

Study of Factors Influencing Deflections of Continuously Reinforced-Concrete Pavements

WAHEED UDDIN, ALVIN H. MEYER, and W. RONALD HUDSON

ABSTRACT

The results of an investigation of the effects of temperature and location variables on Dynaflect deflections measured on rigid pavements are presented. All the experimental work described in this paper was carried out during the fall and summer of 1981 on a new 10-in.-thick, continuously reinforced-concrete pavement near Columbus, Texas. Dynaflect deflections and the top and bottom temperatures of the concrete slab were analyzed by using analysis of variance and multiple linear-regression techniques. The findings of this study are included in a procedure recommended for making Dynaflect measurements and for applying suitable temperature corrections to deflections measured near the pavement edge.

Nondestructive evaluation of existing pavements was carried out to assess their structural adequacy and rehabilitation needs. The Dynaflect, a steady-state vibratory device, is widely used 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 pavement. Dynaflect deflection data are used for in situ characterization of pavement layers and subgrade as a basic step in several current overlay design procedures. In the case of rigid pavements the distress manifestations indicate other deficiencies and problems, such as inadequate subgrade support conditions, existence of voids beneath the concrete pavement, and insufficient load transfer across transverse cracks and joints. A major rehabilitation program for an existing rigid pavement may include rectification of these deficiencies plus an overlay for the structural strengthening required for future design axle load applications. Dynaflect deflection data can also provide diagnostic information related to the evaluation of load transfer and detection of voids.

According to the available structural models based on the plate theory, the deflection of rigid pavements is influenced by the position of the applied loads. Furthermore, daily variations of temperature create a cycle of temperature differential in the concrete slab, which results in curling (1).

OBJECTIVES AND SCOPE OF STUDY

Several factors influence any deflection measurement made on a specific slab. Two of these are temperature and load position. In the case of a rigid pavement, these effects are significant. A temperature gradient through the thickness of the slab induces thermal stresses and, subsequently, curling. The de-

flection measurements may therefore be affected by temperature, particularly at the slab edge.

The principal objectives of this study are to

1. Identify temperature effects and other factors related to load position across the test section that may influence the Dynaflect deflections in rigid pavements,
2. Investigate the influence of these factors on measured Dynaflect deflections,
3. Develop, if necessary, a procedure for correcting the measured deflections to remove the effects of temperature, and
4. Recommend the most suitable placement of the Dynaflect for making deflection measurements for characterizing placement or for detecting voids beneath pavements in place.

The experimental program carried out on a continuously reinforced-concrete (CRC) pavement, the summary data, and the results of statistical analyses are described in this paper.

DEFLECTION BEHAVIOR OF RIGID PAVEMENTS

Environmental Variables

Temperature Effects

The average temperature of a concrete slab varies daily and yearly. Concrete pavement adjusts to yearly seasonal variations in temperatures by contraction or expansion over a considerable period of time. The major effect of seasonal variations in temperature is the development of frictional forces between the concrete slab and the underlying layer.

Daily temperature variations within the concrete slab are more important to deflection measurements because (a) there is a large deviation in temperature on the concrete surface in a daily cycle, and (b) the temperature gradient between the top and bottom of the concrete slab can vary considerably during a 24-hr cycle. The temperature gradient through a concrete slab causes surfaces to warp. For example, if the top of the slab is warmer than the bottom (e.g., near noon on a sunny day), the slab corners will tend to curl downwards. Upward curling will occur when the top surface is cooler than the bottom, such as late on a cool night. A parameter commonly used to study the effect of temperature gradient is temperature differential (DT), the algebraic difference between the temperatures of the top and the bottom of a concrete slab. DT is a positive value when the temperature of the top of the slab is higher than the temperature of the bottom, and it is negative when the bottom of the slab is warmer than the upper surface. The temperature differential is the result of the slow conduction of heat in concrete and therefore is 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. During the present study the maximum temperature differential (24.6°F) was observed in August 1981 for

the 10-in. concrete slab. The 1965 deflection study on CRC pavements reported by McCullough and Treybig (2) revealed an inverse relationship between temperature differential and the edge deflection (Benkelman beam) measured at the crack position.

Seasonal Effect

Any seasonal changes in deflections are generally the result of seasonal variations of moisture in the unbound base layer and the subgrade. The seasonal effects on deflections on rigid pavements are thoroughly discussed elsewhere (1,3). Metwali (4) described the results of analysis of variance (ANOVA) applied to the Dynaflect deflection data collected during fall and spring on different rigid pavement test sections. Metwali concluded that jointed-concrete pavements and asphalt pavements demonstrated statistically significant changes in the maximum Dynaflect deflections because of seasonal variations. CRC pavements did not experience appreciable seasonal variations in their deflection contrast. The findings by Metwali (4) are interesting and somewhat in conflict with current data and belief. Further research is needed, especially for CRC pavements.

Location Variable

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

Effect of Pavement Edge

Pumping in underlying unbound layers eventually results in the creation of voids under the pavement edge. Voids may also result from any movement in the subgrade or natural material, such as swelling or uneven settlement. The presence of voids beneath a pavement will result in relatively higher deflections. Birkhoff and McCullough (5) recommended a deflection survey along a pavement section to detect voids under the pavement edge. An important assumption in 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. Therefore a rehabilitation program should include a deflection survey to identify void areas.

Effect of Edge Support Conditions

The type of edge support will have a marked influence on the deflection behavior near the pavement edge. It is known from Westergaard's solutions that, for the case of edge loading, stresses at the pavement edge are much higher than stresses resulting from interior loading, and, because deflection is proportional to load stress, a larger deflection occurs at the pavement edge. For a concrete shoulder, deflection can be expected to be less than for 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 pavements are usually tightly held, but a loss in the load transfer will

result in deflections larger than those measured between cracks (midspan position). Deflection at a crack will increase as the crack width increases. For material characterization, the midspan 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.

DESCRIPTION OF SETUP FOR DYNAFLECT AND TEMPERATURE MEASUREMENTS

A testing scheme was designed for making Dynaflect deflection and temperature measurements to investigate the effects of temperature and of the Dynaflect position. A newly constructed CRC 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 on the southbound lanes. The first measurements were made on August 6 and 7, 1981, and resulted in four cycles at each test location (Figure 1). The pavement consists of a 10-in. concrete surface layer, a 4-in. asphalt

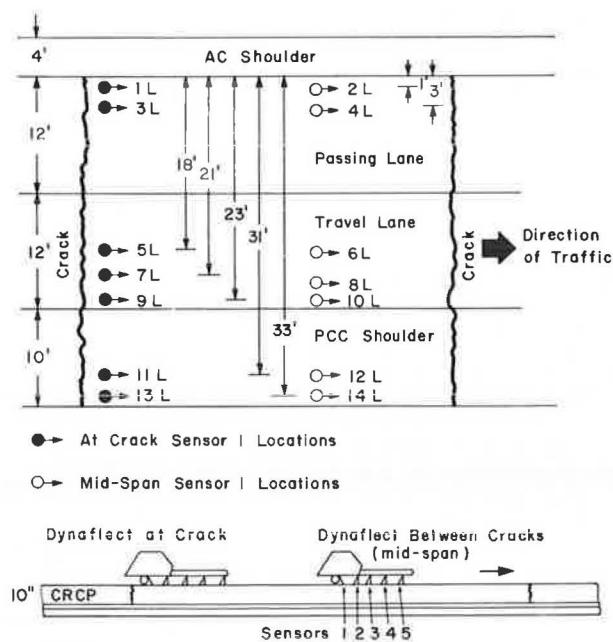


FIGURE 1 Layout plan of selected test locations, sections 1, 2, and 3.

base, and a 6-in. lime-treated subgrade overlaying the natural subgrade.

The second set of Dynaflect deflection data and slab temperatures were obtained on November 30 and December 1, 1981. Because of 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 smoothly and resulted in eight complete cycles. During summer measurements, average crack spacings were 11.3, 14.2, and 10.1 ft in test sections 1, 2, and 3, respectively, when the road was not opened to traffic. However, during the fall tests the average crack spacings were 7.4, 8.1, and 8.3 ft in test sections 1, 2, and 3, respectively, as a result of the occurrence of more cracks. The average crack width, as measured on the surface in fall 1981, was approximately 0.06 in.

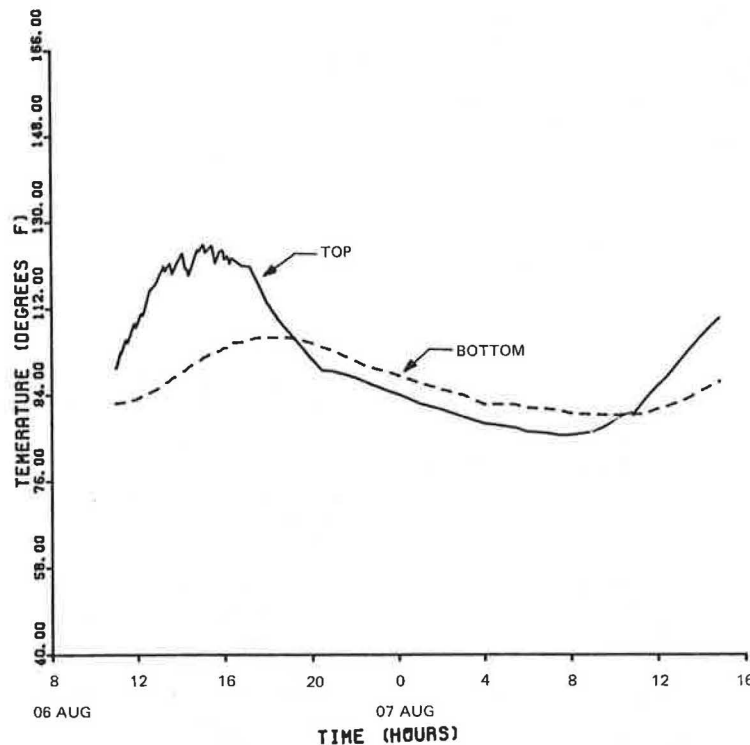


FIGURE 2 Temperature of top and bottom of concrete slab versus time, summer 1981.

The temperature block was placed in a preselected position so that the temperature of the concrete block could stabilize and be representative of the temperature conditions in the CRC pavement. Figure 2 shows the temperature records for the top and the bottom of the concrete block. The plot indicates that the temperatures in the concrete slab vary as a sinusoidal function of time, with the temperature at the bottom lagging behind the temperature at the top of the slab. This time lag occurs because of the low thermal conductivity of concrete. Details of the deflection measurements and a record of the temperatures at the top and bottom of the concrete slab are given elsewhere (1).

ANALYSIS AND DISCUSSION

The data setup for the statistical analysis is shown in Figure 1. For the comparison of means, only locations 1L and 12L are considered, forming 72 nonempty cells. The factors and their levels considered in the analysis are

1. Section (SEC) at three levels: SEC 1, SEC 2, SEC 3;
2. Season (S) at two levels: summer and fall;
3. Position with respect to the transverse crack (C) at two levels: near the crack (N) and midspan (M); and
4. Distance from the pavement edge (D) at six levels (Figure 1).

Analysis of Variance

Statistical Model

The following model was used in the analysis of variance of the deflection data:

$$W_{ijklm} = \mu + SEC_i + S_j + C_k + D_l + \epsilon_{(ijkl)m} \quad (1)$$

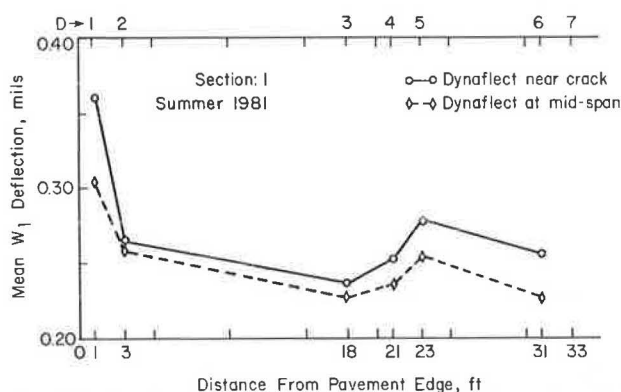
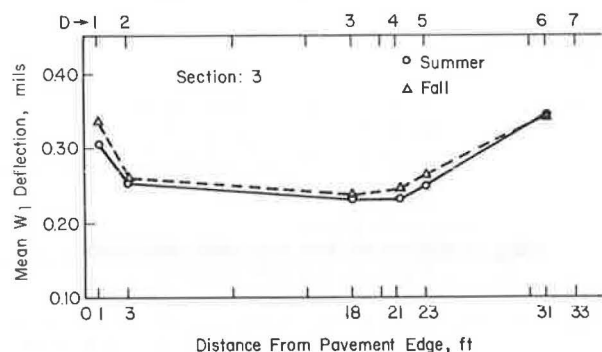
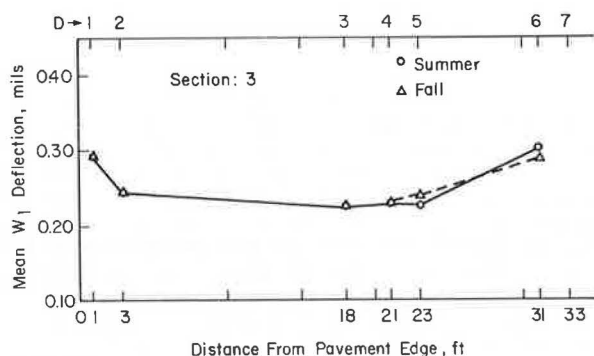
where

- W_{ijklm} = mth Dynaflect deflection at sensor 1 measured at the lth location in the kth test position with respect to the crack in the jth season at the ith test section;
- μ = overall mean;
- SEC_i = effect of the ith test section;
- S_j = effect of the jth season;
- C_k = effect of the kth test position;
- $\epsilon_{(ijkl)m}$ = random error caused by the mth test at the ith test section in the jth season on the kth position at lth distance from the edge [$NID(0, \sigma^2)$];
- D_l = effect of the lth distance from the pavement edge;
- $l = 1, 2, 3, 4, 5, 6$;
- $m = \text{replications in each cell}$;
- $i = 1, 2, 3$;
- $j = 1, 2$; and
- $k = 1, 2$.

The results of the ANOVA are given in Table 1. It can be concluded that the mean deflection is significantly different at different levels of all the factors, except season. For season, the null hypothesis cannot be rejected, which leads to the conclusion that the difference in mean deflections taken in summer and fall is not statistically significant. Figure 3 shows the effect of the Dynaflect position with respect to the transverse crack on the mean deflection W_1 , thus indicating the significant difference, as found earlier from ANOVA. The significant influence of the distance of the Dynaflect from the edge on the mean deflection W_1 is shown in Figures 3-5. Figures 4 and 5 show the mean

TABLE 1 Summary of ANOVA

Source of Variation	Sum of Squares	DF	Mean Square	F	Significance of F
Within cells	0.295	360	0.001		
Constant	35.415	1	35.415	43183.36	0 ^a
SEC	0.4048	2	0.202	246.78	0 ^a
S	0.0000	1	0.000	0.01	0.915 ^b
C	0.0426	1	0.043	51.95	0 ^a
D	0.2498	5	0.050	60.93	0 ^a

^aSignificant (i.e., reject the null hypothesis).^bNot significant.FIGURE 3 Variation in mean W_1 deflections at midspan and near crack as a function of distance from the pavement edge.FIGURE 4 Effect of season on mean W_1 deflection at locations near transverse cracks.FIGURE 5 Effect of season on mean W_1 deflections at midspan locations.

deflection W_1 for summer and fall measurements, thus indicating no significant difference.

Consideration of Full Factorial Design

ANOVA was also performed considering all the possible interaction terms in addition to the main effects. It is concluded that

1. Except for season, the levels of all factors significantly influence sensor 1 deflections;
2. The effects of most of the two-, three-, and four-way interaction terms on sensor 1 deflection are not significant; and
3. The two-way interactions that significantly affected deflections are SEC with C and SEC with D; these interactions are shown in Figures 6 and 7.

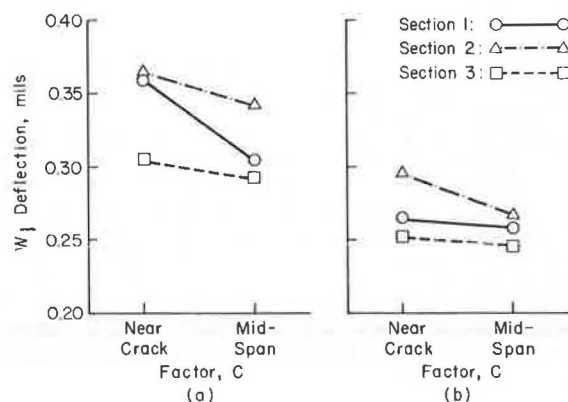


FIGURE 6 Graphical illustrations of two-way interaction SEC by C, summer 1981 data.

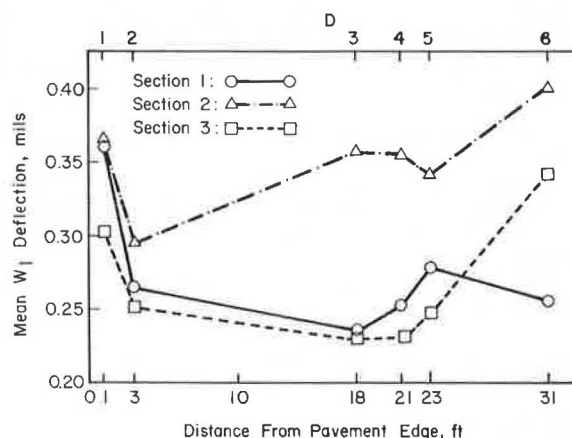


FIGURE 7 Graphical illustration of two-way interaction SEC by D, summer 1981 data.

TABLE 2 Summary of Analysis of Covariance

Source of Variation	Sum of Squares	DF	Mean Square	F	Significance of F
Within cells	0.269	359	0.001		
Regression	0.026	1	0.026	34.19	0 ^a
Constant	17.670	1	17.670	23532.25	0 ^a
SEC	0.411	2	0.205	273.66	0 ^a
S	0.000	1	0.000	0.57	0.452 ^b
C	0.042	1	0.042	56.54	0 ^a
D	0.250	5	0.050	66.69	0 ^a

Note: DT is the covariate.

^aSignificant (i.e., reject the null hypothesis).

^bNot significant.

ANOVA on Log (Variance)

The basic assumption in ANOVA of the homogeneity of variance was checked by specifying Bartlett's test (6), which led to the rejection of the null hypotheses of homogeneous variance. ANOVA was also performed on log (variance) data. The results are as follows:

1. There is a significant influence of the levels of the factors SEC (sections), C (position with respect to the crack), and D (distance from the pavement edge) on the variance of the observed W_1 deflections.

2. The differences in variances of the observed W_1 deflections are not statistically significant with respect to season.

3. The plot of cell means versus cell variance indicated that four data points were associated with comparatively high variances. These correspond to summer data. The two in the top right-hand corner were in sections 2 and 3 at location 11L on the concrete shoulder. The other two correspond to location 1L in sections 1 and 2 [1 ft from the asphalt concrete (AC) shoulder]. These four points can be considered as outliers. Further investigation indicated that these large variances were caused by temperature differential.

Analysis of Covariance

DT in the concrete slab has a marked influence on the deflection measurements, as discussed earlier and in the report by Uddin et al. (1). An analysis of covariance was, therefore, performed in which DT was used as a covariate in conjunction with the factors considered in Equation 1. The model considered for the analysis of covariance is

$$W_{1ijk\ell m} = \mu + B(DT_m) + SEC_i + S_j + C_k + D_\ell + \epsilon_{(ijk\ell)m} \quad (2)$$

where B is the regression coefficient.

In this model the regression procedure is used to remove the variation in the dependent variable caused by the covariate (6). The summary of the results is given in Table 2. The conclusions are essentially the same as those discussed for the ANOVA, as summarized in Table 1.

Effect of Temperature Variables on Dynaflect Deflections

The analyses performed thus far indicate that

1. W_1 deflections in summer and fall could be lumped together,

2. W_1 deflections are significantly different in each test section,

3. W_1 deflections near cracks are significantly different from those measured in the midspan position, and

4. W_1 deflections vary significantly with respect to the distance of the Dynaflect from the edge.

Therefore, the deflection measurements at each location should be treated as a sample from the individual population. The multiple linear-regression approach was used to identify the significant variables that could explain the variation in the measured W_1 deflections at each location (1). The explanatory variables considered in this study are (a) continuous variables and (b) dichotomous variables. The continuous variables are DT, mid-depth temperature (TMID), and spacing of the adjacent transverse cracks (CS). Mid-depth temperature is an average of the temperature of the top and the bottom of the slab. The dichotomous or dummy variables are used to represent the following qualitative variables:

1. Season (S): summer and fall, and
2. Section (SEC): sections 1, 2, and 3.

The results are given in Table 3. The following are the major findings (1).

TABLE 3 Effect of Removing Temperature Variables on R^2 of the Resulting Regression Equations for W_1 as Response Variables

Location	Dependent Variable (W_1)			
	Analysis A ^a		Analysis B ^b	
	Temperature Variables	R^2	R^2	Reduction in R^2 ^c (%)
1L	DT	0.65	0.18	72.3 ^d
2L	DT	0.68	0.40	41.2 ^d
3L	DT	0.41	0.34	17.1 ^e
4L	DT	0.49	0.40	18.4 ^e
5L	TMID, DT	0.93	0.89	4.3 ^d
6L	DT	0.71	0.61	14.1 ^d
7L	TMID, DT	0.91	0.90	1.1 ^f
8L	DT	0.79	0.65	17.7 ^d
9L	-	0.67	0.67	0.0
10L	DT	0.71	0.61	14.1 ^e
11L	DT	0.82	0.62	24.4 ^d
12L	DT	0.90	0.82	8.9 ^d
13L	DT	0.65	0.25	61.5 ^e
14L	DT	0.83	0.55	33.7 ^d

^aAll independent variables were considered in regression.

^bTemperature variables were removed from the independent variables list before applying stepwise regression.

^cReduction in R^2 values of the resulting regression equations from analysis B as compared with the R^2 values of analysis A.

^dSignificant at 1 percent α level.

^eSignificant at 5 percent α level.

^fNot significant.

1. The effect of DT on Dynaflect deflections varies with the position of the Dynaflect.

(a) For the Dynaflect located in the midspan position (between transverse cracks) in the wheelpath or at the centerline of the slab, the measured deflections indicate a direct relationship with DT.

(b) For the Dynaflect positioned anywhere near the pavement edge, the measured deflections exhibit an inverse relationship with DT (Figure 8).

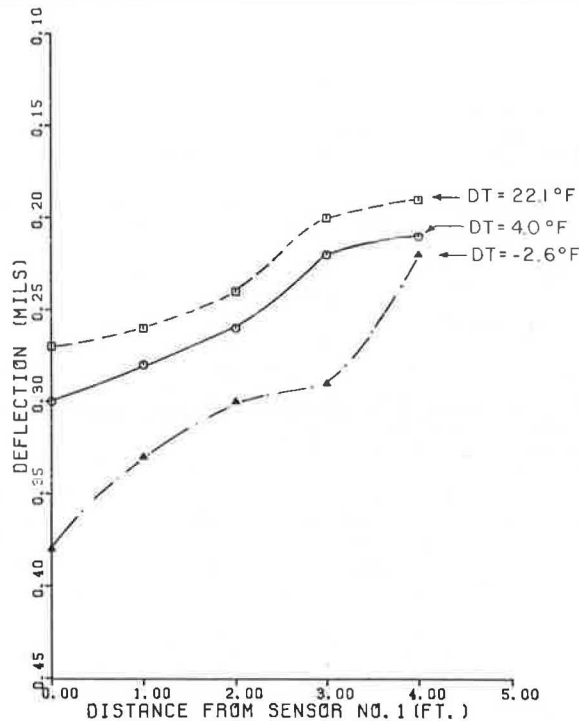


FIGURE 8 Deflection basins measured near pavement edge at different temperature differentials.

2. In the case of 1(a), the Dynaflect position corresponds to the interior condition. The errors caused by a very high positive DT (expected at the Columbus site) on measured deflections and the back-calculated elastic moduli of the pavement layers are practically negligible.

3. In the case of 1(b), the errors in measured deflections caused by a positive DT greater than 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 with a portland cement concrete shoulder.

These findings are also shown in Figure 9. Figure 10 is an example of daily variation of DT at the test site. The DT of a concrete slab is zero about 2 hr after sunrise on a clear day. The maximum DT occurs in the afternoon, about 2:00 or 3:00 p.m. It is important to recognize that DT will cause changes in the mean and variance of the deflections near the pavement edge.

TEMPERATURE CORRECTION PROCEDURE

A procedure for applying a temperature correction to the Dynaflect deflections measured at or near the edge of a rigid pavement is described in this sec-

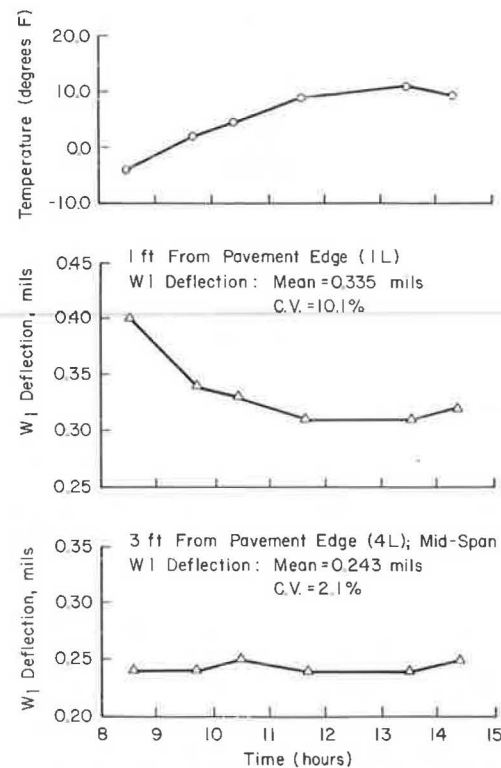


FIGURE 9 Variations in temperature differential and Dynaflect deflections with time (12/1/81) on section 3 at Columbus bypass SH-71, Texas.

tion. As discussed earlier, DT in the slab is the most important temperature parameter that influences the deflections measured at the pavement edge. The deflection measured at any DT should be corrected to bring it to zero DT. The step-by-step procedure is as follows:

1. Collect replicate 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 at the same time as the deflection measurements. Use the data to estimate the corresponding DT. An estimate of the hourly distribution of the DT can also be made by using the predictive model described by Uddin et al. (1) and by making use of the climatological data for the test location.
3. Develop a simple linear-regression equation with sensor 1 deflection, W_1 as the dependent variable, and DT as an independent variable.
4. Use the slope of the best-fit line to calculate the required amount of correction to the measured deflection (W_1). In the case of a positive DT, the corrected deflection will be larger than the measured deflection; in other words, the correction will be additive. The corrected deflection corresponds to zero DT.

An example is presented (1) to illustrate how the measured W_1 deflections were corrected to a zero DT condition. The data for W_1 and DT correspond to location 1L. Each data set corresponds to 12 replicate deflection measurements for sections 1, 2, and 3, respectively. The corrections were applied as explained in the preceding section. Figure 11 shows the best-fit lines for the measured and corrected deflections. As expected, the regression lines for the corrected deflections are practically horizon-

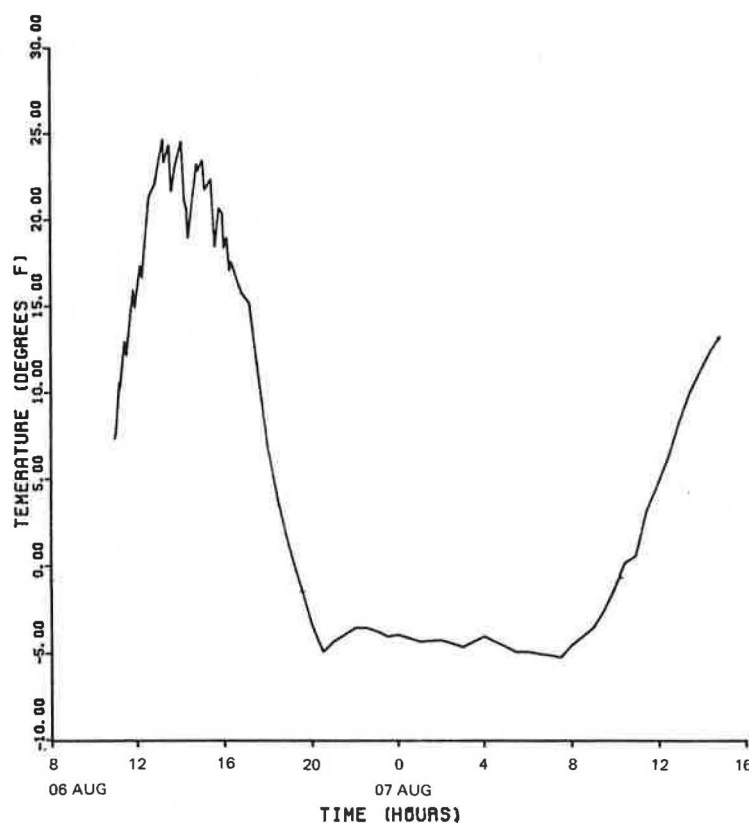
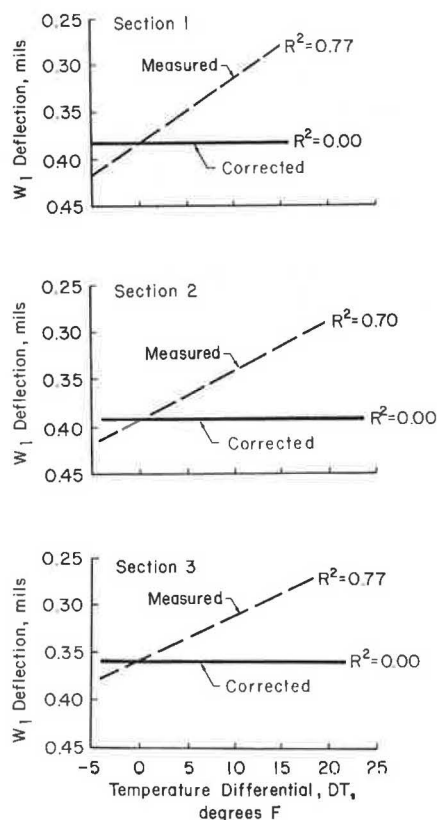


FIGURE 10 Temperature differential versus time relationship, summer 1981.

FIGURE 11 Best-fit lines for measured and corrected W_1 deflections at location 1L, Columbus bypass, SH-71, 1981 data.TABLE 4 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
	SD	0.049	0.025
	CV (%)	14.0	6.6
	R^{2a}	0.72	0.00
2	Mean (mils)	0.357	0.393
	SD	0.045	0.025
	CV (%)	12.8	6.4
	R^{2a}	0.70	0.00
3	Mean (mils)	0.325	0.358
	SD	0.038	0.018
	CV (%)	11.8	5.1
	R^{2a}	0.77	0.00

^aFrom simple linear-regression analysis with DT as independent variable on combined data of summer and fall 1981.

tal, with values of R^2 near zero. This means that the influence of DT has been removed from the measured W_1 deflections. The summary statistics for measured and corrected deflections are given in Table 4. Note that coefficients of variation for corrected deflections (5 to 7 percent) are practically within the expected range of inherent variability in the equipment and in the test procedure.

CONCLUSIONS

The major findings, as summarized in the following list, are based on the limited data collected on CRC pavements.

1. No significant difference in mean W_1 deflection with respect to the season is found in this study.

2. The mean W_1 deflections vary significantly for different sections.

3. W_1 deflections measured at locations that correspond to different distances from the edge are significantly different.

4. The mean W_1 deflections are influenced significantly by the position of the Dynaflect with respect to the transverse crack.

5. All these conclusions apply equally to the corresponding variance of W_1 deflections.

6. It is important to treat the W_1 deflections measured at each location (corresponding to crack position and distance from the edge) separately in order to develop a regression equation and statistical inferences.

The following recommendations relate to removal of the influence of the DT in the surface concrete layer on measured Dynaflect deflections.

1. Dynaflect deflection measurements should begin at least 2 hr after sunrise to avoid making any deflection measurements under negative DT conditions.

2. For material characterization, Dynaflect deflection data should be obtained in the midspan position (between the transverse cracks) in the wheelpath or at the centerline of the slab. In practice, the data do not need to be corrected for any positive DT 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 zero DT.

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