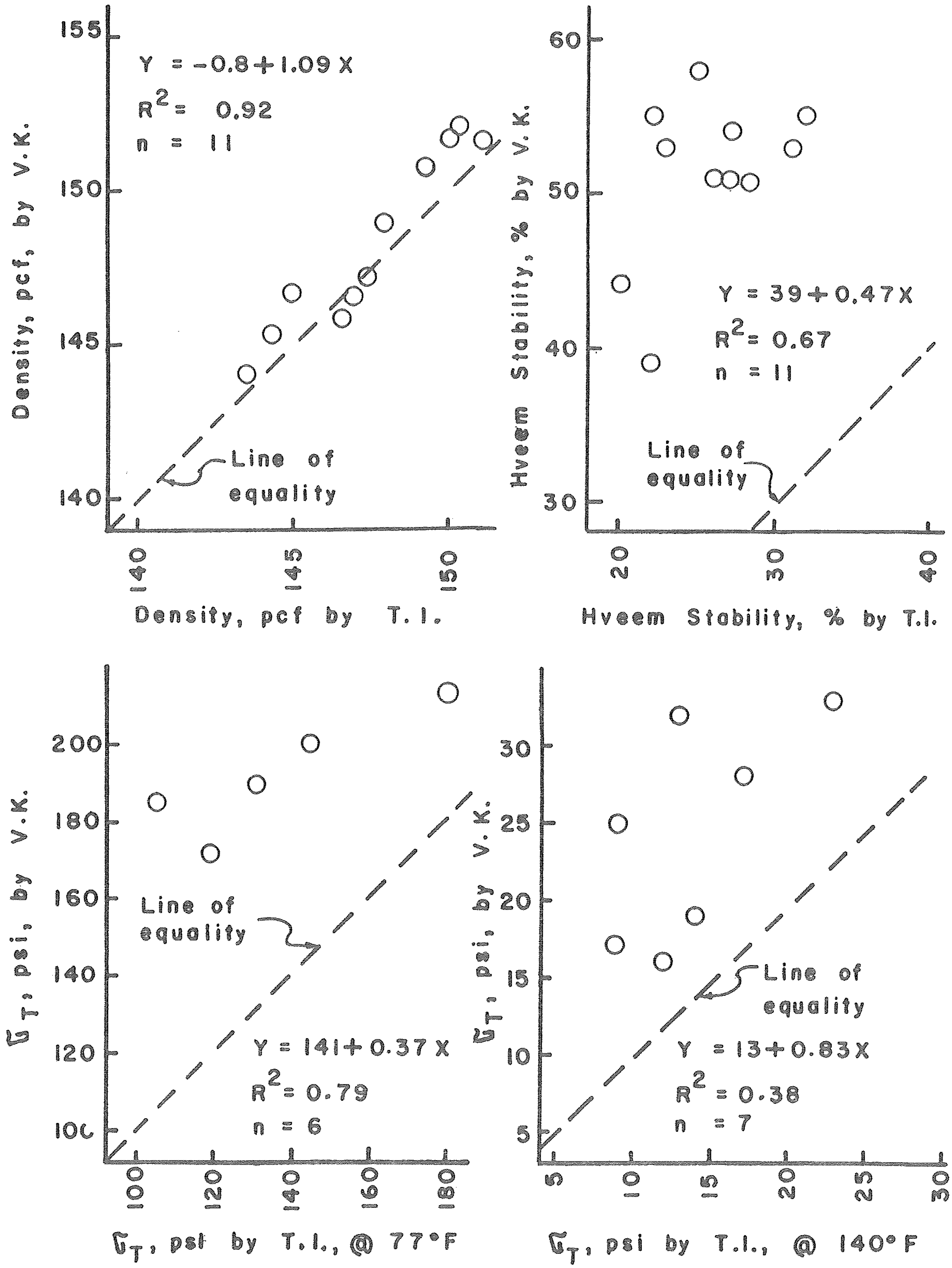

Figure 4. Comparison of Compaction Effects of Specimen Properties

both procedures for all eleven asphaltic mixtures. However, Hveem stability values and double punch tensile strengths were all higher for specimens compacted by vibratory kneading. The reason for this is not apparent except perhaps that less aggregate is broken by the V.K. procedure in which the maximum pressure applied is estimated to be approximately 75 pounds per square inch (5.18×10^5 N/m^2) while the compaction pressure under the T.I. procedure is 500 pounds per square inch (34.5×10^5 N/m^2).

Deflectometer Testing. The principal purpose for running this test was to establish the coefficient and exponent of equation 1. Examination of the values for I_o and b in Appendix B shows that these are not of constant values for all mixtures. The deflectometer data are summarized in Table 1 to aid in the analysis. In the table the mixtures have been separated into groups of approximately equal value for I_o. With this separation the grouping of most of the mixtures can be explained in consideration of b value and other characteristics. Mixture AC-8 has the lowest absolute value of b (slope of the σ_t vs N curve in log-log coordinates) and I_o on the basis of the high asphalt content and the grade of asphalt used. The next grouping for mixtures AC-9, 11, 2 and 1 appear to be based on being drum mixed and also on asphalt content and grade. The third grouping for AC-3, 5, 4 and 10 seems to be located on the basis of the lowest asphalt content. The data of Table 1 do not give any clues for the grouping of mixtures AC-6 and 4. Of particular interest is the linear regression analysis information presented at the bottom of the table which indicates that I_o has a strong effect on b. This relationship is beneficial in the search for a correlation between a simple standard test result and I_o

TABLE 1 SUMMARY OF DEFLECTOMETER TESTING FOR EVALUATION OF EQUATION $\sigma_t = I_o N^{-b}$

Sample	Asphalt Content, %	I_o	-b	n	R^2	Comments
AC-8	6.3	1,150	0.236	6	0.90	Basalt + cement & AR 2000 over-asphalted for ramp
AC-9	4.9	1,980	0.276	9	0.76	Gravel & AR 4000, drum mixer
AC-11	5.1	1,940	0.281	7	0.81	Basalt + cement & AR 2000, drum mixer
AC-2	4.9	2,120	0.281	9	0.85	Gravel & AR 4000, drum mixer
AC-1	5.5	2,770	0.288	7	0.97	Gravel & 85/100 pen.
AC-3	4.6	3,890	0.318	6	0.94	Gravel + cement & AR 4000
AC-5	4.8	6,540	0.329	6	0.88	Gravel & AR 4000
AC-10	4.9	5,610	0.346	7	0.85	Gravel & AR 4000
AC-6	5.9	12,500	0.417	6	0.97	Gravel & AR 2000, drum mixer
AC-4	5.1	9,020	0.424	5	0.92	Gravel & AR 4000

Regression of I_o on -b

$$b = 0.244 + 0.158 \times 10^{-4} I_o$$
$$R^2 = 0.90$$
$$n = 10$$

or b for identifying the fatigue life of asphaltic concrete.

In order to visualize the fatigue curves (σ_t vs N) of the four groups obtained for these mixtures, plots of these using average values of I_o and b are shown in Figure 5. It would appear that all four lines should intersect at a point near 60 pounds per square inch (4.14×10^5 N/m^2) and 150,000 repetitions. The concept that fatigue curves based on strain vs repetitions have a point in common has been suggested by several investigators represented by Deen, Southgate and Havens (7), Monismith and McLean (8) and Cooper and Pell (9). An implication of the curves shown in Figure 5 is that one may have one of two ways to minimize fatigue effects depending on the anticipated number of load applications on the pavement system. If the number of load applications will be less than 150,000, then a thinner layer of asphaltic concrete having a higher b can be used over a mixture having a lower b; that is, a larger stress can be tolerated. However, if the number of load applications is higher than about 150,000, then the opposite is true, a thinner course of a mixture having lower b can be used.

Deen *et al* (7) and Monismith *et al* (8) have associated specific values of modulus of elasticity or stiffness with each of certain fatigue curves. An examination of our limited data does not show good or acceptable correlation between modulus E_D and I_o; nor did we find good correlations between I_o and other specimen properties established on 4-inch (1.02×10^{-1} m) diameter specimens. Table 2 shows a listing of comparisions made between deflectometer specimen properties and standard 4-inch (1.02×10^{-1} m) diameter specimens. As can be seen from the R^2 (coefficient of determination) values which are relatively low, there is not a very good relationship between the test results obtained on

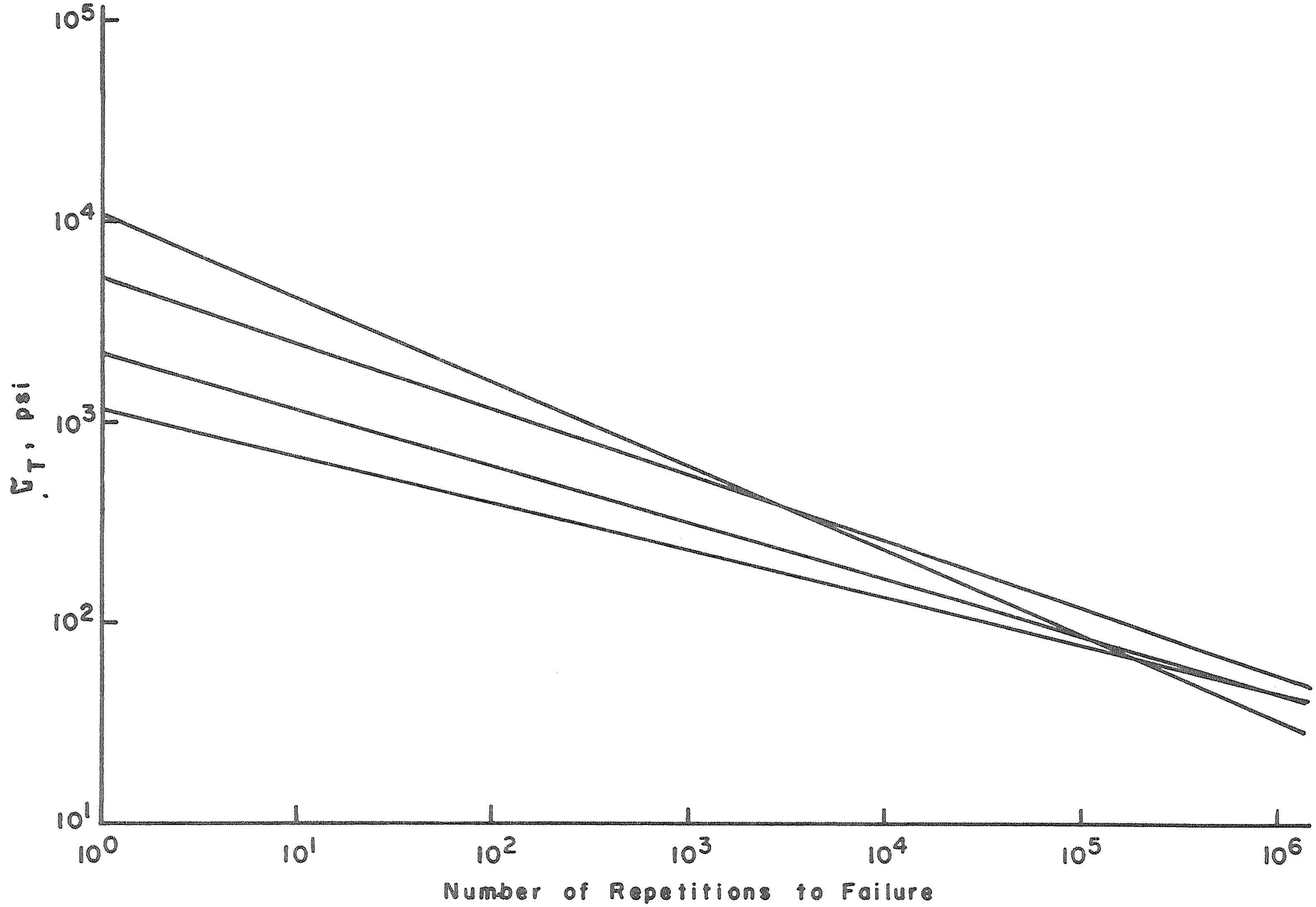

Figure 5. Fatigue Curves Resulting from Grouping of Mixtures

TABLE 2 LINEAR REGRESSION ANALYSIS FOR EFFECTS OF SMALL SPECIMEN PROPERTIES ON DEFLECTOMETER SPECIMEN PROPERTIES

Variable Name: Y	Variable Name: X	Equation	n	R^2
I_o	σ_t, 4" D core (w/E_D), 77^oF	Y = 2955 + 22.4 X	9	0.02
I_o	σ_t, 4" D V.K. 77^oF	Y = 1989 + 14.7 X	10	0.01
I_o	σ_t, 4" D V.K. (w/E_D), 77^oF	Y = 9240 - 24.4 X	10	0.03
I_o	E_D, 4" D core by D.P.	Y = -452 + 0.05 X Y = -4.61 + 0.83 X	9 6	0.34 0.35
I_o	E_D, 4" D V.K. by D.P.	Y = 10940 - 0.045 X	10	0.17
E_D, 4" D core by D.P.	E_D by defl. H ≡ 1.5 in.	Y = 87.76 - 0.17 X	9	0.30
σ_t, 4" D core (w/E_D), 77^oF	σ_t, 4" V.K. (w/E_D), 77^oF	Y = -6.48 + 0.55 X	10	0.44

the small specimens and those obtained from the deflectometer test. It is also noted that the comparison between dynamic modulus of elasticity and I_o from the deflectometer test shows poor correlation. This result is in contrast to Deen et al (7) and Monismith et al (8) who associate definite stiffness values with particular fatigue curves defined on the basis of strain rather than on stress as is reported here.

Road Cores. Another section of the report is concerned with the testing of pavements with the dynaflect; however, since the sites had the surfacing sampled and tested these results are discussed at this time. The 4-inch (1.02×10^{-1} m) diameter road cores received were trimmed of seal coats, thin overlays, and other material to obtain a specimen of 2.2 to 3.2 inches (5.58 to 8.13×10^{-2} m) in height. This range of height for specimens was desired since it is the largest one showing the least change for the values of the coefficient used for computing E_D by the double punch procedure. Examination of the data presented in Table B12 of Appendix B shows that the average values for tensile strength of about 115 pounds per square inch (791×10^3 N/m^2) and for dynamic modulus of elasticity of 118,000 pounds per square inch (811×10^6 N/m^2) for the road cores are of the same order as for the field mixutes compacted by vibratory kneading in the laboratory.

Soil

A review was made of the literature related to the repeated-load-triaxial testing of subgrade soils. Since a portion of this review was made for the report of citation 1, the primary interest in this search was related to determining both a dynamic modulus of elasticity and a fatigue life characteristic for use in the pavement design procedure proposed. Most references (10, 11, 12, and 13) examined indicated the use of expensive equipment and recording devices. Additionally, these did not suggest a procedure which we thought should be capable of furnishing the needed characteristics of E_D and fatigue model for subgrade soils.

Our proposed method of testing was to apply a repeated axial compressive stress at a frequency comparable to that used in the deflecometer test to a cylindrical specimen confined with low fluid pressure; the data to be recorded were to be (a) number of repetitions, (b) the total and repeated axial deformation of the specimen, and (c) the volume change occurring. It was considered that failure of a specimen could be identified with some particular rate of volume change in a comparison with number of load applications. The limited amount of work performed made use of the deflectometer loading system as shown in Figure 3, the triaxial cell of Figure 6 and the volume change measuring device of Figure 7. A schematic drawing and loading procedure for performing the test are presented in Appendix C. The triaxial cell is of a commercial type manufactured by Clockhouse Engineering of England. The volume change measuring device was built to be similar to the one designed by Bishop and Henkel (13). Gandhi and Gallaway (14) have reported on the satisfactory use of this measuring system for determining volume changes of asphaltic concrete under triaxial loadings.

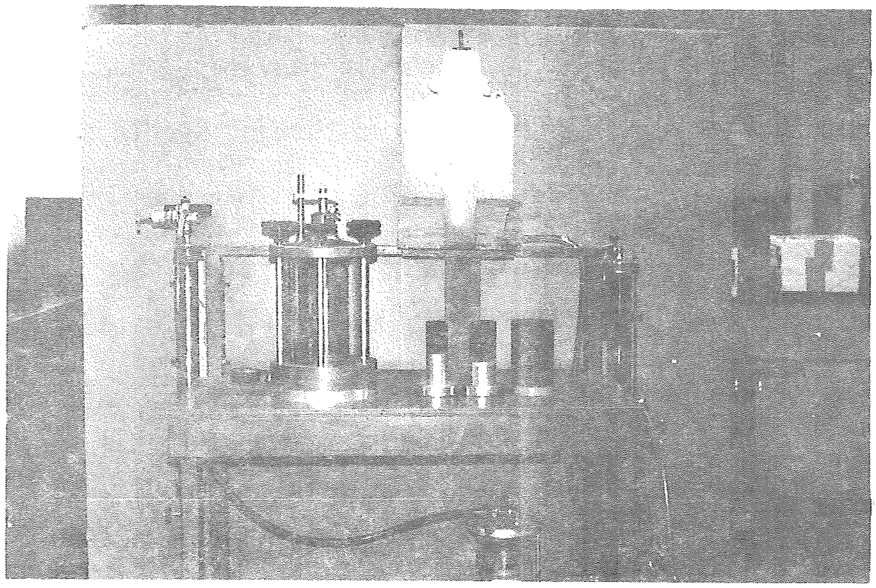

Figure 6. Triaxial Cell and Specimens

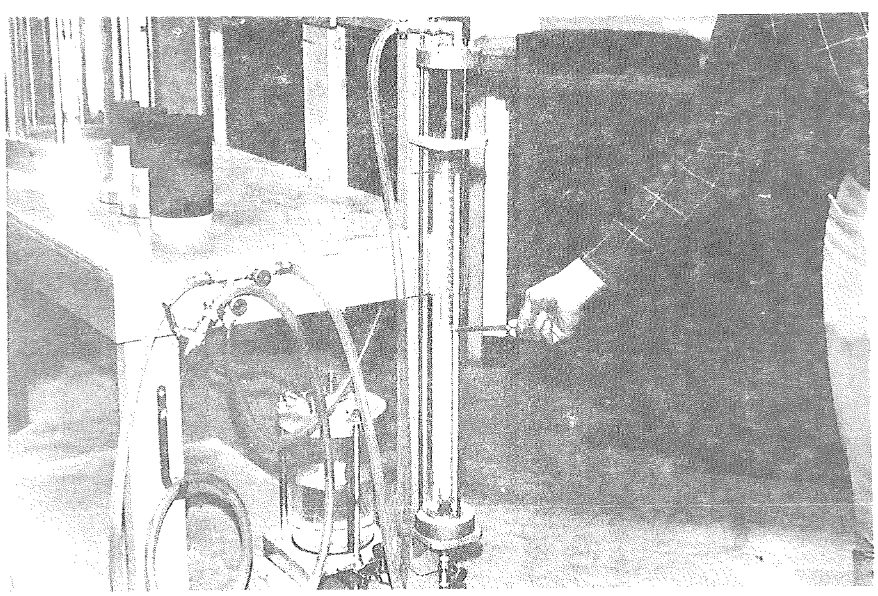

Figure 7. Volume Change Measuring Device

The preliminary work was done with a local soil labeled as Yaqui Soil by Zakhour (15) and having the following characteristics:

Sand, %	69.0
Silt, %	20.0
Clay, %	11.0
Plasticity Index	7.0
Proctor Density, pcf	129.8
Optimum Moisture, %	8.5

Soil samples were compacted by vibratory kneading to produce specimens of three sizes having diameters of 2.0, 2.5 and 4 inches (5.08, 6.35, and 10.2 x 10^{-2} m) and heights of 3.0, 3.75 and 6 inches (7.62, 9.53 and 15.2 x 10^{-2} m) respectively. The variable of diameters was necessary because of the loading system and to obtain variable vertical stress (or strain) for the fatigue study. The repeated load applied was comparable to that for the evaluation of E_D by the double punch procedure, that is, its magnitude varied from 40 to 300 pounds (178 to 1335 N) and at a rate of 690 times per minute. The confining pressure was held approximately constant at 5 pounds per square inch (34.5 x 10^3 N/m^2).

It is unfortunate that no duplicate specimens of any size with reference to density and moisture content were tested; however, means for defining failure for the specimens tested was fulfilled. The number of load repetitions associated with failure was identified from a plot of the log of volume change vs the log of load repetitions where the initial linear graph changes to a curve. A data sheet for the test is shown in Figure 2C of Appendix C and typical plots of volume change and vertical deflection versus number of load repetitions are shown in Figure 8. The shape of the two curves shown in Figure 8 was the same for all tests. However, as mentioned earlier, data were not available

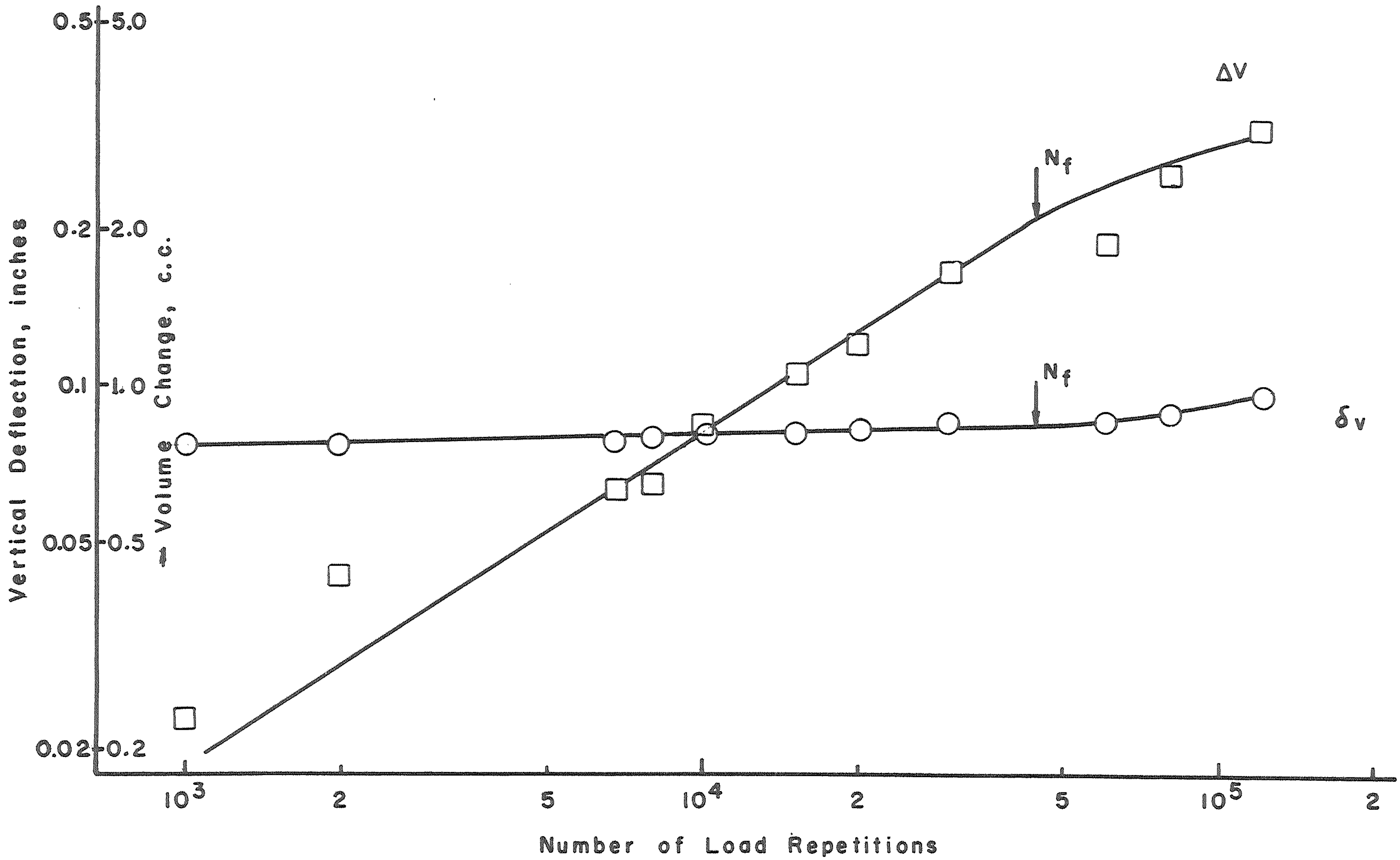

Figure 8. Relationship Between Vertical Deflection or Volume Change and Number of Load Repetitions in a Triaxial Test

to establish a fatigue equation in the form of

$$\varepsilon_v = I_o N^{-b} \qquad 2.$$

where: ε_v is the repeated vertical strain

N is the number of repetitions of ε_v for failure

I_o and b are constants to be derived.

The reader is reminded that a control equation in the new pavement design procedure is of the same form as above with I_o being equal to 0.0105 and b is equal to 0.2.

WHEEL LOADS

The first report (1) concerning this pavement design procedure illustrated that wheel loads were assumed to be characterized by five types of axle. These axles were identified as to load and inflation pressure per tire and classified as (a) Passenger, (b) 2 P for pick-up, (c) 2S for a delivery van, (d) SA for single axle, and (e) TA for tandem axle. The number of each axle used for pavement design was calculated from traffic classifications, counts, and growth factors given by the Highway Division of the Arizona Department of Transportation (ADOT). Since the proposed pavement design procedure is based on stress and strain criteria, it is necessary to select proper wheel loads and tire inflation pressures. It is believed not to be necessary nor justified to establish or use "wheel load equivalency factors"; it has been shown that such factors are not of constant value for a particular load (16, 17). The work performed to characterize the traffic on Arizona's highways was divided into two parts involving a questionnaire and a review of loadometer data.

Questionnaire

A questionnaire was developed to obtain truckers' data on their vehicles. The questionnaire sent to truckers located in Arizona and its adjacent states is shown in Appendix D. A total of 188 letters were sent to trucking firms in Arizona, California, Colorado, Utah and Texas.

Results and Discussions to Questionnaire

The response to the questionnaire was not as large as anticipated. About 8 percent or 14 of the letters were returned for non-delivery and only 29 responses (15.4 percent) were available for analysis. Table D1 in Appendix D presents the information received. A review of the data shows that the predominant vehicles in the response are the semis (3S2) and the semi plus trailer (2S1-2). The data show that the predominant axle load for the single axle (SA) is 18,000 pounds (8.17×10^3 kg) and for the tandem axle (TA) it is 32,000 pounds (1.45×10^4 kg). These values are as expected since they represent the legal limits in Arizona. It is noted that overloads have been admitted.

The tandem axle spacing is mainly at 4.0 feet (1.22 m) and the cold inflation pressure is usually 90 pounds per square inch (651×10^3 N/m^2) or more. Use of these data will be presented in a later section.

Loadometer Study

Arizona Truck Weight Study (18) reports were obtained for several years so that counts and weights were available for 1965, 1966, 1967, 1968, 1969, 1970, 1972 and 1973. Data for 1971 were not available. Of primary interest to our study was the information given by the W4 and W2 tables for interstate rural highways. The intent of this phase was to develop a procedure for characterizing highway traffic for pavement design purposes. Data for the other categories of highways are not considered in this report.

Results and Discussion on Loadometer Study

A review of table W4 in any of the reports shows that axle weights are divided between single axle and tandem axle groups. Each of these groups is further subdivided into a variety of trucks with a different number of axles. Our examination of this table indicated that two desirable design load data are missing; these are tire inflation pressure and the separation of front or steering axle (FA) from single axles. The identification of the FA is possible for the 3S2 and the 3D. Our need for the identification of FA's is based on the fact that an FA axle has single wheels while an SA axle usually has duals.

Distribution of Trucks and Axle Loads. Table D2 in Appendix D shows the distribution of truck types for eight years. Examination of the data shows that 5 types of trucks (2D, 2S1, 2S2-3S1, and 2S1-2) account for 90 percent of all trucks. Especially noticeable is the fact that the 3S2 truck represents at least 50 percent of all trucks. The 1969 data is suspected to be in error.

The tables from D3-D14 list the percentages and percentiles of axle load groups for pickups (2P) and trucks and for all single or tandem axles. A summary of the data follows:

2P (pickups) - the majority (74%) of the pickups have axle loads of less than 2.0 kips (906 kg) and this average has been relatively constant over the study period.

3S2 Front axle only - a decided majority (86%) of this axle carries 8.0-11.9 kips (3.63-5.40 x 10^3 kg) and this value has been quite constant over the years.

2D Single axle with duals - has carried 3.0-6.9 kips (1.36-3.14 x 10^3 kg) most of the time (58%) since 1965.

2S1 Single axle - the front axle weights are not separable from the single axle ones; however, it would seem that the axle loads are principally distributed among 3 load groups.

2S2 & 3S1 Single axle - as in the 2S1 group the front axle is not separable from a single axle and three axle groups account for the greatest number.

2S1-2 Single axles - the distribution of these loads is similar to that of 2S1 single axles.

All single axles, Figure D13 - the load group of 8.0-11.9 kips (3.63-5.40×10^3 kg) accounted for about 45 percent of all single axles.

All tandem axles, Figure D14 - the majority axle-weights are distributed over a fairly large range of 6.0 to 29.9 kips (2.72-13.6×10^3 kg). It is noticed that is a significant number of axles over the legal limit of 32 kips (14.5×10^3 kg).

A portion of the data from Tables D13 and D14 have been plotted to develop a visual distribution of single and tandem axle load. These plots are shown in Figures 9 and 10.

The study of the questionnaire and loadometer data was performed to develop information for the modification of axle load descriptions for use in the new pavement design procedure. Table D15 lists the 85 percentile load for the various axle groups. The 85 percentile load is now assumed to be the designs load.

A telephone survey of local distributors of passenger, pickup, and recreation vehicles was made to aid in selecting axle loads and tire inflation pressures for these vehicles.

The design axles proposed now are as follows:

Passenger - 2 wheels each loaded to 1,000 pounds (454 kg) and 28 pounds per square inch (193×10^3 N/m^2) inflation pressure.

2P - 2 wheels each loaded to 1,600 pounds (725 kg) and 32 pounds

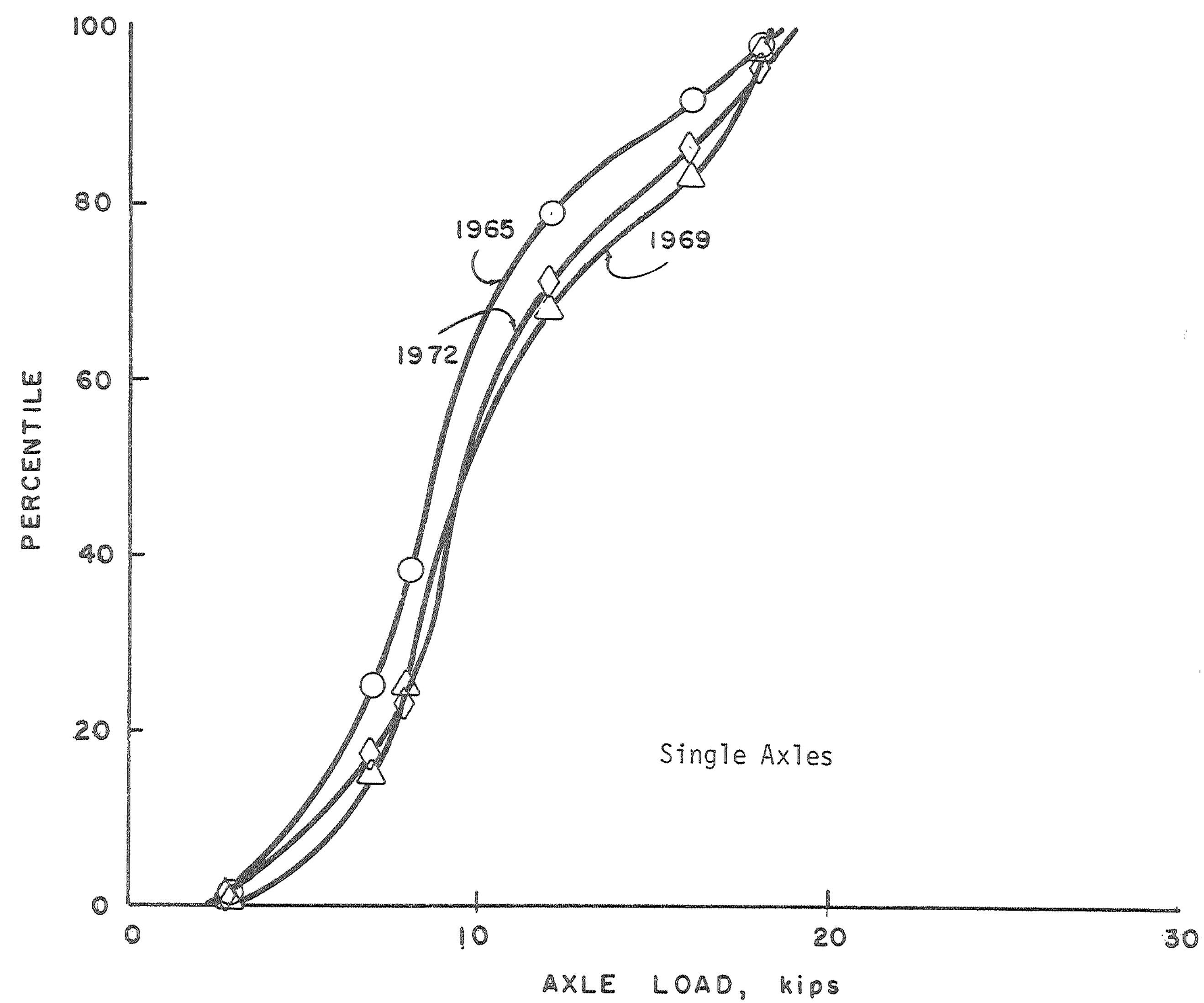

Figure 9. Load Distribution of Single Axles

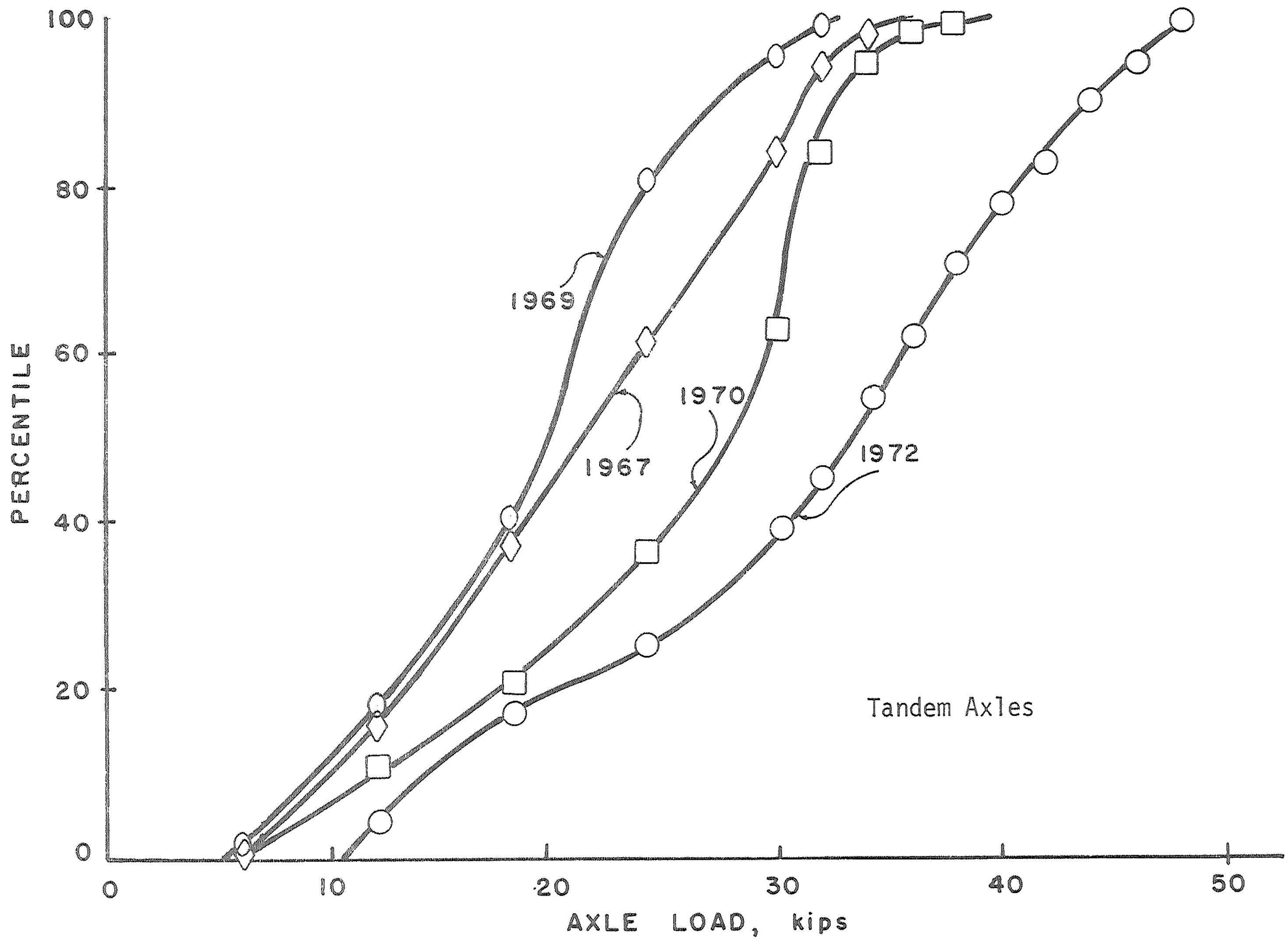

Figure 10. Load Distribution of Tandem Axles

per square inch (220×10^3 N/m^2) inflation pressure.

FA - front axle, 2 wheels each loaded to 5,500 pounds (250×10^3 kg) and 105 pounds per square inch (724×10^3 N/m^2) inflation pressure.

SA - dual wheels 13 inches center-to-center each wheel at 4,000 pounds (1.82×10^3 kg) and 105 pounds per square inch (724×10^3 N/m^2) inflation pressure.

TA - tandem axle spaced at 48 inches (1.22 m) and dual tires to same as for SA.

Number of Axles. The Arizona Truck Weight Study (18) reports also contain information (W-2 Table) on total vehicles counted at various stations in the highway system. Assuming that these counts are representative of the average number of vehicles using the highways then these counts can be broken down to obtain the average daily number of each design axle using the highway.

The data reviewed for the eight-year study period are presented in Table D16 of Appendix D. The use of the percentages of each type of axle listed in the right-most column of Table D16 must allow for the fact that the passenger vehicle and tandem axle (TA) each yield two load applications per passage.

DYNAFLECT STUDY

During 1974 the Highway Division of the Arizona Department of Transportation initiated a research program entitled "Environmental Factor Determination From In-Place Temperature and Moisture Measurements Under Arizona Pavements". At several of the test sites the pavement system was to be identified as to layer type, thickness, density and dynaflect measurements were to be made. Ten of these sites were selected for studying in our program and the data requested from ADOT were (a) site location, layer thicknesses, 4-inch (1.02×10^{-1} m) diameter cores of the asphaltic concrete, and dynaflect deflection data taken at different times of the year.

The dynaflect device is described by Scrivner, Swift and Moore in citation 19. Use of the dynaflect device for the evaluation of pavement systems was reported by the Utah State Highway Department in 1972 (20). The dynaflect has been used for determining layer stiffness in flexible pavements; these efforts have been reported by Scrivner et al (21) and Lai (22). The use of the dynaflect deflection data in this study was to obtain a measure of change of layer stiffness with time of year and also for a comparison of relative stiffness of the pavement layers.

Dynaflect Sites and Test Procedure

Location

From a listing of test site descriptions for the ADOT study, ten locations were selected on the basis that these were essentially a three-layered system and also had a range of elevation and rainfall representative of conditions in the state. Description of the test sites are given in Table E1 of Appendix E. It is to be noted that in this section the base and subbase will be considered as one layer.

Testing and Sampling

The pavement loading and sampling was performed by personnel from ADOT. For a particular section, dynaflect deflections were obtained at five different places on the section, pavement temperature was measured, surface course was sampled, and other information concerning the location was obtained. Of particular concern to our study were the deflection data and surface course samples.

Characteristics of Deflection Curves

It had been mentioned earlier (1) that the criterion on surface course stress was selected because it was independent of the modulus of elasticity of the material; rather it is dependent on the modular ratio $E1/E2 = K1$. Additionally, the selections of the basic values of E1 and E2 were such that K1 would not ordinarily exceed 10 and the modular ratio $E2/E3 - K2$ would not exceed 4. With these values as loose limits for K1 and K2 and $E1 = 200,000$ pounds per square inch (1380 M N/m^2), a family of surface deflection curves were calculated for the dynaflect loading and layer characteristics for all sites. It is being assumed that deflections are primarily dependent on K1 and K2. These calculations were performed with the Chevron program (23). The family of 20 curves was plotted with the log of the vertical deflection of each geophone against the radial distance of the geophone from one wheel.

The actual dynaflect deflection readings were examined so that the average value contained all measurements within $\pm$ 15 percent of the average. The average geophone deflection values were plotted on transparent paper to the same scale as for the family of curves obtained from calculations. The measured deflection curve was superimposed on the family curve in order to obtain a first estimate for the values for K1 and K2. With these values of K1 and K2, a new deflection curve was calculated and compared to the field curve and new estimates for K1 and K2 made. The procedure was repeated until the calculated and measured curves were in close agreement. The effects of K1 and K2 on the shape and position of dynaflect deflection curves are illustrated in Figures 11 and 12 on two pavement sections. It is seen that K2 has a principal effect on slope and K1 on position. Figure 13 shows the completed trials to establish K1 and K2 for one of the test sites.

Results and Discussion

The results obtained from testing of the asphaltic concrete cores taken from the surface have been presented in Table B12 and discussed in the section entitled Asphaltic Concrete.

Table E2 in Appendix E presents a listing of K1 and K2 modular ratios obtained for the test sites at various times of the year. The values of K1 and K2 were found as indicated earlier assuming a single value for E1. Additionally, K1 and K2 values were found for sites D6 and D9 assuming E1 values of 800,000 pounds per square inch (5520 M N/m^2) and also 50,000 pounds per square inch (345 M N/m^2). The data in the table show that K1 was materially affected by the value of E1 chosen; however, the values of E2 and E3 corresponding to the various E1's were not significantly affected for the two sites.

The data of Table E2 related to E1 of 200,000 pounds per square inch (1380 M N/m^2) are interpreted to show the following:

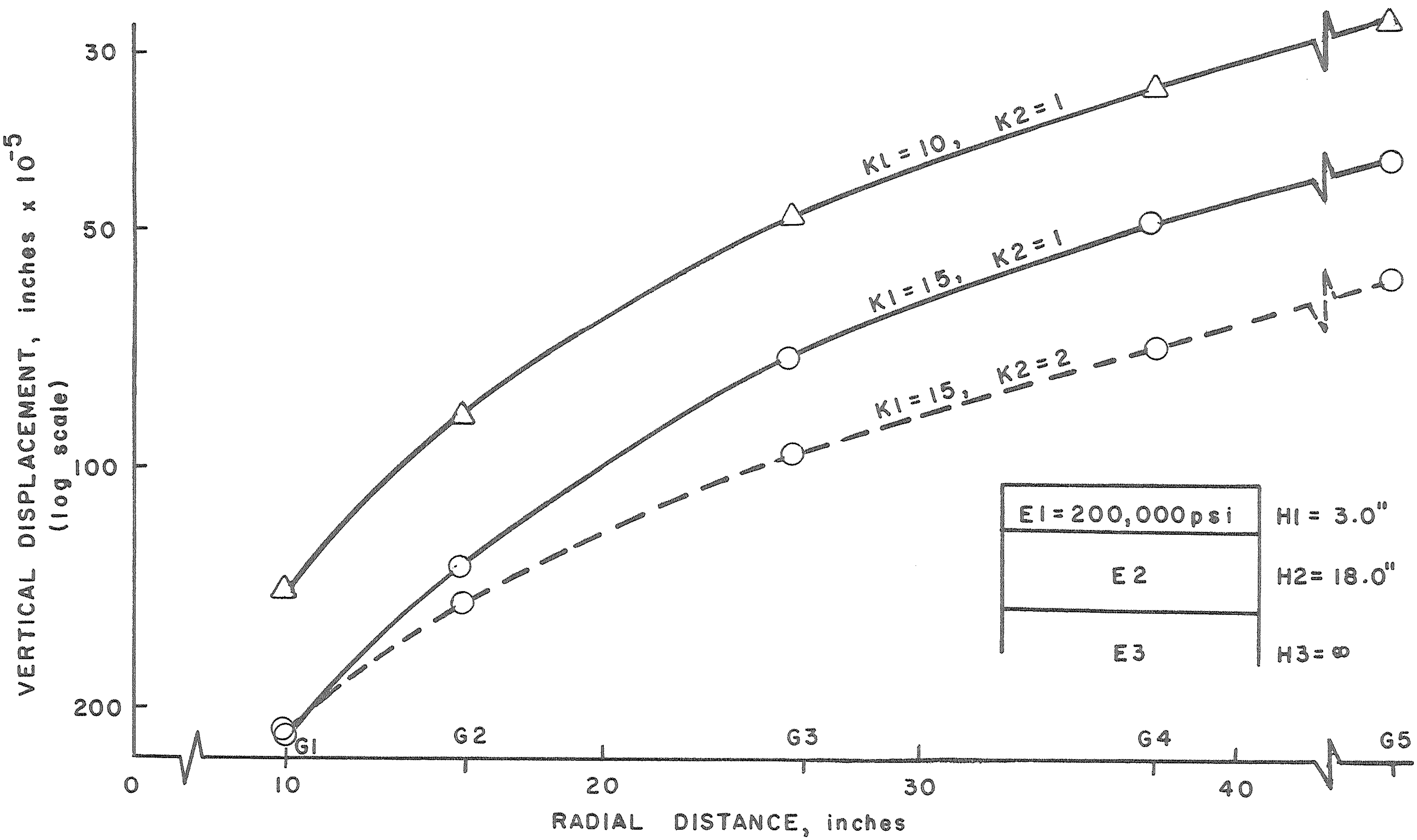

Figure 11. Effects of K1 and K2 on the Shape and Position of a Dynaflect Deflection Curve

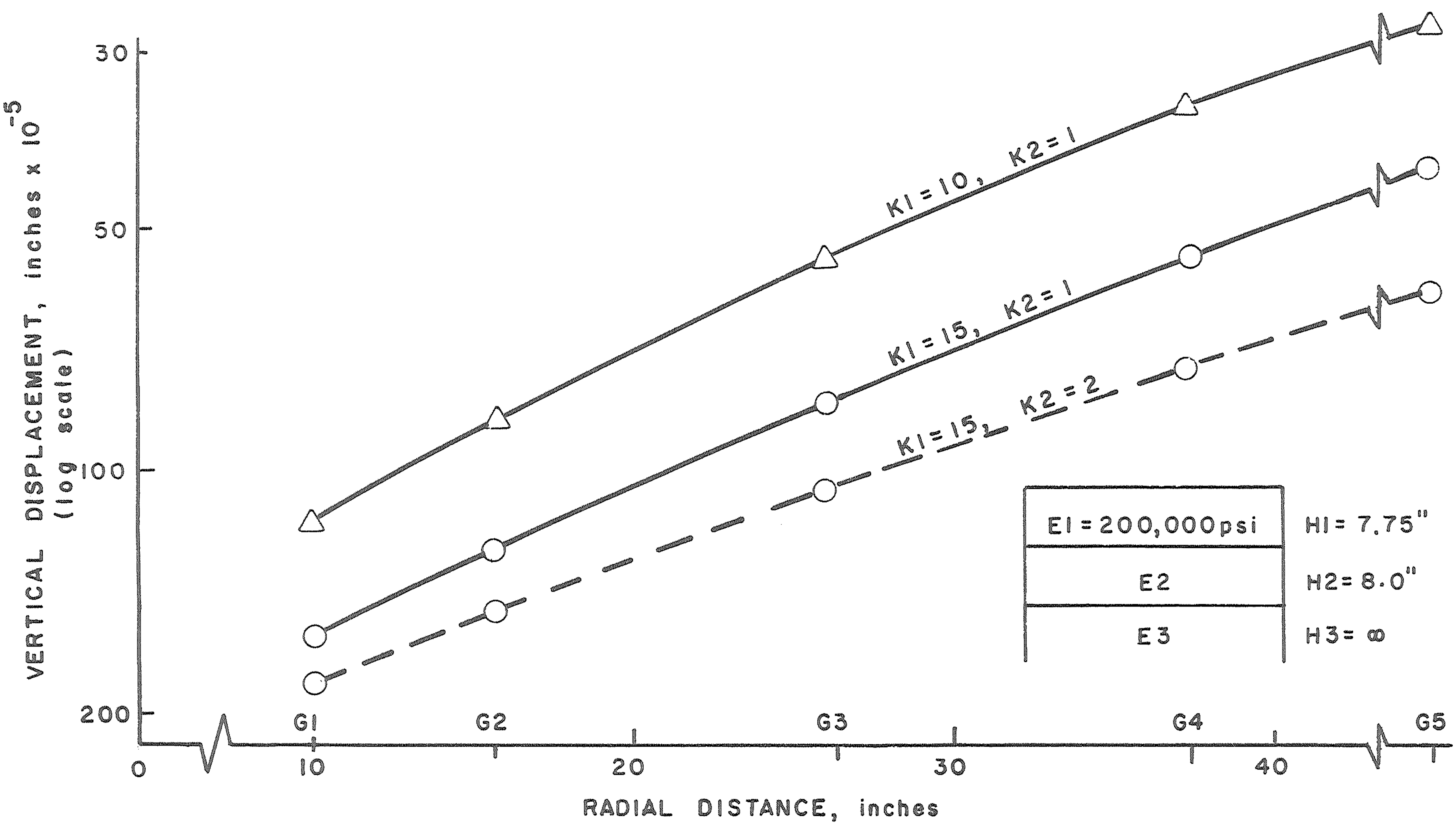

Figure 12. Effects of K1 and K2 on the Slope and Position of a Dynaflect Deflection Curve

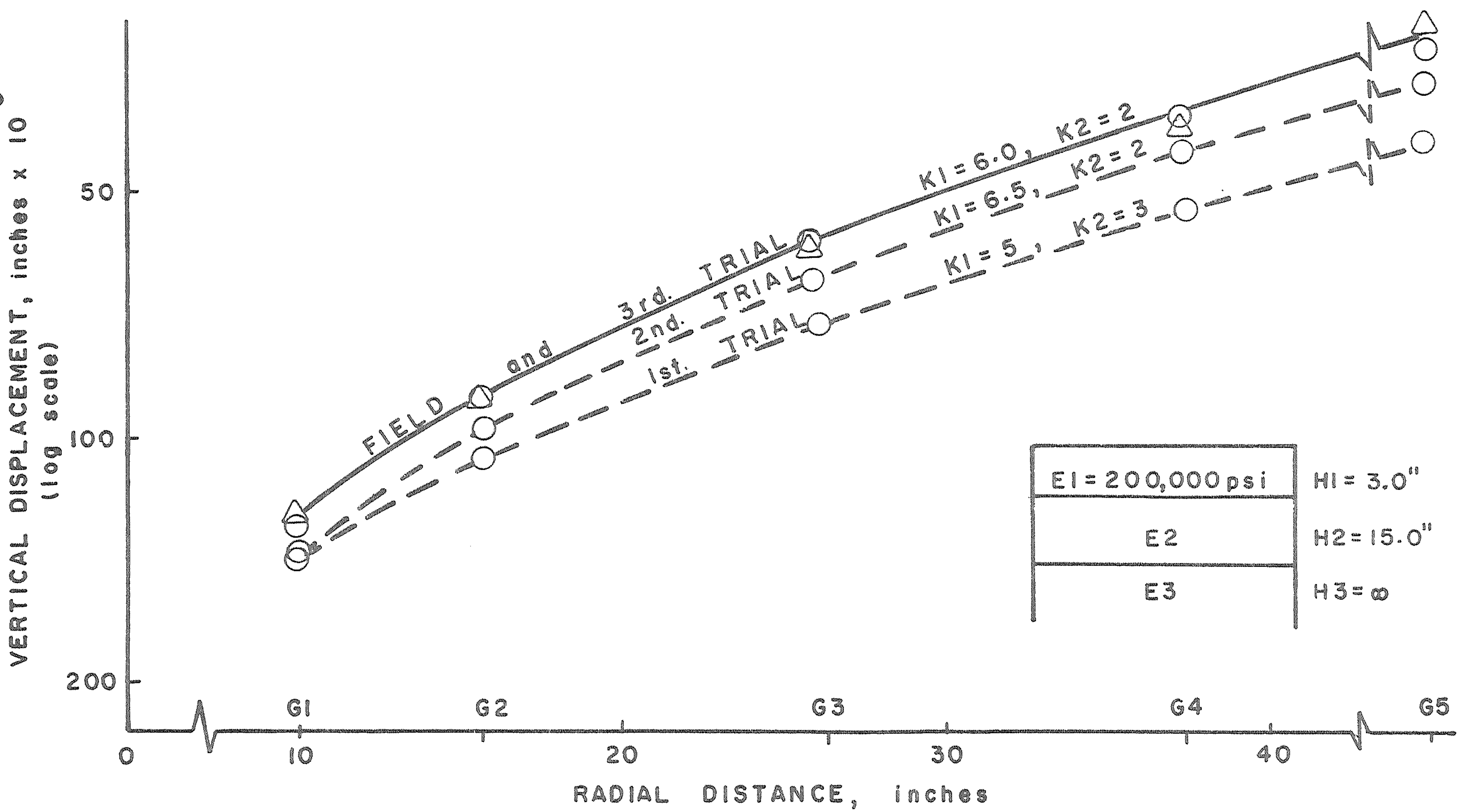

Figure 13. Example of Trial-and-Error Solution for K1 and K2 under Dynaflect Loading

1. Except for site D11, the time-of-year had no effect on the value of K2, which is a direct function of E3.
2. There is some effect of time-of-year measurement on K1 but it is not consistent since K1 should be higher in January than in May, but the opposite is shown in the table.
3. Test site D11 has 6 inches (1.52×10^{-1} m) of cement treated base. The relatively low values of K1 and high values of K2 would indicate that this base is performing as a rigid layer.
4. The average values for K1 and K2 are 10.2 and 1.2 respectively which are similar to the values assumed in the first report on pavement design.

The K2 values of less than 1.0 can not logically be explained but this low ratio is not surprising since both Scrivner et al (21) and Lai (22) found such low ratios. The data of Lai (22) are based on a 5-layered system and that of Scrivner (21) on a 2-layered one. Scrivner found modular ratios (K2 for our comparison) ranging from 0.9 to 6.3 and Lai found K1 values to be less than 3.0 for a temperature range of 40°F (4.4 °C) to 110°F (43.3 °C).

At the bottom of Table E2 a linear equation relating K1 to K2 is shown as

$$K1 = 14.7 - 4.81\ K2 \qquad 3.$$

This equation was derived from data obtained on all the test sites and under the assumption that the dynaflect deflections are principally dependent on K1 and K2. The implication of this relationship is that if E3 is of low value then E1 is of low value (holding E2 constant) or if E3 is of high value then E1 is of high value. This means that if the subgrade soil has high deflection (low E) then the surface course will behave as a "soft" (low E) material. The opposite is also implied, that is, if the subgrade soil has low deflections (high E) then the surface course will behave as a "hard" (high E) material. These same statements apply to the base course material if E1 is held constant. However, if E3 is held constant, then E1 will be high if E2 is low and *vice versa* E1 will be low when E2 is high. Comparable finding was reported by Ueshita, Yoshikane, and Tamano (24) from Benkleman beam test performed on three layered pavements.

If the double punch dynamic modulus of elasticity value obtained for the pavement cores and the corresponding values of K1 and K2 are used then it can be seen that E2 values range from 7,000 to 30,000 pounds per square inch (48-207 M N/m^2) and E3 values range from 4,000 to 31,000 pounds per square inch (27-214 M N/m^2).

There is a certain amount of concern over the values of K2 that are less than one and also over the general lack of effect from time-of-year on K1 and K2. The writer accepts a certain amount of variability from experimental error in the data acquisition and the graphical reduction; but also believes that there is additional useful data that could be obtained from the dynaflect. For example, the deflection at the first geophone is not the maximum deflection caused by the loading. Figure 14 shows plots of calcualted surface deflections under the dynaflect loading for two pavement systems. It is readily seen that the first geophone (G1) does not correspond to the maximum deflection. If one is to attempt to calculate E3 from surface deflection then one should use the largest value of practical measurement. The plot of G1 deflections vs K1 values shown in Figure 15 suggest that the G1 value is closely related to K1. As shown in Figure 15 the R^2 value for the comparison between G1 de-

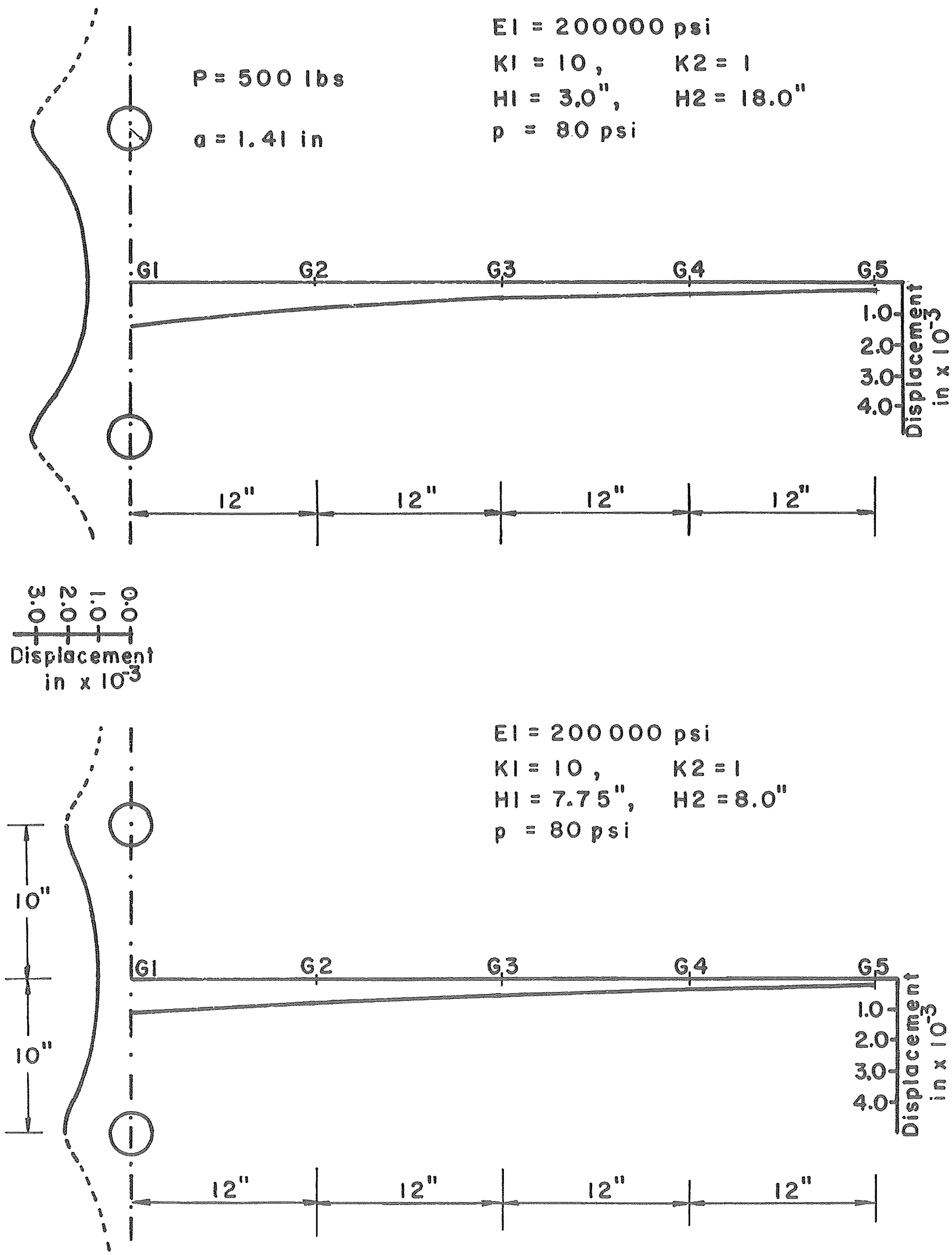

Figure 14. Calculated Dynaflect Deflections

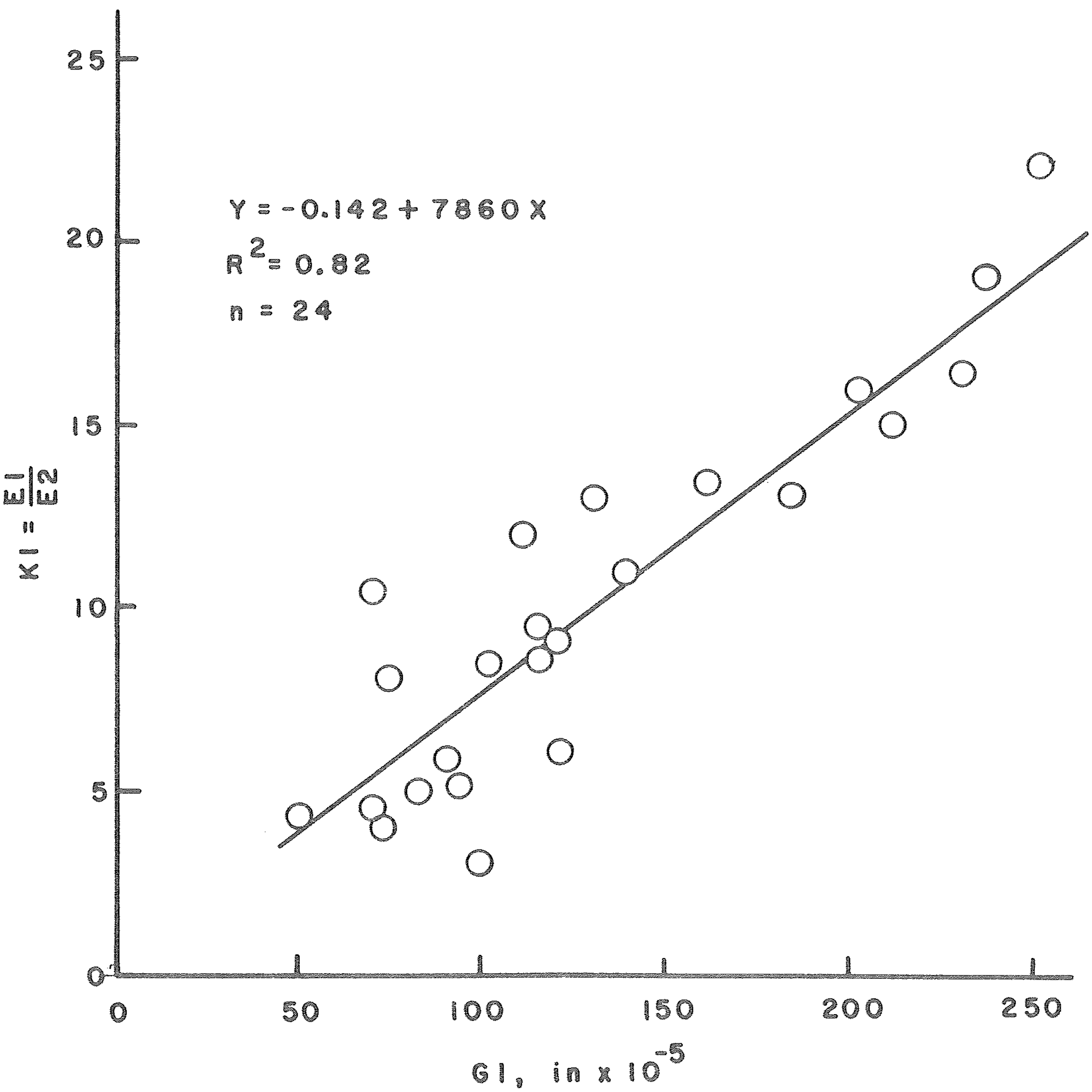

Figure 15. Comparison of Dynaflect Geophone Deflection G1 with K1 of Test Sites

flection and K1 is 0.82. Other regression analyses between deflection differences G1-G2 or G4-G5 and K1 yielded R^2 values of less than 0.23.

An interesting relationship is shown in Figure 16 where K1 values obtained from dynaflect data are compared to E1 correction factors which modify the basic E1 value for temperature (elevation) effects. From the graph of Figure 16, it appears that the relative stiffness of the asphaltic concrete to the base (K1) increases as the elevation of the site increases; one would wounder whether K1 is then independent of the original material stiffness. Do bases become less stiff at higher elevation or does asphaltic concrete become stiffer at higher elevations?

From the above it is assumed that the dynaflect deflections are affected principally by the pavement layers and not much by the subgrade. This may be due to the locations of the geophone since the highest deflection of the loading is not determined.

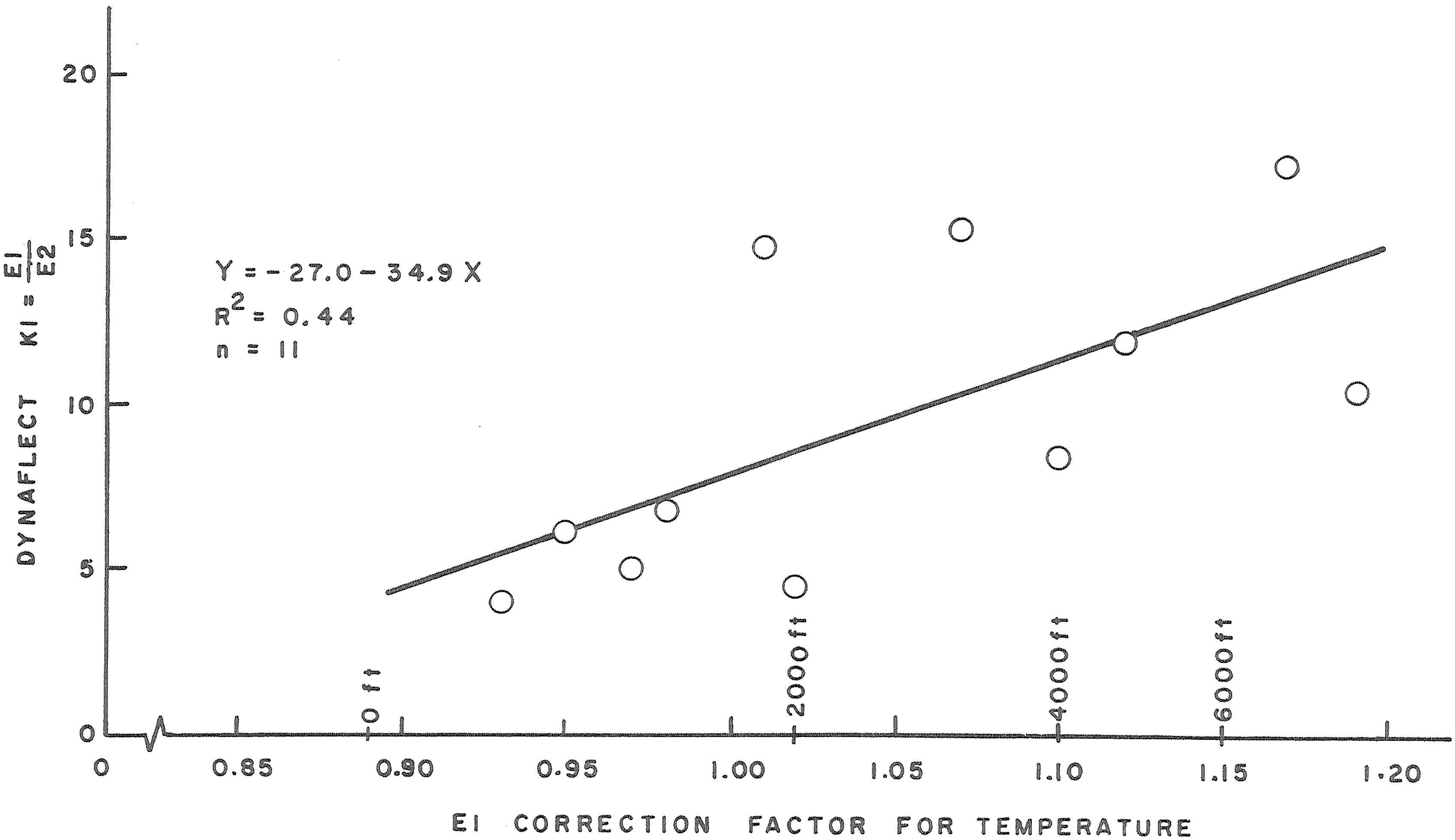

Figure 16. Comparison Between Temperature Correction Factors and K1's

MODIFICATIONS TO THE PAVEMENT DESIGN COMPUTER PROGRAM

In Reference 1, the new pavement design procedure was demonstrated. As was noted then certain parameters were assumed to be constant. The results of present research programs have furnished data to change the values and descriptions of certain design factors, as discussed in the following paragraphs.

Traffic

The loadometer and questionnaire data suggested that traffic can be characterized quite simply as described in this report. The reader is cautioned that the values of load and number of vehicles reported here are for only the interstate rural type of highway in Arizona. The specific changes in traffic definitions made in the program are listed below:

1. Consider the type of highway, e.g., interstate, primary, etc.
2. The 2D axle has been replaced with an FA (front axle).
3. The wheel loads and inflation pressures have been generally increased.
4. A new method for determining the number of load applications has been developed.

Material Property

The investigation to define material properties was devoted primarily to asphaltic concrete. Although dynamic modulus of elasticity for soil and asphaltic concrete were determined in the laboratory, it is not now being recommended to change the value of dynamic modulus E1 in the design method.

Asphaltic Concrete

As indicated above, E_D for asphaltic concrete was determined in the laboratory; however, we are not proposing to change the fixed value of 200,000 pounds per square inch (1378 M N/m^2) included in the design concept.

The study on fatigue characteristics indicated that this property should be treated as a variable or input quantity into the computer program. As a consequence, four fatigue equations can be used for characterizing this property of asphaltic concrete. These equations are as follows.

1. $\sigma_t = 1150\ N^{-0.236}$
2. $\sigma_t = 2200\ N^{-0.281}$
3. $\sigma_t = 5350\ N^{-0.331}$
4. $\sigma_t = 10{,}600\ N^{-0.420}$

The use of these new equations will generally lead to thicker surfacing when load repetitions exceed one million applications.

Example Computations

Instructions for input of data into the computer program and also the program itself are attached as Appendix F. The detailed trial-and-error procedure of estimating the thicknesses of surface and base courses will not be presented here since this and the criteria for the design method have been given before in the first report (1).

The tabulation of Table 3 shows that for this example the conditions are as follows:

1. The road is classified as interstate rural and has four lanes.

TABLE 3 EXAMPLE OF TRAFFIC CALCULATION

CALCULATION FOR NUMBER OF STRESS APPLICATIONS

Location ________ Highway Classification Int.-rural Number of Lanes 4

Elev.: 3600 ft. R.F.: 1.8 Rainfall 11 in./yr. R.F.: 1.4

Present 1971 ADT 2255 Future 1991 ADT 3022 Average ADT 2638

Directional Distribution Factor 0.5 Lane Distribution Factor 0.9

Design Lane Distribution Factor 0.5 x 0.9 = 0.45

Average ADT of Design Lane 2638 x 0.45 = 1187

Axle Type	No. of Axles		% of ADT for Hwy Type		Avg. ADT of Design Lane		No. of days, Design Life		Total Stress Repetitions, 10^6
Passenger	2	x	70	x	1187	x	7300	=	12.13
2P	1	x	23	x	"	x	"	=	1.99
FA	1	x	10	x	"	x	"	=	0.87
SA	1	x	25	x	"	x	"	=	2.17
TA	2	x	22	x	"	x	"	=	3.81

2. It is located in an area having an elevation of 3600 feet (1.09×10^{3} m) and an annual rainfall of 11 inches (2.79×10^{-1} m)
3. The present and future ADT's are 2255 and 3022 respectively and the growth is assumed to be linear.
4. The directional and lane distribution of traffic are 0.5 and 0.90.
5. The percentage distribution of axle type for the particular highway is indicated.

The values for wheel load, tire inflation pressure, and tandem axle spacing are stored in the computer corresponding to this highway classification. The input data are listed in six cards as described in Appendix F.

The percent fatigue life used over the design life is calculated by the computer program for various paired values of H1 and H2. The paired value of H1-H2 yielding a fatigue life close to one hundred percent is the design thickness for the pavement. A set of out-put data for the pavement design program is shown on Table 4.

The tabulation of Table 5 is to show the effect and a comparison of results obtained from the change of the flexural fatigue equation. It is evident that for identical design situation the value of the exponent in the fatigue equation is extremely critical. In fact with higher absolute values of the exponent a balanced design will result in thickness of base (H2) being required and thus lead to a two-layered system.

TABLE 4. ASPHALT DESIGN DATA FOR TRIAL NO. 7

E1 =217921.
E2 = 20000.
E3 = 4379.

H1 = 15.0 IN.
H2 = 4.0 IN.

RF1=1.8 RF2=1.4

ISO= 2200. EXPON= 3.56

THE ACTUAL REPETITIONS ARE AS FOLLOWS

PASSENGER .121E+08 2P .199E+07 FA .870E+06 SA .217E+07 TA .381E+07

AXLE TYPE	RADIAL STRESS	---VERTICAL STRAIN---- AT W.C.	AT A.C.
PASSENGER	.523E+01	-.352E-04	NA
2P	.814E+01	-.549E-04	NA
FA	.279E+02	-.188E-03	NA
SA	.282E+02	-.224E-03	-.242E-03
TA	.265E+02	-.237E-03	-.256E-03

AXLE TYPE	-------ALLOWABLE REPETITIONS-------- FOR STRESS	FOR STRAIN AT W.C.	AT A.C.
PASSENGER	.218E+10	.235E+13	NA
2P	.451E+09	.256E+12	NA
FA	.562E+07	.540E+09	NA
SA	.543E+07	.226E+09	.154E+09
TA	.676E+07	.169E+09	.116E+09

AXLE TYPE	-----PERCENT FATIGUE LIFE USED------ FOR STRESS	FOR STRAIN AT W.C.	AT A.C.
PASSENGER	.56	.00	NA
2P	.44	.00	NA
FA	15.47	.16	NA
SA	39.95	.96	1.41
TA	56.38	2.25	3.28
TOTALS	112.81	3.38	4.69

TABLE 5. PAVEMENT DESIGN LAYER THICKNESSES FOR THE EXAMPLE PROBLEM AND FOR TWO FLEXURAL FATIGUE EQUATIONS

H1 in.	H2 in.	Total Percent Fatigue Life Used: Stress W.C.	Strain W.C.	Strain A.C.
		$\sigma_t = 2200\ N^{-0.281}$		
13	4	228	9	14
15	4	113	3	5
		$\sigma_t = 1800\ N^{-0.200}$		
6	14	115	109	181
6	16	104	67	106

CLOSURE AND RECOMMENDATIONS

Examination of the test results and discussions presented lead to recognition of certain factors that were not fully appreciated before. These are listed below and recommendations are made where appropriate.

1. Flexural Fatigue. The deflectometer test responded to mixture variables and the results separated the mixtures into four groups fitting the basic fatigue equation. The evaluation of the mixtures showed that Arizona mixtures are much more brittle than that originally assumed. As a consequence, thicker surface layers will be required for high volume roads unless the mixtures are designed to be more pliable. No tests on standard sized specimens could be correlated satisfactorily with the deflectometer test; therefore, it is recommended that this search be continued.
2. Modulus of Elasticity for Asphaltic Concrete. There were no data evolved to require changing the assumption that E1 is constant and equal to 200,000 pounds per square inch (1378 M N/m^2).
3. Fatigue Test for Subgrade Soils. The literature review and the limited testing using a new method of repeated load triaxial testing indicated a fruitful procedure for characterizing fine grained soil for fatigue and dynamic modulus of elasticity characteristics. It is recommended that the new procedure be investigated to a greater extent than reported.
4. Traffic Characterization. The procedure developed to establish the weight and number of the five "design axles" appears to be

adequate; however, its validation requires its usage in actual pavement design. The format of W4 tables should be modified to separate front axles from single axles. Also it is recommended that tire pressures be recorded in loadometer surveys.

5. Dynaflect Deflections. Close examination of the dynaflect deflection data indicated that the deflection basin was influenced principally by the character of the surface and base course; the subgrade had a minor effect on these deflections. It is believed that the device or procedure can be modified to yield more useful and significant data for pavement and subgrade evaluation. There was a significant relationship between dynaflect deflection G1 and K1 (E1/E2) and of particular interest K1 and the correction factor for E1. We strongly recommend further studies with/of the dynaflect.

6. It is recommended that ADOT determine the traffic characteristics for other classifications of highways and use the pavement design procedure for comparison with their present method.

ACKNOWLEDGEMENT

The cooperation received from the Arizona Department of Transportation is greatly appreciated. Their efforts in obtaining the paving materials and dynaflect deflections were significant contributions to the research effort. We recognize the help from Professor R. Richard of the Civil Engineering Department for facilitating the modification to the computer program used for design. As indicated in the text Professor D. DaDeppo developed the relationship between the double punch test procedure and the modulus of elasticity for asphaltic concrete. We sincerely appreciate the sponsorship by ADOT and FHWA of this work since we believe that it is through such efforts that a "theoretical" design procedure will be evolved.

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