Program for the Analysis of CRC Pavement. Research Report 177-9, CFHR, The University of Texas, Austin, 1977.
16. B. F. McGullough, J. Ma, and C. S. Noble. *Limiting Criteria for the Design of CRCP.* Research Report 177-17, CFHR, The University of Texas, Austin, 1979.
17. G. J. De Salvo and J. A. Swanson. *ANSYS Examples Manual.* Swanson Analysis Systems Inc. Houston, Pennsylvania, 1972.
18. G. J. De Salvo and J. A. Swanson. *ANSYS User's Manual.* Swanson Analysis Systems Inc. Houston, Pennsylvania, 1978.
19. S. K. Saxena and S. G. Militsopoulos. "Model Study of Anchored Pavement." In *Transportation Research Record 814*, TRB, National Research Council, Washington, D.C., 1981, pp. 55–62.
20. R. S. Nordal. "The Thermal Regime of the Pavement and the Subgrade at the Vormsund Test Road." *Proc., Symposium on Frost Action*, Norwegian Road Research Laboratory, Oslo, Norway, Oct. 1973.
21. *AASHTO Interim Guide for Design of Pavement Structures.* AASHTO, Washington, D.C., 1972.
22. *Design of Continuously Reinforced Concrete for Highway.* Associated Reinforcing Bar Producers. Chicago, Illinois, 1981.
23. M. I. Darter. Design of Zero Maintenance Plain Jointed Concrete Pavements. In *Development of Design Procedures, Vol. 1., 1977.* Report FHWA-RD-77-111, 253 pp.

Concrete Pavement Joint Stiffness Evaluation

JAMSHID M. ARMAGHANI, JOHN M. LYBAS, MANG TIA, AND BYRON E. RUTH

Concrete pavement distress is often associated with the effectiveness of load transfer at joints and contributing factors such as pumping. Current analytical methods attempt to simulate load transfer, curling, and load effects in the modeling of pavement response. In general these analytical models do not accurately define load transfer and thermal effects. Therefore, research has been initiated to develop improved methods for analysis and design of concrete pavements. The initial results of tests conducted on a Florida Department of Transportation test pavement indicate that pavement and joint response can be effectively modeled using a three-slab, two-joint, finite-element computer program (FEACONS III). Besides conventional layer parameter input, the program requires spring constants for pavement-edge friction, joint shear, and joint moment. The analysis of plain concrete pavement was performed using the falling weight deflectometer (FWD). Data were collected during different seasons, when the differential (ΔT) and average slab temperatures varied substantially. Generally four different load levels were used in the FWD to assess load-deflection linearity. Temperature-curling and contraction–expansion effects were also monitored independently. Spring stiffnesses were varied in the FEACONS III analyses until the predicted deflection basins matched those measured for different temperature and loading conditions. The results obtained with a downward curling ($\Delta T \simeq 9°F$ or 5°C) indicated that spring stiffnesses representing edge friction, joint shear, and moment at the joint remained constant regardless of loading position. This suggests that differential drying shrinkage or a moisture differential had produced upward warping, which was offset by the 9°F (5°C) downward curling. At other differential temperatures, the spring stiffness varied according to slab lift-off and load position. The average slab temperature (seasonal) was found to have a pronounced effect on joint stiffness. At high temperatures, the shear and moment stiffnesses were very high, providing close deflections for loaded and unloaded sides of the joint. When mean slab temperature was lowered, the analyses indicated a significant reduction in joint stiffness.

The critical element of a concrete pavement is the joint that influences load transfer and pavement performance. Pavement engineers should therefore be primarily concerned with the analysis of joints to better describe their behavior. A thorough understanding of the effects of thermal and load conditions on concrete joints should provide for an improvement in design methodology and durability.

Thermal conditions imposed on concrete pavements influence the joint stiffness that affects load transfer characteristics. The average temperature of the concrete pavement influences load transfer of undowelled joints according to the degree of aggregate interlock. On the other hand, the temperature differential between the top and bottom surfaces determines the degree of warping and the curling conditions at the joint that, in effect, cause the variability in the stiffness along the joint.

A number of finite-element computer programs have been developed to analyze the structural behavior of jointed pave-

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ments. Among these programs, WESLIQUID (*1*), ILLI-SLAB (*2*), and the model developed by Huang (*3*), have been widely used for analysis. In these programs the joint stiffness is related to joint efficiency, which is a physical property of the joint. The joint efficiency is defined as the percent ratio of deflections between the unloaded and the loaded sides of a joint. For any loading position, the joint efficiency as defined may vary for different locations along the joint. Moreover, the thermal condition may also influence the value of joint efficiency regardless of loading position. Therefore, relating the stiffness to joint efficiency may, in many cases, result in an inaccurate modeling of joint behavior.

Described in this paper is a procedure to determine the stiffness of an undowelled joint in a concrete pavement using a finite-element program, FEACONS III, as an analytical tool, and the results from the loading tests using the falling weight deflectometer (FWD). Tests were conducted on a specially prepared test pavement. The test pavement was constructed to be representative of in-service concrete pavements in the state of Florida. Load tests were performed at different slab positions such as, center, edge, corner, and two other locations along the undowelled joint. The tests were conducted at different temperature differentials of the pavement and at different seasonal concrete temperatures. Deflection profiles of the pavement at the undowelled joint were also measured for different temperature differentials to determine the warping conditions at the joint.

This study is a part of an ongoing research program between the University of Florida and the Florida Department of Transportation (FDOT) to evaluate

1. Behavior of dowelled and undowelled joints,
2. Effects of thermal conditions of the pavements on the response to the applied FWD loads, and
3. Effects of voids and their locations on the pavement response.

The goal of this research is to accurately model the response of the test pavement when it is subjected to different thermal and loading conditions. Some early findings of this research were presented in a previous paper by Lybas et al. (*4*). Since then, extensive work has been done toward accomplishing the three aforementioned objectives of the main research. The information presented in this paper is a part of the findings of this ongoing research.

FEACONS III COMPUTER PROGRAM

The finite-element analysis of concrete slabs (FEACONS III) computer program was developed at the University of Florida (*5*) to analyze the response of a concrete pavement subject to concentrated or uniform vertical loads.

The program considers the following factors in the analysis:

1. Weight of the concrete slabs,
2. Voids beneath the concrete slabs,
3. Effects of joints and edges, and
4. Effects of temperature differentials between the top and bottom surfaces of the slabs.

FEACONS III models a concrete pavement as a three-slab system. A concrete slab is modeled as an assemblage of rectangular plate finite elements with three degrees of freedom at each node. Load transfer across the joints between the adjoining slabs are modeled by linear and rotational springs connecting the slabs at the nodes of the elements along the joint. Frictional effects at the edges are modeled by linear springs at the nodes along the edges. The subgrade is assumed as a Winkler foundation modeled by a series of vertical springs at the nodes. Subgrade voids are modeled as initial gaps between the slab and the springs at the specified nodes.

There are four input parameters for the program:

1. Subgrade spring stiffness (K_s) in kips per cubic inch modeling the subgrade stiffness of a pavement;
2. Edge spring stiffness (K_{EG}) in kips per square inch modeling the frictional resistance at the edge of the pavement;
3. Joint linear spring stiffness (K_L) in kips per square inch modeling the shear stiffness of the joint; and
4. Joint rotational stiffness (K_R) in kips per inch modeling the moment stiffness of the joint.

DESCRIPTION OF TEST PAVEMENT

A six-slab concrete pavement test road incorporating two dowelled and four undowelled joints was constructed at the FDOT Bureau of Materials and Research. Each slab is 6.1-m (20-ft) long, 3.66-m (12-ft) wide, and 23-cm (9-in) thick. The test road, as shown in Figure 1, incorporates voids of two different depths and various sizes. Slab 4 is a control slab, cast with no voids, and has been used for comparison of response with the slabs with voids.

TESTING SYSTEMS AND DATA COLLECTION

FWD Measurements

FWD loads were applied at the center, edge, and corner of Control Slab 4. Two other locations along the undowelled joint were also tested; their locations were at 75 cm (30 in.) and 165 cm (66 in.) from the edge, respectively. Magnitudes of the testing loads ranged from 250 kPa (36 psi) to 950 kPa (138 psi). The tests were conducted at various temperature differentials (ΔT) that occurred during the test day. The tests were repeated during summer, fall, and winter. A typical load deflection relation at various temperature differentials for corner loading is shown in Figure 2.

For each joint loading, deflections were measured with sensors along the loaded and unloaded sides of the joints. Thus the measured deflection basins on both sides of the joints were obtained.

Temperature Measurements

Air and concrete temperatures were measured using thermocouples. Thermocouples were embedded in Slabs 3 and 4 as shown in Figure 1. Thermocouple Locations a and b in Slab 3

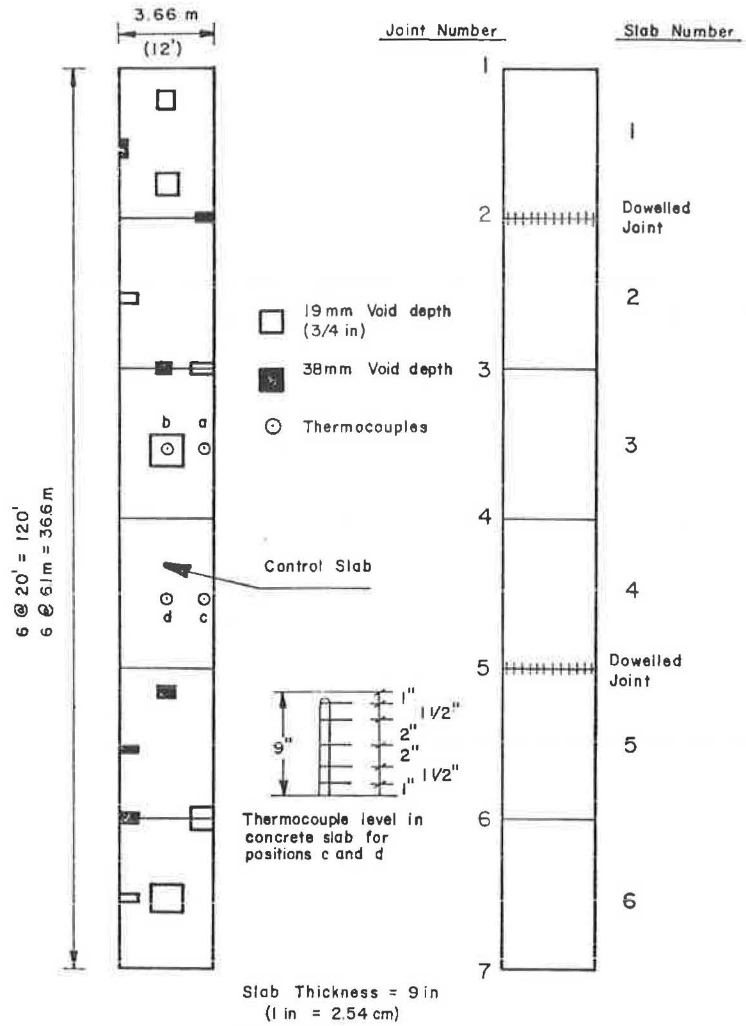

FIGURE 1 Details of test road.

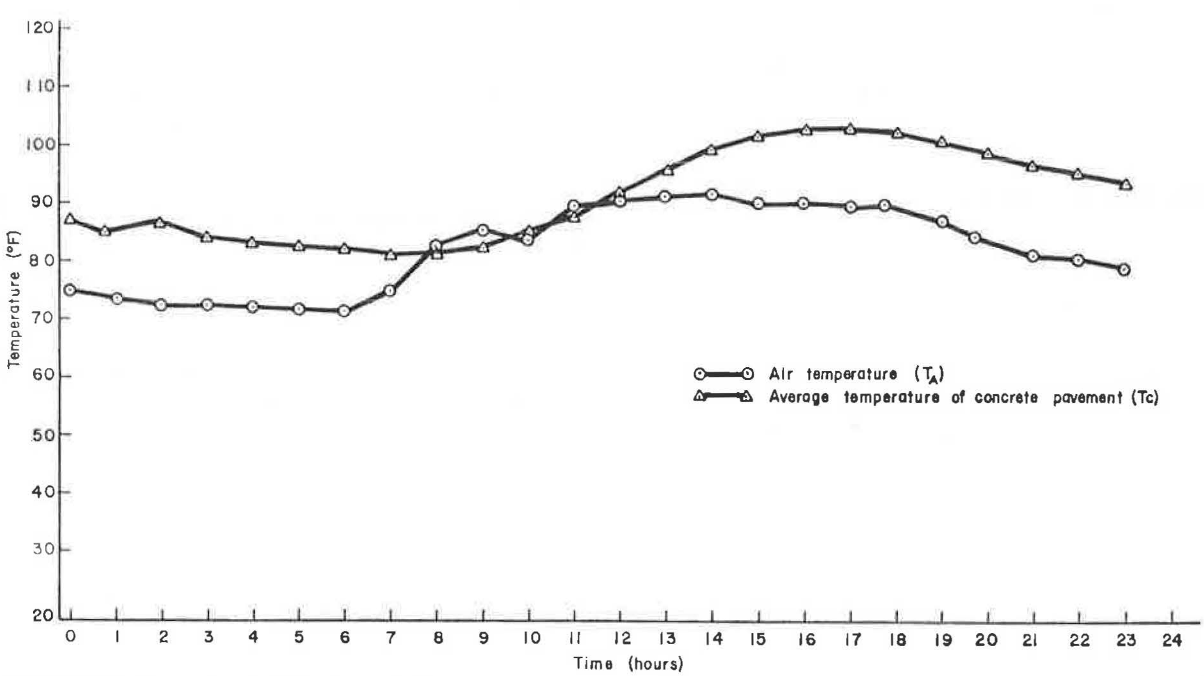

FIGURE 2 Typical load–deflection relations at the slab corner.

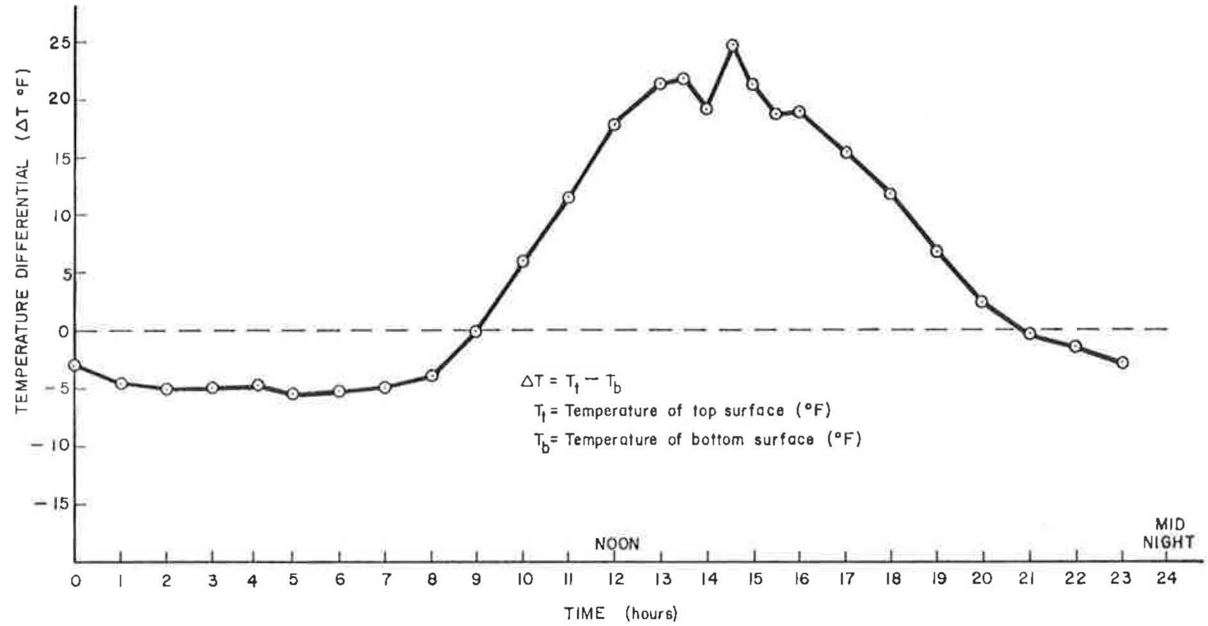

FIGURE 3 Typical hourly temperature records of air and of the concrete pavement for the summer season.

include a thermocouple 1 in. below the top and 1 in. above the bottom surface of the concrete. Thermocouple Locations c, and d in Slab 4 include five thermocouples positioned at different levels in the concrete as shown in Figure 1.

Concrete and air temperatures were recorded every 15 min during the FWD loading tests. The temperatures were also recorded every hour before and after the FWD tests for the complete 24-hr cycle. A typical hourly air temperature (T_A) and average concrete temperature (T_c) are shown in Figure 3. The average concrete temperature represents the average of the measured temperatures from all thermocouples in the pavement. Typical hourly values of temperature differentials (ΔT) computed as the difference between the temperatures of the top and bottom surfaces of the pavement are shown in Figure 4.

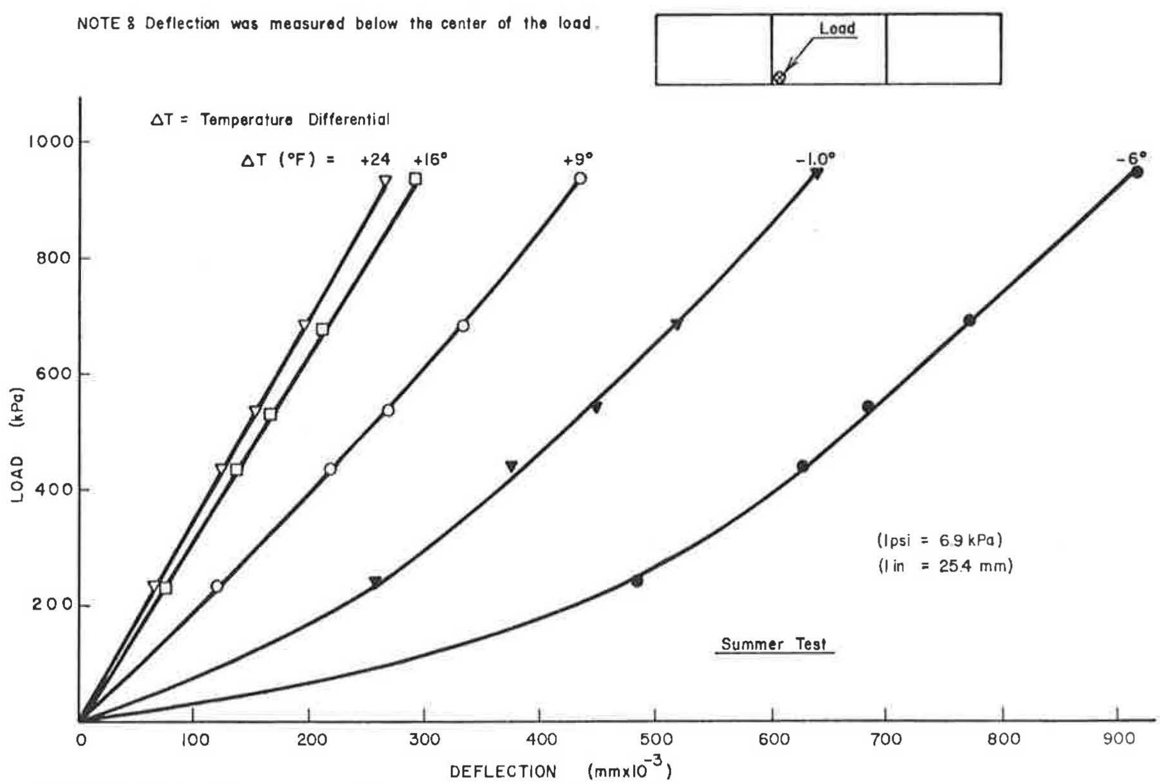

FIGURE 4 Typical 24-hr cycle of temperature differential for the pavement during the summer season.

Deflection Profiles at the Joint

Deflection profiles of the pavement along the undowelled joint (Joint 4) were measured at various temperature differentials using linear variable differential transducers (LVDTs). A timber frame was placed over the pavement width to hold the LVDTs. Seven LVDTs were used to record the surface elevations along the undowelled joint. A data acquisition unit HP3497 controlled by an HP9825A computer, was programmed to record LVDT readings and store them in the computer every 30 min. Another data control unit was programmed to record temperature measurements from the thermocouples simultaneously with the LVDT readings. The deflection profiles from the LVDT measurements at various temperature differentials are shown in Figure 5.

SELECTION OF INPUT PARAMETERS FOR FEACONS III

In order to use the FEACONS III program to evaluate joint stiffness, the main input parameters of the model had to be determined first. The main assumption in the model was that uniform subgrade support existed with no voids beneath the slabs. All test results for the analysis presented in this paper were obtained from Control Slab 4.

Selection of Subgrade Spring Stiffness (K_s)

Different subgrade spring stiffnesses (K_s) were assumed in the FEACONS III program. Predicted deflection basins representing the different subgrade spring stiffnesses were compared with the measured deflection basin for loading at the slab center. The actual deflection basin in this comparison represented the linear response of the pavement or the condition of full contact between the center of the slab and the subgrade.

The predicted deflection basin that best correlated with the measured deflection basin was considered to represent the subgrade spring stiffness of the pavement.

Selection of the Edge Spring Stiffness (K_{EG})

With the subgrade spring stiffness (K_s) evaluated, predicted and measured deflections from the edge loading were correlated to determine the edge spring stiffness (K_{EG}). Different K_{EG} values were assumed in the program. Comparisons were made between the predicted and the actual deflection basins.

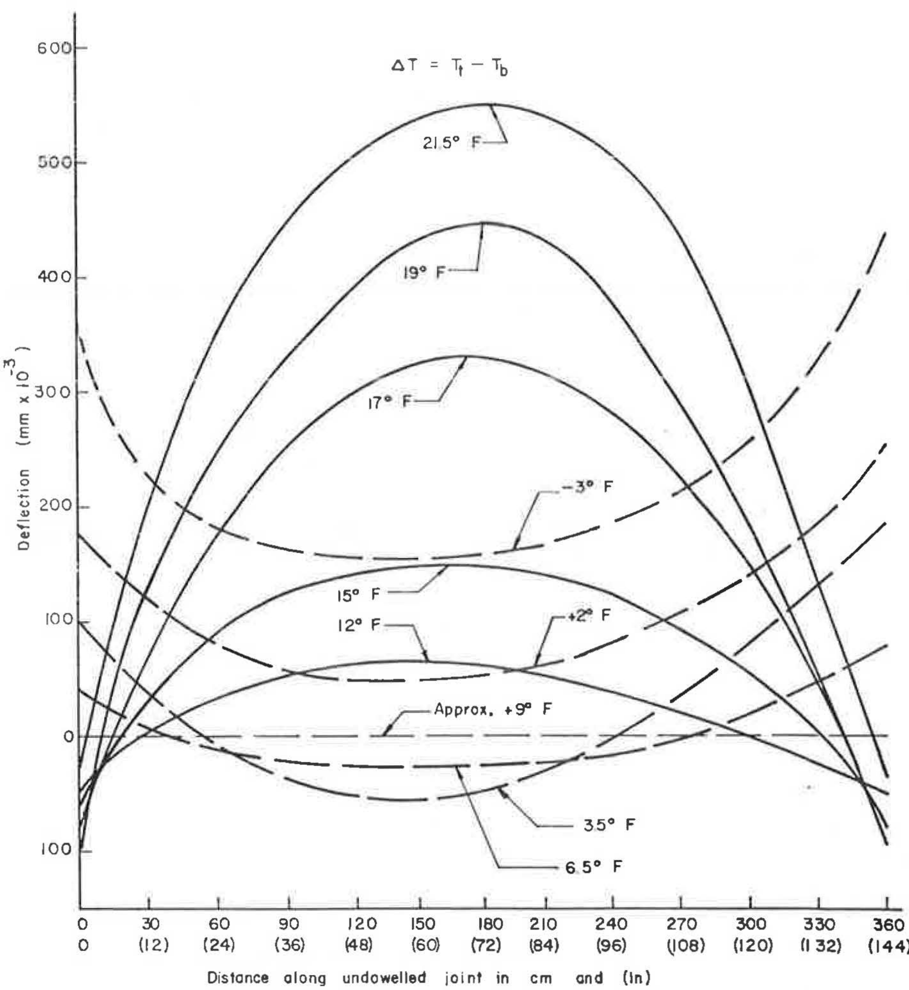

FIGURE 5 Deflection profiles along the joint due to the change in the temperature differential (ΔT) in concrete pavement.

The predicted deflection basin that correlated closely to the actual deflection basin represented the edge spring stiffness that best modeled the frictional resistance at the pavement edges.

Selection of the Linear and Rotational Spring Stiffnesses at the Joint (K_L), (K_R)

Linear spring stiffness (K_L) representing the shear stiffness, and the rotational spring stiffness (K_R) representing the moment stiffness had to be determined individually to assess the actual joint stiffnesses. With the load applied at the joint, the predicted deflection basins were compared with the measured deflection basins. This comparison was made for deflection basins on the loaded and on the unloaded side of the undowelled joint. As in the center and edge loading case, only measured deflection basins exhibiting linear load response were used in the analyses.

Different combinations of K_L and K_R values were assumed in the FEACONS III program. The combination of K_L and K_R, that resulted in deflection basins that best correlated with the measured deflection basins on both sides of the joint, represented the joint stiffness for the specified loading condition.

ANALYSIS OF THE FWD LOAD–DEFLECTION DATA

The test results from corner loading at Slab 4 were analyzed. Figure 2 shows the load–deflection relation for various temperature differentials (ΔT). This relation is nonlinear at ΔT of −6°F, representing an upward curling of the corner, as is evident from the deflection profiles in Figure 5. As the temperature differential (ΔT) became more positive, the condition of the slab corner changed from upward to downward curling as shown in Figure 5. This change is reflected in the load–deflection relation as it became linear at ΔT of +9°F and above, and the pavement system response to loads became uniform. In Figure 5, the +9°F temperature differential represents a flat position of the joint. The load–deflection relation was also determined for the other two load positions along the joint, and the condition of linear pavement response was selected for comparison with the predicted deflections. The linear load–deflection relations at the three load positions along the undowelled joint are shown in Figure 6.

Typical load–deflection relations at the slab center are shown in Figure 7. At ΔT of −3°F the load–deflection is linear, indicating linear response of the pavement system to the applied loads. This temperature differential (−3°F) represents a downward curling position of the slab center, where the slab may be in full contact with the subgrade. However, at ΔT of +11°F and more, the response is nonlinear; this is due to the upward lifting of the slab center from the subgrade.

In order to evaluate the subgrade stiffness accurately, the condition of the linear pavement response should be used in the analysis, and not any arbitrarily chosen deflections from the test results.

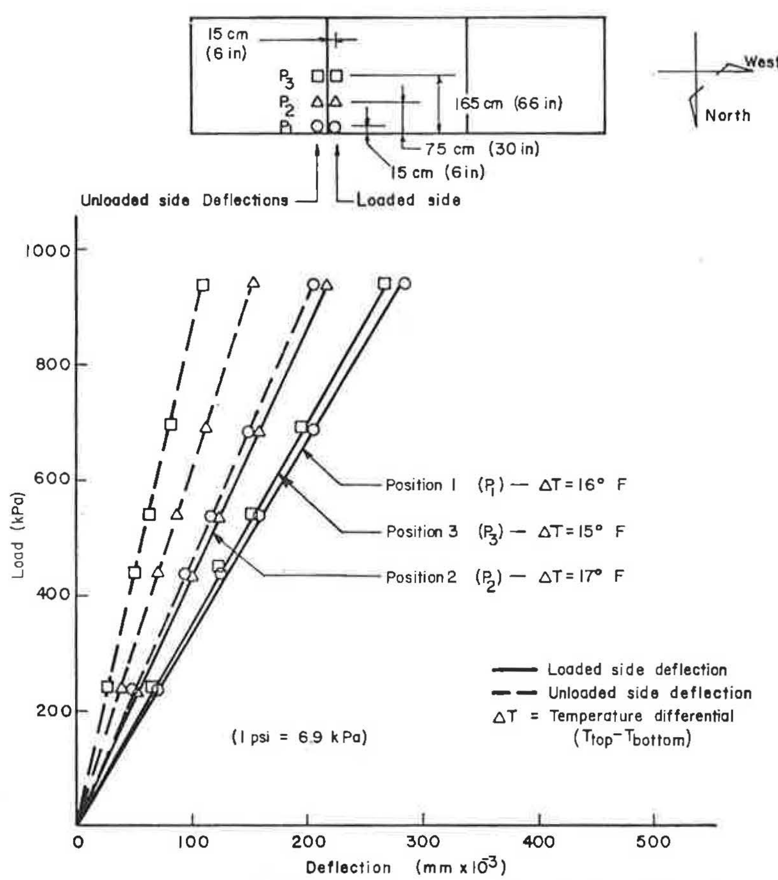

FIGURE 6 Linear load–deflection relations for three load positions along the undowelled Joint 4 of the test pavement.

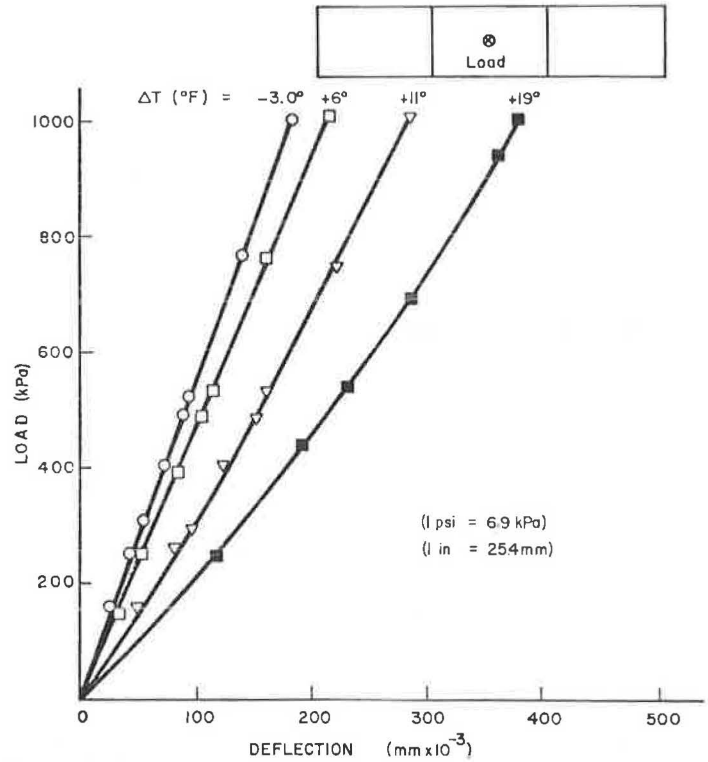

FIGURE 7 Typical load–deflection relations at the slab center.

RESULTS OF FEACONS III ANALYSES

Subgrade Stiffness of the Pavement

The predicted deflections that correlated best with the measured deflections from the summer and winter tests are shown in Figure 8. There appears to be a variation in the subgrade stiffness (K_s) between summer and winter. As shown in Figure 8, the K_s for summer was 0.35 pci and 0.25 pci for winter.

Different values of K_{EG}, K_L, and K_R were tried in the FEACONS III program. Results of the analytic solution showed no change in the values of the deflections at the slab center. This indicates that deflections in the slab center are not affected by changes in the joint and edge stiffnesses.

Edge Stiffness

Predicted deflection basins that correlated very closely with the actual deflection basin along the slab edge are shown in Figure 9. The deflection basin, representing K_s of 0.25 pci and K_{EG} of 10 psi, correlated very well with the actual deflection. Edge spring stiffness values of 15 ksi and 5 ksi were also tried in the program, but correlated poorly with the actual deflection basin as shown in Figure 8. Various combinations of K_L and K_R were also assumed, but showed no effect on the deflection basin along the joint.

Joint Stiffness

Joint stiffness was evaluated at two thermal conditions, A and B, for the summer test, and at two other seasons, fall and winter. Figures 10–13 show evaluations of the shear and moment stiffnesses at three positions along the undowelled joint for Thermal Condition A of the summer test. It is evident from the analyses that the stiffness along the joint varied at a ΔT 16°F. From Load Position 1 to Load Position 3, there were sharp reductions in the values of K_L and K_R as shown in Figures 10 to 13.

An examination of the joint stiffnesses in Figures 14 and 15 for Thermal Condition B indicates a uniform, constant stiffness along the joint. For this thermal condition the K_L and K_R remained constant at values of 10 ksi and 2,500 kips/in., respectively, regardless of load position along the joint.

Joint stiffness evaluations for the fall and winter conditions are shown in Figures 16 and 17. Compared with summer (Figures 10 and 11), the joint stiffness decreased in fall and winter. For K_s of 0.25, the value of K_L decreased from 750 ksi in the summer to 60 ksi in the fall to 10 ksi in the winter, and the K_R decreased from 5,000 kips/in. in the summer and fall to 2,500 kips/in. in the winter.

DISCUSSION OF RESULTS

Joint Stiffness

In this paper, the joint stiffness was evaluated by comparing predicted and measured deflection basins. No attempt was made to relate the joint stiffness to the joint efficiency that had been used in some previous studies (*2*, *3*). Joint efficiency was defined (*2*) as the percent ratio of deflections of the unloaded to the loaded sides of the joint. However, it was concluded from analyzing the test data for the present study, that relating joint stiffness to joint efficiency may be inaccurate and misleading

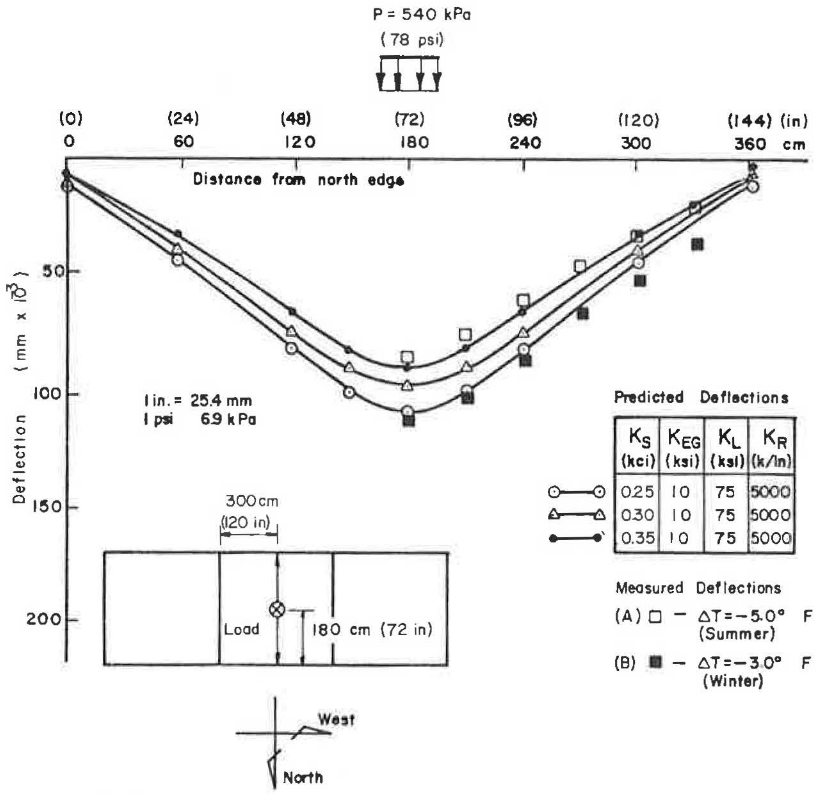

FIGURE 8 Deflection basin, center of slab, transverse direction.

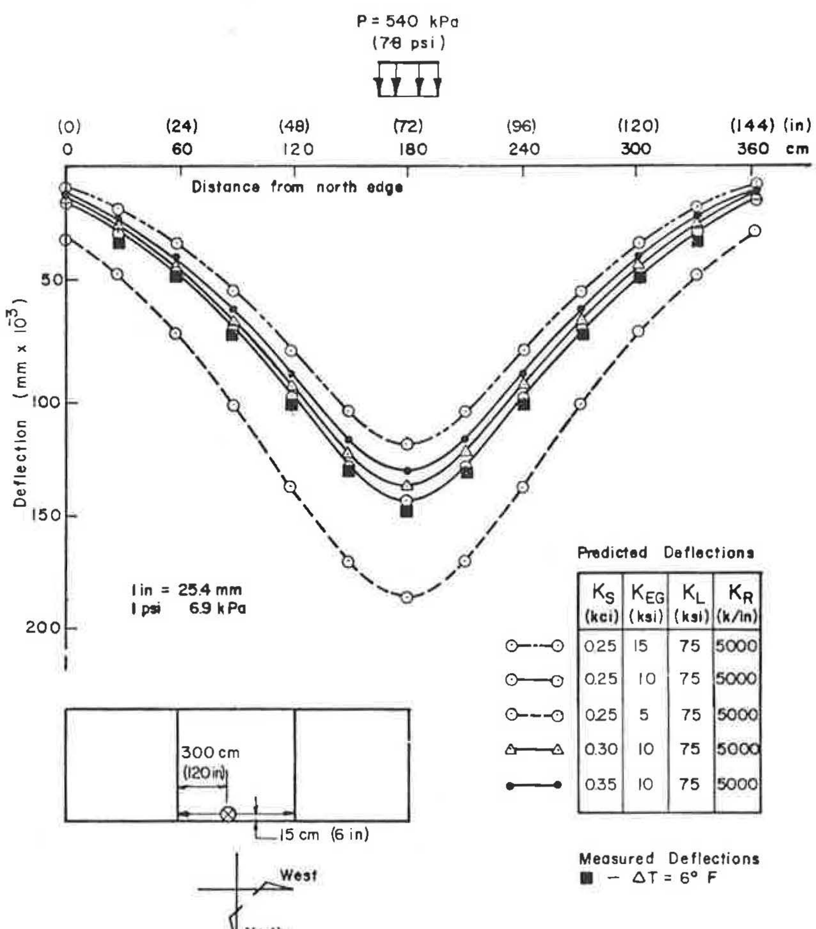

FIGURE 9 Deflection basin, slab edge on the longitudinal direction.

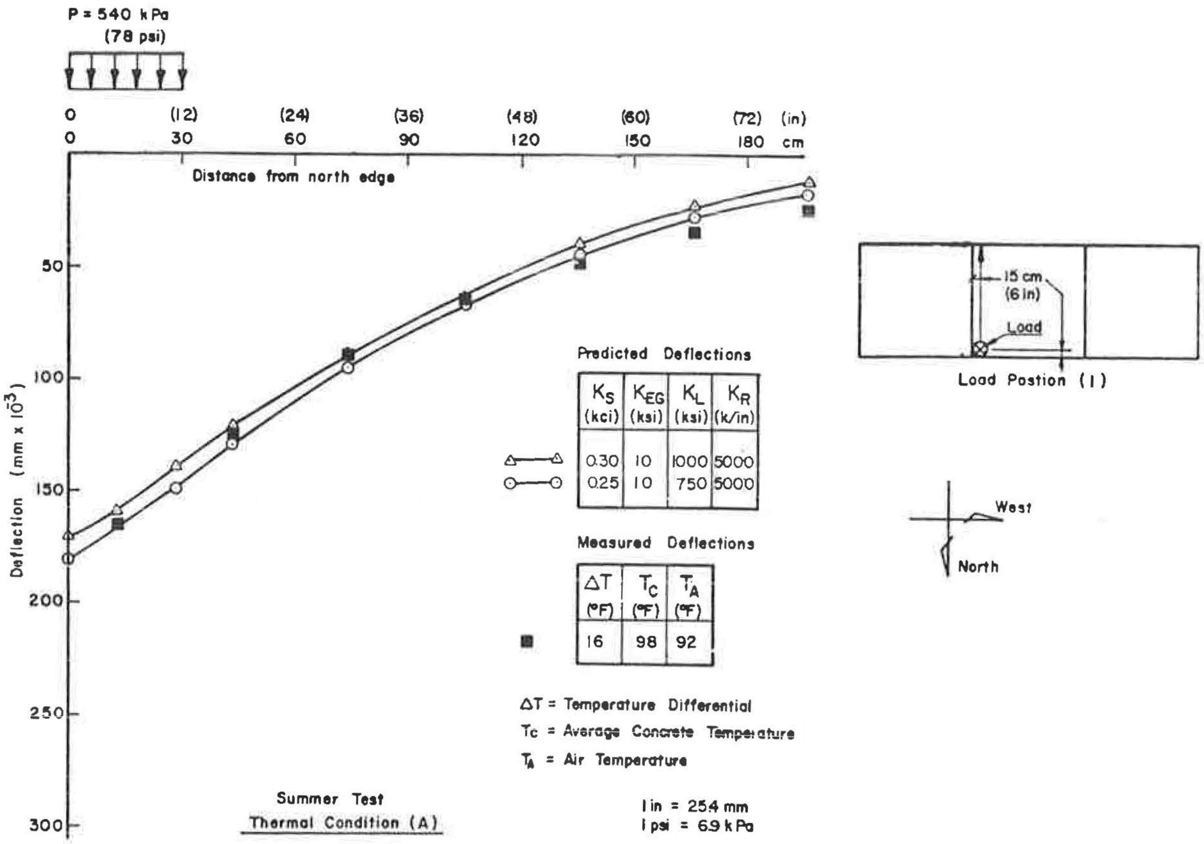

FIGURE 10 Deflection basins on the loaded side of undowelled joint, transverse direction.

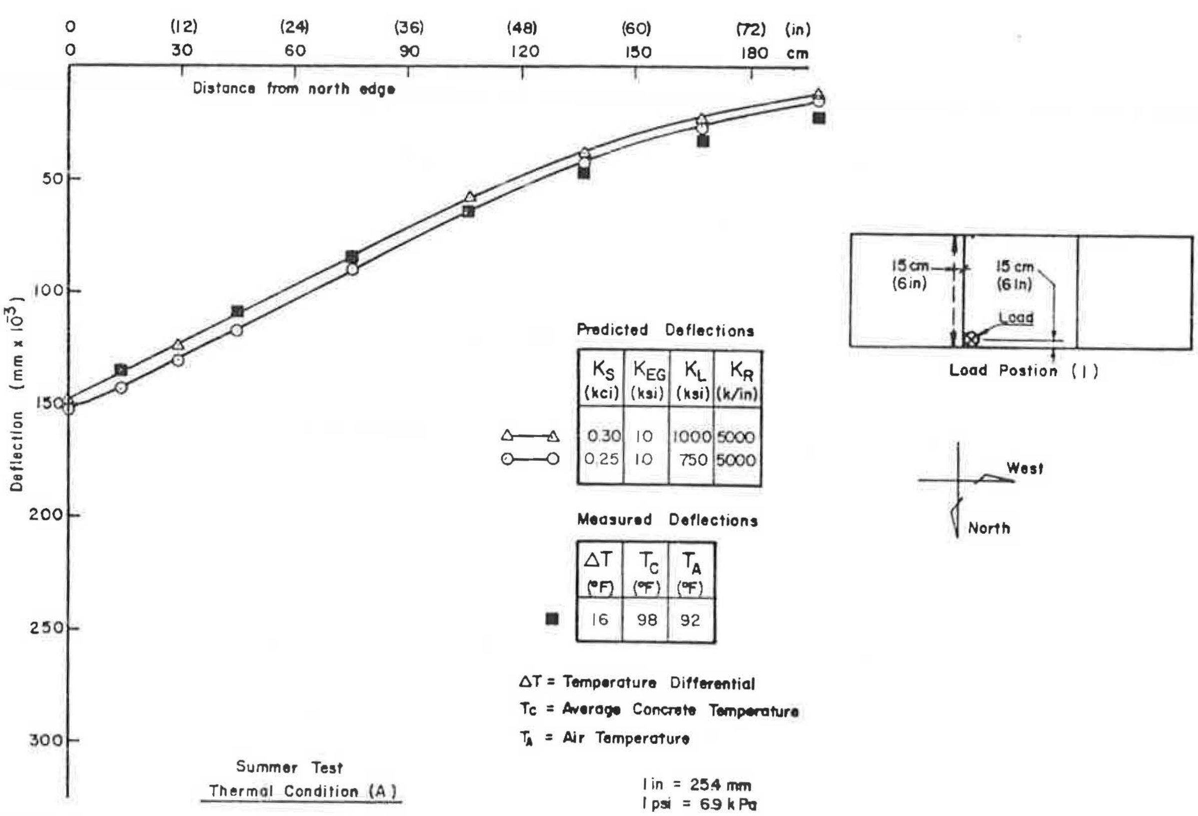

FIGURE 11 Deflection basins on the unloaded side of undowelled joint.

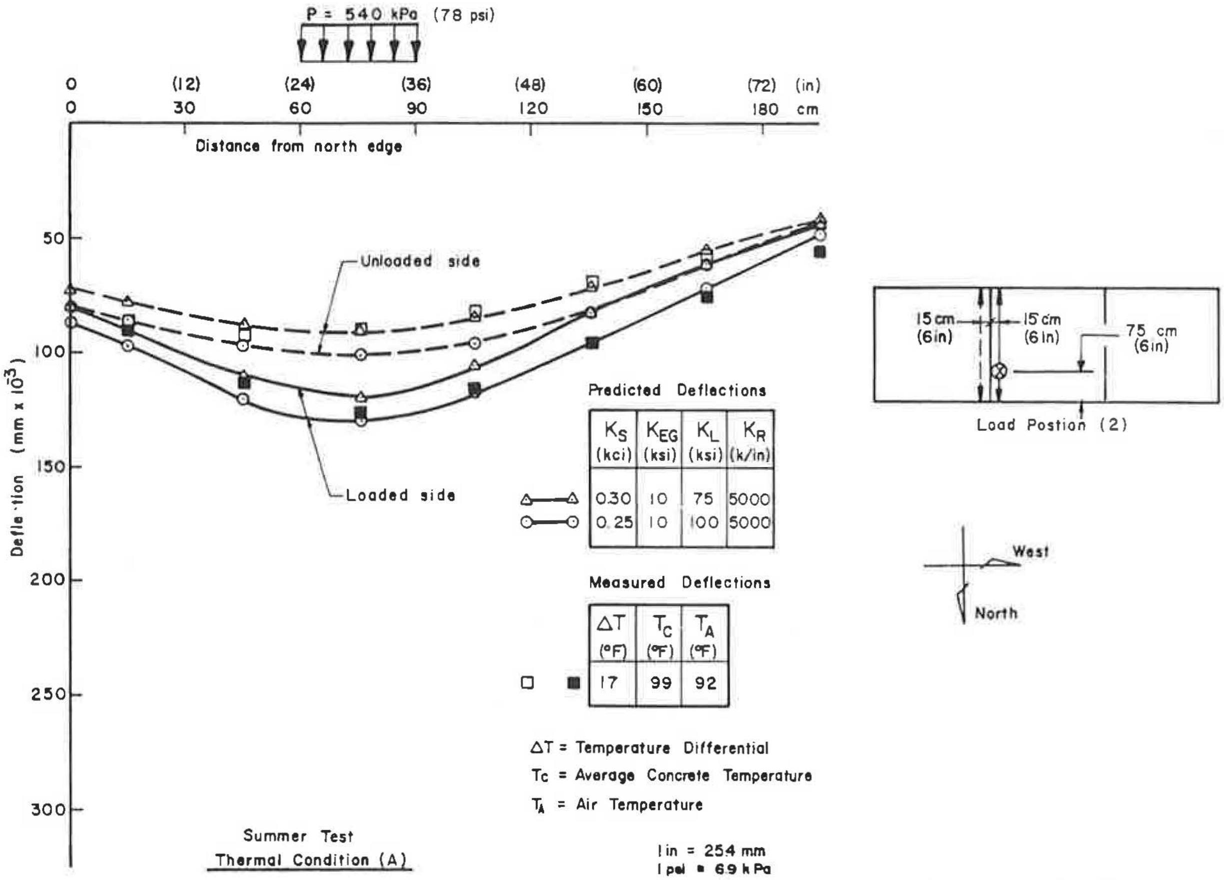

FIGURE 12 Deflection basins on the loaded and the unloaded sides of the undowelled joint, transverse direction.

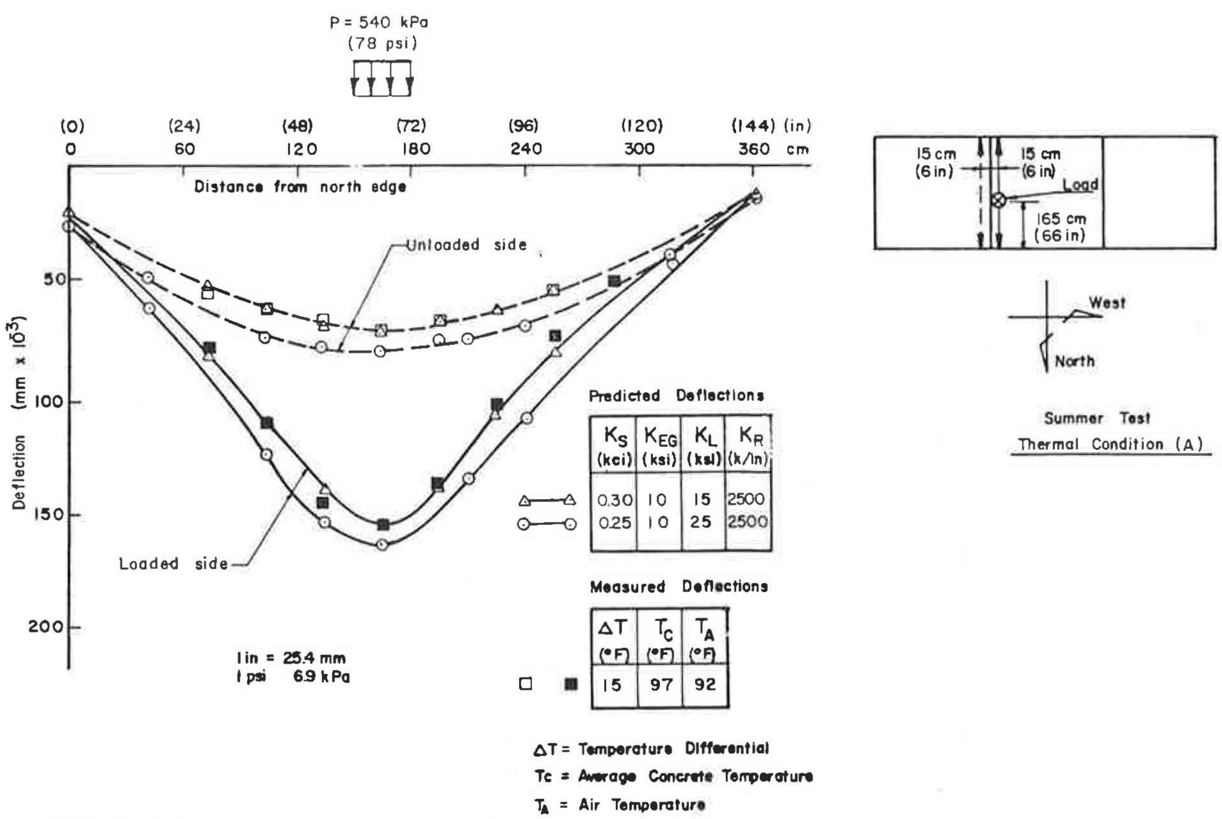

FIGURE 13 Deflection basins on the loaded and the unloaded sides of the undowelled joint, transverse direction.

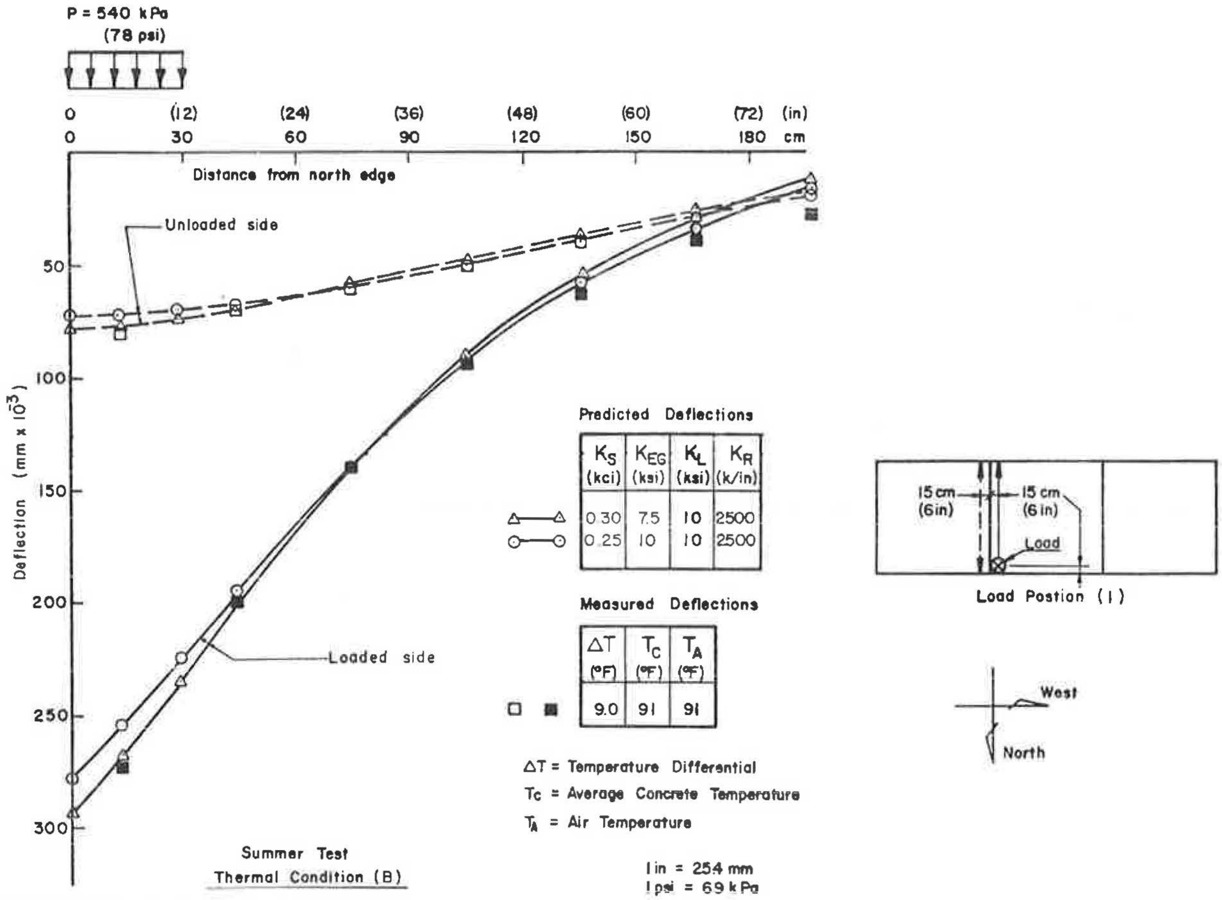

FIGURE 14 Deflection basins on the loaded and the unloaded sides of the undowelled joint.

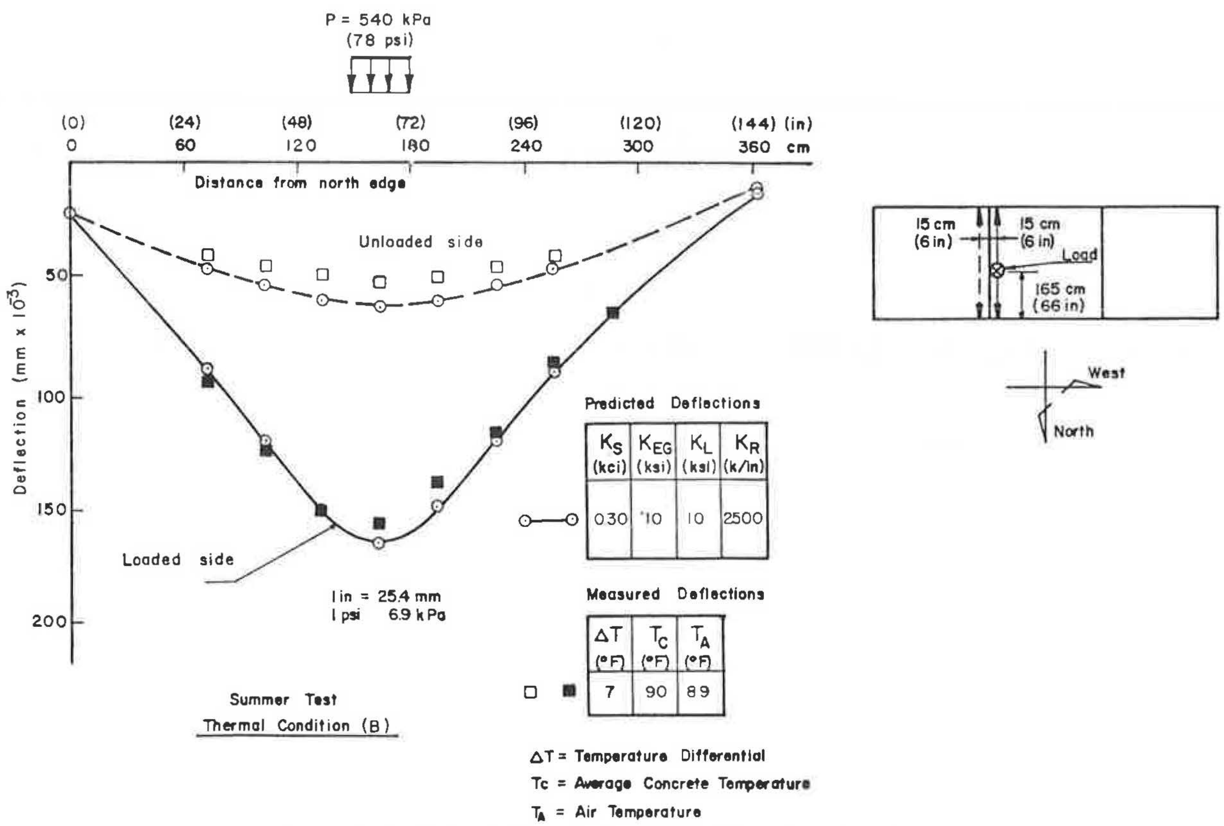

FIGURE 15 Deflection basins on the loaded and the unloaded sides of the undowelled joint (summer test).

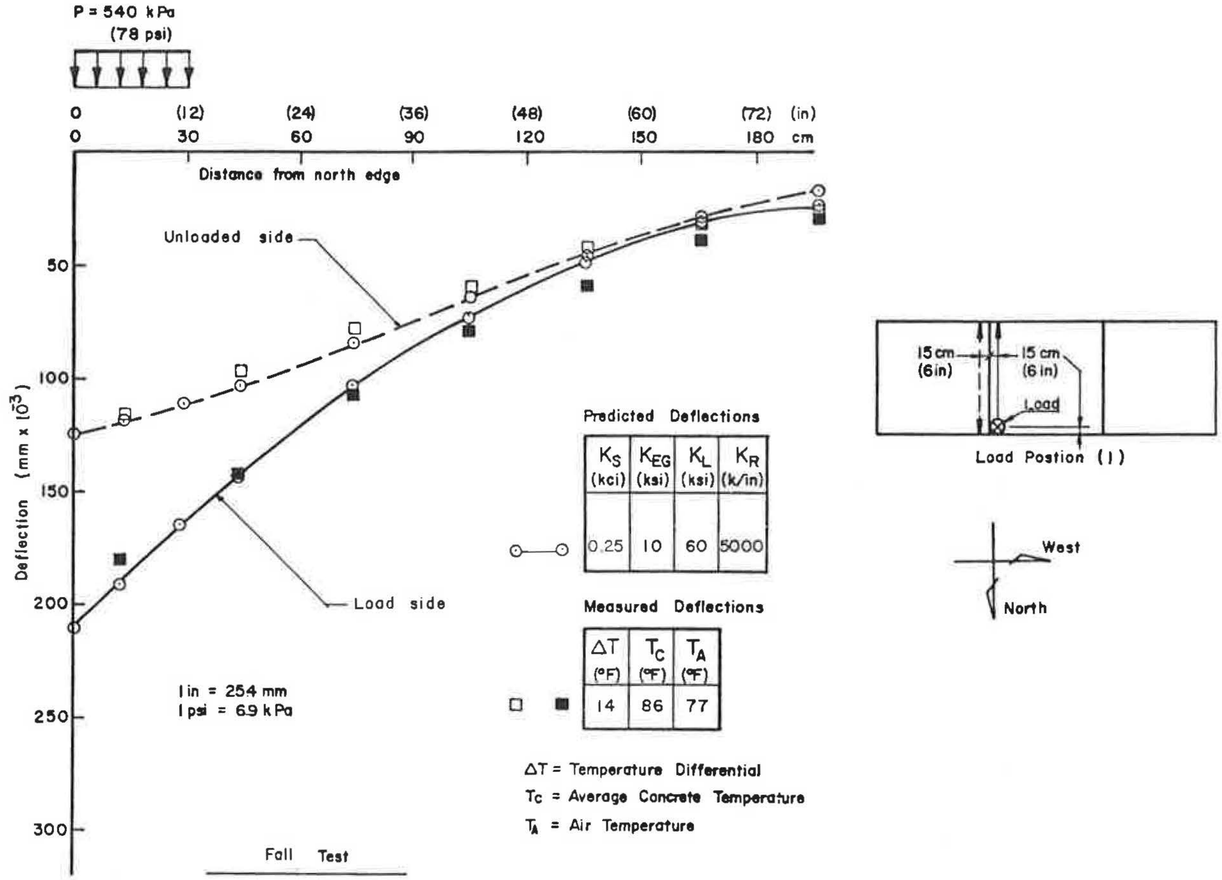

FIGURE 16 Deflection basins on the loaded and the unloaded sides of the undowelled joint (fall test).

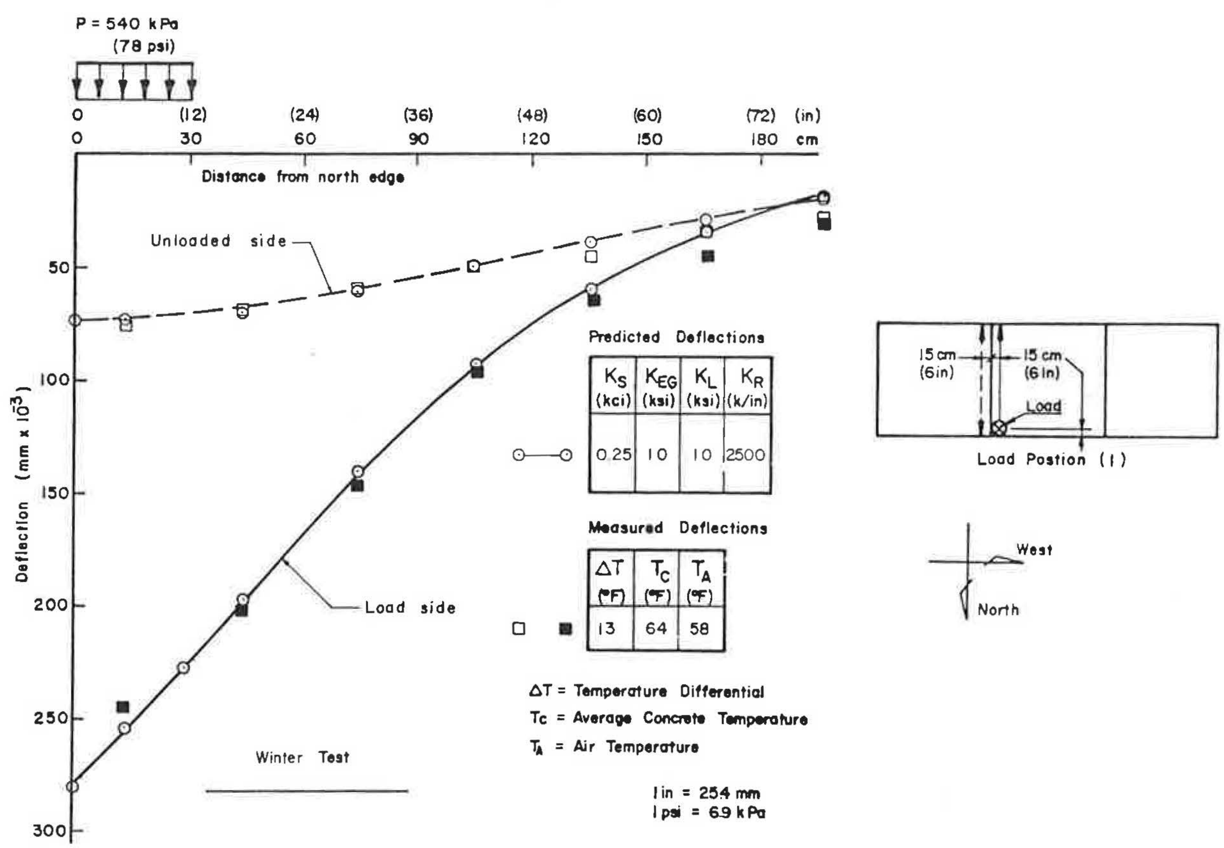

FIGURE 17 Deflection basins on the loaded and the unloaded sides of the undowelled joint (winter test).

TABLE 1 JOINT EFFICIENCIES ALONG THE JOINT FOR THREE LOAD POSITIONS

Distance From North Edge cm (in)	Load Position (1) Deflection (mm x 10^{-3}) Loaded Side	Unloaded Side	Joint Eff.%	Load Position (2) Deflection (mm x 10^{-3}) Loaded Side	Unloaded Side	Joint Eff.%	Load Position (3) Deflection (mm x 10^{-3}) Loaded Side	Unloaded Side	Joint Eff.%
15 (6)	165	136	82	89	86	97	-	-	-
45 (18)	124	110	89	107	92	86	-	-	-
75 (30)	90	86	96	127	88	69	77	56	73
105 (42)	67	66	99	115	81	70	111	62	59
135 (54)	50	49	99	96	69	72	147	67	46
165 (66)	37	37	100	77	59	77	153	69	45
195 (78)	28	28	100	57	49	86	132	67	51
225 (90)	-	-	-	-	-	-	105	63	60
255 (102)	-	-	-	-	-	-	72	56	78

Note: Load = 540 kPa (78 psi). 1 psi = 6.9 kPa, and 1 in. = 25.4 mm. Thermal conditions: ΔT = +17°F, and T_c = 99°. Joint efficiency = (deflection, unloaded side/Deflection, loaded side) × 100. Load Positions 1, 2, & 3, see Figure 6.

as illustrated in Table 1. In Table 1 the values of joint efficiency changed from the 82 percent at Load Position 1 to 99 percent at 90 cm (36 in.) away from the load center. The joint efficiency measured at Load Positions 1, 2, and 3, also changed from 82 percent (Position 1) to 69 percent (Position 2) to 45 percent (Position 3). As a result of the inconsistent values of joint efficiencies, the evaluation procedure of the shear and moment stiffnesses was based on deflection basins correlations and not on ratios of measured deflections at the joint.

Variability of Stiffness Along the Undowelled Joint

In Figure 18, the shear and moment stiffnesses along the joint for Thermal Condition A are shown to have varied considerably, whereas for Thermal Condition B the stiffnesses remained constant along the joint. The temperature differentials for Thermal Conditions A and B were 16°F and 9°F, respectively. In Figure 5, the deflection profiles for ΔT of +15°F and +17°F indicate a downward curling of the joint. This

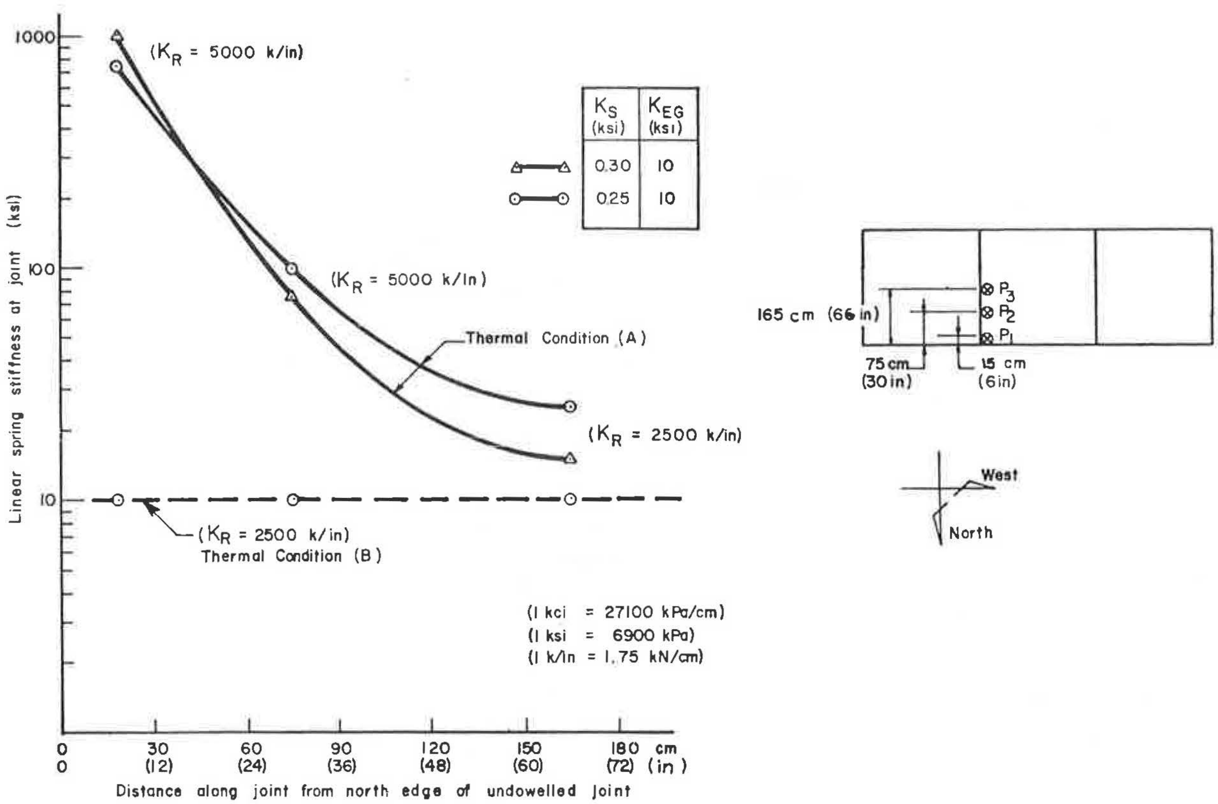

FIGURE 18 Effects of temperature differential of the concrete pavement on variability of joint stiffness along the undowelled joint.

curling along the joint may have caused variable joint opening and, consequently, may have induced a variable degree of aggregate interlock resulting in the variation of the stiffness along the joint.

In the case of Thermal Condition B, the temperature gradient ranged between +7.5°F and 10°F. As shown in Figure 5, the deflection profiles for this range of temperature differentials indicate an almost level surface or no warping condition along the joint. This thermal condition may have caused a uniform joint opening and subsequently a uniform aggregate interlock that in turn may have resulted in uniform shear and moment stiffnesses along the joint.

It should be noted from Figure 5 that the no warping or curling condition occurred at ΔT of +9°F and not at ΔT of 0°F. This may be a result of the effects of moisture in the concrete or the differential drying shrinkage that might have occurred in the slabs after placing the concrete.

Seasonal Changes in Joint Stiffness

Seasonal changes in the average temperature (T_c) of the concrete pavement resulted in the variability of the shear and moment stiffnesses. The variability in stiffness between summer, fall, and winter as T_c is decreased from 98°F in the summer to 64°F in the winter is shown in Figure 19.

The average concrete temperature affects the expansion or contraction of the pavement slabs and controls the degree of the joint locking. When T_c was reduced from 98°F to 64°F the joint between the adjoining slabs might have opened enough to cause the sharp reduction in the shear and the moment stiffnesses of the undowelled joint.

CONCLUSIONS

A procedure was presented to evaluate a test pavement, using the finite-element computer program FEACONS III and field deflection data from the FWD tests. Subgrade, edge, and joint stiffnesses were evaluated to correlate predicted and measured deflection basins. Based on the evaluation of the undowelled joint, the following conclusions were made:

1. The concept of joint efficiency has been determined to be an unrealistic measure of the joint stiffness due to its variability with changes in load positions and thermal conditions.

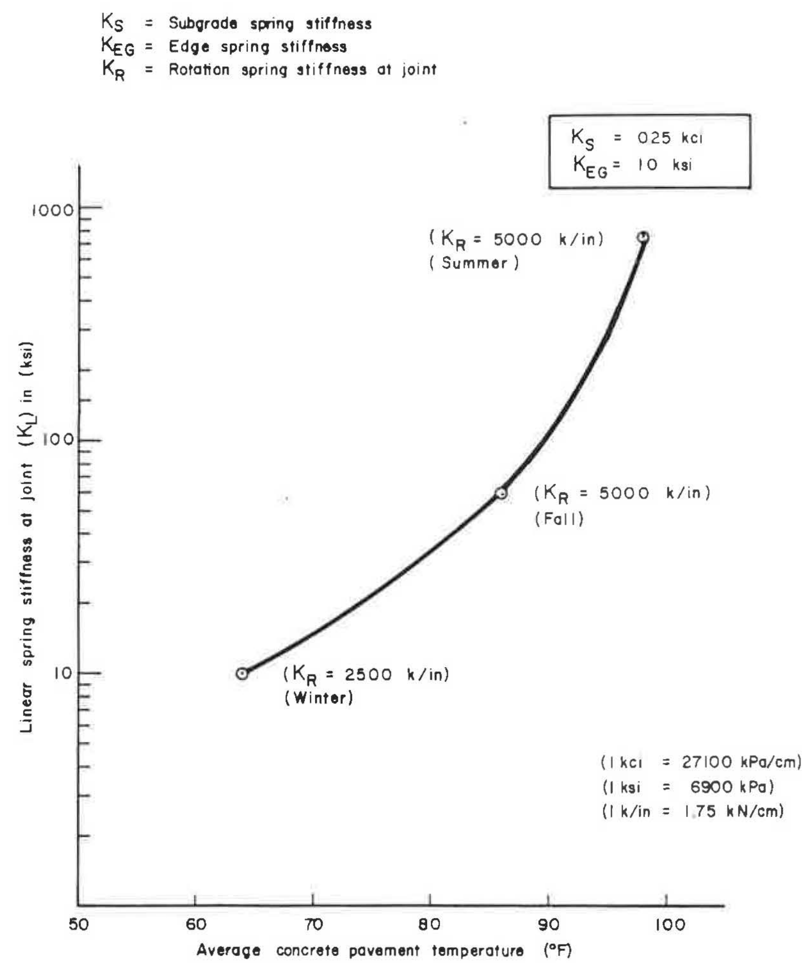

FIGURE 19 Effects of concrete pavement temperature on the joint stiffness of the undowelled joint.

2. The shear and moment stiffness varied along the joint when the deflection profile of the slab showed a condition of downward curling.

3. The shear and moment stiffnesses were constant when the deflection profile at the slab along the joint showed a condition of no warping or curling.

4. The shear and moment stiffnesses decreased as the average temperature of the concrete pavement decreased between the summer and the winter seasons.

FEACONS III will be further tested to determine its capability in modeling various joint types, slab conditions such as warping, and the presence of voids below the pavement. If all of the variables affecting pavement response can be modeled by this finite-element program, it should be equally applicable to the analysis of concrete pavements with different thicknesses, slab lengths, skewed joints, and so on. It is intended that charts, functions, or both be developed to predict the values of the K_s, K_{EG}, K_L, and K_R, which formulate the direct input into FEACONS III for use in the analyses or development of design charts for concrete pavements.

ACKNOWLEDGMENTS

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REFERENCES

1. Y. T. Chou. Structural Analysis Computer Program for Rigid Multicomponent Pavement Structures with Discontinuities. Wesliquid and Weslayer. *Technical Report GL-80*, U.S. Army Waterways Experiment Station, Vicksburg, Mississippi, Sept 1980.
2. A. M. Tabatabaie and E. J. Barenberg. "Finite Element, Analysis of Jointed or Cracked Concrete Pavements." In *Transportation Research Record 671*, TRB, National Research Council, Washington, D.C., 1978, pp. 11–19.
3. Y. H. Huang and S. T. Wang. "Finite Element Analysis of Concrete Slabs and Its Implication for Rigid Pavement Design." In *Highway Research Record 466*, HRB, National Research Council, Washington, D.C., 1973, pp. 55–69.
4. J. M. Lybas, M. Tia, and D. A. Twiddy. "Evaluation of a Concrete Test Pavement Using the FWD and WESLIQUID." *Proc., Third International Conference on Concrete Pavement Design and Rehabilitation*, Purdue University, LaFayette, Indiana, April 1985.
5. M. Tia, J. M. Armaghani, L. Lei, and K. L. Toye. "Development of FEACONS III Computer Program for Jointed Concrete Pavement Analysis." Unpublished paper.