On the Evaluation of Concrete Pavement Response with a Falling Weight Deflectometer

Mustaque Hossain, Ph.D., P.E., Affan Habib, Bing Long
Dept. of Civil Engineering, Kansas State University
Andrew J. Gisi, P.E., Assistant Geotechnical Engineer
Kansas Department of Transportation, Bureau of Materials & Research

ABSTRACT

Seasonal variations in pavement material properties and behavior, primarily due to variations in temperature and moisture conditions, are presumed to affect deflection response of concrete pavements. Currently, concrete pavements are tested for deflection response in Kansas with the Falling Weight Deflectometer (FWD). Temperature, subgrade moisture content, and FWD-deflection data were collected monthly on three concrete pavement test sections for a year. The subgrade and concrete pavement slab moduli were backcalculated using the elastic layer theory. Joint load transfer efficiencies were also calculated from the FWD deflections measured at the joints. The results show that the range of moisture contents encountered in the in-service concrete pavement subgrades over the seasons was not broad and did not appear to affect the subgrade response appreciably. High temperature induces slab curling in concrete pavements, thereby affecting the subgrade moduli obtained by the backcalculation process. This effect is more pronounced for the concrete pavement with cement-treated subbase. Lower temperature affects backcalculated concrete slab moduli and higher temperature results in higher joint load transfer efficiencies. Based on the studies of the hourly variation of deflection data and the effect of variations of load transfer efficiencies on rehabilitation design, it is recommended that the FWD tests be done at moderate temperatures in order to avoid high temperature effects and a reference temperature be established to evaluate joint load transfer efficiency of the pavements.

INTRODUCTION

Seasonal variations in pavement material properties and behavior due to climatic effects, primarily due to variations in temperature and moisture conditions, have long been known to affect pavement structural performance, or in other words, deflection response (1). In concrete pavement evaluation, the effect of temperature is considered negligible. Temperature effect is considered in expansion/contraction joint design as well as in the reinforcement design for jointed, reinforced concrete pavements. The 1993 AASHTO Guide for Design of Pavement Structures recommends a procedure for determining the "effective" modulus of subgrade reaction to characterize the subgrade by taking into account the seasonal variations of subgrade materials due to variations in moisture content (2). It is also well known that temperature also affects the deflection measurements at the joints during load transfer evaluation. This paper discusses the effects of seasonal variations on the structural response of concrete pavements as evaluated by the Falling Weight Deflectometer.

SITE SELECTION

Three 152 m long concrete pavement sections were selected as test sites in northeast and southwest Kansas. Table 1 lists the locations and characteristics of the sites. The pavement on I-70 is a jointed, non-reinforced concrete pavement (JPCP) whereas the US-24 and K-14 sites are jointed, reinforced concrete pavements (JRCP). The I-70 and K-14 sites have 150 mm and 100 mm treated subbases, respectively and the US-24 site has a sandy subbase of 100 mm thickness. All sites have silty clay soils as subgrade materials.

INSTRUMENTATION AND DATA COLLECTION

At each site, three time domain reflectometry (TDR) waveguides were installed in the subgrade in 100-mm diameter core holes at a spacing of 76 m. An 8-meter coaxial cable was extended from each waveguide to the edge of the shoulder along a saw-cut groove in the paved surface to house the cable end in a secured housing for future moisture measurements. Measurements for soil-moisture content were done monthly for all locations for one year with a Tektronix Model 1502 TDR cable tester starting in October of 1993. Soil-moisture measurements were made twice a month during the thaw-period (February 15 - April 15) on I-70 and US-24 (3).

Deflection data were collected at ten locations at approximately 15-m intervals on each test section with a Dynatest 8000 FWD simultaneously with the moisture measurements. The first sensor was located at the center of the loading plate with six others at a uniform radial distance of 300 mm apart. Three drops of FWD load were used for target loadings of 31, 40 and 67 kN. Tests were done in the middle of the slabs on the travel lane and also at the transverse joints approximately on the outer wheel path to determine joint load transfer efficiencies. In the latter case, two sensors were placed across the joints at a spacing of 300 mm. However, on K-14 joint deflection data were collected only for eight months starting from February 1994. Table 2 lists the pavement surface temperatures measured during monthly FWD tests on all three sites. In addition to these, hourly deflection tests were conducted on I-70 for 3 days in the summer of 1994.

BACKCALCULATION OF LAYER MODULI

A linear elastic analysis backcalculation program, MODULUS, was used to backcalculate the layer moduli (concrete slab and combined subbase/subgrade moduli) from the FWD deflection basins obtained at the mid-slab locations corresponding to a target loading of 40 kN (3). All pavements were modelled as two-layer, linear elastic systems with semi-infinite subgrades. MODULUS is a microcomputer program which can be applied to a two-, three-, or four-layer pavement system with or without a bedrock (4). The linear elastic program generates a data base of deflection basins corresponding to different modulus ratios of the layers, and a pattern search technique is used to fit the measured and calculated deflections by minimizing the objective function:

$$\varepsilon^2 = \Sigma [(w_i^m - w_i^c) / (w_i^m)]^2 \quad \text{for } i = 1,.....,n. \qquad (1)$$

In equation (1), ε^2 is the squared error, w_i^m is the measured deflection, w_i^c is the calculated deflection and n is the number of sensors (usually 7). The search routine finds the optimum set of modulus ratios, or in other words, a set of backcalculated layer moduli, so that a minimum ε^2 value is obtained.

Effect of Subgrade Moisture Contents on Backcalculated Subgrade Moduli

Figures 1, 2 and 3 show the variations of backcalculated subgrade moduli with the measured subgrade moisture contents on I-70, US-24 and K-14, respectively. As shown in the figures, the variations are not very significant (except for K-14). Table 3 lists the subgrade moduli values obtained for the entire year as well as the summary statistics, and Figure 4 illustrates the results.

For I-70, the average subgrade moduli varied from 190 MPa to 258 MPa with an average value of 206 MPa and a coefficient of variation of 9%. The highest modulus was obtained during January due to frozen subgrade. During FWD testing in January, the subgrade temperature was recorded at -1° C and the pavement surface temperature was -2° C. The subgrade moisture content on this site varied from 16.8% to 25.4%, approximately 9% over the year despite 652 mm annual rainfall which was, however, lower than normal for the year. On I-70, lower-than-average subgrade moduli were consistently obtained for the summer months indicating that FWD tests during summer months may well characterize the concrete pavement subgrades. The highest pavement surface temperature during tests on I-70 was 31° C and no evidence of the effect of curling on backcalculated subgrade moduli was evident on this site.

As shown in Table 3, the average value of subgrade moduli on US-24 was approximately 187 MPa with a coefficient of variation of about 18% over the seasons. The change in moisture content over the same period was about 6%, as shown in Figure 2, despite 560 mm rainfall over the months. Thus, most of the variation can be attributed to the 287-MPa subgrade modulus obtained in January as shown in Figure 4. Like I-70, during FWD testing in January, the subgrade temperature was recorded at -1° C. The subgrade moduli obtained in December, January and February were consistently higher than the average value. The lower subgrade moduli values calculated during May and June correspond to higher pavement surface temperatures of 43° C and 42° C, respectively, indicating that slab curling might have affected the measured deflection values. However, the pavement surface temperatures of 37° C during August did not seem to have similar effect as illustrated in Figure 4.

On K-14, the backcalculated subgrade moduli varied from 67 MPa to 162 MPa with an average value of 110 MPa and a coefficient of variation of 29%. The highest modulus was obtained during January due to near-frozen subgrade as illustrated in Figure 4. During FWD testing in January, the subgrade temperature was recorded at 1° C and the pavement surface temperature was 5° C. Lower-than-average subgrade moduli were consistently obtained for the summer months and the lowest value was obtained in May when the pavement surface reached 51° C as shown in Figure 4. Since K-14 is the thinnest slab tested and the test temperatures were consistently higher, slab curling might have affected the deflection measurements. Also, upward curling is known to be prominent on cement-treated subbases because the PCC slabs cannot "sink" into such subbases.

Thus, it is apparent that the range in moisture contents encountered under the concrete pavements does not affect the structural response of subgrades significantly. However, slab curling due to high pavement temperature during FWD testing may have a significant effect on backcalculated subgrade moduli. It is to be noted that all three pavements are fairly new and have paved shoulders. Although no positive subsurface drainage is present on any of the pavements, the paved shoulders and well-sealed joints apparently helped keep water out of these pavements. All three pavements are on fill sections and appeared to be drained well by the cross slopes.

Effect of Temperature on Backcalculated Concrete Pavement (PCC) Moduli

Figure 5 shows the variation of backcalculated PCC moduli over the seasons for I-70, US-24 and K-14, and Table 4 lists the summary statistics for this parameter for all sites over the entire year.

On I-70, the average value of PCC moduli is 33.9 GPa with a coefficient of variation of 9.9%. Above-average PCC moduli values were generally obtained for the colder months (November, December, January and February). As shown in Figure 5, the PCC moduli during spring-thaw months (February and March) are not significantly affected and are similar to those obtained during summer months (May through August).

On US-24, the backcalculated PCC moduli showed variations similar to I-70 (the coefficient of variation is approximately 12%). The highest moduli of 55 GPa was obtained for January. The pavement surface temperature was 5° C during FWD testing for that month (Table 2). Like I-70, in general, higher PCC moduli were obtained for this site for the colder months and the moduli obtained during spring/thaw months are similar to those in summer months as illustrated in Figure 5.

On K-14, the backcalculated PCC moduli also showed variations similar to I-70 and US-24 with an average of 37 GPa and a coefficient of variation of 8.3%. Higher PCC moduli were also obtained for this site for the colder months and the moduli obtained during spring/thaw months are similar to those found in summer months (Figure 5).

The above results indicate that the PCC moduli obtained from the FWD tests are somewhat temperature dependent. Temperature effects on concrete compressive strength has been outlined by Neville (5). For a 20° C drop in test temperature, laboratory specimens showed approximately 30% increase in compressive strength. The apparent increase in the compressive strength of PCCP concrete is beneficial taking into account the fact that the joint load transfer efficiencies of the pavements would be the lowest during winter months due to contraction of the slabs.

Although it is anticipated that the pavement structural response during spring/thaw months is the weakest, tests during summer months revealed similar responses. Thus, FWD tests can be conducted during summer months to characterize concrete pavements. Tests should be at moderate pavement surface temperatures in order to minimize the effects of curling.

EVALUATION OF JOINT LOAD TRANSFER

The joint load transfer is evaluated from the deflection test results at the joints using the following equation (2):

$$d_{je} = d_u/d_l \times 100 \qquad (2)$$

In equation (2), d_{je} is the deflection load transfer efficiency (LTE,%), d_u is the deflection at the joint of the unloaded slab and d_l is the deflection of the loaded slab. The deflections are measured by one sensor at the center of the load and another one at 300-mm distance across the joint. A slab bending correction factor, B, is necessary because the deflections d_u and d_l, measured 300 mm apart, would not be equal even if measured in the interior of a slab. The factor B was determined in this study from the deflections measured at the center of the slab as suggested by the AASHTO Guide (2):

$$B = d_0 \text{ (center)}/ d_{12} \text{ (center)} \qquad (3)$$

The computed B values using equation (3) varied from 1.08 to 1.12. An average value of 1.1 was chosen for all three sites.

The seasonal variation of LTE at three sites is illustrated in Figure 6. The decrease of LTE during colder months could be somewhat compensated by the increase in PCC moduli during that period. Figure 7 shows the scatter plot of the load transfer efficiencies (LTEs) computed for joints at three different stations on I-70 over the seasons. The plot shows that the load transfer efficiency is highly affected by the pavement surface temperature - as the temperature increases, the LTE increases. As shown in Figures 8 and 9, the trend is also similar for US-24 and K-14. Thus, it is imperative that a reference temperature be chosen when evaluating LTE of concrete pavements. On these pavements, the load transfer is provided by dowels and the joint spacing on US-24 is almost twice of that on I-70. However, the effects of temperature are similar as indicated by the slopes of pavement surface temperature versus LTE equations obtained by a linear regression analysis:

JPCP (I-70/northeast Kansas):

$$\text{LTE (\%)} = 0.718 + 0.0085 * \text{Surface Temperature (°C)} \qquad (R^2 = 0.62) \qquad (4)$$

JRCP (US-24/northeast Kansas):

$$LTE(\%) = 0.661 + 0.0085 * \text{Surface Temperature } (^{\circ}C) \qquad (R^2 = 0.56) \quad (5)$$

JRCP (K-14/southwest Kansas):

$$LTE = 0.70 + 0.005 * \text{Surface Temperature } (^{\circ}C) \qquad (R^2 = 0.53) \quad (6)$$

From equations (4) and (5), it appears that the upper limits for the pavement surface temperature for doing FWD tests to determine LTE on JPCP and JRCP in northeast Kansas should be about 33° C and 39° C, respectively. Tests above these temperatures would be unreliable as the LTEs measured would always approach 100%, possibly due to locked joints. These temperatures are higher than 27° C recommended by the AASHTO Guide for any concrete pavement (2).

As indicated by equation (6), in southwest Kansas, the gradient is lower and the concrete pavement surface temperature at which the load transfer would approach 100% is about 60° C for JRCP. This temperature seems to be extremely high and might not occur on jointed reinforced concrete pavements in Kansas. However, it is apparent that because of these linear relationships, FWD tests could be conducted at *different temperatures* in order to establish the relationship between LTE and pavement surface temperature for any concrete pavement in Kansas. As a minimum, one morning (AM) and one afternoon (PM) tests are recommended for this purpose.

EFFECT OF VARIATION OF JOINT LOAD TRANSFER EFFICIENCIES ON REHABILITATION DESIGN

The effect of variation of joint load transfer efficiencies on rehabilitation design (for asphalt concrete, or AC, overlays) at these sites was analyzed using the 1993 AASHTO Design Guide algorithm and the AASHTO software DARWIN. The FWD data for twelve months on all the sites were used to calculate the "effective" static k , i.e, the "effective" modulus of subgrade reaction values. Assuming a 90% reliability, a J value of 3.2 and an overall standard deviation of 0.34, a traffic of 10 million ESALs was found to warrant a 100 mm AC overlay on I-70. Now, for traffic of 10 million ESALs, the required AC overlay thicknesses were calculated corresponding to the load transfer efficiencies at -5 ° and 15 ° C. The first temperature (-5° C) represents the extreme cold temperature that might be experienced on I-70 during monthly test cycle. The LTE values were computed using Equations 4, 5 and 6, and in turn, the J values were determined corresponding to these LTE values following the AASHTO design guidelines. The average value of the backcalculated PCC modulus of elasticity was used to compute the modulus of rupture of concrete (from the regression equations) for a given site. Knowing these input values, the effective PCC thickness (D_{eff}) and the required thickness for future traffic (D_f) were computed. The required AC overlay thickness was calculated based on the difference of these values. Table 5 tabulates the analysis results for all sites. For all sites, concrete pavement evaluation with FWD at two different temperatures, one below and one above 0° C, with a gradient of 19° C would result in 25 mm difference in computed AC overlay thickness. Since both I-70 and K-14 have higher LTEs at 0° C, the situation is not critical for either pavement, partly because both pavements are fairly new. However, a temperature gradient of 20° C during FWD tests done at temperatures above 0° C on US-24 would result in 25 mm difference in computed AC overlay thickness. This type of temperature gradient is not uncommon in Kansas where early morning concrete pavement temperature after a cool night would be approximately 10° C and afternoon temperature would climb up to 40° C. These results indicate that the joint load transfer efficiency (or in other words, selection of J value) significantly affects the AC overlay thickness required on the PCC pavements. Since the load transfer efficiency is a function of the deflection values obtained at a certain temperature, it is important that a reference temperature be selected for evaluation of joint load transfer efficiency of concrete pavements.

EFFECTS OF HOURLY TEMPERATURE VARIATION ON FWD DEFLECTIONS

It was realized that an underlying assumption for evaluating temperature effects on pavement performance is to keep other environmental factors (such as, subgrade moisture content) relatively constant. Thus, a 12-hour test period was chosen to evaluate the effect of temperature on FWD deflections. During the summer months-June, July, and August of 1994, FWD tests were carried out on an hourly basis over an entire day on I-70. The purpose of these tests was to obtain data on pavement deflections under as much temperature change as possible while other environmental variables remained constant.

The hourly FWD tests lasted from about 7:00 AM until 4:00 PM. The measured deflections on the test sites were found to vary from one test station to the next along the length of the test section. As mentioned earlier, ten measurements were made on the site at 15 m intervals. The deflections measured on an hourly basis during one cycle were compared on a station by station basis. The first sensor deflections at four different stations on I-70, normalized to an FWD load of 40 kN, are shown in Figure 10. The following observations were made on the variations of deflection with the hourly temperature cycle for this site:

I. For each test station on I-70, there is an apparent saddle point around the pavement surface temperature of 32° C. This phenomenon reveals an important fact that the mechanism causing pavement deflection variation with temperature is different for concrete pavement than the asphalt pavements where an increase in temperature is known to cause an increase in deflection (4). The valid explanation for deflection variation on concrete pavements could be: temperature variation does not change the stiffness of concrete material significantly, but it does cause downward or upward curling of concrete slab. Curling results in loss of support for the concrete slab, which in turn, increases the measured deflection values. From Figure 10, the lowest point of deflection occurred around a pavement surface temperature of 32° C. This may imply that when the temperature reaches 32° C at about noon, the temperatures on the top and bottom of slab become uniform and the entire slab stretches and obtains adequate support again. After the noon time, the slab is in the downward curling condition without adequate support. The former case, i.e., when the temperature is around 32 ° C , has been modeled by Huang (6) as full-contact between the PCC slab and the subgrade represented by the springs. Thus, evaluation of deflections in this condition would be more realistic than the latter case (i.e. in the afternoon) when the contact between the slab and the subgrade is partially lost due to downward curling. It is to be noted that deflections measured in this case would be higher and if any assumption is made regarding full contact, the higher deflections would be interpreted by the backcalculation scheme to be due to weaker subgrade. This, in part, may be responsible for unusually lower backcalculated subgrade moduli on K-14 during summer months in this study. The results from I-70 indicate that FWD testing before noon hours at temperatures below 32° C would be preferable since the contact between the PCC and the subgrade would not be lost.

II. At a given test site, station deflection values are different from one another. This station-specific structural difference may be due to the random variation in pavement stiffness/strength which may be caused by the variations in layer thicknesses, consolidation, material properties, etc.

CONCLUSIONS

Based on this study, the following conclusions can be drawn about the temperature and moisture effects on concrete pavement response as measured by the FWD:

1. The range of moisture content encountered in the in-service concrete pavement subgrades in Kansas over the seasons is not broad and appears to affect neither the subgrade deflection response nor the backcalculated subgrade moduli appreciably. High temperature induces slab curling in concrete pavements, thereby affecting the subgrade moduli obtained by the backcalculation process. Thus, FWD tests should be done at moderate temperatures in order to avoid high temperature effects.

2. The concrete pavement/slab moduli obtained by backcalculation from the FWD tests are somewhat temperature dependent. Although it is anticipated that the pavement structural response during spring/thaw months is the weakest, tests during summer months revealed similar responses. Thus, FWD tests can be conducted during summer months to characterize concrete pavements.

3. The joint load transfer efficiency (LTE), computed from the FWD test results, is highly affected by the pavement surface temperature. As the temperature increases, the LTE also increases. Thus, it is imperative that a reference temperature be chosen when evaluating LTE of concrete pavements. Variation in FWD test temperature may cause variation in calculated LTE which, in turn, causes variation in the selected J value, thereby affecting design AC overlay thickness on concrete pavements.

4. Considering the effects of temperature on concrete pavement characterization from the FWD test results, it is recommended that FWD tests be conducted during summer months at pavement surface temperatures lower than 32° C in order to avoid slab curling effects. Special attention also needs to be paid to PCC pavements with cement-treated subbases.

LIST OF TABLES

Table 1: Location and characteristics of the sites selected for the study

Table 2: Pavement surface temperatures during FWD tests

Table 3: Variation of backcalculated subgrade moduli over the seasons

Table 4: Variation of backcalculated PCC moduli over the seasons

Table 5: Effect of variations of load transfer efficiencies on design AC overlay thickness

TABLE 1 Location and characteristics of the sites selected for the study

Route	Layer Thick-nesses (surface + subbase)	Soil Type (Unified)	LL (%)	PI (%)	% Passing 0.075 mm sieve	Average Annual Precipi-tation (mm)	Average Annual Max. Temp. (° C)
I-70	292 mm PCC + 150 mm LTSG	CL	25 24 25	9 8 8	61 61 53	838	33
US-24	229 mm PCC + 100 mm SS	CL	31 33 34	9 9 10	70 72 75	838	33
K-14	203 mm JRCP + 100 mm CTB	CL-ML, CL	25 29 26	6 10 8	56 53 51	737	34

Note: PCC: Portland Cement Concrete slab
JRCP: Jointed Reinforced Concrete Pavement
LTSG: Lime-treated subgrade
SS : Sand subbase
CTB: Cement-treated subbase

TABLE 2 Pavement surface temperatures during FWD tests

Route	Pavement Surface Temperature (°C)													
	Oct.	Nov.	Dec.	Jan.	Feb. 1	Feb. 2	Mar. 1	Mar. 2	Apr.	May.	Jun.	July	Aug.	Sep.
I-70	19	11	2	-2	16	2	21	16	21	31	27	31	30	27
US- 24	21	19	6	8	9	21	32	18	32	43	42	32	37	29
K-14	15	13	7	5	-	-7	-	26	29	51	50	51	47	42

TABLE 3 Variation of backcalculated subgrade moduli over the seasons

Route	Subgrade Moduli (MPa)													
	Oct.	Nov.	Dec.	Jan.	Feb.1	Feb.2	Mar.1	Mar.2	Apr.	May	Jun.	July	Aug.	Sep.
I-70	201	203	230	258	200	213	192	203	194	190	197	195	206	202
	Average =206 MPa, Std. Deviation= 18 MPa and Coefficient of Variation (%) =8.7													
US-24	182	188	206	287	204	179	164	195	157	147	157	189	183	182
	Average = 187.1MPa, Std. Deviation = 33.8 Mpa and Coefficient of Variation(%) =18.1													
K-14	128	117	144	162		135		89	121	68	68	67	99	120
	Average = 110 MPa, Std. Deviation= 32 MPa and Coefficient of Variation (%) = 28.8													

TABLE 4 Variation of backcalculated PCC moduli over the seasons

Route	PCC Moduli (GPa)													
	Oct.	Nov.	Dec.	Jan.	Feb.1	Feb.2	Mar.1	Mar.2	Apr.	May	Jun.	July	Aug.	Sep.
I-70	34	35	42	39	31	37	33	31	30	31	33	33	32	35
	Average =33.9 GPa, Std. Deviation = 3.4 GPa and Coefficient of Variation(%) =9.9													
US-24	45	42	46	55	40	36	38	44	38	37	40	39	41	39
	Average =41.4 GPa , Std. Deviation = 4.96 GPa and Coefficient of Variation(%) =12.0													
K-14	37	32	39	43		40		36	39	36	32	38	36	35
	Average=37 GPa, Std. Deviation =3.1 GPa and Coefficient of Variation (%)= 8.3													

TABLE 5 Effect of variations of load transfer efficiencies on design AC overlay thickness

Site	Temperature(C)	LTE (%)	J	D_{eff} (mm)	D_f (mm)	AC Overlay Thickness (mm)
I-70	-5	67.5	3.5	210	270	127
	15	84.5	3.2	210	258	102
US-24	-5	61.8	3.5	165	251	165
	15	78.8	3.2	165	239	140
K-14	-5	67.5	3.5	146	258	203
	15	77.5	3.2	146	246	178

LIST OF FIGURES

Figure 1: Variation of subgrade moduli with moisture content on I-70

Figure 2: Variation of subgrade moduli with moisture content on US-24

Figure 3: Variation of subgrade moduli with moisture content on K-14

Figure 4: Seasonal variation of backcalculated subgrade moduli

Figure 5: Fig. 5 Seasonal variation of backcalculated PCC moduli

Figure 6: Seasonal variation of Load Transfer Efficiencies

Figure 7: Variation of load transfer efficiency with pavement surface temperature on I-70

Figure 8: Variation of load transfer efficiency with pavement surface temperature on US-24

Figure 9: Variation of load transfer efficiency with pavement surface temperature on K-14

Figure 10: First sensor deflection vs. pavement surface temperature for I-70

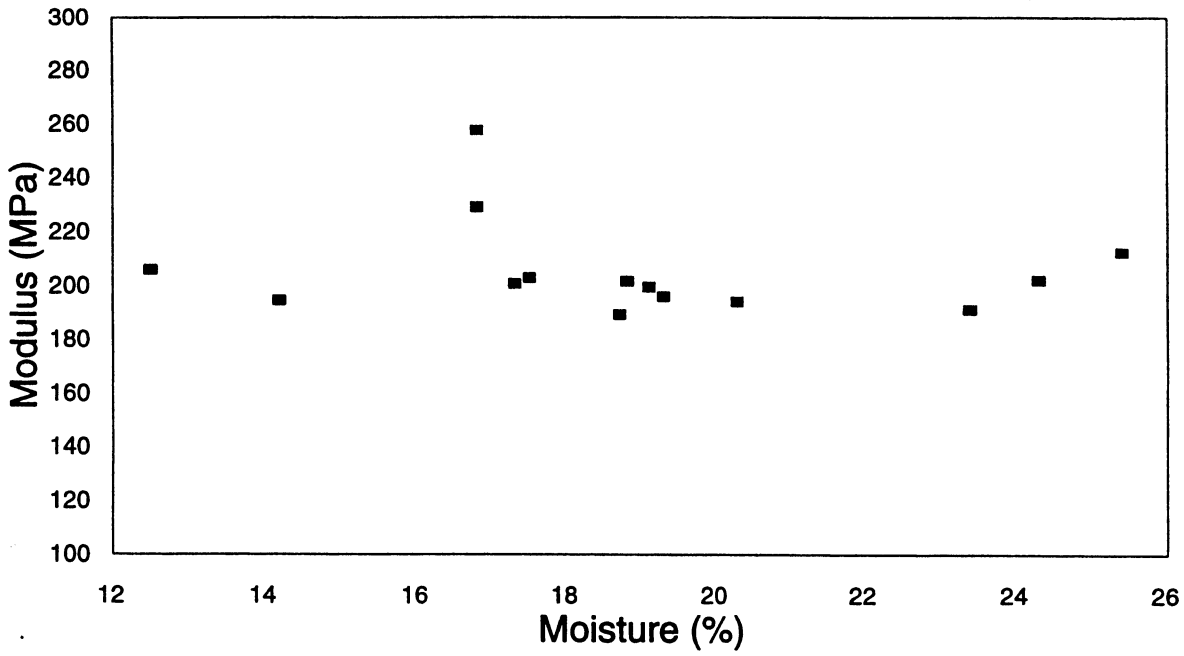


Figure 1 Variation of subgrade moduli with moisture content on I-70

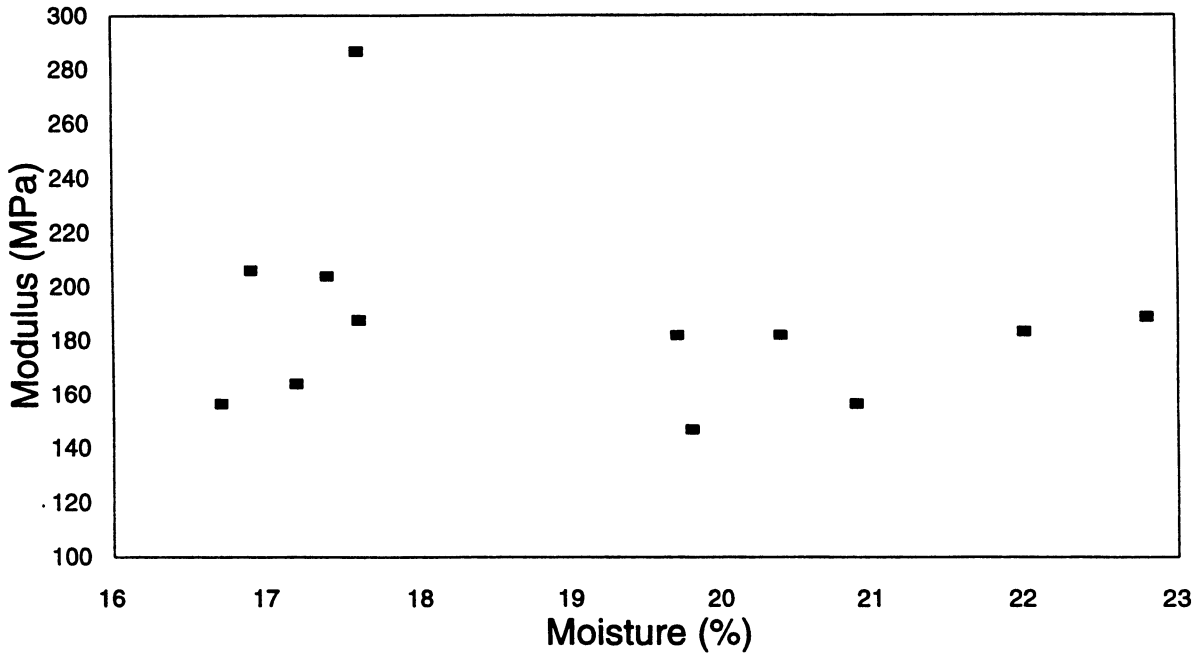


Figure 2 Variation of subgrade moduli with moisture content on US-24

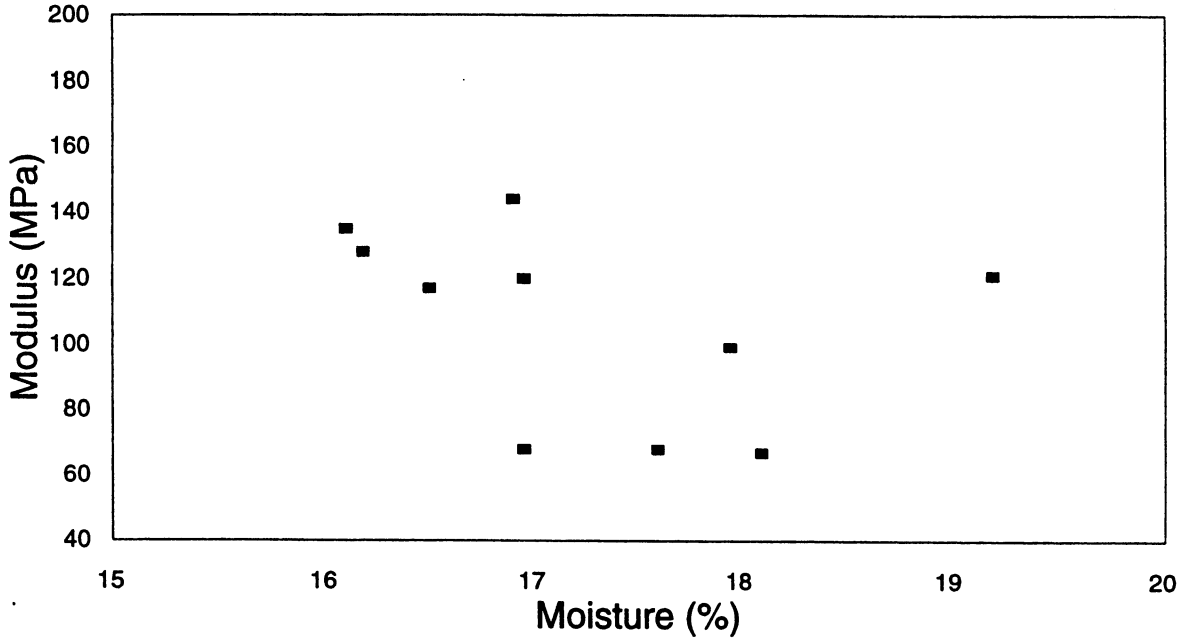


Figure 3 Variation of subgrade moduli with mositure content on K-14

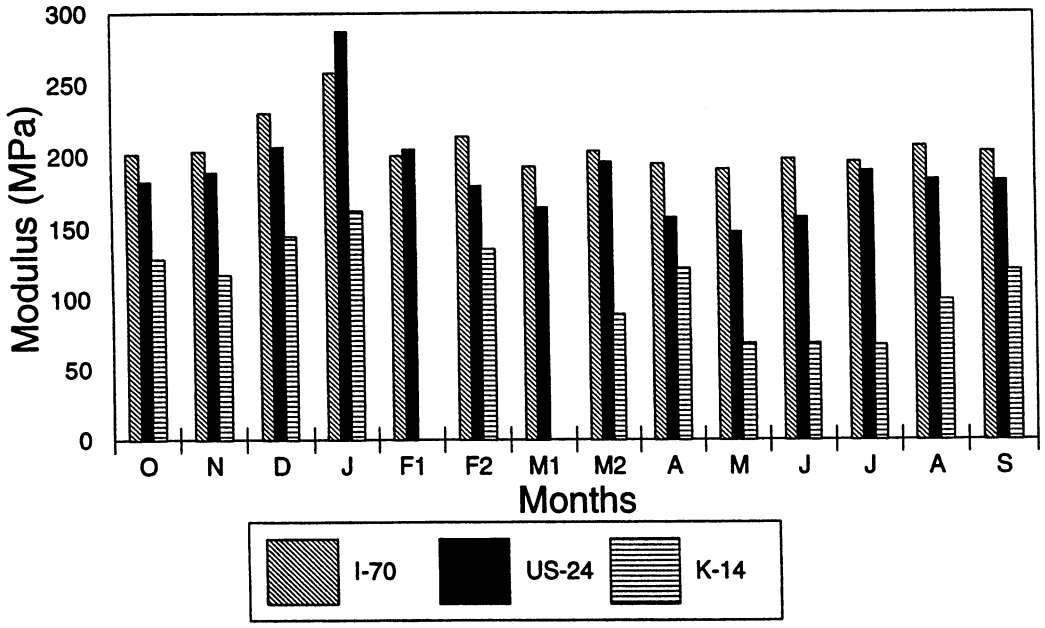


Figure 4 Seasonal variation of backcalculated subgrade moduli

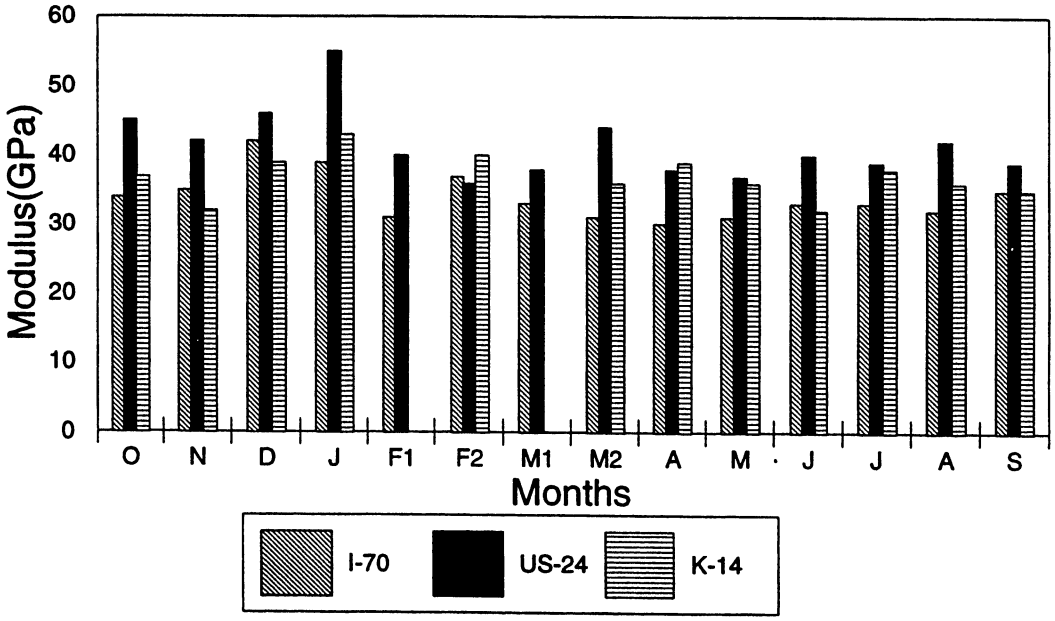


Figure 5 Seasonal variation of backcalculated PCC moduli

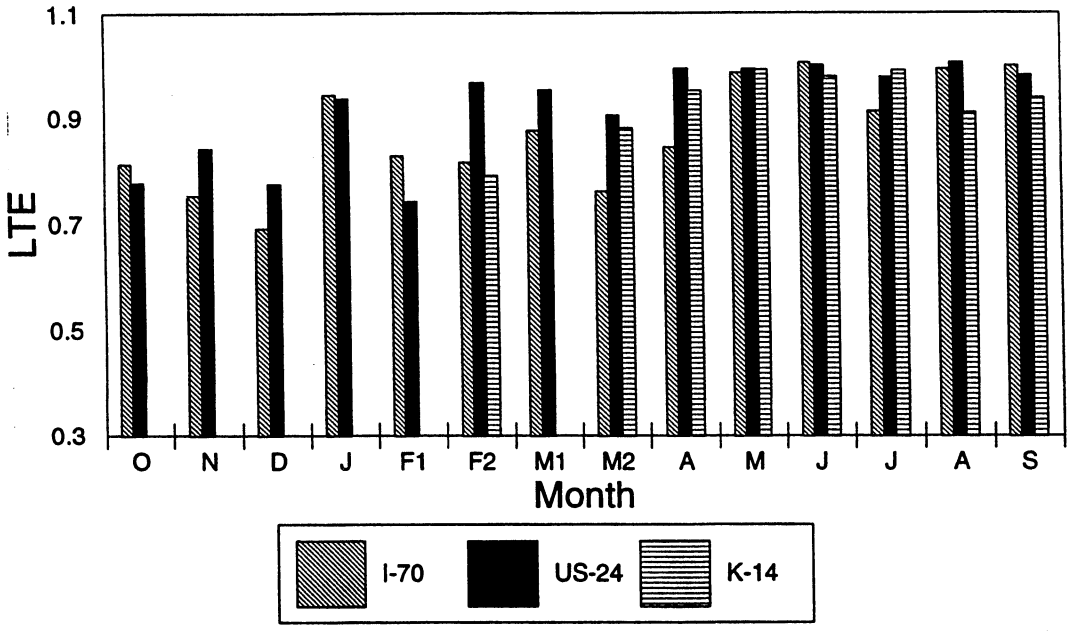


Figure 6 Seasonal variation of Load Transfer Efficiencies

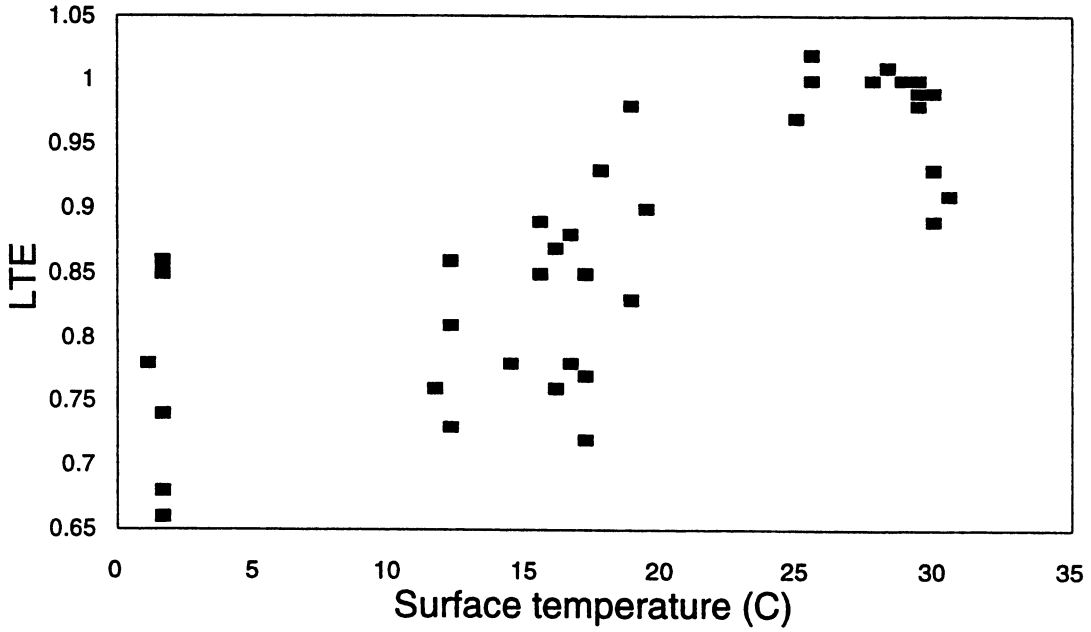


Figure 7 Variation of load trnasfer efficiency with pavement surface temperature on I-70

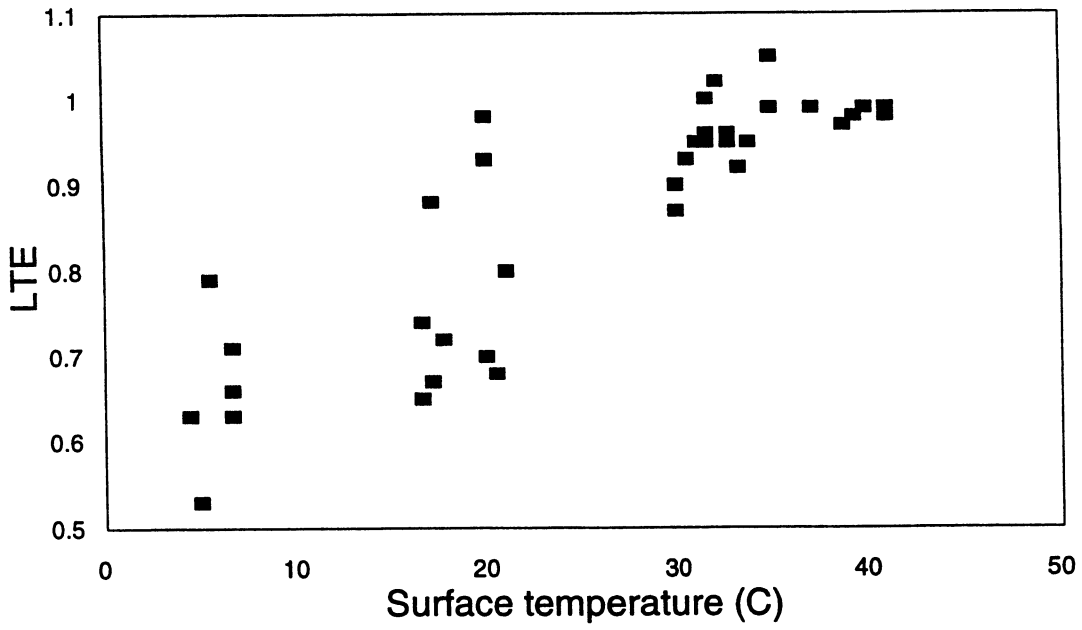


Figure 8 Variation of load transfer efficiency with pavement surface temperature on US-24

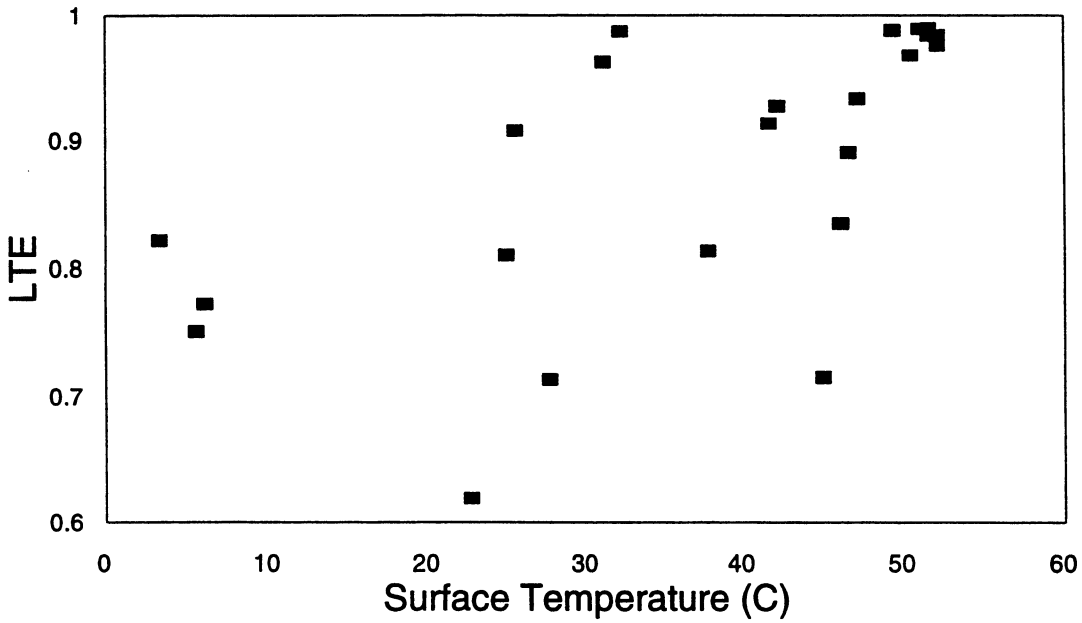


Figure 9 Variation of load transfer efficiency with pavement surface temperature on K-14

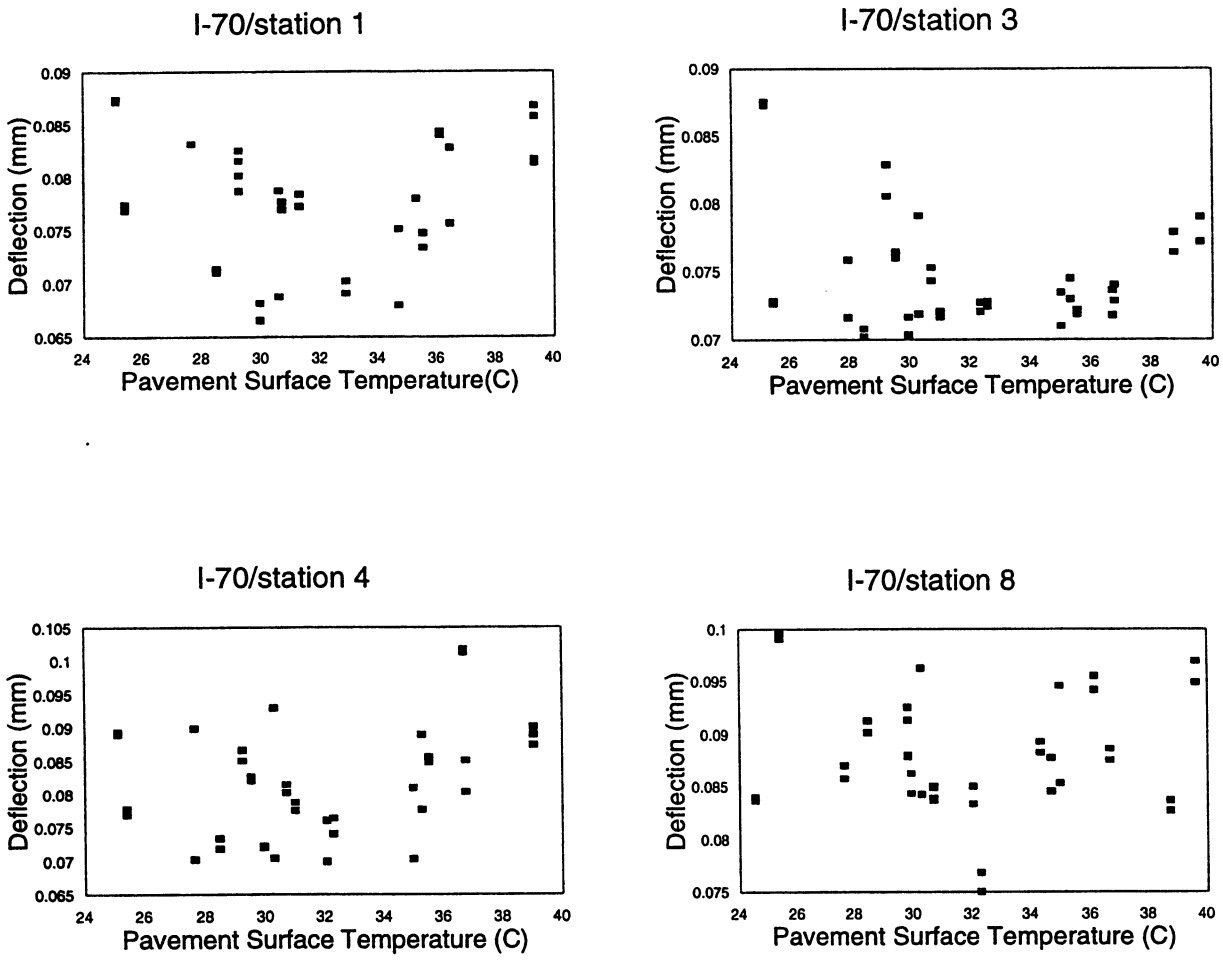


Figure 10 First sensor deflection vs. pavement surface temperature for I-70

REFERENCES

(1) Richter, C.A. Seasonal Monitoring of Pavements - A Whole Lot More. *Proceedings of the Conference on Road and Pavement Response Monitoring Systems*, ASCE, New York, 1991, pp. 182-195.

(2) *Guide for Design of Pavement Structures*, American Association of State Highway and Transportation Officials (AASHTO), Washington, D.C., 1993.

(3) Hossain, M., Long, B. and Kotdwala, S. J. Seasonal and Daily Variations of Deflections Measured with the Falling Weight Deflectometer (FWD). *Final Report No. K-TRAN KSU 94-3,* Kansas Department of Transportation, Topeka, December 1996.

(4) Scullion, T, Uzan, J. and Paredes, M. MODULUS: A Microcomputer-Based Backcalculation System. In *Transportation Research Record No. 1260*, Transportation Research Board, Washington, D.C., pp. 180-191.

(5) Neville, A.M. *Properties of Concrete,* 3rd Edition. Longman, U.K., 1981, pp. 557-558.

(6) Huang, Y. H. *Pavement Analysis and Design*. Prentice Hall, Englewood Cliffs, New Jersey, 1993, pp. 223 - 228.

ACKNOWLEDGEMENTS

This study was supported by the Kansas Department of Transportation (KDOT). Cooperation of Richard Barezinsky of KDOT in preparation of this manuscript is gratefully acknowledged.