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16. Abstract

This report presents a statistical analysis of Dynaflect deflection and slab temperature data to investigate different test location variables and temperature parameters that affect Dynaflect deflections measured on rigid pavement. A procedure is developed for making Dynaflect deflection measurements and applying a suitable temperature correction to deflections measured near the pavement edge. A computer program is included that will facilitate the estimation of temperature in a concrete slab using local weather and climatological data. Improvements are suggested in the procedure of using elastic layered theory (static loading) based computer packages to back-calculate Young's moduli from the measured Dynaflect deflection basin. The "spectral analysis of surface waves" method and crosshole testing used on the Columbus site are also presented and discussed.

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INVESTIGATIONS INTO DYNAFLECT DEFLECTIONS IN RELATION TO LOCATION/TEMPERATURE PARAMETERS AND INSITU MATERIAL CHARACTERIZATION OF RIGID PAVEMENTS

by

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Research Report Number 256-5

The Study of New Technologies for Pavement Evaluation
Research Project 3-8-80-256

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Texas State Department of Highways
and Public Transportation

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by the

Center for Transportation Research
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December 1983

The contents of this report reflect the views of the authors, who are responsible for the facts and the accuracy of the data presented herein. The contents do not necessarily reflect the official views or policies of the Federal Highway Administration. This report does not constitute a standard, specification, or regulation.

PREFACE

The report is the fifth in the series documenting the research work accomplished on Research Project 3-8-80-256, "The Study of New Technologies for Pavement Evaluation." The project is being conducted as part of the Cooperative Highway Research Program sponsored by the Texas State Department of Highways and Public Transportation and the Federal Highway Administration.

The findings from the study presented in this report have resulted in a recommended procedure for removing the influence of any temperature differential in the measured Dynaflect deflections on rigid pavements.

The authors gratefully acknowledge the constructive comments and suggestions given by Dr. B. F. McCullough, especially during the analyses of field data. Thanks are due to Gary Fitts, Graduate Research Assistant who designed and carried out most of the experimental work and helped in the preliminary analysis; thanks are also due to Jim Long and Leon Snider for helping in the field tests, to Darrell Smith, David Luhr, K. Kailasananthan and other staff of the Center for Transportation Research who provided support.

The authors also appreciate and acknowledge the continued support from Gerald Peck, Richard Rogers, and Ken Hankins of the Texas State Department of Highways and Public Transportation. Special thanks are also due to the Resident Engineer of District 13 and his staff for cooperation and assistance during field tests.

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LIST OF REPORTS

Report No. 256-1, "Comparison of the Falling Weight Deflectometer and the Dynaflect for Pavement Evaluation," by Bary Eagleson, Scott Heisey, W. Ronald Hudson, Alvin H. Meyer, and Kenneth H. Stokoe, presents the results of an analytical study undertaken to determine the best model for pavement evaluation using the criteria of cost, operational characteristics, and suitability.

Report No. 256-2, "Determination of In Situ Shear Wave Velocities From Spectral Analysis of Surface Waves," by J. Scott Heisey, Kenneth H. Stokoe II, W. Ronald Hudson, and A. H. Meyer, presents a method for determining elastic moduli at soil and pavement sites. Criteria considered in developing this method included the restraint of nondestructive testing, accuracy of moduli for all layers regardless of thickness, and quickness and efficiency for rapid, extensive testing.

Report No. 256-3, "Detection of Cracks on Highway Pavements," by C. H. Chien, W. N. Martin, A. H. Meyer, and J. K. Aggarwal, presents algorithms for the detection of cracks of highway pavements in aerial photographs.

Report No. 256-4, "Evaluation of Moduli and Thicknesses of Pavement Systems by Spectral-Analysis-of-Surface-Waves Method," by Soheil Nazarian and Kenneth H. Stokoe, presents the Spectral-Analysis-of-surface-waves (SASW) method for determination of moduli and thicknesses of pavement systems. Testing procedure is simple, and a unique solution to the problem is obtained.

Report No. 256-5, "Investigations Into Dynaflect Deflections in Relation to Location/Temperature Parameters and Insitu Material Characterization of Rigid Pavements," Waheed Uddin, Soheil Nazarian, W. Ronald Hudson, Alvin H. Meyer, and Kenneth H. Stokoe II, presents a recommended procedure for removing the influence of any temperature differential in the measured Dynaflect deflections on rigid pavements.

ABSTRACT

This report presents a statistical analysis of Dynaflect deflection and slab temperature data to investigate different test location variables and temperature parameters that affect Dynaflect deflections measured on rigid pavement. A procedure is developed for making Dynaflect deflection measurements and applying a suitable temperature correction to deflections measured near the pavement edge. A computer program is included that will facilitate the estimation of temperature in a concrete slab using local weather and climatological data. Improvements are suggested in the procedure of using elastic layered theory (static loading) based computer packages to back calculate Young's moduli from the measured Dynaflect deflection basin. The "spectral analysis of surface waves" method and crosshole testing used on the Columbus site are also presented and discussed.

KEYWORDS: Dynaflect, deflection, continuously reinforced concrete pavement, temperature differential, elastic moduli, material characterization, spectrum analyzer, crosshole testing, dynamic moduli.

SUMMARY

This report presents results of an investigation of (1) the effect of some environmental factors and location variables on measured Dynaflect deflections, and (2) material characterization using measured deflection basins. Additionally "spectral analysis of surface waves" and crosshole testing techniques are presented. All the experimental work described in this report was carried out during the fall and summer of 1981 on the Columbus bypass (CRC pavement) at SH71.

The experimental data, Dynaflect deflections and the top and bottom temperatures of the concrete slab, were analyzed using measured and dichotomous variables and multiple linear regression techniques. The findings of this study are combined into a procedure recommended for making Dynaflect measurements and applying suitable temperature correction to deflections measured near the pavement edge. A computer program to predict temperature in the concrete slab based on a theoretical model that uses daily weather information is also presented.

The results of a parametric study to improve the procedure for back calculation of the elastic moduli of pavement layers from the measured deflection basins are also presented and discussed. The test procedures and the results of the "Spectral-Analysis-of-Surface-Waves" method and crosshole tests are presented and discussed. The in-situ dynamic moduli obtained from these two methods based on the theory of wave propagation, are compared with the back-calculated static elastic moduli using multilayered linear elastic theory.

IMPLEMENTATION STATEMENT

Based on the analysis of Dynaflect deflection and temperature data, a procedure has been suggested for taking the Dynaflect deflection measurements and applying suitable corrections to remove the effect of temperature differential on the measured deflections near the pavement edge. A procedure is suggested to estimate the temperature of the concrete slab using local weather and climatological information, in order to apply any temperature correction on a routine basis.

It is recommended that these proposed procedures be implemented as a part of any future structural evaluation of rigid pavements.

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CHAPTER 1. INTRODUCTION

GENERAL

Nondestructive evaluation of existing pavements is carried out to assess their structural adequacy and rehabilitation needs. The Texas State Department of Highways and Public Transportation uses the Dynaflect, a steady state vibratory device, for nondestructive evaluation of asphalt and rigid pavements. The response of a pavement to an external test load is measured in terms of surface deflection, which is indicative of the load carrying capacity of the road pavement. The Dynaflect deflection data are used for in-situ characterization of pavement layers and subgrade as the basic step in the current overlay design procedures.

In the case of rigid pavement, the distress manifestations indicate other deficiencies and problems, such as inadequate subgrade support conditions, existance of voids beneath concrete pavement, and insufficient load transfer across joints in a jointed concrete pavement. A major rehabilitation program in an existing rigid pavement will include rectification of the above deficiencies plus an overlay for the structural strengthening required for the design axle load applications in the future. The Dynaflect deflection data can also be used to provide diagnostic information related to the rigid pavement which can be used to detect voids beneath the concrete slab and to determine the load transfer efficiency at transverse joints.

The Spectrum Analyzer is another form of nondestructive test equipment which can be used to ascertain the in-situ dynamic moduli based on elastic waves analysis.

OBJECTIVES AND SCOPE OF STUDY

There are several factors that influence any deflection measurement made on a slab of specific thickness. Two of these are temperature and load position. In the case of a rigid pavement effects are very prominent. The temperature gradient through the thickness of the slab induces thermal stresses and subsequently results in curling. The deflection measurements may therefore be affected by temperature, particularly at the edge of the slab. The principal objectives of this study are

(1) to identify temperature effects and other factors related to load position across the test section that may influence the Dynaflect deflections in rigid pavements,

(2) to investigate the significance and extent of the influence of these factors on measured Dynaflect deflections,

(3) to develop a procedure for correcting the measured deflections in order to correct the effects of temperature if necessary, and

(4) to recommend the most suitable position of the Dynaflect for making deflection measurements for material characterization or for detection of voids beneath concrete pavement.

The experimental program carried out on a continuously reinforced concrete pavement and the summary data are described in Chapter 2. The concrete slab was 10 inches in thickness. The Dynaflect deflection and temperature data generated during the testing phase were later subjected to a comprehensive statistical analysis. A multiple regression technique is used to delineate significant factors affecting the measured deflections. The procedures and results of the statistical analyses are discussed in Chapter 3. The guide lines for temperature correction procedures are developed in Chapter 4, which includes recommendations for a modified and calibrated model to predict temperature at any depth of a concrete pavement using climatological data from daily weather reports.

This report is devoted to the study of Dynaflect deflections measured on rigid pavement and the findings are limited to a continuously reinforced concrete pavement.

In addition, procedures for in-situ material characterization using methods based on layered elastic theory and wave propagation theory are also applied at the same site and results are to be compared.

CHAPTER 2. EFFECTS OF ENVIRONMENTAL FACTORS AND DYNAFLECT POSITION ON MEASURED DEFLECTIONS

INTRODUCTION

This chapter includes (1) a discussion of factors influencing the deflection behavior of rigid pavements, and (2) a brief review of some previous research on environmental effects and other factors related to load position, describes the testing program, and presents a summary of Dynaflect deflections and temperatures for the concrete slab measured during summer and fall 1981 at three sections selected on a newly built continuously reinforced concrete pavement.

Temperature changes in the concrete slab and moisture changes in the unbound and subgrade layers are the two environmental factors showing a major influence on the measured deflections. In the wet season, deflections will be larger due to an increase in moisture content of unbound layers and softening of the subgrade. A dry summer, on the other hand, will result in relatively lower deflections. The seasonal effects on the Dynaflect deflections are thoroughly discussed in Ref 1. The temperature gradient occurring in the concrete slab during a normal day will cause the slab to curl upwards if the concrete surface is hotter than the bottom (i.e., in the case of a positive temperature gradient). This will cause the deflection measured near the edge to be different from the deflection measured in the center of the slab. Studies on continuously reinforced concrete pavement (Ref

2) indicated that edge deflections measured in the mid span position were in general inversely related to the temperature differential (i.e., the algebraic difference between temperatures of the top and the bottom of the concrete slab). Dynaflect deflection data were therefore collected in the present study to investigate the effects of temperature parameters in relation to the position of the Dynaflect on the measured deflections. The collected Dynaflect deflection data were analyzed using statistical procedures to determine the significant explanatory variables and their effects on the deflection parameters.

LITERATURE REVIEW

Environmental Variables

Temperature Effects. The temperature of a concrete slab shows two types of variation in the average temperature: (1) daily and (2) yearly. Arndt (Ref 3) reported, in 1943, the results of five years of continuous study of temperature changes in an experimental concrete pavement in Arkansas. The air temperature and the temperature of the top of the slab for the year 1940, as reported in Ref 3, are reproduced in Fig 2.1. Some interesting points can be inferred from this figure:

(1) generally, over a year, the temperature of the concrete slab follows very closely, the pattern of the air temperature variation;

(2) the greatest variation in the daily range of the pavement temperature is observed to occur in the months of May through September; and

(3) for any one day the range of the temperatures of the bottom of the slab was about 15°F less than the range of the temperatures of the top.

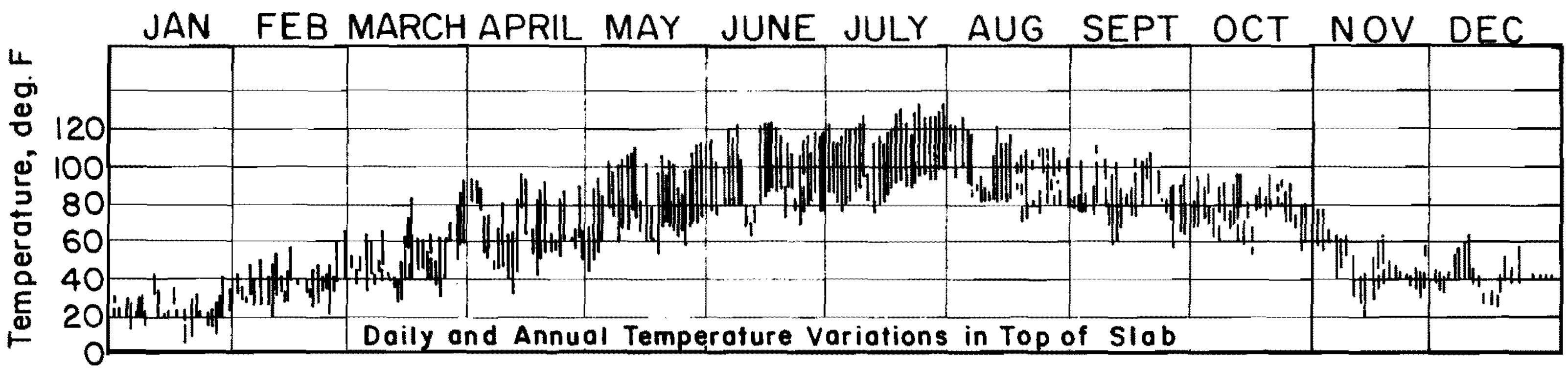


Fig 2.1(a). Temperature variations in top of P.C. concrete slab, Arkansas, 1940 (Ref 3).

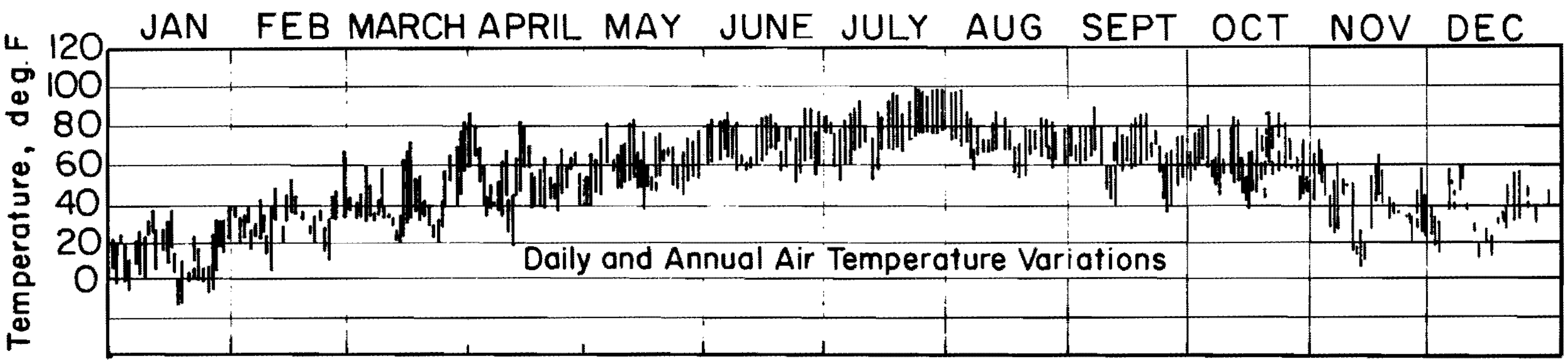


Fig 2.1(b). Air temperature data, Arkansas, 1949 (Ref 3).

The data from Bates Road Test (1922) used by Barber (Ref 4) are plotted in Fig 2.2. They also show that the maximum temperature of the pavement at the surface is in general higher than the corresponding air temperatures. The seasonal variations in temperatures cause the concrete pavement to adjust to these uniform temperature changes by contraction or expansion over a considerable period of time. The major effects of the seasonal variations in temperature will be the development of frictional forces between the concrete slab and the underlying layer and closing and opening of cracks and joints.

The daily variations of temperature within the concrete slab are of much more importance because (1) there is a large deviation in temperature on the concrete surface in a daily cycle and (2) a temperature gradient exists between the top and bottom of the concrete slab that will vary considerably, and in different directions, during a 24-hour cycle. The temperature gradient through a concrete slab causes its surface to warp (Ref 5). For example, if the top of the slab is hotter than the bottom, as at noon on a normal day, the corners will tend to curl downwards. Upward curling will occur when the top surface is cooler than the bottom, such as late at night. Figure 2.3 shows a conceptual presentation of curling behavior of a concrete slab during a typical 24-hour cycle on a normal day. A parameter commonly used to study the effect of temperature gradient is temperature differential. As defined earlier, temperature differential is the algebraic difference between the temperatures of the top and the bottom of the concrete slab. Temperature differential is assigned the notation DT in this report. Temperature differential is taken as a positive value if the temperature of the top of the slab is higher than the temperature of the bottom. A negative temperature differential indicates that the bottom of the

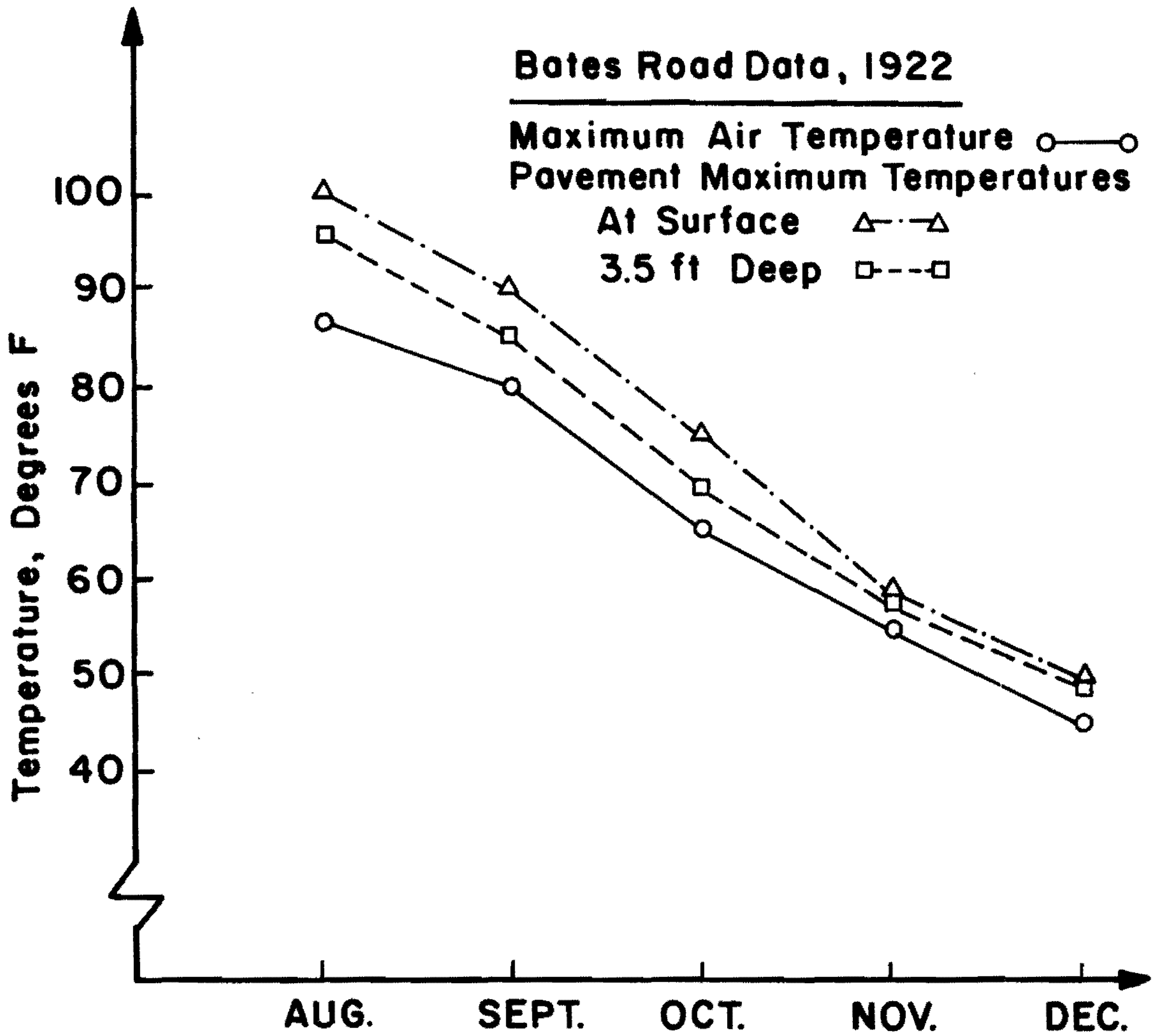


Fig 2.2. Monthly variation in air and concrete pavement temperatures - Bates Road Test (Ref 4).

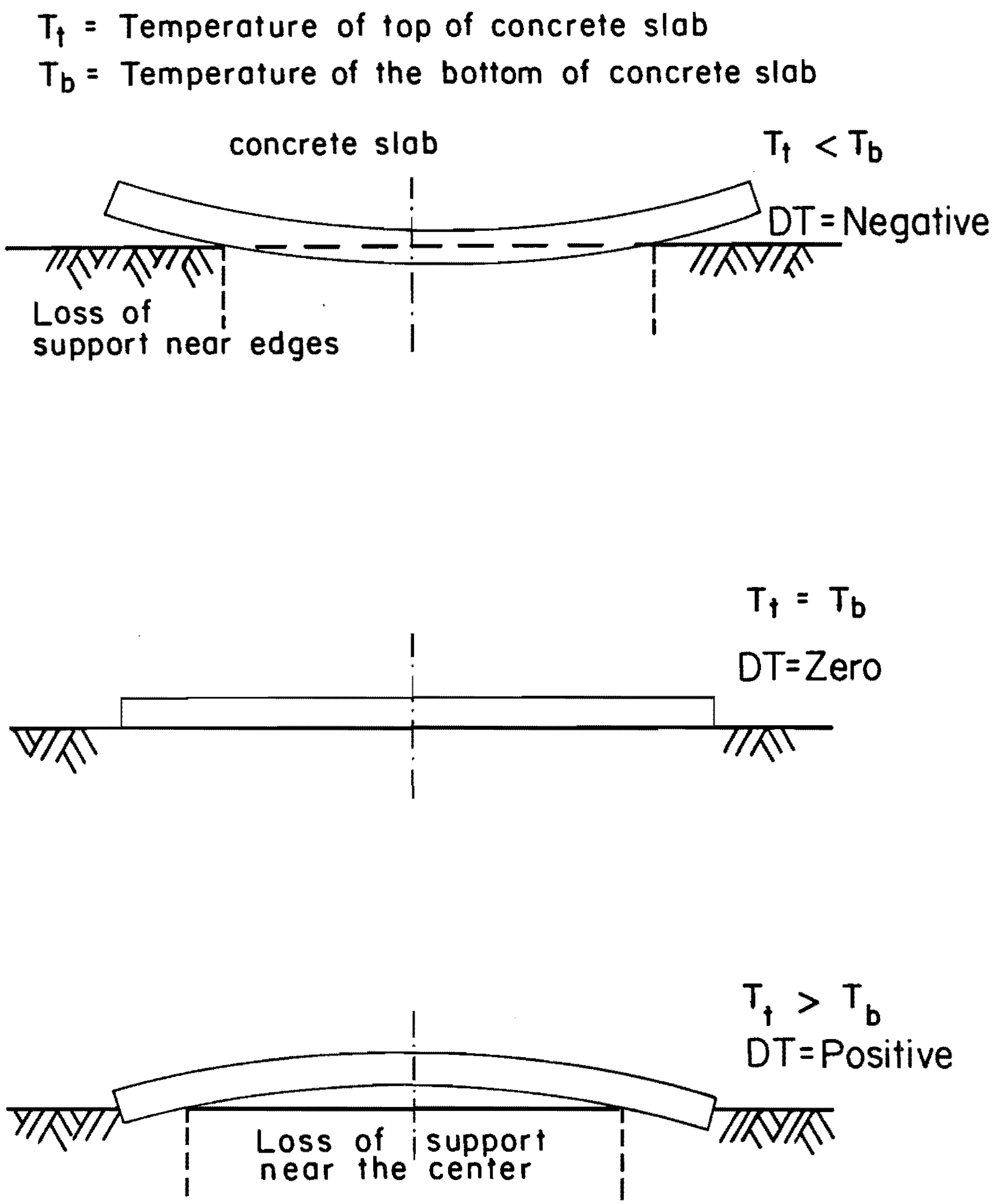
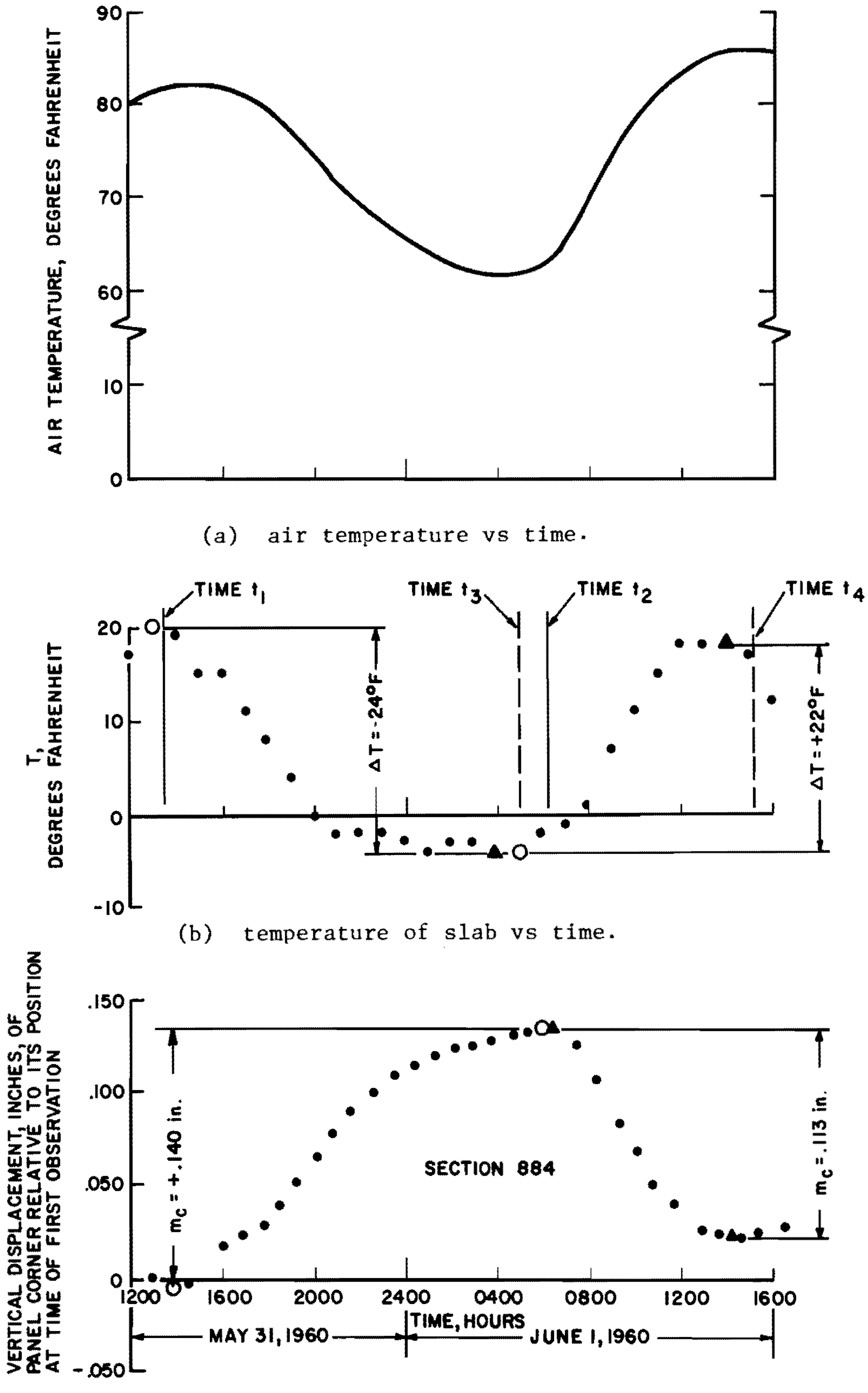


Fig 2.3. Conceptual illustration of curling in a concrete slab.

slab is warmer than the surface. The temperature differential is caused by the time required for heat to transfer through the thickness of the concrete slab because of the slow conduction of heat in concrete. Temperature differential in a concrete pavement is therefore a function of the thermal properties of concrete and the thickness of the concrete slab. Maximum temperature differentials occur during the day in the spring and summer (Ref 5). During the present study the maximum temperature differential, 24.6°F, was observed in August 1981, for the 10-inch concrete slab. Twenty-four-hour studies on curling of panel corners due to fluctuating air temperature and the resulting temperature differential were made in the AASHO Road Test (Ref 6). The studies showed that the deflection of panel corners under the vehicles travelling near the pavement edge at times increased several fold during the period from afternoon to early morning (Ref 6). This may be explained by upward curling of corners due to a negative temperature differential. Figure 2.4 shows the time, temperature, and displacement data from a corner movement study of a rigid pavement section. In Fig 2.4 t_1 and t_2 correspond to the start and the end of upward movement of any panel corner. In the same figure, t_3 and t_4 are respectively the earliest and latest times at the beginning and at the end of downward movement of any panel corner (Ref6).

The deflection study on continuously reinforced concrete pavements reported by McCullough and Treybig (1965) showed an inverse relationship between temperature differential and the edge deflection (Benkelman Beam) measured at the crack position, as shown in Fig 2.5 (Ref 7). Figure 2.6 shows the effect of crack width on deflection. In the same study, crack width and deflection were found to be dependent on mid-depth temperature (the



(c) displacement vs time.

Fig 2.4. Time, temperature and displacement data from corner movement study; AASHO Road Test (Ref 6).

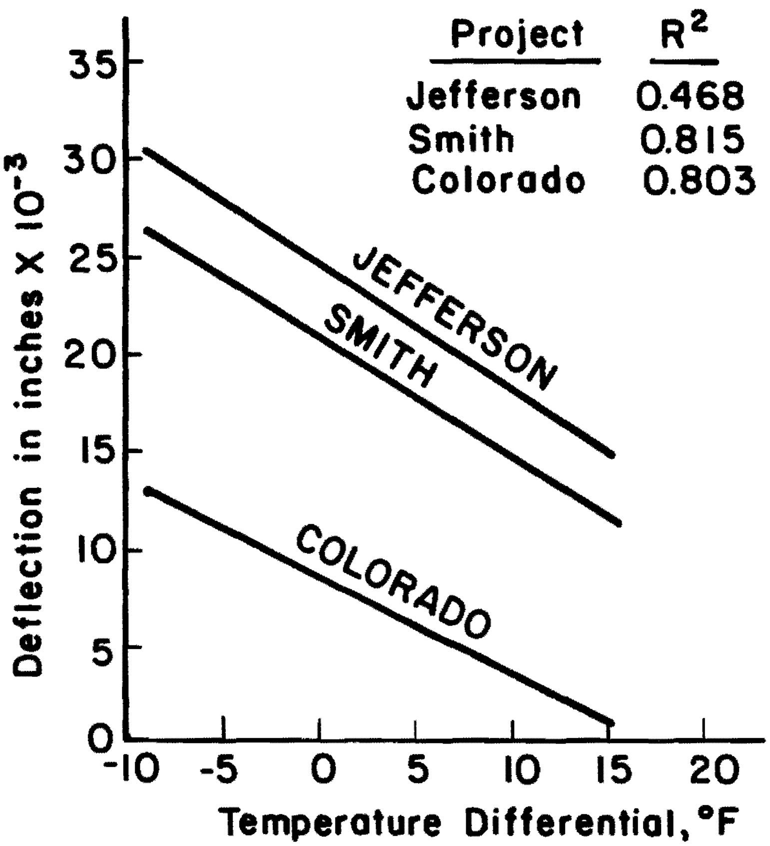


Fig 2.5. Edge deflection versus temperature differential (Ref 7).

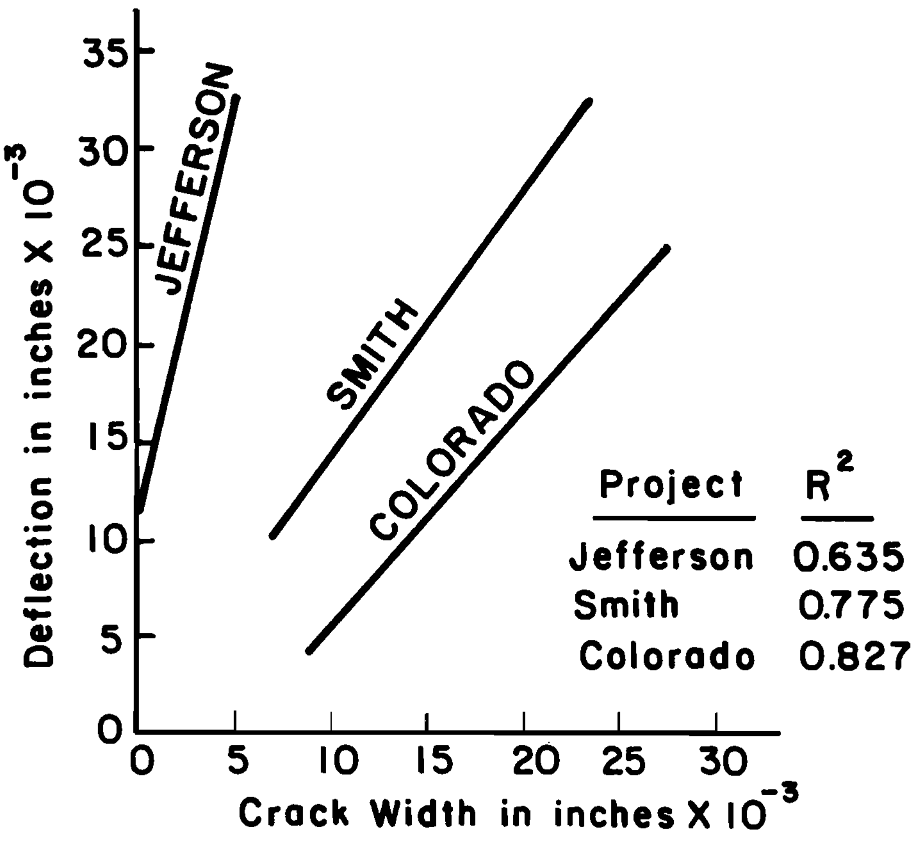


Fig 2.6. Deflection versus crack width (Ref 7).

average of the temperatures of the top and the bottom of the concrete slab). These relationships are shown in Figs 2.7 and 2.8.

Seasonal Effects. Taute et al (Ref 1) discussed the seasonal effects on deflections in CRC pavements. Following their discussion on effects of moisture changes, they concluded that wet, cold and winter weather will result in an increase in maximum deflection (at sensor 1 of the Dynaflect), due to the wet, soft subgrade and due to the low effective modulus of the surface layer caused by shrinkage and the resulting relatively wide transverse cracks. A dry summer will result in a decrease in this deflection due to the dry stiff subgrade and the high effective subgrade modulus caused by expansion and the resulting narrowing of the transverse cracks in the CRC pavement.

Metwali (1981) presented the results of an experimental study on seasonal variations in pavement deflections (Ref 8). The Dynaflect deflection data were collected on asphalt overlaid, jointed reinforced concrete and continuously reinforced concrete pavements. The analysis of variance technique was used to analyze these deflection data. In the case of asphalt overlaid and jointed reinforced concrete pavements, the maximum deflection (sensor 1) and the sensor 5 deflections were found to be significantly higher in spring than in fall. Metwali found that CRC pavements showed no significant changes in deflections due to seasonal variations (Ref 8). These findings are very interesting and somewhat in conflict with the current data and belief.

Location Variables

The type of shoulder support at the pavement edge and the Dynaflect position with respect to the pavement edge and the locations of cracks or

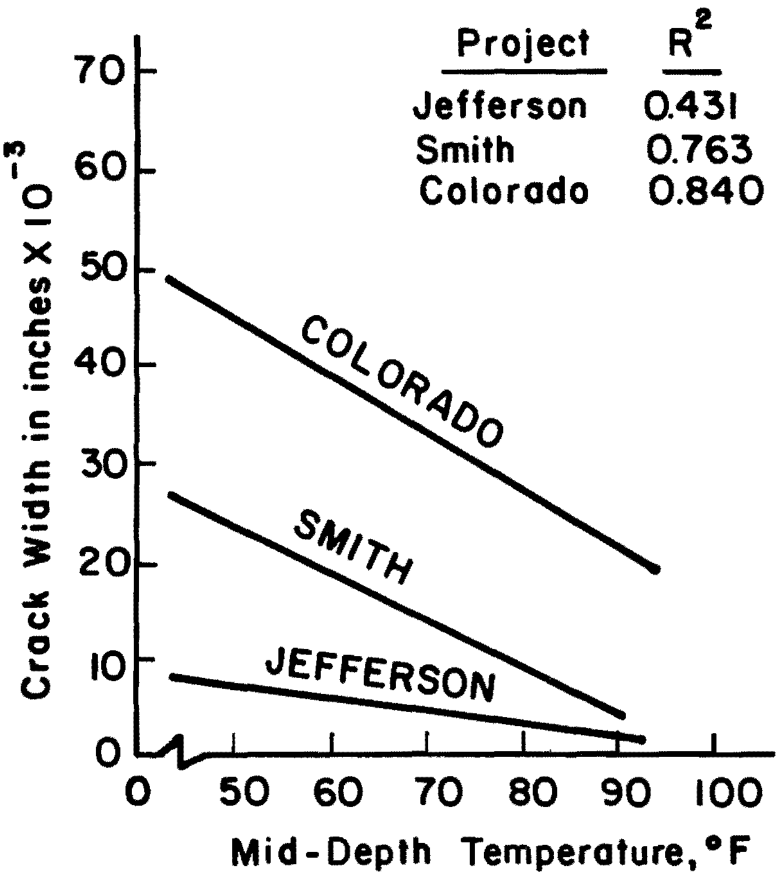


Fig 2.7. Crack width versus mid-depth temperature (Ref 7).

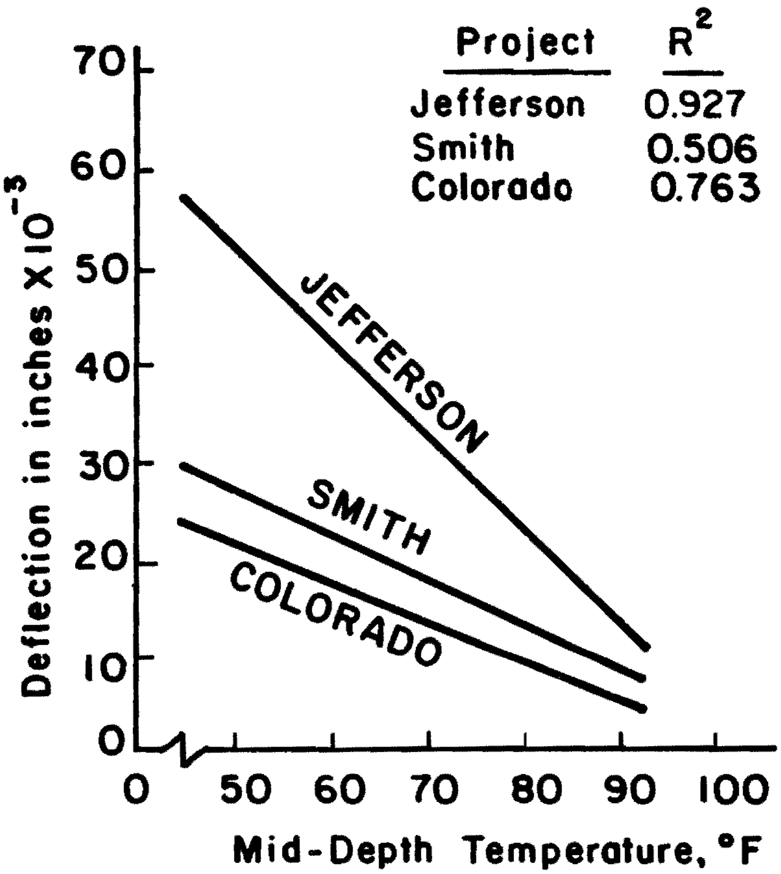


Fig 2.8. Deflection versus mid-depth temperature (Ref 7).

joints are also important factors that influence the deflection behavior of rigid pavement. These factors are discussed below.

Effect of Pavement Edge. In the AASHO Road Test (Ref 6), pumping of the subbase material was found to be a major factor in the majority of the failures of sections of rigid pavement. Another observation at the AASHO Road Test was that the amount of material pumped through joints and cracks was negligible when compared with the amount ejected along the edge. Pumping eventually results in creation of voids under pavement edge. Voids may also result from any movement in the subgrade or natural material, such as swelling or differential settlement. The presence of voids beneath pavement will result in relatively higher deflections. Birkhoff and McCullough (Ref 9) recommended a deflection survey along a pavement section to detect voids under the pavement edge. Figure 2.9 shows a typical deflection profile that can be used to detect void areas. An important assumption in the pavement design that there is uniform ground support, is violated in the presence of voids. The voids will result in higher load stresses and eventually lead to deterioration of the pavement. A rehabilitation program therefore should include a deflection survey to identify void areas. Figure 2.10 presents results of a theoretical study (Ref 10) to investigate the effect of void size and the distance of the Dynaflect from the pavement edge on computed deflection.

Edge Support Condition. The type of edge support will have a marked influence on the deflection behavior near pavement edge. It is known from Westergaard's solutions that for the same load, stresses at the pavement edge are much higher than those in the interior. And since deflection is proportional to load stress, a larger deflection occurs at the pavement edge. When there is a concrete shoulder deflection can be expected to be less than

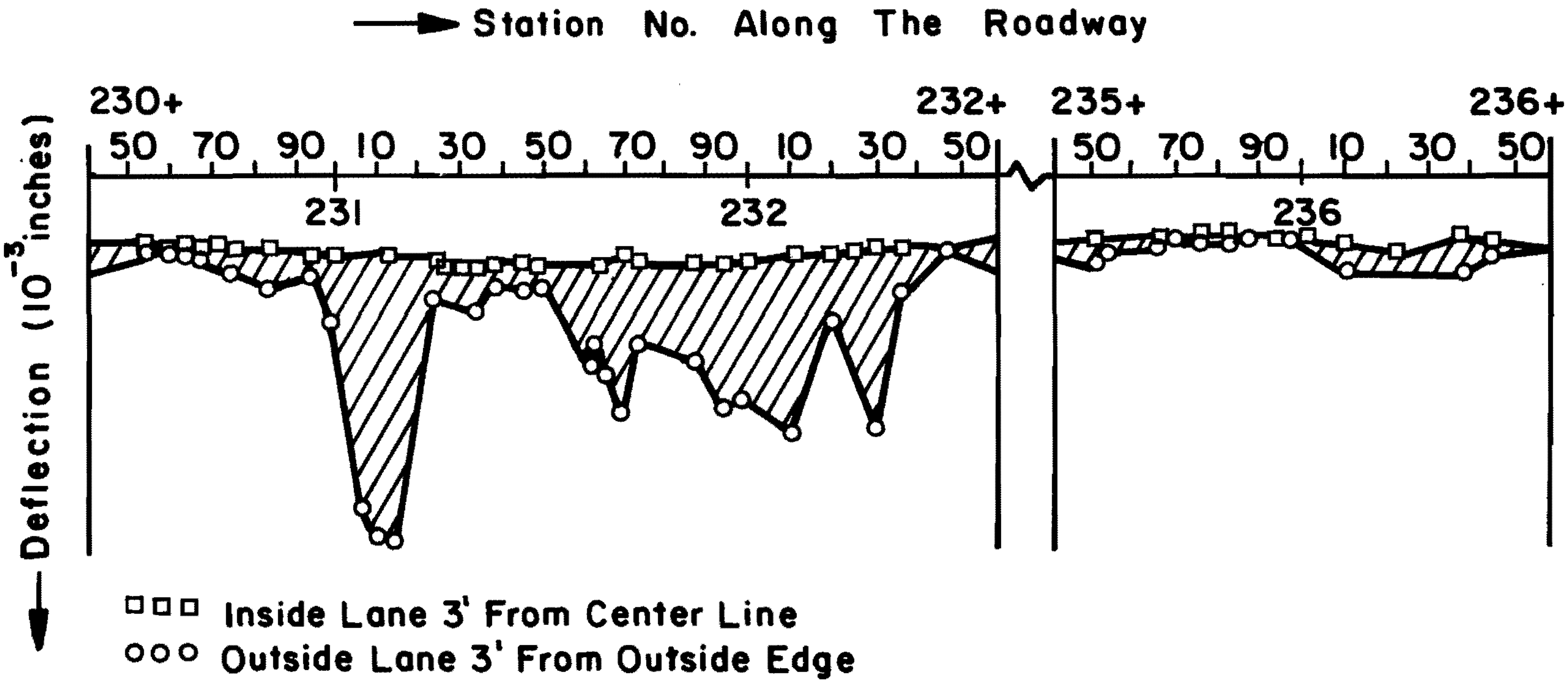


Fig 2.9. Deflection profile of inside and outside lanes (Ref 9).

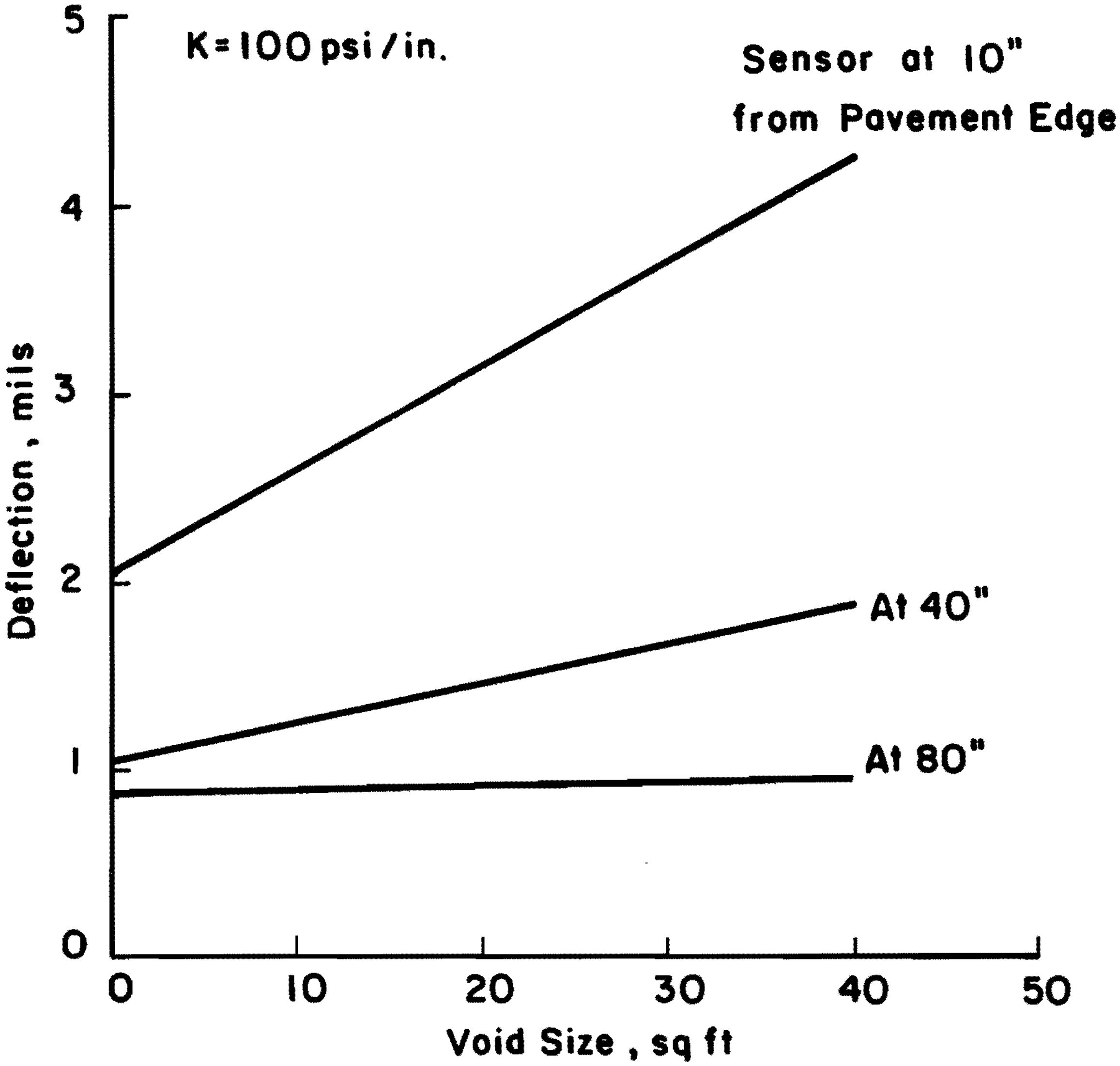


Fig 2.10. Effect of void size and Dynaflect position on pavement deflection (Ref 10).

when there is a gravel shoulder. Another possible effect of a shoulder is the restraint offered to any lateral movement of the concrete slab by the edge support.

Effect of Cracks. Transverse cracks in CRC pavement are usually very tightly held but the load transfer of less than 100 percent will result in deflections larger than those measured between cracks (mid-span position). Deflection at a crack will increase as the crack width increases and the crack width was found to be a function of mid-depth temperature (Ref 7). These relationships are shown in Fig 2.6. For material characterization, the mid-span deflection (interior condition) is preferred. However, measuring the deflection at a crack position will give valuable information about load transfer efficiency and an indication of any excessive distress. The result of a theoretical study supplemented by a condition survey record indicates that, once load transfer has been reduced to such an extent that the deflections at the cracks exceed the uncracked pavement deflections by more than 50 percent, punchouts may occur in areas with crack spacing of approximately one foot (Ref 1).

DESCRIPTION OF SET UP FOR DYNAFLECT AND TEMPERATURE MEASUREMENTS

In this section a brief description of the Dynaflect system and the testing programs for Dynaflect deflection and temperature measurements are presented.

The Dynaflect and the Procedure for Deflection Measurements

Dynaflect Operating Characteristics. The Dynaflect system is used extensively by the Texas State Department of Highways and Public Transportation for nondestructive evaluation of flexible and rigid pavements.

A detailed comparison of the Dynaflect with other nondestructive deflection measuring equipment has been made in an earlier report (Ref 11). Information on the development of the Dynaflect system is contained in Ref 12. The Dynaflect is marketed as a small two wheel trailer housing a dynamic force generator and deflection measuring system. The Dynaflect is towed by a light vehicle and travels on the two pneumatic tired wheels at normal highway speed to the test section and between test sections. The dynamic force is transmitted to the pavement by lowering two 4-inch-wide, (16-inch-outside diameter) rubber coated steel wheels. The operations control unit and a meter unit calibrated to read deflection are carried in the towing vehicle and the driver of the towing vehicle can also operate the Dynaflect. The operations control unit is hooked up to the power source of the towing vehicle.

The dynamic force generator employs two counter-rotating eccentric masses to generate steady state vibrations that are a sinusoidal function of time. The Dynaflect is operated at a fixed frequency of 8 Hz, which results in a 1,000-pound peak-to-peak magnitude of the vibratory force (Fig 2.11). Bush (Ref 13) reported results of a comparative study on four nondestructive vibratory devices. The findings related to the Dynaflect are (1) the measured frequency was within 3 percent of the indicated frequency of 8 Hz and (2) the peak-to-peak dynamic force of the Dynaflect was 4 percent below the measured force for the rigid pavement. These findings show that the frequency and amplitude of the sinusoidal loading force of the Dynaflect are reasonably reliable.

Deflection Measuring System. Five equally spaced geophones are used to measure deflection response of the pavement. Figure 2.12 shows the load configuration and the arrangement of the geophones. The steady state vibratory force of the Dynaflect predominantly generates Rayleigh waves. The

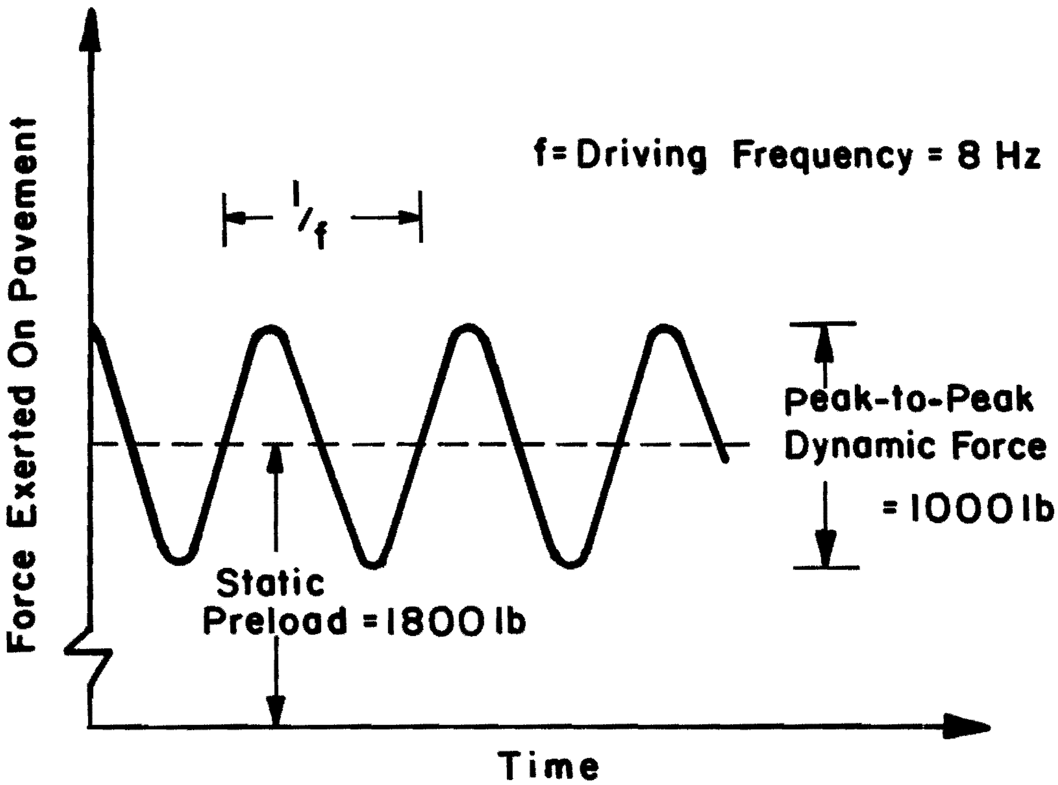
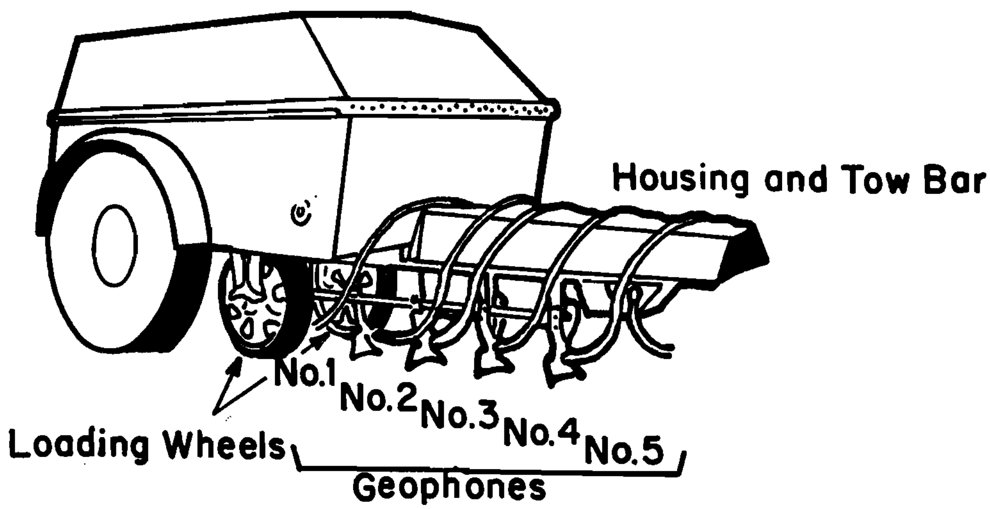
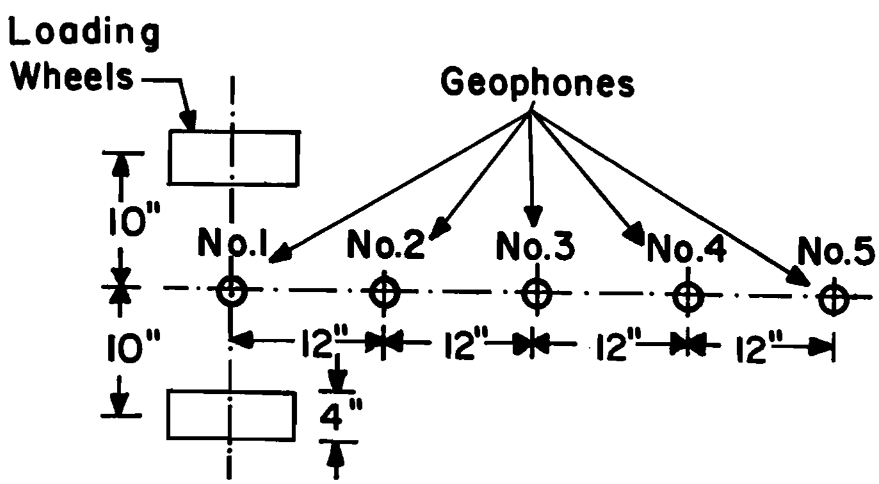


Fig 2.11. Typical dynamic force output signal of Dynaflect.



(a) The Dynaflect system in operating position (Ref 26).



(b) Configuration of load wheels and geophones.

Fig 2.12. Configuration of Dynaflect load wheels and geophones in operating position.

geophones are velocity transducers, which employ an inertial reference and give an output signal in volts. The peak to peak dynamic deflection is proportional to the output voltage of the geophone. Prior to testing, each geophone is calibrated at the driving frequency of 8 Hz so that, during the test, deflection can be recorded directly from the readout meter. Additional information about the characteristics of geophones can be found in Ref 14. The arrangement of five geophones in the Dynaflect provides (1) maximum deflection under sensor 1 and (2) half of the so called deflection basin if the measured deflections under all sensors are plotted and joined by drawing a smooth curve. For material characterization, the measured Dynaflect deflection basin is often used to back-calculate Young's moduli using computer programs based on multilayer linear elastic theory. The major assumption in using this approach is that the dynamic force amplitude is a static load. Texas Transportation Institute (TTI) (Ref 15) investigated the effect of assuming static load by measuring deflection basins while operating the Dynaflect at frequencies varying between 4 and 12 Hz at the same amplitude of dynamic force. The results showed that the vertical deflections measured at the surface are independent of the frequency in the range of 6 to 10 Hz.

The Dynaflect deflections measured at the same location on two consecutive days have been found to repeat within close limits (Ref 12). Potter (Ref 16) reported investigations made on the repeatability of the Dynaflect deflections. The first phase of these investigations was the recording of the deflection at a test point following the standard procedure and then, without moving from the test point, raising the geophones, lowering them again, and recording the deflection values. The results are presented in Fig 2.13. It indicates that the variation in measured deflections due to the

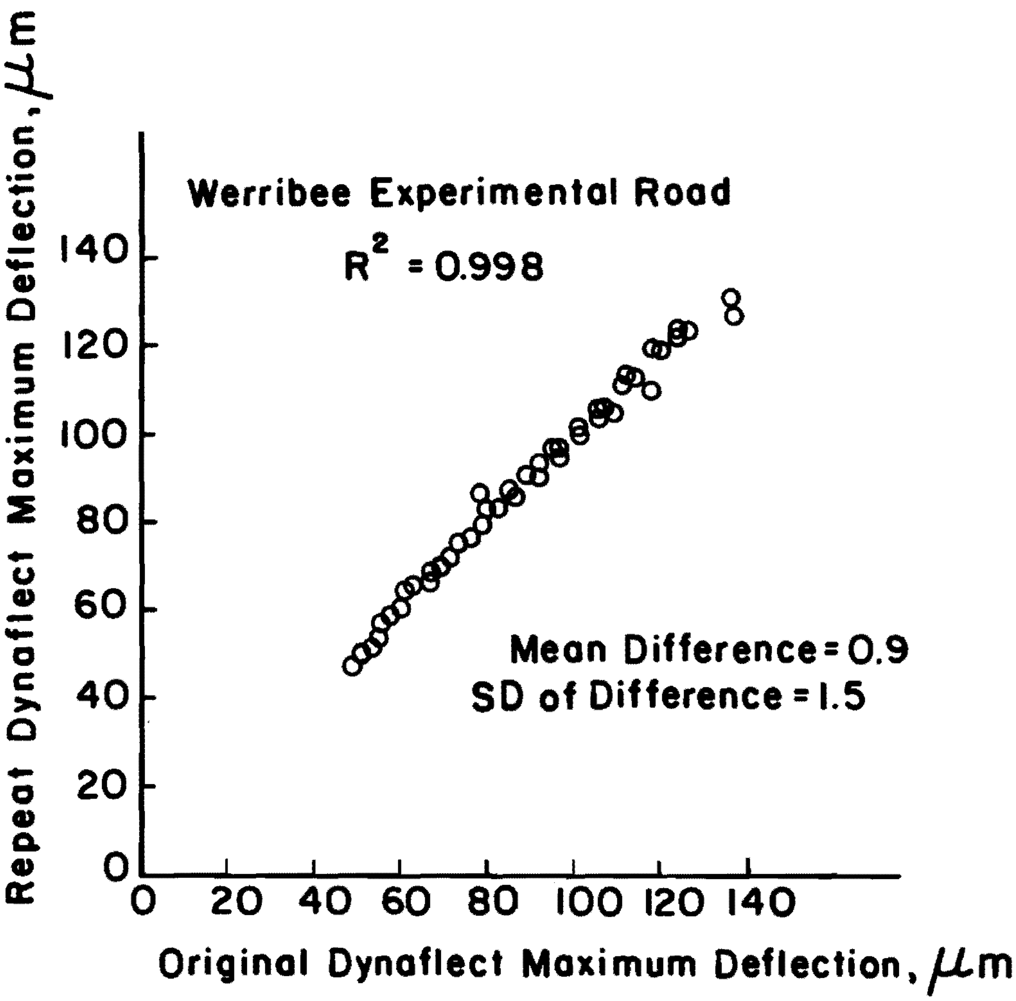


Fig 2.13. Original and repeat Dynaflect sensor 1 deflections without moving the Dynaflect from it's original position (Ref 16).

device itself and placement of the geophones is negligible. In the second phase, all locations were tested on one day with the Dynaflect and then the sites were retested. Figure 2.14 shows these results indicating the error involved due to placement of the Dynaflect in the repeat measurements.

Test Procedure. The calibration of all five geophones is carried out every day prior to taking the Dynaflect to the test location. Geophones are placed in the calibrator unit, which provides a repetitive vertical motion of 0.005 inch at an operating frequency of 8 Hz. The calibrator unit is connected to the control unit. The sensor selector switch in the control unit is then switched to the position corresponding to geophone no. 1 and the respective sensitivity control is adjusted to obtain the correct deflection reading. The calibration procedure is repeated for each of the other geophones. The calibrator is disconnected from the control unit after all geophones are calibrated. The geophones are then refixed on their bases and connected to the draw-bar of the Dynaflect. The draw-bar is raised and the towing vehicle tows the Dynaflect on its pneumatic tired wheels to the marked test location. The sequence of operations for routine digital Dynaflect measurements is as follows:

(1) The Dynaflect is positioned so that geophone no. 1 (in the center of the two solid steel wheels) rests over the marked location.

(2) The Dynaflect trailer is raised onto its solid wheels.

(3) The dynamic force generator is switched on and frequency is adjusted to 8 Hz.

(4) The geophone-bar is lowered to the surface of the pavement.

(5) The voltage output of each geophone is read on the digital readout meter directly in milli-inches of vertical deflection at the pavement surface and recorded by the operator. (The procedure for the analog type unit will be slightly different.)

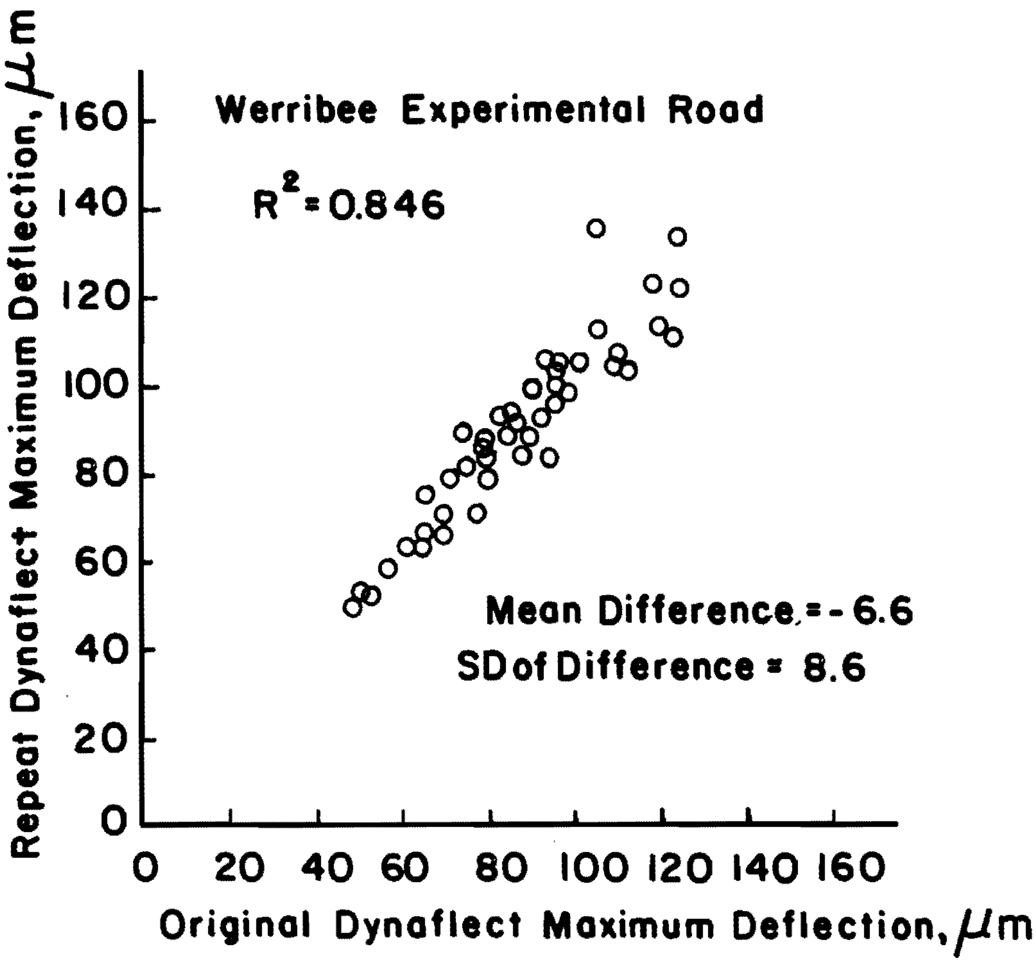


Fig 2.14. Repeatability of the Dynaflect; repeat deflections after 24 hours (Ref 16).

(6) The geophone bar is raised and the dynamic force generator is switched off and the Dynaflect is towed on its solid wheels to the next location in the same test section.

Scheme for Collection of Dynaflect Deflection Data

The test site, selected sections, test locations on each section, and other details of the two sets of deflection measurements are described in the following sections.

Site Description. A testing scheme was designed for making Dynaflect deflection and temperature measurements to investigate the effects of temperature and the Dynaflect position. A newly constructed continuously reinforced concrete pavement on the Columbus bypass of SH-71 was selected as the test site. Columbus, Texas, is located about 90 miles southeast of Austin and 70 miles west of Houston. Three test sections were selected in late July 1981. Figure 2.15 shows the locations of the site and the test sections. The first measurements were made on August 6 and 7, 1981, and at that time the bypass was still not opened to traffic. Figure 2.16 illustrates the typical cross section of CRC pavement at this site. The pavement consists of a 10-inch concrete surface layer, a 4-inch asphalt base, and a 6-inch lime-treated subgrade overlying the natural subgrade.

Design of Testing Program. The three test sections were selected with the objective of obtaining locations with transverse crack spacing of 8 feet or more in each section. This would facilitate deflection measurements with the Dynaflect (1) close to the transverse crack and (2) positioned between the two adjacent cracks (mid-span position). The set-up of the Dynaflect with respect to the transverse cracks are shown in Fig 2.17. Test locations near the transverse cracks were designated with odd numbers. The locations corresponding to mid-span position (between cracks) were given even numbers. Another factor considered in the selection of locations near the edge was the

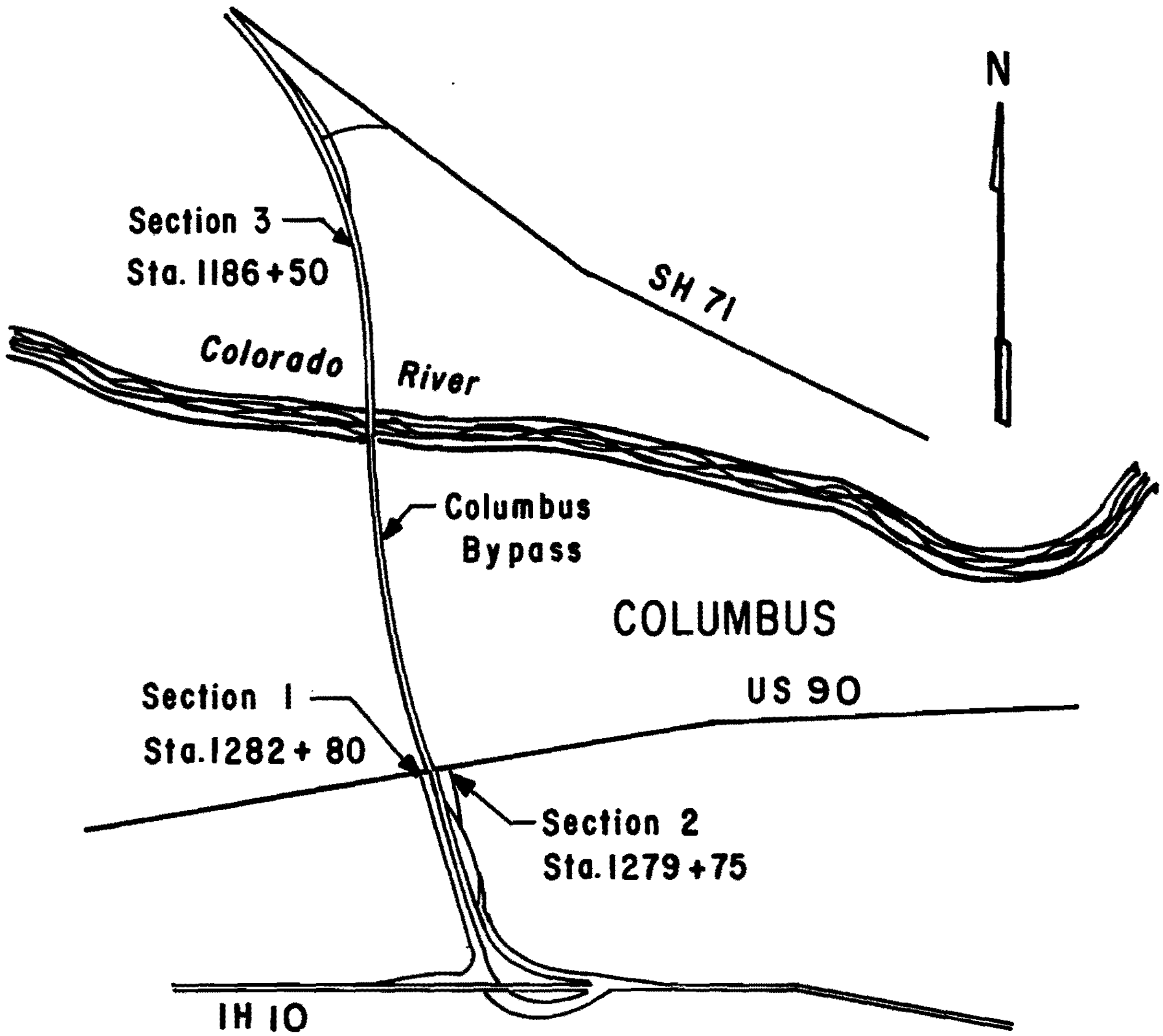


Fig 2.15. Location of the test site.

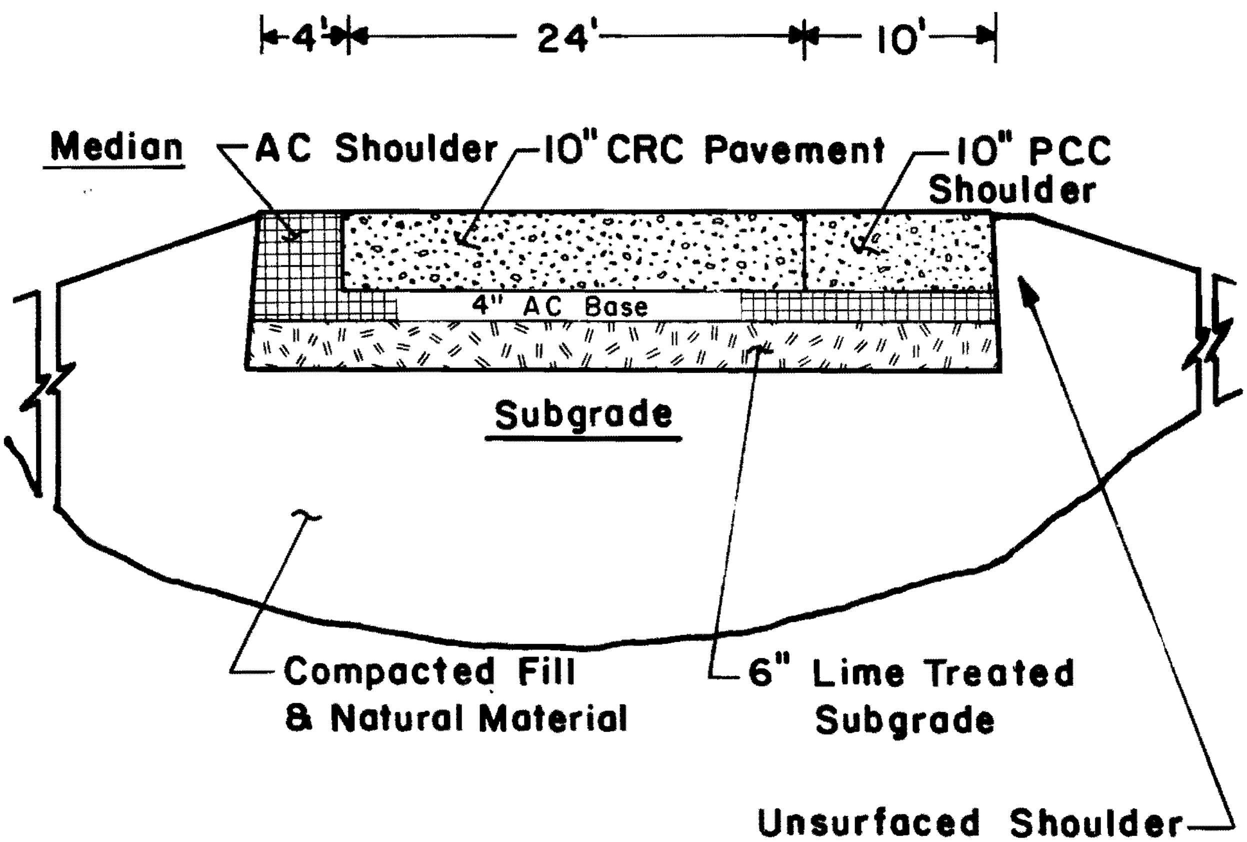


Fig 2.16. Typical details of CRC pavements, Columbus bypass (southbound direction only), Texas.

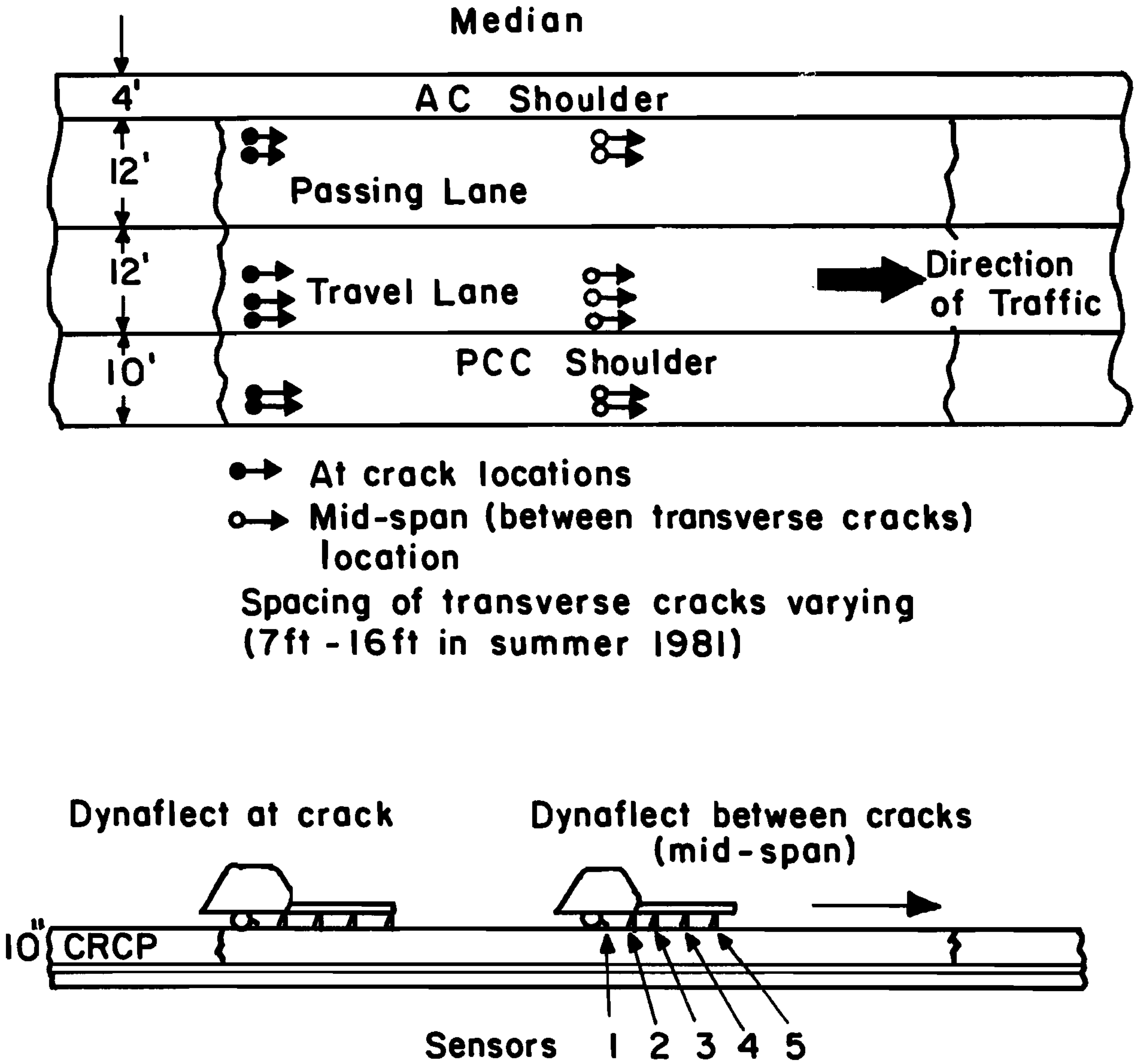


Fig 2.17. Dynaflect positions with respect to transverse cracks.

inclusion of different types of lateral support, in other words, an asphalt shoulder versus a concrete shoulder. Locations were selected near the edge as well as in the wheel path in the passing lane, in the travel lane, and on the concrete shoulder. Figure 2.18 shows the layout plan of selected test locations used in each of the three test sections. A continuous record of top and bottom temperatures was obtained using a 9.5-inch concrete block which was successfully used in a previous study. A total of 552 sets of Dynaflect half-deflection bowls were measured during this study. Table 2.1 presents description of each test designation illustrated in Fig 2.18.

Summer Measurement. Fourteen locations in each section were used for Dynaflect deflection measurements during the summer of 1981. Each test represents deflection measurements from the five geophones. The summer testing was carried out on August 6 and 7, 1982. Four complete cycles of deflection measurements were made, resulting in a total of 168 data sets. Figure 2.18 illustrates the test locations used for each of the three sections in the summer of 1981. Table 2.2 presents the distribution of the Dynaflect deflection data sets with respect to the Dynaflect position. Data related to the average crack spacing are presented in Table 2.3.

Fall Measurements. The second set of Dynaflect deflection data and the slab temperatures were obtained on November 30 and December 1, 1981. The pavement had been opened to traffic in October 1981. Due to muddy conditions of the soil beyond the concrete shoulder, Dynaflect deflection data could not be acquired on locations 13L and 14L in all three sections. The deflection measurements were made very smoothly, resulting in eight complete cycles with a total of 384 data points. Another problem faced on the site was that transverse cracks developed in sections 1 and 2 between the two

TABLE 2.1. DESCRIPTION OF TEST DESIGNATIONS USED IN SECTIONS 1, 2, AND 3 AT COLUMBUS BYPASS, SH-71 DURING SUMMER AND FALL, 1981

Test Designation	Lane	Type of Edge Support	Location*	Dynaflect Position
1L	Passing	A.C. Shoulder	Edge	At Crack
2L	Passing	A.C. Shoulder	Edge	Mid-Span
3L	Passing	A.C. Shoulder	Wheelpath	At Crack
4L	Passing	A.C. Shoulder	Wheelpath	Mid-Span
5L	Travel	P.C. Concrete	Center	At Crack
6L	Travel	P.C. Concrete	Center	Mid-Span
7L	Travel	P.C. Concrete	Wheelpath	At Crack
8L	Travel	P.C. Concrete	Wheelpath	Mid-Span
9L	Travel	P.C. Concrete	Edge	At Crack
10L	Travel	P.C. Concrete	Edge	Mid-Span
11L	P. C. C. Shoulder	Gravel Shoulder	Wheelpath	At Crack
12L	P. C. C. Shoulder	Gravel Shoulder	Wheelpath	Mid-Span
13L	P. C. C. Shoulder	Gravel Shoulder	Edge	At Crack
14L	P. C. C. Shoulder	Gravel Shoulder	Edge	Mid-Span

*All edge, wheelpath, and center locations are 1, 3, and 6 feet, respectively, from the edge support.

TABLE 2.2. DISTRIBUTION OF MEASURED DYNAFLECT DEFLECTION BASINS

Dynaflect	Test Designation	Summer 1981 Section 1	Summer 1981 Section 2	Summer 1981 Section 3	Fall 1981 Section 1	Fall 1981 Section 2	Fall 1981 Section 3
At Crack	1L	4	4	4	8	8	8
	3L	4	4	4	8	8	8
	5L	4	4	4	8	8	8
	7L	4	4	4	8	8	8
	9L	4	4	4	8	8	8
	11L	4	4	4	8	8	8
	13L	4	4	4	8	8	8
In Midspan	2	4	4	4	*8 #8	*8 ##8	*8
	4	4	4	4	*8 #8	*8 ##8	*8
	6	4	4	4	*8 #8	*8 ##8	*8
	8	4	4	4	*8 #8	*8 ##8	*8
	10	4	4	4	*8 #8	*8 ##8	*8
	12	4	4	4	*8 #8	*8 ##8	*8
	14	4	4	4	-	-	-

*All tests correspond to designation "L"
#All tests correspond to designation "N"
##All tests correspond to designation "A"

TABLE 2.3. AVERAGE CRACK SPACING BETWEEN TRANSVERSE CRACKS (IN FEET)

Lane	Season	Section 1	Section 2	Section 3
Passing	Summer	11.9	14.6	11.5
	Fall	6.8 7.8+	8.5 7.8*	6.0 ---
Travel	Summer	10.8	16.8	10.3
	Fall	7.5 7.8+	8.0 7.8*	10.3 ---
P.C.C. Shoulder	Summer	11.2	11.2	8.5
	Fall	7.8 13.0+	7.8 7.8*	8.5 ---

+ Locations N (see Fig 2.19)
* Locations A (see Fig 2.20)

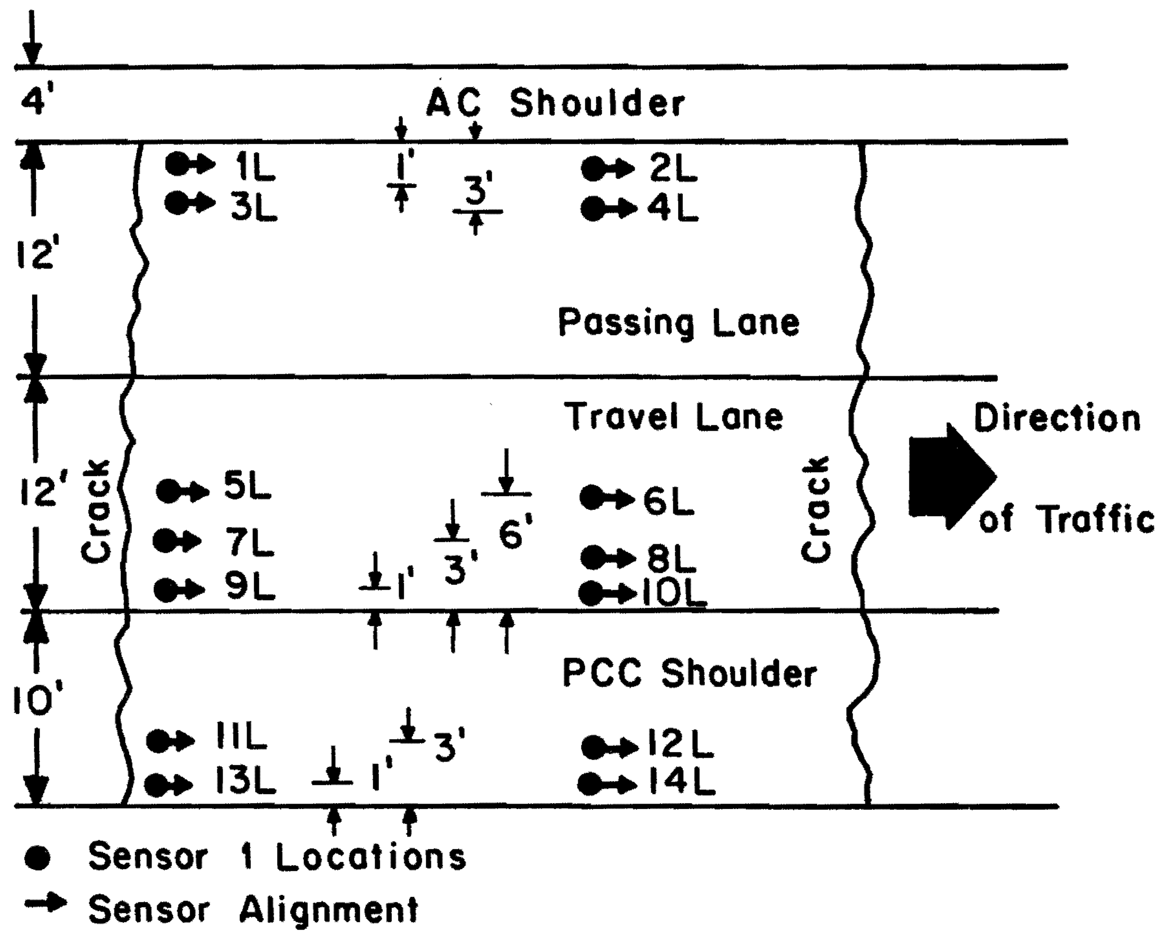


Fig 2.18. Layout plan of selected test locations in Summer 1981, sections nos. 1, 2, and 3.

transverse cracks marked earlier during summer testing. Therefore in addition to the existing locations, five more locations were selected in sections 1 and 2 so that the mid-span (between cracks) deflection data could be obtained. The layout plans of sections 1 and 2 are illustrated in Figs 2.19 and 2.20, respectively. Locations in section 3 are shown in Fig 2.21.

Temperature Measurement for Surface Concrete Layer

An instrumental concrete block was used to estimate the temperature of the surface concrete layer of the CRCP on test site. The concrete block was 12 in. by 16 in. by 9.5 in. deep and instrumented with two Honeywell High Speed Resistance Thermometer Bulbs (Model No.#921 A3). The thermometers are 6 in. long and contained in stainless steel tube. To obtain the representative estimate of the temperature of the concrete pavement slab, the concrete (temperature) block was buried in the ground near a source of an electrical power with the exposed top surface flush with the ground. The location was near the Resident Engineer's office of District 13 and carefully selected so that the exposed surface of the concrete block would receive the same amount of sunlight and solar radiation as the three selected CRCP test sections. The temperatures were recorded for both top and bottom of the block. Leads from the top and bottom thermometers were connected to a Honeywell Universal Electronic 15 Multipoint Recorder. It has a 12 point recording capability and facilitated a continuous record of the temperature data for the top and bottom of the slab. The concrete block and recorder was acquired from the Texas State Department of Highways and Public Transportation. Before the summer measurements, the concrete block was checked for temperature calibration in the laboratory and found satisfactory. The movement of the chart in the recorder was also checked to make sure that the speed of the chart corresponded to the hour marks on the chart.

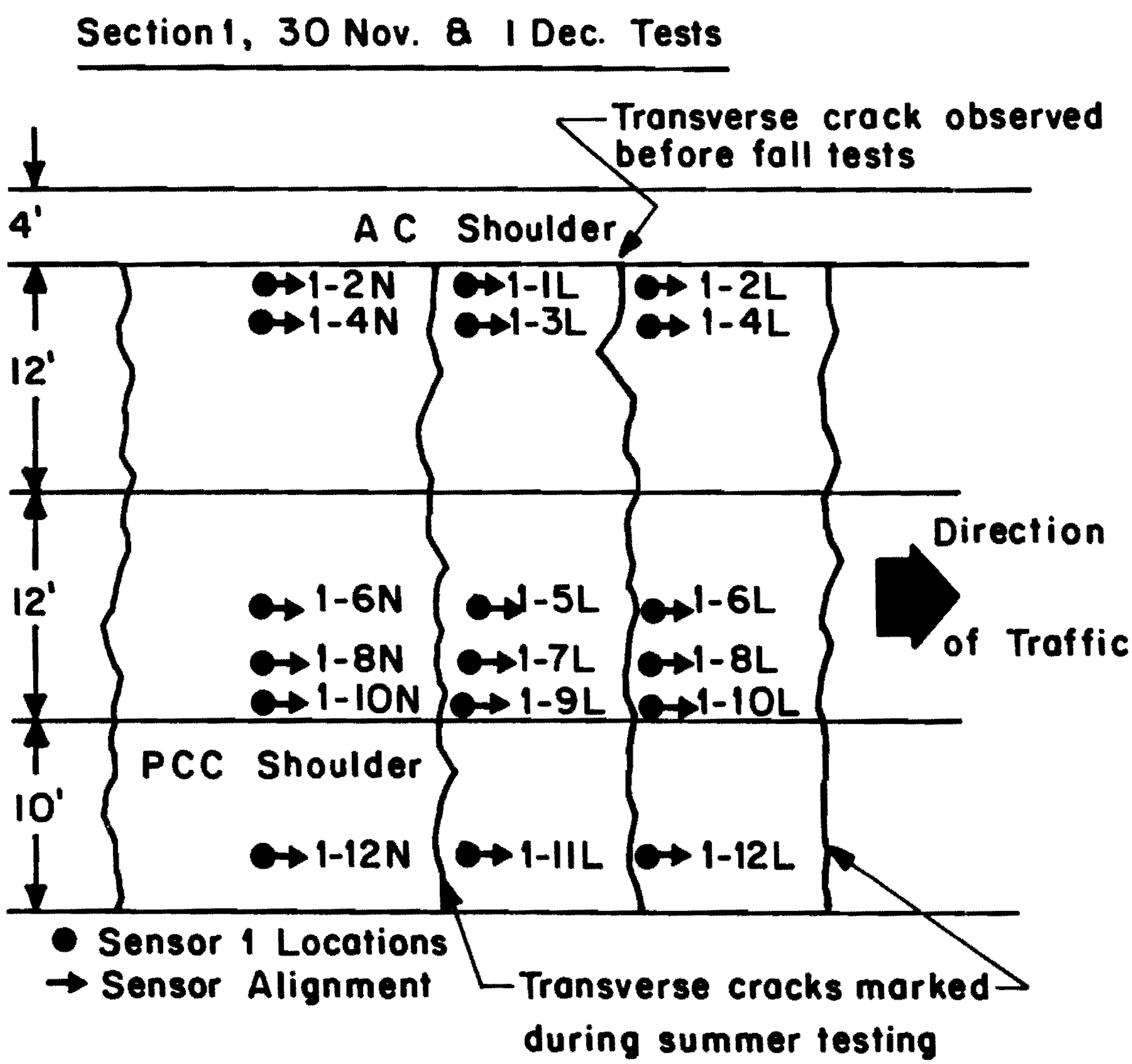


Fig 2.19. Layout plan of test locations in Fall 1981, section No. 1.

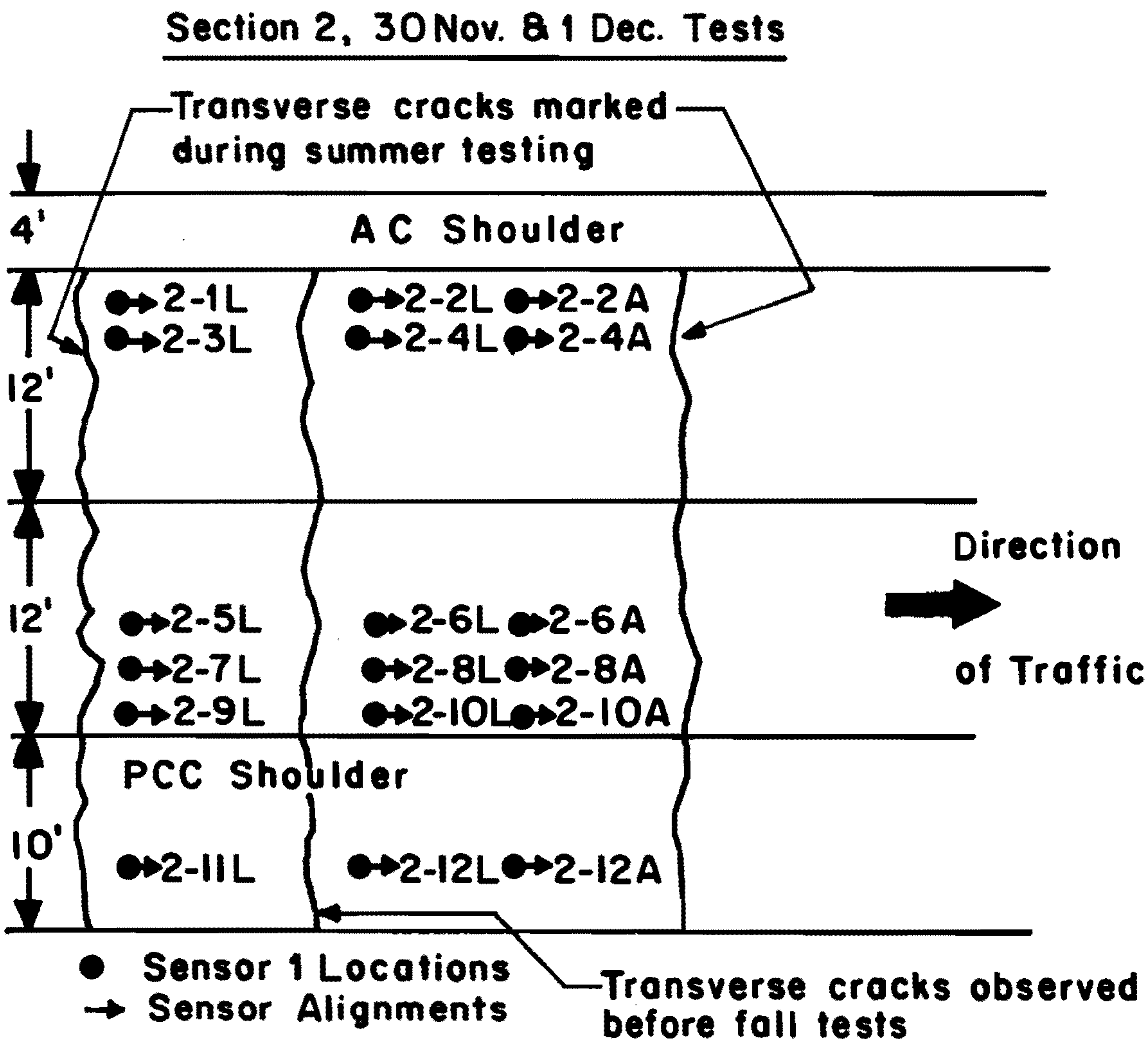


Fig 2.20. Layout plan of test locations in Fall 1981, section no. 2.

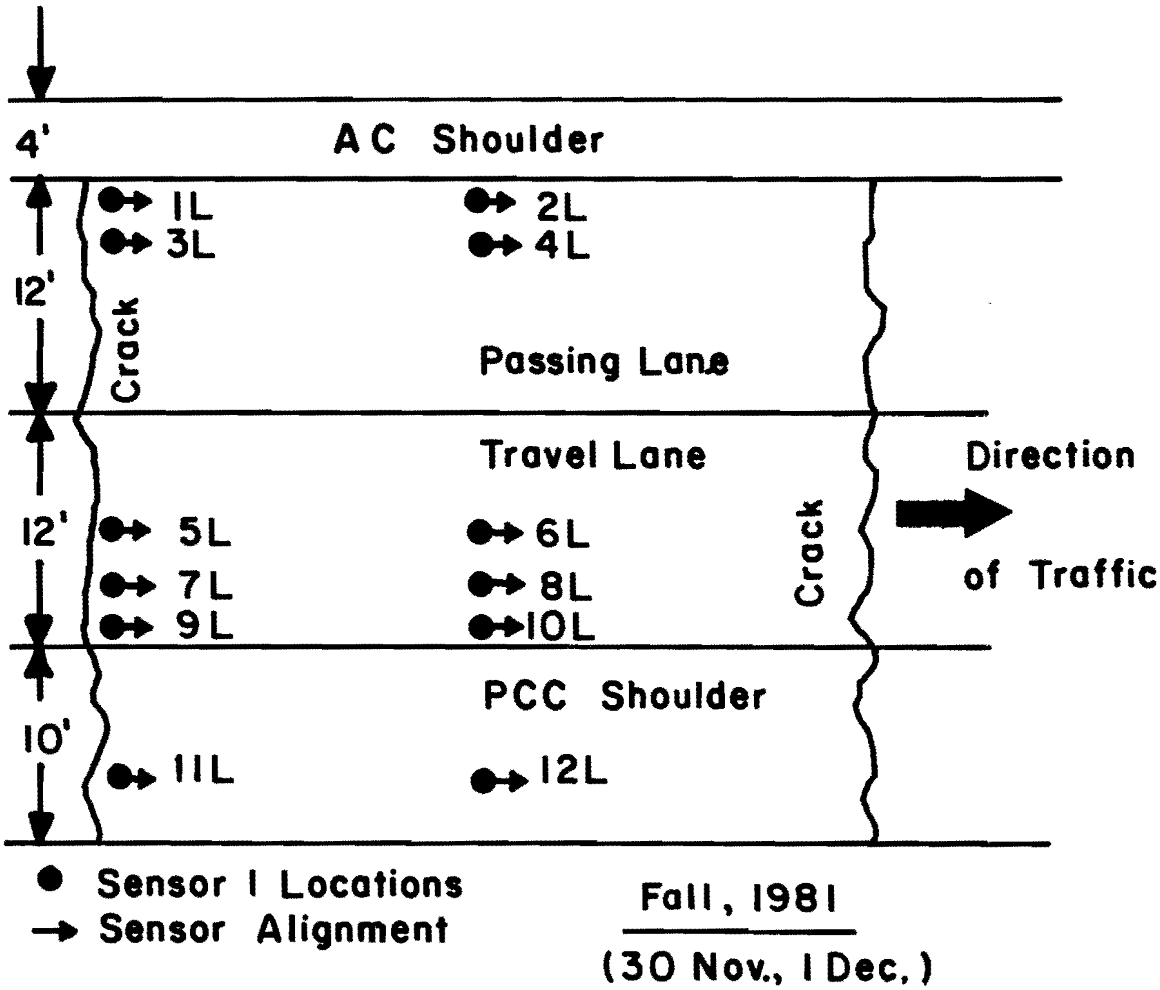


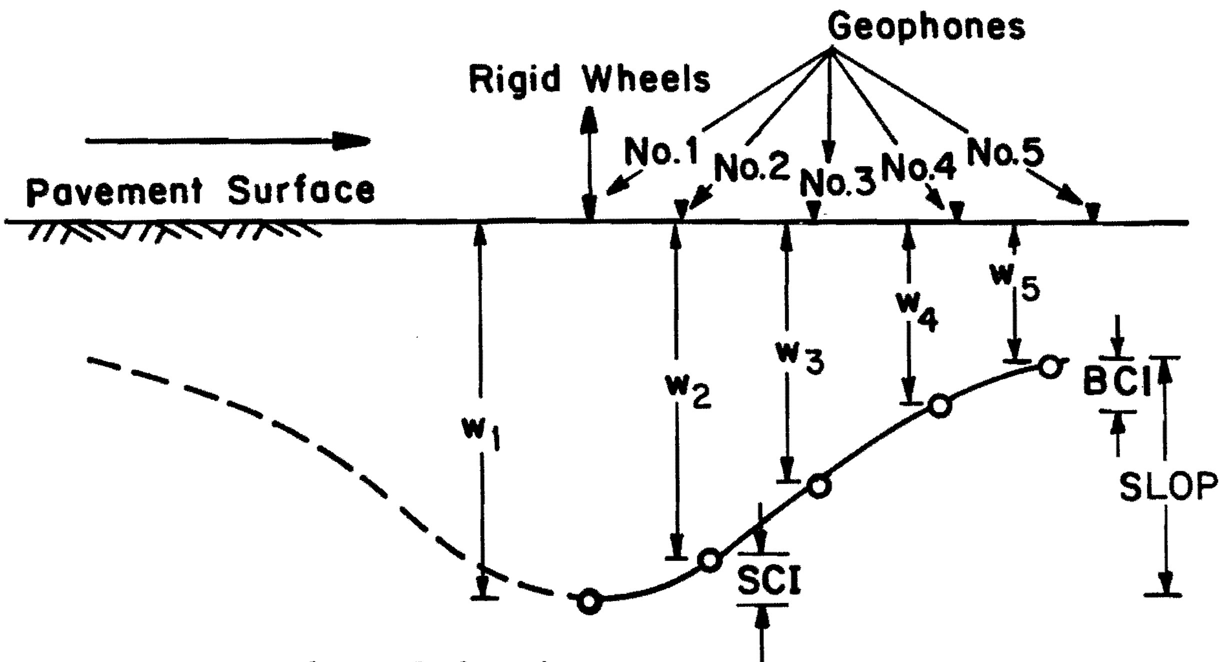
Fig 2.21. Layout plan of test locations in Fall 1981, section no. 3.

PRESENTATION AND PRELIMINARY ANALYSIS OF FIELD DATA

In this section, summaries of the Dynaflect deflection data and estimated temperature data for the concrete slab are presented. Results of a preliminary analysis to study the effect of temperature differential on measured deflection are also included.

Summary of the Dynaflect Data

Deflection Parameters. The measured deflections from the five geophones of the Dynaflect are used to define the half position of a deflection basin. A typical deflection basin is illustrated in Fig 2.22. The five geophones of the Dynaflect are normally sufficient to define a deflection basin in most pavements. The deflection basin has been characterized by different researchers using various parameters, such as maximum deflection, SCI, BCI, and spreadability (Refs 17 and 18). These parameters are defined in Fig 2.22. These parameters are related to the stiffness of one or more of the pavement layers in varying degrees. SCI, or the difference between sensor 1 and sensor 2 deflections, was found to be an indicator of the structural integrity of the pavement surface layer (Ref 17). Taute et al (Ref 1) studied thick concrete pavements (8-inch concrete surface layers). It is shown that, for a thick rigid pavement, a typical deflection basin is relatively very flat and has a large radius of curvature, resulting in a very small value of SCI and subject to a large variation. Taute et al (Ref 1) correlated "basin slope", i.e., the difference between sensor 1 and sensor 5 deflections, to the upper layer stiffness rather than SCI. Sensor 1 deflection is the maximum deflection under the Dynaflect loading which is affected by the stiffness of all pavement layers. Sensor 1 deflection will also be affected by environmental factors. In CRC pavements, the transverse cracks are very



Maximum Dynaflect Deflection = w_1

Surface Curvature Index, SCI = $w_1 - w_2$

Base Curvature Index, BCI = $w_4 - w_5$

Spreadibility, % = $100(w_1 + w_2 + w_3 + w_4 + w_5)/(5w_1)$

Basin Slope, SLOP = $w_1 - w_5$

Fig 2.22. Typical Dynaflect deflection basin.

tightly held but a drop in temperature can cause the cracks to open. This will cause an increase in the sensor 1 deflection (Ref 1). On the other hand the sensor 5 deflection will be least sensitive to temperature effects, as it is indicative of the subgrade stiffness and subgrade will not be generally affected by temperature, with the exception of freezing conditions. The deflection parameters considered in this study are (1) maximum (sensor 1) deflection, W_1, (2) sensor 5 deflection, W_5, and (3) basin slope $(W_1 - W_5)$.

Summary of the Dynaflect Data. The Dynaflect deflection data collected during summer and fall of 1981 are presented in Appendix A. They include section, location, time of measurement, and deflection measured at each sensor (notations used in the Appendix are W_1, W_2, W_3, W_4, and W_5, respectively, for deflections corresponding to geophones no. 1, no. 2, no. 3, no. 4, and no. 5). The deflection measured at each sensor represents peak-to-peak deflection at the surface of the pavement due to the steady state vibratory force of the Dynaflect. The temperature data were read from the record corresponding to the time of the Dynaflect deflection readings and included in the Appendix A. A summary of maximum deflection (W_1) for summer and fall is presented in Table 2.4. Each cell shows mean value and coefficient of variation of the sensor 1 deflections (W_1) measured in all cycles at a particular location and corresponding to one section in summer or fall. As discussed earlier, W_1 should be indicative of any temperature effect on the deflection behavior of CRC pavement. In summer four cycles of deflection measurements were made at each location and in every section. In other words each cell in Table 2.4 corresponds to four repeat deflection measurements at any one test location in summer. Similarly, fall deflection data correspond to eight repeat deflection measurements at any of the test

TABLE 2.4. SUMMARY DATA OF MAXIMUM DYNAFLECT DEFLECTION, W_1 (AT SENSOR 1)

Dynaflect	Season	Test Designation	Section 1 Mean Deflection, mils	Section 1 Coefficient of Variation,%	Section 2 Mean Deflection, mils	Section 2 Coefficient of Variation,%	Section 3 Mean Deflection mils	Section 3 Coefficient of Variation,%
At Crack	Summer 1981	1L	0.360	23.0	0.365	20.8	0.305	17.0
		3L	0.265	9.0	0.295	10.2	0.252	5.0
		5L	0.237	7.2	0.357	7.7	0.230	5.0
		7L	0.252	8.2	0.355	6.7	0.232	2.2
		9L	0.278	18.7	0.342	8.0	0.247	3.9
		11L	0.255	14.5	0.402	33.0	0.342	32.8
		13L	0.335	18.0	0.562	37.0	0.497	46.2
	Fall 1981	1L	0.333	6.0	0.352	7.8	0.335	8.6
		3L	0.261	3.2	0.286	2.6	0.261	3.2
		5L	0.232	6.4	0.345	7.4	0.236	3.9
		7L	0.247	4.2	0.371	3.6	0.245	3.1
		9L	0.246	6.5	0.343	8.9	0.262	4.9
		11L	0.241	5.2	0.370	11.5	0.340	8.0
		13L	--	---	---	---	---	---
At Midspan	Summer 1981	2L	0.305	8.7	0.342	16.8	0.292	6.5
		4L	0.258	8.6	0.267	5.6	0.245	9.7
		6L	0.227	4.2	0.300	14.1	0.227	7.5
		8L	0.235	2.5	0.317	18.1	0.232	5.4
		10L	0.252	3.8	0.317	18.1	0.240	9.0
		12L	0.225	7.7	0.357	11.7	0.307	15.7
		14L	0.290	14.1	0.505	21.7	0.422	25.4
	Fall 1981	2L	0.352	2.5	0.312	4.8	0.295	3.6
		4L	0.299	2.8	0.270	2.8	0.246	3.0
		6L	0.235	3.9	0.311	2.1	0.227	7.3
		8L	0.241	5.6	0.304	2.4	0.234	4.5
		10L	0.252	5.1	0.294	2.5	0.241	5.3
		12L	0.224	2.3	0.362	10.0	0.290	2.6
		14L	---	---	---	---	---	---

locations no. 1 to 12. The Dynaflect is reportedly very reliable for its repeatability of measured deflections (Refs 12, 13, and 16 and Fig 2.14). Any large variation in the repeat deflections may indicate a possible temperature effect on the measured deflections. The mean W_1 deflections and coefficient of variations for all data from the three sections in summer and fall as observed in Table 2.4 indicate

(1) At crack deflection is larger than the mid-span or between cracks deflection for all locations in the wheel path and at the edge.

(2) For the at crack and mid-span positions, the mean deflections in the passing lane are relatively larger as compared to the corresponding deflections in the travel lane, for the locations in the wheel path and at the edge. This behavior can be explained by considering the condition of the edge support. The edge support for the passing lane is an asphalt concrete shoulder, which will provide less lateral restraint in comparison to that offered to the travel lane by the concrete shoulder.

(3) In the passing lane, the mean deflections at any edge location are in general larger than the corresponding wheel path deflections for both at-crack and mid-span positions.

(4) The coefficients of variation associated with the edge and wheel path deflections in the passing lane are greater in summer than the corresponding coefficient of variation associated with the fall measurements, which indicates that in this case there is possibly some temperature effect on the measured deflections because, in summer, larger temperature differentials were observed.

(5) It is also observed that, in summer, the coefficients of variation associated with the measured W_1 deflections at the edge location in the passing lane (17 to 23 percent) are considerably larger than the corresponding coefficients of variation associated with the wheel path deflections (5 to 10.2 percent). This is important for the CRC pavements with asphalt concrete shoulders. If the analysis of the deflection data shows that a temperature parameter (such as temperature differential or mid-depth temperature) is a major explanatory variable for the variations in edge deflection, then a temperature correction will be required to obtain the edge deflections under some standard temperature condition.

Temperature Data

The temperature block was placed in the preselected position several days before making the Dynaflect deflection measurements in both summer and fall so that the temperature of the concrete block could stabilize and be representative of the temperature conditions similar to the CRC pavement. During summer measurements, the recorder was turned on at 11:10 AM on August 6 and turned off at 3:00 PM on August 7. Figure 2.23 shows the temperature records for the top and the bottom of the concrete block. The corresponding temperature records in fall (from 11:05 AM on November 30 to 3:00 PM on December 1 1981) are presented in Fig 2.24. These plots indicate that the temperatures in the concrete slab vary as a sinusoidal function of time with the temperature of the bottom lagging behind the temperature of the top of the slab. This time lag occurs due to the low thermal conductivity of concrete.

As discussed earlier, the two temperature parameters to be investigated in this study in relation to the measured Dynaflect deflections are (1) temperature differential and (2) mid-depth temperature. These are defined as

$$DT = T_T - T_B \tag{2.1}$$

where

DT = temperature differential, °F;

T_T = temperature of the top of the concrete slab, °F, and

T_B = temperature of the bottom of the slab, °F.

The mid-depth temperature is calculated as below, assuming a linear temperature gradient through the concrete slab:

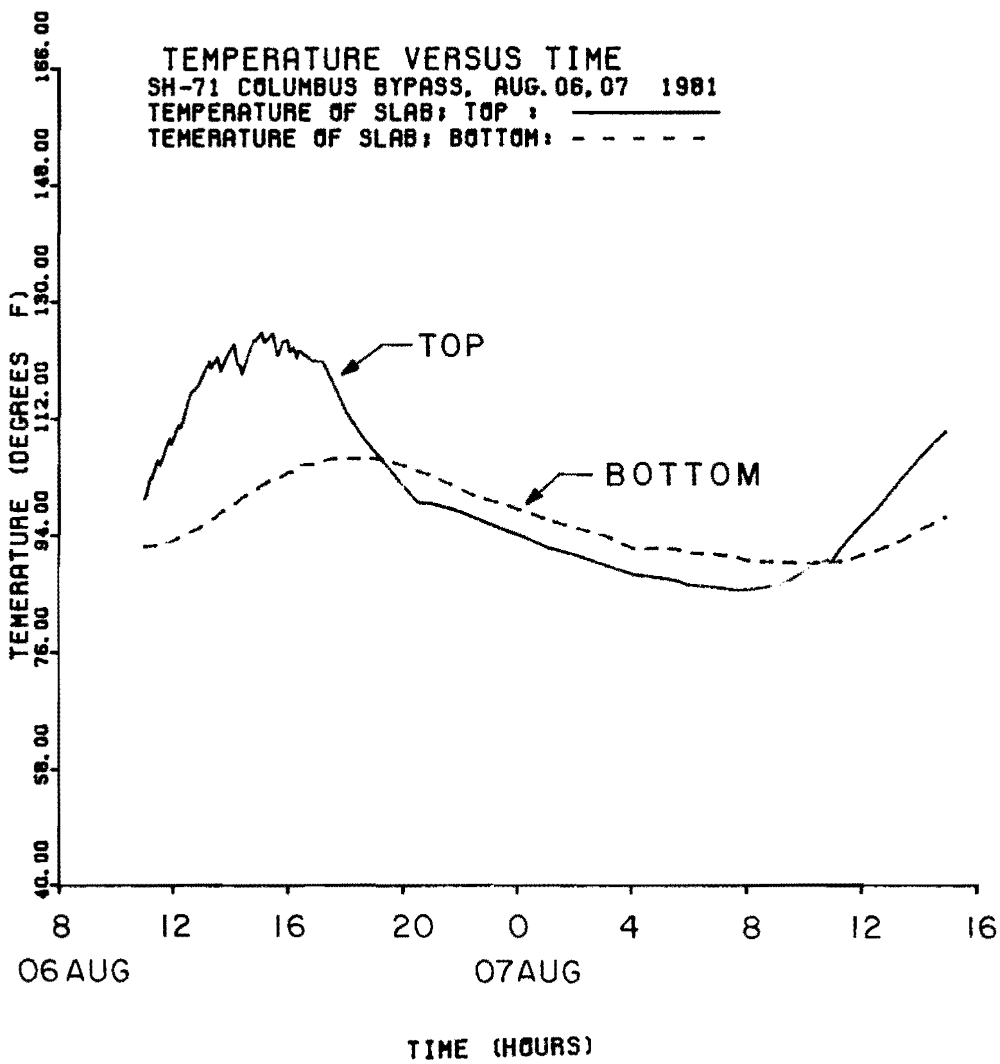


Fig 2.23. Temperature of top and bottom of concrete slab versus time, Summer 1981.

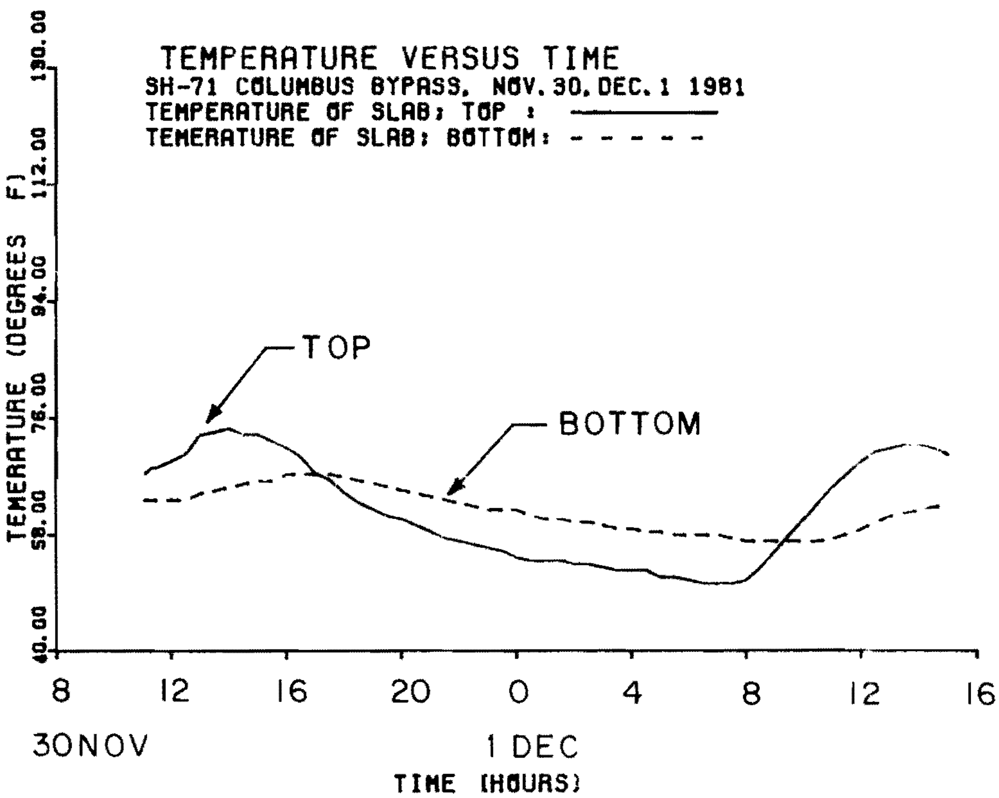


Fig 2.24. Temperature of top and bottom of concrete slab versus time, Fall 1981.

$$TMID = (T_T = T_B)/2$$

where

TMID = mid-depth temperature, °F.

The temperature differential versus time plots for the summer and the fall measurements are presented in Figs 2.25 and 2.26, respectively. A zero temperature differential indicates that the temperatures of the top and the bottom of the concrete slab are equal. This condition occurs twice in a 24-hour cycle. Table 2.5 shows the times of occurrence of zero temperature differential conditions and the corresponding slab temperatures for the summer and the fall measurements. The maximum positive and the maximum negative temperature differential conditions are summarized in Table 2.6. The maximum positive temperature differentials occur in the afternoon hours. The variations of mid-depth temperature with time are presented in Figs 2.27 and 2.28 for the summer and fall measurements, respectively.

Preliminary Analysis of Field Data

In this section the results of a preliminary analysis on the measured Dynaflect deflections and temperature data are described.

Seasonal and Temperature Effects. The seasonal effects on the Dynaflect deflections have been discussed earlier in this chapter. In the present study, only limited data on the Dynaflect deflections and temperature were obtained. In the preliminary analysis the summer and fall data were combined. The seasonal effects are reflected in (1) moisture change in the subgrade layer and unbound layers and (2) the average temperature of the concrete slab. To get an idea of the moisture changes in the subgrade, the daily

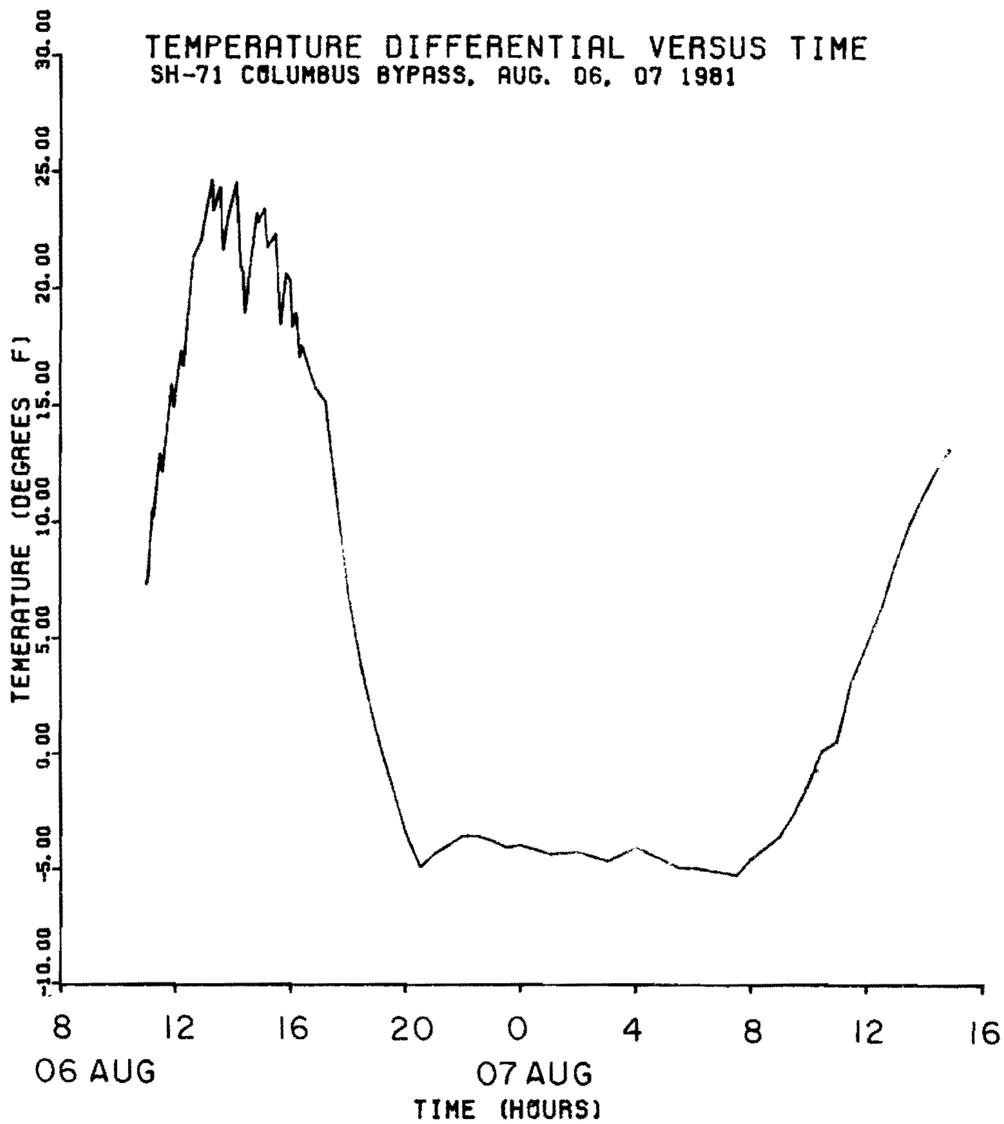


Fig 2.25. Temperature differential versus time relationship, Summer 1981.

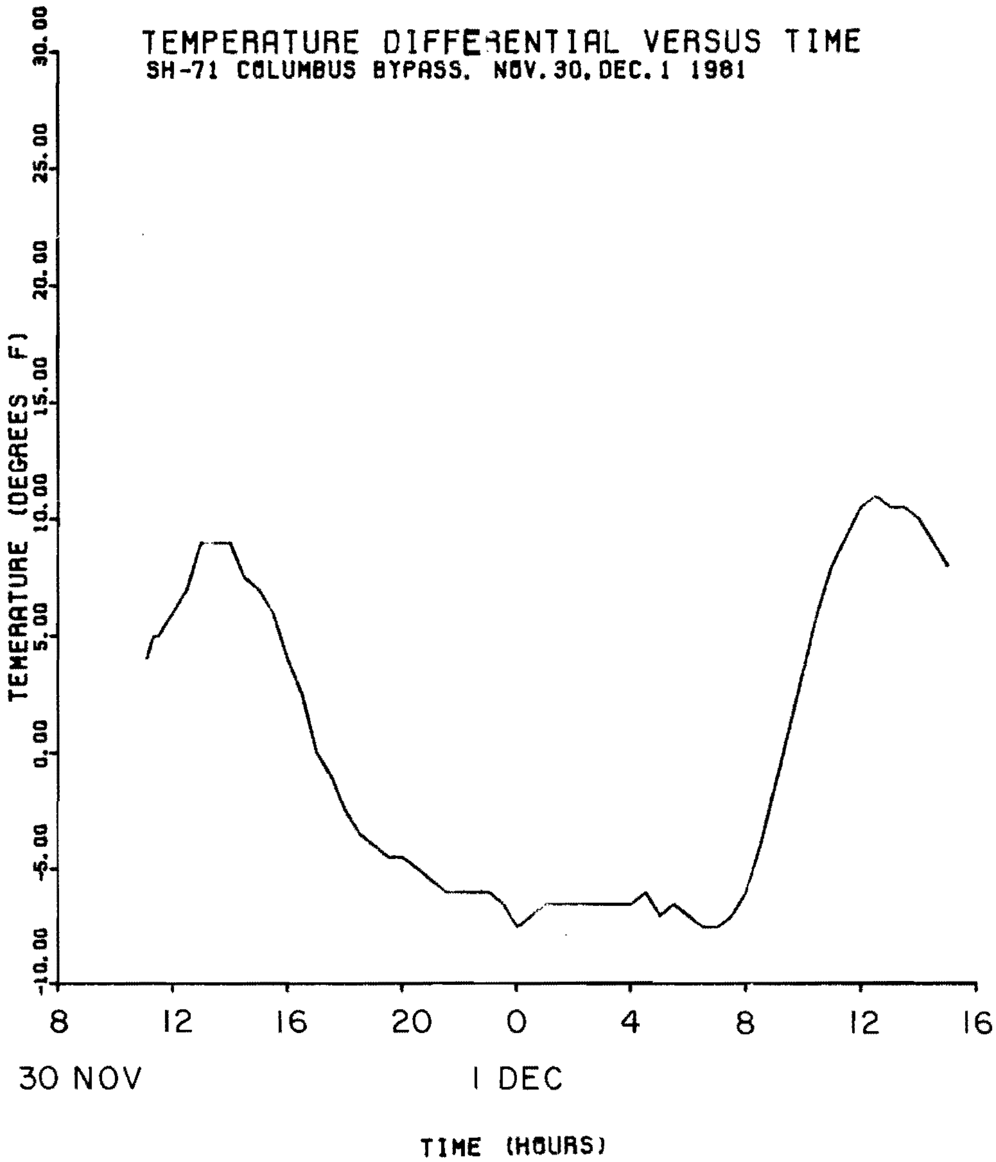


Fig 2.26. Temperature differential versus time relationship, Fall 1981.

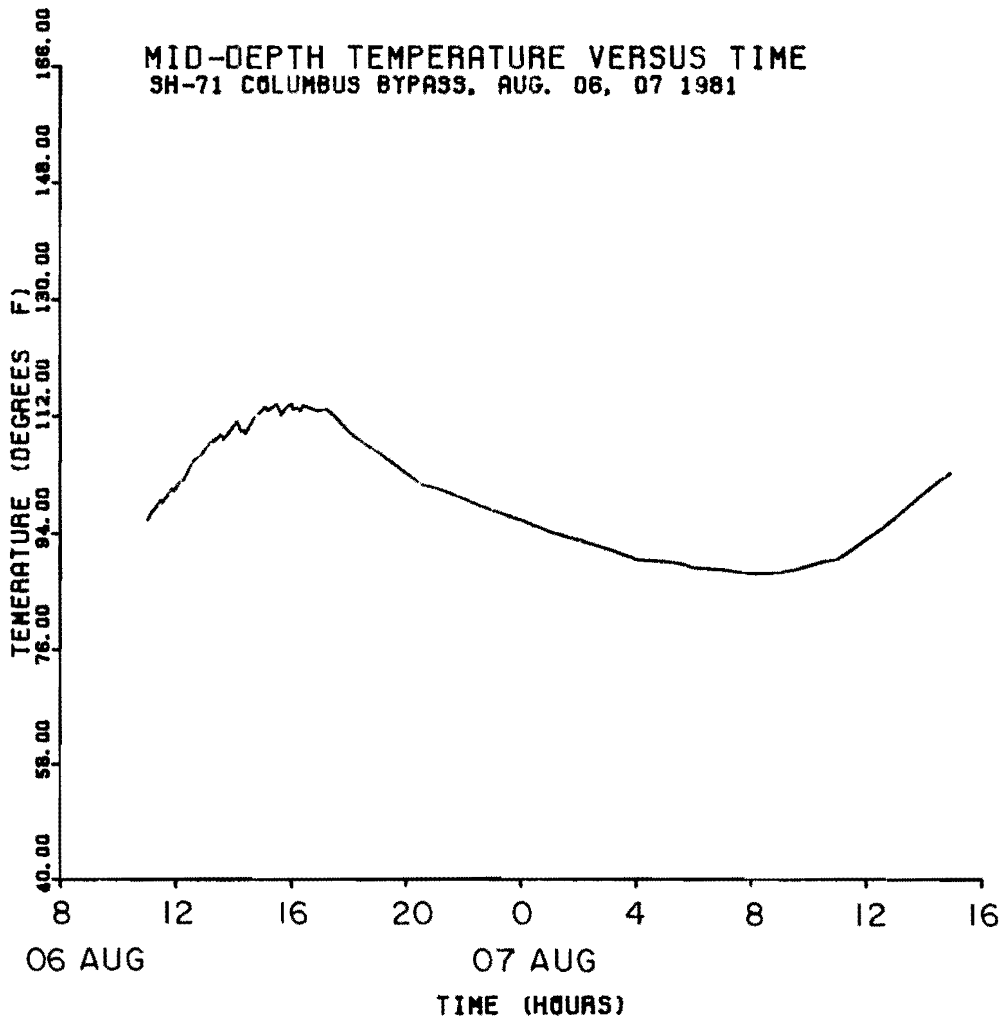


Fig 2.27. Mid-depth temperature of concrete slab versus time relationship, Fall 1981.

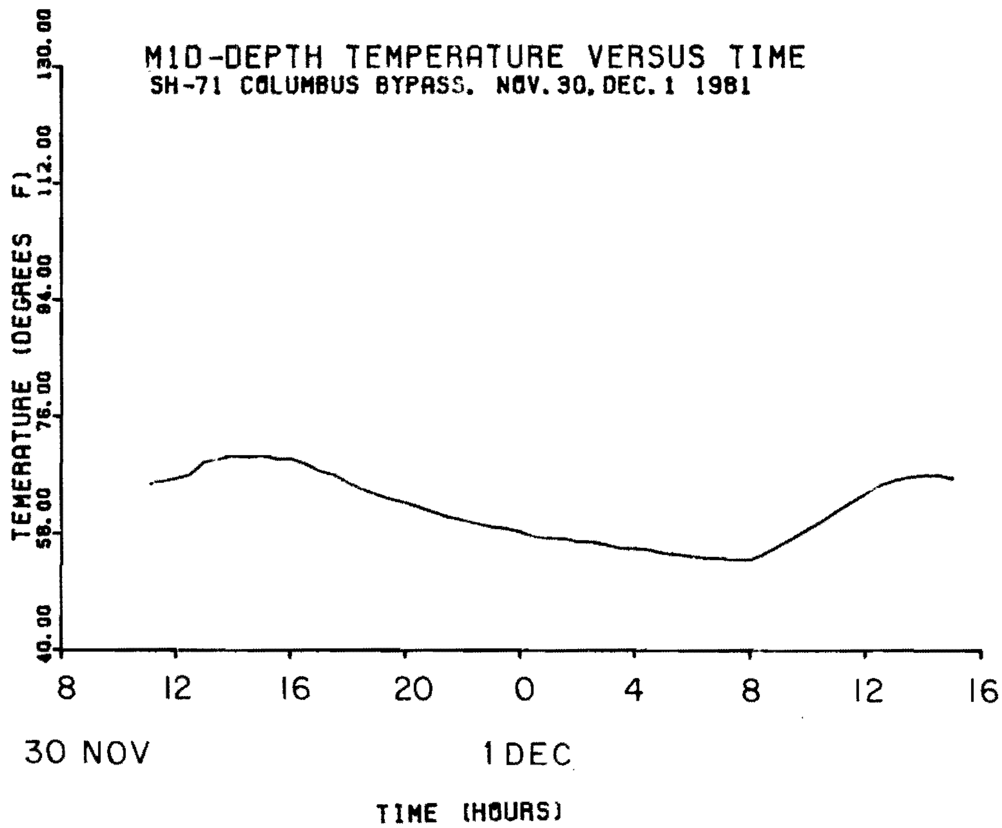


Fig 2.28. Mid-depth temperature of concrete slab versus time relationship, Summer 1981.

TABLE 2.5. ZERO TEMPERATURE DIFFERENTIAL CONDITIONS IN A 24-HOUR DAILY CYCLE

	Zero Temperature Differential Condition		
Test Period	Time, Hours	Day	Temperature of Concrete Slab, °F
Summer 1981	19:15	06 August	105.8
	10:30	07 August	89.7
Fall 1981	17:00	30 November	67.5
	09:15	01 December	57.0

TABLE 2.6. MAXIMUM TEMPERATURE DIFFERENTIAL (DT) CONDITIONS IN A 24-HOUR DAILY CYCLE

Test Period	Positive DT, ° F	Time, Hours	Day	Negative DT, ° F	Time, Hours	Day
Summer 1981	+ 24.6	14:07	06 August	- 5.2	07:30	07 August
	+ 14.5	14:43	07 August			
Fall 1981	+ 9.0	13:45	30 November	- 7.5	06:45	01 December
	+ 11.0	13:45	01 December			

precipitation data for Columbus (Ref 19) were reviewed. The monthly precipitation data recorded at Columbus are presented in Fig 2.29. The record indicates that there was no rain during the first week of August 1981, but a total precipitation of 3.99 inches is recorded for the month of July 1981. It rained during the night of November 30/December 1. However, the deflection data collected during the fall do not indicate any apparent trend in terms of larger deflections (see Table 2.3).

The maximum temperature differential in summer was much higher than the maximum temperature differential in fall. Also the maximum mid-depth temperature in the summer was higher as compared to the maximum TMID in fall. As discussed earlier, the effect of temperature differential on the Dynaflect deflection will be much more pronounced than the effect of mid-depth temperature. As observed in Figs 2.25 and 2.26, the temperature differential is zero around 9:00 AM and then increases steadily until around 2:00 to 3:00 PM, when a maximum positive temperature differential occurs. During this time the concrete slab curls down (Fig 2.3). Deflections measured at the edges will be less than the true deflection at zero temperature differential. Location 1L corresponds to the edge of the concrete slab with an asphalt concrete shoulder as the edge support. This is a typical and common example of CRC pavements in Texas. Figure 2.30 shows the plots of the maximum deflection (W_1) versus temperature differential for the three sections. The slopes of the best fit lines are negative. The same finding is reported in Ref 7. This indicates that the Dynaflect deflections measured near the edge (especially at transverse cracks) at the time of high positive temperature differential will be less than the corresponding "true" deflections. The "true" deflection is related to the condition of zero temperature differential when the temperatures of the top and the bottom of the slab are

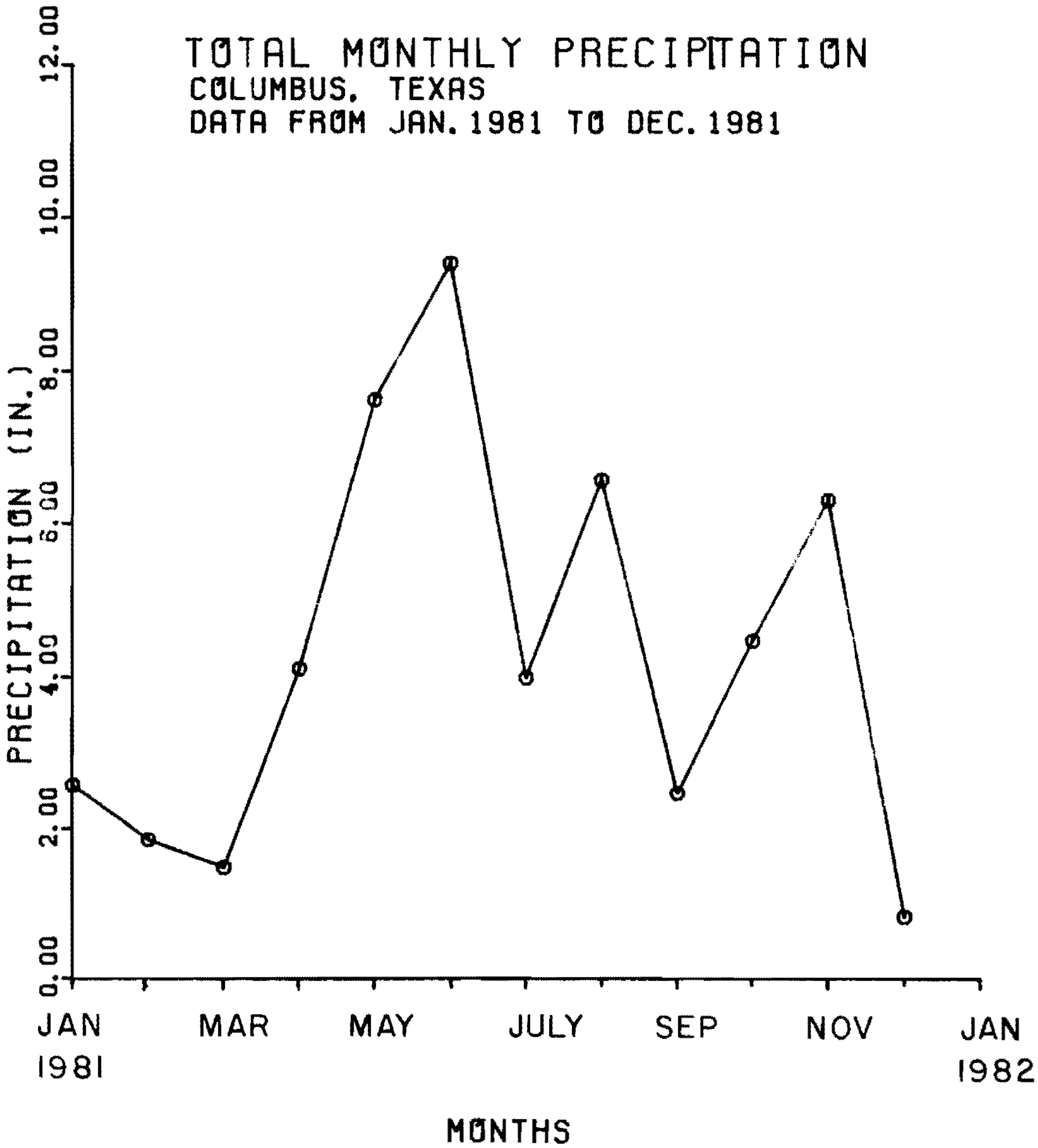


Fig 2.29. Variation of monthly precipitation, Columbus, Texas (Ref 19).

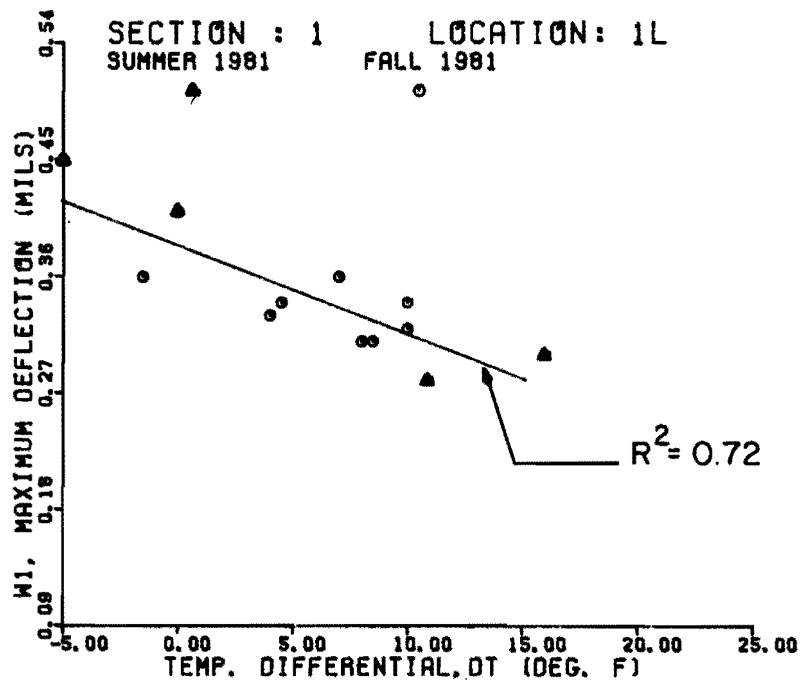


Fig 2.30(a). Maximum deflection (W_1) versus temperature differential relationship at location 1L, section 1.

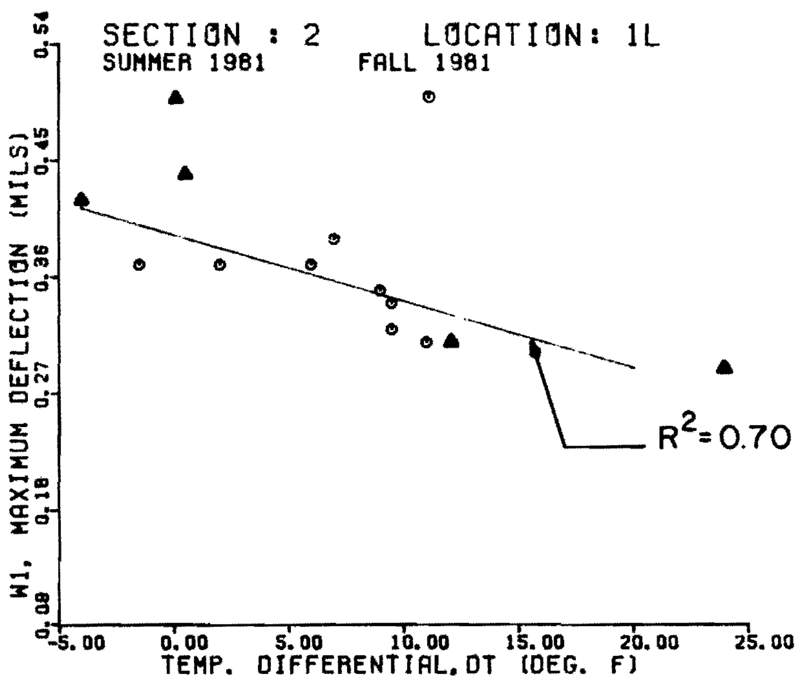


Fig 2.30(b). Maximum deflection (W_1) versus temperature differential relationship at location 1L, section 2.

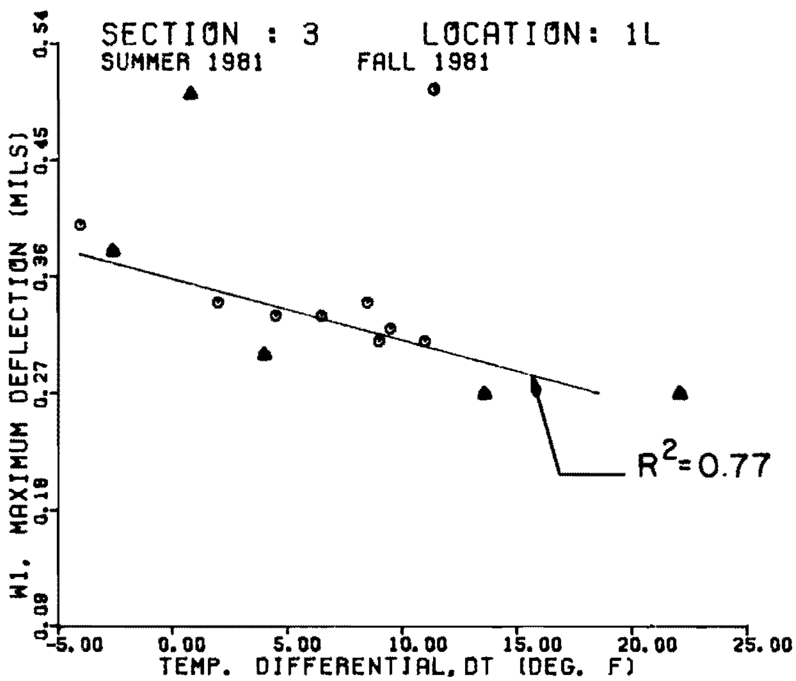


Fig 2.30(c). Maximum deflection (W_1) versus temperature differential relationship at location 1L, section 3.

the same. The best fit lines for W_5 vs DT plots are illustrated in Fig 2.31 for location 1L in all three sections. These indicate the same trend as that found for W_1 vs DT plots. In Fig 2.31, the R^2 value related to deflections in section 3 is appreciably different from the R^2 values corresponding to section 1 and 2. This indicates that section 3 behaves differently when compared to sections 1 and 2. This difference may possibly be due to the subsoil characteristics and moisture variations. It should be noted that section 1 and 2 are within 300 feet of each other while section 3 is some 1,000 feet away (see Fig 2.15). Figure 2.32 illustrates the measured deflection basins at location 1L in section 3 on August 7, 1981, at different temperature differentials.

The Dynaflect deflection measurements are commonly made in the wheel path or near the center of the concrete slab for the purpose of material characterization of the pavement layers, e.g., locations 6L and 8L in Fig 2.18. These positions will represent the interior condition. In the case of high positive temperature differential, the top of the slab is warmer than the bottom. The downward curling in this case is illustrated in Fig 2.3. At the center of the slab (mid-span position; i.e., between the transverse cracks), there will be some loss of support. This is the physical explanation for measuring larger deflections (at high positive temperature differentials) as compared to the corresponding "true" deflections at zero temperature differential. For illustration, the measured deflection basins at location 6L in section 1 are plotted in Fig 2.33. It indicates that the best fit line for the W_1 vs DT plot will have a positive slope. However, it may be noted that this effect is not as pronounced as the opposite effect of DT found on the edge deflections. The deflection parameter, such as W_1 or W_5, was used as a dependent variable and regressed on the independent

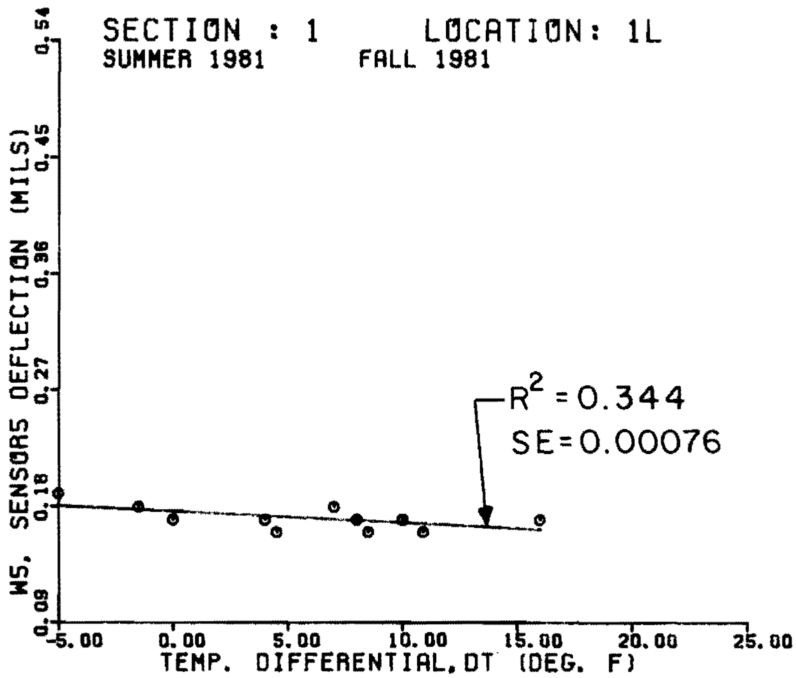


Fig 2.31(a). Sensor 5 deflection (W_5) versus temperature differential relationship at location 1L, section 1.

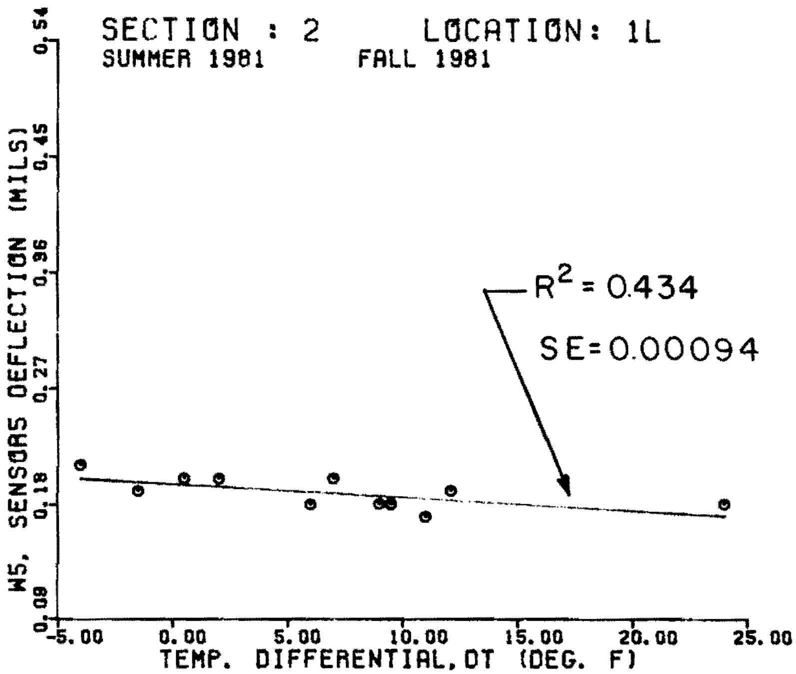


Fig 2.31(b). Sensor 5 deflection (W_5) versus temperature differential relationship at location 1L, section 2.

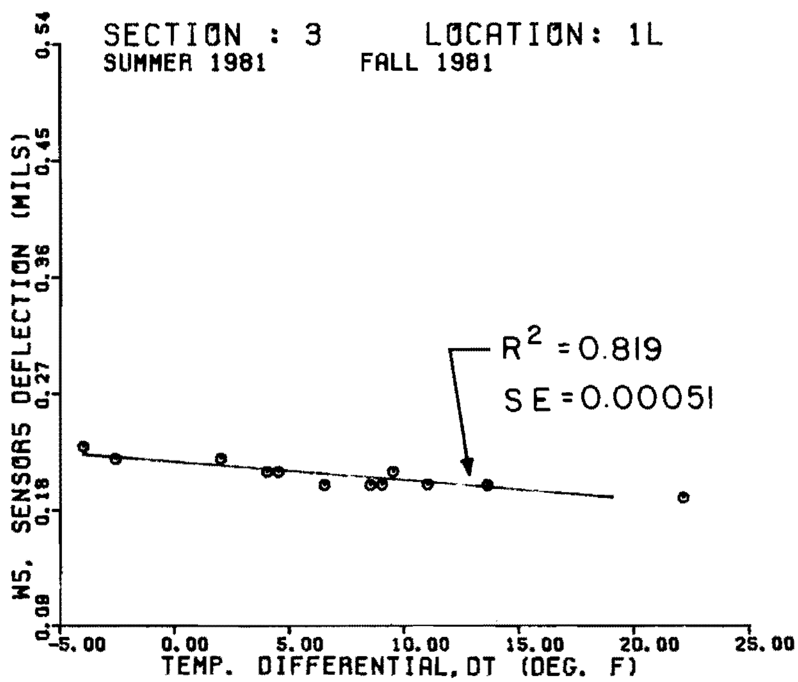


Fig 2.31(c). Sensor 5 deflection (W_5) versus temperature differential relationship at location 1L, section 3.

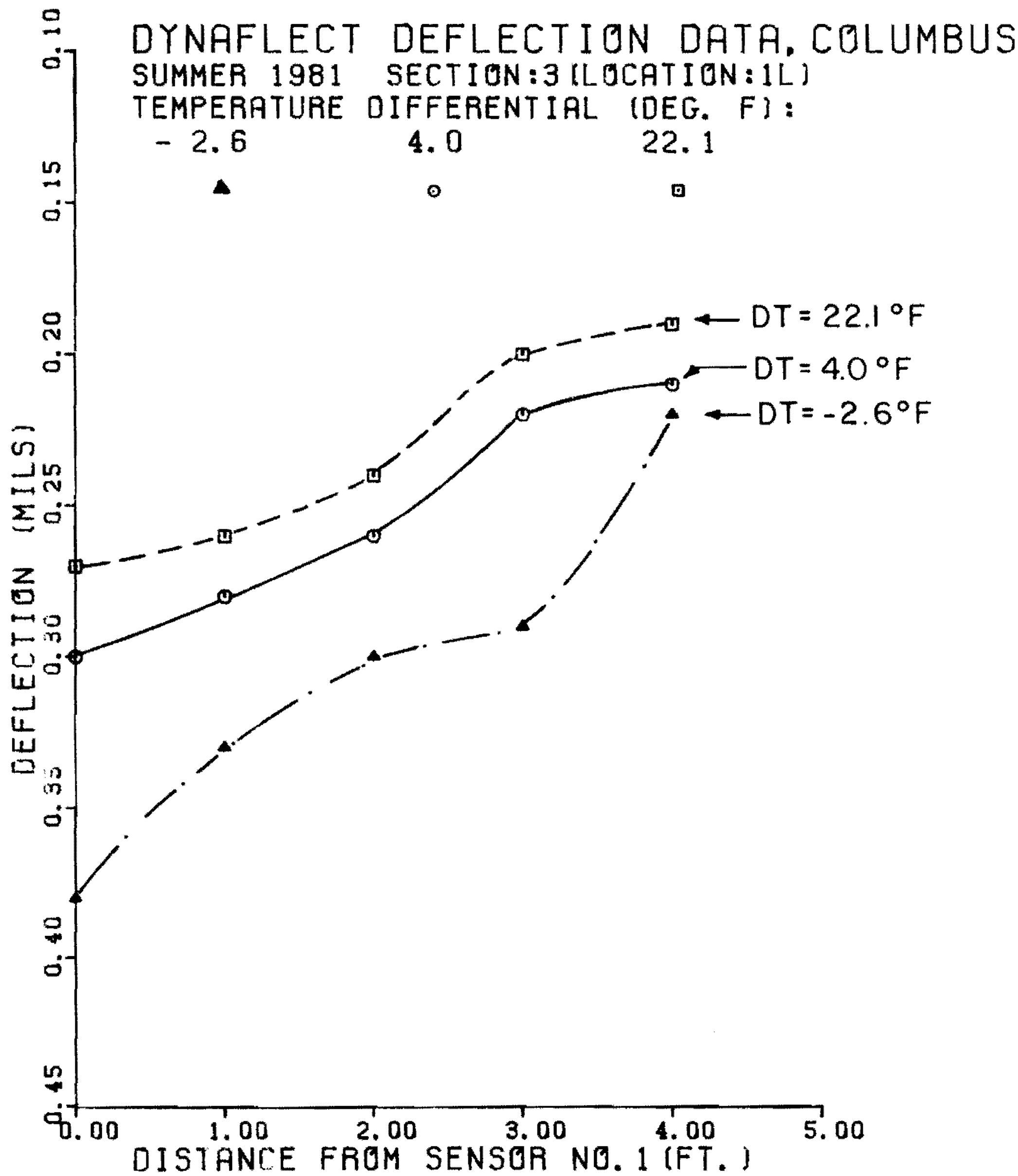


Fig 2.32. Deflection basins measured near the pavement edge at different temperature differentials.

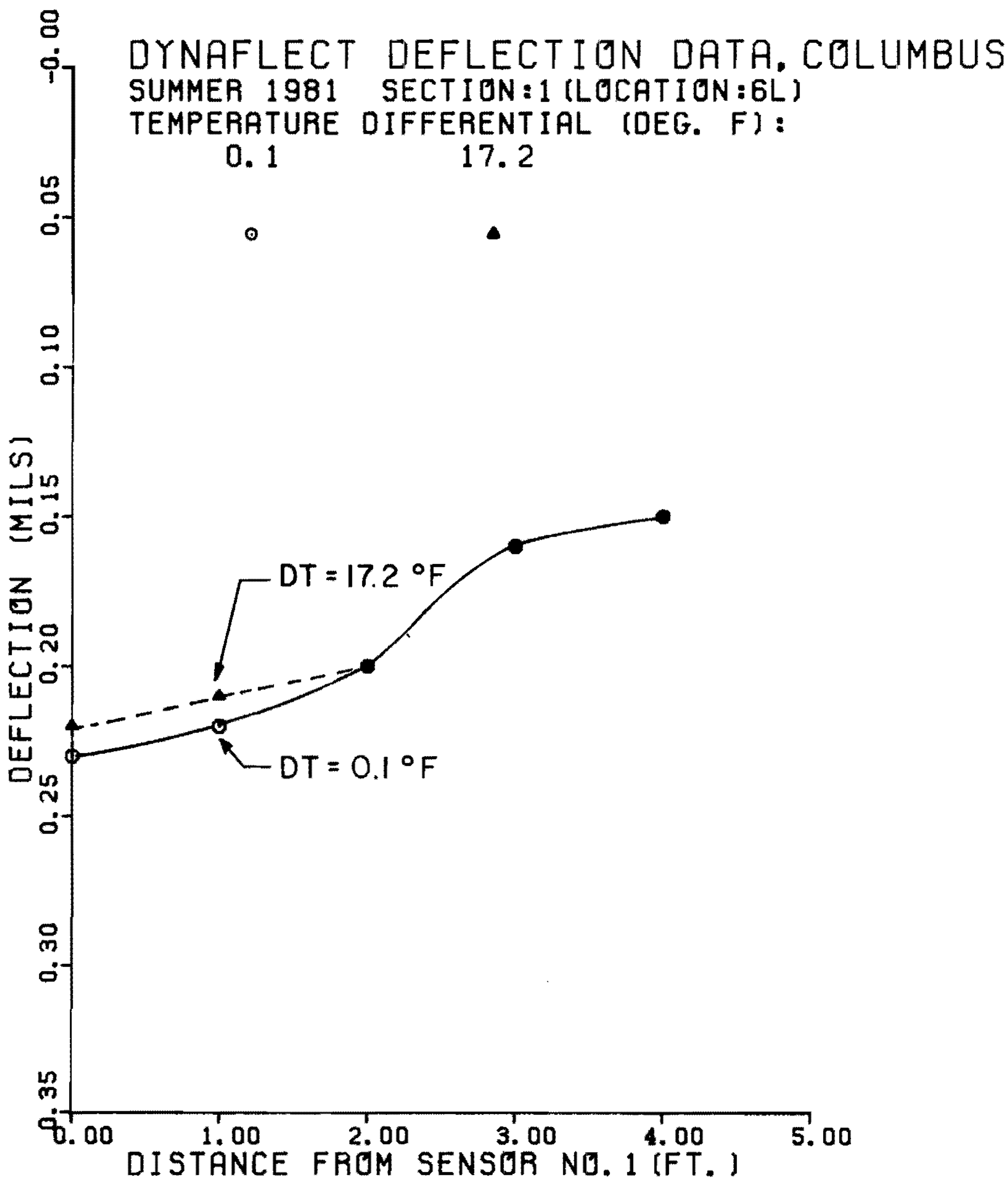


Fig 2.33. Deflection basins measured in mid span position (interior condition) at different temperature differentials.

(explanatory) variable, DT . This simple linear regression analysis was carried out for the summer and fall data. Each data set of 12 observations corresponds to every location (1L to 12L) in each section. The simple linear regression analysis gives the estimate of the coefficients (intercept and slope) of the regression equation for the best fit line corresponding to each data set. The statistic used to measure the explanatory power of a regression line is the coefficient of determination, R^2 . An R^2 of zero means that W_1 or W_5 is not dependent on DT. An R^2 of one indicates that DT explains all the variation in the dependent variable W_1 or W_5 , or, in other words, there is perfect correlation between the observed deflection and the deflection predicted by the regression equation. It is impossible to obtain an R^2 equal to one, but an R^2 of around 0.90 is desirable in order to say, for example, that in our case DT is the only explanatory variable. Simple regression analyses were made with DT as the explanatory variable and W_1 , W_5 and SLOP $(W_1 - W_5)$ as the response variable, respectively. The R^2 statistic in all the cases was generally low with considerable scatter. The temperature effects and deflection behavior are influenced by the position of the Dynaflect relative to the edge and the type of edge support, etc. These effects are discussed in the next section.

Effect of the Dynaflect Position. The preceding discussions indicate that the effect of temperature differential on the Dynaflect deflection is influenced by the position of the Dynaflect relative to the CRC pavement edge. Other position variables that can affect the Dynaflect deflections are (1) position relative to transverse cracks, and (2) type of edge support. The measured deflections when the Dynaflect is positioned close to a transverse crack are obviously expected to be relatively larger than the mid-span deflections when the Dynaflect is positioned between two transverse cracks and the geophone-bar is oriented in the longitudinal direction. The difference in the at-crack and mid-span deflections is larger at a zero or negative temperature differential (see Fig 2.34). However, this will depend on the distance of the Dynaflect from the edge of the concrete. To illustrate these observations, in Fig 2.35, the best fit lines for W_1 vs DT plots at location 2L are drawn for sections 1, 2, and 3, respectively. The deflection basins presented in Fig 2.34 indicate:

(1) At a zero or negative temperature differential, W_1 (Dynaflect near edge) is much larger at-crack as compared to the mid-span deflection. It can be expected as the crack width in this condition will be more than in the condition when the top of the concrete slab is warmer than the bottom, i.e., at a high positive temperature differential.

(2) W_5 deflections remain practically the same when the Dynaflect is positioned near the transverse crack or in mid-span.

Type of edge support has great influence on the magnitude of the Dynaflect deflections (see Table 2.3). The behavior of the Dynaflect deflections is also influenced by the distance of the Dynaflect from the pavement edge. The deflection data in the wheel path are expected to be different from the deflection measurements near the edge. A complete analysis of the measured deflection and temperature data requires consideration of all these factors. The next chapter is devoted to this end.

SUMMARY

In this chapter, some environmental factors and other factors related to the position of the Dynaflect were discussed. The previous investigations to study the effects of these factors on the Dynaflect deflections were reviewed. The review and discussions were confined to rigid pavements, with

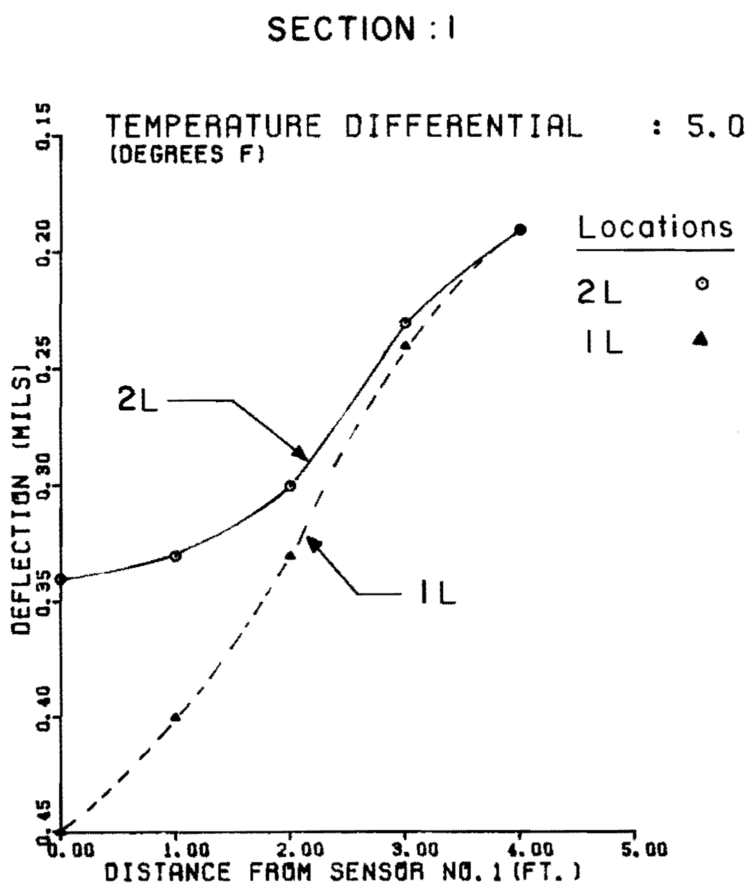


Fig 2.34(a). Comparison of deflection basins in mid-span and at crack locations measured at low temperature differential.

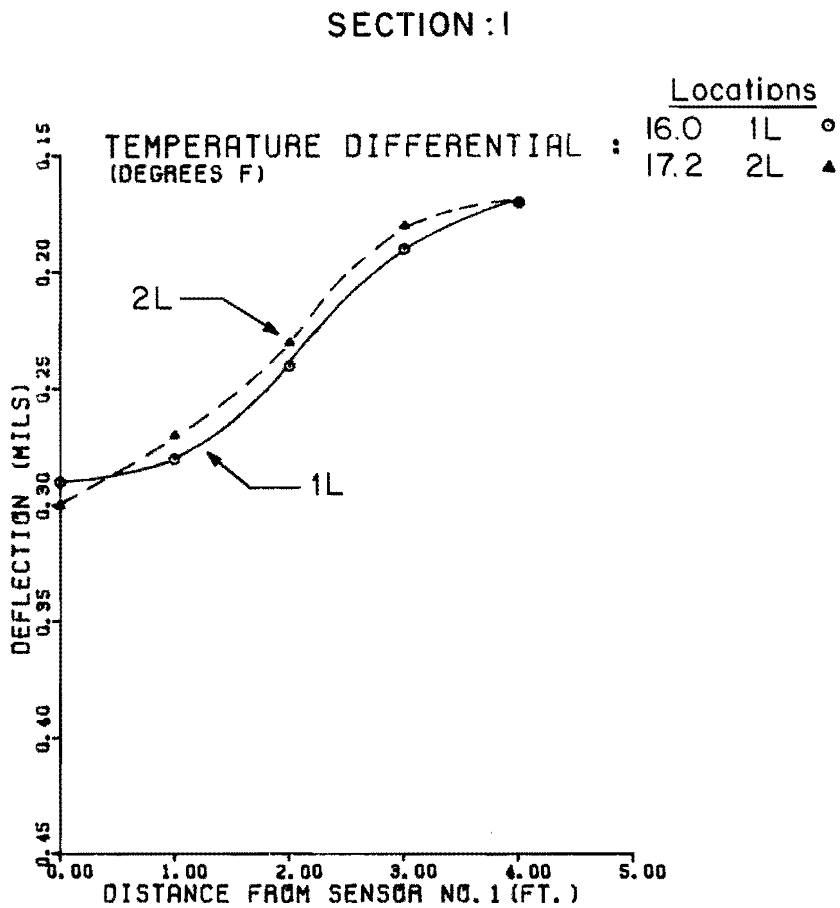


Fig 2.34(b). Comparison of deflection basins in mid-span and at crack locations measured at higher positive temperature differential.

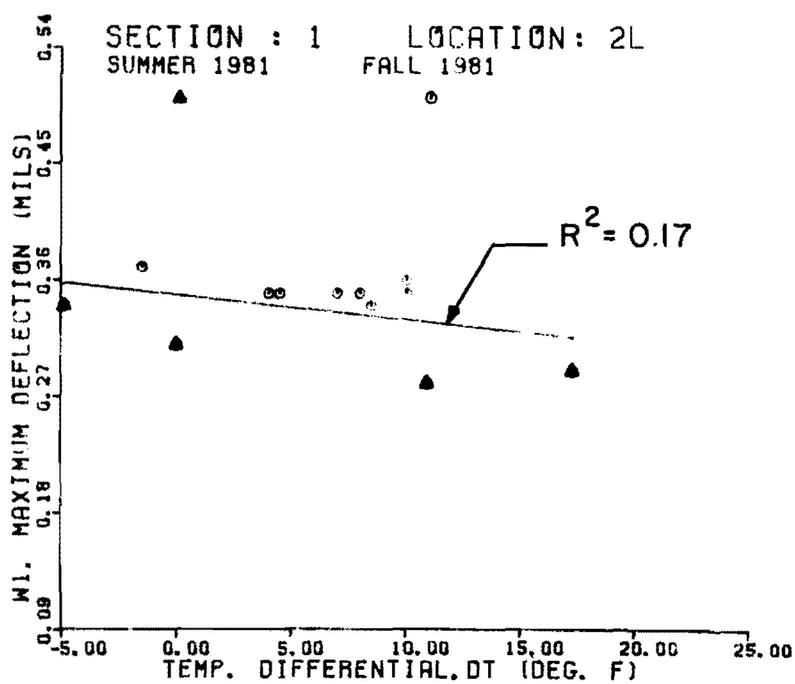


Fig 2.35(a). Maximum deflection (W_1) versus temperature differential relationship at location 2L, section 1.

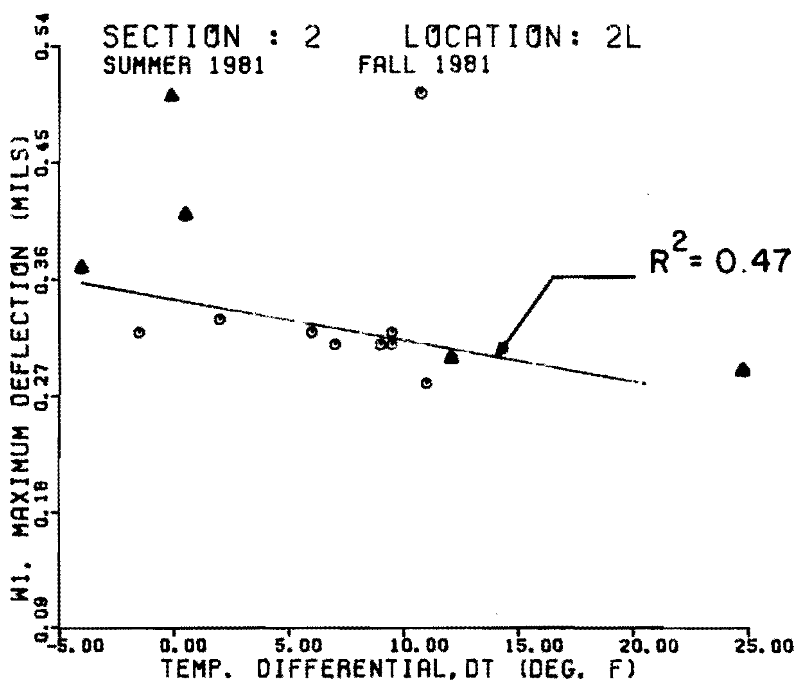


Fig 2.35(b). Maximum deflection (W_1) versus temperature differential relationship at location 2L, section 2.

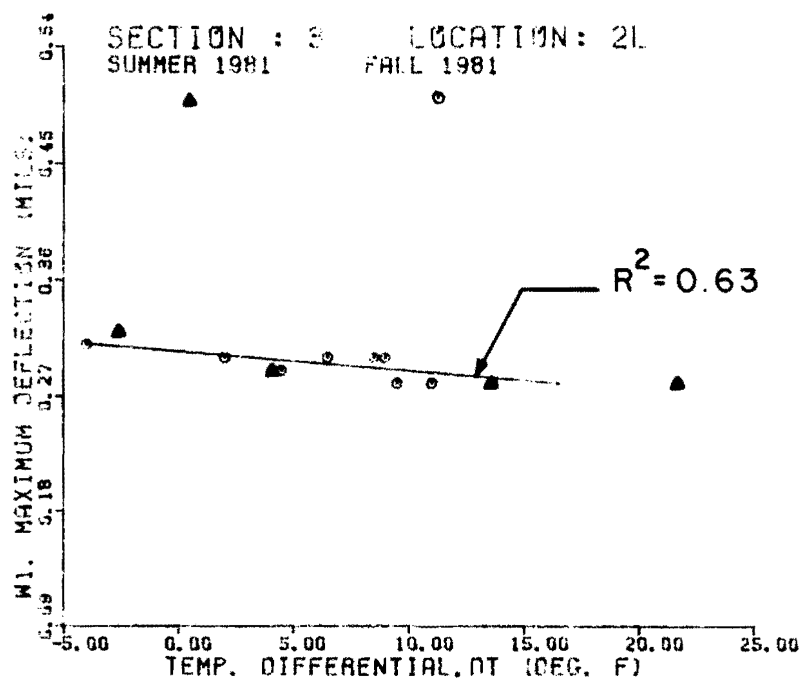


Fig 2.35(c). Maximum deflection (W_1) versus temperature differential relationship at location 2L, section 3.

special attention to continuously reinforced concrete pavements. The set-up for the Dynaflect deflection and temperature measurements on a recently constructed CRC pavement near Columbus, Texas, and the results of a preliminary analysis are also described in this chapter. The discussions made in the preceding sections lead to the following factors that can influence the Dynaflect deflections on CRC pavement:

(1) temperature differential,

(2) type of edge support,

(3) Dynaflect position relative to the transverse cracks, and

(4) distance of the Dynaflect from the edge.

A conclusive finding can not be inferred from the results of this preliminary analysis. More rigorous analysis of the multifactor data of the Dynaflect deflections is presented in the next chapter.

CHAPTER 3. STATISTICAL ANALYSIS OF THE DYNAFLECT DEFLECTION AND TEMPERATURE DATA

UNIVARIATE MULTIPLE REGRESSION ANALYSIS

Multiple regression analysis is a powerful statistical tool for identifying relationships among variables. The relationship is formed through an equation relating a dependent or response variable to more than one independent or explanatory variable. As a result of the preliminary analysis in the preceding chapter many factors influencing the Dynaflect deflections were identified. These factors can be used as independent variables and one of the measured deflection parameters can be used as the response variable. The procedure of regression analysis, brief descriptions of statistical terms, the data setup, and the resulting regression equations are presented and discussed in the following sections.

Multiple Linear Regression Technique

Model and Parameter Estimation. The general univariate regression model can be written in the following form:

$$\underline{Y} = \underline{X}\,\underline{\beta} + \underline{\varepsilon} \qquad (3.1)$$

where

$\underline{Y}$ is an (n x 1) vector of observations,

$\underline{X}$ is an (n x p) design matrix,

$\underline{\beta}$ is a (p x 1) vector of parameters, and

$\underline{\varepsilon}$ is an (n x 1) vector of errors associated with $\underline{Y}$.

The elements of $\underline{\varepsilon}$ are assumed random. We desire to minimize the error sum of squares in the selection of the parameters $\underline{\beta}$. The least squares estimate of $\underline{\beta}$ is b . The elements of $\underline{b}$ are linear functions of the observations Y_1 , Y_2, ..., Y_n. These parameters are also called regression coefficients. In the multiple linear regression model, "linear" refers to linearity in the parameters. For detailed treatment of linear regression methods, reference is made to any good text book, such as Ref 20.

The estimates of the regression coefficients are based on the sampled values of Y (dependent or response variable) and independent variables X_1 , X_2 , ..., X_p . The independent variables are also called explanatory variables. The estimated regression equation is written as

$$\hat{Y} = b_o + b_1X_1 + b_2X_2 + \ldots b_pX_p \tag{3.2}$$

where

$\hat{Y}$ is the estimated value of response variable,

b_o is a constant term or intercept; it takes care of the scaling effects due to different units of measurements used with X_1 , X_2 , ..., X_p ,

$b_1, b_2, b_3, \ldots, b_p$ are the regression coefficients associated with the independent or explanatory variables X_1 , X_2 , X_3 , ... X_p , respectively.

The interpretation of the estimated regression equation and the associated statistics are explained in a later section.

<u>Stepwise Regression Procedure.</u> In many regression situations, such as those in this study, the researcher has collected data of many explanatory variables in which he has interest corresponding to the sampled observations of the dependent variable. The researcher does not know the order of

importance of these independent variables. The stepwise regression procedure is as follows:

(1) criteria are assigned by the researcher for entering independent variables and a rule for removing variables,

(2) only one independent variable is entered in the first step which is most highly correlated with the criterion, and

(3) then the program searches for the variable to find which explanatory variable, in combination with the one already in the equation, will yield the highest R^2 (coefficient of determination).

In this study the forward stepwise regression procedure of the SPSS computer package was employed in all multiple linear regression analyses. SPSS is the abbreviation for "Statistical Package for Social Sciences"). Reference 21 is the main source for a detailed explanation of the multiple regression method used in this study.

Definition and Interpretation of Statistical Terms

In this section, interpretation of coefficients of the estimated equation, analysis of variance tables in SPSS regression outputs, and definitions of different statistics and criteria are explained. For more rigorous discussions, Refs 20, 21, and 22 can be consulted.

Analysis of Variance Table. The least squares fitting of the observed values of the dependent variable is the method used to estimate regression coefficients; it is also a basis for many other interpretations. The sum of squared deviations from the mean value of observed Y values (total SS) is a measure of how much the dependent variable varies from its mean. The total SS can be partitioned in the following form:

$$\text{Total SS} = \text{Explained SS} + \text{Unexplained SS} \tag{3.3}$$

or, in other words,

$$\begin{matrix}\text{Sum of Squares} & = & \text{SS due to} & + & \text{SS about} \\ \text{about mean} & & \text{regression} & & \text{regression}\end{matrix} \tag{3.4}$$

In the SPSS regression output, the partitioned sums of squares(SS), their degrees of freedom(df), and the resulting mean squares(MS) are summarized in what is called an analysis of variance table. "Degrees of freedom" refers to the number of independent pieces of information involving the dependent variable Y needed to compile the sums of squares (Ref 22). A mean square is obtained by dividing a sum of squares by the corresponding degrees of freedom. The SPSS output provides additional information based on the analysis of variance table.

Standard Error of Estimate (SE). The standard error of estimate is calculated by taking the square root of the mean square about regression, also called mean square due to error (MSE). The statistic MSE is also an estimator for σ^2, the population variance. The standard error of estimate when divided by the mean value and expressed as a percentage is referred to as the coefficient of variability.

F-test. MS (due to regression) divided by MS (about regression) is a very useful statistic which has F distribution with ν_1 and ν_2 degrees of freedom, (where ν_1 is equal to degrees of freedom associated with SS due to regression and ν_2 corresponds to df associated with SS about regression.) The above statistic is used to make a test of significance that the fitted relationship is not due to chance.

The test of significance is

$$\text{Null hypothesis } H_o : \beta_1 = \beta_2 = \ldots = \beta_p = 0$$

The alternative hypothesis is

$$H_1 : \text{ Not all } \beta_L \ (i > 0) \text{ equals to zero.}$$

The critical value of F is computed and published in tables at or any desired level of significance. If a calculated value for $F = \frac{\text{MS due to regression}}{\text{MS about regression}}$ is greater than the critical F value, the null hypothesis is rejected. In other words, it can be confidently said that the regression slope's (coefficient's) being different from zero is not purely by chance.

Coefficient of Multiple Determination. The Coefficient of Multiple Determination is the ratio of the SS (explained) to the SS (total) and is given the symbol R^2. Obviously R^2 can approach two extreme values, 0 and 1. R^2 can approach one only in the case of perfect fit of the linear regression equation. R^2 is therefore a measure of the explanatory power of the regression (Ref 22). R^2 is also closely related to F.

Interpretation of Regression Coefficients. The student t-test of significance is made to guard against including a variable in the regression equation that is not important. The SPSS output also gives standard error of regression coefficients, 95 percent confidence interval estimates, and calculated t values.

BETA Coefficients. The estimated regression coefficients can not be used to compare the order of importance of the independent variables in the regression equation, because these estimated values are influenced by the units of measurements. To compare and rank the effectiveness of each of the explanatory variables X_1, X_2, ..., X_p, the standardized regression coefficients, BETA, printed in the output can be used. BETA coefficients are used in this study to rank the explanatory variables in the regression equation.

Elasticity. The elasticity is also printed in the SPSS output, along with BETA. The elasticity is roughly a measure of the percent change in Y caused by a one percent change in X_j.

Criteria for Adding and Deleting Independent Variables

Certain criteria are used in the stepwise regression procedure for adding and deleting an independent variable in the regression equation at each step. These are briefly described below.

Partial F-test. A partial F-test is used to test the hypothesis $H_o : \beta_j = 0$ against $H_1 : \beta_j \neq 0$ for some variable X_j. This statistic is used to test similar hypotheses regarding a number of parameters simultaneously. It is a test of whether a variable in the regression has contributed significantly to reducing the unexplained variation in Y or, if the variable is not yet included in the regression, whether it would contribute significantly to reducing the unexplained variation of Y. In the stepwise regression procedure of SPSS, a critical value of $F = 1.0$ was specified in the analyses discussed in a later section. In this procedure the variables already in the equation are reevaluated at each stage. Because of the intercorrelation, a variable that was important at an earlier step may not be important at the later one (Ref 22). The stepwise regression procedure is summarized in Fig 3.1.

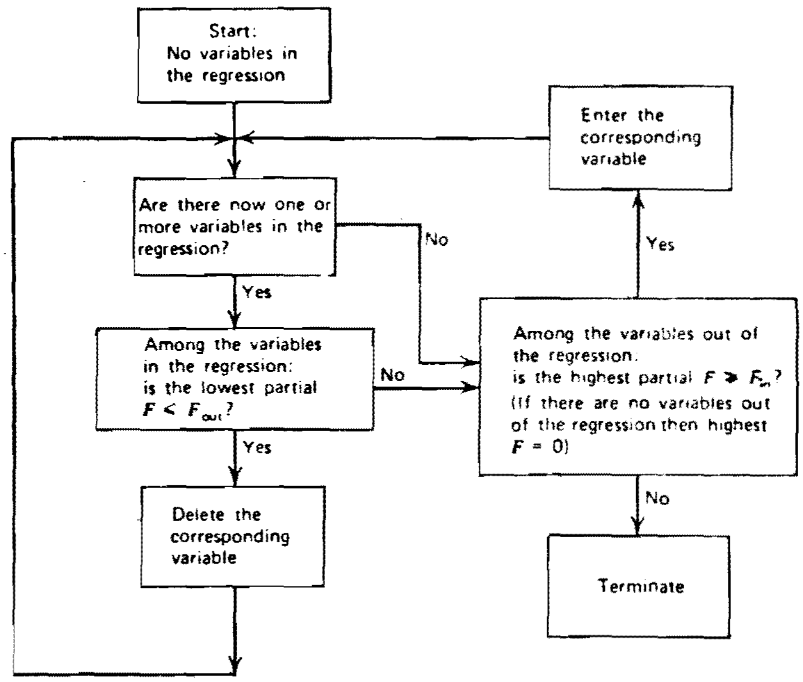


Fig 3.1. The stepwise regression procedure (Ref 22).

Tolerance. The tolerance parameter is used in the SPSS stepwise regression procedure card. The tolerance of an independent variable being considered for inclusion is the proportion of the variance of that variable not explained by the independent variable already in the equation (Ref 21). It is a way of avoiding the multicollinearity problem with the independent variables. The tolerance is a number between 0 and 1. A tolerance of zero indicates that the variable is a perfect linear combination of other variables already in the equation. A tolerance of one indicates that the variable is uncorrelated with the other variables already in the equation. In this study, a tolerance of 0.1 was specified which means that 10 percent of the variance of a potential independent variable is unexplained by the independent variables already entered in the equation.

Coefficients of Partial Determination and Correlation. The coefficient of partial determination (R^2)is that proportion of the unexplained sum of squares in Y that is removed by adding an independent variable. It is a number between 0 and 1 similar to coefficient of determination. The square root of the coefficient of partial determination is called the partial correlation coefficient (printed as partial in SPSS regression output). The multiple correlation coefficient (R) and R^2 are calculated for Y and for independent variables at each step.

Dichotomous Variables in Multiple Regression Analysis. Introduction in the preliminary analysis it was concluded that some "qualitative" variables, such as the type of edge support and the Dynaflect position with respect to edge, wheelpath, and transverse cracks, could influence the deflections measured on CRC pavements. The influence of the qualitative variables on the Dynaflect deflections can in reality be greater than the effect of a continuous variable such as temperature differential. In addition it has also been observed that the Dynaflect deflections can also be categorized in relation to the test section number (as indicated in Fig 2.30). These qualitative and categorical variables can be used as "dichotomous" or "dummy" variables in the multiple linear regression analysis. When the dummy variables are used as independent variables, the multiple regression analysis technique becomes a powerful analytic tool in forming a relationships between the response variable and predictor variables.

Rules. The dichotomous variable is that variable which is assigned only two values, i.e., zero or one. These two values signify that the observation belongs to one category or the other. It is important to realize that the numerical values of a dichotomous variable, more commonly known as a dummy variable do not reflect any quantitative ranking of the categories. The other important rule is that a categorical variable with p categories will be represented by (p - 1) dummy variables (Ref 22). For example, in the present investigations the Dynaflect data were collected from three different sections. If section (symbol SEC) is to be used as an explanatory variable it can be represented by (3-1) or 2 dichotomous (dummy) variables in the following form:

$$SEC1_j = \begin{cases} 1 & \text{if the } j^{th} \text{ response (say } W_1\text{) belongs to section 1} \\ 0 & \text{otherwise} \end{cases}$$

and

$$SEC2_j = \begin{cases} 1 & \text{if the } j^{th} \text{ response (say } W_1\text{) belongs to section 2} \\ 0 & \text{otherwise} \end{cases}$$

The effect of section 3 will be included in the intercept or constant term of the final regression equation. If only temperature differential, DT , is used as an explanatory variable to predict W_1 (maximum deflection), with SEC1 and SEC2 as dummy variables and other factors having fixed values, then the final regression equation will be of this form

$$W_1 = b_o + b_1 \text{ (DT)} + d_1 \text{ (SEC1)} + d_2 \text{ (SEC2)} \qquad (3.5)$$

where b_o , b_1 , d_1 , and d_2 are estimated regression coefficients. This equation in essence represents three different straight lines with the same slope, b_1, but different intercepts. Appendix B presents an illustrative example showing the difference between the regression analysis using dummy variables and the separate regression analyses made on each of the three categories.

Categorical Interaction. The multiple linear regression technique allows one to investigate interaction between continuous and dummy variables being used as explanatory variables. References 20, 21, and 22 provide a good source of detailed discussions on other applications of dummy variables in solving practical problems.

PRESENTATION OF RESULTS AND DISCUSSIONS

The application of multiple linear regression analyses to the Columbus Dynaflect deflection and temperature data is described in this section. The continuous and dichotomous explanatory variables of interest and response variables used in the stepwise regression procedure are also defined. In order to arrive at some meaningful relationship with preferably high R^2 (multiple coefficient of determination), different subsets of the collected data are analyzed and the results are presented generally in tabular form.

Application of Stepwise Regression Procedure

Description of Variables. The Dynaflect deflections measured on CRC pavement during summer and fall of 1981 and the associated deflection basin parameters are candidates for representing the response (dependent) variables. In this investigation maximum deflection (W_1) and sensor 5 deflection (W_5) are primarily used as major response variables due to the reasons discussed in the preceding chapter. Estimated regression equations were developed for each response variable separately. In the final regression analysis, the basin slope, SLOP ($W_1 - W_5$), is also used as another response variable. The explanatory variables (Table 3.1) considered in this study are (1) continuous variables and (2) dichotomous variables. The continuous variables are temperature differential (DT), the mid-depth temperature (TMID), spacing of the adjacent transverse cracks (CS), and the distance from the appropriate edge support (DE). The dichotomous or dummy variables are used to represent the following qualitative variables:

(1) Season (S): summer, fall;

(2) Section (SEC): section 1, 2, and 3;

(3) the Dynaflect position with respect to the transverse cracks (B): close to transverse crack (odd location numbers), corresponding to mid-span position (even location numbers, tested in summer and fall) and the new mid-span positions tested only in the fall.

(4) Type of the edge support (X): asphalt shoulder (for locations in the passing lanes), concrete shoulder (for locations in the travel lanes), and unsurfaced shoulder (for locations on the concrete shoulder).

Data Setup for Regression Analyses. The main purpose of the multiple regression analysis was to identify the important explanatory variables that influence the Dynaflect deflections. The combined data set is comprised of 552 data points. First the regression equation was developed for the combined

TABLE 3.1. THE EXPLANATORY VARIABLES CONSIDERED IN THE STEPWISE REGRESSION ANALYSES

Continuous Or Quantitative Variables:

DT	Temperature differential of the slab, °F
TMID	Mid-depth temperature of the concrete slab, °F
CS	Spacing between adjacent transverse cracks, ft
DE	Distance from the appropriate edge, ft

Dichotomous or Dummy Variables:

$$S1 = \begin{cases} 1 & \text{Summer, 1981} \\ 0 & \text{Otherwise} \end{cases}$$

$$SEC1 = \begin{cases} 1 & \text{Section 1} \\ 0 & \text{Otherwise} \end{cases}$$

$$SEC2 = \begin{cases} 1 & \text{Section 2} \\ 0 & \text{Otherwise} \end{cases}$$

$$B1 = \begin{cases} 1 & \text{The Dynaflect is close to transverse crack} \\ 0 & \text{Otherwise} \end{cases}$$

$$X1 = \begin{cases} 1 & \text{Edge Support is asphalt shoulder (the Dynaflect is in the passing lane)} \\ 0 & \text{Otherwise} \end{cases}$$

$$X2 = \begin{cases} 1 & \text{Edge support is concrete shoulder (the Dynaflect is in the travelling lane)} \\ 0 & \text{Otherwise} \end{cases}$$

data. The combined data set was then subdivided into subsets so that some of the explanatory variables could be controlled by fixing them on a constant value. Regression equations developed for each data set were assessed according to the value of the corresponding R^2 statistic. Table 3.2 describes various data sets used in the regression analyses.

Estimated Regression Equations and Statistics

The results of the regression analyses on different data sets are summarized in this section.

Combined Data. The estimated parameters and summary of statistics of the final regression equations for the response variables (W_1 and W_5) are presented in Table C.1 (Appendix C). The explanatory variables are presented in the order of decreasing importance as determined by the appropriate BETA coefficients. The coefficients of multiple determinations are respectively 0.46 and 0.57. The temperature effects are significant in the case of W_1. Both TMID and DT are in the regression equation estimated for W_1. However, R^2 for W_1 and W_5 is low. Therefore, combining all deflection data is not appropriate.

Summer/Fall. The results of regression analyses for W_1 and W_5 are summarized in Table C.2 (Appendix C) for summer data (data set 2-S). Results on the fall data (data set 2-F) are presented in Table C.3. The values of R^2 statistic indicate that, for the fall data, better estimated regression equations are developed. The next data sets subjected to the regression analyses correspond to the Dynaflect positions with respect to the transverse cracks.

At Crack/Mid-span. Tables C.4 and C.5, in Appendix C, present, respectively, the summary of regression equations for at-crack and mid-span measurements. The values of R^2 statistics do not show any appreciable

TABLE 3.2. DATA SETS ANALYZED BY MULTIPLE REGRESSION TECHNIQUE

Data Category	Data Set Designation	Data Points	Description	Independent Variables (fixed values)
1	1-All	552	Combined data of all sections measured in Summer and Fall 1981	
2	2-S	168	Summer data of all sections	S
	2-F	384	Fall data of all sections	
3	3-CR	216	Summer and Fall data of all sections at crack position	B
	3-MS	216	Summer and Fall data of all sections at mid-span (between transverse cracks locations)	
4			Summer and Fall data of all Sections:	DE, X
	4-P1	72	Passing Lane; Edge locations	
	4-P2	72	Passing Lane; Wheel path locations	
	4-T1	72	Travel lane; Center locations	
	4-T2	72	Travel lane; Wheel path locations	
	4-T3	72	Travel lane; Edge locations	
	4-C1	72	Concrete shoulder; wheel path locations	

(continued)

TABLE 3.2. (continued)

Data Category	Data Set Designation	Data Points	Description				Independent Variables (fixed values)
			Sections:	1	2	3	
	5-1	52	Summer:	1L	1L	1L	
			Fall:	1N	1A	1L	
				1L	1L		
	5-2	36	Summer:	2L	2L	2L	
			Fall:	2N	2A	2L	
	5-3	58	Summer:	3L	3L	3L	
			Fall:	3N	3A	3L	
				3L	3L		
	5-4	30	Summer:	4L	4L	4L	
			Fall:	4N	4A	4L	
	5-5	52	Summer:	5L	5L	5L	
			Fall:	5N	5A	5L	
				5L	5L		
	5-6	36	Summer:	6L	6L	6L	
			Fall:	6N	6A	6L	
5	5-7	52	Summer:	7L	7L	7L	DE, X
			Fall:	7N	7A	7L	
				7L	7L		
	5-8	36	Summer:	8L	8L	8L	
			Fall:	8N	8A	8L	
	5-9	52	Summer:	9L	9L	9L	
			Fall:	9N	9A	9L	
				9L	9L		
	5-10	36	Summer:	10L	10L	10L	
			Fall:	10N	10A	10L	
				10L	10L		
	5-11	52	Summer:	11L	11L	11L	
			Fall:	11N	11A	11L	
				11L	11L		
	5-12	36	Summer:	12L	12L	12L	
			Fall:	12N	12A	12L	
	5-13	12	Summer:	13L	13L	13L	
			No Fall Data				
	5-14	12	Summer:	14L	14L	14L	
			No Fall Data				

change as compared to the preceding analyses. The results show X_1 and X_2 as important explanatory variables. In the next analyses X_1 and X_2 were fixed values.

Passing Lane/Travel Lane/Concrete Shoulder. The results of the regression analyses are presented in Tables C.6 to C.8, in Appendix C. The results indicate a marked increase in the values of R^2 statistics. DT and TMID both are important explanatory variables. All the analyses until now indicate that by keeping the dummy variables (representing edge support) at fixed values, a substantial increase in R^2 was achieved. In the next analyses, regression equations were developed for the data corresponding to each location. A summary of the results carried out so far appears in Table 3.3.

Data Corresponding to Each Test Location. In this case, X_1, X_2 (dummy variables for edge support), B_1, B_2 (dummy variables for the Dynaflect position with respect to transverse cracks) and DE (representing the Dynaflect position in the wheel path, center of the slab, or near the pavement edge) becomes controlled variables at fixed values. The fall deflection data at even number locations in sections 1 and 2 were included with the appropriate at-crack deflection data. The deflection data in the new mid-span locations selected in the fall were treated with the summer data at the appropriate even number test locations. The data were analyzed by stepwise regression in three ways:

(1) Analysis I - With some interaction terms included as the possible independent variables.

(2) Analysis II - Without interaction terms.

(3) Analysis III - Without DT and TMID in the list of independent variables.

TABLE 3.3. SUMMARY OF MULTIPLE REGRESSION ANALYSES (DATA SETS 1 to 4)

Variable	Data Sets										
	1-All	2-S	2-F	3-CR	3-M5	4-P1	4-P2	4-T1	4-T2	4-T3	4-C1
Independent*	SEC2 X2 X1 TMID DT DE B1 CS SEC1 B2 Constant	SEC2 X2 X1 DT CS DE B1 SEC1 Constant	SEC2 X2 TMID DT B1 DE X1 SEC1 CS B2 Constant	SEC2 DT X2 TMID X1 DE CS B1 SEC1 Constant	X2 SEC2 X1 DE S1 Constant	DT CS SEC1 SEC2 B1 TMID Constant	SEC2 SEC1 B2 Constant	SEC2 B1 DT Constant	SEC2 B1 B2 SEC1 DT S1 Constant	TMID S1 SEC2 DT B1 CS SEC1 Constant	SEC1 DT SEC2 S1 B2 B1 Constant
R^2	0.46	0.496	0.54	0.45	0.50	0.628	0.35	0.856	0.866	0.72	0.80
Mean, W_1 (mils)	0.289	0.308	0.281	0.299	0.274	0.33	0.268	0.264	0.273	0.275	0.308
C. V., %	23.5	32.14	16.57	24.21	21.03	12.29	7.98	18.94	19.0	15.74	23.86

*In order of effectiveness.
Dependent Variable (W_1)

The corresponding results from these analyses at each test location are presented in Table 3.4. In general, Analysis II gives the best regression equations.

Effect of Temperature Variables on the Dynaflect Deflections. To find the influence of DT and TMID on the deflection and R^2 of the resulting regression equation, Analysis III was performed. Table 3.5 presents a comparison of R^2 values for Analyses II and III (W_1 as the responsible variable). The results indicate that (1) for the deflection data corresponding to edge locations, R^2 (Analysis II) is much higher than the R^2 (Analysis III); and (2) in the wheel path and center locations R^2 values do not change appreciably. Table 3.6 shows similar results from the regression analyses when W_5 is used as the response variable.

Tables C.9 to C.22 present the estimated regression equations from Analysis II for W_1, W_5 and SLOP as the response variables, for each location. The results so far indicate that DT is a much more important explanatory variable than TMID for most locations. In these tables, elasticity indicates approximate percentage change in the response variable due to one percent change in an explanatory variable.

Similar analyses were performed using W_5 and SLOP as response variables. The corresponding regression equations are not included in Appendix C, to avoid repetition. The most significant temperature parameter is again temperature differential. The R^2 statistics ranged between 0.56 and 0.90 with the majority of these being above 0.80.

Errors Due to Temperature Differential. When the Dynaflect is positioned near the edge of a CRC pavement with an asphalt shoulder, the measured deflections are influenced significantly by DT as observed by the negative regression coefficients for locations 1 and 2 (Tables C.9 and C.10, in

TABLE 3.4. SUMMARY OF MULTIPLE REGRESSION ANALYSES (DATA SETS 5-1 to 5-14)

	Analysis I				Analysis II				Analysis III			
Data Set	Independent Variables	Ranking*	R^2	S.E.	Independent Variables	Ranking*	R^2	S.E.	Independent Variables	Ranking*	R^2	S.E.
	DT	1			DT	1			B1	3		
	CS	2			CS	5			SEC1	1		
5-1	SEC1	3	0.66	0.025	SEC1	2	0.65	0.025	SEC2	2	0.18	0.037
	TMID*S1	4			SEC2	3						
	B1	5			B1	4						
	SEC2	6										
	SEC2	1			SEC2	1			SEC2	1		
5-2	DT	2	0.68	0.018	DT	2	0.68	0.018	CS	2	0.40	0.024
	CS	3			CS	3						
	SEC2	2			SEC2	1						
	SEC1	1			SEC1	2			SEC2	1		
5-3	TMID*DT	5	0.45	0.016	DT	3	0.41	0.0166	SEC1	2	0.34	0.017
	CS	3										
	TMID*S1	4										
5-4	SEC2	1	0.49	0.015	SEC2	1	0.49	0.015	SEC2	1	0.40	0.016
	DT	2			DT	2						
	SEC2	1			SEC2	1			SEC2	1		
	B1	6			B1	6			B1	2		
5-5	CS	5	0.93	0.015	CS	5	0.93	0.015	CS	3	0.89	0.018
	SEC1	7			SEC1	7						
	TMID*S1	2			S1	2						
	TMID	3			TMID	3						
	DT	4			DT	4						
	SEC2	1			SEC2	1			SEC2	1		
5-6	DT	2	0.71	0.019	DT	2	0.71	0.019	SEC1	2	0.61	0.022
	SEC1	3			SEC1	3						
	SEC2	1			SEC2	1			SEC2	1		
	B1	2			B1	4			B1	2		
5-7	SEC1	4	0.90	0.018	SEC1	5	0.91	0.017	SEC1	3	0.90	0.018
	S1	3			S1	2			S1	4		
	TMID*CS	5			TMID	3						
					DT	6						
					CS	7						
	SEC2	4			SEC2	1						
	TMID*CS	2			DT	3			SEC2	1		
5-8	S1	1	0.85	0.014	CS	2	0.79	0.017	CS	2	0.65	0.021
	TMID	3			SEC1	4						
	SEC1	5			S1	5						
5-9	SEC2	1	0.67	0.025	SEC2	1	0.67	0.025	SEC2	1	0.67	0.025
	B1	2			B1	2			B1	2		
	SEC2	4			SEC2	1			SEC2	1		
	TMID*CS	3			CS	2			CS	2		
5-10	S1	1	0.78	0.017	DT	3	0.71	0.019	SEC1	3	0.61	0.022
	TMID	2			SEC1	4						
	SEC1	6			S1	5						
	DT	5										
	SEC1	1			SEC1	1			SEC1	1		
	DT	2			DT	2			SEC2	2		
5-11	CS	4	0.82	0.036	CS	4	0.82	0.036	CS	3	0.62	0.051
	SEC2	3			SEC2	3						
	B1	5			B1	5						
	SEC1	1			SEC1	1						
	SEC2	2			SEC2	2			SEC1	1		
5-12	DT	3	0.90	0.0212	DT	3	0.90	0.0212	SEC2	2	0.82	0.0269
	TMID*S1	4			S1	4						
	B2	5			B2	5						
5-13	DT	1	0.65	0.125	DT	1	0.65	0.125	SEC2	1	0.25	0.176
	SEC1	2			SEC2							
	SEC1	1			SEC1	1						
5-14	TMID*S1	2	0.84	0.059	TMID	2	0.83	0.06	SEC1	1	0.55	0.09
	TMID*CS	3			CS	3						

Ranking* indicates the order of effectiveness based on Beta values.

TABLE 3.5. EFFECT OF REMOVING TEMPERATURE VARIABLES ON R^2 OF THE RESULTING REGRESSON EQUATIONS FOR W_1 AS RESPONSE VARIABLES

		Dependent Variable, W_1			
		Analyses II[1]		Analyses III[2]	Reduction in[3]
Data Set[4]	Data Points	Temperature Variables	R^2	R^2	R^2
5-1	58	DT	0.65	0.18	72.3 %
5-2	30	DT	0.68	0.40	41.2 %
5-3	58	DT	0.41	0.34	17.1 %
5-4	30	DT	0.49	0.40	18.4 %
5-5	52	TMID, DT	0.93	0.89	4.3 %
5-6	36	DT	0.71	0.61	14.1 %
5-7	52	TMID, DT	0.91	0.90	1.1 %
5-8	36	DT	0.79	0.65	17.7 %
5-9	52	--	0.67	0.67	0.0 %
5-10	36	DT	0.71	0.61	14.1 %
5-11	52	DT	0.82	0.62	24.4 %
5-12	36	DT	0.90	0.82	8.9 %
5-13	12	DT	0.65	0.25	61.5 %
5-14	12	DT	0.83	0.55	33.7 %

[1]All independent variables were considered in regression.

[2]Temperature variables were removed from the independent variables list prior to applying stepwise regression.

[3]Reduction in R^2 values of the resulting regression equations from Analyses III as compared to the R^2 values of Analyses II.

[4]See Table 3.2 for locations.

TABLE 3.6. EFFECT OF REMOVING TEMPERATURE VARIABLES ON R^2 OF THE RESULTING REGRESSION EQUATIONS FOR W_5 AS RESPONSE VARIABLES

		Dependent Variable, W_5			
		Analyses II[1]		Analyses III[2]	Reduction in[3]
Data Set[4]	Data Points	Temperature Variables	R^2	R^2	R^2
5-1	58	DT	0.88	0.74	15.9 %
5-2	30	DT	0.86	0.70	18.6 %
5-3	58	DT	0.85	0.85	0.0 %
5-4	30	TMID	0.81	0.65	19.7 %
5-5	52	DT	0.90	0.88	2.2 %
5-6	36	DT	0.83	0.76	8.4 %
5-7	52	DT	0.88	0.84	4.5 %
5-8	36	DT	0.82	0.73	11.0 %
5-9	52	DT, TMID	0.86	0.82	4.7 %
5-10	36	DT	0.85	0.78	8.2 %
5-11	52	DT	0.90	0.85	5.5 %
5-12	36	DT	0.90	0.85	5.5 %
5-13	12	TMID	0.79	0.56	29.1 %
5-14	12	TMID	0.83	0.59	28.9 %

[1] All independent variables were considered in regression.

[2] Temperature variables were removed from the independent variables list prior to applying stepwise regression.

[3] Reduction in R^2 values of the resulting regression equations from Analyses III as compared to the R^2 values of Analyses II.

[4] See Table 3.2 for locations.

Appendix C). The measured deflection will be less than the true deflection at a high positive temperature differential. For the worst condition, the errors in W_1 due to four different levels of DT are presented in Table 3.7. The inherent variations in the measured Dynaflect deflections are also presented in the table. It can be observed that it is desirable to apply a correction to W_1 deflection under these conditions if a positive temperature differential exists during the measurement. This is an important finding, as the edge deflections are measured to detect voids under CRC pavements as a part of pavement evaluation.

Dynaflect in Wheel Path or Center of Slab. The Dynaflect deflection measurements are routinely made in the mid-span position (between two adjacent transverse cracks) in the wheel path. The measured deflection basins are used for material characterization. In this investigation, locations 4 and 8 correspond to wheel paths in passing and travel lanes, respectively, and location 6 represents the center of the concrete slab. These locations may be assumed to represent the "interior" condition. It is noted from the appropriate tables in Appendix C that DT has a positive regression coefficient and is relatively smaller in absolute value than the one estimated in the regression equation for an edge deflection case. A positive coefficient of DT indicates that the measured deflection will be higher than the true deflection at the time of a high positive temperature differential existing in the concrete pavement. Table 3.8 presents the influence of three different levels of DT on W_1 deflection along with the random variation in measured Dynaflect deflections observed during repeat measurements. These results indicate that the errors in the measured deflection due to a positive DT are relatively negligible. For the Dynaflect deflections measured in an interior condition, the influence of a positive temperature differential on

TABLE 3.7. ERROR DUE TO POSITIVE TEMPERATURE DIFFERENTIAL ON DYNAFLECT DEFLECTION (W_1) NEAR PAVEMENT EDGE IN TEST LOCATIONS 1 AND 2

Edge Support (Asphaltic Concrete Shoulder)		
DT*	Percent Decrease in Measured Deflection	C. V. of Measured Deflection Values, %
+ 10° F	- 10.4	10 - 12
+ 13° F	- 13.5	
+ 17° F	- 17.7	
+ 25° F	- 26.0	

* Largest estimated regression coefficient of the temperature differential, DT = -0.00468 (Tables C.1 and C.2)

TABLE 3.8. ERROR DUE TO POSITIVE TEMPERATURE DIFFERENTIAL ON DYNAFLECT DEFLECTION (W_1) CORRESPONDING TO LOCATIONS 4, 6, AND 8 USED FOR MATERIAL CHARACTERIZATION

Edge Support (Asphaltic Concrete or P. C. Concrete Shoulder)		
DT*	Percent Increase in Measured Deflection	C. V. of Measured Deflection Values, %
+ 13° F	+ 6.9	
+ 17° F	+ 8.9	8 - 14
+ 25° F	+ 13.2	

*Largest estimated regression coefficient of the temperature differential, DT = + 0.00185 (Tables C.4, C.6, and C.8) the back-calculated pavement moduli was also investigated in this study. Figure 3.2 shows a typical deflection basin measured at a 2.5°F temperature differential and the corresponding basin at a DT of 25°F, assuming the worst condition (largest regression coefficients). The effect of the errors due to the calculated deflection basin at 25°F DT on the back-calculated moduli is illustrated in Table 3.9. It is concluded that the influence of a positive temperature differential on the Dynaflect deflection basins measured in the interior condition is practically negligible. It should be realized that the test data were limited to a new pavement and all seasons were not considered.

SUMMARY

The Dynaflect deflection and the concrete pavement temperature parameters measured at the CRC pavement have been analyzed using stepwise linear regression analyses. The season (S), section (SEC), type of edge support (X), and the Dynaflect position with respect to the transverse crack (B) were presented by dichotomous variables for consideration as explanatory variables. The best regression equations as assessed by R^2 were estimated in Analysis II. Dummy variables X_1, X_2, B_1, and B_2 were not considered in Analysis II as these were controlled at fixed values for each data set. The findings from these investigations are summarized below.

(1) These Dynaflect deflections were appreciably affected by

(a) the position of the Dynaflect with respect to the pavement edge and
(b) the temperature differential in the concrete slab.

(2) For the purpose of void detection, the Dynaflect deflections (near the pavement edge) are appreciably influenced by the temperature differential, DT. In the estimated regression equations for the deflection data investigated in this study, DT is found to be an important explanatory variable, with a negative regression

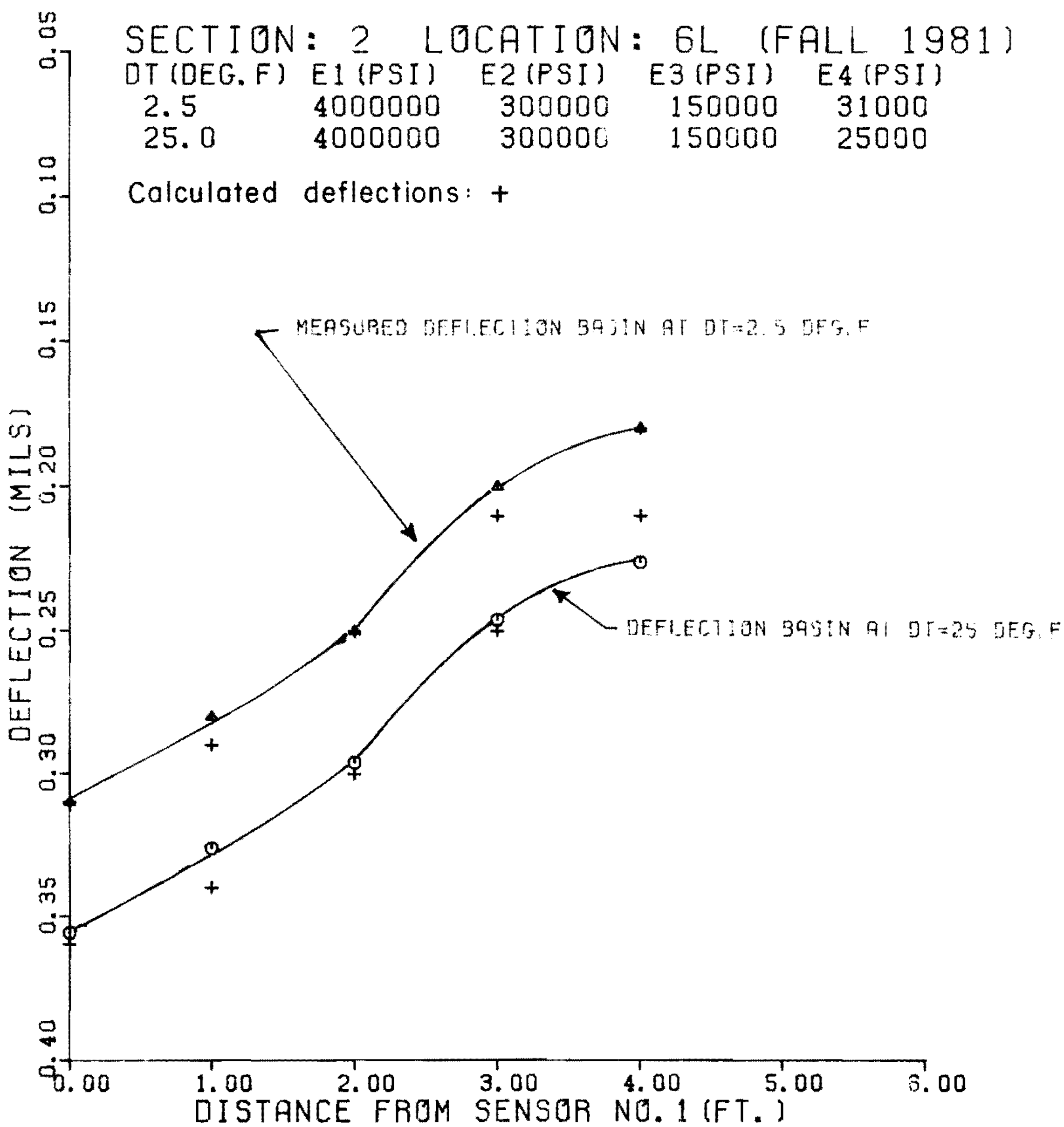


Fig 3.2. Effect of increase in positive temperature differential on the Dynaflect deflection basin and the back-calculated Young's moduli.

TABLE 3.9. ERROR DUE TO POSITIVE TEMPERATURE DIFFERENTIAL ON YOUNG'S MODULI OF THE PAVEMENT LAYERS BACK CALCULATED FROM DYNAFLECT DEFLECTION MEASURED AT SECTION 2, LOCATION 6L

	Deflection Basin					
	DT = + 2.5° F			DT = + 25.0° F		
Geophone No.	Measured	Calculated	[1] Young's Moduli (psi)	[2] Corrected	Calculated	[1] Young's Moduli (psi)
W_1 (mils)	0.31	0.31	E_1 = 4,000,000	0.356	0.36	E_1 = 4,000,000
W_2 (mils)	0.28	0.29	E_2 = 300,000	0.326	0.34	E_2 = 300,000
W_3 (mils)	0.25	0.25	E_3 = 150,000	0.296	0.30	E_3 = 150,000
W_4 (mils)	0.20	0.21	E_4 = 31,000	0.246	0.25	E_4 = 25,000
W_5 (mils)	0.18	0.18		0.226	0.21	

[1] Backcalculated moduli from the measured deflection basin as outlined in Chapter 5.

[2] The measured deflections corrected using a regression coefficient of + 0.00185 for DT.

Note: Error in Young's moduli due to an increase of DT of +25.0° F is about 19.3% reduction in the Young's modulus of natural subgrade. E_1, E_2, E_3, and E_4 correspond to the pavement layers as shown in Fig 2.16.

coefficient. Deflections measured during the daytime (at a high positive DT) need to be corrected to the true deflections (measured in a morning hour, at the zero temperature differential).

(3) For the CRC pavement investigated in this study, the influence of DT is practically negligible on the Dynaflect deflections measured in interior conditions. The regression coefficient of DT is positive but errors due to even very high positive temperature differential (+ 25°F) are insignificant on the back-calculated moduli of the pavement layer.

However, it should be realized that the regression coefficients (intercept and slopes) estimated for the best fit regression equations will be dependent on the concrete layer thickness and the geometry of the CRC pavement structure.

CHAPTER 4. PROCEDURE FOR TEMPERATURE CORRECTION TO MEASURE DYNAFLECT DEFLECTIONS

INTRODUCTION

The major finding from the statistical analyses of the Dynaflect deflection and pavement temperature data is that the temperature differential in the concrete slab of a CRC pavement can influence the Dynaflect deflections. The temperature differential was found to be an important explanatory variable in the estimated regression equation to fit the repeat deflections (particularly in the case of W_1 as the response variable) measured at an edge location as well as in an interior condition. It is also established that, in the case of the Dynaflect positioned at an interior location, the error involved in the Dynaflect deflections measured at any positive temperature differential, as experienced in Columbus, Texas, is practically insignificant. On the other hand, the edge deflections (measured for the purpose of voids detection and the subsequent rehabilitation needs) are greatly influenced by a positive temperature differential. A 10-inch thick CRC pavement at a positive temperature differential of 25°F can cause a measured maximum deflection near the pavement edge (with asphalt surfaced shoulder) to be as much as 30 percent lower than the corresponding "true" deflection. The "true" deflection is referred to as the value of the Dynaflect deflection measured at the condition of zero temperature differential. This condition in a normal day occurs in the morning hours around 9:00 AM. This example was for a worst condition but it indicates that the measurements made at noon time in summer days will be much lower than the true deflections. Therefore the measured deflections should be corrected to correspond to the standard condition such as zero temperature differential.

For the reasons discussed above, there is a strong need to record the temperature of the top and the bottom of the concrete slab while the Dynaflect deflection survey is being undertaken for the evaluation of a rigid pavement. The temperature record can be used to calculate the variations of the temperature differential in the rigid pavement for structural evaluation. However, for various practical reasons it is not feasible to make a continuous record of the temperature of the top and the bottom of the concrete slab on a routine basis. To overcome this problem, a predictive procedure is therefore desirable for estimating the temperature in a concrete slab using the readily available daily data. The appropriate predictive model should be capable of estimating the concrete temperature at any time of day and at any depth of the concrete slab.

USE OF CLIMATOLOGICAL DATA TO PREDICT PAVEMENT TEMPERATURE

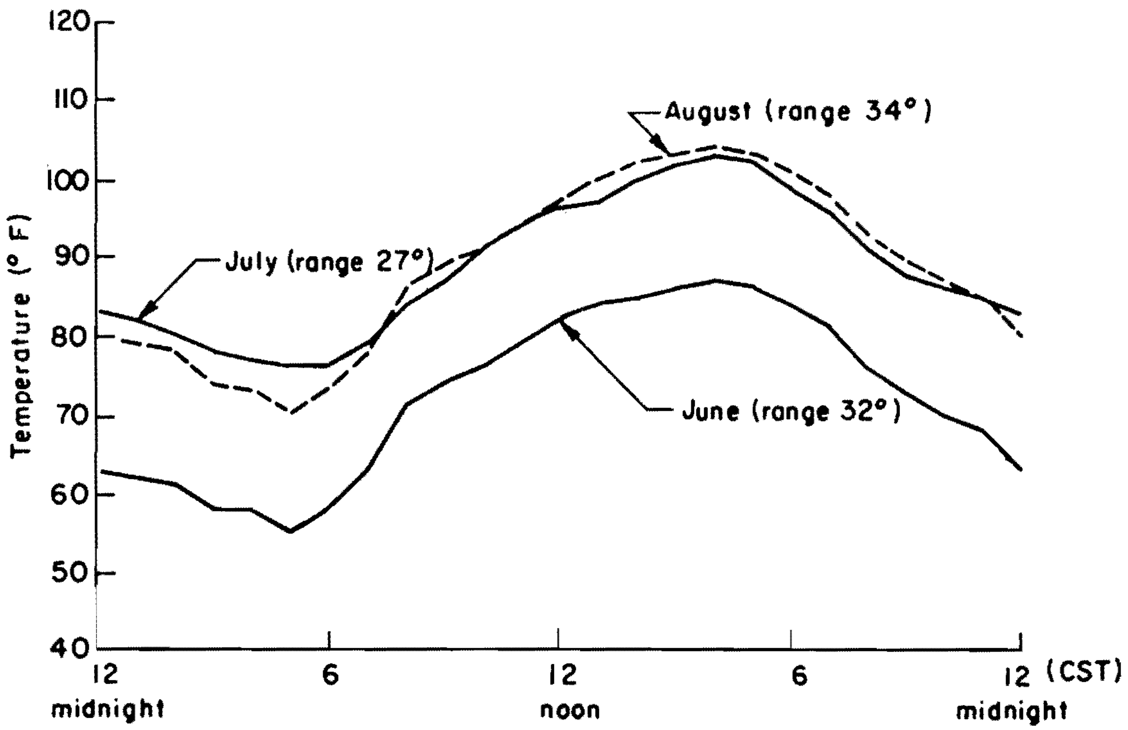
The obvious advantage of utilizing the climatological data to predict slab temperature is that these data are continuously recorded all over the U. S. and regularly published by the National Oceanic and Atmospheric Administration (NOAA), Asheville, North Carolina (Ref 19). All major cities have local offices that can also provide the pertinent climatological information.

Factors Affecting Pavement Temperature

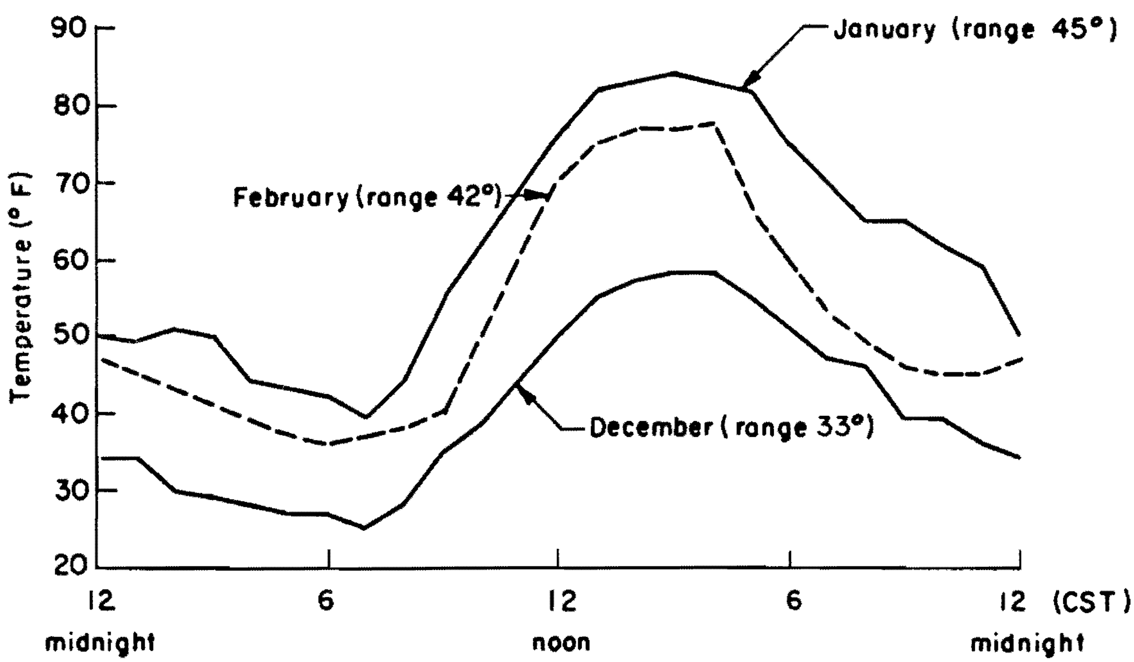
In this section, various climatic factors and material properties that affect the temperature in a concrete pavement are discussed.

Ambient Air Temperature. The daily air temperature variation is an important factor because it influences the surface temperature of a concrete pavement. The air temperature shows a cyclic behavior. The amplitudes and periods of the daily cycles of air temperature are affected by cloud cover, presence of rain or snow, and seasonal changes. Figure 4.1 shows typical hourly distributions of air temperature in Austin, Texas (Ref 23). The daily weather reports include only maximum and minimum air temperature. In some localities only this record is available. For example at Columbus, Texas, the local weather station does not have the facilities to maintain a continuous 24-hour record of air temperature. The seasonal variation of the maximum and minimum air temperature in 1981 reported for Columbus, Texas, (Ref 19) is illustrated in Fig 4.2. The highest range, in air temperature of 61°F, was observed in February.

Solar Radiation. Solar radiation is a major contributor to the temperature changes in the concrete pavement. The solar radiation is partly absorbed by the concrete causing the surface to be heated rapidly while the interior is heated slowly, due to the poor conduction of heat in concrete resulting in a temperature gradient through the thickness of the concrete slab. Solar radiation can be greatly influenced by cloud cover. Daily solar radiation also varies with season and latitude. Variations of daily solar radiation intensity on horizontal surface are approximated by a sine function. Figure 4.3 shows hourly distribution of solar radiation intensity for a clear day (Ref 23). The weather stations normally report the total solar radiation received in a day in Langleys per day. The monthly solar radiation data (averaged over many years) for Columbus, Texas, are presented in Table 4.1. These data were obtained through personal contact with the weather station of Austin Municipal Airport.



a) Summer



b) Winter

Fig 4.1. Hourly distribution of air temperature, Austin, Texas (Ref 23).

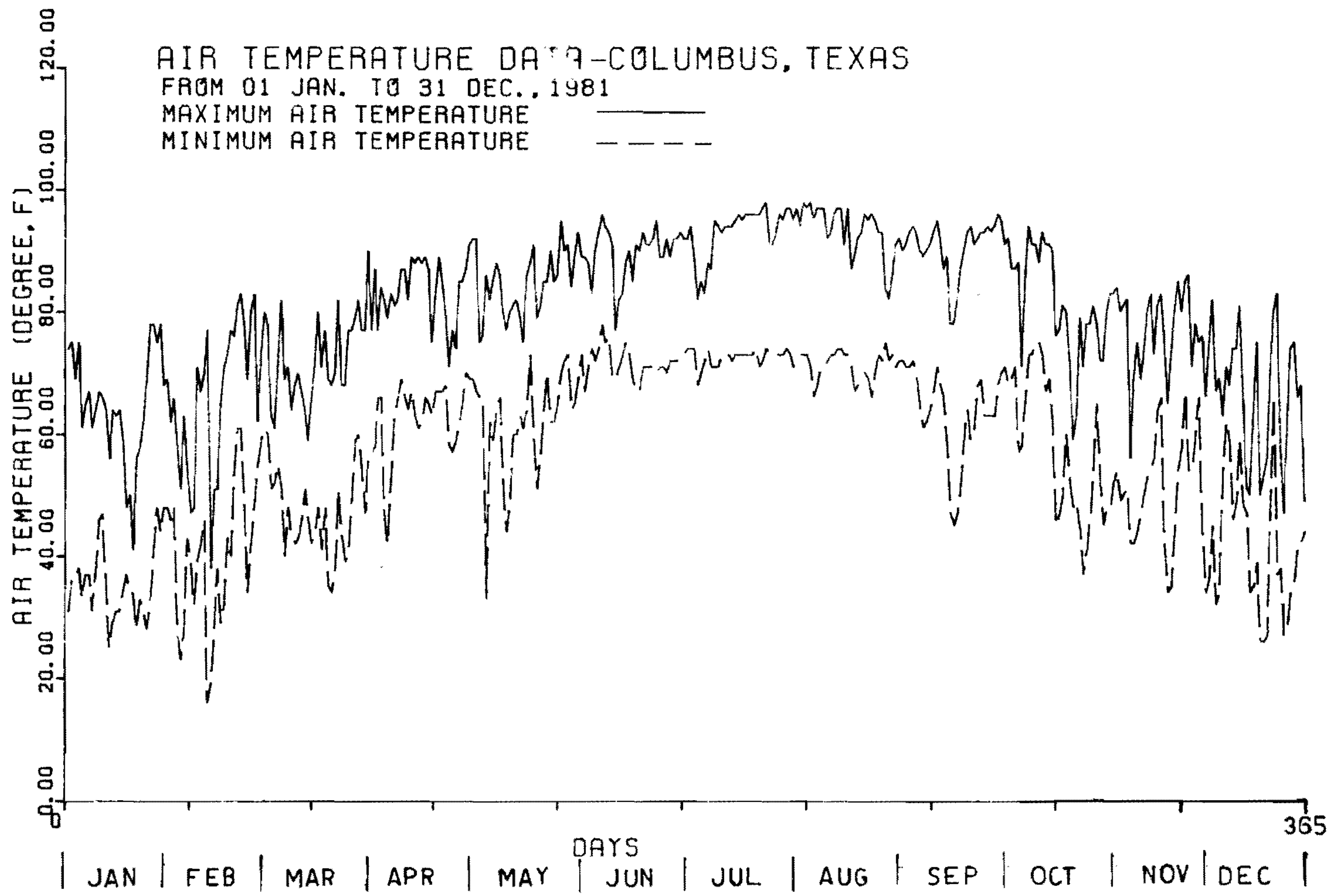


Fig 4.2. Seasonal variation in maximum and minimum air temperature at Columbus, Texas, 1981 (Ref 19).

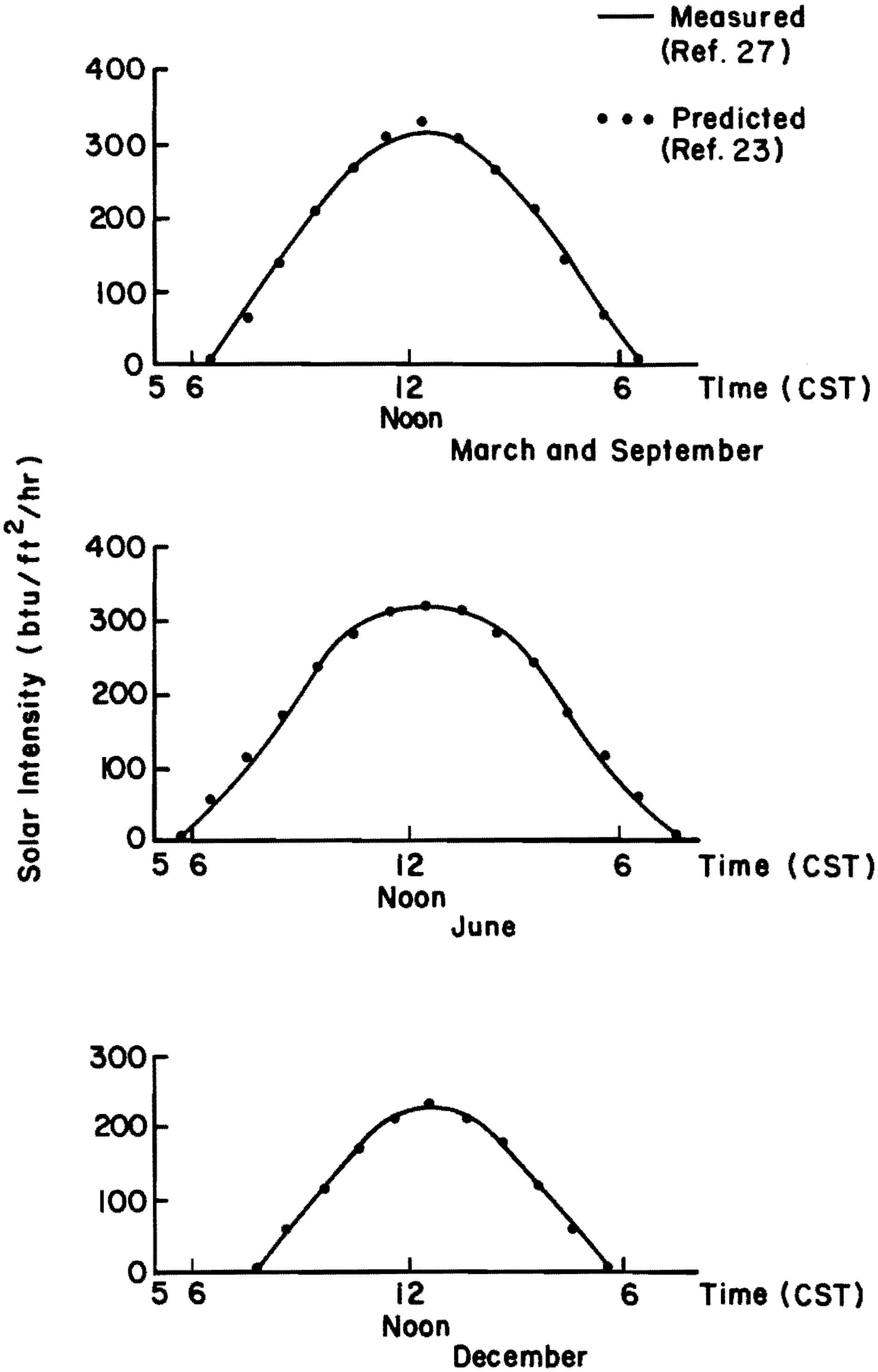


Fig 4.3. Hourly distributions of solar radiation intensity for a clear day, latitude 30° North.

TABLE 4.1. AVERAGE SOLAR RADIATION DATA, COLUMBUS, TEXAS

Month	Average Solar Radiation (Langleys per day)
January	255
February	320
March	420
April	445
May	550
June	620
July	620
August	575
September	490
October	400
November	295
December	255

Wind speed. Wind influences the surface temperature of a concrete pavement. On a sunny day, strong wind will tend to decrease the surface temperature.

Thermal Properties of Concrete. The amount of heat induced on the surface and heat transfer through the concrete slab depend on climatological factors, absorbtivity, and other thermal properties of concrete. Table 4.2 presents the pertinent thermal properties of the pavement-quality concrete. For comparison, the typical thermal properties of an asphalt concrete surface are also included in Table 4.2. Thermal conductivity of concrete in a wet condition is relatively higher than in a dry state (Ref 23).

Selection of a Temperature Prediction Model

General. Different predictive models for temperatures in pavements and concrete structures have been reported in literature by various researchers such as Tomlinson (Ref 24), Barber (Ref 4), and Thepchatri et al (Ref 23). The mathematical model presented by Barber is a general model and can be used for both asphalt and concrete pavements. The input required in this model is directly available from local weather records. The model is based on the theory of conduction of heat through a semi-infinite, homogeneous and isotropic mass. The mathematical model can be used to predict maximum temperature. Barber's model was modified by Shahin and McCullough (Ref 25) to simulate both maximum and minimum temperatures of asphalt pavements. The computerized version of Shahin and McCullough's model was easily accessible and required little additional effort to extend its application to concrete pavement. Therefore it was selected to estimate the temperature differential in a concrete slab of any thickness.

TABLE 4.2. THERMAL PROPERTIES OF PAVEMENT MATERIALS

Properties	Pavement Quality P. C. Concrete	Asphaltic Concrete
1. Absorptivity of surface to solar radiation	0.65 - 0.80 (Ref 23)	0.95**
2. Thermal conductivity (BTU/ft^2/hr, °F)		0.7 **
Aggregates:		
Gravel	0.9 **	
Igneous	0.83 *	
Dolomite/limestone	2.13 *	
3. Specific Heat (BTU/lb, °F)	0.20 - 0.28*	0.22 **

* (Ref 35)
** (Ref 4)

Model Adoption for Concrete Pavement

The theory and concepts used by Barber in the basic model for calculation of maximum pavement temperatures are available in Ref 4. The final form of the modified model as developed by Shahin and McCullough (Ref 25) is described below:

$$T(X,t) = T_m + T_v \frac{H.\mathrm{Exp}(-XC)}{\sqrt{(H + C)^2 + C^2}} \quad \mathrm{Sin}(S_i) \quad i = 1, 2, 3 \tag{4.1}$$

where

$S_1 = 6.81768\ (.0576t - .075Xc - .288)$

for $t = 2$ to 9 (7:00 AM to 2:00 PM)

$S_2 = 14.7534\ (.02057t - .075Xc - .288)$

for $t = 10$ to 14 (3:00 PM to 7:00 PM)

$S_3 = -6.94274\ (.02057t - .12Xc - .288)$

for $t = 15$ to 25 (8:00 PM to 6:00 AM)

$$\left.\begin{aligned} T_V &= 0.5\ T_R + 3R \\ T_M &= T_A + R \end{aligned}\right\} \quad \text{if } \mathrm{Sin}\ (S_i) \geq 0;$$

$$\left.\begin{aligned} T_V &= Z\ T_R \\ T_M &= T_A + B\ R \end{aligned}\right\} \quad \text{if } \mathrm{Sin}\ (S_i) < 0$$

Various notations and terms in Eq 4.1 and the above expressions are explained as follows:

$T(X, t)$ = temperature of seminfinite mass, °F;

T_M = mean effective air temperature, °F;

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

t = time from beginning of cycle (one cycle = 24 hours), hours;

X = depth below surface, feet;

H = h/R;

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

k = thermal conductivity, BTU per square foot per hour, °F per foot;

$C = \sqrt{0.131 \text{ per } C}$;

c = diffusivity, square foot per hour;

$$c = \frac{k}{sw}$$

s = specific heat, BTU per pound, °F;

w = density, lbs. per cubic foot;

B = constant that is determined by trial and error to be 1.0 in the present study; and

Z = 0.4 determined by trial and error;

T_R = daily air temperature range, °F;

T_A = mean air temperature, °F; and

R is the term related to the effects of solar radiation and wind.

The following relationships are used to include the effects of solar radiation and wind speed:

$$h = 1.3 \text{ to } .62\ (V)^{3/4} \tag{4.2}$$

where

$$V = \text{wind speed, mph}$$

and

$$R = \frac{2}{3} \times b \times \text{solar radiation} \times \frac{1}{h}$$

where

$$b = \text{surface absorptivity to the solar radiation.}$$

Or Eq 4.2 can be rewritten as

$$R = \left(\frac{2}{3}\right) \times b \times \left(\frac{3.69 \times L}{24}\right) \times \frac{1}{h} \qquad (4.3)$$

where

$$L = \text{solar radiation in Langleys per day}$$

or

$$R = 0.1025 \cdot \frac{b \times L}{h} \qquad (4.4)$$

Figures 4.4, 4.5, and 4.6 illustrate, respectively, (1) surface temperature without radiation and wind effects, (2) distribution of insulation, and (3) effective air temperature. The other major assumptions

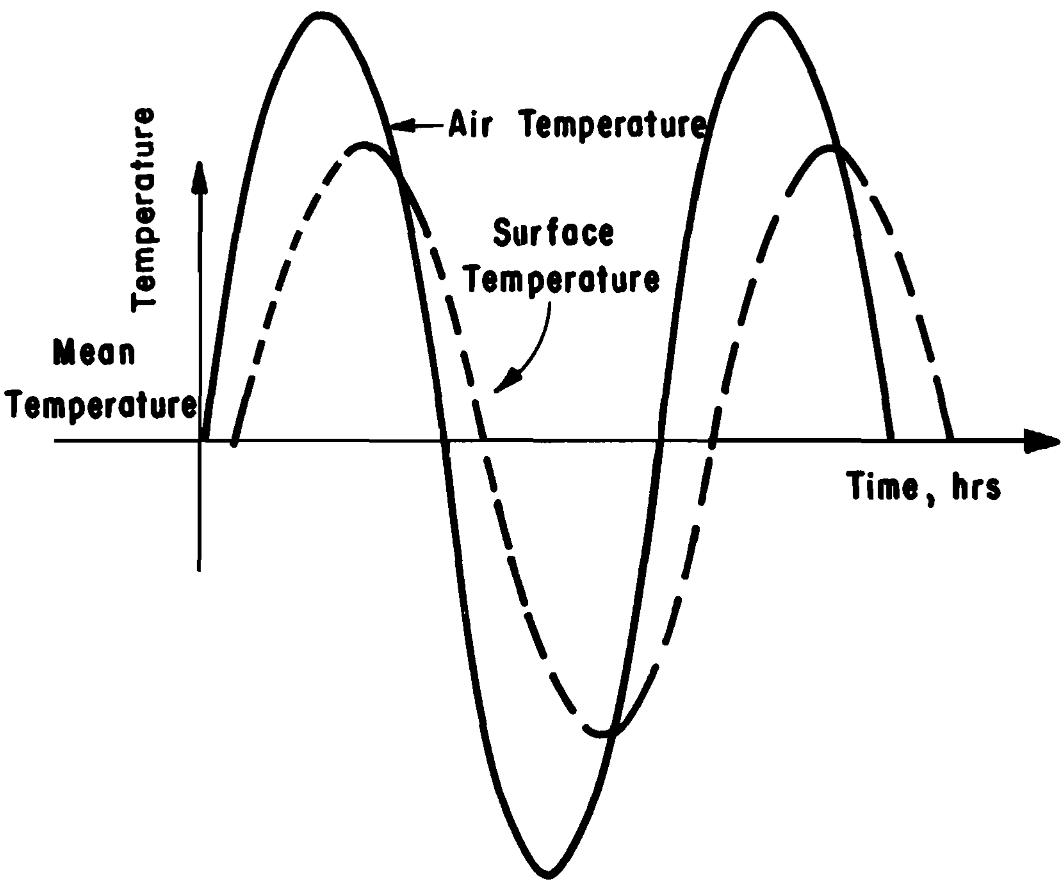


Fig 4.4. Surface temperature versus time relationship without the effects of solar radiation and wind (Ref 4).

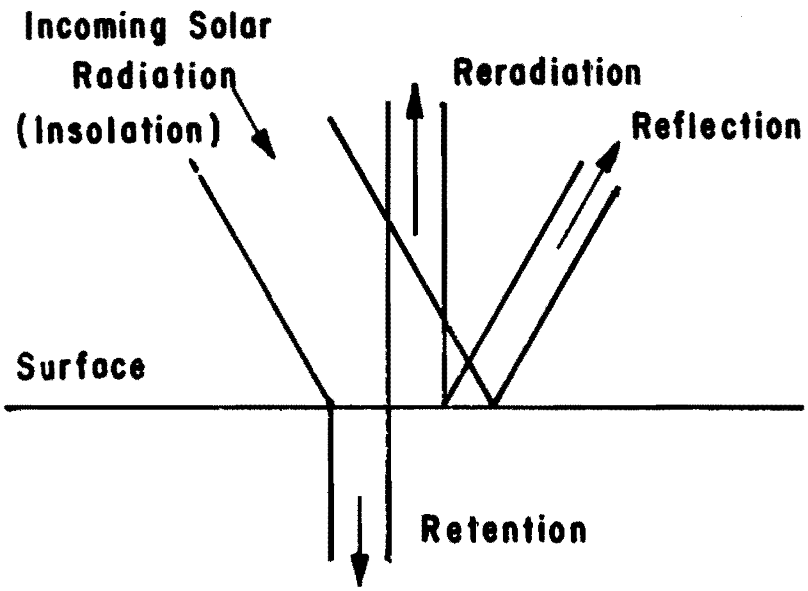


Fig 4.5. Distribution of incoming solar radiation (Ref 4).

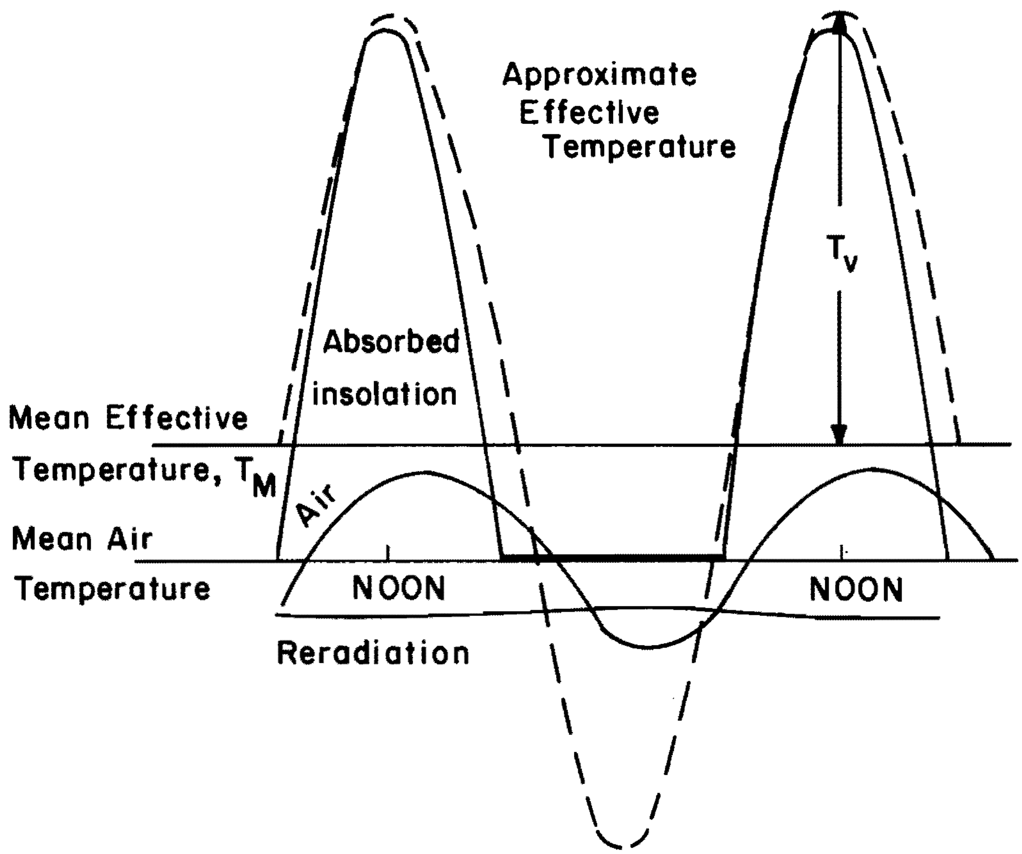


Fig 4.6. Comparison between effective temperature and air temperature (Ref 4).

are that there is a clear cloudless sky and there is no trace of rain or snow.

The original computer program of Shahin and McCullough is revised to meet the needs of present study and is included in Appendix D.

Model Prediction vs Measured Temperature

The temperature predictive model was used to calculate temperature at the surface and at the bottom of the concrete slab. The data for thermal properties and unit weight of concrete are presented in Table 4.3. The climatological data of Columbus, Texas are presented in Table 4.4. The predicted temperatures and the measured temperatures are plotted in Figs 4.7 to 4.10, for both summer and fall testing days.

The temperature differential and mid-depth temperature were calculated from the temperatures predicted for the top and the bottom of the slab. The calculated DT and TMID plots are presented in Figs 4.11 and 4.12 together with the measured values. These plots indicate that the model performs well.

A comprehensive sensitivity analysis for asphalt pavements was carried out by Shahin and McCullough on their model and the findings are included in Ref 25.

TEMPERATURE CORRECTION TO MEASURED DYNAFLECT DEFLECTION

Dynaflect Locations for Material Characterization

The analysis of the Dynaflect data (Chapter 3) has shown that in the wheel path or in the center, if Dynaflect deflections are measured in the mid-span position (between transverse cracks), then practically no correction is necessary with respect to any variation of temperature differential in the concrete slab.

TABLE 4.3. P. C. CONCRETE PROPERTIES USED FOR TEMPERATURE PREDICTION

Material Properties	Values
1. Unit weight, lb/c. ft	150.0
2. Absorptivity of surface to solar radiation	0.75
3. Thermal conductivity, BTU/ft^2/hr, ° F	0.90
4. Specific heat, BTU/lb, °F	0.24

TABLE 4.4. WEATHER DATA, COLUMBUS, TEXAS

Weather Information	Summer, 1981		Fall, 1981	
	August 06	August 07	November 30	December 01
1. Mean Air Temperature, °F	85.5	85.5	70.5	60.0
2. Air Temperature Range, °F	25.0	24.0	9.0	32.0
3. Average Wind Velocity, mph	8.3	7.5	10.6	10.8
4. Solar radian Langleys per day	575	575	255	255

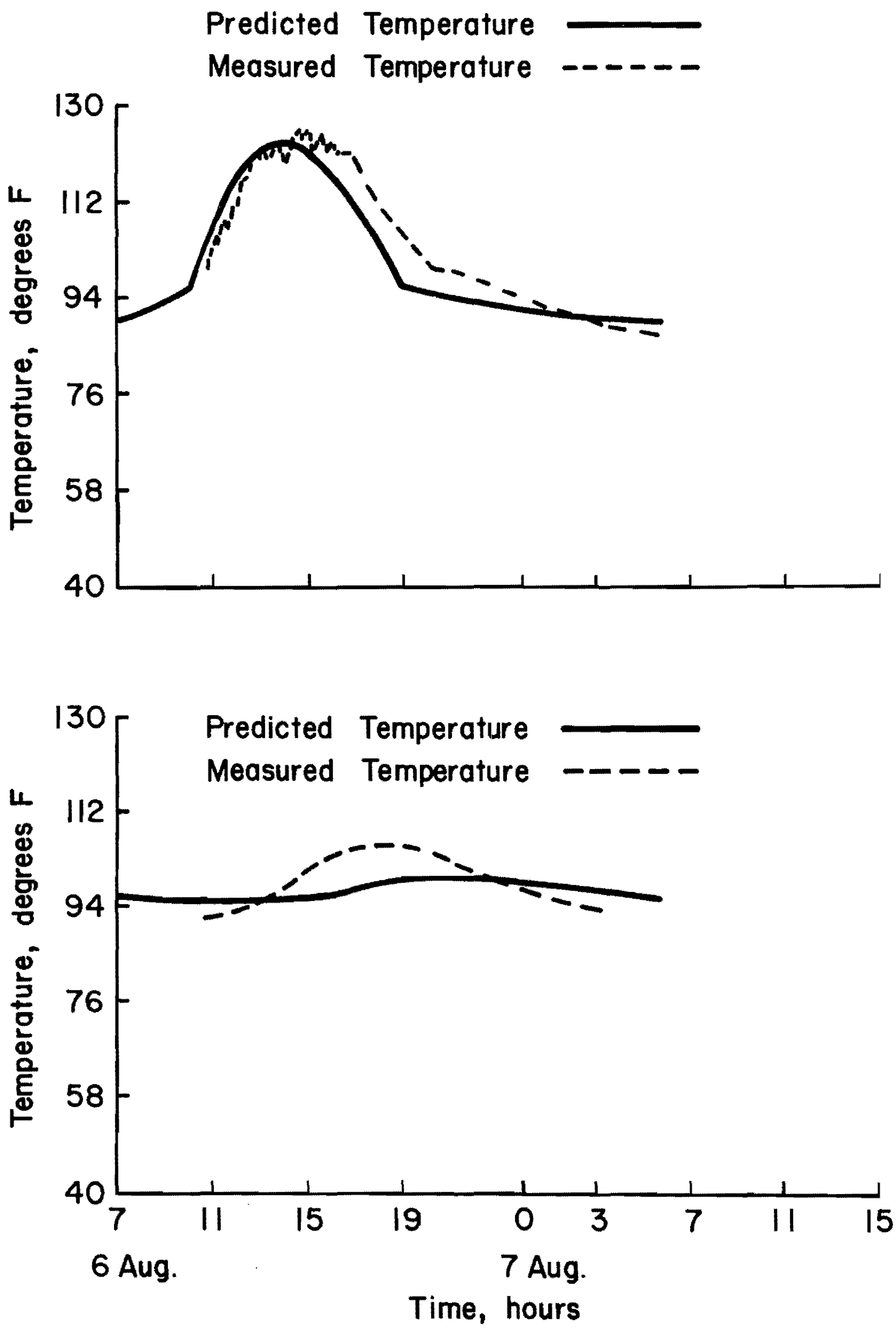


Fig 4.7. Variation in temperature of concrete slab on 6-7 Aug. 1981, Columbus Bypass, SH-71.

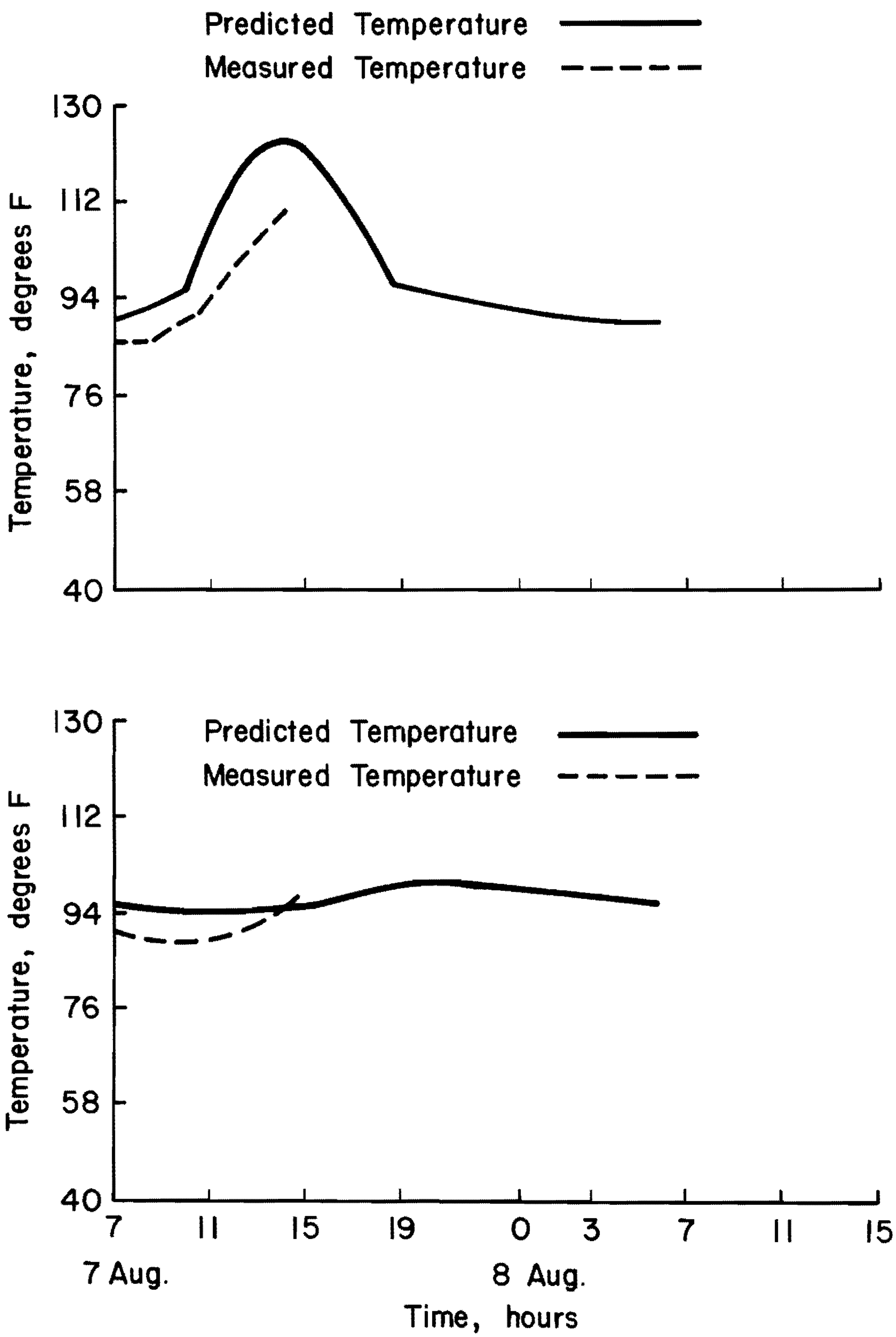


Fig 4.8. Variation in temperature of concrete slab on 7-8 Aug. 1981, Columbus Bypass, SH-71.

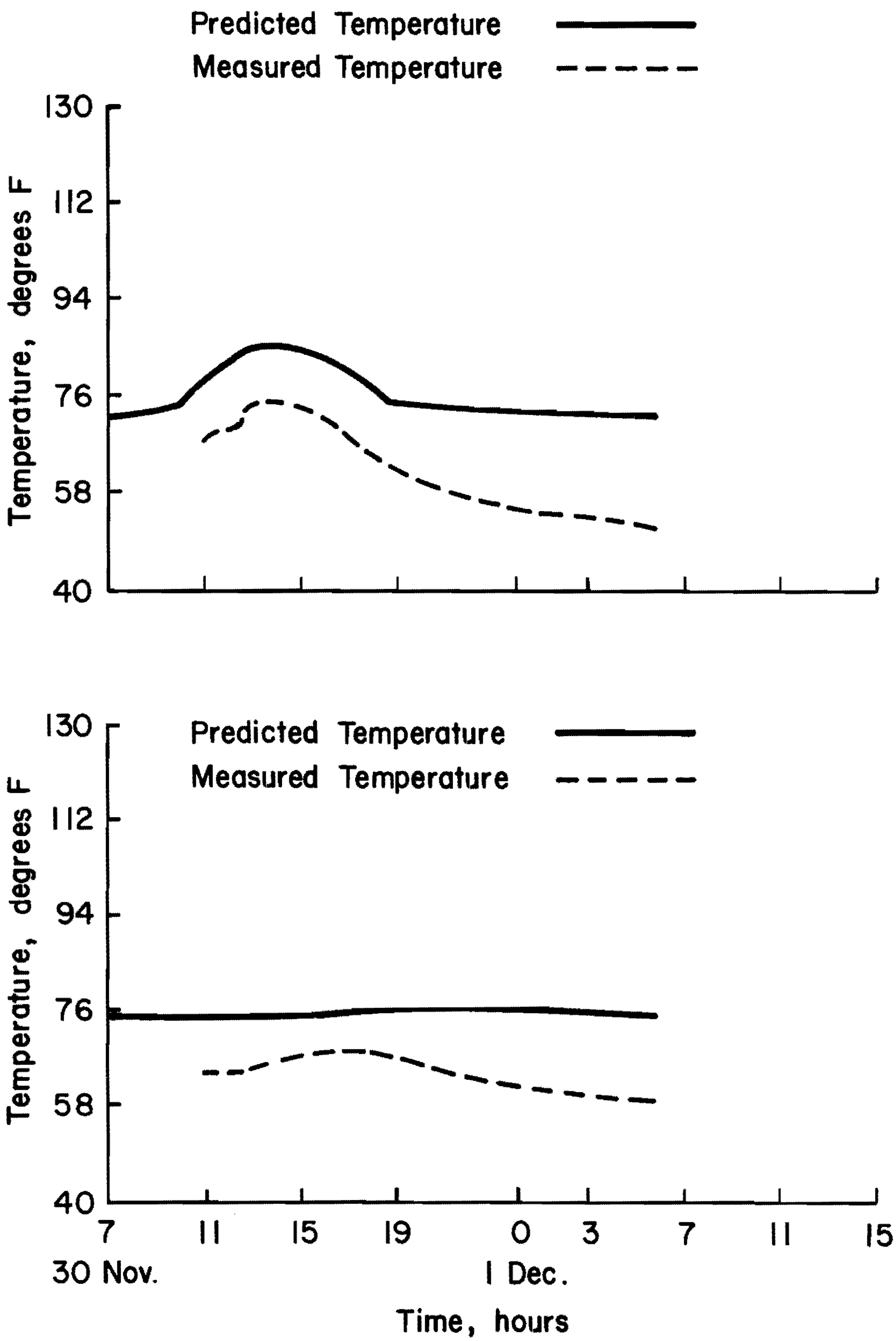


Fig 4.9. Variation in temperature of concrete slab on 30 Nov. - 1 Dec. 1981, Columbus Bypass, SH-71.

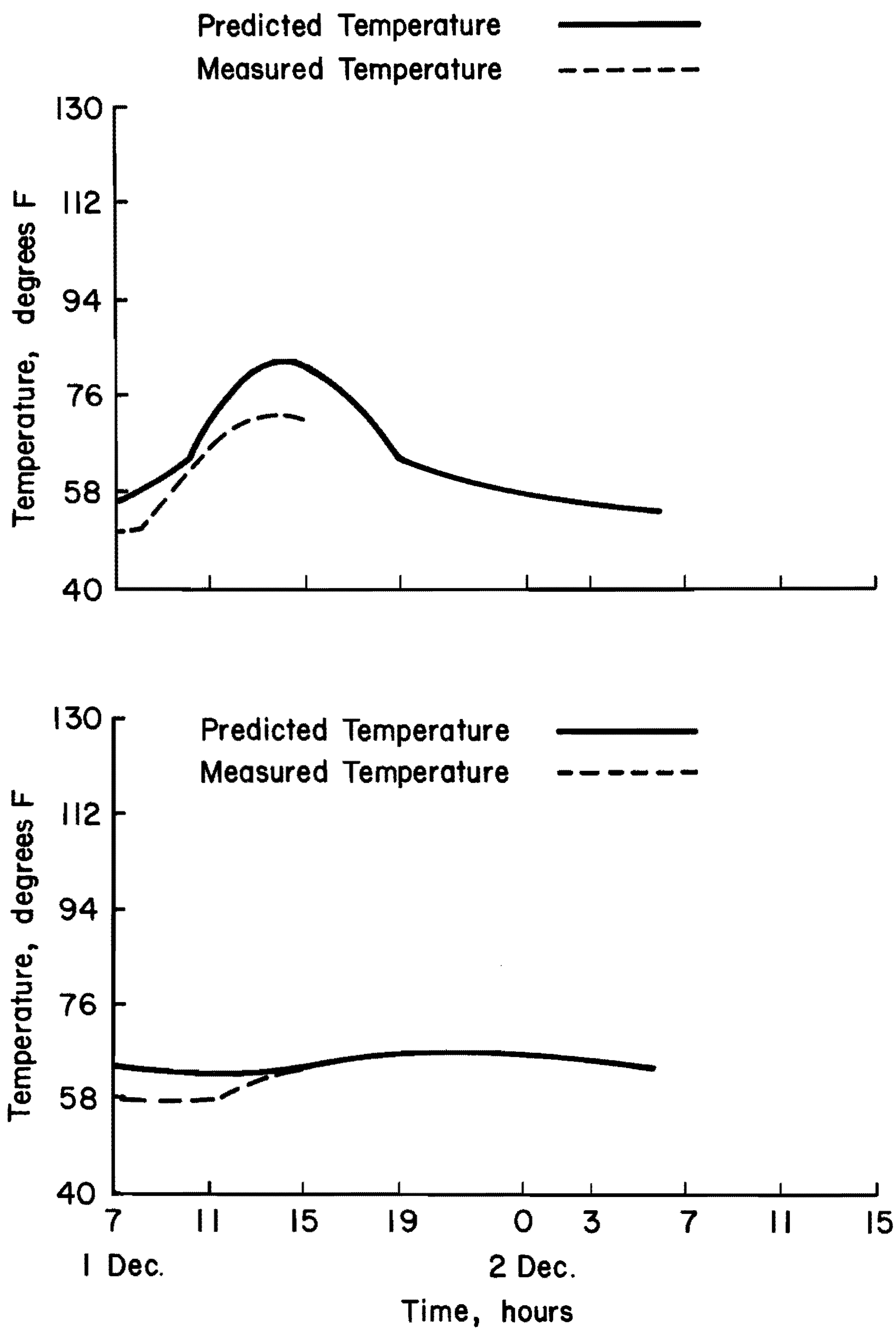


Fig 4.10. Variation in temperatures of concrete slab on 1, 2 Dec. 1981, Columbus Bypass, SH-71.

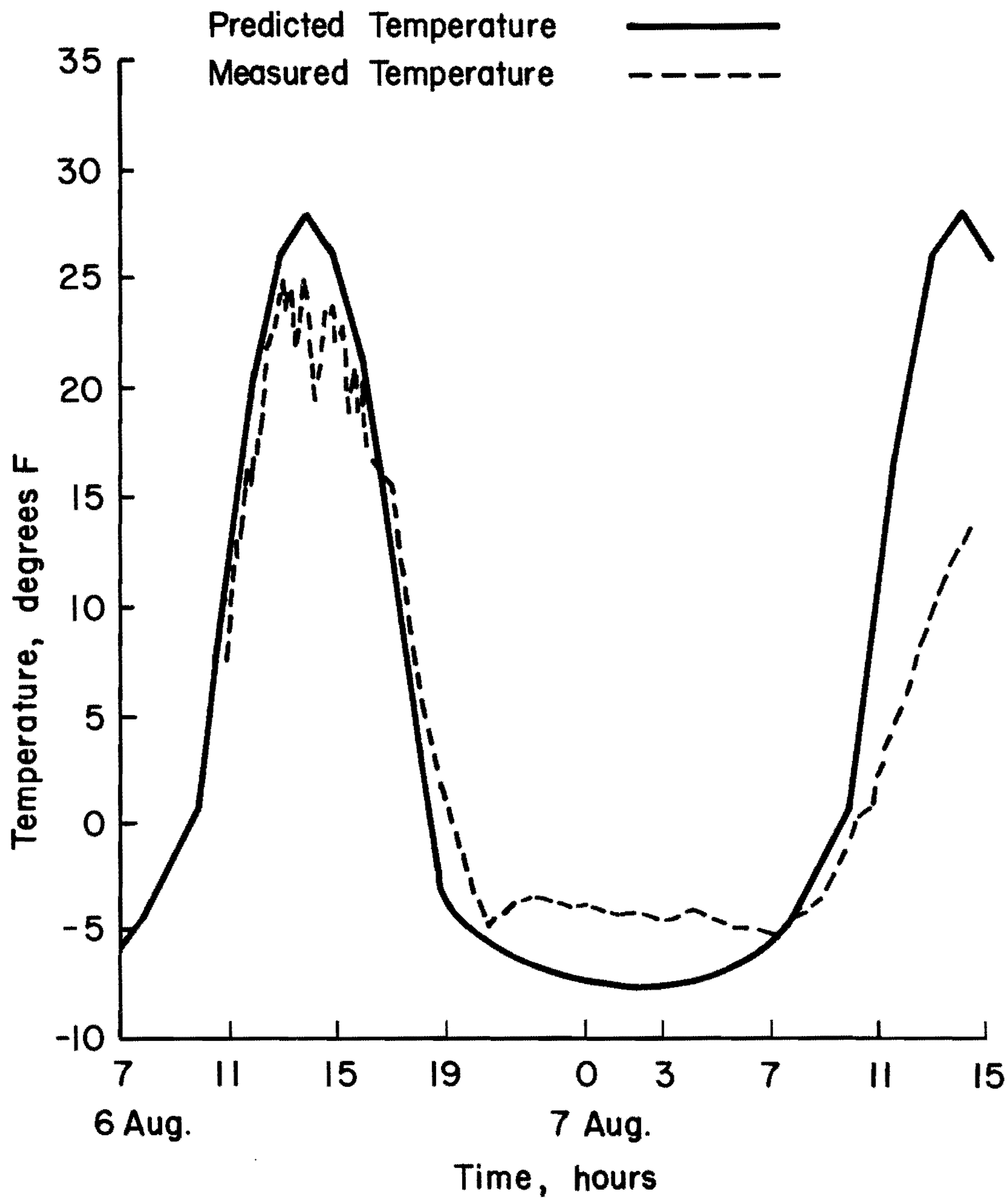


Fig 4.11(a). Variation in temperature differential based on Summer 1981 data, Columbus Bypass, SH-71.

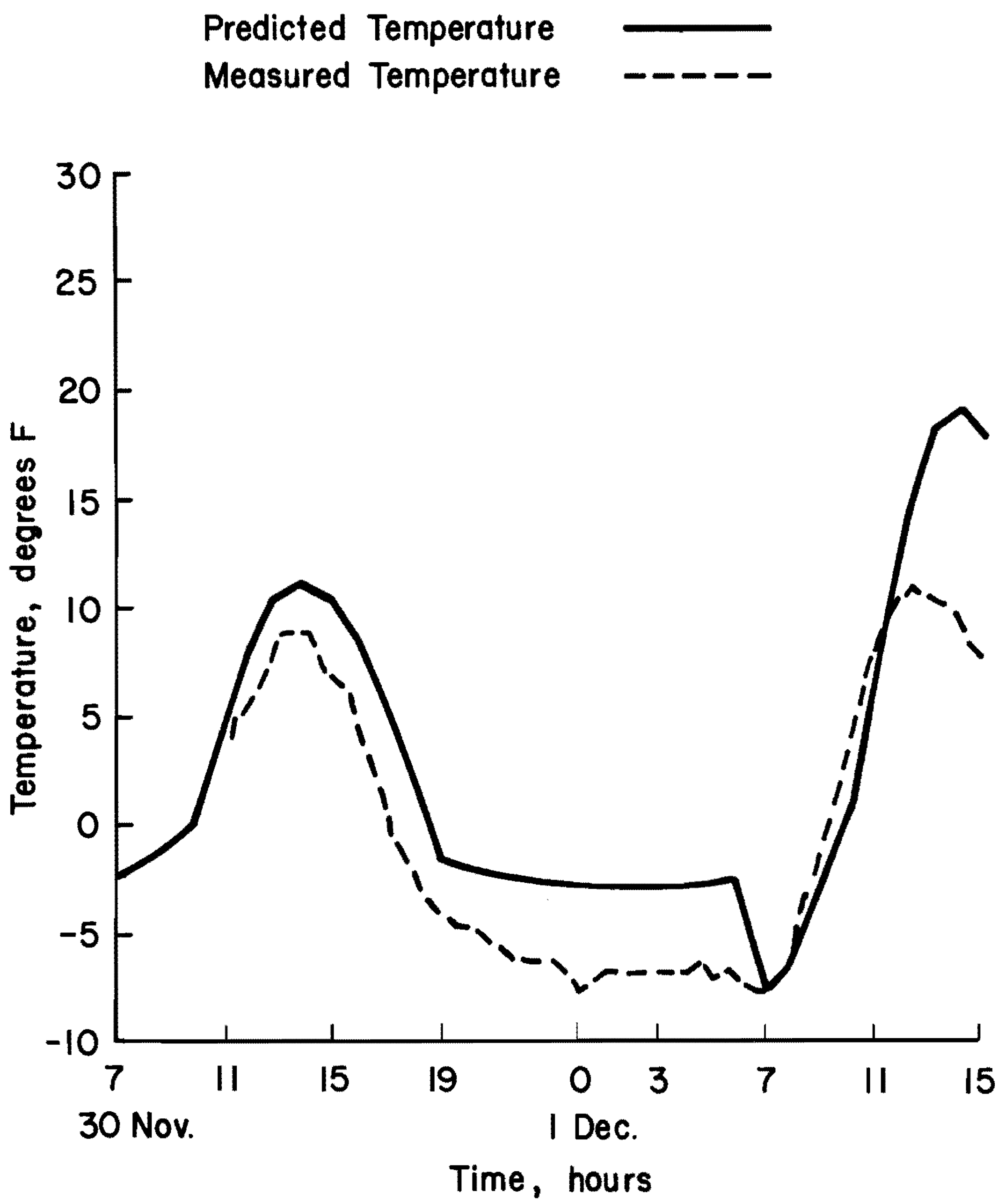


Fig 4.11(b). Variation in temperature differential based on Fall 1981 data, Columbus Bypass, SH-71.

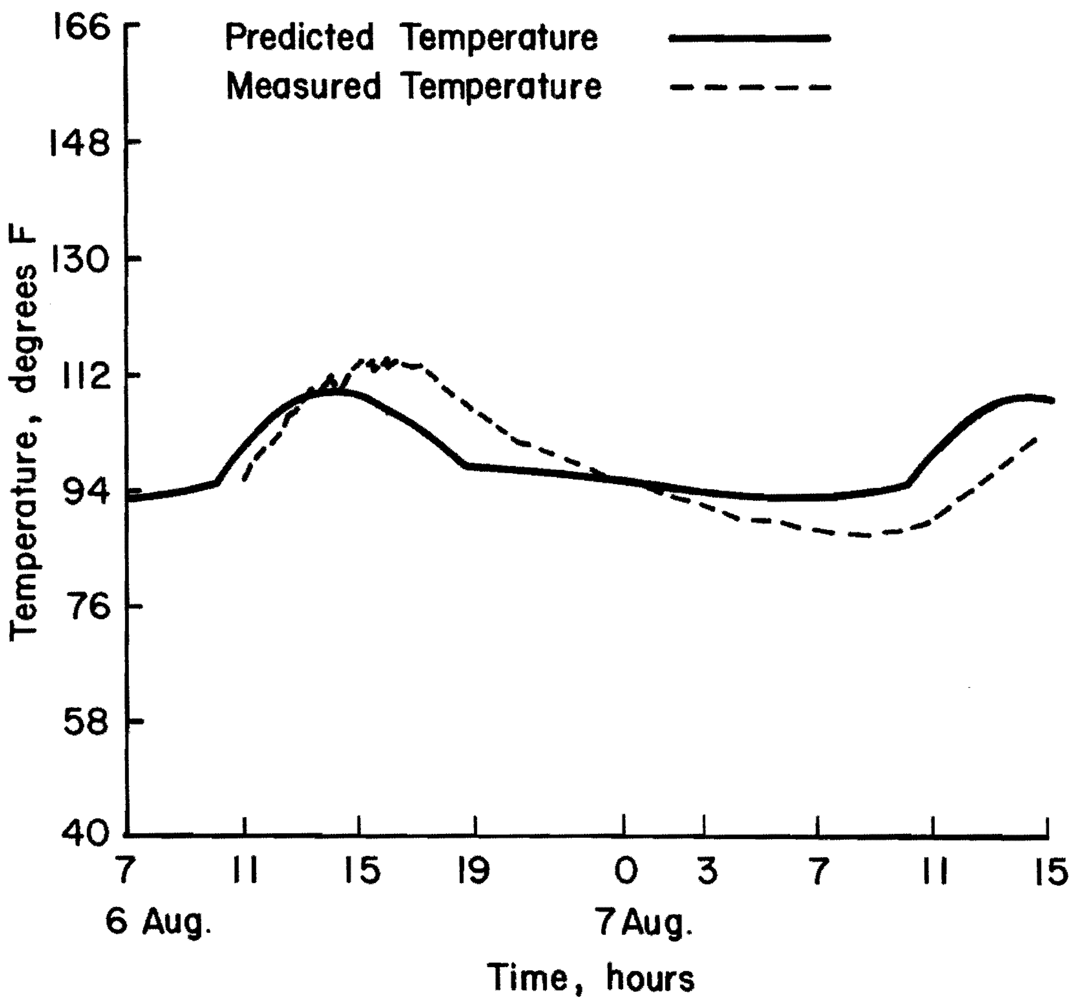


Fig 4.12(a). Variation in mid-depth temperature based on Summer 1981 data, Columbus Bypass, SH-71.

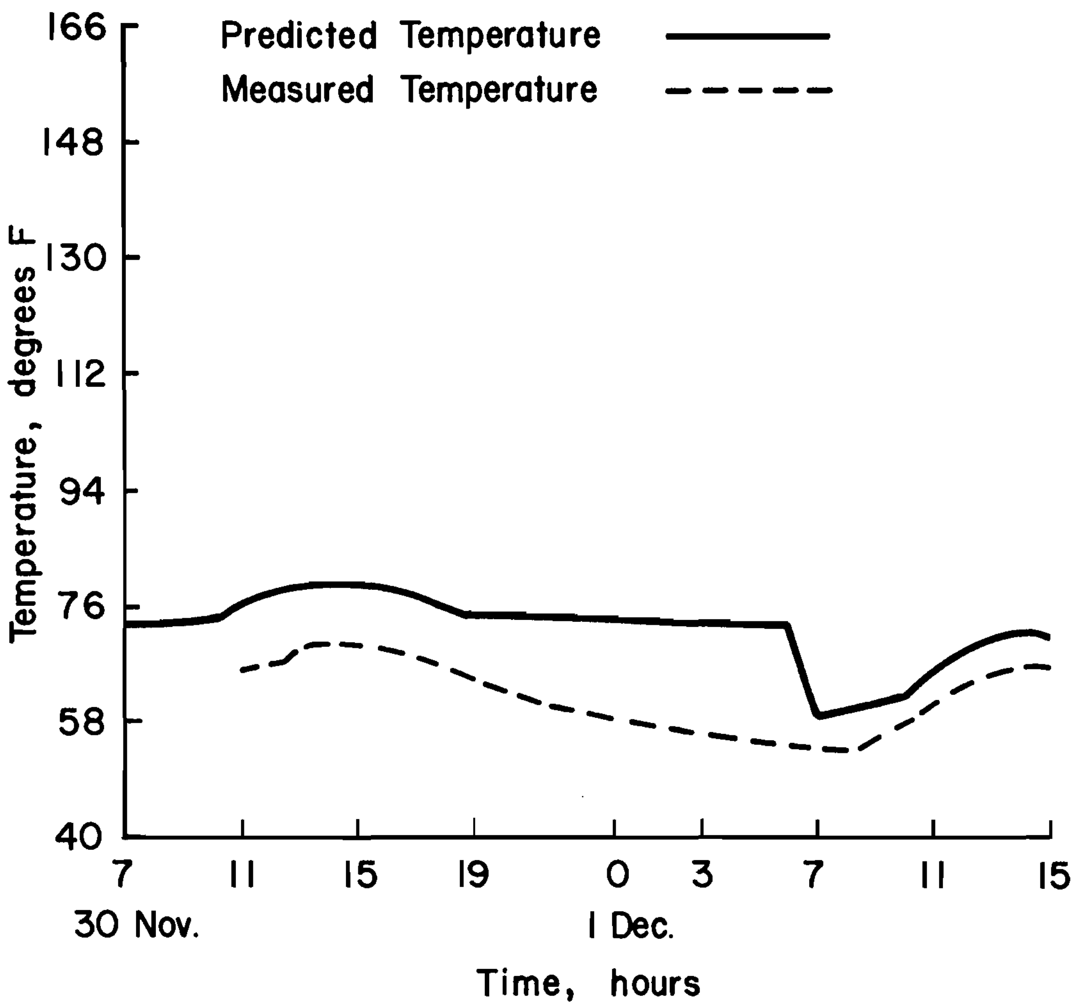


Fig 4.12(b). Variation in mid-depth temperature based on Fall 1981 data, Columbus Bypass, SH-71.

Dynaflect Locations Near the Pavement Edge

The Dynaflect deflections measured near the pavement edge in the passing lane need to be corrected for the effect of varying temperature differential. The procedure to calculate the true deflection (at sensor 1) corresponding to zero temperature differential from the measured deflection at some positive temperature differential is outlined in Appendix E. Figure 4.13 illustrates the corrected maximum deflections at location 1L after applying temperature correction to the measured deflections. The best fit linear regression lines are also plotted in the same figure, showing $R^2 = 0.00$, which indicates that the influence of the temperature differential is completely removed from the measured deflections. Coefficients of variation of the corrected deflections range between 5 and 7 percent. This scatter is within the acceptable range of variability in the deflection measurements.

Recommended Procedure

Dynaflect deflections are measured in the interior condition for the purpose of material characterization and at the edge locations for void detection. For routine pavement evaluation, the following procedure should be adopted for CRC or other rigid pavements.

(1) For the Dynaflect deflection measurements, select locations at the edge and the corner as well as interior condition. The corrections are to be applied to deflections measured near edge and corner locations.

(2) Start deflection measurements in the morning hours (2 hours after sunrise) so that the first deflections should correspond to zero temperature differential.

(3) Repeat deflection measurements every hour or two hours on the first locations. It is necessary because the range of regression coefficients of the estimated regression equations are for 10-inch slab, and for any other pavement structure and aggregate type these regression coefficients may vary.

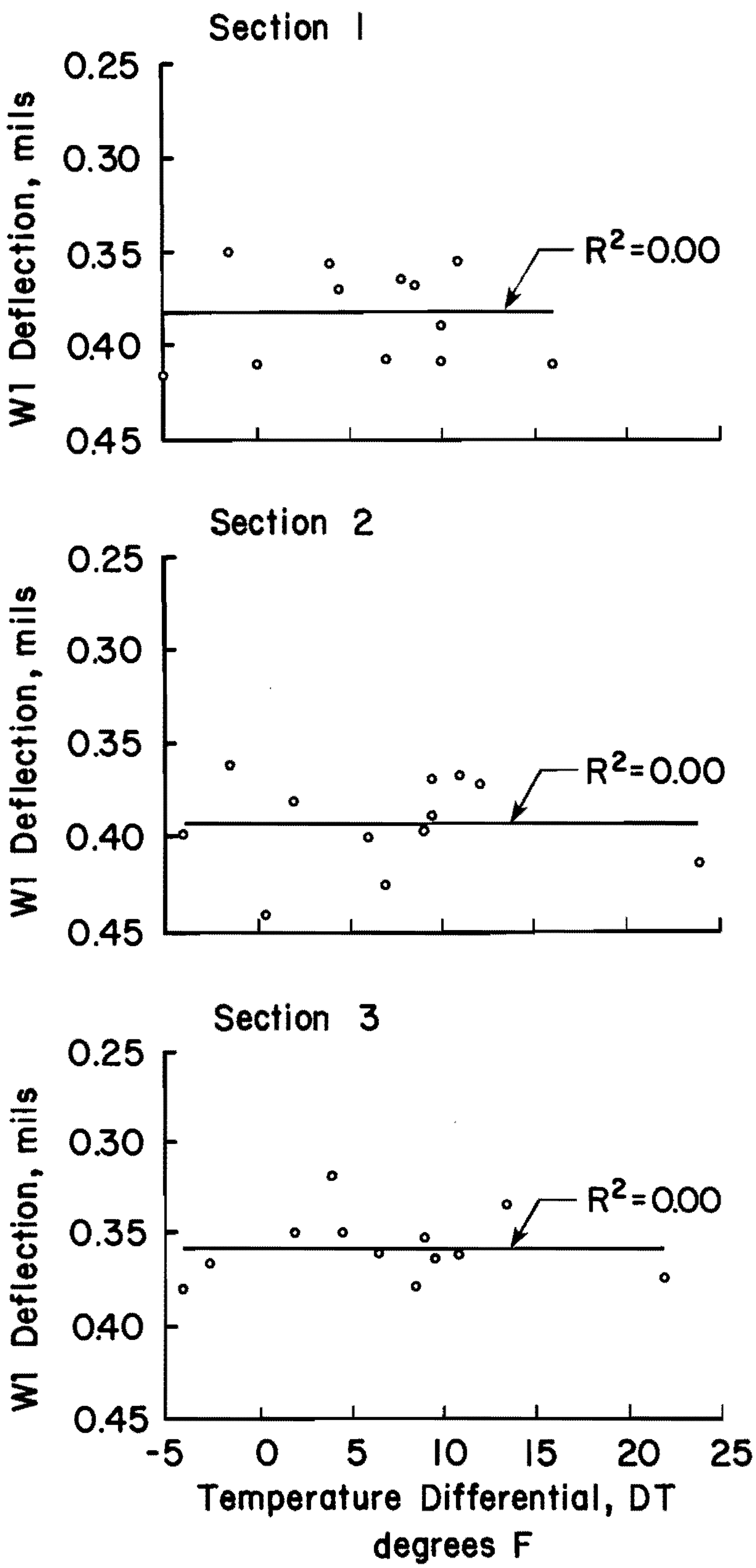


Fig 4.13. Corrected deflections at location IL after applying the temperature correction to the measured sensor 1 deflections, (Summer and Fall 1981 data).

(4) Record weather condition, cloud cover, condition of the pavement surface. The effects of these factors were discussed earlier as related to temperature prediction.

(5) Collect information from NOAA (Ref 19) or local weather stations regarding

(a) wind speeds,
(b) maximum and minimum air temperatures, and
(c) average solar radiations per day.

(6) Using weather and solar radiation data and best estimate of the thermal properties of concrete, predict temperatures at the surface and at some depth below the surface (equal to the thickness of the concrete slab) for a one-day cycle.

(7) Calculate temperature differentials and develop the linear regression equation with repeated deflection (W_1) as the response variable and DT as the predictor variable. The resulting regression coefficient of DT can be used to convert the measured deflections to the standard zero temperature differential condition, or follow the procedure outlined in Appendix E.

(8) The results from repeated deflection measurements should be saved to examine the effect of thickness or type of rigid pavement on the regression coefficients (slopes) of DT.

SUMMARY

A predictive model to estimate the temperature of a concrete pavement at any depth is described and used in this section for comparison with the measured pavement temperature. The results are acceptable. An example of the correction of a measured Dynaflect deflection to the standard zero temperature differential condition is illustrated. Finally guidelines are presented for a tentative procedure to collect the Dynaflect deflection data and to correct these to the zero temperature differential.

CHAPTER 5. BACK CALCULATION OF ELASTIC MODULI FROM MEASURED DEFLECTION BASINS

INTRODUCTION

The principles of pavement evaluation by non-destructive procedures, such as the Dynaflect, Falling Weight Deflectometer, and Road Rater, are based on measuring the pavement response by means of geophones placed at varying distances from the source. One of the obvious advantages of using the above methods is their capability of defining the shape of the deflection basin in addition to recording the maximum deflection (in the Dynaflect system the deflection basin is measured at five equally spaced points, and in general the measured deflection basin shows the points of inflection occurring before the position of the farthest sensor). If the pavement structure is modelled as a multilayer linearly elastic system with homogeneous and isotropic material within each layer, the material of each layer can be characterized by its Modulus of Elasticity (E) and Poisson's ratio (ν). The in-situ moduli are determined from a theoretical analysis of a measured deflection basin. These moduli are used to determine stress or strain, i.e., the basic input to the predictive equations, to determine the remaining fatigue life of the existing pavement structure. The present study as described herein is focussed on the estimation of the in-situ elastic moduli from the deflection basins measured with the Dynaflect. It is an iterative procedure involving the following steps:

(1) Determine the thickness of each layer and the applied load assumed to be known.

(2) Assign reasonable values of elastic modulus and Poisson's ratio to each layer.

(3) Input the thickness, modulus, and Poisson's ratio of each layer and the applied load into such computer programs Chevron's LAYER; Shell's BISAR or ELSYM5 (all based on linear elastic theory with static loading condition). The only output required from these programs is an array of computed surface deflections on the relative positions of the five sensors.

(4) Compare the computed deflections with the measured values; a new value is assigned to the modulus and the deflections are recomputed. This iterative procedure is continued until a "best" fit to the measured deflection basin is achieved.

(5) Assume the final combination of the elastic moduli (giving the best fitted deflection basin) to represent the in-situ elastic moduli.

There are two main problems inherent with such an analysis:

Problem 1: If the pavement structure is composed of three or more layers of different materials, it may require a large number of iterations in order to achieve the best fit for the measured deflection basin.

Problem 2: If, in addition to load, thickness and the Poisson's ratio of each layer, the elastic moduli are known, the computer program (based on elastic layer theory) will give only one set of fixed surface deflections. However, the reverse is not true. In other words if the moduli are initially guessed, the iterative procedure as described above will not give a unique solution for the in-situ moduli that give the same best fit basin.

LITERATURE REVIEW

There are basically three distinct approaches (based on the concepts as discussed earlier) to back calculate the elastic moduli from the measured surface deflection basin.

(1) Development of empirical equations to predict pavement deflections, such as reported by Scnivner et al (1971) in Ref 27. Later a graphical technique was developed for a two-layer system (Ref 28)

by Swift (1972). These methods can be applied to a limited number of pavement structures.

(2) Formulation of various deflection basin curvature parameters and relating them with the modular ratios. Graphical solutions developed in this approach are generally limited to structures of two or a maximum of three layers (the last layer considered as semi-infinite in all these cases). Majedzadeh (Ref 17) used the following parameters to provide interpretation of the deflection basin.

(a) Surface Curvature Index (SCI) is defined as the difference between the deflections recorded by sensors 1 and 2.

(b) Base Curvature Index (BCI) is defined as the difference between the deflections recorded by sensors 4 and 5 (for a Dynaflect).

(c) Dynaflect Maximum Deflection (DMD), recorded at sensor 1.

Vaswani in 1971 (Ref 18) used spreadibility (average deflection as a percent of the maximum deflection) to characterize the deflection basin. Vaswani presented a nomograph using the spreadibility and maximum deflection for evaluation of the moduli. Majedzadeh (Ref 17) also developed graphs, relating the deflection basin parameters to the modulus ratio for estimation of the individual layer's modulus of elasticity. Visser (1978) described The Shell procedure (Ref 29) using the BISAR program. The deflection basin is characterized by the maximum deflection and the deflection ratio (i.e., deflection at distance r /maximum deflection). Hoffman and Thompson (1981) used the "AREA" of the basin and shape factors to interpret the deflection basin (Ref 30). Taute et al (1981) studied the rigid pavement structure (Ref 1). Their main findings are that (1) the subgrade modulus can be predicted from the sensor 5 deflection with fair accuracy and (2) the deflection basin slope (difference of deflections measured by sensors 1 and 5) can be used to estimate the surface and base moduli using an iterative procedure. Nomographs have been prepared using the above concepts by Taute et al.

(3) Use of computer programs (based on multilayered linear elastic theory) in reverse order (trial and error iterative procedure). This approach has been used and recommended by many researchers, e.g., Irwin 1977, 1982 (Refs 31 and 32); Wang and Anani (Ref 33), and Taute et al in 1981 (Ref 1). Wang and Anani (Ref 33) and Irwin (Ref 32) describe their self iterative computer programs.

FEATURES OF THE PRESENT STUDY

Objectives

In the summer of 1981, Dynaflect deflection data were collected to evaluate the effects on the data of the temperature differential in the concrete slab and of the test location with respect to the discontinuities, edge and interior loading conditions. The testing site was the CRC pavement of the SH-71 bypass at Columbus, Texas. The data were collected before and after the pavement was opened to traffic. A few sets of deflection data were selected from the accumulated data sets where the effect of temperature differential was thought to be less significant. The selected deflection basins were used to characterize the in-situ moduli.

Figure 4.1 shows a measured deflection basin and the pavement structure. This particular deflection basin was analyzed for back calculation of layer moduli using the available computer packages of ELSYM5 and LAYER8 (based on Chevron's n-layer program). The same basin was further used (1) to investigate the effect of changing the elastic moduli on the deflection basin and (2) to see the effect of a rigid foundation at some finite depth below the subgrade layer.

Additional analyses were made to see the general shape of the measured deflection basin for different pavement structures. An existing interactive program (that used LAYER8) was used extensively. This package, BASFIT, facilitated considerable reduction of computer time in view of the iterations made during the course of the study. BASFIT (Version 3.0) gave deflection results which compare reasonably with the results of ELSYM5. A few plots showing comparisons of the calculated deflection basins using ELSYM5 and the version 3.0 of BASFIT are included in Appendix F (Figs F.1 and F.2).

Assumptions and Procedures

Conventionally, the majority of investigators consider the subgrade layer as semi-infinite while back calculating the elastic moduli from the measured deflection basin. The basic iterative procedure was outlined in the introduction. For the particular pavement structure (Fig 5.1), the depths of the first three layers and their Poisson's ratios were kept fixed. The depths in inches of the concrete surface layer, asphalt concrete base course, and lime-treated subbase are 10, 4, and 6, respectively, and the subgrade extends to infinity. However, in the case of a rigid foundation, the depth of the subgrade is finite and variable. Poisson's ratios of the concrete surface layer, asphalt concrete base course, lime-treated subgrade, and natural subgrade are assumed to be 0.15, 0.35, 0.35, and 0.45, respectively. It should be noted that the calculated deflection basins by elastic theory are not appreciably affected by slight changes in the Poisson's ratio of the layers underlying the concrete layer (Ref 32). Keeping in view the typical configuration of the Dynaflect load the geophones (sensors), the principle of superposition is applied in BASFIT to calculate the total surface deflection at each sensor's location.

PAVEMENT STRUCTURE WITH INFINITE SUBGRADE

Back Calculation of Moduli of Layers

Figure 5.2 shows various calculated deflection basins that match very closely the measured basin. The calculated basins are based on different combinations of the elastic moduli of the four layers. The following findings are based on these results.

(1) There is no unique combination of the elastic moduli which can give the desired deflection basin.

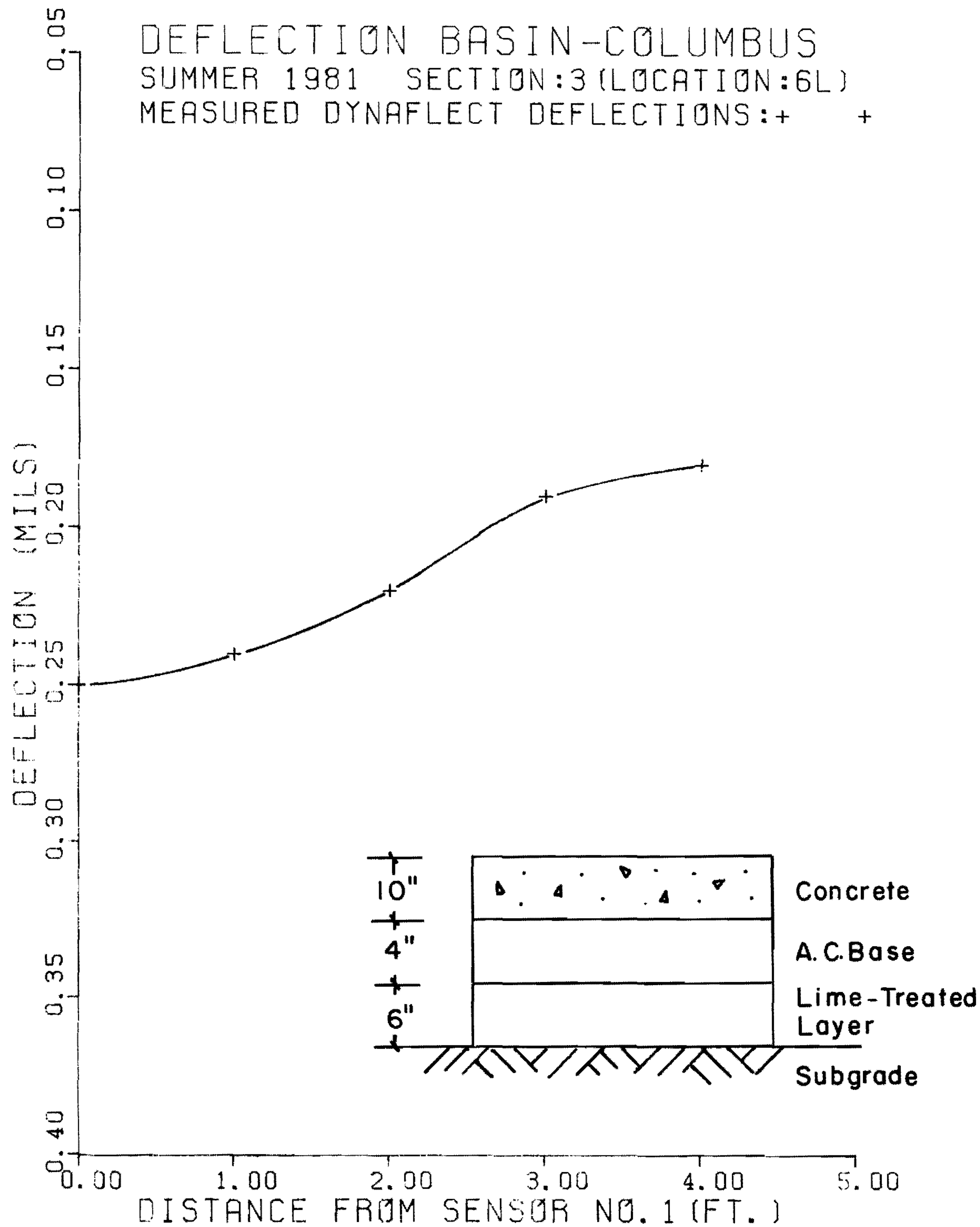


Fig 5.1. Measured deflection basin and pavement structure of the test section.

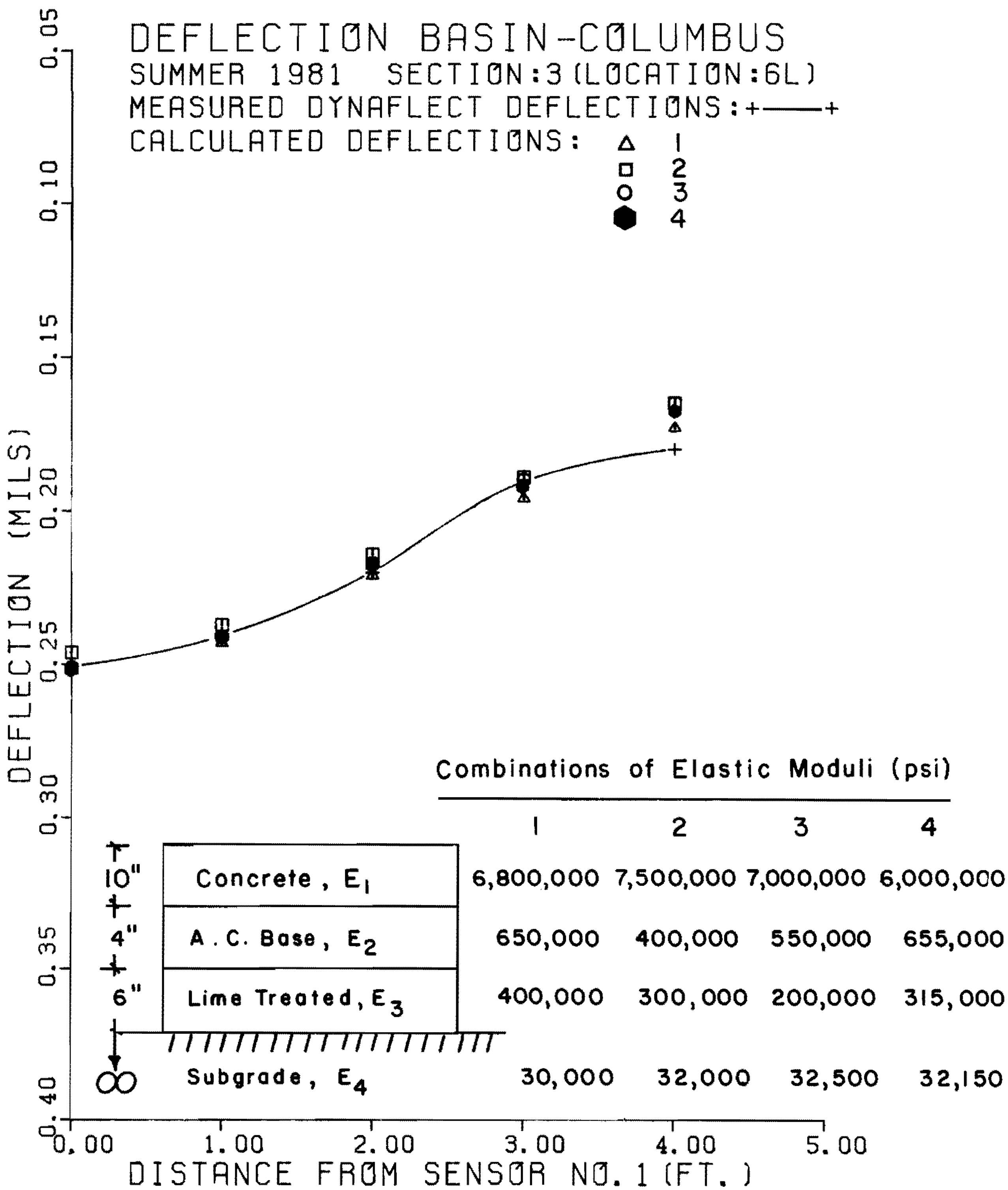


Fig 5.2. Results of deflection basin fitting.

(2) Some acceptable tolerance should be assigned to the deflection value of each sensor in order to converge the iteration process.

(3) Selection of the optimum combination of elastic moduli can be based on

(a) the elastic modulus of each layer, to be within reasonably practical and established limits for the material of the particular layer, or

(b) the shape of the calculated deflection basin, to be similar to that of the measured basin.

Effect of Rate of Change of the Elastic Moduli on Calculated Deflections

A well-defined strategy is needed for an efficient iteration process that begins from a set of assumed elastic moduli. Keeping this objective in mind, a parametric study was performed to see the effects of the rate of change of the elastic moduli on the calculated deflection basin. For the measured deflection basin of Fig 5.1, the optimum combination of elastic moduli giving the best fit is shown in Fig 5.3. Therefore, these elastic moduli (E_1 , E_2 , E_3 , and E_4) were used in the parametric study.

For the same pavement structure (the same thicknesses and Poisson's ratios); E_1 was doubled (E_2 , E_3 , E_4 were unchanged), and the new deflections were calculated as plotted in Fig 5.4. Next E_1 was reduced to half of the original value and deflections were recalculated (also plotted in Fig 5.4). Similarly the effects of rates of change in E_2 (E_1 , E_3 , E_4 were unchanged) were studied by applying factors of 2 and 1/2 successively to the original E_2 value. The two newly calculated deflection basins are plotted in Fig 5.5). Similarly Figs 5.6 and 5.7 show the corresponding deflection basins calculated after changing the values of E_3 and E_4 , respectively, as done earlier for E_1 and E_2 . This study gave a reasonably clear understanding of how to formulate a strategy for the iteration process of changing the elastic moduli. This strategy will facilitate the attainment

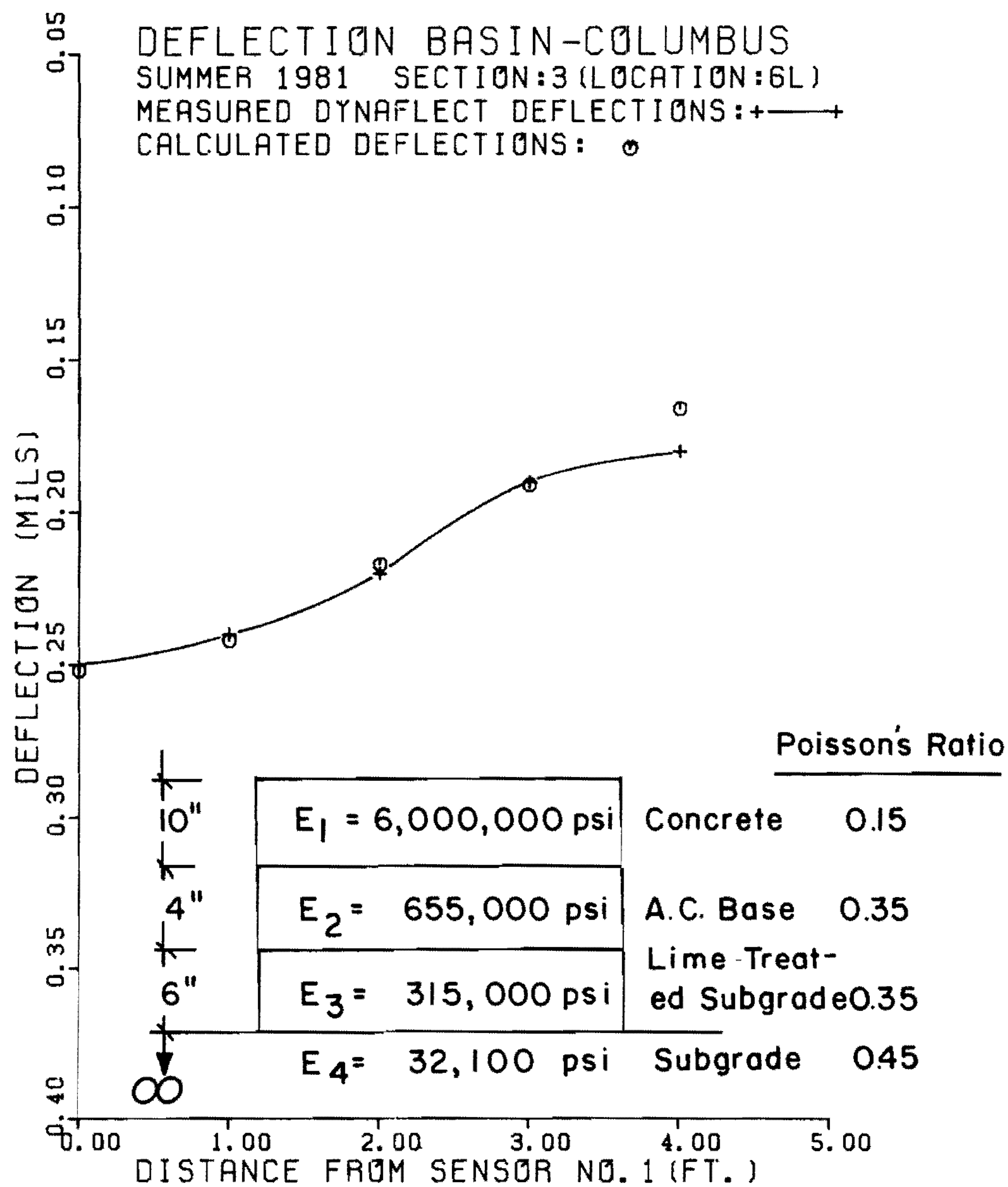


Fig 5.3. Back calculated Young's moduli assuming infinite subgrade.

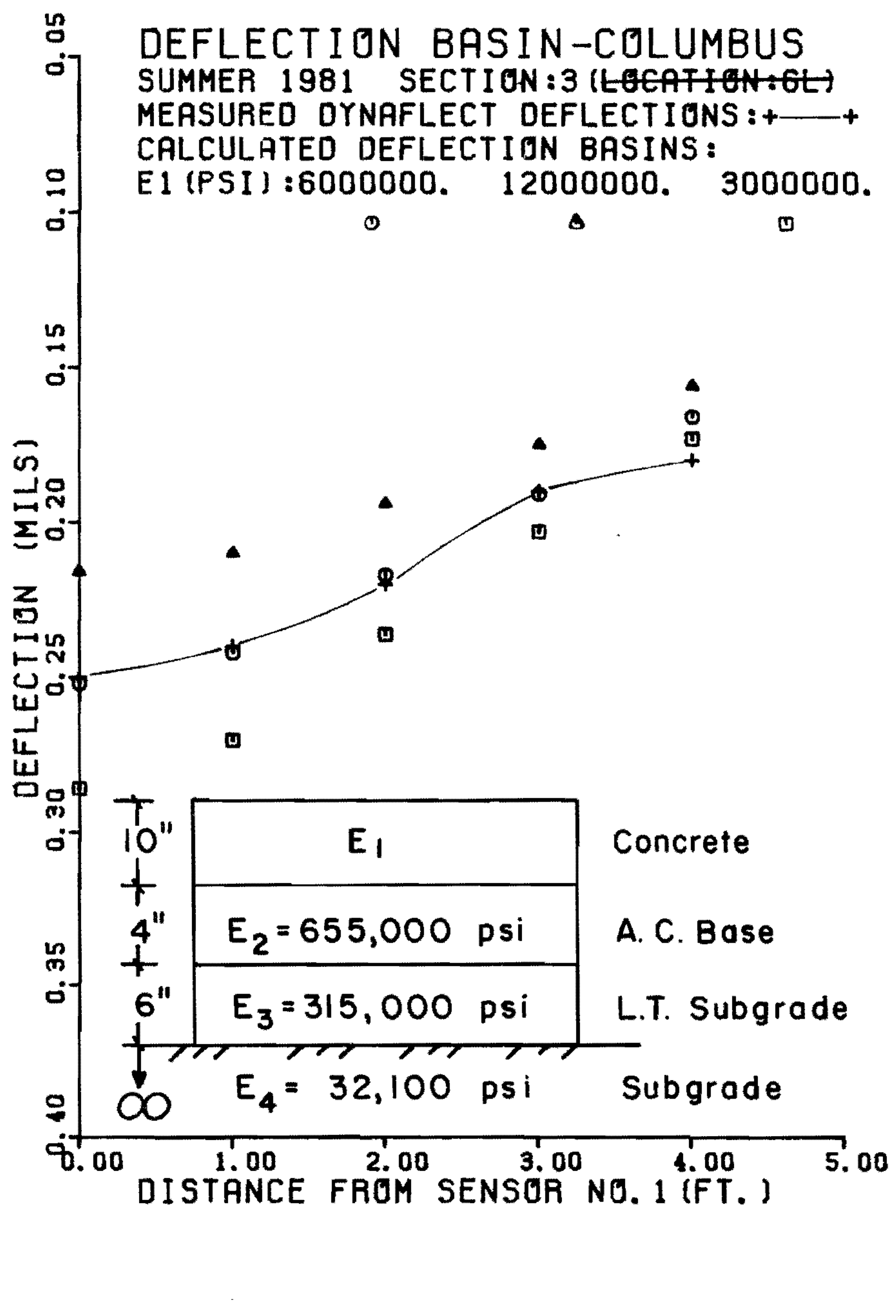


Fig 5.4. Effect of change of E_1 on calculated basin (infinite subgrade).

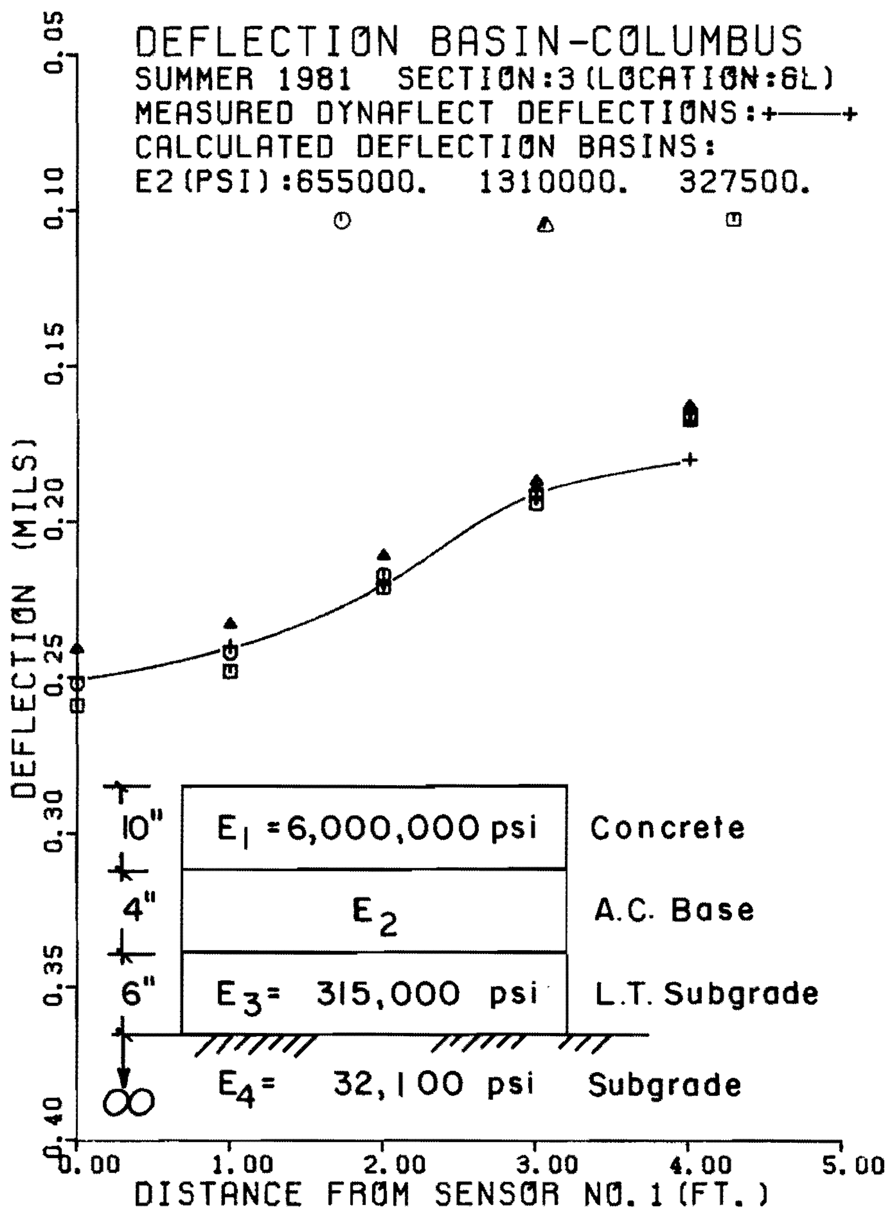


Fig 5.5. Effect of change of E_2 on calculated basin (infinite subgrade).

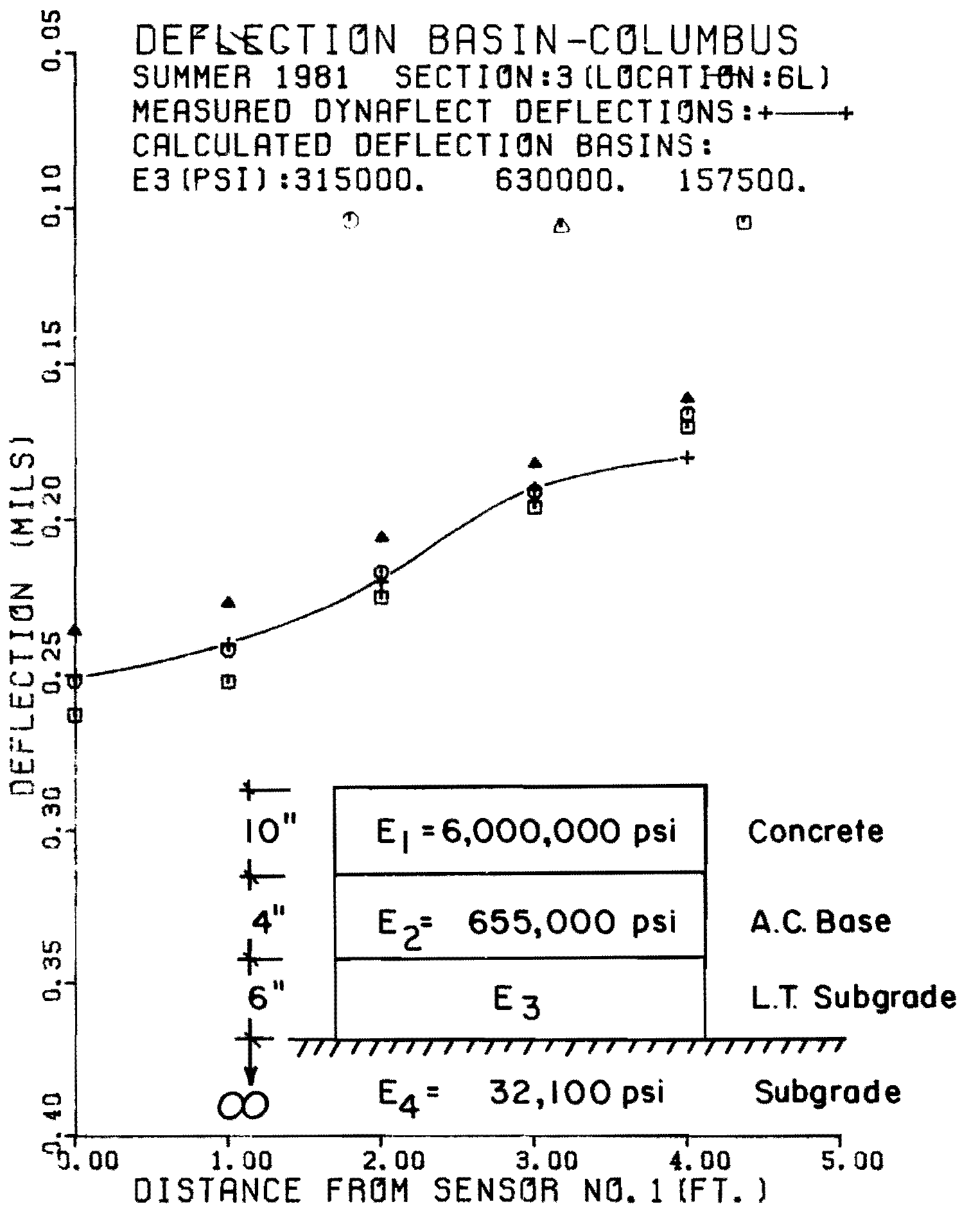


Fig 5.6. Effect of change of E_3 on claculated basin (infinite subgrade).

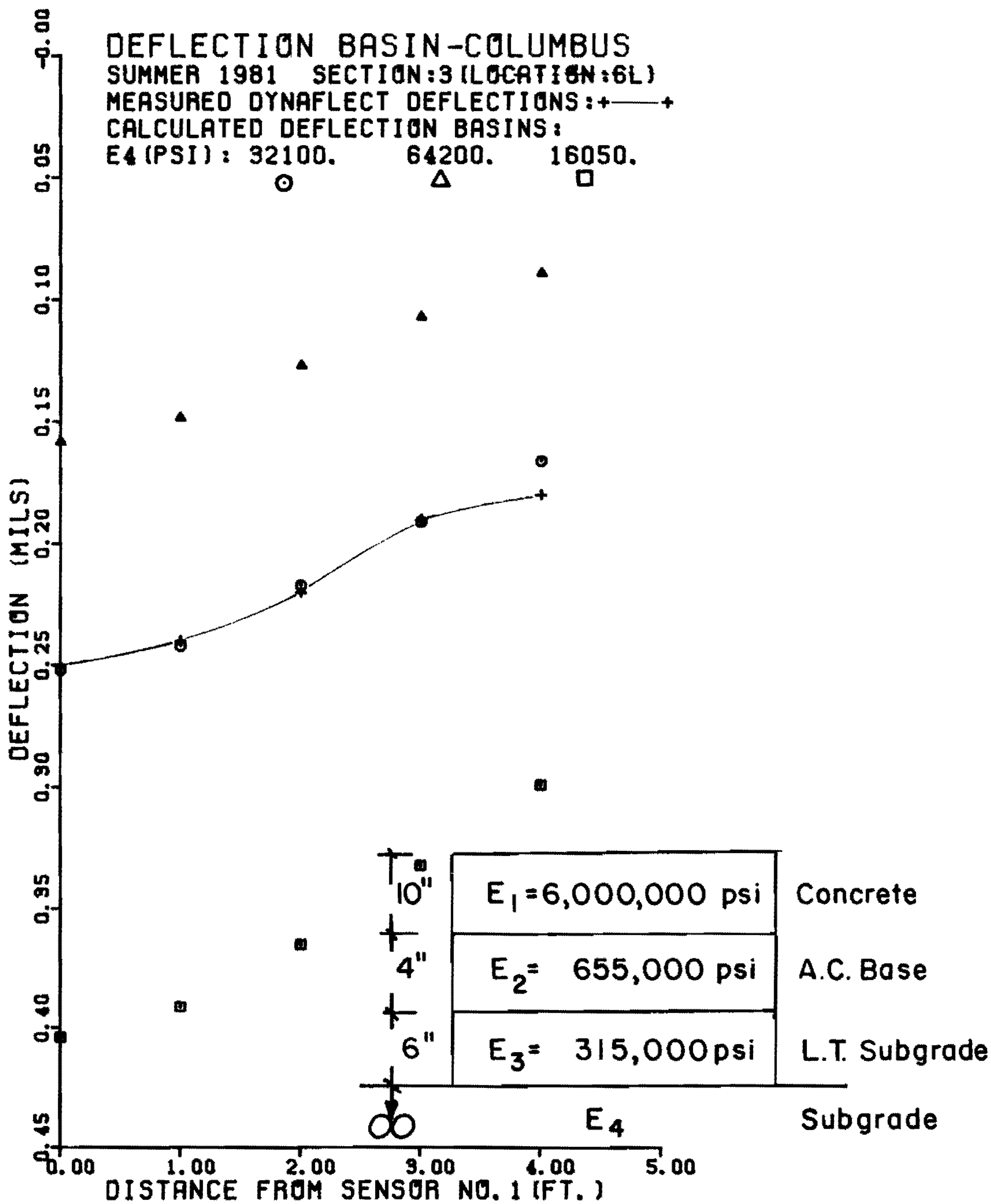


Fig 5.7. Effect of change of E_4 on calculated basin (infinite subgrade).

of a better match of the calculated and measured deflection basins. Figures 5.4, 5.5, 5.6 and 5.7 indicate:

(1) An increase in the previous value of the elastic modulus of any layer is accompanied by a decrease in the calculated deflections of all sensors. Also, a decrease in the original value of the elastic modulus of any layer is associated with a corresponding increase in the deflections of all sensors.

(2) Any increase or decrease in any of the elastic moduli, E_1 , E_2 , and E_3 shows a corresponding but opposite change in the calculated deflections. However any change in E_4 is accompanied by a relatively higher percent decrease or increase in the calculated deflections.

(3) In all cases the relative change in the calculated deflections (due to a change in an elastic modulus) is not the same for all sensors. In general sensors 1 and 2 exhibit the largest change and sensor 5 exhibits the least change.

(4) The calculated deflection basins corresponding to changing in elastic modulus of each layer, reveal that;

(a) If E_4 is increased by 100 percent (an increase of 32,100 psi in Fig 5.7) the deflection at sensor 5 is reduced by 46 percent and sensor 1 deflection decreased by 37 percent of the original value. It is found effective to start from an initial set of assumed moduli and iterate until the calculated deflection at sensor 5 matches closely the measured deflection.

(b) For this pavement structure (with a 10-inch surface concrete layer and intermediate layers of 4 and 6-inch); a change in E_1 affects the deflection at sensor 1 more than that at sensor 5. For example, if E_1 is decreased by 50 percent (a decrease of 3,000,000 psi), the calculated deflections at sensors 1 and 2 are increased by 14 and 10 percent respectively, whereas the deflection at sensor 5 is increased by only 4 percent. Therefore E_1 can be effectively used for matching sensors 1 and 2 deflections.

(c) The deflection basin is the least sensitive to changes in E_2 and E_3 . Any change in E shows relatively more effect on sensors 1 and 1 as compared to the effect of an equal change in E_2. These observations are limited to the pavement structure discussed in this study in that the thicknesses of the layers certainly play a role in the measured or calculated deflections.

Based on the above discussions, the most effective strategy to optimize the iteration process can be summarized as below:

(1) In the initial estimate, assume reasonable values for E_2 and E_3. Assume an average value of the elastic modulus (E_1) of the concrete surface layer. Assume an initial higher value of E_4.

(2) Iterate with E_4 (elastic modulus of subgrade) until the calculated deflection at sensor 5 approaches the measured deflection.

(3) Iterate with E_1 until the calculated deflections match closely the measured basin, with special attention to sensor 1.

(4) Iterate with E_2 and E_3 for very small changes in the calculated deflections and to improve the shape of the calculated basin. If necessary make more iterations with small changes in E_4 and E_1 to achieve the best fit.

The above guidelines were followed in the later analyses of measured deflection basins and found very useful and effective in reducing the number of iterations.

CONSIDERATION OF RIGID FOUNDATION

Theoretically the subgrade layer is often assumed to extend to infinity. This assumption is not realistic for many cases. The strains become practically negligible at some depth from the top surface (1) as the result of non linear behavior of subsoil strata or (2) due to the existance of a rigid foundation, e.g., bed rock. This condition can be simulated for the application in multilayer linear elastic theory based program by assuming a large elastic modulus at the bottom of a subgrade layer of finite depth.

Selection of the Depth of Rigid Bottom

In the case where bed rock is not present at some unknown depth, the depth to the rigid bottom must be selected. There is very little published work on this topic. Generally, this depth is arbitrarily selected. Wiseman et al (Ref 34) suggest relating the depth of the subgrade layer to the lateral extent of the measured deflection.

Criteria for Determination of an Optimum Depth to the Rigid Bottom

Three different approaches were employed, as discussed below:

(1) The optimum solution obtained for the elastic moduli in the case of an infinite subgrade layer was the basic step in the first approach. Different depths to the rigid bottom were assigned. In other words, the pavement structure now consists of 5 layers.

The fourth layer is the subgrade layer of varying thickness (ranging from 5 feet to 300 feet). The fifth layer is the rigid foundation with an assigned elastic modulus of 1×10^{99} psi. The deflection basin was recalculated for each case. The basins are plotted in Fig 5.8. It is found that, at some depth, the recalculated deflection basin matches very closely the measured basin. In this example, the optimum depth to the rigid bottom was found to be 300 feet.

(2) The second approach was to examine the deflection basin corresponding to each assumed value of the depth of the subgrade layer to the rigid bottom, as calculated in (1). It is noted that the shapes of the deflection bowls are different. It is observed that at 19 or 20 feet, the shape of the bowl is very similar to that of the measured bowl. At the selected depth of 19 feet, iterations were made with gradual reduction in the subgrade modulus, until the deflection basin matched the measured basin. A reduction of 36 percent in the subgrade modulus is obtained in this way (see Fig 5.9). Taute et al (Ref 1) discussed this finding.

(3) The third approach is based on wave propagation characteristics. The Dynaflect generates Rayleigh waves at a fixed frequency of 8 Hz. The velocity of Rayleigh waves can be determined by the relation

$$V_R = f \cdot L_R \quad (f = \text{frequency;} \quad L_R = \text{wave length}).$$

The velocity to a first approximation corresponds to that of the material at a depth of $L_R/2$. In the case of pavements this analysis is complicated because of the layers of different moduli. However, this approach presents a method of considering a rigid bottom at the depth of L_R. Based on field experience, Rayleigh wave velocities (V_R) of most natural soils range from

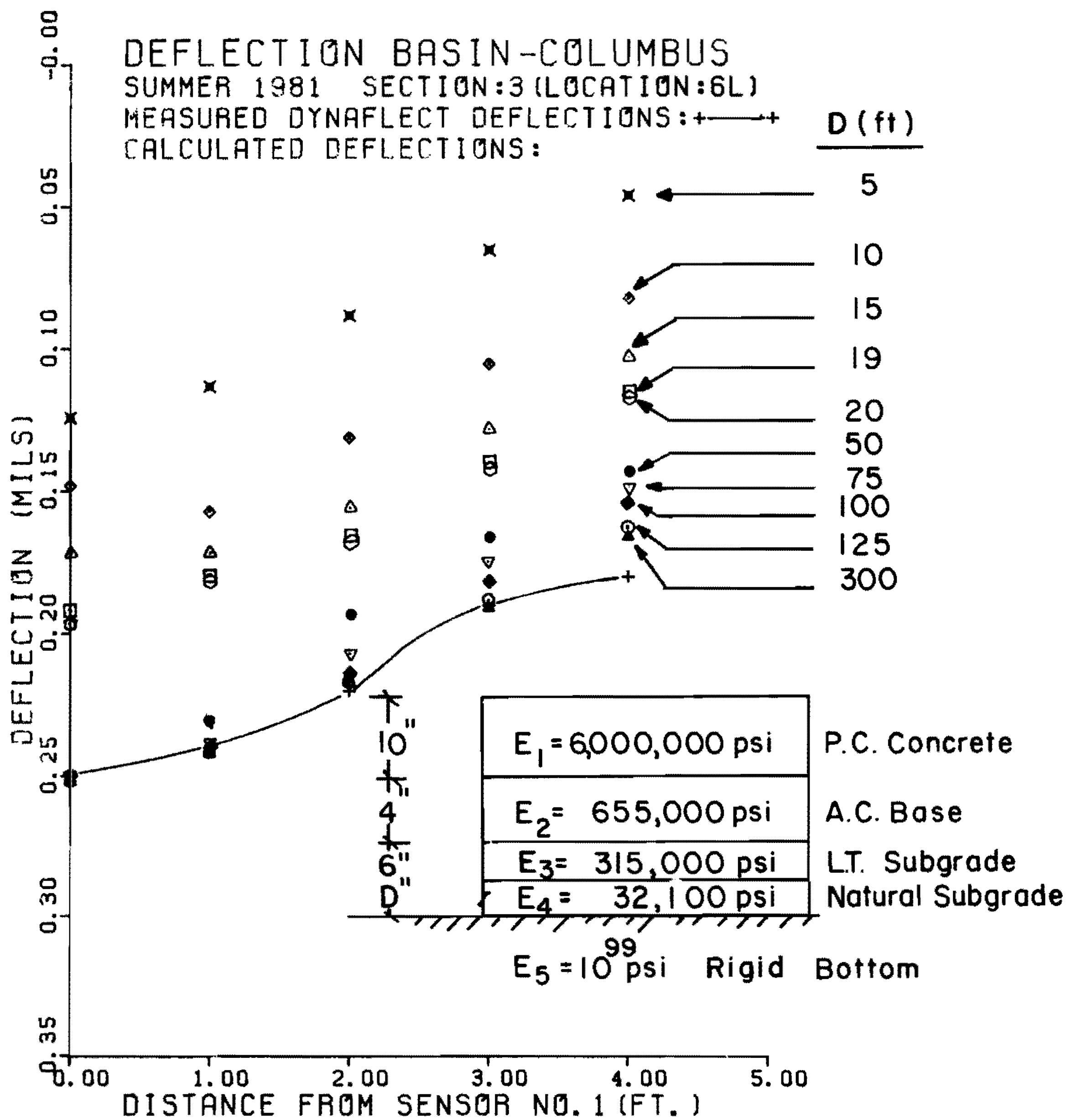


Fig 5.8. Effect of consideration of rigid bottom on calculated deflection basin.

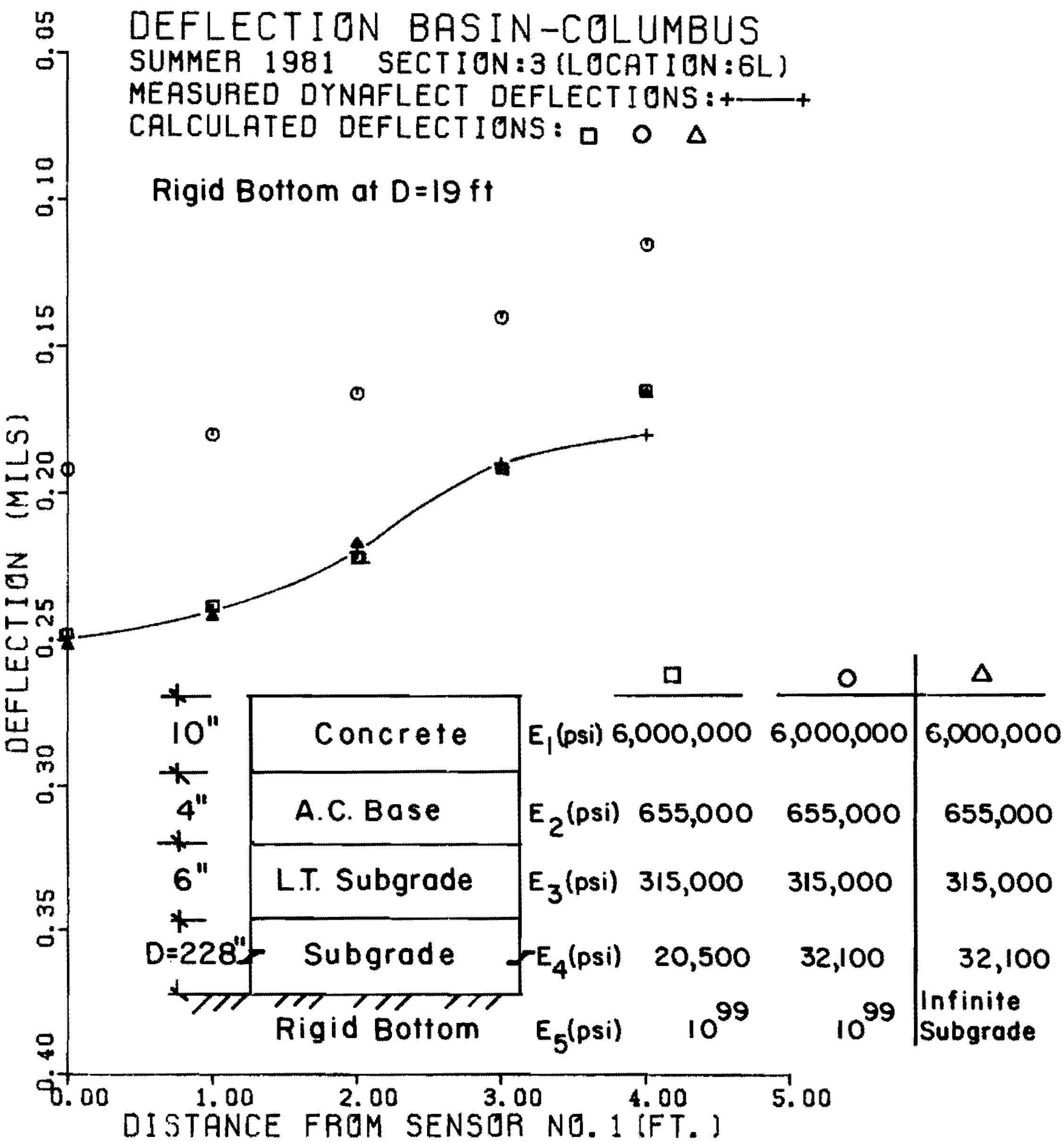


Fig 5.9. Reduction in subgrade modulus assuming a rigid bottom at some finite depth.

approximately 400 to 1000 fps. The Dynaflect is operated at a fixed frequency (f) or 8 Hz per second. Therefore the wavelength generated during the steady state vibrations of the Dynaflect ranges from 50 and 125 feet. Assuming no rock formation occurs the rigid bottom can be considered to range between 50 to 125 feet. The optimum combination of elastic moduli and the calculated deflection basins for this case (rigid bottom at 125 feet) are shown in Fig 5.10. This approach is very realistic. It also indicates that it is not necessary to reduce the modulus of subgrade (as discussed in the second approach) to obtain a good fit of the deflection basin in the case of a rigid bottom.

Effect of Rate of Change of the Elastic Moduli on Calculated Deflection Base

The optimum combination of the elastic moduli considering a rigid bottom of some finite depth was used in a parametric study. The parametric study to investigate the effects of rate of change of the elastic moduli on deflection basins was very similar to the one described in the case of infinite subgrade layer. The results are presented in Figs 5.11 to 5.14. The major findings are similar to those discussed in the infinite case.

ANALYSIS OF ADDITIONAL DEFLECTION BASINS

The strategy developed for the back calculation of elastic moduli in the previous sections was successfully used in the analysis of some additional measured deflection basins. The deflection basins were measured on different pavement structures. The number of iterations were considerably less in each case. Typical results are presented in Appendix F in Figs F.3 to F.11. Each figure shows the measured and calculated deflection basins, and the corresponding elastic moduli of each layer for the pavement structure with infinite subgrade. The back calculation of elastic moduli for three-layer pavements was accomplished with a relatively fewer number of iterations.

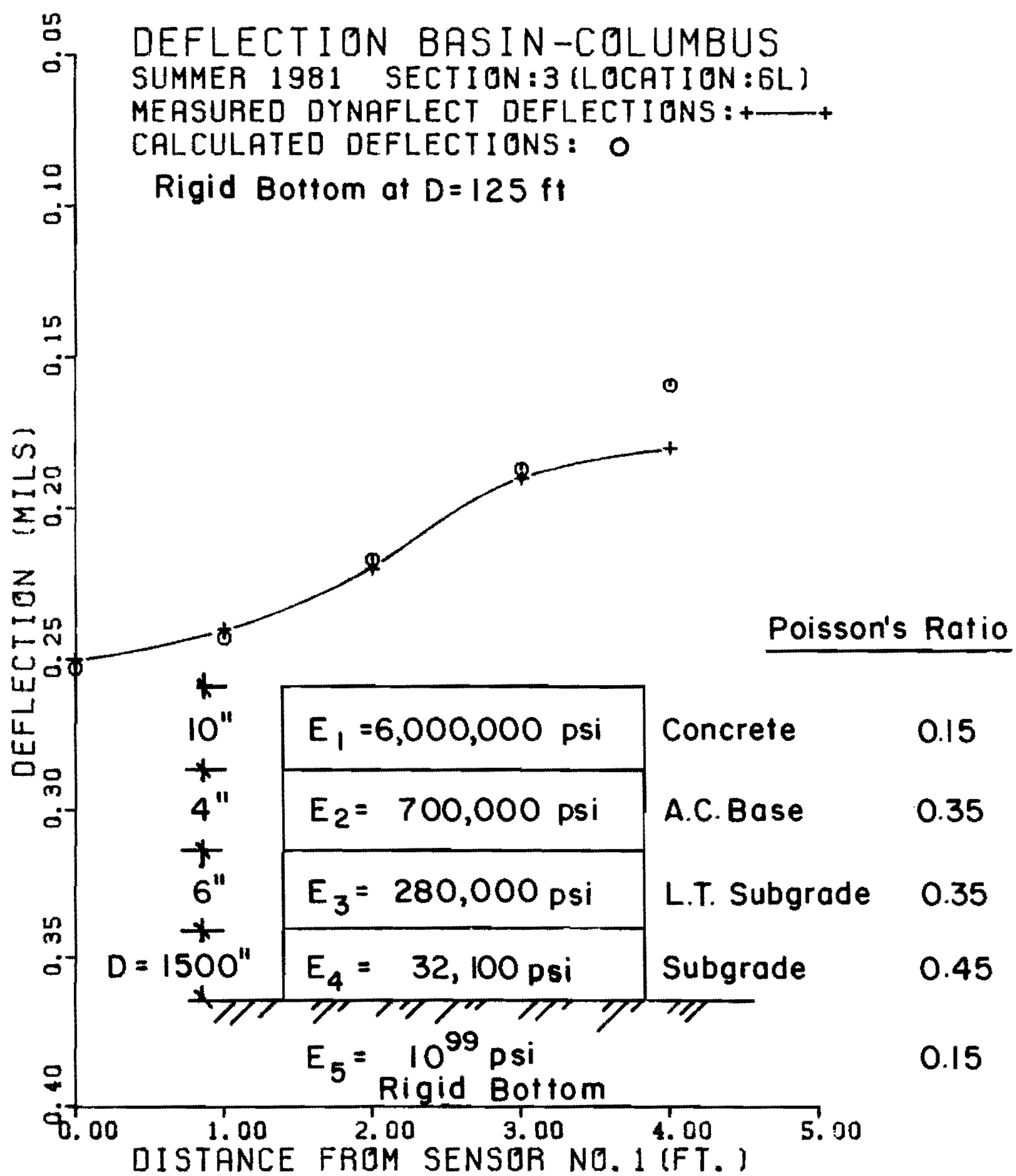


Fig 5.10. The back calculated Young's moduli (case of rigid bottom under 125 ft. of natural subgrade).

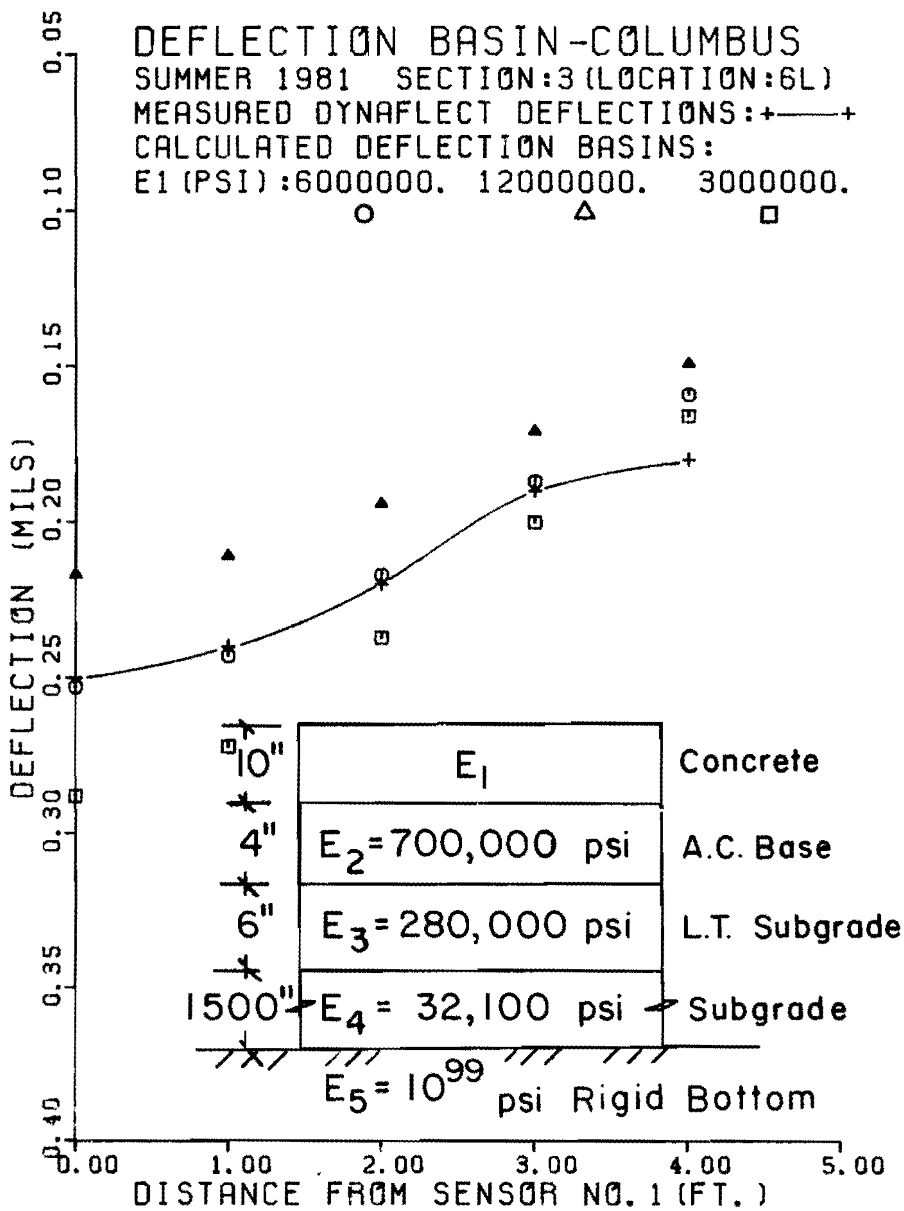


Fig 5.11. Effect of change of E_1 on calculated basin (case of rigid bottom).

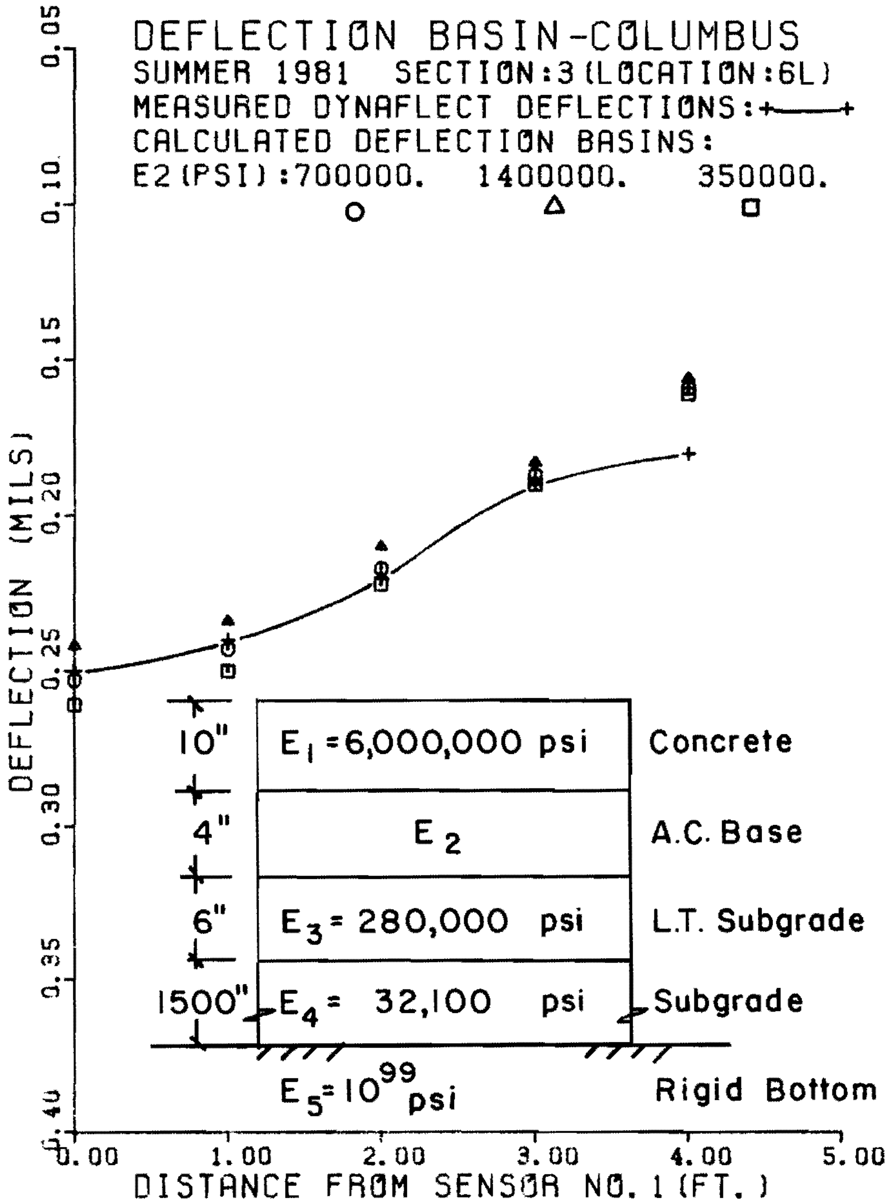


Fig 5.12. Effect of change of E_2 on calculated basin (case of rigid bottom).

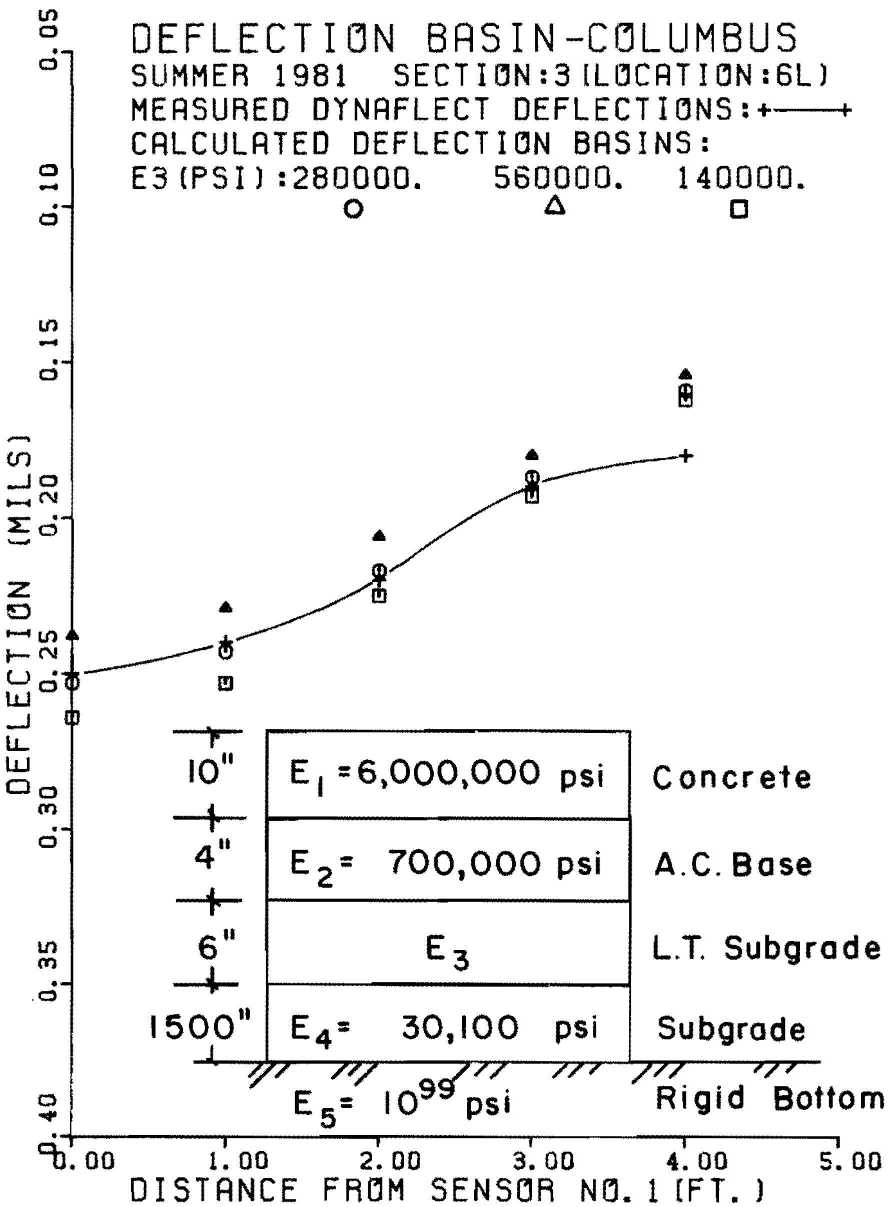


Fig 5.13. Effect of change of E_3 on calculated basins (case of rigid bottom).

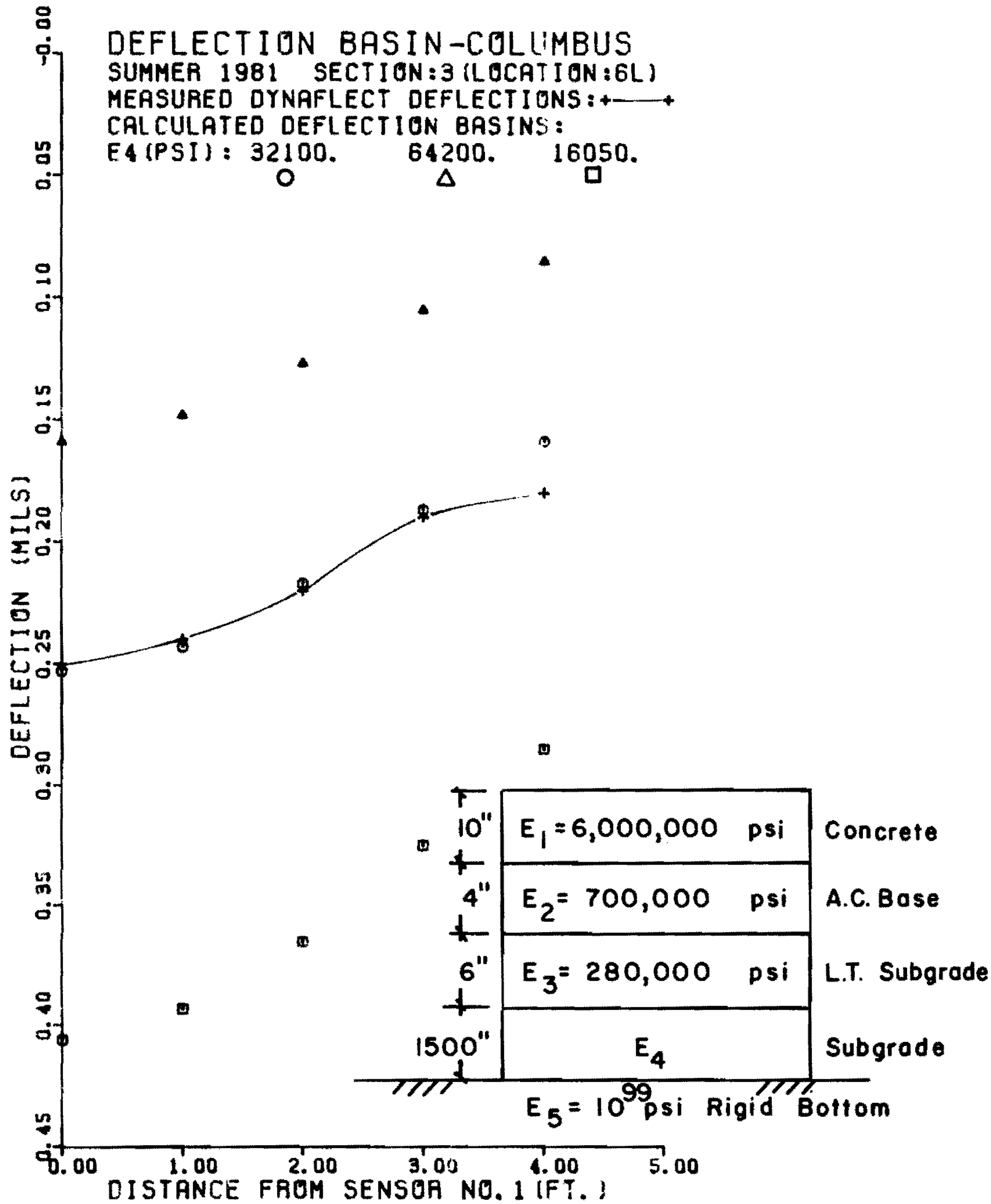


Fig 5.14. Effect of change of E_4 on calculated basin (case of rigid bottom).

SUMMARY

The pavement structural evaluation is commonly carried out by deflection surveys using nondestructive vibratory testing methods. The pavement response in terms of measured deflection basin provides a feasible source for in-situ material characterization of each pavement layer. This study was done to improve the understanding and ability of back calculation of elastic moduli from the measured deflection basin. The principal findings are stated below:

(1) The deflection basin is sensitive to any change in the elastic modulus of any of the pavement layers. Any changes in the moduli of subgrade and surface layers show marked effects on the deflection basin. The deflection basin is less sensitive to changes in the moduli of intermediate layers.

(2) Assumption of a rigid bottom at some finite thickness is realistic consideration. Three different approaches for selection of a finite thickness of the subgrade are presented and discussed. A rigid bottom at finite thickness influences the shape of the deflection basin that is more pronounced for thinner subgrades.

(3) Assumption of a rigid bottom at some finite thickness affects the final estimation of the subgrade elastic modulus. Considerable reduction in the subgrade modulus can be expected as the rigid bottom is moved toward the surface.

(4) Concepts from wave propagation theory in elastic media provide a rational approach to select the depth of the rigid bottom without the necessity to reduce the subgrade modulus to obtain the best fit of the measured deflection basin.

All the structures used in this study were rigid pavements. More deflection basins need to be analyzed to examine the shape of the measured deflection basins and to apply and expand the findings of this study. Furthermore, the present study should be extended to include the analysis of the deflection basins measured on flexible pavements.

CHAPTER 6. IN-SITU DETERMINATION OF DYNAMIC MODULI

INTRODUCTION

Many different methods have been proposed for evaluating the elastic properties of pavement systems. In-depth reviews of these methods, including their advantages and disadvantages, have been made by Lytton et al (Ref 14) and Nazarian and Stokoe (Ref 36). In this chapter the Spectral-Analysis-of surface-Waves (SASW) method for determining moduli and thicknesses of pavement systems is briefly presented, and the results of tests performed on SH-71, near Columbus, Texas, are presented. Despite the complicated theory behind this method, the testing procedure is simple, and a unique solution to the problem is obtained. The nondestructive nature of the SASW method and the minimal amount of time necessary to conduct this test are significant. The fact that it is possible to automate fully the method by means of microprocessors makes it even more promising.

Use of the SASW method in pavement systems was originated by Heisey et al (Ref 37) and now is under continuous development at The University of Texas at Austin. This chapter presents a summary of new refinements in collecting and analyzing the data and of three case histories. The moduli and layer thicknesses determined with the SASW method are shown to compare closely with results from borings and with seismic velocities determined by the crosshole seismic test. This is the first time that the SASW method has been used on a concrete pavement.

EVALUATION OF ELASTIC PROPERTIES FROM SEISMIC WAVES

Wave motion created by a disturbance within an infinite, homogeneous, isotropic, elastic half-space can be described by two kinds of seismic waves, body and surface (Ref 38). Body waves consist of shear (S) and compression (P) waves. Derivations of the mathematical relationships for obtaining elastic properties from P-wave velocity (V_P) and shear wave velocity (V_S) are presented in Ref 36. The most important relationships involve shear wave velocity and shear modulus (G) which are related by

$$G = \rho V_s^2 \tag{6.1}$$

and, Young's modulus (E) which can be written as

$$E = 2(1 + \nu) V_s^2 \tag{6.2}$$

where ρ and ν are mass density and Poisson's ratio, respectively. From Eqs 6.1 and 6.2, Young's modulus and/or shear modulus of the medium can be easily evaluated once the body wave velocity of the medium have been determined. For an isotropic material, P- and S-wave velocities are interrelated by Poisson's ratio by

$$\nu = \left[0.5 \, (V_p/V_s)^2 - 1 \right] \;/\; \left[(V_p/V_s)^2 - 1 \right] \tag{6.3}$$

The second kind of seismic wave is a surface wave, which is also called a Rayleigh wave (Ref 39). Rayleigh (R) wave velocity is constant in a homogeneous half-space and is independent of frequency. Each frequency has a corresponding wavelength according to

$$V_R = f \cdot L_R \tag{6.4}$$

where

V_R = Rayleigh wave velocity,

f = frequency of excitation, and

L_R = wavelength of R-wave.

Rayleigh wave velocity and shear wave velocity are related by Poisson's ratio. Although the ratio of R-wave to S-wave velocities increases as Poisson's ratio increases, the change in this ratio is not significant, and it can be assumed that the ratio is approximately equal to 0.90 without introducing an error larger than 5 percent.

SPECTRAL-ANALYSIS-OF-SURFACE-WAVES METHOD

The Spectral-Analysis-of-Surface-Waves (SASW) method is an economical and powerful method for evaluating elastic properties of pavement systems as well as natural soil deposits. The SASW method is a nondestructive test method in which both the source and receivers are placed on the pavement surface, and Rayleigh waves at low-strain levels are generated and detected (Ref 36).

Investigation of each site with the SASW method consists of the following three phases:

(1) field testing,

(2) determination of the R-wave dispersion curve, and

(3) inversion of the R-wave dispersion curve.

Brief discussions of these phases are presented in the following paragraphs.

Field Testing

A simplified illustration of the test procedure is shown in Fig 6.1. Two or more vertical geophones (velocity transducers) are located on the surface at the site. A transient signal is generated by an appropriate source. The generated wave front is detected by the geophones as it propagates past them and is recorded on the appropriate device.

In the SASW method, the area between the two receivers is important, and the properties of the materials between the source and the near geophone have little effect on the experiment. The two receivers are moved away from the imaginary centerline at an equal pace, and the source is moved such that the distance between the source and the near geophone is equal to the distance between the two receivers. This geometry of source and receivers is called the Common Receivers Midpoint (CRMP) geometry. Nazarian and Stokoe (Ref 36) have shown that use of the CRMP geometry in different tests reduces scatter at pavement sites.

Determination of R-wave Dispersion Curve

The variation of wave velocity with frequency (wavelength) is known as dispersion and a plot of velocity versus wavelength is called a dispersion curve. To determine a dispersion curve, SASW testing is performed at several geophone spacings. Since the distance between geophones at each spacing, X, is a known parameter, R-wave velocity (V_R) can be calculated from the travel time t(f) for a given frequency (f) from the crosspower spectrum (see Ref 36 for mathematical details). The relationship between V_R, X and t(f) is:

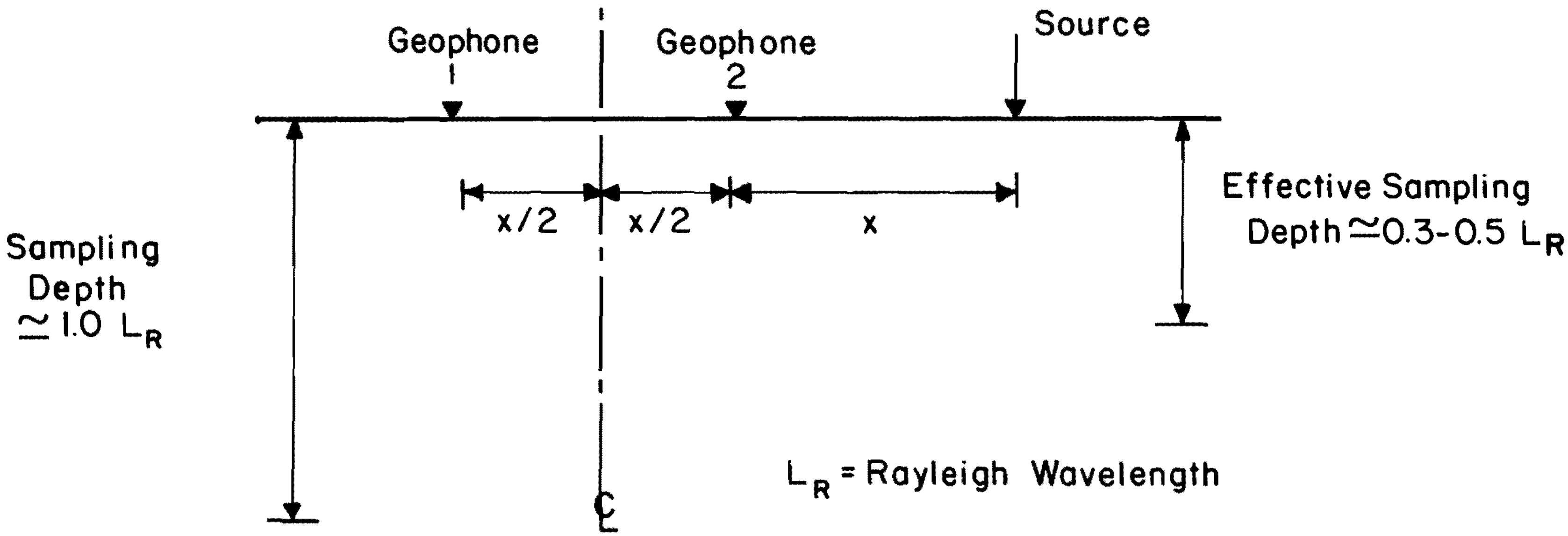


Fig 6.1. Schematic of Spectral-Analysis-of-Surface-Waves (SASW) Method.

$$V_R = X/t(f) \tag{6.5}$$

Wavelength of the R-wave at each frequency is then simply calculated from Eq 6.4. By repeating this procedure over the frequency range of interest, a dispersion curve is determined.

Inversion of R-wave Dispersion Curve

R-wave velocities determined by this method are not actual velocities of the separate layers but are the apparent R-wave velocities. Existance of a layer with very high or very low velocity at the surface of the medium affects measurement of the velocities of the underlying layers. The procedure of evaluating actual R-wave velocities from apparent R-wave velocities is termed inversion. The inversion process used in the present investigation is based upon Haskell's matrix (Ref 40) and is discussed in detail by Nazarian and Stokoe in Ref 36.

EXPERIMENT NEAR COLUMBUS, TEXAS

The SASW method was used on three sections with different layerings near Columbus, Texas. The selected site was located on SH-71 at station 1279 + 75, about half a mile south of the SH-71 overpass on US-90. The highway consists of two continuously reinforced concrete pavement (CRCP) lanes, each 12-feet wide, a 4-feet wide asphalt concrete (ACP) inside shoulder, a 10 feet CRC outside shoulder and a median (natural soil); as illustrated in Fig 2.16.

In August 1981, a preliminary set of SASW tests was conducted on all three sections (CRCP, ACP, and median) by Heisey. In March 1982, a second set of tests was performed at approximately the same location. In conjunction with these tests, a series of crosshole seismic tests were performed under the asphalt shoulder and median (Ref 36).

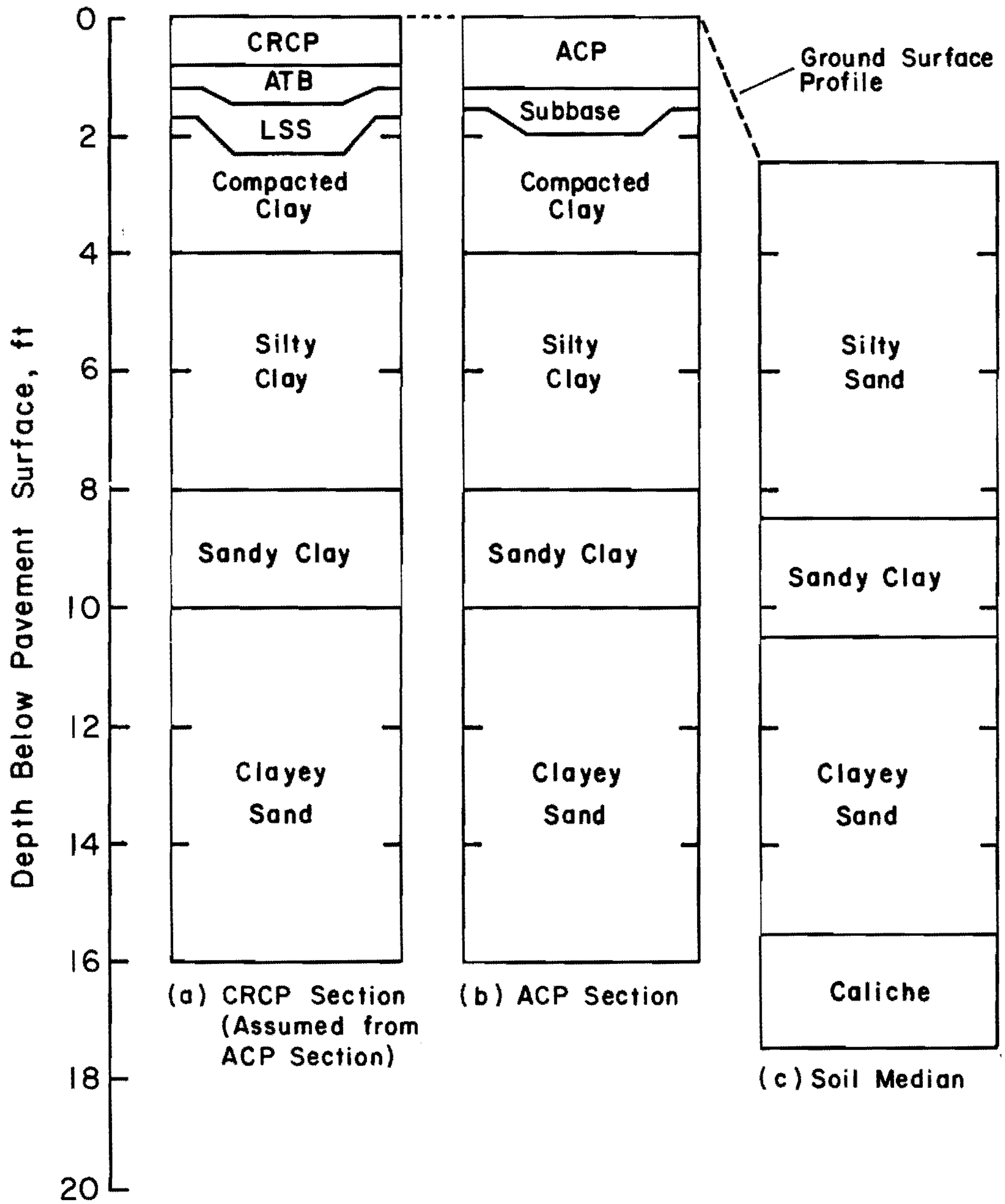
The soil profiles under the asphalt shoulder and median determined from the boreholes drilled for the crosshole tests are shown in Fig 6.2. It is assumed that the soil profile under the concrete and the asphalt sections are identical below the subbase. The assumed profile for CRCP section is also shown in Fig 6.2.

Setup and Procedure

The general configuration of the source, receivers, and recording equipment is shown in Fig 6.3. Vertical geophones with a natural frequency of about 8 Hz were used as receivers. The distance between the two geophones was doubled in each test about an imaginary centerline (CRMP method). The distance between geophones ranged from one to 16 feet. The distance between the source and near receive was always equal to the distance between the two receivers. In addition, the location of the source relative to the receivers was reversed for each test (i.e., the location of the source was changed without changing the position of the receivers so that the far receiver in the first test functioned as the near receiver in the second test. The closer spacings are appropriate for determining the properties of the shallower depths and the larger spacings for deeper layers.

REPRESENTATION OF RESULTS

The primary objective of the tests performed by SASW method was to evaluate the elastic properties and thicknesses of the different layers of the ACP and CRCP sections. As this method has been used very little on



CRCP = Continuously Reinforced Concrete Pavement
ATB = Asphaltic Concrete Base
LSS = Lime-Stabilized Subbase
ACP = Asphaltic Concrete Pavement

Fig 6.2. Soil profile under different test sections.

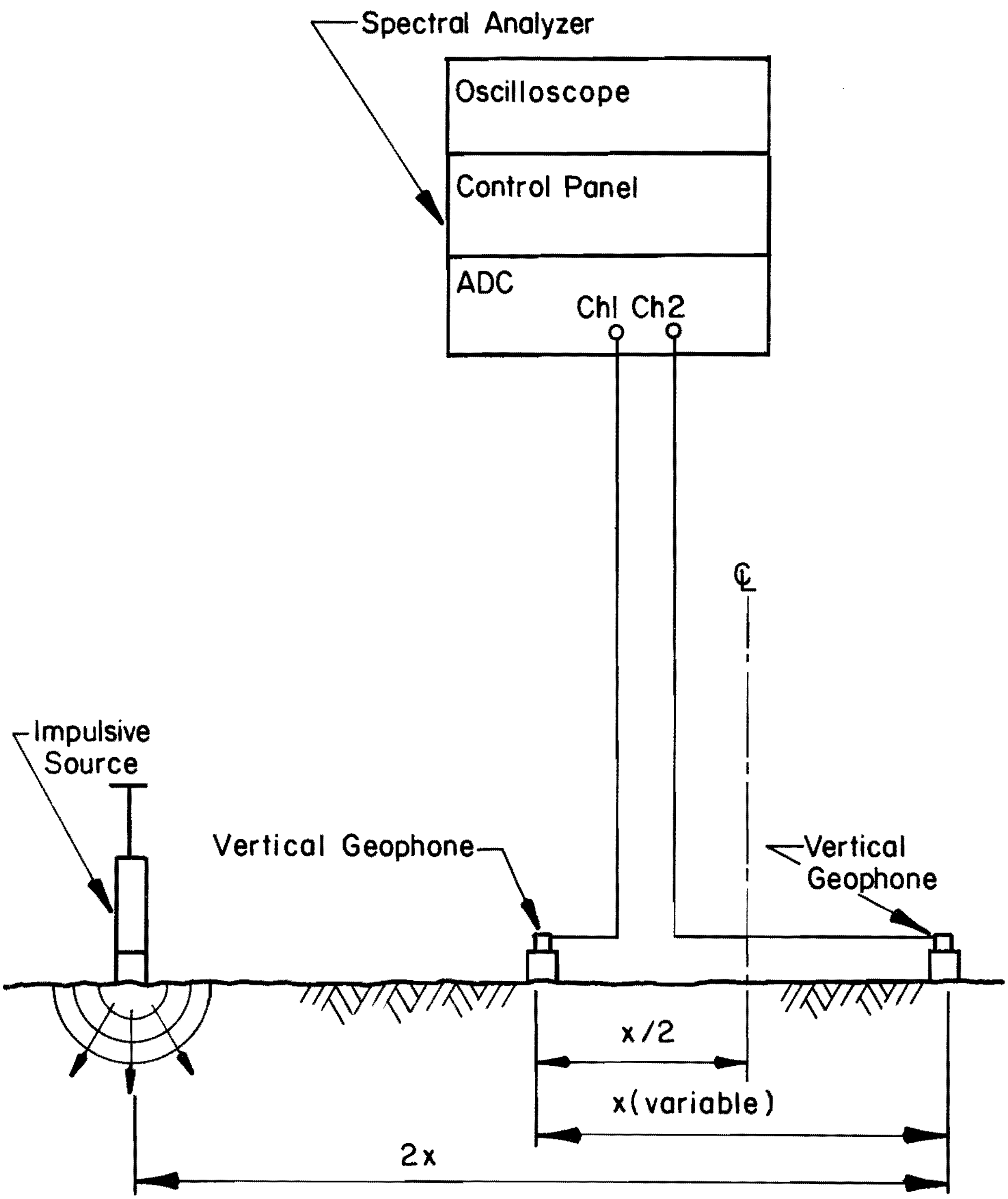


Fig 6.3. Schematic of Experimental Arrangement for SASW Tests.

pavement sections, the reproducibility of the results by different operators and for different attempts was of great concern. As such, the first series of tests was conducted by Heisey in August 1981, and the next two series were performed by the authors in March and May 1982. In addition, the SASW test was tried for the first time on a concrete pavement.

Soil Section (Median)

The dispersion curves for tests performed at this site in August 1981 are shown in Fig 6.4(a). Scatter in the data at high and low frequencies (short and long wavelengths) could be due to lateral inhomogeneity of soil properties. At low frequencies, scatter could also be due to the insensitivity of the receivers at these low frequencies. Overall, the maximum scatter is less than 15 percent.

The average dispersion curves of the tests performed in August 1981 and March 1982 are shown in Fig 6.4(c). Upon comparing these curves, it can be seen that there is no major difference in the results for wavelengths longer than 10 feet, with a maximum difference of 8 percent at a wavelength of about 36 feet. Determination of the average dispersion curve for the data from August 1981 was difficult because of scatter in the data. Due to extensive precipitation on the day before the tests were performed in March 1982, the first few feet of the median was very soft, causing a significant drop in the elastic properties of the near-surface material of this time. Thus, R-wave velocities of the near-surface layer are low, as shown in Fig 6.4(b).

Asphalt (ACP) Section

In the first attempt on the asphalt section in 1981, only two sets of data were gathered (geophone spacings of 4 and 8 feet) due to a malfunction of the equipment. These results are shown in Fig 6.5(a).

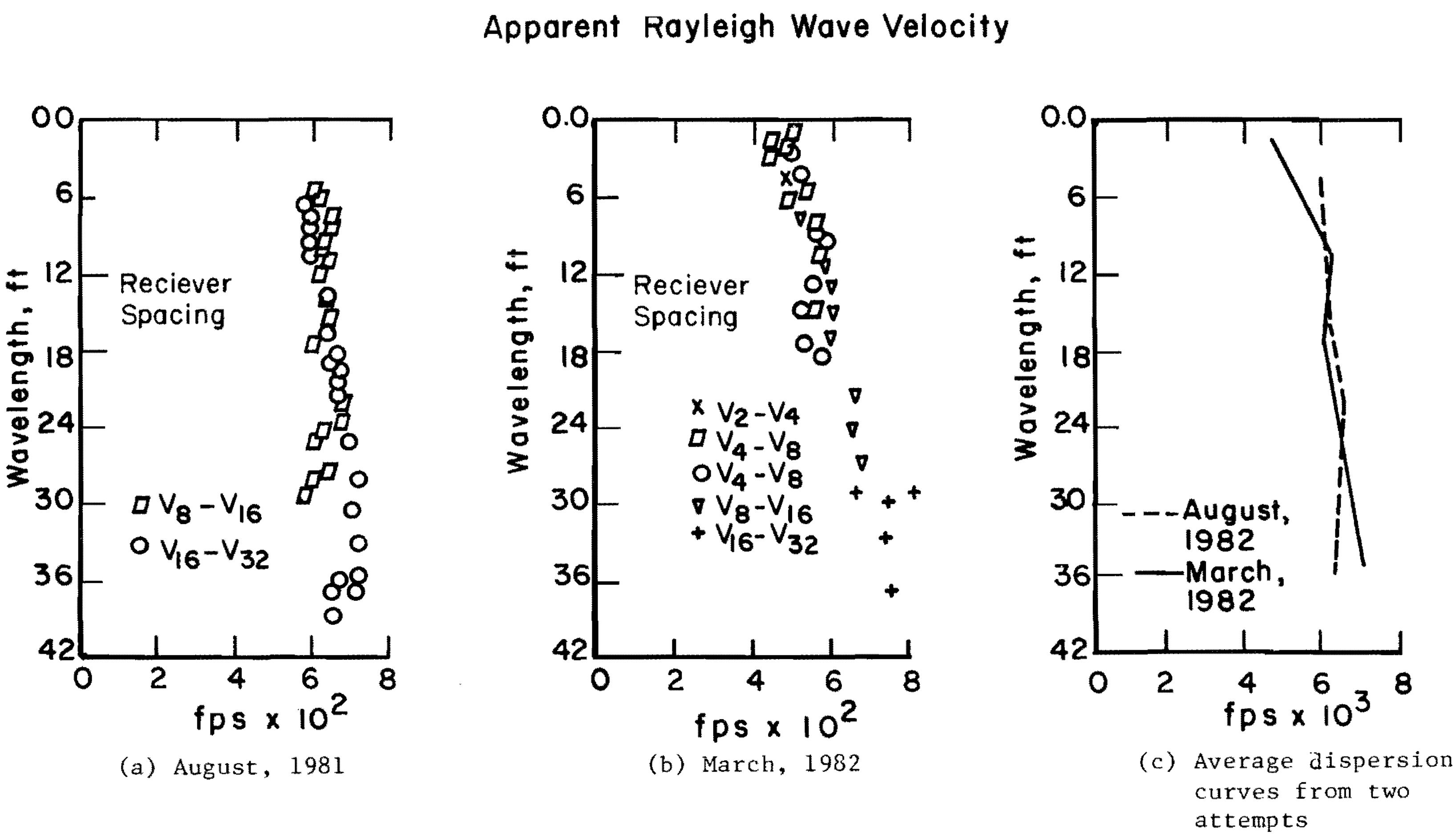
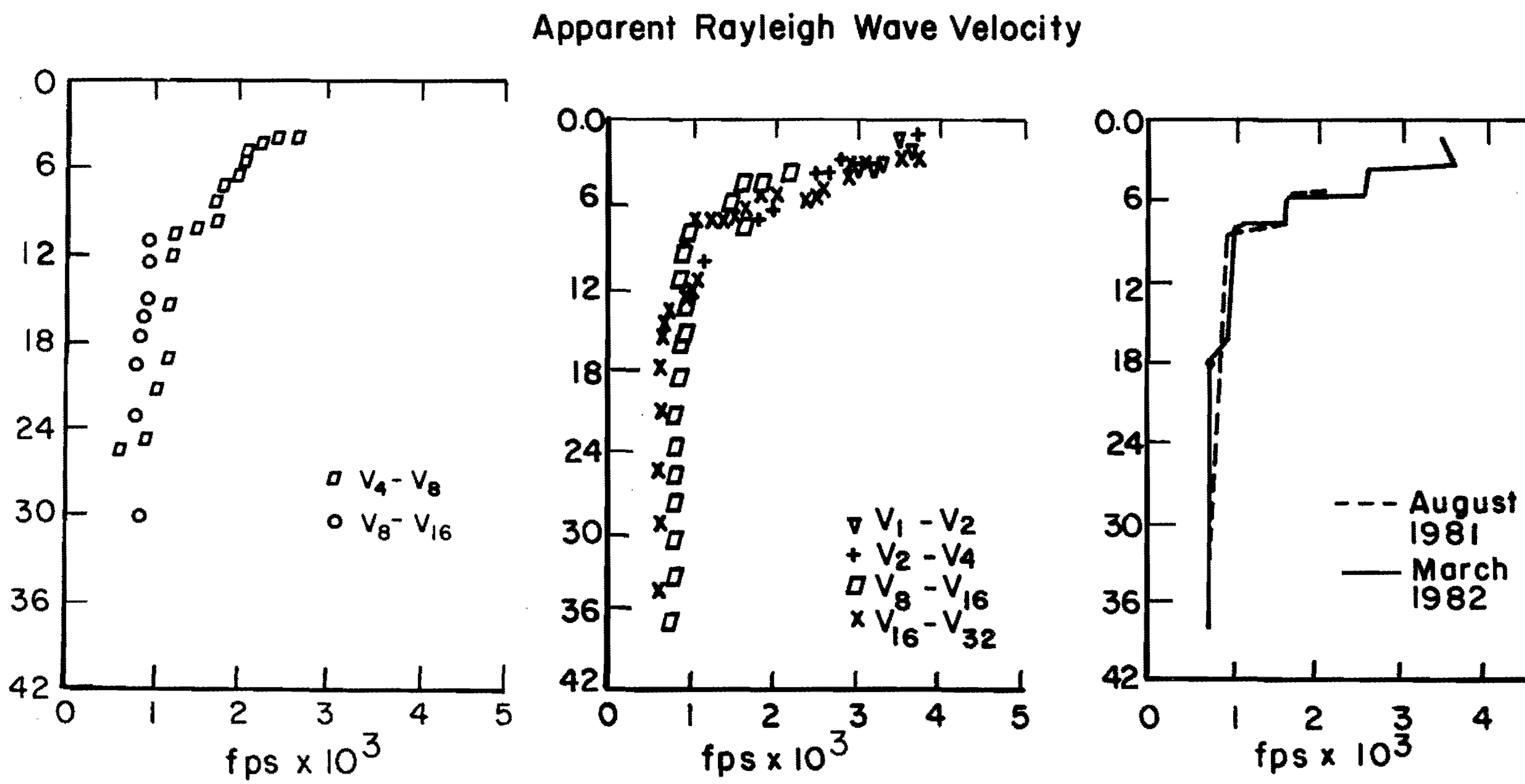


Fig 6.4. Dispersion curves for median.



(a) August, 1981

(b) March, 1982

(c) Average dispersion curves from two attempts

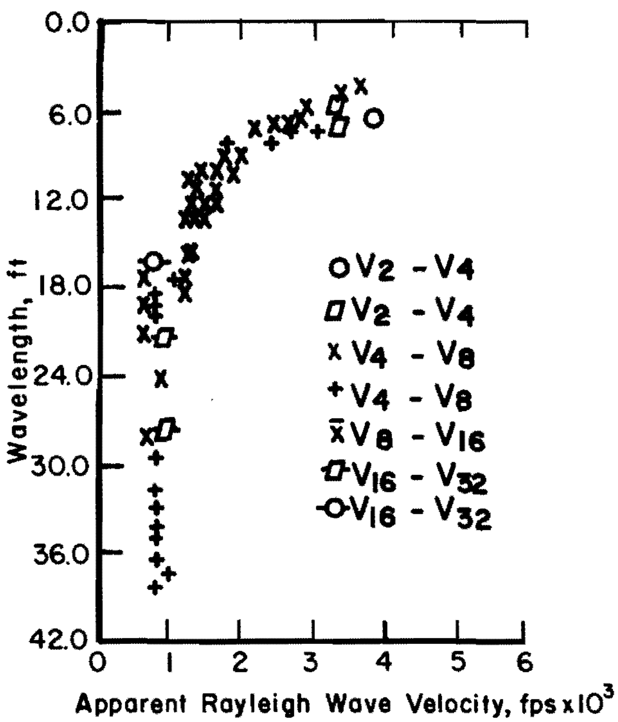
Fig 6.5. Dispersion curves for ACP section.

The dispersion curves for the experiments conducted on this section in March 1982 are shown in Fig 6.5(b). The thickness and apparent R-wave velocities for different layers from the 1981 and 1982 testing are in good agreement, and no significant differences can be detected in the average dispersion curves from the attempts, as shown in Fig 6.5(c). The relative difference between the two curves does not exceed 6 percent. Adequate high frequencies were not generated in the tests performed in 1981. Therefore, no sampling was done in the asphalt concrete layer in this series.

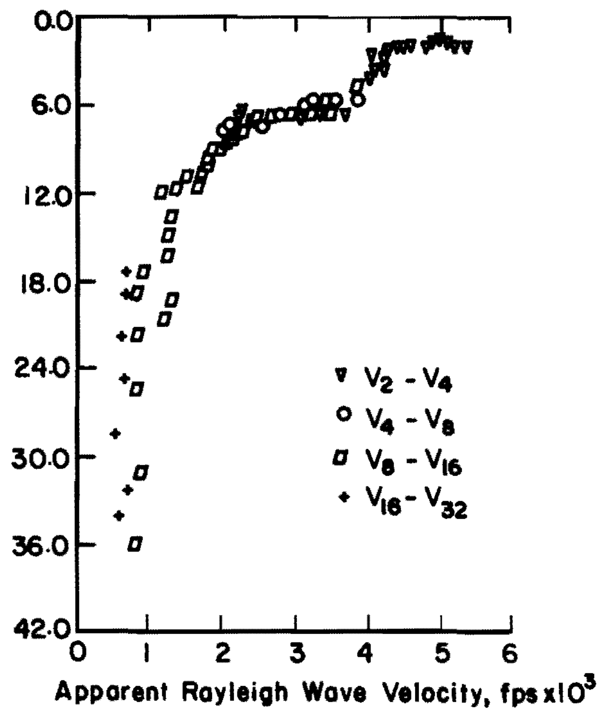
Concrete (CRCP) Section

The dispersion curves for the first attempt on the CRCP section in 1981 are shown in Fig 6.6(a). As high-frequency waves were not excited, no information on the properties of the concrete and base layers could be obtained. Dispersion curves for the tests performed in March 1982 are presented in Fig 6.6(b). The number of tests performed on this site in this set of tests was less than that in August 1981, due to time limitations. However, the two sets of dispersion curves compare closely in layering. The shortest wavelength obtained in the second attempt was approximately one foot (equivalent to an effective sampling depth of about 4 inches).

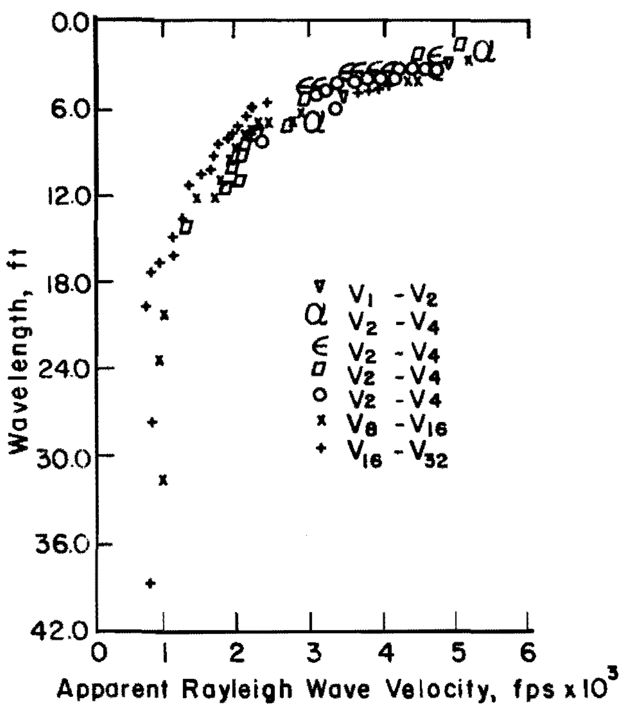
The primary concerns in the May 1982 testing at the CRCP section were to sample even shallower depths as well as to check the reproducibility of the results. Figure 6.6(c) shows the dispersion curves from these tests. Several tests with close spacings (spacing between the geophones equal to 1 and 2 feet) were performed and resulted in decreasing the depth of sampling to 3 inches. It should be mentioned that the highest frequency excited in this set was 3900 Hz, whereas in the first attempt it was 3100 Hz. The 800-Hz increase in the upper bond of the frequency content only decreased in the depth of sampling by about 1 inch.



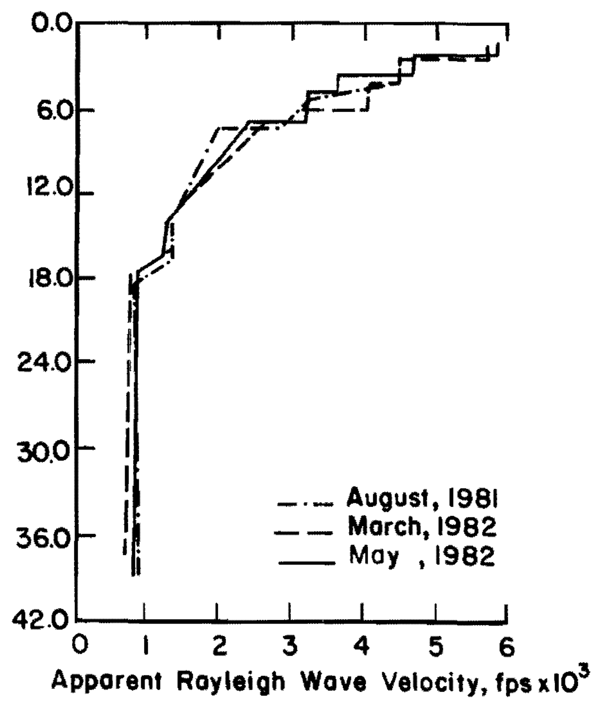
(a) August, 1981



(b) March, 1982



(c) May, 1982



(d) Average

Fig 6.6. Dispersion Curves for CRCP section.

Average dispersion curves obtained from the three attempts on the CRCP section are illustrated in Fig 6.6(d). Except for the range of wavelengths from 5 to 8 feet in which there is some scatter, these curves agree with less than a 9 percent difference. This deviation, which corresponds to the few inches above and below the boundary between the subbase and the compacted fill (wavelengths in 5 to 8 feet range), may be due to inaccuracy in leveling the fill before placement of the subbase during construction along the distance covered by the geophones. However, as great emphasis was placed on measurement of the pavement system in May 1982, the results of this series of tests seem more reliable.

The reproducibility of the tests is very good, as shown in Fig 6.6(d).

Evaluation of Elastic Properties

Profiles of Young's moduli determined from wave velocities measured at the three sections are shown in Fig 6.7. In crosshole tests, elastic moduli were calculated from the P-wave velocities measured in-situ (Eq 2.5 of Ref 36). In the case of the SASW tests, shear moduli were first determined from the shear wave velocities (Eq 6.1). Then, with values of Poisson's ratio evaluated from the crosshole tests (Eq 6.3), elastic moduli were calculated. Once again, it should be mentioned that these Poisson's ratios were lower than those generally found in static tests, because of the strain dependence of Poisson's ratio (Ref 36).

Upon comparing Young's moduli evaluated from the crosshole and SASW tests, very good agreement is found as shown in Fig 6.7. For the median, Young's moduli from the two methods differ by less than 11 percent, except for a depth of 5 feet, at which moduli from the two methods differ by about 30 percent. In the cases of the ACP and CRCP sections, variations in elastic

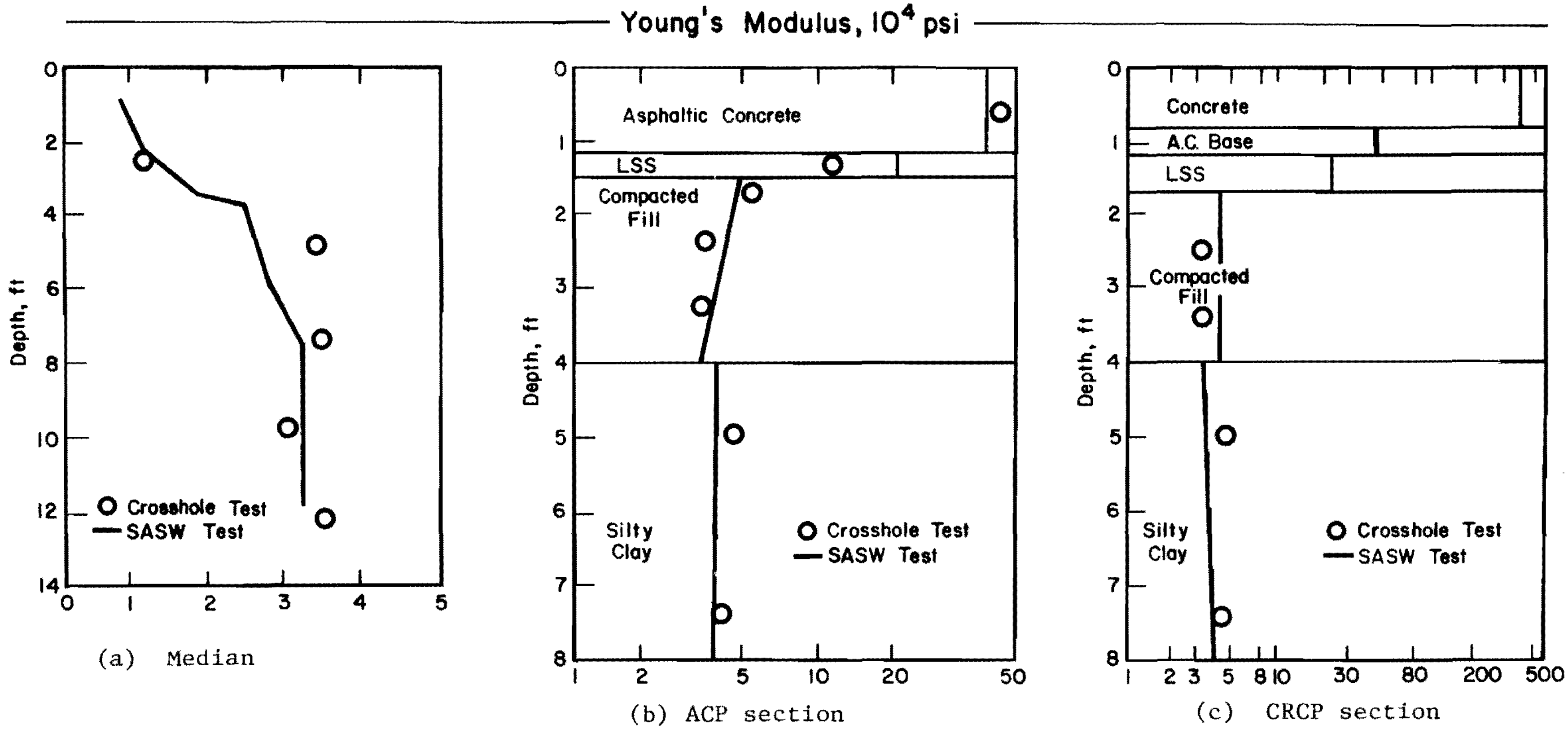


Fig 6.7. Comparison of Young's moduli from crosshole and SASW methods.

moduli are less than 13 and 20 percent, respectively. However, for the subbase in ACP and base in CRCP these moduli are significantly different. To solve this problem, a more refined and sophisticated inversion process is essential. Nevertheless, the close comparison between moduli by the two independent methods shows the value and potential of the SASW method.

Comparison of Insitu Dynamic and Static Elastic Moduli

Table 6.1 presents a comparison of Young's moduli calculated from SASW tests and static moduli back-calculated from the Dynaflect deflection basin. The static moduli were determined according to the procedure described in Chapter 5. The static modulus of the concrete surface layer is less than the dynamic modulus obtain from SASW tests. Lime stabilized and underlying natural soil layers show dynamic moduli larger than the corresponding static moduli.

TABLE 6.1. COMPARISON OF INSITU DYNAMIC AND STATIC ELASTIC MODULI AT CRCP SECTION

	Young's Modulus (psi)			
	SASW Method*	Static Analysis+		
Layer	May, 1982	Summer 1981	Fall 1981	Average
CRCP Surface	3,928,000	5,000,000	6,000,000	5,500,000
A. C. Base	462,380	400,000	400,000	400,000
Lime Stabilized Subgrade	223,380	150,000	100,000	125,000
Natural Subgrade (soil)	37,960 - 41,450 (up to 7.5 ft)	25,000	31,000	28,000

*Location of SASW test is in Section 2 (Fig 2.15)

+The Dynaflect deflection basin was measured on Location 6L, section 2 (Figs 2.18 and 2.20)

CHAPTER 7. SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

SUMMARY

Experimental data on the Dynaflect deflections on a CRC pavement and temperatures of the top and the bottom of concrete slab were collected with the objective of investigating the important location variables and temperature factors which influence the measured deflections on rigid pavements. Extensive statistical analyses of the data were performed to identify the important explanatory variables affecting the deflection parameters. A multiple regression technique was principally utilized considering the measured and dichotomous variables. The extent of errors expected in Dynaflect deflections due to positive temperature differential was also evaluated in relation to Dynaflect testing position. A procedure is suggested that can be used to calculate temperature parameters, given the thickness of concrete slab, thermal properties,and climatological data, such as solar radiation per day, maximum and minimum air temperature, and average wind speed.

The Dynaflect deflection basins measured at locations normally tested for material characterization were used in parametric studies to improve the procedure of back-calculation of elastic moduli. The surface-analysis-of-surface-waves method currently under development is also a nondestructive testing procedure for estimating insitu dynamic moduli. The SASW method and crosshole testing were also carried out on the same test site. A brief summary of these tests and their results is also included in this report.

CONCLUSIONS

The following conclusions are based on the analyses of the test data collected on a newly constructed CRC pavement in Columbus, Texas. Seasonal effects were not thoroughly investigated as the Dynaflect deflection data were not collected in all seasons.

Investigation Into Dynaflect Deflections

The principal conclusions regarding the effects of location and temperature variables on Dynaflect deflections measured on CRC pavements are summarized below.

(1) Dynaflect deflections are significantly affected by

  (a) position of Dynaflect with respect to transverse cracks,

  (b) distance of test locations from the pavement edge, and

  (c) the temperature differential.

(2) The effect of temperature differential on Dynaflect deflections varies with the position of Dynaflect.

  (a) For the Dynaflect located in the mid-span position (between transverse cracks) in the wheel path or at the center line of the slab, the measured deflections show a direct relationship with temperature differential.

  (b) For the Dynaflect positioned anywhere near the pavement edge, the measured deflections exhibit an inverse relationship with temperature differential.

(3) In the case of 2(a) the Dynaflect position corresponds to the the interior condition. The errors due to very high positive temperature differential (expected at Columbus site) on measured deflections and the back-calculated elastic moduli of the pavement layers are practically negligible.

(4) In the case of 2(b), the errors in measured deflections due to positive temperature differentials above 10°F are significantly high. This effect is more pronounced when the edge support is an asphaltic concrete shoulder or a gravel shoulder, as compared to a portland cement concrete shoulders.

(5) The temperature differential of a concrete slab is zero around 2 hours after sunrise. The maximum temperature differential occurs in the afternoon hours around 2 to 3 p.m.

(6) The deflection data obtained in this study on CRC pavement do not indicate any significant seasonal effects.

Back-Calculation of Elastic Moduli from Deflection Basin

The findings from this study are stated below.

(1) The deflection basin is very sensitive to any change in the assumed Young's moduli of subgrade and the concrete surface layers. For the same rate of change, the subgrade modulus results in relatively much larger changes in the deflection basin as compared to the effect of concrete surface modulus. These results hold for both an infinite subgrade and the case of a rigid bottom of some finite thickness.

(2) Assumption of a rigid bottom at some finite thickness affects the final estimate of subgrade modulus. Concepts from elastic wave propagation theory provide an acceptable criterion for selecting the depth to the rigid bottom when prior information about the existance of a rock bottom is unavailable.

Insitu Determination of Dynamic Moduli

The major conclusions arrived at from the field tests of the SASW method and crosshole tests are state below.

(1) The Common Receivers Midpoint (CRMP) geometry utilized in SASW tests has resulted in less scatter in the data.

(2) A refined inversion program has been successfully used to determine the actual propagation velocity of Rayleigh waves at different depths from the measured dispersion curve.

(3) The Young's moduli calculated from SASW and crosshole tests compare very well for

   (a) soil layers in the median,

   (b) all layers in an asphaltic concrete shoulder except for a lime stabilized subgrade layer, and

(4) The dynamic modulus of a CRC layer determined from the SASW method is smaller than the static elastic moduli back-calculated from the Dynaflect deflection basin. The dynamic moduli of lime stabilized subgrade and natural subgrade layers are much larger than the

corresponding static Young's moduli. There is not enough data to determine the correlation between the two test procedures.

RECOMMENDATIONS

Dynaflect deflections are measured as a standard procedure for structural evaluation of existing pavement. For rigid pavement, deflections are measured for insitu material characterization and for void detection under pavement edges. Based on the findings of the present study the following recommendations are made to remove the influence of temperature differential in the surface concrete layer on measured Dynaflect deflections.

(1) Dynaflect deflection measurements should begin at least 2 hours after sunrise in order to avoid any deflection measurements under negative temperature differential conditions.

(2) For material characterization, Dynaflect deflection data should be obtained in the mid-span position (between the transverse cracks) in the wheel path or at the center line of the slab. Therefore the data do not need to be corrected for any positive temperature differential within the range observed in this study.

(3) For void detection purposes, Dynaflect deflections should be measured near the pavement edge and the data should be corrected to correspond to the deflection in the standard condition, i.e., at a zero temperature differential. The procedure outlined in Chapter 4 should be used to predict the temperature differential from weather data to apply corrections to measured deflection.

It is recommended that deflection data be obtained for similar analyses in CRC pavements of different structures and on JRC pavements.

It is also recommended to extend the continuing study on measurements existing procedures of obtain static Young's moduli of pavement layers from measured Dynaflect deflection basins.

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APPENDIX A

SUMMARY OF DYNAFLECT DEFLECTIONS AND TEMPERATURE DATA

APPENDIX A. SUMMARY OF DYNAFLECT DEFLECTION AND TEMPERATURE DATA

Summaries of Dynaflect deflections and temperature data for the concrete slab are contained in the following pages. The data were gathered on the southbound lanes of the Columbus bypass, SH-71 in Texas.

The data collected in the Summer of 1981 are summarized in the first four pages and followed by the summary data for the Fall 1981.

DYNAFLECT DEFLECTION AND TEMP. DATA (COLUMBUS,TX)-SUMMER 1981

SECTION- LOCATION	TIME		DEFLECTION(MILS) AT SENSORS W1	W2	W3	W4	W5	DT. DEG.F	TMID. DEG.F
1 - 1L	12:13PM	06AUG	.30	.27	.23	.18	.17	16.0	102.2
1 - 2L	12:15PM		.29	.24	.24	.19	.17	17.2	102.1
1 - 3L	12:17PM		.25	.23	.21	.16	.15	17.0	102.1
1 - 4L	12:18PM		.28	.26	.23	.18	.16	17.0	102.1
1 - 5L	12:20PM		.22	.21	.17	.15	.14	16.8	102.4
1 - 6L	12:22PM		.23	.22	.23	.16	.15	17.2	102.8
1 - 7L	12:24PM		.24	.22	.20	.16	.15	18.2	103.3
1 - 8L	12:25PM		.24	.23	.21	.16	.15	18.4	103.8
1 - 9L	12:28PM		.24	.22	.21	.16	.15	19.1	103.9
1 -10L	12:29PM		.25	.21	.21	.18	.17	19.2	104.0
1 -11L	12:31PM		.23	.21	.19	.15	.14	19.3	104.2
1 -12L	12:32PM		.21	.21	.18	.15	.14	19.9	104.3
1 -13L	12:37PM		.31	.29	.26	.20	.18	20.3	105.1
1 -14L	12:38PM		.29	.27	.24	.19	.18	21.2	105.1
2 - 1L	1:15PM		.29	.28	.24	.20	.18	24.0	108.1
2 - 2L	1:16PM		.29	.28	.25	.20	.18	24.8	108.1
2 - 3L	1:18PM		.27	.25	.23	.19	.17	23.9	108.1
2 - 4L	1:19PM		.26	.25	.23	.19	.17	23.8	108.2
2 - 5L	1:21PM		.37	.33	.30	.25	.23	23.7	108.2
2 - 6L	1:22PM		.33	.32	.29	.25	.23	23.6	108.2
2 - 7L	1:24PM		.37	.35	.32	.28	.25	23.6	108.4
2 - 8L	1:25PM		.36	.35	.32	.28	.25	24.0	108.5
2 - 9L	1:27PM		.36	.34	.32	.26	.25	24.0	108.6
2 -10L	1:28PM		.36	.35	.32	.27	.25	24.1	108.8
2 -11L	1:30PM		.32	.31	.29	.25	.23	24.1	109.0
2 -12L	1:31PM		.33	.32	.30	.25	.23	24.2	109.1
2 -13L	1:33PM		.40	.38	.35	.29	.26	24.3	109.2
2 -14L	1:34PM		.41	.41	.36	.30	.27	24.4	109.0
3 - 1L	2:15PM		.27	.26	.24	.20	.19	22.1	109.7
3 - 2L	2:17PM		.28	.26	.24	.20	.19	21.7	109.8
3 - 3L	2:18PM		.25	.24	.22	.19	.18	21.0	109.8
3 - 4L	2:21PM		.28	.27	.24	.21	.20	20.8	109.8
3 - 5L	2:23PM		.24	.22	.21	.18	.17	20.7	109.6
3 - 6L	2:24PM		.23	.22	.21	.18	.17	19.5	109.2
3 - 7L	2:26PM		.23	.22	.21	.18	.17	19.0	109.3
3 - 8L	2:27PM		.25	.24	.23	.20	.18	19.4	109.5
3 - 9L	2:32PM		.26	.23	.22	.19	.18	20.0	110.0
3 -10L	2:33PM		.23	.22	.21	.19	.18	20.1	110.3
3 -11L	2:36PM		.28	.27	.26	.21	.20	21.2	110.8
3 -12L	2:37PM		.28	.27	.26	.22	.21	21.3	110.9
3 -13L	2:39PM		.38	.36	.33	.27	.25	21.4	110.9
3 -14L	2:41PM		.35	.34	.31	.26	.25	21.5	111.0

DYNAFLECT DEFLECTION AND TEMP. DATA (COLUMBUS,TX)-SUMMER 1981

SECTION- LOCATION	TIME	DEFLECTION(MILS) AT SENSORS W1	W2	W3	W4	W5	DT. DEG.F	TMID. DEG.F
1 - 1L	7:38AM 07AUG	.45	.40	.33	.24	.19	-5.0	88.0
1 - 2L	7:41AM	.34	.33	.30	.23	.19	-4.9	88.0
1 - 3L	7:42AM	.29	.26	.24	.17	.15	-4.9	88.0
1 - 4L	7:43AM	.23	.22	.21	.17	.15	-4.9	88.0
1 - 5L	7:59AM	.24	.22	.21	.18	.14	-4.6	87.9
1 - 6L	8:00AM	.22	.21	.20	.18	.14	-4.5	87.9
1 - 7L	8:01AM	.27	.24	.23	.17	.15	-4.5	87.9
1 - 8L	8:02AM	.24	.23	.21	.17	.15	-4.5	87.9
1 - 9L	8:03AM	.34	.30	.27	.20	.17	-4.4	87.8
1 -10L	8:04AM	.26	.24	.23	.18	.16	-4.4	87.8
1 -11L	8:05AM	.30	.26	.24	.18	.15	-4.3	87.8
1 -12L	8:05AM	.25	.24	.23	.18	.16	-4.3	87.8
1 -13L	8:07AM	.42	.36	.32	.24	.20	-4.3	87.8
1 -14L	8:08AM	.34	.32	.31	.24	.21	-4.3	87.8
2 - 1L	8:33AM	.42	.37	.33	.25	.21	-4.0	87.9
2 - 2L	8:34AM	.37	.33	.31	.24	.21	-4.0	87.9
2 - 3L	8:35AM	.33	.29	.27	.21	.17	-4.0	87.9
2 - 4L	8:36AM	.29	.26	.25	.20	.17	-4.0	87.9
2 - 5L	8:37AM	.39	.31	.29	.23	.19	-3.9	87.9
2 - 6L	8:38AM	.25	.24	.23	.19	.17	-3.9	87.9
2 - 7L	8:39AM	.34	.30	.28	.22	.19	-3.9	87.9
2 - 8L	8:41AM	.25	.24	.23	.20	.17	-3.9	87.9
2 - 9L	8:42AM	.33	.30	.28	.22	.20	-3.9	87.9
2 -10L	8:42AM	.25	.24	.23	.19	.18	-3.9	87.9
2 -11L	8:43AM	.62	.52	.48	.39	.32	-3.9	87.9
2 -12L	8:44AM	.42	.40	.39	.33	.29	-3.9	87.9
2 -13L	8:45AM	.86	.77	.68	.55	.46	-3.8	87.9
2 -14L	8:46AM	.66	.63	.60	.50	.43	-3.8	87.9
3 - 1L	9:28AM	.38	.33	.30	.29	.22	-2.6	88.5
3 - 2L	9:28AM	.32	.31	.30	.29	.22	-2.6	88.5
3 - 3L	9:30AM	.27	.25	.24	.19	.18	-2.5	88.5
3 - 4L	9:30AM	.23	.22	.22	.18	.18	-2.5	88.5
3 - 5L	9:31AM	.24	.21	.20	.17	.16	-2.5	88.5
3 - 6L	9:32AM	.25	.24	.22	.19	.18	-2.4	88.5
3 - 7L	9:33AM	.24	.22	.21	.17	.16	-2.4	88.6
3 - 8L	9:34AM	.22	.21	.21	.17	.16	-2.3	88.6
3 - 9L	9:38AM	.25	.23	.22	.18	.17	-2.2	88.6
3 -10L	9:39AM	.22	.21	.21	.17	.16	-2.1	88.6
3 -11L	9:42AM	.51	.44	.41	.33	.28	-2.0	88.7
3 -12L	9:43AM	.38	.37	.36	.31	.28	-1.9	88.7
3 -13L	9:45AM	.84	.70	.62	.49	.39	-1.9	88.7
3 -14L	9:46AM	.58	.53	.51	.44	.37	-1.8	88.8

DYNAFLECT DEFLECTION AND TEMP. DATA (COLUMBUS,TX)-SUMMER 1981

SECTION-LOCATION	TIME		DEFLECTION(MILS) AT SENSORS W1	W2	W3	W4	W5	DT. DEG.F	TMID. DEG.F
1 - 1L	10:26AM	07AUG	.41	.32	.28	.20	.17	0.0	89.5
1 - 2L	10:27AM		.31	.29	.27	.20	.17	0.0	89.5
1 - 3L	10:28AM		.28	.26	.23	.17	.15	0.0	89.5
1 - 4L	10:29AM		.25	.23	.22	.17	.15	0.0	89.6
1 - 5L	10:30AM		.26	.24	.22	.16	.15	0.1	89.6
1 - 6L	10:31AM		.22	.21	.20	.16	.15	0.1	89.6
1 - 7L	10:32AM		.27	.24	.22	.16	.15	0.1	89.6
1 - 8L	10:32AM		.23	.22	.21	.16	.15	0.1	89.6
1 - 9L	10:34AM		.30	.26	.24	.18	.17	0.2	89.7
1 -10L	10:35AM		.26	.25	.23	.18	.17	0.2	89.7
1 -11L	10:37AM		.27	.24	.23	.17	.16	0.2	89.7
1 -12L	10:38AM		.22	.21	.20	.16	.15	0.2	89.7
1 -13L	10:39AM		.33	.29	.27	.20	.18	0.3	89.8
1 -14L	10:39AM		.29	.27	.26	.20	.18	0.3	89.8
2 - 1L	10:57AM		.44	.35	.30	.23	.20	0.5	90.0
2 - 2L	10:58AM		.41	.30	.28	.22	.20	0.5	90.1
2 - 3L	10:59AM		.31	.26	.25	.19	.18	0.5	90.1
2 - 4L	10:59AM		.26	.24	.23	.18	.17	0.5	90.1
2 - 5L	11:01AM		.33	.30	.29	.23	.22	0.6	90.1
2 - 6L	11:01AM		.28	.27	.26	.22	.21	0.6	90.1
2 - 7L	11:02AM		.33	.30	.29	.23	.22	0.7	90.2
2 - 8L	11:06AM		.29	.28	.27	.22	.21	1.0	90.4
2 - 9L	11:07AM		.31	.29	.28	.23	.21	1.1	90.5
2 -10L	11:07AM		.29	.28	.27	.22	.21	1.1	90.5
2 -11L	11:08AM		.36	.35	.32	.27	.25	1.1	90.6
2 -12L	11:10AM		.34	.32	.31	.25	.24	1.2	90.6
2 -13L	11:11AM		.55	.48	.45	.36	.33	1.4	90.7
2 -14L	11:12AM		.50	.45	.42	.34	.31	1.5	90.8
3 - 1L	11:50AM		.30	.28	.26	.22	.21	4.0	92.7
3 - 2L	11:51AM		.29	.28	.26	.22	.20	4.1	92.8
3 - 3L	11:52AM		.24	.23	.22	.18	.17	4.1	92.9
3 - 4L	11:53AM		.23	.22	.22	.18	.17	4.1	93.0
3 - 5L	11:54AM		.22	.21	.20	.17	.16	4.2	93.0
3 - 6L	11:55AM		.21	.21	.20	.17	.16	4.3	93.1
3 - 7L	11:56AM		.23	.22	.21	.17	.17	4.3	93.2
3 - 8L	11:57AM		.23	.22	.22	.18	.18	4.4	93.2
3 - 9L	11:59AM		.24	.22	.22	.18	.18	4.4	93.3
3 -10L	12:00PM		.23	.22	.21	.18	.18	4.5	93.3
3 -11L	12:01PM		.30	.28	.27	.22	.21	4.5	93.4
3 -12L	12:02PM		.29	.28	.27	.23	.21	4.6	93.4
3 -13L	12:03PM		.42	.38	.35	.26	.26	4.7	93.5
3 -14L	12:03PM		.40	.38	.36	.30	.27	4.7	93.5

DYNAFLECT DEFLECTION AND TEMP. DATA (COLUMBUS,TX)-SUMMER 1981

SECTION-LOCATION	TIME		DEFLECTION(MILS) AT SENSORS W1	W2	W3	W4	W5	DT, DEG,F	TMID, DEG,F
1 - 1L	1:53PM	07AUG	.28	.25	.23	.18	.16	10.9	99.8
1 - 2L	1:54PM		.28	.27	.24	.19	.17	10.9	99.9
1 - 3L	1:56PM		.24	.23	.21	.17	.16	11.0	100.0
1 - 4L	1:57PM		.27	.25	.23	.18	.17	11.0	100.1
1 - 5L	1:59PM		.23	.22	.20	.16	.15	11.1	100.2
1 - 6L	1:59PM		.24	.23	.20	.17	.16	11.1	100.2
1 - 7L	2:00PM		.23	.22	.18	.16	.15	11.2	100.2
1 - 8L	2:01PM		.23	.22	.20	.17	.15	11.2	100.3
1 - 9L	2:02PM		.23	.22	.20	.17	.16	11.2	100.3
1 -10L	2:03PM		.24	.23	.21	.17	.16	11.3	100.4
1 -11L	2:05PM		.22	.21	.19	.16	.14	11.3	100.5
1 -12L	2:06PM		.22	.21	.19	.16	.15	11.3	100.6
1 -13L	2:07PM		.28	.24	.22	.18	.17	11.4	100.7
1 -14L	2:08PM		.24	.23	.21	.17	.16	11.4	100.8
2 - 1L	2:24PM		.31	.29	.27	.22	.19	12.1	101.9
2 - 2L	2:24PM		.30	.27	.26	.20	.19	12.1	101.9
2 - 3L	2:25PM		.27	.25	.24	.20	.18	12.1	102.0
2 - 4L	2:26PM		.26	.25	.24	.19	.18	12.2	102.0
2 - 5L	2:28PM		.34	.33	.31	.26	.24	12.3	102.1
2 - 6L	2:28PM		.34	.33	.32	.27	.24	12.3	102.1
2 - 7L	2:29PM		.38	.36	.35	.29	.27	12.4	102.2
2 - 8L	2:30PM		.37	.36	.34	.28	.26	12.4	102.3
2 - 9L	2:32PM		.37	.36	.34	.29	.27	12.4	102.4
2 -10L	2:32PM		.37	.36	.34	.30	.26	12.4	102.4
2 -11L	2:33PM		.33	.32	.31	.27	.24	12.5	102.5
2 -12L	2:34PM		.34	.33	.31	.26	.23	12.5	102.6
2 -13L	2:36PM		.44	.41	.39	.32	.29	12.6	102.6
2 -14L	2:36PM		.45	.42	.39	.33	.29	12.6	102.6
3 - 1L	3:15PM		.27	.26	.24	.21	.20	13.6	104.6
3 - 2L	3:16PM		.28	.26	.25	.23	.20	13.6	104.6
3 - 3L	3:17PM		.25	.23	.22	.19	.18	13.6	104.7
3 - 4L	3:17PM		.24	.23	.22	.19	.18	13.6	104.7
3 - 5L	3:18PM		.22	.21	.20	.17	.17	13.7	104.7
3 - 6L	3:19PM		.22	.22	.21	.18	.17	13.7	104.7
3 - 7L	3:21PM		.23	.22	.22	.19	.19	13.7	104.8
3 - 8L	3:22PM		.23	.22	.22	.19	.19	13.8	104.8
3 - 9L	3:24PM		.24	.23	.22	.19	.19	13.8	104.9
3 -10L	3:24PM		.24	.23	.23	.19	.19	13.8	104.9
3 -11L	3:26PM		.28	.27	.26	.22	.21	13.9	105.0
3 -12L	3:27PM		.28	.27	.26	.22	.21	13.9	105.0
3 -13L	3:28PM		.35	.34	.32	.27	.25	14.0	105.1
3 -14L	3:28PM		.36	.34	.33	.27	.26	14.0	105.1

DYNAFLECT DEFLECTION AND TEMP. DATA (COLUMBUS,TX) - FALL 1981

SECTION- LOCATION	TIME		DEFLECTION(MILS) AT SENSORS W1	W2	W3	W4	W5	SLAB TEMP. DEG.F TOP	BOTTOM
3 - 1L	12:54PM	30NOV	.34	.30	.27	.22	.20	71.5	63.0
3 - 2L	12:55PM		.30	.27	.25	.21	.19	71.5	63.0
3 - 3L	12:58PM		.26	.24	.22	.18	.17	71.5	63.5
3 - 4L	12:59PM		.25	.23	.21	.18	.17	71.5	63.5
3 - 5L	1:00PM		.24	.22	.20	.17	.16	71.5	63.5
3 - 6L	1:01PM		.24	.22	.19	.17	.16	71.5	63.5
3 - 7L	1:05PM		.26	.23	.21	.18	.17	72.0	63.5
3 - 8L	1:06PM		.24	.22	.20	.17	.16	72.0	63.5
3 - 9L	1:08PM		.27	.24	.22	.19	.17	72.5	64.0
3 -10L	1:09PM		.25	.23	.21	.18	.17	72.5	64.0
3 -11L	1:12PM		.33	.29	.25	.22	.20	73.0	64.0
3 -12L	1:13PM		.30	.28	.25	.22	.20	73.0	64.0
2 - 1L	2:07PM		.35	.30	.26	.21	.18	74.0	65.0
2 - 2L	2:08PM		.31	.28	.24	.21	.18	74.0	65.0
2 - 3L	2:14PM		.29	.25	.22	.19	.16	73.5	65.0
2 - 4L	2:15PM		.27	.24	.22	.18	.16	73.5	65.0
2 - 5L	2:03PM		.38	.33	.29	.24	.21	74.0	65.0
2 - 6L	2:03PM		.32	.28	.26	.21	.18	74.0	65.0
2 - 7L	1:59PM		.38	.33	.28	.23	.20	74.0	64.5
2 - 8L	1:59PM		.31	.28	.26	.21	.18	74.0	64.5
2 - 9L	1:52PM		.38	.32	.28	.23	.20	73.5	64.5
2 -10L	1:57PM		.30	.27	.24	.20	.18	74.0	64.5
2 -11L	1:42PM		.34	.30	.27	.23	.20	73.5	64.5
2 -12L	1:45PM		.33	.29	.25	.22	.19	73.5	64.5
2 - 2A	2:09PM		.33	.29	.25	.21	.18	73.5	65.0
2 - 4A	2:16PM		.29	.26	.23	.19	.16	73.5	65.0
2 - 6A	2:04PM		.30	.27	.26	.21	.18	73.5	65.0
2 - 8A	2:00PM		.29	.26	.25	.20	.18	74.0	65.0
2 -10A	1:58PM		.29	.26	.24	.20	.18	74.0	65.0
2 -12A	1:44PM		.31	.28	.25	.22	.19	73.5	64.5
1 - 1L	2:31PM		.31	.27	.23	.18	.16	73.5	65.0
1 - 2L	2:31PM		.34	.29	.24	.20	.17	73.5	65.0
1 - 3L	2:33PM		.27	.24	.21	.17	.14	73.0	65.0
1 - 4L	2:33PM		.29	.26	.22	.16	.15	73.0	65.0
1 - 5L	2:43PM		.26	.22	.19	.16	.14	73.0	65.5
1 - 6L	2:46PM		.25	.22	.20	.16	.14	73.0	65.5
1 - 7L	2:48PM		.25	.22	.20	.15	.14	73.0	65.5
1 - 8L	2:48PM		.25	.23	.20	.16	.14	73.0	65.5
1 - 9L	2:52PM		.25	.22	.19	.16	.14	73.0	65.5
1 -10L	2:53PM		.26	.24	.21	.17	.15	73.0	65.5
1 -11L	2:57PM		.24	.20	.18	.14	.13	73.0	66.0
1 -12L	2:58PM		.23	.21	.19	.15	.13	73.0	66.0
1 - 2N	2:30PM		.29	.25	.21	.18	.15	73.5	65.0

DYNAFLECT DEFLECTION AND TEMP. DATA (COLUMBUS,TX) - FALL 1981

SECTION-LOCATION	TIME		DEFLECTION(MILS) AT SENSORS W1	W2	W3	W4	W5	SLAB TEMP. DEG.F TOP	BOTTOM
1 - 4N	2:32PM	30NOV	.27	.25	.22	.17	.14	73.5	65.0
1 - 6N	2:45PM		.27	.24	.21	.17	.15	73.0	65.5
1 - 8N	2:47PM		.25	.23	.21	.16	.15	73.0	65.5
1 -10N	2:50PM		.24	.22	.20	.16	.14	73.0	65.5
1 -12N	2:55PM		.26	.23	.20	.17	.15	73.0	66.0
3 - 1L	3:24PM		.33	.29	.26	.22	.20	72.5	66.0
3 - 2L	3:25PM		.30	.27	.25	.22	.19	72.5	66.0
3 - 3L	3:23PM		.27	.25	.23	.19	.17	72.5	66.0
3 - 4L	3:23PM		.26	.24	.22	.19	.17	72.5	66.0
3 - 5L	3:21PM		.25	.23	.21	.18	.17	72.5	66.0
3 - 6L	3:21PM		.26	.23	.22	.19	.18	72.5	66.0
3 - 7L	3:19PM		.25	.23	.21	.18	.17	72.5	66.0
3 - 8L	3:19PM		.25	.23	.21	.18	.17	72.5	66.0
3 - 9L	3:15PM		.28	.25	.23	.21	.19	73.0	66.0
3 -10L	3:16PM		.27	.24	.22	.20	.18	73.0	66.0
3 -11L	3:13PM		.31	.27	.25	.21	.19	73.0	66.0
3 -12L	3:14PM		.30	.28	.26	.22	.19	73.0	66.0
2 - 1L	3:33PM		.37	.32	.29	.22	.18	72.0	66.0
2 - 2L	3:34PM		.32	.28	.25	.21	.18	72.0	66.0
2 - 3L	3:36PM		.28	.25	.23	.19	.16	72.0	66.0
2 - 4L	3:37PM		.28	.25	.23	.19	.17	72.0	66.0
2 - 5L	3:39PM		.38	.32	.28	.24	.20	72.0	66.0
2 - 6L	3:40PM		.32	.28	.25	.21	.18	72.0	66.0
2 - 7L	3:42PM		.39	.34	.29	.25	.20	72.0	66.0
2 - 8L	3:43PM		.30	.27	.24	.21	.18	72.0	66.0
2 - 9L	3:45PM		.38	.33	.29	.24	.20	72.0	66.5
2 -10L	3:45PM		.30	.26	.24	.20	.18	72.0	66.5
2 -11L	3:47PM		.36	.33	.30	.25	.21	72.0	66.5
2 -12L	3:48PM		.35	.32	.28	.24	.20	72.0	66.5
2 - 2A	3:34PM		.32	.29	.25	.21	.17	72.0	66.0
2 - 4A	3:37PM		.30	.27	.24	.20	.17	72.0	66.0
2 - 6A	3:41PM		.31	.28	.26	.22	.19	72.0	66.0
2 - 8A	3:43PM		.29	.27	.25	.21	.18	72.0	66.0
2 -10A	3:47PM		.29	.26	.25	.21	.18	72.0	66.5
2 -12A	3:52PM		.33	.30	.28	.24	.20	72.0	66.5
1 - 1L	4:08PM		.34	.28	.24	.20	.16	71.0	66.5
1 - 2L	4:08PM		.35	.30	.26	.21	.17	71.0	66.5
1 - 3L	4:04PM		.27	.24	.21	.17	.15	71.0	66.5
1 - 4L	4:04PM		.30	.26	.22	.18	.15	71.0	66.5
1 - 5L	4:01PM		.25	.22	.19	.16	.14	71.0	66.5
1 - 6L	4:02PM		.25	.23	.21	.18	.15	71.0	66.5
1 - 7L	3:59PM		.27	.23	.20	.17	.14	71.5	66.5
1 - 8L	3:59PM		.27	.24	.21	.18	.15	71.5	66.5

DYNAFLECT DEFLECTION AND TEMP. DATA (COLUMBUS,TX) - FALL 1981

SECTION-LOCATION	TIME		DEFLECTION(MILS) AT SENSORS W1	W2	W3	W4	W5	SLAB TEMP. DEG.F TOP	BOTTOM
1 - 9L	3:57PM	30NOV	.25	.23	.20	.17	.15	71.5	66.5
1 -10L	3:58PM		.28	.26	.22	.18	.15	71.5	66.5
1 -11L	3:54PM		.25	.22	.20	.16	.14	72.0	66.5
1 -12L	3:55PM		.23	.21	.19	.16	.14	72.0	66.5
1 - 2N	4:10PM		.29	.26	.22	.19	.16	71.0	66.5
1 - 4N	4:03PM		.26	.23	.21	.17	.14	71.0	66.5
1 - 6N	4:00PM		.27	.25	.22	.18	.15	71.5	66.5
1 - 8N	3:58PM		.25	.24	.21	.17	.15	71.5	66.5
1 -10N	3:57PM		.25	.23	.20	.17	.14	71.5	66.5
1 -12N	3:53PM		.25	.22	.20	.16	.14	72.0	66.5
3 - 1L	8:30AM	01DEC	.40	.35	.31	.25	.23	52.0	56.0
3 - 2L	8:31AM		.31	.31	.29	.24	.22	52.0	56.0
3 - 3L	8:33AM		.27	.26	.23	.19	.18	52.0	56.0
3 - 4L	8:34AM		.24	.24	.23	.20	.19	52.0	56.0
3 - 5L	8:36AM		.24	.23	.20	.17	.16	52.5	56.0
3 - 6L	8:37AM		.21	.21	.19	.17	.16	52.5	56.0
3 - 7L	8:38AM		.25	.23	.21	.17	.16	52.5	56.0
3 - 8L	8:38AM		.22	.22	.21	.18	.17	52.5	56.0
3 - 9L	8:39AM		.27	.26	.22	.18	.17	53.0	56.0
3 -10L	8:40AM		.23	.22	.21	.18	.17	53.0	56.0
3 -11L	8:42AM		.38	.35	.30	.25	.22	53.0	56.0
3 -12L	8:42AM		.29	.28	.26	.23	.21	53.0	56.0
2 - 1L	9:01AM		.37	.33	.28	.22	.19	54.5	56.0
2 - 2L	9:02AM		.32	.31	.26	.21	.19	54.5	56.0
2 - 3L	8:59AM		.29	.28	.24	.19	.16	54.0	56.0
2 - 4L	8:59AM		.28	.25	.22	.18	.16	54.0	56.0
2 - 5L	8:57AM		.31	.29	.25	.21	.18	54.0	56.0
2 - 6L	8:57AM		.31	.28	.24	.19	.17	54.0	56.0
2 - 7L	8:54AM		.35	.31	.26	.21	.19	54.0	56.0
2 - 8L	8:55AM		.31	.27	.23	.19	.17	54.0	56.0
2 - 9L	8:52AM		.30	.28	.25	.21	.18	54.0	56.0
2 -10L	8:53AM		.28	.27	.23	.19	.17	54.0	56.0
2 -11L	8:49AM		.45	.39	.33	.27	.23	53.5	56.0
2 -12L	8:50AM		.42	.38	.32	.26	.22	53.5	56.0
2 - 2A	9:02AM		.31	.30	.26	.21	.18	54.5	56.0
2 - 4A	9:00AM		.26	.25	.23	.18	.16	54.5	56.0
2 - 6A	8:58AM		.26	.25	.23	.19	.17	54.0	56.0
2 - 8A	8:56AM		.25	.24	.22	.19	.17	54.0	56.0
2 -10A	8:53AM		.24	.23	.22	.18	.17	54.0	56.0
2 -12A	8:50AM		.33	.32	.30	.26	.23	53.5	56.0
1 - 1L	9:04AM		.36	.33	.27	.21	.18	54.5	56.0
1 - 2L	9:04AM		.37	.32	.27	.21	.17	54.5	56.0
1 - 3L	9:06AM		.25	.24	.21	.17	.15	54.5	56.0

DYNAFLECT DEFLECTION AND TEMP. DATA (COLUMBUS,TX) - FALL 1981

SECTION-LOCATION	TIME		DEFLECTION(MILS) AT SENSORS W1	W2	W3	W4	W5	SLAB TEMP. DEG.F TOP	BOTTOM
1 - 4L	9:06AM	01DEC	.29	.27	.23	.18	.15	54.5	56.0
1 - 5L	9:08AM		.23	.22	.19	.15	.13	55.0	56.0
1 - 6L	9:09AM		.23	.22	.20	.16	.14	55.0	56.0
1 - 7L	9:10AM		.25	.24	.20	.16	.15	55.0	56.0
1 - 8L	9:11AM		.24	.24	.21	.16	.14	55.0	56.0
1 - 9L	9:13AM		.28	.25	.22	.17	.14	55.0	56.0
1 -10L	9:13AM		.25	.25	.21	.17	.14	55.0	56.0
1 -11L	9:16AM		.26	.25	.20	.16	.14	55.5	56.0
1 -12L	9:16AM		.22	.21	.19	.15	.14	55.5	56.0
1 - 2N	9:03AM		.27	.26	.23	.19	.17	54.5	56.0
1 - 4N	9:05AM		.23	.22	.20	.16	.15	54.5	56.0
1 - 6N	9:08AM		.21	.20	.18	.15	.13	55.0	56.0
1 - 8N	9:10AM		.22	.21	.19	.15	.14	55.0	56.0
1 -10N	9:12AM		.22	.21	.19	.15	.14	55.0	56.0
1 -12N	9:15AM		.22	.21	.19	.15	.14	55.5	56.0
3 - 1L	9:41AM		.34	.32	.29	.25	.22	58.0	56.0
3 - 2L	9:42AM		.30	.29	.28	.24	.21	58.0	56.0
3 - 3L	9:39AM		.27	.26	.23	.20	.19	57.5	56.0
3 - 4L	9:40AM		.24	.23	.22	.19	.18	58.0	56.0
3 - 5L	9:38AM		.23	.22	.21	.17	.16	57.5	56.0
3 - 6L	9:38AM		.21	.21	.20	.17	.16	57.5	56.0
3 - 7L	9:37AM		.24	.24	.22	.19	.17	57.5	56.0
3 - 8L	9:37AM		.24	.23	.23	.19	.17	57.5	56.0
3 - 9L	9:35AM		.26	.25	.22	.19	.17	57.0	56.0
3 -10L	9:36AM		.24	.23	.22	.19	.18	57.0	56.0
3 -11L	9:33AM		.38	.34	.30	.25	.22	57.0	56.0
3 -12L	9:33AM		.29	.29	.26	.23	.20	57.0	56.0
2 - 1L	9:46AM		.37	.36	.29	.24	.20	58.0	56.0
2 - 2L	9:47AM		.33	.32	.28	.23	.20	58.0	56.0
2 - 3L	9:48AM		.29	.27	.25	.19	.17	58.5	56.0
2 - 4L	9:48AM		.26	.25	.22	.18	.16	58.5	56.0
2 - 5L	9:50AM		.32	.30	.26	.22	.19	58.5	56.0
2 - 6L	9:51AM		.31	.28	.25	.20	.18	58.5	56.0
2 - 7L	9:52AM		.36	.31	.27	.22	.19	59.0	56.0
2 - 8L	9:53AM		.29	.27	.24	.19	.17	59.0	56.0
2 - 9L	9:55AM		.31	.30	.26	.22	.19	59.0	56.0
2 -10L	9:56AM		.30	.27	.24	.20	.17	59.0	56.0
2 -11L	9:57AM		.40	.36	.32	.26	.23	59.0	56.0
2 -12L	9:58AM		.41	.37	.32	.26	.22	59.0	56.0
2 - 2A	9:47AM		.33	.32	.29	.23	.19	58.0	56.0
2 - 4A	9:49AM		.26	.25	.23	.19	.16	58.5	56.0
2 - 6A	9:51AM		.27	.26	.24	.20	.18	58.5	56.0
2 - 8A	9:53AM		.25	.24	.23	.19	.17	59.0	56.0

DYNAFLECT DEFLECTION AND TEMP. DATA (COLUMBUS,TX) - FALL 1981

SECTION- LOCATION	TIME		DEFLECTION(MILS) AT SENSORS W1	W2	W3	W4	W5	SLAB TEMP. DEG.F TOP	BOTTOM
2 -10A	9:56AM	01DEC	.25	.24	.22	.19	.18	59.0	56.0
2 -12A	9:58AM		.32	.31	.29	.25	.22	59.0	56.0
1 - 1L	10:14AM		.33	.30	.26	.21	.17	60.0	56.0
1 - 2L	10:14AM		.35	.31	.26	.20	.17	60.0	56.0
1 - 3L	10:11AM		.26	.24	.22	.17	.14	60.0	56.0
1 - 4L	10:12AM		.29	.27	.23	.18	.15	60.0	56.0
1 - 5L	10:08AM		.22	.21	.19	.15	.13	60.0	56.0
1 - 6L	10:09AM		.23	.22	.20	.16	.14	60.0	56.0
1 - 7L	10:06AM		.25	.22	.19	.15	.13	60.0	56.0
1 - 8L	10:07AM		.23	.23	.20	.16	.14	60.0	56.0
1 - 9L	10:03AM		.24	.23	.20	.16	.14	59.5	56.0
1 -10L	10:04AM		.25	.25	.21	.17	.14	59.5	56.0
1 -11L	10:00AM		.25	.23	.20	.16	.14	59.5	56.0
1 -12L	10:00AM		.22	.21	.19	.15	.13	59.5	56.0
1 - 2N	10:13AM		.28	.27	.24	.20	.17	60.0	56.0
1 - 4N	10:11AM		.24	.23	.20	.17	.15	60.0	56.0
1 - 6N	10:08AM		.22	.21	.19	.15	.14	60.0	56.0
1 - 8N	10:06AM		.22	.21	.19	.16	.14	60.0	56.0
1 -10N	10:02AM		.23	.22	.19	.16	.14	59.5	56.0
1 -12N	9:59AM		.22	.21	.19	.15	.14	59.5	56.0
3 - 1L	10:24AM		.33	.30	.27	.23	.21	61.0	56.5
3 - 2L	10:25AM		.29	.28	.27	.23	.21	61.0	56.5
3 - 3L	10:27AM		.26	.25	.23	.20	.18	61.5	56.5
3 - 4L	10:27AM		.25	.24	.23	.20	.18	61.5	56.5
3 - 5L	10:29AM		.24	.22	.20	.17	.16	61.5	56.5
3 - 6L	10:29AM		.22	.21	.20	.18	.16	61.5	56.5
3 - 7L	10:30AM		.24	.23	.21	.18	.17	62.0	56.5
3 - 8L	10:31AM		.23	.22	.21	.18	.17	62.0	56.5
3 - 9L	10:32AM		.27	.25	.23	.19	.18	62.0	56.5
3 -10L	10:33AM		.24	.23	.21	.18	.17	62.0	56.5
3 -11L	10:35AM		.35	.32	.29	.24	.21	62.5	57.0
3 -12L	10:36AM		.29	.28	.26	.22	.20	62.5	57.0
2 - 1L	10:54AM		.39	.34	.29	.23	.20	64.0	57.0
2 - 2L	10:54AM		.31	.29	.26	.21	.18	64.0	57.0
2 - 3L	10:52AM		.30	.27	.24	.19	.16	64.0	57.0
2 - 4L	10:52AM		.27	.25	.23	.19	.16	64.0	57.0
2 - 5L	10:49AM		.35	.32	.27	.23	.19	63.5	57.0
2 - 6L	10:50AM		.31	.28	.25	.20	.17	63.5	57.0
2 - 7L	10:47AM		.37	.32	.27	.22	.19	63.5	57.0
2 - 8L	10:48AM		.30	.27	.24	.20	.17	63.5	57.0
2 - 9L	10:44AM		.33	.30	.26	.21	.19	63.0	57.0
2 -10L	10:45AM		.29	.26	.23	.19	.17	63.0	57.0
2 -11L	10:42AM		.40	.37	.32	.26	.22	63.0	57.0

DYNAFLECT DEFLECTION AND TEMP. DATA (COLUMBUS,TX) - FALL 1981

SECTION-LOCATION	TIME		DEFLECTION(MILS) AT SENSORS W1	W2	W3	W4	W5	SLAB TEMP. DEG.F TOP	BOTTOM
2 -12L	10:43AM	01DEC	.38	.34	.29	.24	.20	63.0	57.0
2 - 2A	10:55AM		.32	.30	.27	.22	.18	64.0	57.0
2 - 4A	10:53AM		.28	.27	.24	.20	.17	64.0	57.0
2 - 6A	10:50AM		.27	.26	.24	.20	.18	63.5	57.0
2 - 8A	10:48AM		.27	.26	.24	.20	.18	63.5	57.0
2 -10A	10:46AM		.25	.24	.23	.19	.17	63.0	57.0
2 -12A	10:43AM		.32	.31	.28	.24	.21	63.0	57.0
1 - 1L	10:57AM		.36	.31	.27	.21	.18	64.0	57.0
1 - 2L	10:58AM		.35	.31	.26	.21	.17	64.0	57.0
1 - 3L	11:00AM		.25	.23	.21	.17	.14	64.5	57.5
1 - 4L	11:00AM		.30	.27	.22	.18	.15	64.5	57.5
1 - 5L	11:02AM		.23	.22	.20	.17	.14	64.5	57.5
1 - 6L	11:03AM		.23	.22	.21	.16	.14	64.5	57.5
1 - 7L	11:04AM		.24	.22	.20	.15	.14	65.0	57.5
1 - 8L	11:05AM		.24	.23	.21	.16	.14	65.0	57.5
1 - 9L	11:07AM		.25	.24	.21	.17	.14	65.0	57.5
1 -10L	11:07AM		.24	.23	.21	.16	.14	65.0	57.5
1 -11L	11:08AM		.24	.22	.20	.15	.14	65.0	57.5
1 -12L	11:09AM		.22	.21	.20	.16	.14	65.0	57.5
1 - 2N	10:57AM		.30	.28	.25	.20	.17	64.0	57.0
1 - 4N	10:59AM		.24	.23	.21	.17	.15	64.5	57.0
1 - 6N	11:02AM		.24	.23	.21	.17	.15	64.5	57.5
1 - 8N	11:04AM		.23	.22	.20	.16	.15	65.0	57.5
1 -10N	11:06AM		.23	.22	.20	.16	.15	65.0	57.5
1 -12N	11:08AM		.22	.21	.19	.16	.14	65.0	57.5
3 - 1L	11:36AM		.31	.30	.26	.22	.20	67.0	58.0
3 - 2L	11:37AM		.30	.29	.27	.23	.21	67.0	58.0
3 - 3L	11:38AM		.25	.24	.22	.19	.17	67.0	58.0
3 - 4L	11:38AM		.24	.24	.22	.19	.18	67.0	58.0
3 - 5L	11:33AM		.23	.22	.20	.18	.16	67.0	57.5
3 - 6L	11:34AM		.22	.21	.20	.17	.16	67.0	57.5
3 - 7L	11:32AM		.24	.23	.23	.18	.16	67.0	57.5
3 - 8L	11:32AM		.22	.22	.20	.17	.16	67.0	57.5
3 - 9L	11:29AM		.25	.24	.22	.19	.17	67.0	57.5
3 -10L	11:30AM		.23	.23	.21	.18	.17	67.0	57.5
3 -11L	11:27AM		.33	.31	.27	.23	.20	66.5	57.5
3 -12L	11:28AM		.28	.28	.26	.22	.20	66.5	57.5
2 - 1L	11:45AM		.34	.31	.27	.21	.18	67.5	58.0
2 - 2L	11:45AM		.31	.29	.26	.21	.18	67.5	58.0
2 - 3L	11:47AM		.28	.26	.22	.18	.16	68.0	58.0
2 - 4L	11:47AM		.27	.25	.22	.18	.16	68.0	58.0
2 - 5L	11:49AM		.33	.32	.28	.23	.20	68.0	58.0
2 - 6L	11:49AM		.31	.30	.26	.22	.17	68.0	58.0

DYNAFLECT DEFLECTION AND TEMP. DATA (COLUMBUS,TX) - FALL 1981

SECTION-LOCATION	TIME		DEFLECTION(MILS) AT SENSORS W1	W2	W3	W4	W5	SLAB TEMP. DEG.F TOP	BOTTOM
2 - 7L	11:51AM	01DEC	.36	.34	.29	.23	.20	68.0	58.0
2 - 8L	11:51AM		.30	.28	.25	.20	.18	68.0	58.0
2 - 9L	11:54AM		.33	.31	.28	.22	.20	68.0	58.0
2 -10L	11:54AM		.29	.27	.24	.20	.17	68.0	58.0
2 -11L	11:56AM		.34	.32	.28	.24	.21	68.5	58.0
2 -12L	11:57AM		.34	.32	.28	.23	.20	68.5	58.0
2 - 2A	11:46AM		.31	.30	.26	.21	.18	67.5	58.0
2 - 4A	11:48AM		.28	.27	.24	.19	.16	68.0	58.0
2 - 6A	11:50AM		.28	.27	.25	.21	.18	68.0	58.0
2 - 8A	11:52AM		.27	.26	.24	.20	.18	68.0	58.0
2 -10A	11:55AM		.26	.25	.24	.19	.18	68.5	58.0
2 -12A	11:57AM		.31	.30	.28	.23	.20	68.5	58.0
1 - 1L	12:12PM		.32	.29	.25	.20	.17	69.0	59.0
1 - 2L	12:12PM		.35	.31	.27	.21	.17	69.0	59.0
1 - 3L	12:14PM		.26	.24	.21	.17	.14	69.0	59.0
1 - 4L	12:14PM		.31	.27	.22	.17	.15	69.0	59.0
1 - 5L	12:08PM		.22	.21	.19	.15	.13	69.0	58.5
1 - 6L	12:09PM		.23	.22	.20	.16	.14	69.0	58.5
1 - 7L	12:06PM		.24	.22	.19	.15	.14	69.0	58.5
1 - 8L	12:06PM		.23	.23	.20	.16	.14	69.0	58.5
1 - 9L	12:04PM		.23	.21	.19	.16	.14	69.0	58.5
1 -10L	12:04PM		.24	.23	.20	.16	.14	69.0	58.5
1 -11L	12:01PM		.24	.22	.20	.15	.14	69.0	58.5
1 -12L	12:02PM		.22	.21	.19	.15	.13	69.0	58.5
1 - 2N	12:11PM		.26	.25	.23	.18	.16	69.0	59.0
1 - 4N	12:13PM		.24	.23	.21	.17	.14	69.0	59.0
1 - 6N	12:08PM		.25	.24	.21	.17	.15	69.0	58.5
1 - 8N	12:05PM		.23	.22	.20	.15	.14	69.0	58.5
1 -10N	12:03PM		.23	.22	.20	.16	.14	69.0	58.5
1 -12N	12:00PM		.22	.21	.20	.16	.14	69.0	58.5
3 - 1L	1:29PM		.31	.29	.26	.22	.20	71.5	60.5
3 - 2L	1:29PM		.28	.27	.26	.22	.20	71.5	60.5
3 - 3L	1:26PM		.25	.24	.22	.19	.17	71.5	60.5
3 - 4L	1:27PM		.24	.24	.22	.19	.17	71.5	60.5
3 - 5L	1:24PM		.22	.22	.20	.17	.16	71.5	60.5
3 - 6L	1:24PM		.23	.22	.21	.18	.17	71.5	60.5
3 - 7L	1:22PM		.24	.22	.21	.18	.17	71.5	60.5
3 - 8L	1:23PM		.23	.22	.21	.18	.17	71.5	60.5
3 - 9L	1:20PM		.24	.23	.21	.18	.17	71.5	60.5
3 -10L	1:21PM		.24	.23	.22	.18	.17	71.5	60.5
3 -11L	1:19PM		.32	.30	.27	.22	.20	71.5	60.5
3 -12L	1:19PM		.28	.28	.26	.22	.20	71.5	60.5
2 - 1L	1:35PM		.31	.28	.24	.19	.17	71.5	60.5

DYNAFLECT DEFLECTION AND TEMP. DATA (COLUMBUS,TX) - FALL 1981

SECTION-LOCATION	TIME		DEFLECTION(MILS) AT SENSORS W1	W2	W3	W4	W5	SLAB TEMP. DEG.F TOP	BOTTOM
2 - 2L	1:35PM	01DEC	.28	.27	.25	.20	.18	71.5	60.5
2 - 3L	1:37PM		.28	.26	.23	.18	.16	71.5	61.0
2 - 4L	1:38PM		.26	.25	.23	.18	.17	71.5	61.0
2 - 5L	1:39PM		.34	.31	.28	.23	.20	71.5	61.0
2 - 6L	1:40PM		.30	.28	.25	.20	.18	72.0	61.0
2 - 7L	1:42PM		.38	.34	.29	.24	.21	72.0	61.0
2 - 8L	1:42PM		.31	.28	.25	.20	.18	72.0	61.0
2 - 9L	1:44PM		.35	.32	.28	.23	.20	72.0	61.0
2 -10L	1:44PM		.29	.27	.24	.20	.18	72.0	61.0
2 -11L	1:46PM		.33	.32	.28	.24	.21	72.0	61.0
2 -12L	1:47PM		.33	.30	.27	.23	.20	72.0	61.0
2 - 2A	1:36PM		.29	.27	.24	.19	.16	71.5	60.5
2 - 4A	1:38PM		.28	.27	.24	.19	.17	71.5	61.0
2 - 6A	1:41PM		.28	.27	.25	.21	.18	72.0	61.0
2 - 8A	1:43PM		.27	.26	.24	.20	.18	72.0	61.0
2 -10A	1:45PM		.27	.26	.24	.20	.18	72.0	61.0
2 -12A	1:47PM		.31	.30	.28	.23	.21	72.0	61.0
1 - 1L	1:58PM		.34	.30	.26	.21	.17	71.0	61.0
1 - 2L	1:59PM		.36	.31	.26	.20	.17	71.0	61.0
1 - 3L	2:00PM		.27	.24	.21	.17	.15	71.0	61.0
1 - 4L	2:01PM		.30	.27	.23	.18	.15	71.0	61.0
1 - 5L	1:56PM		.22	.21	.19	.15	.13	71.0	61.0
1 - 6L	1:57PM		.23	.22	.20	.16	.14	71.5	61.0
1 - 7L	1:54PM		.24	.22	.20	.16	.14	71.5	61.0
1 - 8L	1:54PM		.23	.22	.20	.16	.14	71.5	61.0
1 - 9L	1:52PM		.24	.22	.20	.16	.14	71.5	61.0
1 -10L	1:52PM		.25	.24	.21	.17	.15	71.5	61.0
1 -11L	1:49PM		.22	.21	.19	.17	.13	72.0	61.0
1 -12L	1:50PM		.23	.22	.20	.16	.14	71.5	61.0
1 - 2N	1:58PM		.30	.28	.25	.20	.17	71.0	61.0
1 - 4N	2:00PM		.24	.23	.20	.16	.15	71.0	61.0
1 - 6N	1:55PM		.25	.24	.21	.17	.15	71.5	61.0
1 - 8N	1:53PM		.23	.22	.20	.16	.14	71.5	61.0
1 -10N	1:51PM		.23	.22	.20	.16	.15	71.5	61.0
1 -12N	1:48PM		.23	.22	.20	.16	.15	72.0	61.0
3 - 1L	2:19PM		.32	.29	.27	.23	.21	71.0	61.5
3 - 2L	2:19PM		.28	.27	.25	.22	.20	71.0	61.5
3 - 3L	2:20PM		.26	.25	.23	.19	.18	71.0	61.5
3 - 4L	2:21PM		.25	.24	.23	.19	.18	71.0	61.5
3 - 5L	2:16PM		.24	.23	.21	.18	.17	71.0	61.5
3 - 6L	2:17PM		.23	.22	.21	.18	.17	71.0	61.5
3 - 7L	2:15PM		.24	.23	.21	.18	.17	71.0	61.5
3 - 8L	2:15PM		.24	.23	.22	.18	.17	71.0	61.0

DYNAFLECT DEFLECTION AND TEMP. DATA (COLUMBUS,TX) - FALL 1981

SECTION-LOCATION	TIME		DEFLECTION(MILS) AT SENSORS W1	W2	W3	W4	W5	SLAB TEMP. DEG.F TOP	BOTTOM
3 - 9L	2:12PM	01DEC	.26	.24	.22	.19	.17	71.0	61.0
3 -10L	2:13PM		.24	.23	.22	.19	.17	71.0	61.0
3 -11L	2:10PM		.32	.30	.27	.22	.20	71.5	61.0
3 -12L	2:10PM		.29	.28	.26	.23	.20	71.5	61.0
2 - 1L	2:28PM		.32	.30	.26	.21	.18	71.0	61.5
2 - 2L	2:28PM		.32	.30	.26	.21	.17	71.0	61.5
2 - 3L	2:30PM		.28	.25	.22	.19	.16	71.0	61.5
2 - 4L	2:31PM		.27	.25	.22	.19	.16	71.0	61.5
2 - 5L	2:33PM		.35	.32	.28	.24	.21	71.0	61.5
2 - 6L	2:34PM		.31	.28	.25	.21	.18	71.0	61.5
2 - 7L	2:36PM		.38	.34	.29	.24	.21	71.0	62.0
2 - 8L	2:36PM		.31	.28	.25	.21	.18	71.0	62.0
2 - 9L	2:38PM		.37	.33	.29	.24	.20	71.0	62.0
2 -10L	2:38PM		.30	.27	.24	.20	.18	71.0	62.0
2 -11L	2:40PM		.34	.32	.28	.24	.21	70.5	62.0
2 -12L	2:40PM		.34	.32	.28	.23	.20	70.5	62.0
2 - 2A	2:29PM		.31	.29	.25	.21	.17	71.0	61.5
2 - 4A	2:32PM		.28	.26	.23	.19	.16	71.0	61.5
2 - 6A	2:34PM		.28	.27	.25	.21	.18	71.0	61.5
2 - 8A	2:36PM		.27	.26	.24	.21	.18	71.0	62.0
2 -10A	2:39PM		.27	.26	.24	.20	.18	71.0	62.0
2 -12A	2:41PM		.31	.30	.28	.24	.21	70.5	62.0
1 - 1L	2:52PM		.31	.28	.24	.19	.17	70.0	62.0
1 - 2L	2:53PM		.35	.31	.26	.20	.17	70.0	62.0
1 - 3L	2:54PM		.26	.24	.21	.17	.15	70.0	62.0
1 - 4L	2:55PM		.31	.27	.23	.18	.15	70.0	62.0
1 - 5L	2:50PM		.23	.22	.19	.16	.14	70.0	62.0
1 - 6L	2:51PM		.23	.22	.20	.16	.14	70.0	62.0
1 - 7L	2:48PM		.24	.23	.20	.17	.15	70.0	62.0
1 - 8L	2:49PM		.24	.23	.21	.16	.14	70.0	62.0
1 - 9L	2:46PM		.23	.22	.20	.16	.14	70.5	62.0
1 -10L	2:46PM		.25	.25	.22	.17	.15	70.5	62.0
1 -11L	2:43PM		.23	.21	.19	.16	.14	70.5	62.0
1 -12L	2:43PM		.22	.21	.19	.16	.14	70.5	62.0
1 - 2N	2:52PM		.27	.25	.22	.18	.16	70.0	62.0
1 - 4N	2:54PM		.24	.23	.20	.17	.14	70.0	62.0
1 - 6N	2:50PM		.25	.24	.21	.18	.15	70.0	62.0
1 - 8N	2:47PM		.23	.22	.20	.17	.15	70.5	62.0
1 -10N	2:45PM		.23	.22	.20	.16	.14	70.5	62.0
1 -12N	2:42PM		.23	.22	.20	.16	.14	70.5	62.0

APPENDIX B

AN ILLUSTRATIVE EXAMPLE OF USING DICHOTOMOUS VARIABLES IN MULTIPLE LINEAR REGRESSION ANALYSIS

APPENDIX B. AN ILLUSTRATIVE EXAMPLE OF THE USE OF DICHOTOMOUS VARIABLES IN MULTIPLE LINEAR REGRESSION ANALYSIS

Let us assume that a linear relationship exists between maximum Dynaflect deflection (W_1) and temperature differential (DT). The estimated regression equation, based on a simple regression model, is of the following form

$$W_1 = b_o + b_1 \text{ (DT)} \tag{B.1}$$

where b_o is the intercept term and b_1 is the slope of the estimated regression line.

For this comparative study, deflection and temperature data at location 6L (summer ad fall data) were used. Separate regression equations were developed for section 1, section 2, and section 3. The estimated regression equations are summarized in Table B.1. The actual data points and the respective regression line are also plotted in Fig B.1 for the three sections. In each case, W_1 is the dependent or response variable and DT is the independent or explanatory variable. It is easily observed that R^2 statistics is not very consistent and in general is very low. The three regression lines are replotted in Fig B.2.

The data points from the three sections were later pooled and a stepwise multiple regression analysis was performed using sections as dichotomous or dummy variables. The estimated regression equation is of the following form

$$W_1 = b_o + b_1 \text{ (DT)} + d_1 \text{ (SEC1)} + d_2 \text{ (EC2)} \tag{B.2}$$

TABLE B.1. ESTIMATED REGRESSION EQUATIONS FROM SIMPLE REGRESSION ANALYSES

Section	Estimated Regression Equation	R^2	Number of Data Points* n
1	$W_1 = 0.229775 + 0.0001495(DT)$	0.207	12
2	$W_1 = 0.267499 + 0.0002837(DT)$	0.587	12
3	$W_1 = 0.225958 + 0.0000224(DT)$	0.008	12

*All data points correspond to location 6L.

Dependent Variable = W_1 (mils)

Independent Variable = DT(° F)

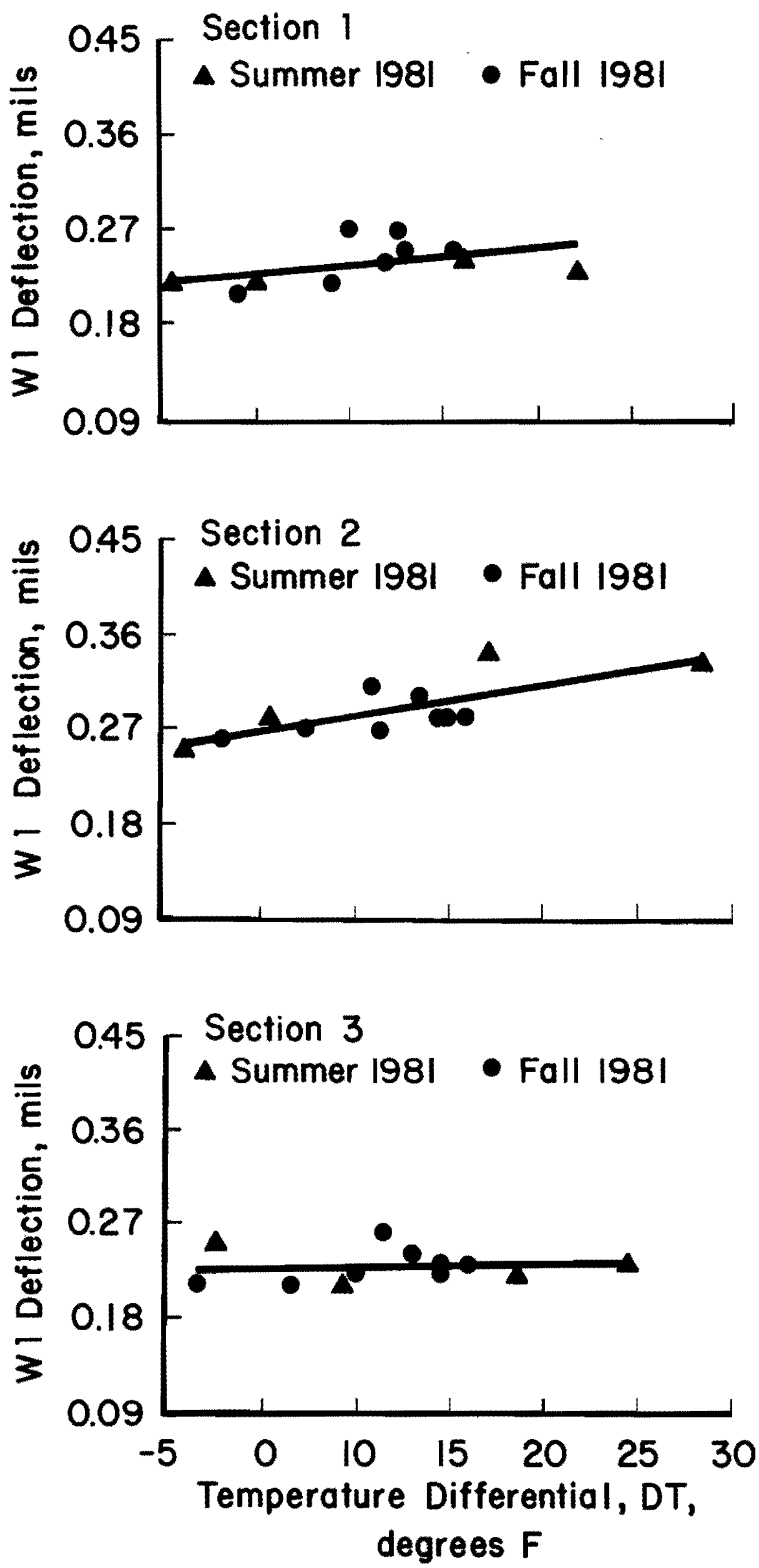

Fig B.1. The best fit lines estimated from simple linear regression analyses, (location 6L).

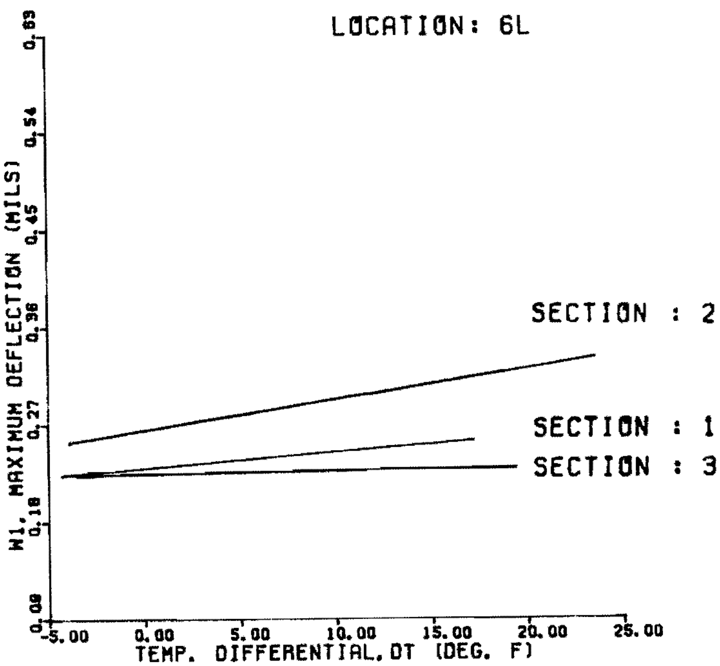

Fig B.2. Estimated regression lines from the simple regression analyses.

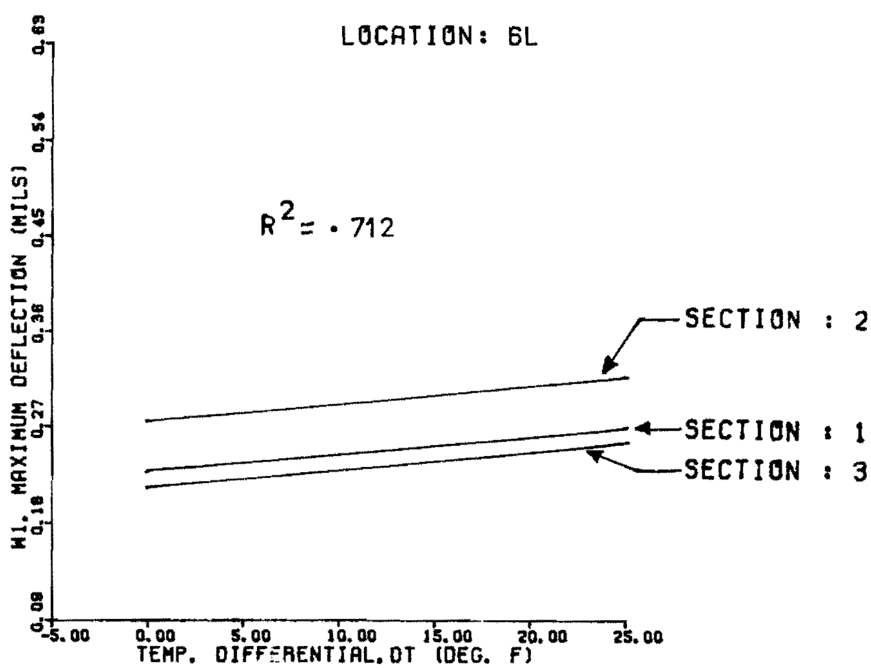

Fig B.3. Estimated regression lines from multiple regression analyses considering sections as dichotomous variables.

where W_1, DT, b_o, and b_1 are the same as defined earlier. SEC1 and SEC2 are the two dummy variables.

$$\text{SEC1} = \begin{cases} 1 & \text{if the data points correspond to section 1} \\ 0 & \text{otherwise} \end{cases}$$

$$\text{SEC2} = \begin{cases} 1 & \text{if the data points correspond to section 2} \\ 0 & \text{otherwise} \end{cases}$$

d_1 and d_2 are the estimated regression coefficient of SEC1 and SEC2, respectively.

Table B.2 presents the estimated regression equation and the resulting equations for the three sections. It is observed that only two dummy variables are used in the regression model. It is unnecessary to use SEC3 as the third dummy variable as its effect is already present in the intercept term of the original estimated regression equation. The estimated regression lines for the three sections are plotted in Fig B.3. It is noted that they have the same slopes but different intercepts. The R^2 statistic is comparable higher and is based on data points of all the three sections. The use of dummy variables allowed different levels of deflection W_1 for each section while keeping the same marginal effect associated with the independent variable, DT. It is evident from this example that the simple regression analysis on separated data points resulted in three different

TABLE B.2. THE ESTIMATED REGRESSION EQUATIONS USING DUMMY VARIABLES

Section	Dummy Variable Values	Equation
1	SEC1 = 1; SEC2 = 0	$W_1 = 0.22889 + 0.001635(DT)$
2	SEC1 = 0; SEC2 = 1	$W_1 = 0.27597 + 0.001635(DT)$
3	SEC1 = 0; SEC2 = 0	$W_1 = 0.216244 + 0.001635(DT)$

The original estimated regression equation:

$$W_1 = 0.216244 + 0.001635(DT) + 0.012648(SEC1) + 0.059727(SEC2)$$

R^2 statistic = 0.712

Number of data points, n = 36

slopes and low R^2 (as illustrated in Fig B.2). This example showed that the dummy variables provided a flexible tool for handling the categories in the observed data and resulted in a more meaningful relationship between W_1 and DT at this particular location with a remarkable increase in the R^2 statistic.

APPENDIX C

SUMMARY OF ESTIMATED REGRESSION EQUATIONS FROM MULTIPLE LINEAR REGRESSION ANALYSES USING DICHOTOMOUS VARIABLES

APPENDIX C. SUMMARY OF ESTIMATED REGRESSION EQUATIONS FROM MULTIPLE LINEAR REGRESSION ANALYSES USING DICHOTOMOUS VARIABLES

This appendix provides the best regression equations and summary statistics developed for each data set (see Table 3.2). Tables C.1 to C.8 present the summaries of regression equations for data sets 1 (ALL), 2 (Summer/Fall), 3 (At Crack/Mid-span), and 4 (Passing Lane/Travel/Lane/Concrete Shoulder).

The estimated regression equations and summary statistics for data set number 5 (each location) are presented in Tables C.9 to C.22 for test locations 1 to 14, respectively. All the results correspond to multiple regression analysis II (without interaction terms).

TABLE C.1. SUMMARY OF MULTIPLE REGRESSION ANALYSES (DATA SET 1-ALL)

Dependent Variables	Independent Variables	Regression Coefficient	Ranking*	R^2
	SEC2	.6059E-01	1	
	X2	- .5588E-01	2	
	X1	- .4231E-01	3	
	DE	- .7877E-02	6	
	B1	.1757E-01	7	
W_1	DT	- .2688E-02	5	0.46
	TMID	.1022E-02	4	
	CS	- .3221E-02	8	
	SEC1	- .1119E-01	9	
	B2	- .8963E-02	10	
	Constant	.3043		
	SEC1	- .3612E-01	1	
	S1	.2706E-01	4	
	DE	- .3924E-02	5	
	X1	- .3233E-01	2	
W_5	X2	- .2963E-01	3	0.57
	SEC2	.1252E-01	6	
	DT	- .3770E-03	8	
	CS	- .1170E-02	7	
	Constant	.2281		

*Ranking indicates the order of effectiveness based on Beta values (the standardized regression coefficients).

TABLE C.2. SUMMARY OF MULTIPLE REGRESSION ANALYSES (DATA SET 2-S)

Dependent Variable	Independent Variable	Regression Coefficient	Ranking*	R^2
	SEC2	.1138	1	
	CS	- .9632E-02	5	
	DE	- .1345E-01	6	
	DT	- .2430E-02	4	
W_1	B1	.2900E-01	7	0.496
	X2	- .6532E-01	2	
	X1	- .5792E-01	3	
	SEC1	- .1708E-01	8	
	Constant	.4747		
	SEC1	- .3928E-01	3	
	DE	- .6742E-02	5	
	X1	- .4818E-01	2	
W_5	X2	- .3558E-01	4	0.592
	SEC2	.4794E-01	1	
	DT	- .5089E-03	7	
	CS	- .4250E-02	6	
	Constant	.2967		

*Ranking indicates the order of effectiveness based on Beta values (the standardized regression coefficient).

TABLE C.3. SUMMARY OF MULTIPLE REGRESSION ANALYSES (DATA SET 2-F)

Dependent Variable	Independent Variables	Regression Coefficient	Ranking*	R^2
	SEC2	.4536E-01	1	
	X2	- .3021E-01	2	
	B1	.1648E-01	5	
	DE	- .4410E-02	6	
	B2	- .1032E-01	10	
W_1	X1	- .1368E-01	7	0.54
	CS	- .4521E-02	9	
	SEC1	- .1284E-01	8	
	TMID	.1909E-02	3	
	DT	- .2310E-02	4	
	Constant	.2306		
	SEC1	- .3859E-01	1	
	CS	- .4134E-02	3	
	DE	- .2054E-02	5	
	X2	- .1338E-01	4	
W_5	X1	- .1366E-01	2	0.68
	B1	.4557E-02	6	
	B2	.3993E-02	7	
	DT	- .4083E-03	8	
	TMID	.2176E-03	9	
	Constant	.2210		

*Ranking indicates the order of effectiveness based on Beta values (the standardized regression coefficient).

TABLE C.4. SUMMARY OF MULTIPLE REGRESSION ANALYSES (DATA SET 3-CR)

Dependent Variables	Independent Variable	Regression Coefficient	Ranking*	R^2
	SEC2	.6955E-01	1	
	X2	- .4745E-01	3	
	DT	- .4247E-02	2	
	TMID	.1481E-02	4	
	DE	- .9160E-02	6	
W_1	X1	- .3633E-01	5	0.45
	B1	.2011E-01	8	
	CS	- .6332E-02	7	
	SEC1	- .1248E-01	9	
	Constant	.3026		
	SEC1	- .3900E-01	1	
	S1	.3298E-01	2	
	DE	- .4162E-02	5	
	X2	- .2367E-01	4	
W_5	X1	- .2525E-01	3	0.58
	SEC2	.1306E-01	7	
	CS	- .2736E-02	6	
	DT	- .5331E-03	8	
	B1	.5005E-02	9	
	Constant	.2345		

*Ranking indicates the order of effectiveness based on Beta values (the standardized regression coefficient).

TABLE C.5. SUMMARY OF MULTIPLE REGRESSION ANALYSES (DATA SET 3-MS)

Dependent Variables	Independent Variables	Regression Coefficient	Ranking*	R^2
	SEC2	.5687E-01	2	
	X2	- .7504E-01	1	
	X1	- .5911E-01	3	
W_1	DE	- .5626E-02	4	0.50
	S1	.1359E-01	5	
	Constant	.3241		
	SEC1	- .2789E-01	3	
	S1	.1930E-01	4	
	DE	- .3227E-02	6	
W_5	X1	- .4919E-01	1	0.60
	X2	- .4323E-01	2	
	SEC2	.1776E-01	5	
	Constant	.2228		

*Ranking indicates the order of effectiveness based on Beta values (the standardized regression coefficient).

TABLE C.6. SUMMARY OF MULTIPLE REGRESSION ANALYSES (DATA SET 4-P)

Locations	Dependent Variable (W_1)			R^2
	Independent Variables	Regression Coefficient	Ranking*	
1, 2	DT	-.3463E-02	1	0.628
	B1	.1828E-01	5	
	SEC2	.1987E-01	4	
	SEC1	.2665E-01	3	
	CS	.5247E-02	2	
	TMID	-.5229E-03	6	
	B2	-.1323E-01	7	
	Constant	.3211		
3, 4	SEC2	.2609E-01	1	0.35
	SEC1	.2066E-01	2	
	B2	-.1201E-01	3	
	Constant	.2550		

*Ranking indicates the order of effectiveness based on Beta values (the standardized regression coefficient).

TABLE C.7. SUMMARY OF MULTIPLE REGRESSION ANALYSES (DATA SET 4-T)

	Dependent Variable (W_1)			
Locations	Independent Variables	Regression Coefficient	Ranking*	R^2
	SEC2	.9600E-01	1	
5, 6	B1	.1667E-01	2	0.856
	DT	.4773E-03	3	
	Constant	.2206		
	SEC2	.1065E-	1	
	B1	.3629E-01	2	
	DT	.8235E-03	5	
7, 8	SEC1	.1428E-01	4	0.866
	B2	.2024E-01	3	
	S1	-.1078E-01	6	
	Constant	.2066		

*Ranking indicates the order of effectiveness based on Beta values (the standardized regression coefficient).

TABLE C.8. SUMMARY OF MULTIPLE REGRESSION ANALYSES (DATA SET 4)

		Dependent Variable (W_1)			
Data Set	Locations	Independent Variables	Regression Coefficient	Ranking*	R^2
		SEC2	.7333E-01	3	
		B1	.2168E-01	5	
		TMID	.2586E-02	1	
4-T	9, 10	S1	- .9254E-01	2	0.72
		DT	- .1817E-02	4	
		CS	.2900E-02	6	
		SEC1	.1224E-01	7	
		Constant	.5713E-01		
		SEC1	- .9541E-01	1	
		DT	- .4443E-02	2	
		SEC2	.4239E-01	3	
4-C1	11, 12	B1	.1373E-01	6	0.80
		S1	.2745E-01	4	
		B2	- .2714E-01	5	
		Constant	.3483		

*Ranking indicates the order of effectiveness based on Beta values (the standardized regression coefficients).

TABLE C.9. SUMMARY OF MULTIPLE REGRESSION ANALYSIS II
(DATA SET 5-1, RESPONSE VARIABLE W_1)

Independent Variables	Estimated Regression Coefficient	STD Error B	F / Significance	Beta / Elasticity
DT	- .4683E-02	.5670E-03	68.208478 .000	-.6849887 -.09105
CS	.2511E-02	.1549E-02	2.6295396 .111	.1595420 .06378
SEC1	.3191E-01	.8115E-02	15.460166 .000	.3812747 .03295
SEC2	.2308E-01	.8692E-02	7.0493722 .010	.2757669 .02383
B1	.1875E-01	.7511E-02	6.2314931 .016	.2287131 .03485
Constant	.3124	.1258E-01	616.71554 .000	

Dependent Variable: W_1 (mils)

Standard Error of Estimate: 0.0249

Mean: 0.334

Standard Deviation: 0.0401

C. V.: 12 %

R^2: 0.65

n = 58

TABLE C.10. SUMMARY OF MULTIPLE REGRESSION ANALYSIS II (DATA SET 5-2, RESPONSE VARIABLE W_1)

Independent Variables	Estimated Regression Coefficient	STD Error B	F / Significance	Beta / Elasticity
SEC2	.3224E-01	.6737E-02	22.910284 .000	.5271520 .04234
DT	- .2320E-02	.4826E-03	23.118811 .000	-.5320057 -.05354
CS	.4792E-02	.1317E-02	13.223265 .001	.4024415 .15720
Constant	.2601	.1387E-01	351.62451 .000	

Dependent Variable: W_1 (mils)

Standard Error of Estimate: 0.018

Mean: 0.305

Standard Deviation: 0.0305

C. V.: 10 %

R^2: 0.68

n = 30

TABLE C.11. SUMMARY OF MULTIPLE REGRESSION ANALYSIS II
(DATA SET 5-3, RESPONSE VARIABLE W_1)

Independent Variables	Estimated Regression Coefficient	STD Error B	F / Significance	Beta / Elasticity
SEC2	.2857E-01	.5395E-02	28.049989 .000	.6514163 .03633
SEC1	.2343E-01	.5393E-02	18.869572 .000	.5341279 .02979
DT	- .9628E-03	.3772E-03	6.5150934 .014	- .2671416 -.02294
Constant	.2594	.4597E-02	3185.7526 .000	

Dependent Variable: W_1 (mils)

Standard Error of Estimate: 0.0166

Mean: 0.271

Standard Deviation: 0.0210

C. V.: 7.7 %

R^2: 0.41

n = 58

TABLE C.12. SUMMARY OF MULTIPLE REGRESSION ANALYSIS II (DATA SET 5-4, RESPONSE VARIABLE W_1)

Independent Variables	Estimated Regression Coefficient	STD Error B	F / Significance	Beta / Elasticity
SEC2	.2597E-01	.5669E-02	20.984772 .000	.6312438 .04006
DT	.8753E-03	.4147E-03	4.4546051 .044	.2908370 .02358
Constant	.2428	.4593E-02	2795.0801 0	

Dependent Variable: W_1 (mils)

Standard Error of Estimate: 0.015

Mean: 0.259

Standard Deviation: 0.0205

C. V.: 7.9 %

R^2: 0.49

n = 30

TABLE C.13. SUMMARY OF MULTIPLE REGRESSION ANALYSIS II (DATA SET 5-5, RESPONSE VARIABLE W_1)

Independent Variables	Estimated Regression Coefficient	STD Error B	F / Significance	Beta / Elasticity
SEC2	.1071	.5852E-02	335.02259 .000	1.0014013 .15108
B1	.1518E-01	.5266E-02	8.3112377 .006	.1346500 .03854
CS	.3721E-02	.1417E-02	6.8946130 .012	.1787128 .12648
SEC1	.1267E-01	.6141E-02	4.2606944 .045	.1185123 .01788
S1	- .1045	.2408E-01	18.822945 .000	-.8461288 -.08844
TMID	.2864E-02	.6892E-03	17.275153 .000	.8441735 .74679
DT	- .2547E-02	.6921E-03	13.543098 .001	-.2830531 -.06210
Constant	.1902E-01	.4292E-01	.19644170 .660	

Dependent Variable: W_1 (mils)

Standard Error of Estimate: 0.015

Mean: 0.273

Standard Deviation: 0.0525

C. V.: 19.2 %

R^2: 0.93

n = 52

TABLE C.14. SUMMARY OF MULTIPLE REGRESSION ANALYSIS II (DATA SET 5-6, RESPONSE VARIABLE W_1)

Independent Variables	Estimated Regression Coefficient	STD Error B	F / Significance	Beta / Elasticity
SEC2	.5972E-01	.7711E-02	59.983955 .000	.8486018 .07920
DT	.1635E-02	.4930E-03	10.998929 .002	.3150969 .04384
SEC1	.1264E-01	.7717E-02	2.6861406 .111	.1796989 .01677
Constant	.2162	.6422E-02	1133.5656 .000	

Dependent Variable: W_1 (mils)

Standard Error of Estimate: 0.019

Mean: 0.251

Standard Deviation: 0.0336

C. V.: 13.4 %

R^2: 0.71

n = 36

TABLE C.15. SUMMARY OF MULTIPLE REGRESSION ANALYSIS II (DATA SET 5-7, RESPONSE VARIABLE W_1)

Independent Variables	Estimated Regression Coefficient	STD Error B	F / Significance	Beta / Elasticity
SEC2	.1145	.6593E-02	302.04427 .000	1.0629960 .15664
B1	.3696E-01	.5929E-02	38.872234 .000	.3253600 .09097
SEC1	.2173E-01	.6914E-02	9.8769924 .003	.2015999 .02971
S1	- .8195E-01	.2741E-01	8.9376141 .005	-.6584621 -.06722
TMID	.2056E-02	.7804E-03	6.9436944 .012	.6022963 .52018
DT	- .1723E-02	.7891E-03	4.7678403 .034	-.1886526 -.04133
CS	.1645E-02	.1596E-02	1.0622553 .308	.0784118 .05420
Constant	.7226E-01	.4871E-01	2.2007954 .145	

Dependent Variable: W_1 (mils)

Standard Error of Estimate: 0.017

Mean: 0.281

Standard Deviation: 0.0530

C. V.: 18.8 %

R^2: 0.91

n = 52

TABLE C.16. SUMMARY OF MULTIPLE REGRESSION ANALYSIS II (DATA SET 5-8, RESPONSE VARIABLE W_1)

Independent Variables	Estimated Regression Coefficient	STD Error B	F / Significance	Beta / Elasticity
SEC2	.4934E-01	.7098E-02	48.332229 .000	.6820782 .06558
DT	.1853E-02	.4480E-03	17.121163 .000	.3514946 .05092
CS	.5779E-02	.1632E-02	12.540544 .001	.4606231 .22964
SEC1	.9688E-02	.7468E-02	1.6829352 .204	.1339169 .01288
S1	- .9493E-02	.8965E-02	1.1213203 .298	-.1312248 -.01262
Constant	.1639	.1589E-01	106.40946 .000	

Dependent Variable: W_1 (mils)

Standard Error of Estimate: 0.017

Mean: 0.251

Standard Deviation: 0.0346

C. V.: 13.8 %

R^2: 0.79

n = 36

TABLE C.17. SUMMARY OF MULTIPLE REGRESSION ANALYSIS II (DATA SET 5-9, RESPONSE VARIABLE W_1)

Independent Variables	Estimated Regression Coefficient	STD Error B	F / Significance	Beta / Elasticity
SEC2	.7125E-01	.7202E-02	97.869457 0	.8187424 .09720
B1	.2458E-01	.7591E-02	10.485799 .002	.2679936 .06037
Constant	.2375	.7202E-02	1087.4385 0	

Dependent VAriable: W_1 (mils)

Standard Error of Estimate: 0.025

Mean: 0.282

Standard Deviation: 0.0428

C. V.: 15.2 %

R^2: 0.67

n = 52

TABLE C.18. SUMMARY OF MULTIPLE REGRESSION ANALYSIS II (DATA SET 5-10, RESPONSE VARIABLE W_1)

Independent Variables	Estimated Regression Coefficient	STD Error B	F / Significance	Beta / Elasticity
SEC2	.4066E-01	.7942E-02	26.210417 .000	.5853713 .05350
CS	.7036E-02	.1826E-02	14.843860 .001	.5840871 .27681
DT	.1507E-02	.4962E-03	9.2295763 .005	.3012428 .04129
SEC1	.1232E-01	.8358E-02	2.1758356 .151	.1775018 .01622
S1	- .1060E-01	.1004E-01	1.1141754 .300	-.1526062 -.01395
Constant	.1586	.1779E-01	79.467207 .000	

Dependent Variable: W_1 (mils)

Standard Error of Estimate: 0.019

Mean: 0.0253

Standard Deviation: 0.0332

C. V.: 13.1 %

R^2: 0.71

n = 36

TABLE C.19. SUMMARY OF MULTIPLE REGRESSION ANALYSIS II (DATA SET 5-11, RESPONSE VARIABLE W_1)

Independent Variables	Estimated Regression Coefficient	STD Error B	F / Significance	Beta / Elasticity
SEC1	- .1027	.1393E-01	54.389704 .000	-.6294758 -.12612
DT	- .6004E-02	.8376E-03	51.380490 .000	-.4467418 -.13091
CS	.8633E-02	.4540E-02	3.6152870 .064	.1296341 .23369
SEC2	.3485E-01	.1393E-01	6.2580439 .016	.2134348 .04276
B1	.1268E-01	.1258E-01	1.0163108 .319	.0737116 .02802
Constant	.2985	.3699E-01	65.160100 .000	

Dependent Variable: W_1 (mils)

Standard Error of Estimate: 0.036

Mean: 0.313

Standard Deviation: 0.0802

C. V.: 25.6 %

R^2: 0.82

n = 52

TABLE C.20. SUMMARY OF MULTIPLE REGRESSION ANALYSIS II (DATA SET 5-12, RESPONSE VARIABLE W_1)

Independent Variables	Estimated Regression Coefficient	STD Error B	F / Significance	Beta / Elasticity
SEC1	- .8971E-01	.1369E-01	42.890554 .000	-.6880136 -.10185
SEC2	.4807E-01	.1368E-01	12.344745 .001	.3686422 .05457
DT	- .2488E-02	.5368E-03	21.490935 .000	-.2691092 -.05945
S1	.2552E-01	.1306E-01	3.8149803 .060	.1957515 .02898
B2	- .2449E-01	.1590E-01	2.3718720 .134	-.1979853 -.04634
Constant	.3300	.1468E-01	505.14593 .000	

Dependent Variable: W_1 (mils)

Standard Error of Estimate: 0.021

Mean: 0.294

Standard Deviation: 0.0623

C. V.: 21.2 %

R^2: 0.90

n = 36

TABLE C.21. SUMMARY OF MULTIPLE REGRESSION ANALYSIS II
(DATA SET 5-13, RESPONSE VARIABLE W_1)

Independent Variables	Estimated Regression Coefficient	STD Error B	F / Significance	Beta / Elasticity
DT	-- .1201E-01	.3696E-02	10.561975 .010	-.6408480 -.21615
SEC1	- .2209	.7729E-01	8.1740360 .019	-.5637684 -.15841
Constant	.6391	.5566E-01	131.85465 .000	

Dependent Variable: W_1 (mils)

Standard Error of Estimate: 0.125

Mean: 0.465

Standard Deviation: 0.1930

C. V.: 41.5 %

R^2: 0.65

n = 12

TABLE C.22. SUMMARY OF MULTIPLE REGRESSION ANALYSIS II
(DATA SET 5-14, RESPONSE VARIABLE W_1)

Independent Variables	Estimated Regression Coefficient	STD Error B	F / Significance	Beta / Elasticity
SEC1	- .2278	.4240E-01	28.875027 .001	-.9032983 -.18716
TMID	- .7567E-02	.2085E-02	13.162350 .007	-.5351578 -1.82148
CS	.2487E-01	.1572E-01	2.5022136 .152	.2662976 .63145
Constant	.9647	.2703	12.736854 .007	

Dependent Variable: W_1 (mils)

Standard Error of Estimate: 0.06

Mean: 0.406

Standard Deviation: 0.1242

C. V.: 30.6 %

R^2: 0.83

n = 12

APPENDIX D

TEMPERATURE PREDICTION PROGRAM LISTING, INPUT GUIDE AND EXAMPLE OUTPUT

PROGRAM LISTING OF TEMPERATURE PREDICTION MODEL

```
      PROGRAM PTEMP (INPUT,OUTPUT)
C     ORIGINAL VERSION:      M. SHAHIN  CFHR RES. REPORT 123-14
C     REVISED VERSION 1.0:  WAHEED UDDIN       SEP.1982
C     VERSION 3.0          :  WAHEED UDDIN       12 DEC.1982
C     ********************************************
C     THIS PROGRAM CALCULATES PAVEMENT TEMPERATURES
C     AT ANY DEPTH KNOWING THE AMBIENT TEMPERATURE
C     AND WEATEHER CONDITIONS AND THE THERMAL PRO-
C     PERTIES OF MATERIAL.
C     TA    AVERAGE AIR TEMPERATURE(F)
C     TR    TEMPERATURE DAILY RANGE (F)
C     V     WIND SPEED (MPH)
C     AL    SOLAR RADIATION (LANGLEYS PER DAY)
C     X     DEPTH (INCHES)
C     *********************************************
C     THERMAL PROPERTIES OF MATERIAL      (CONCRETE)
C     W     MATERIAL DENSITY (IB/CU.FT.)     1[illegible].0
C     AK    THERMAL CONDUCTIVITY                0.93
C           (BTU/SQ.FT./HOUR/FT./DEGREE F)
C     S     SPECIFIC HEAT(BTU/IB/DEGREE F)      0.24
C     B     ABSOPTIVITY OF SOLAR RADIATION      0.75
C     *********************************************
      COMMON C,H,R,TA,TR
      DIMENSION TITLE(10),TEMP1([illegible]),TEMP2([illegible]),DT(30),TMID(30)
      DATA TEMP1(1),TEMP2(1),DT(1),TMID(1)/0.0,0. ,0.0,0.0/
      READ 11,NTOT
C     NTOT=TOTAL NO. OF PROBLEMS
      DO 10 IN=1,NTOT
C     DATE AND LOCATION OF MEASUREMENTS
      READ 41,NPROP,(TITLE(I),I=1,5)
      PRINT 42,NPROB,(TITLE(I),I=1,5)
      READ 12,TA,TR
      READ 12,V,W,S,AK,B,AL,X
      PRINT 14,TA,TR,V,W,S,AK,B,AL,X
      PRINT 43
      PRINT 44
      AH=1.3+0.62*V**.75
      H=AH/AK
      AC=AK/(S*W)
      C=(.131/AC)**.5
      R=.667*B*3.69*AL/(24.*AH)
      CALL WTEMP(0.,TEMP1)
      CALL WTEMP(X,TEMP2)
      DO 70 IJ=2,[illegible]
      DT(IJ)=TEMP1(IJ)-TEMP2(IJ)
      TMID(IJ)=(TEMP1(IJ)+TEMP2(IJ))/2.
   70 CONTINUE
```

```
      DO 20 J=2,25
      IHOUR=J-1
      ITIM=J+5.
      IF (ITIM.GT.12.) ITIM=ITIM-12.
      IF(J.GT.7) GO TO 61
      IF(J.LE.6) PRINT 51,IHOUR,ITIM,TEMP1(J),TEMP2(J),DT(J),TMID(J)
      IF(J.EQ.7) PRINT 52,IHOUR,ITIM,TEMP1(J),TEMP2(J),DT(J),TMID(J)
      GO TO 20
61    IF (J.LE.18) PRINT 53,IHOUR,ITIM,TEMP1(J),TEMP2(J),DT(J),TMID(J)
      IF(ITIM.GT.12.) ITIM=ITIM-12.
      IF (J.EQ.19) PRINT 54,IHOUR,ITIM,TEMP1(J),TEMP2(J),DT(J),TMID(J)
      IF (J.GT.19) PRINT 51,IHOUR,ITIM,TEMP1(J),TEMP2(J),DT(J),TMID(J)
20    CONTINUE
10    CONTINUE
41    FORMAT(I5,5X,5A10)
42    FORMAT(1H1,5X,*PROB. NO.    *,I5,5X,5A10,/)
43    FORMAT(/7X,*HOUR OF DAY*,8X,*TEMP,TOP    TEMP,BOTTOM*5X,*DT*,
     17X,*TMID*/)
44    FORMAT(/,3X,*HOURS*,20X,*DEG.-F*,5X,*DEG.-F*,7X,*DEG.-F*,4X,
     1*DEG.-F*/)
11    FORMAT(I5)
12    FORMAT(8F10.3)
51    FORMAT(1X,I4,I9,*  A.M.*,3X,2F10.1,3X,2F10.1)
52    FORMAT(1X,I4,I9,*  NOON*,3X,2F10.1,3X,2F10.1)
53    FORMAT(1X,I4,I9,*  P.M.*,3X,2F10.1,3X,2F10.1)
54    FORMAT(1X,I4,I9,*  MIDNIGHT *,F8.1,F10.1,3X,2F10.1)
14    FORMAT(5X,*AVE. AIR TEMP.=*,F10.3,5X,*DEG.F*,/,
     1        5X,*TEMP.RANGE    =*,F10.3,5X,*DEG.F  *,/,
     2        5X,*WIND VELOCITY =*,F10.3,5X,*MPH.   *,/,
     3        5X,*MATL. DENSITY =*,F10.3,5X,*PCF.   *,/,
     4        5X,*SPECIFIC HEAT =*,F10.3,5X,*BTU.PER POUND DEG.F*,/,
     5        5X,*CONDUCTIVITY  =*,F10.3,5X,*BTU.,HOUR,FT.,DEG.F*,/,
     6        5X,*ABSORBTIVITY  =*,F10.3,/,
     7        5X,*SOLAR RAD.    =*,F10.3,5X,*LANGLEYS PER DAY *,/,
     8        5X,*DEPTH         =*,F10.3,5X,*INCHES*,/)
      END
      SUBROUTINE ATEMP(X,TEMP)
      COMMON C,H,R,TA,TR
      DIMENSION TEMP(30)
      Z2=(-X)*C/12.
      Z3=H*EXP(Z2)/((H+C)**2+C**2)**.5
      DO 20 J=2,25
      ITIM=J
      IF(J.GT.9) GO TO 31
      Z4=6.81768*(.0576*ITIM+.144*Z2-.288)
      GO TO 35
31    IF(J.GT.14) GO TO 32
```

```
      Z4=-14.7534*(.02057*ITIM+.075*Z2-.288)
      GO TO 35
   32 Z4=-6.94274*(.02057*ITIM+.12*Z2-.288)
   35 Z5=SIN(Z4)
      IF (Z5) 21,22,22
   21 TM=TA+R
      TV=.4*TR
      GO TO 23
   22 TV=0.5*TR+3.0*R
      TM=TA+R
   23 TEMP(J)=TM+TV*Z3*Z5
   20 CONTINUE
      RETURN
      END
```

EXAMPLE INPUT OF 1981 DATA FROM COLUMBUS,TEXAS

```
4
1       COLUMBUS BYPASS SH 71  AUG.06,1981
85.500    25.000
 8.300   150.000      .240      .900      .750   575.000    10.000
2       COLUMBUS BYPASS SH 71  AUG.07,1981
85.000    24.000
 7.500   150.000      .240      .900      .750   575.000    10.000
3       COLUMBUS BYPASS SH 71  NOV.30,1981
70.500     9.000
10.500   150.000      .240      .900      .750   255.000    10.000
4       COLUMBUS BYPASS SH 71  DEC.31,1981
60.000    32.000
10.800   150.000      .240      .900      .750   255.000    10.000
```

INPUT GUIDE

NTOT

15		One Card

NTOT = Total number of problems (maximum of 5 problems)

FOR EACH PROBLEM

NPROB — One Card

15	5 x	5 A 10

NPROB = Problem number for identification

TITLE(I) = Date and Location (I = 1 to NTOT).

TA	TR	
F10.3	F10.3	One Card

TA = Average air temperature (°F): (From weather record)

TR = Daily temperature range (°F): (From weather record)

V	W	S	AK	B	AL	X	
F10.3	F10.3	F10.3	F10.3	F10.3	F10.3	F10.3	One Card

V = Wind speed (mph): (From weather record)

W = Mix density (lb/cu.ft.): (See Table 4.3)

S = Specific heat (BTU/lg/°F): (See Table 4.3)

AK = Thermal conductivity (BTU/sq. ft./hour/°F/ft.): (See Tables 4.2 and 4.3)

B = Absorptivity: (See Table 4.3)

AL = Solar radiation (Langley's/day): (From weather record)

X = Depth (inches): (Equal to thickness of concrete slab)

EXAMPLE OUTPUT

PROB. NO. 1 COLUMBUS BYPASS SH 71 AUG.06,1981

```
AVE. AIR TEMP.=    85.500     DEG.F
TEMP.RANGE    =    25.000     DEG.F
WIND VELOCITY =     8.300     MPH.
MATL. DENSITY =   150.000     PCF.
SPECIFIC HEAT =      .240     BTU.PER POUND DEG.F
CONDUCTIVITY  =      .900     BTU.,HOUR,FT.,DEG.F
ABSORBTIVITY  =      .750
SOLAR RAD.    =   575.000     LANGLEYS PER DAY
DEPTH         =    10.000     INCHES
```

HOUR OF DAY			TEMP,TOP	TEMP,BOTTOM	DT	TMID
HOURS			DEG.-F	DEG.-F	DEG.-F	DEG.-F
1	7	A.M.	89.8	95.6	-5.9	92.7
2	8	A.M.	91.1	95.3	-4.1	93.2
3	9	A.M.	93.2	95.0	-1.7	94.1
4	10	A.M.	95.7	94.8	.9	95.3
5	11	A.M.	106.4	94.8	11.6	100.6
6	12	NOON	115.4	94.9	20.5	105.1
7	1	P.M.	121.4	95.1	26.3	108.3
8	2	P.M.	123.5	95.4	28.1	109.5
9	3	P.M.	121.8	95.5	26.2	108.7
10	4	P.M.	117.7	96.2	21.5	106.9
11	5	P.M.	111.6	97.4	14.2	104.5
12	6	P.M.	104.0	98.5	5.6	101.2
13	7	P.M.	95.7	99.3	-3.5	97.5
14	8	P.M.	94.8	99.8	-5.0	97.3
15	9	P.M.	93.9	99.7	-5.8	96.8
16	10	P.M.	93.0	99.5	-6.5	96.3
17	11	P.M.	92.2	99.2	-7.0	95.7
18	12	MIDNIGHT	91.5	98.9	-7.4	95.2
19	1	A.M.	90.8	98.5	-7.6	94.7
20	2	A.M.	90.3	98.0	-7.7	94.1
21	3	A.M.	89.8	97.5	-7.7	93.7
22	4	A.M.	89.5	96.9	-7.4	93.2
23	5	A.M.	89.3	96.4	-7.0	92.8
24	6	A.M.	89.3	95.8	-6.5	92.5

PROB. NO. 2 COLUMBUS BYPASS SH 71 AUG.07,1981

AVE. AIR TEMP. =	85.000	DEG.F
TEMP.RANGE =	24.000	DEG.F
WIND VELOCITY =	7.500	MPH.
MATL. DENSITY =	150.000	PCF.
SPECIFIC HEAT =	.240	BTU.PER POUND DEG.F
CONDUCTIVITY =	.900	BTU.,HOUR,FT.,DEG.F
ABSORBTIVITY =	.750	
SOLAR RAD. =	575.000	LANGLEYS PER DAY
DEPTH =	10.000	INCHES

HOUR OF DAY			TEMP,TOP	TEMP,BOTTOM	DT	TMID
HOURS			DEG.-F	DEG.-F	DEG.-F	DEG.-F
1	7	A.M.	90.2	95.7	-5.5	92.9
2	8	A.M.	91.5	95.3	-3.9	93.4
3	9	A.M.	93.4	95.1	-1.6	94.3
4	10	A.M.	95.8	94.9	.9	95.3
5	11	A.M.	106.5	94.9	11.6	100.7
6	12	NOON	115.5	95.0	20.6	105.3
7	1	P.M.	121.6	95.2	26.4	108.4
8	2	P.M.	123.7	95.5	28.2	109.6
9	3	P.M.	122.0	95.6	26.4	108.8
10	4	P.M.	117.9	96.3	21.6	107.1
11	5	P.M.	111.7	97.5	14.3	104.6
12	6	P.M.	104.1	98.5	5.6	101.3
13	7	P.M.	95.8	99.3	-3.6	97.5
14	8	P.M.	94.9	99.9	-5.0	97.4
15	9	P.M.	94.1	99.8	-5.7	96.9
16	10	P.M.	93.2	99.6	-6.3	96.4
17	11	P.M.	92.5	99.3	-6.8	95.9
18	12	MIDNIGHT	91.8	98.9	-7.2	95.4
19	1	A.M.	91.2	98.5	-7.4	94.9
20	2	A.M.	90.7	98.1	-7.4	94.4
21	3	A.M.	90.2	97.6	-7.3	93.9
22	4	A.M.	89.9	97.0	-7.1	93.5
23	5	A.M.	89.8	96.4	-6.7	93.1
24	6	A.M.	89.7	95.8	-6.1	92.8

PROB. NO. 3 COLUMBUS BYPASS SH 71 NOV.30,1981

AVE. AIR TEMP.=	70.500	DEG.F
TEMP.RANGE =	9.000	DEG.F
WIND VELOCITY =	10.500	MPH.
MATL. DENSITY =	150.000	PCF.
SPECIFIC HEAT =	.240	BTU.PER POUND DEG.F
CONDUCTIVITY =	.900	BTU.,HOUR,FT.,DEG.F
ABSORBTIVITY =	.750	
SOLAR RAD. =	255.000	LANGLEYS PER DAY
DEPTH =	10.000	INCHES

HOURS	HOUR OF DAY		TEMP,TOP DEG.-F	TEMP,BOTTOM DEG.-F	DT DEG.-F	TMID DEG.-F
1	7	A.M.	72.2	74.5	-2.2	73.3
2	8	A.M.	72.8	74.3	-1.6	73.5
3	9	A.M.	73.6	74.2	-.7	73.9
4	10	A.M.	74.5	74.1	.3	74.3
5	11	A.M.	78.7	74.1	4.6	76.4
6	12	NOON	82.4	74.2	8.2	78.3
7	1	P.M.	84.8	74.3	10.5	79.5
8	2	P.M.	85.6	74.4	11.2	80.0
9	3	P.M.	84.9	74.4	10.5	79.7
10	4	P.M.	83.3	74.7	8.6	79.0
11	5	P.M.	80.8	75.2	5.7	78.0
12	6	P.M.	77.8	75.6	2.2	76.7
13	7	P.M.	74.5	75.9	-1.4	75.2
14	8	P.M.	74.1	76.1	-2.0	75.1
15	9	P.M.	73.8	76.1	-2.3	74.9
16	10	P.M.	73.5	76.0	-2.5	74.7
17	11	P.M.	73.2	75.9	-2.7	74.5
18	12	MIDNIGHT	72.9	75.8	-2.9	74.3
19	1	A.M.	72.7	75.6	-2.9	74.1
20	2	A.M.	72.4	75.4	-3.0	73.9
21	3	A.M.	72.3	75.2	-2.9	73.7
22	4	A.M.	72.2	75.0	-2.8	73.6
23	5	A.M.	72.1	74.8	-2.7	73.4
24	6	A.M.	72.1	74.5	-2.5	73.3

PROB. NO. 4 COLUMBUS BYPASS SH 71 DEC.01,1981

AVE. AIR TEMP.	=	60.000	DEG.F
TEMP.RANGE	=	32.000	DEG.F
WIND VELOCITY	=	10.800	MPH.
MATL. DENSITY	=	150.000	PCF.
SPECIFIC HEAT	=	.240	BTU.PER POUND DEG.F
CONDUCTIVITY	=	.900	BTU.,HOUR,FT.,DEG.F
ABSORBTIVITY	=	.750	
SOLAR RAD.	=	255.000	LANGLEYS PER DAY
DEPTH	=	10.000	INCHES

HOUR OF DAY			TEMP,TOP	TEMP,BOTTOM	DT	TMID
HOURS			DEG.-F	DEG.-F	DEG.-F	DEG.-F
1	7	A.M.	55.9	63.8	-7.9	59.9
2	8	A.M.	57.8	63.3	-5.6	60.6
3	9	A.M.	60.6	62.9	-2.3	61.8
4	10	A.M.	63.9	62.7	1.2	63.3
5	11	A.M.	71.2	62.6	8.5	66.9
6	12	NOON	77.3	62.8	14.5	70.0
7	1	P.M.	81.4	63.1	18.3	72.2
8	2	P.M.	82.8	63.5	19.3	73.2
9	3	P.M.	81.6	63.7	17.9	72.7
10	4	P.M.	78.8	64.3	14.6	71.6
11	5	P.M.	74.7	65.1	9.6	69.9
12	6	P.M.	69.6	65.8	3.8	67.7
13	7	P.M.	63.9	66.3	-2.4	65.1
14	8	P.M.	62.7	66.7	-4.0	64.7
15	9	P.M.	61.5	66.6	-5.2	64.1
16	10	P.M.	60.3	66.5	-6.2	63.4
17	11	P.M.	59.2	66.3	-7.1	62.8
18	12	MIDNIGHT	58.2	66.1	-7.8	62.2
19	1	A.M.	57.4	65.8	-8.4	61.6
20	2	A.M.	56.6	65.5	-8.9	61.0
21	3	A.M.	56.0	65.1	-9.1	60.6
22	4	A.M.	55.6	64.8	-9.2	60.2
23	5	A.M.	55.3	64.4	-9.1	59.8
24	6	A.M.	55.2	64.0	-8.7	59.6

APPENDIX E

TEMPERATURE CORRECTION AS APPLIED TO THE DEFLECTIONS MEASURED AT THE PAVEMENT EDGE

APPENDIX E. TEMPERATURE CORRECTION AS APPLIED TO THE DEFLECTIONS MEASURED AT THE PAVEMENT EDGE

TEMPERATURE CORRECTION PROCEDURE

A procedure to apply a temperature correction to the Dynaflect deflections measured near or at the edge of a rigid pavement is described in this appendix. As discussed earlier, in Chapters 3 and 4, temperature differential, DT in the slab was the most important temperature parameter which significantly influences the deflections measured at the pavement edge. The relationship between W_1 (sensor 1 deflection) and DT at the pavement edge is shown in Fig E.1. The deflection measured at any temperature differential should be corrected to bring it to the condition of zero temperature differential. The step-by-step procedure is outlined below.

(1) Collect repeat Dynaflect deflection measurements at a location at or near the pavement edge.

(2) Measure the temperatures of the top and the bottom of the concrete slab corresponding to the time of deflection measurements. The data are to be used to estimate the corresponding temperature differentials. An estimate of hourly distribution of the temperature differential can also be made by utilizing the predictive model described in Chapter 4 and making use of the climatological data for the test location.

(3) Develop a simple linear regression equation with W_1 (sensor 1 deflection) as the dependent variable and DT as the independent variable. This can be accomplished on a programmable hand calculator.

(4) The slope of the best fit regression line (from step 3) represents the change in the W_1 due to a unit change in DT. Calculate required amount of correction in the W_1 measurement by multiplying the slope with the corresponding value of DT.

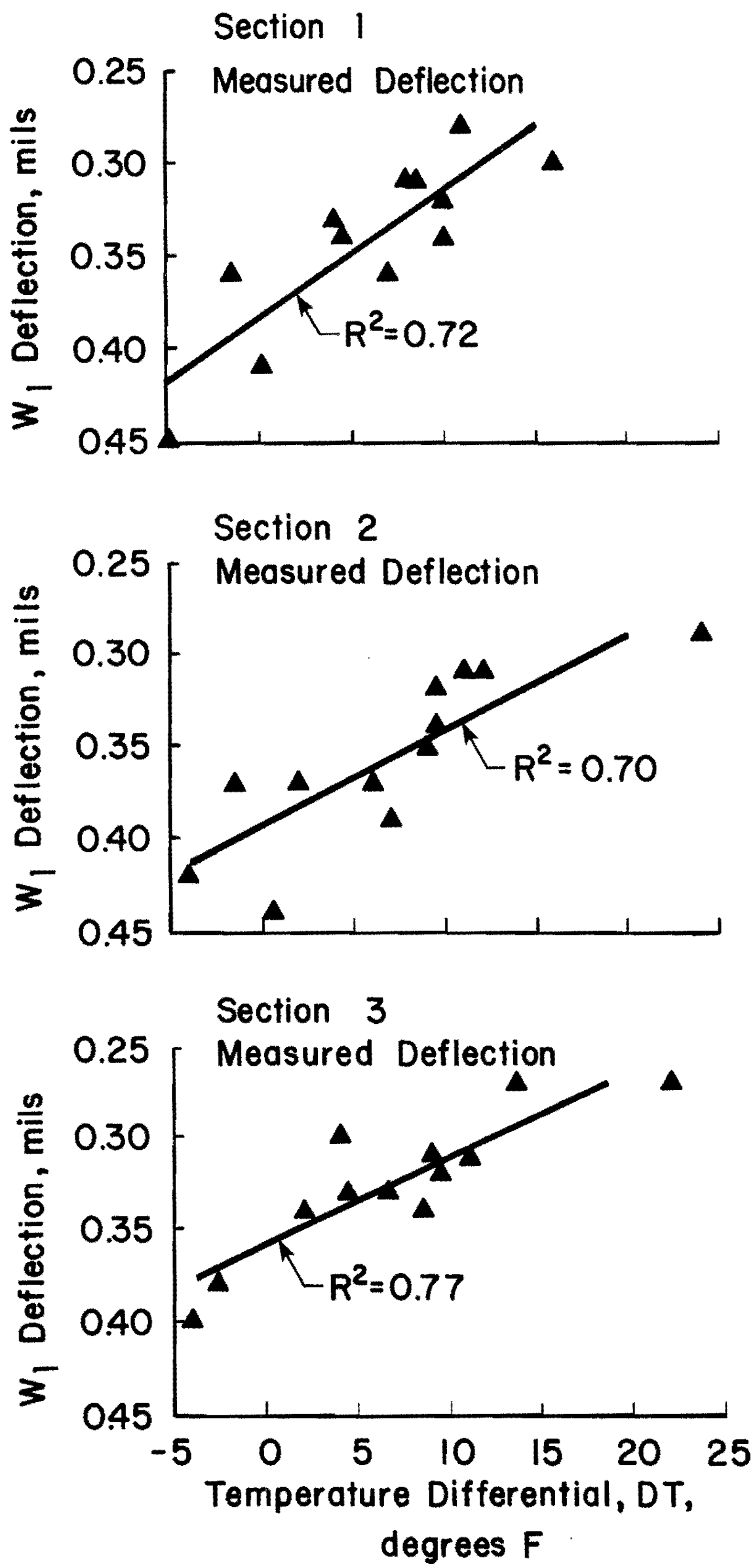

Fig E.1. Measured W_1 deflections versus temperature differential relationship at location 1L, Columbus bypass, SH-71 (1981 data).

(5) Calculate the W_1 corresponding to the zero temperature differential by applying the estimated correction to the measured deflection, W_1. In the case of a positive value of DT, the corrected deflection will be larger than the measured deflection or in other words the correction will be additive.

EXAMPLE OF TEMPERATURE CORRECTION

This section presents an example to illustrate how the measured W_1 deflections were corrected to obtain the true deflections corresponding to a zero temperature differential.

The data for W_1 and DT corresponds to location 1L of the test sections at the Columbus bypass. Each data set corresponds to 12 repeat deflection measurements for section no. 1, 2, and 3, respectively. The estimated regression coefficients of the best fit line in each case are presented in Table E.1. The W_1 versus DT plots and the regression lines are illustrated in Fig E.1. The corrections were applied as explained in steps 4 and 5, in the preceding section. The resulting corrected deflections versus DT are plotted in Fig E.2. The corresponding measured deflections are also plotted in the same figure. Figure E.3 illustrates the best fit lines for the measured and corrected deflections. As expected, the regression lines for the corrected deflections are practically horizontal, with values of R^2 equal to zero. This means that the influence of temperature differential has been removed from the measured W_1 deflections. The summary statistics for measured and corrected deflections are presented in Table E.2. It is noted that coefficients of variation for corrected deflections in all three sections are within 5 to 7 percent, which reflects the acceptable range of inherent variability in the Dynaflect deflections.

TABLE E.1. ESTIMATED PARAMETERS OF THE BEST FIT REGRESSION LINES FOR LOCATION 1L (AT 1 ft FROM THE PAVEMENT EDGE)

Estimated Parameters	Section 1	Section 2	Section 3
(Constant):	0.38384	0.39319	0.35843
Slope: (B)	-0.00685	-0.00515	-0.00477
Beta	-0.8484	-0.8369	-0.8792
Elasticity	-0.1207	-0.1024	-0.1029
Statistics			
R^2	.72	0.70	0.77
S.E.E.	0.0266	0.0263	0.0192

W_1 = Dependent Variable (mils)

DT(°F) = Independent Variable

TABLE E.2. SUMMARY STATISTICS OF MEASURED (W_1) AND CORRECTED (W_T) DEFLECTIONS AT LOCATION 1L

Section	Summary Statistics	Dependent Variable	
		W_1 (Measured)	W_T (Corrected)
1	Mean (mils)	0.342	0.384
	S.D.	0.049	0.025
	C.V.	14.0%	6.6%
	R^2*	0.72	0.00
2	Mean (mils)	0.357	0.393
	S.D.	0.045	0.025
	C.V.	12.8%	6.4%
	R^2*	0.70	0.00
3	Mean (mils)	0.325	0.358
	S.D.	0.038	0.018
	C.V.	11.8%	5.1%
	R^2*	0.77	0.00

*From simple linear regression analysis with DT as independent variable on combined data of Summer and Fall 1981.

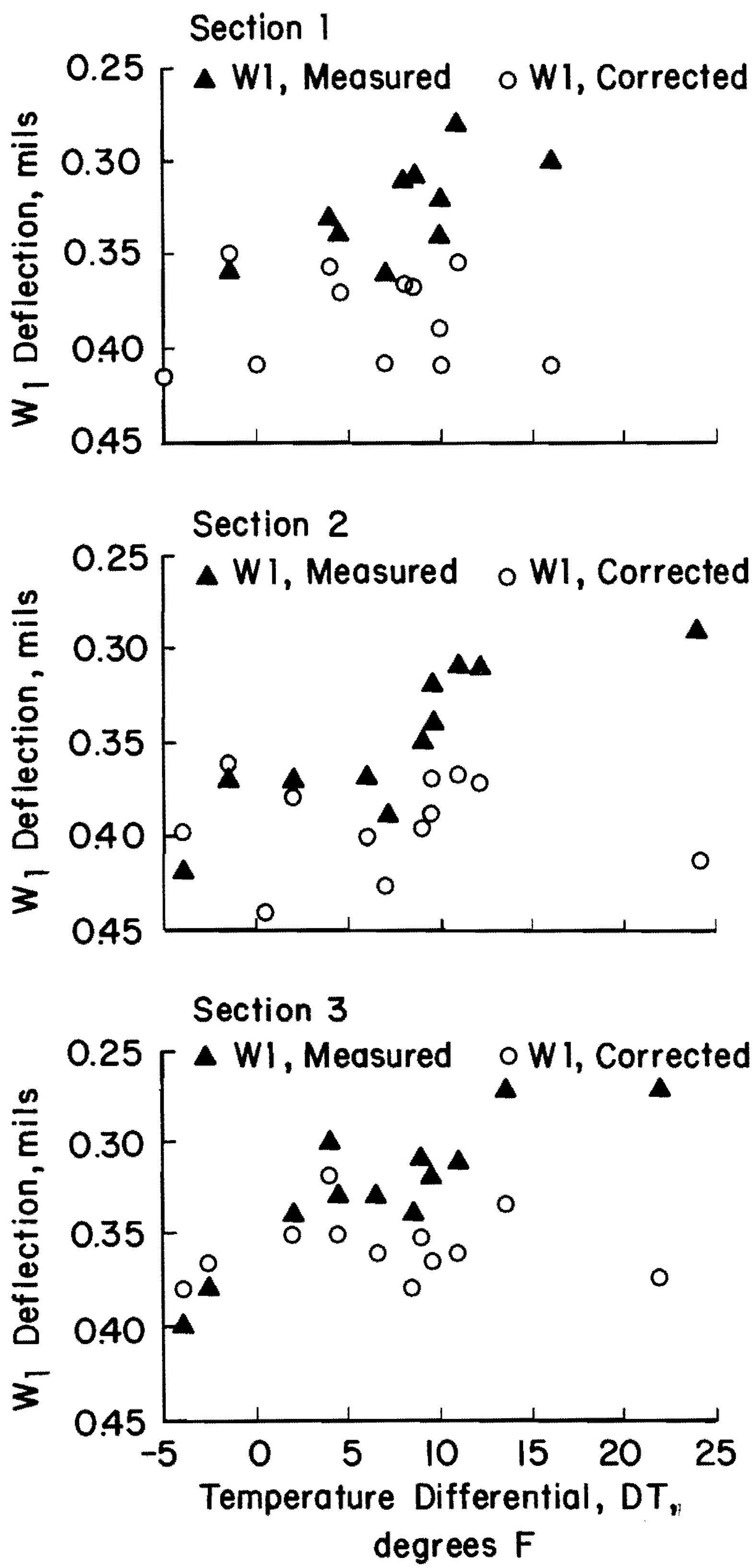

Fig E.2. Measured and corrected W_1 deflections at location 1L, Columbus bypass, SH-71 (1981 data).

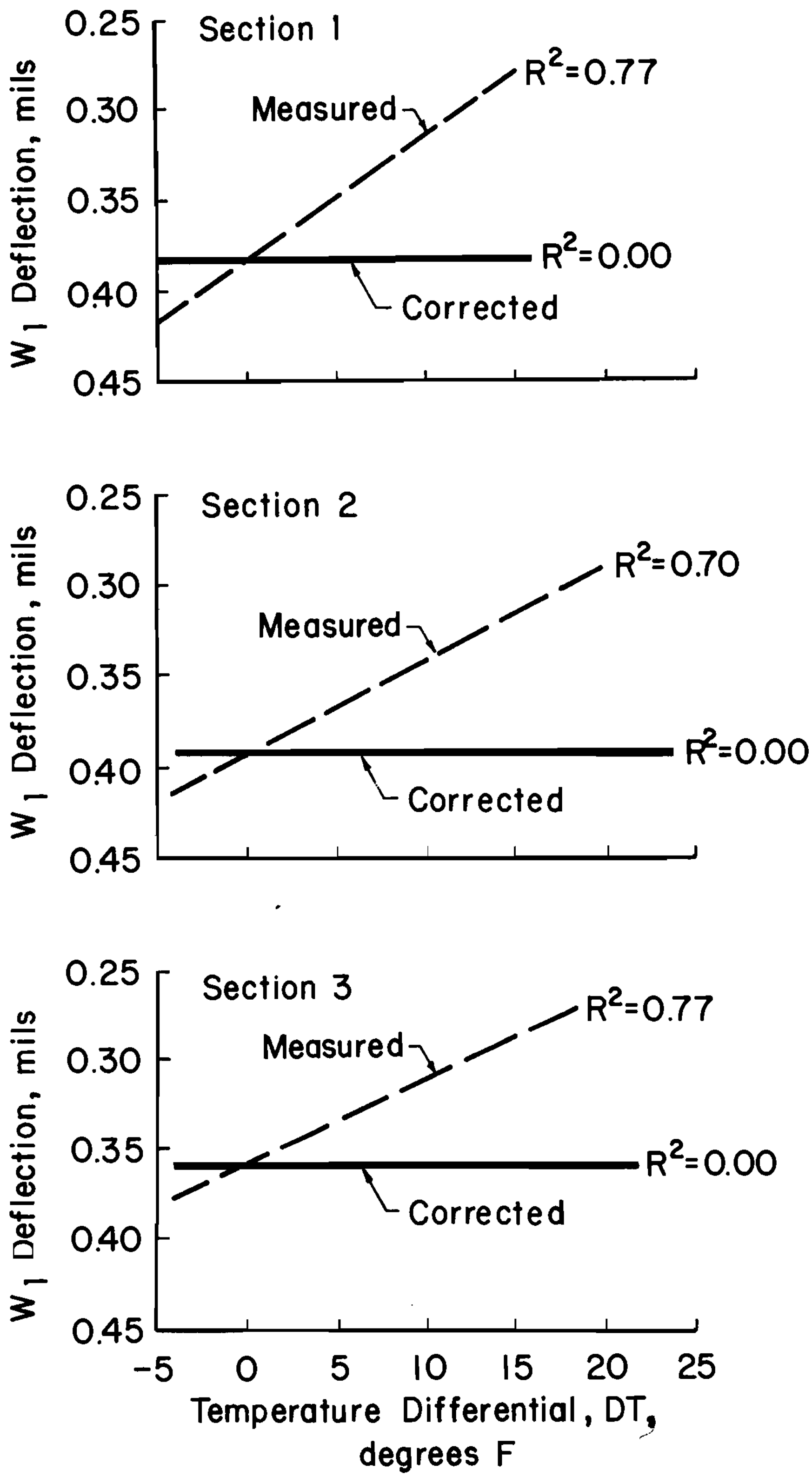

Fig E.3. Best fit lines for measured and corrected W_1 deflections at location 1L, Columbus bypass, SH-71 (1981 data).

APPENDIX F

EXAMPLES OF BACK-CALCULATED YOUNG'S MODULI FROM DYNAFLECT DEFLECTION BASINS

APPENDIX F. EXAMPLES OF YOUNG'S MODULI BACK-CALCULATED FROM DYNAFLECT DEFLECTION BASINS

Figures F.1 and F.2 show a comparison of the two computer programs, BASFIT (Version 3.0) and ELSYM5, used to back-calculate static moduli of the pavement layers. During investigations, it was found that the old version of BASFIT gave erroneous results in the case of a rigid bottom. The version 3.0 of BASFIT was therefore developed employing a recent version of LAYER8; which gave results comparable to the results from ELSYM5 (see Fig F.2). BASFIT (version 3.0) was later used in all the investigations discussed in Chapter 5.

Typical results of Young's moduli back-calculated from deflection basins measured for different pavement structures are illustrated in Figs F.3 to F.11.

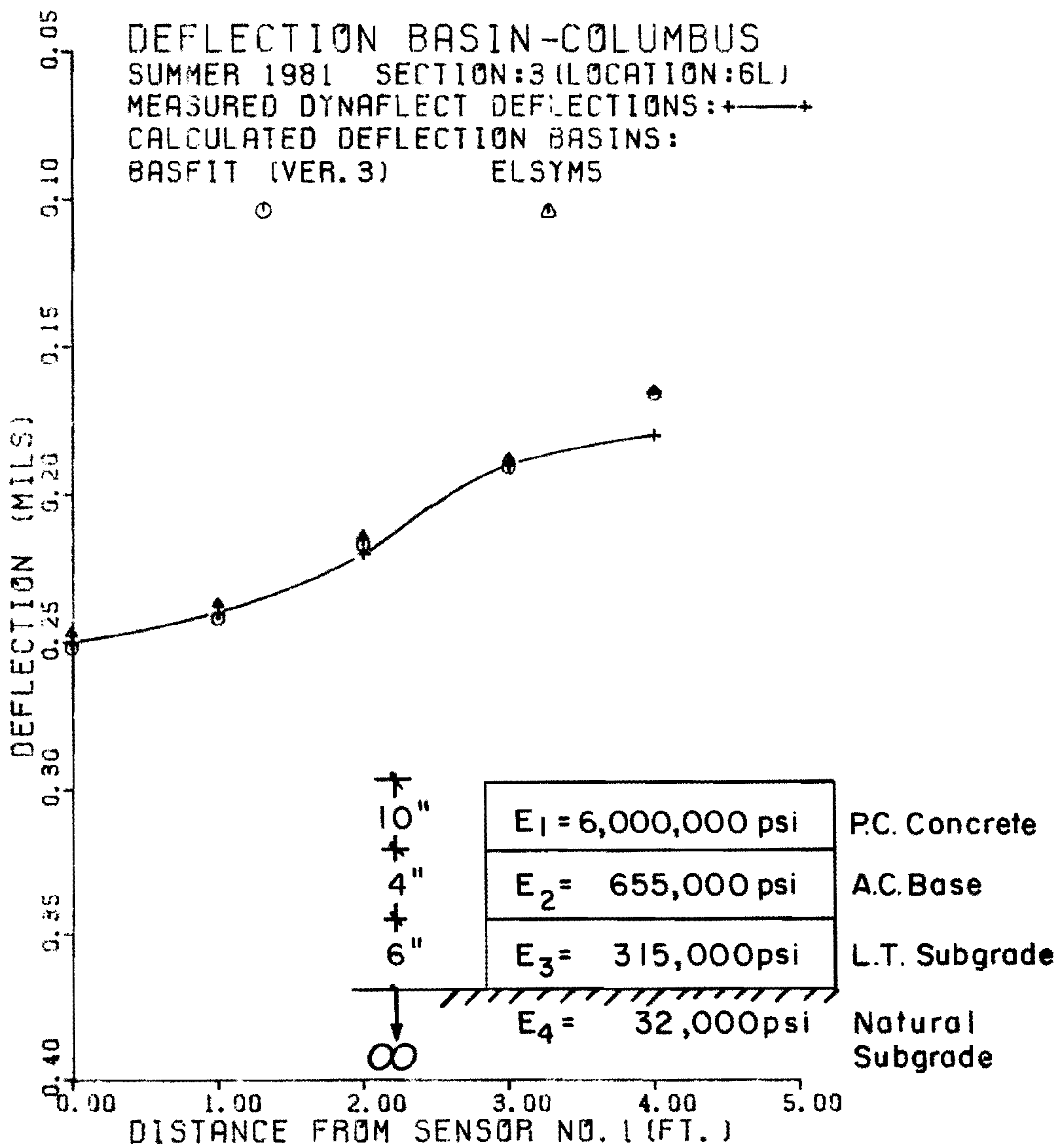

Fig F.1. Comparison of calculated deflection basins (infinite subgrade).

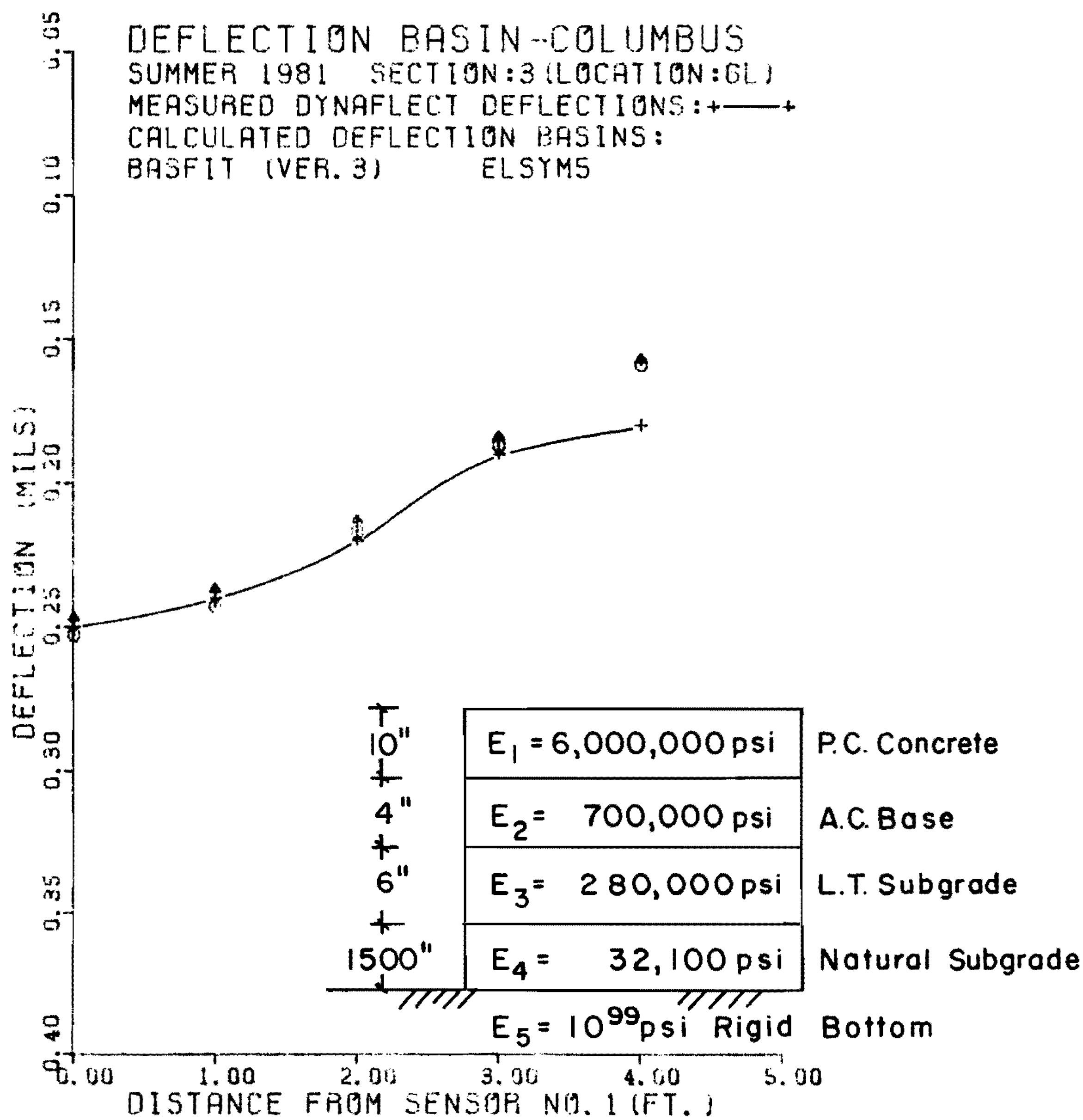

Fig F.2. Comparison of calculated deflection basins (case of rigid bottom).

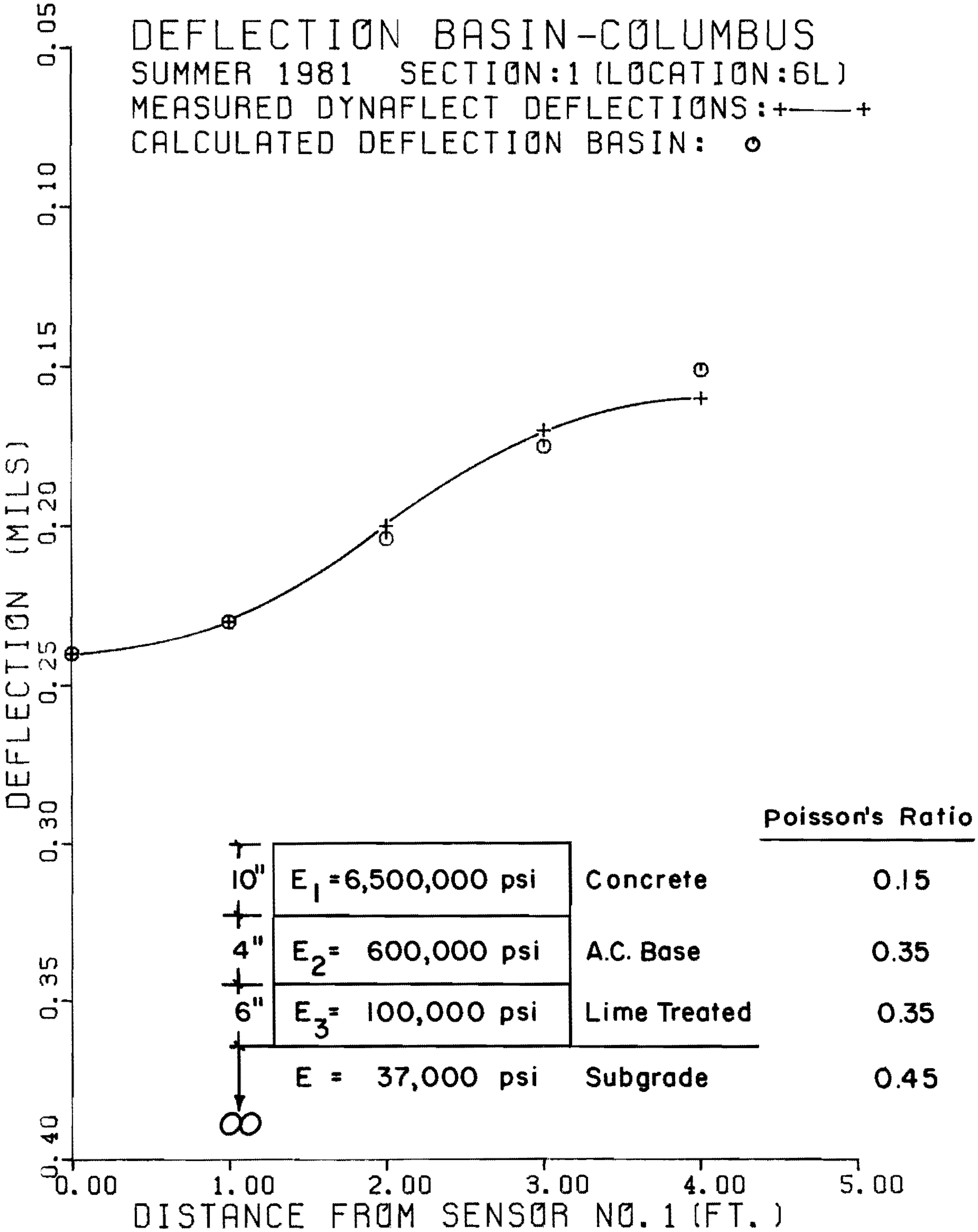

Fig F.3. Measured and calculated deflection basins (Example 1).

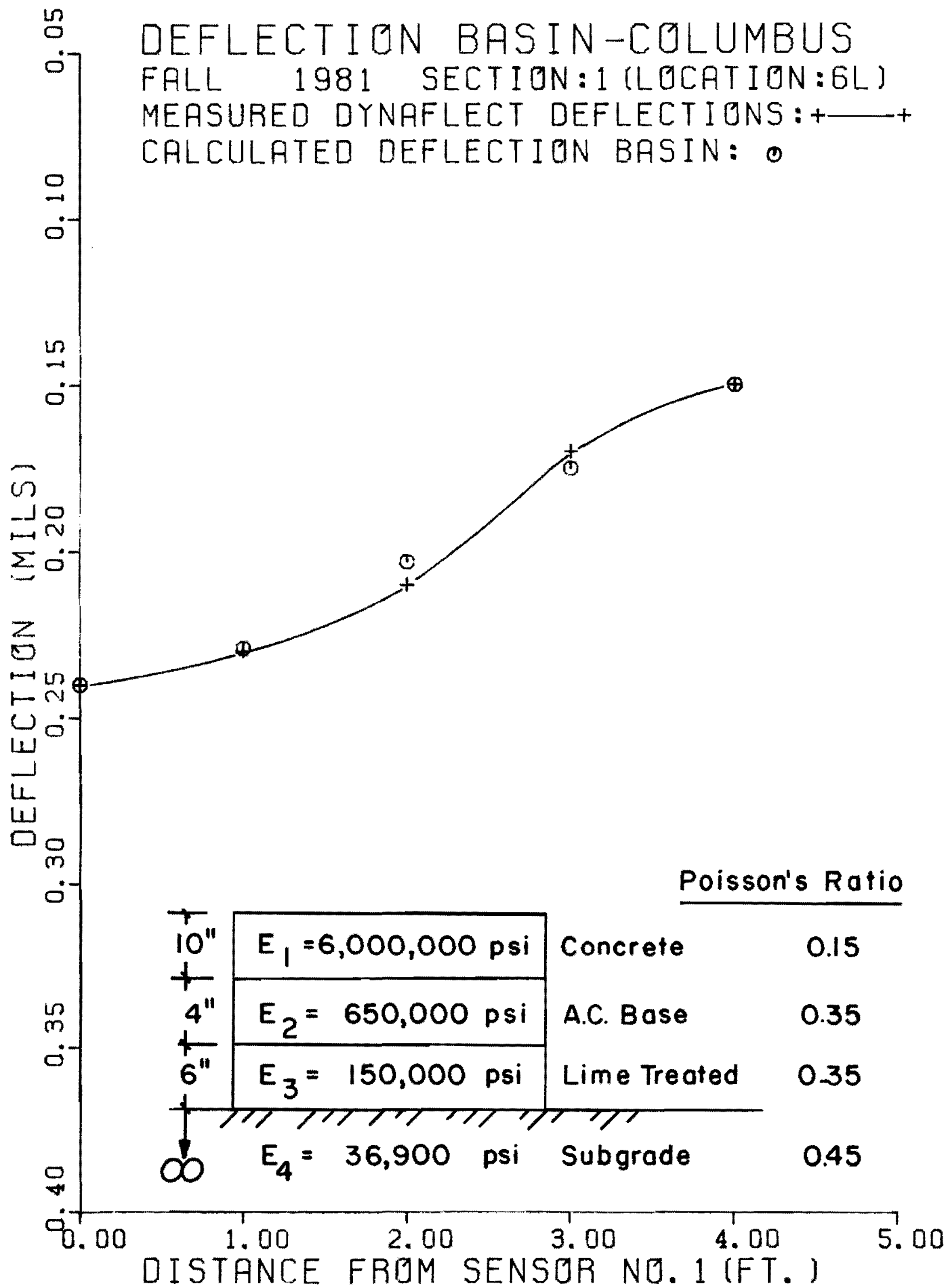

Fig F.4. Measured and calculated deflection basins (Example 2).

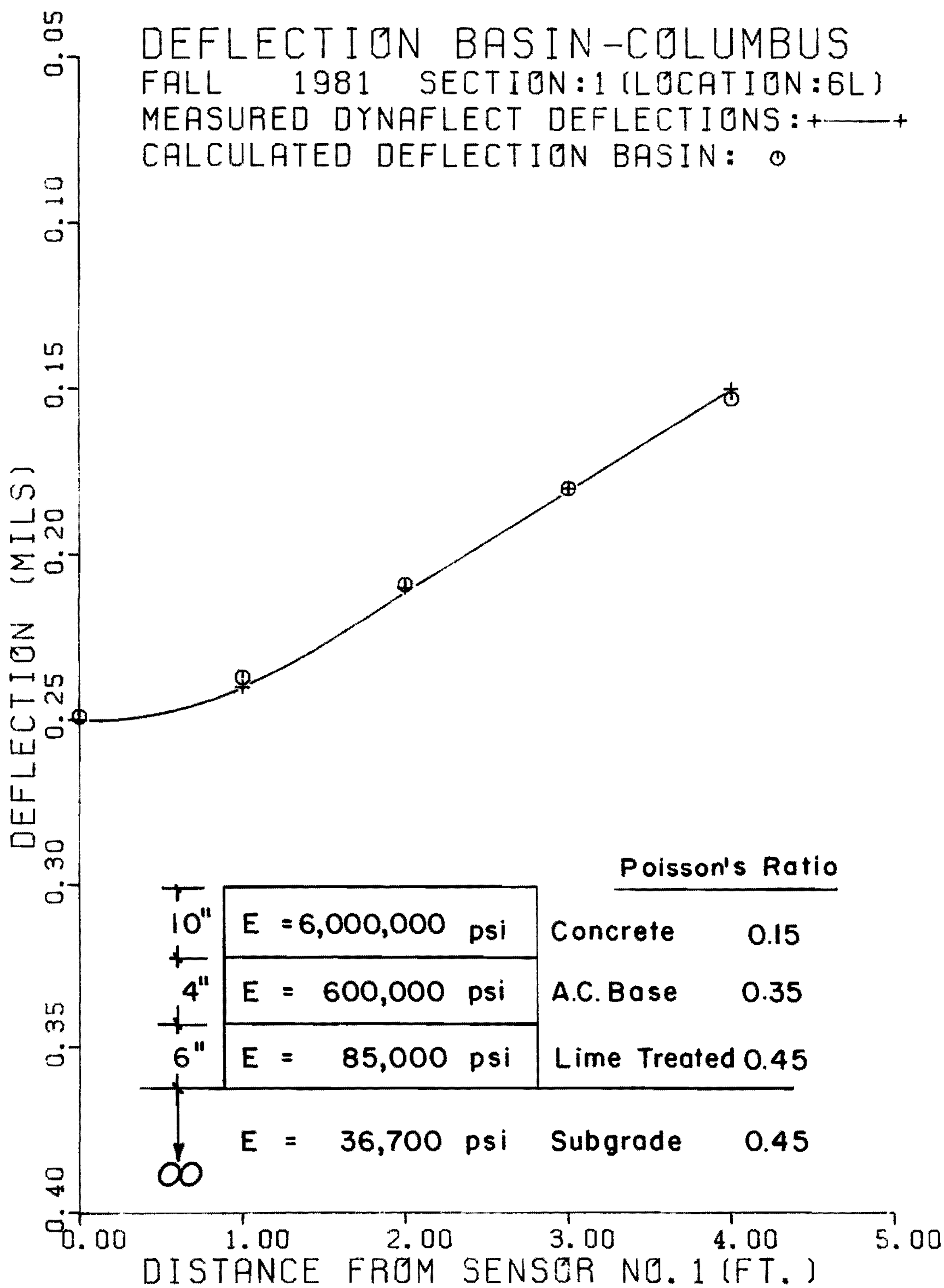

Fig F.5. Measured and calculated deflection basins (Example 3).

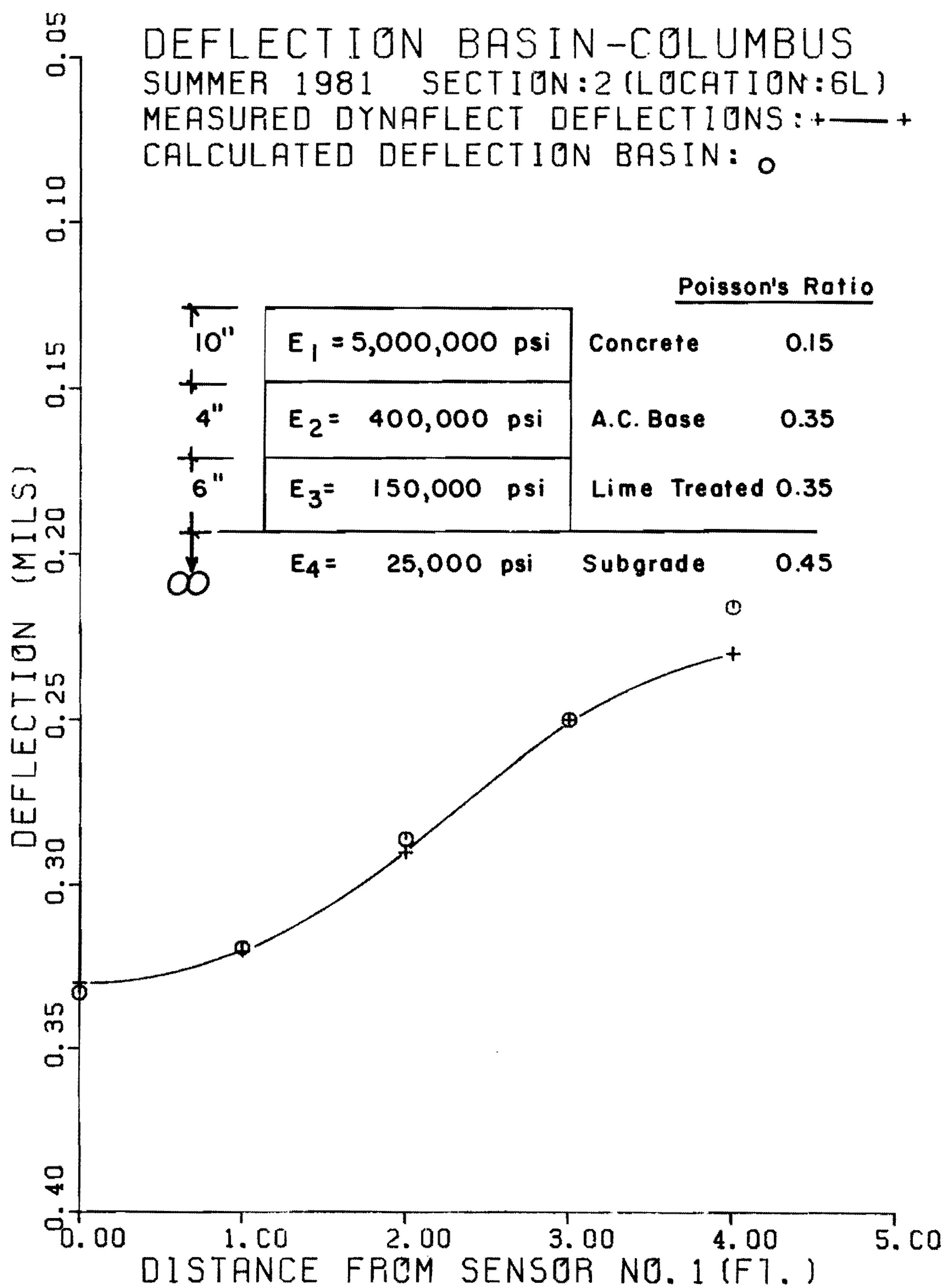

Fig F.6. Measured and calculated deflection basins (Example 4).

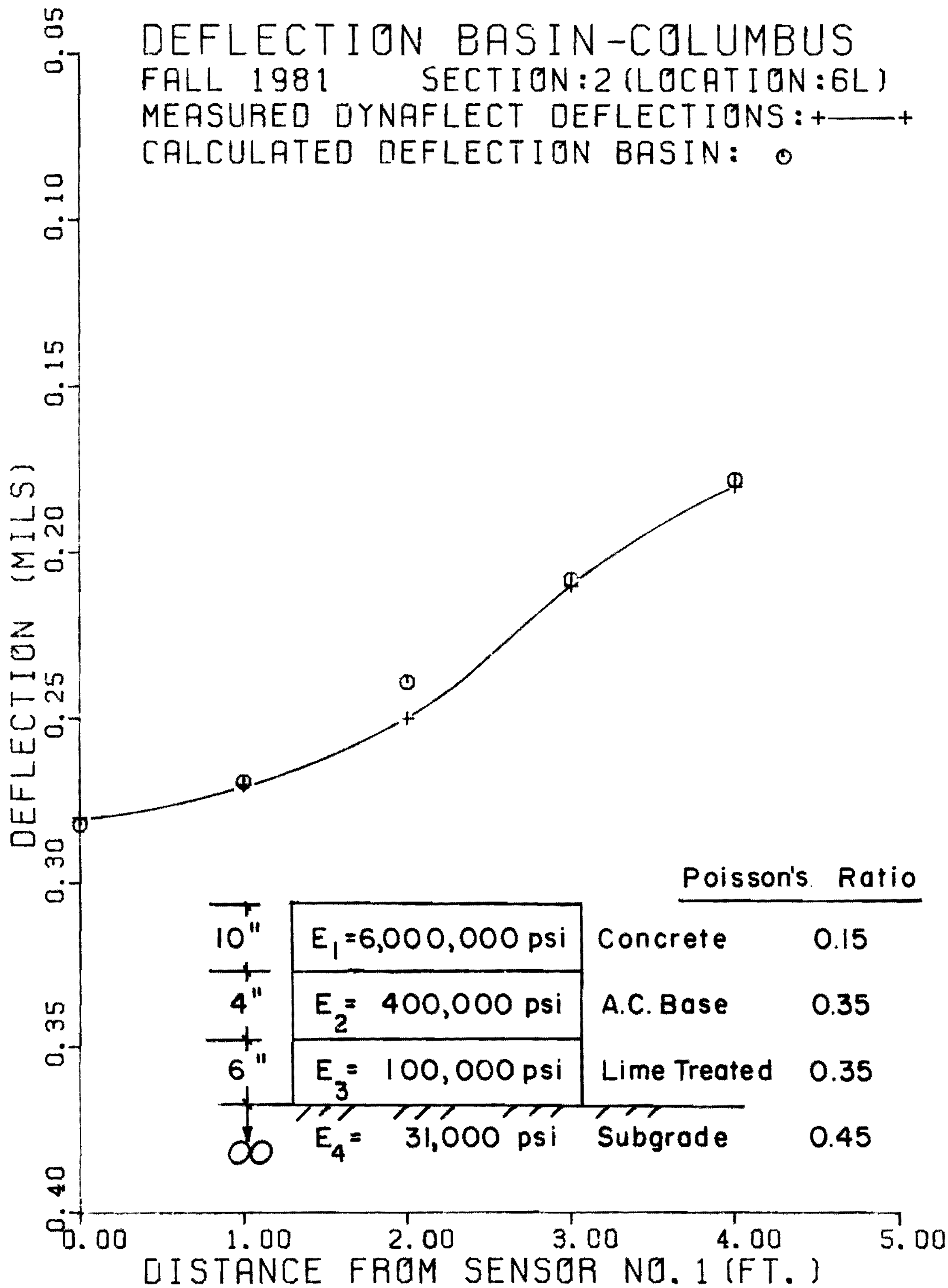

Fig F.7. Measured and calculated deflection basins (Example 5).

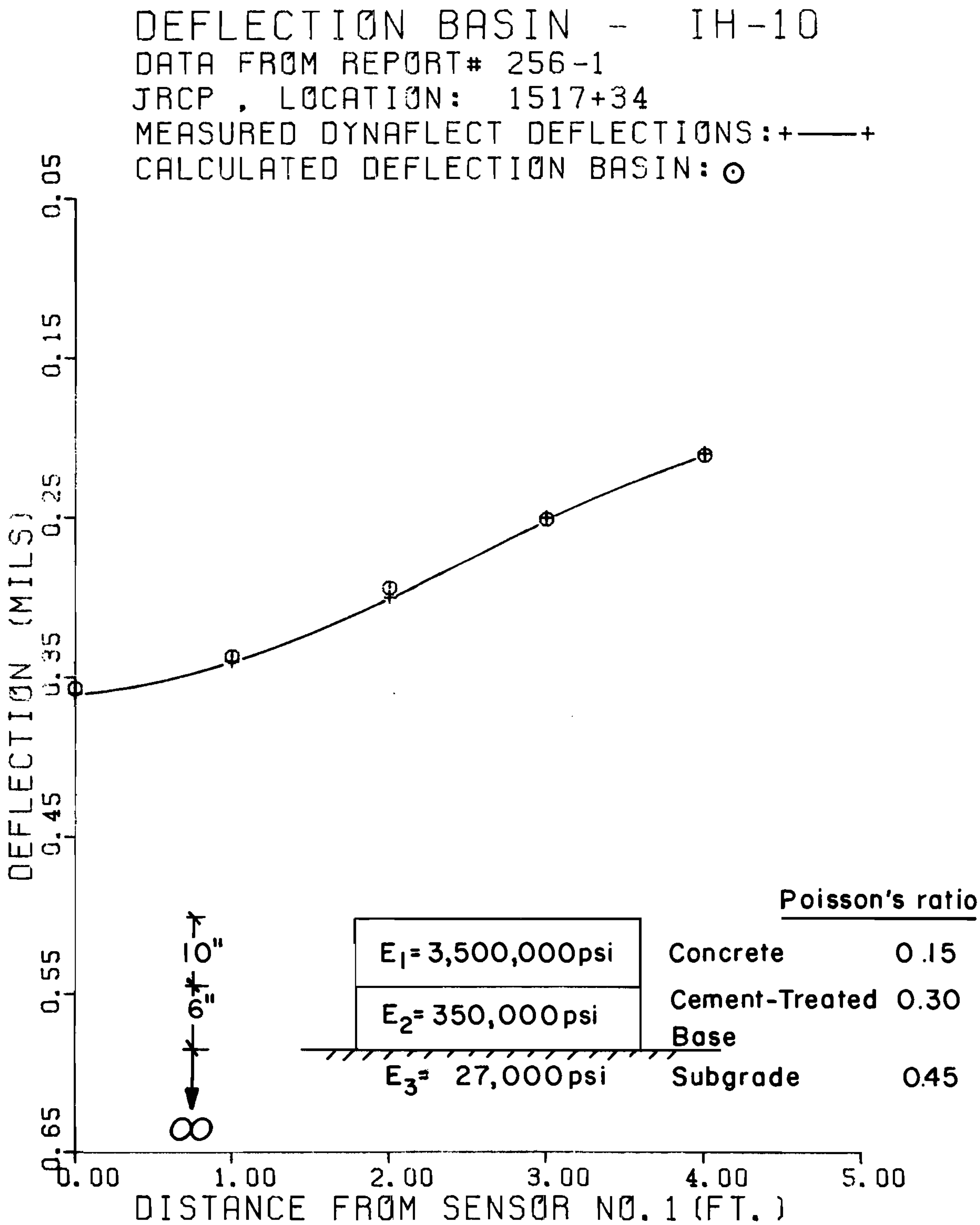

Fig F.8. Measured and calculated deflection basins (Example 6).

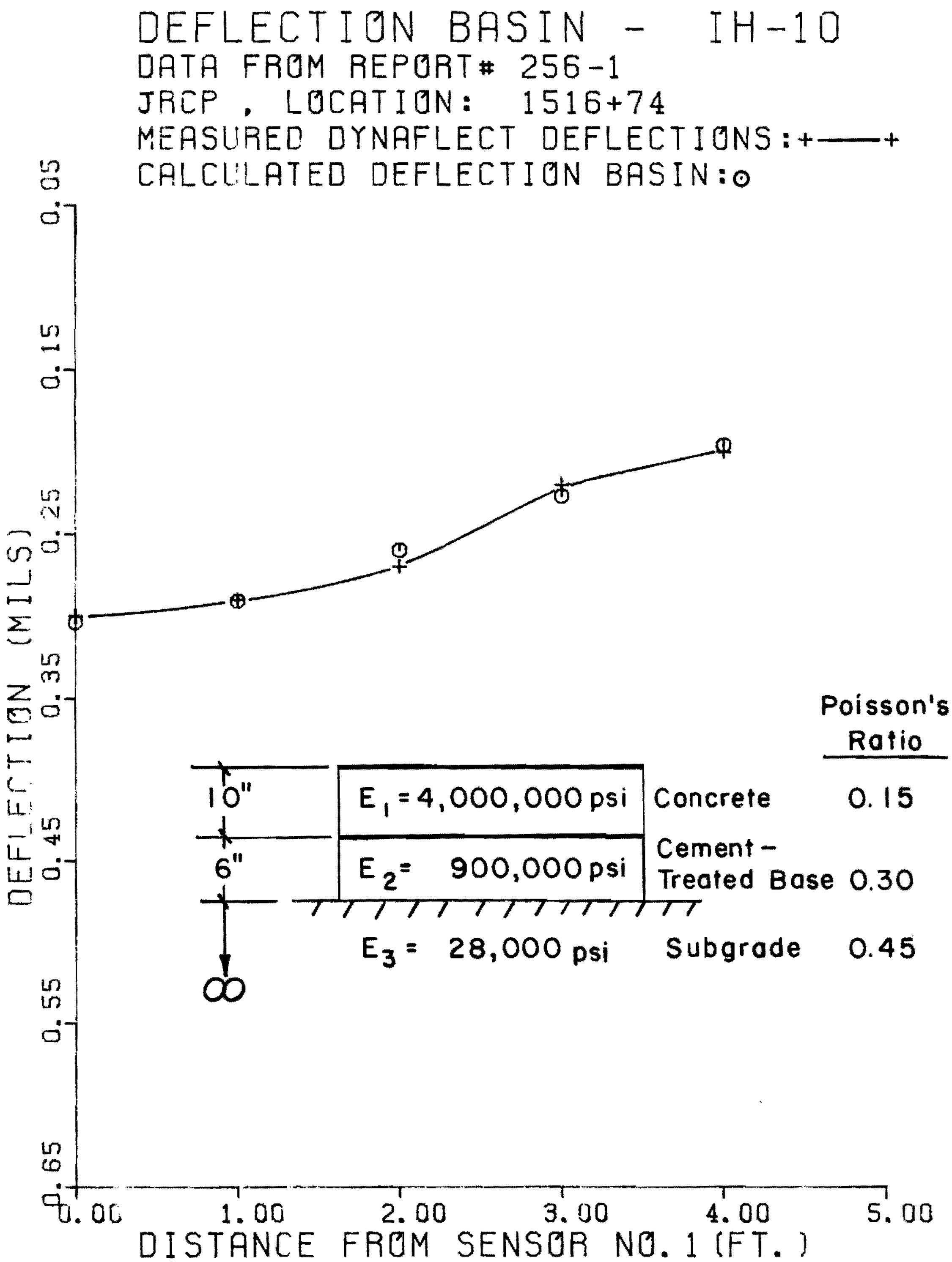

Fig F.9. Measured and calculated deflection basins (Example 7).

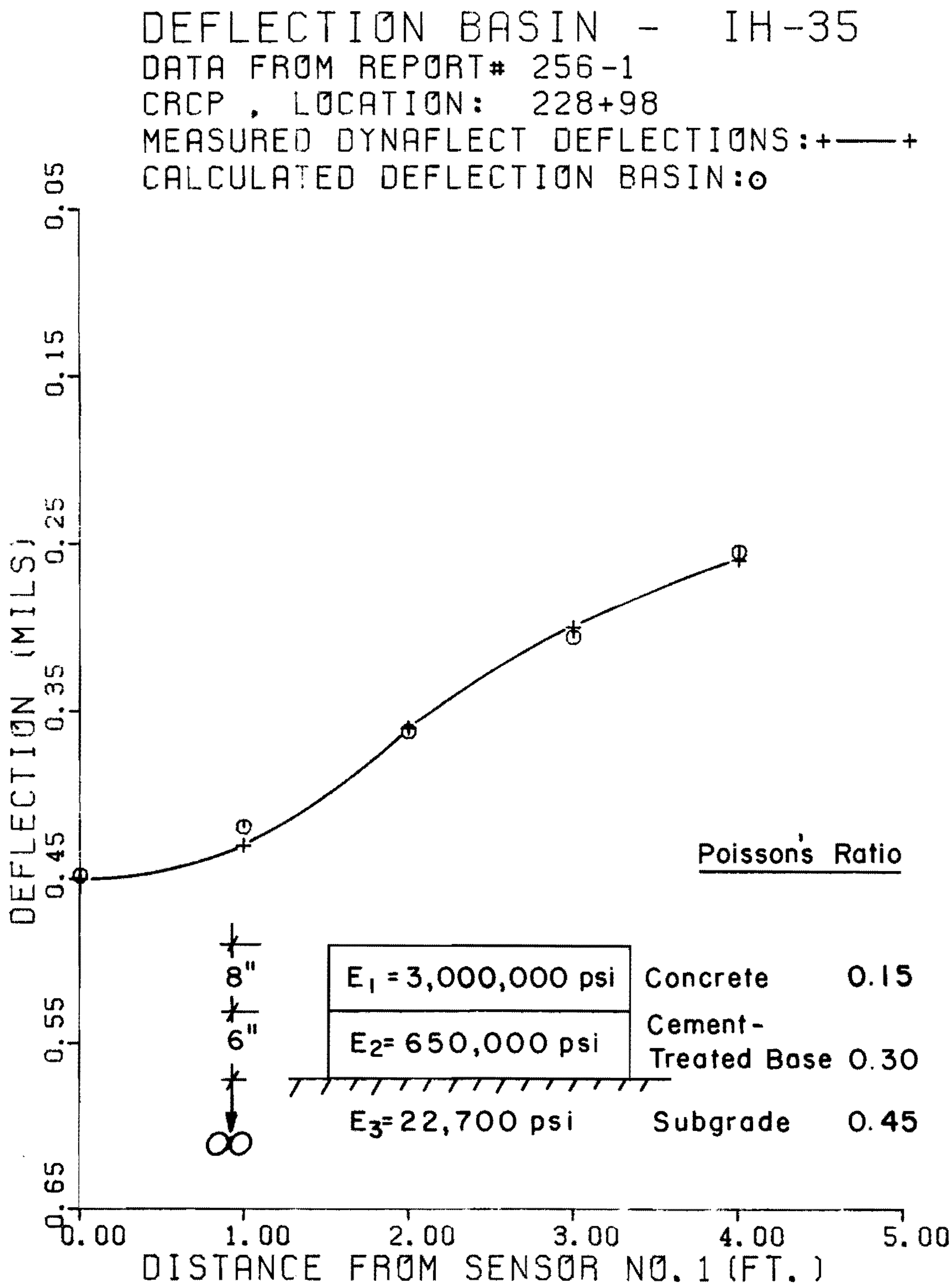

Fig F.10. Measured and calculated deflection basins (Example 8).

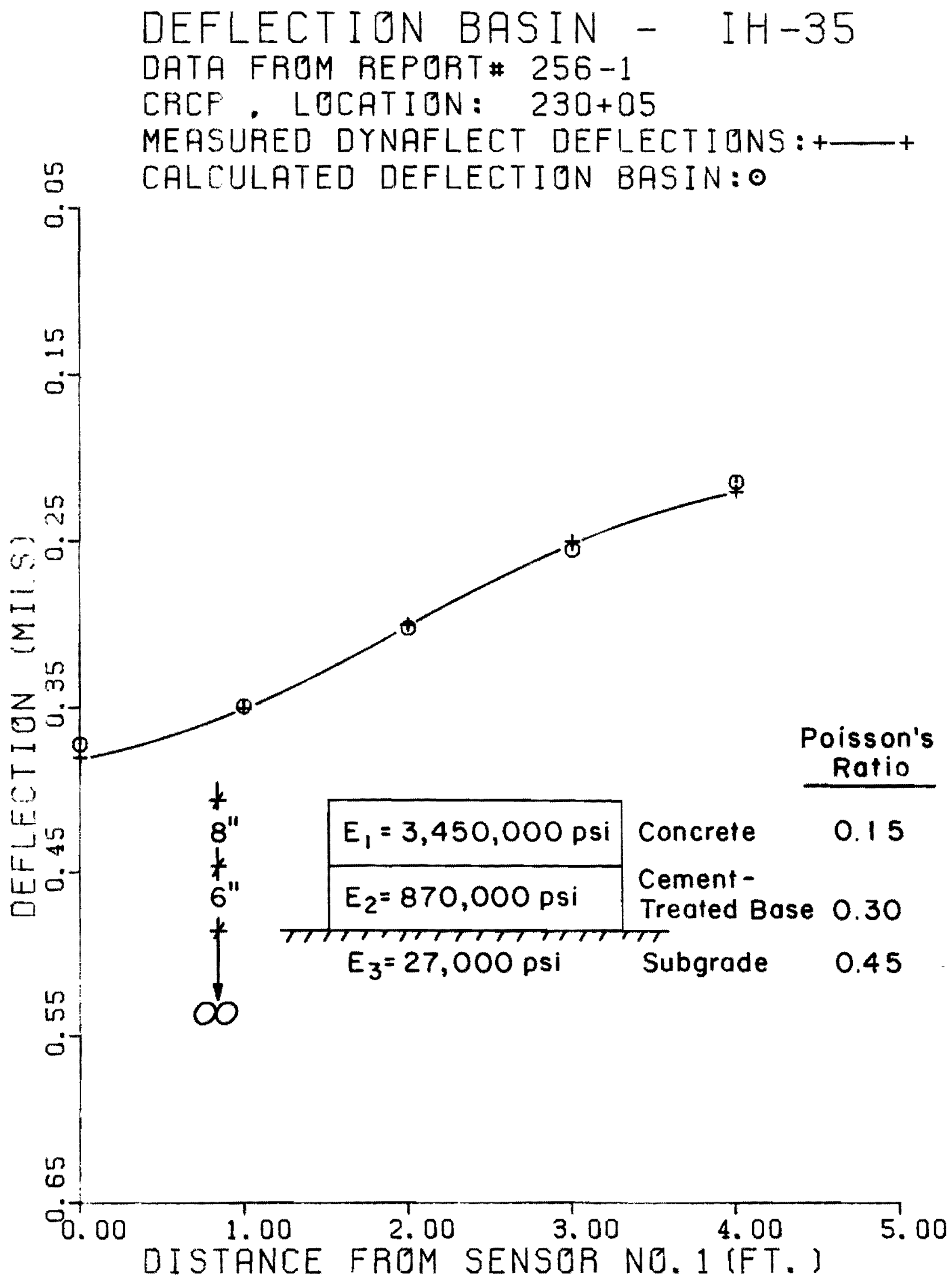

Fig F.11. Measured and calculated deflection basins (Example 9).

THE AUTHORS

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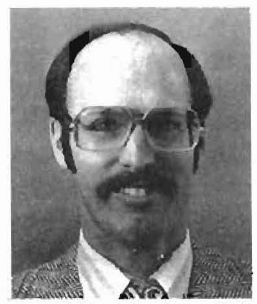

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