Analysis of Horizontal Movements of Joints and Cracks in Portland Cement Concrete Pavements

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To properly design joints in portland cement concrete pavements, it is necessary to know the expected movements to which these joints are subjected during their lifetime. Previous research on a newly constructed pavement has shown that theoretical calculation of the horizontal movements on the basis of $\delta_t = \alpha_c * \Delta T * L$ differ greatly from field measurements. To check this behavior, the study was repeated on the same pavement in Chillicothe, Ohio, when it was 20 years old. The test section on US-23 in Chillicothe was built specifically for this study in 1972 and included a range of variables that may affect the behavior of the pavement and the joints. The variables included slab length, type of dowels, configuration of the sawcut, and type of base. The results are reported of measurements of horizontal movements on six subsections with 21- and 40-ft (6.4- and 12.2-m) spacing of joints, granular and asphalt stabilized base, and standard and plastic-coated dowels. The field program consisted of measuring the horizontal movements during the different seasons of the year. The joints and cracks in the pavement were instrumented with linear variable differential transformers and data loggers to obtain a continuous record of the horizontal movements. Measurements were also made seasonally at all joints and cracks using a hand-held mechanical gauge. The results reveal good correlation between observed and theoretical horizontal movements. A statistical analysis of horizontal movements, measured 20 years after construction, indicates that joint spacing, type of base, and type of dowel bar have only a small effect on joint and crack movements.

Joints have generally been recognized as the most troublesome feature of a jointed concrete pavement. They tend to spall, crack, and fault fairly soon after construction and, among other problems, the sealant may slip or separate from the face of the joint or may undergo a compression set. The failure of the sealant is due in part to a lack of understanding of the behavior of the joint-sealant system. Generally, joint-sealant systems are crude and the understanding of the elements contributing to their success or failure is limited or frequently ignored. Previous research on a newly constructed pavement (*1–3*) indicated that theoretical calculations of the horizontal movements based on the following equation may differ greatly from field measurements:

$$\delta_t = \alpha_c * \Delta T * L$$

where

δ_t = temperature-induced movement,
α_c = 5.5×10^{-6}/°F,
ΔT = temperature change, and
L = slab length.

To check if this behavior changes with time, the study was continued on the same pavement in Chillicothe, Ohio, when it was 20 years old. The results indicate that the behavior has changed. The horizontal movements at the joints now tend to follow more closely the theoretical calculations.

Vertical movements at the joints were also measured, but the results will not be discussed in this paper.

PRESENT STUDY

This study is part of a 20-year research effort for the evaluation of the field performance of an experimental jointed concrete pavement. To find the effect of different design characteristics on the behavior of the pavement, 12 test sections were constructed with various slab lengths, types of base, types of dowel bar, and sawcut configurations. Table 1 gives the characteristics of the test sections.

The complete test section is a reinforced portland cement concrete pavement 3,225 ft (983 m) long and 9 in. (0.229 m) thick. It is a tangent section between two bridges on southbound US-23 in Chillicothe, Ohio. The pavement is built on fill that ranges from 20 to 35 ft (6.1 to 10.7 m) in height. The types of base materials used are granular and stabilized. The granular base is a crushed stone layer 7.5 in. (187.5 mm) thick, and the stabilized base is a layer of asphaltic concrete 4 in. (100 mm) thick. The pavement consists of two lanes 12 ft (3.6 m) wide separated by a longitudinal joint. The total length of the subsections instrumented and monitored in the test program was 1,624 ft (495 m).

This paper reports the results of horizontal movements on six subsections, numbered 3, 4, 6, 7, 9, and 10. Subsection 9 was chosen as the base section, at which temperature and horizontal movements were measured continuously. Here, the instrumentation was left in place permanently. The other five subsections were measured intermittently over periods of 7 to 20 days. For these measurements, the instrumentation was moved from section to section.

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TABLE 1 Details of Sections

Section #	Joint #	Total # of Joints	Type of Joint (in.)	Spacing (ft)	Type of Base	Type of Dowel
3	17 to 24	8	1/8 (3mm) bevel sawcut	21 (6.4m)	Stabilized	Standard
4	25 to 34	10	Std. 1/4 (6mm) sawcut	40 (12.2m)	Stabilized	Standard
6	45 to 53	9	Std. 1/4 (6mm) sawcut	21 (6.4m)	Granular	Plastic Coated
7	54 to 63	10	Std. 1/4 (6mm) sawcut	40 (12.2m)	Granular	Plastic Coated
9	74 to 84	11	Std. 1/4 (6mm) sawcut	40 (12.2m)	Granular	Standard
10	85 to 94	10	Std. 1/4 (6mm) sawcut	21 (6.4m)	Granular	Standard

Subsections 1, 2, 5, 8, 11, and 12 were not tested in this program, mainly because not enough instrumentation was available to cover all subsections. However, the subsections tested were the most representative with respect to the important variables, such as slab length and type of base.

INSTRUMENTATION

Manual Measurements

The hand gauge for manual measurements consisted of a base bar with two 45-degree pointed probes, one fixed and one movable. An Ames dial gauge graduated to 0.0005 in. (0.0125 mm) was mounted on top of the bar between the two probes. Brass plugs were set into the pavement on either side of each joint and crack. These brass plugs were approximately 6 in. (0.152 m) apart and were set so that the top surface of each plug was just below the pavement surface. The tops of the plugs were center-drilled with a 1⁄16-in. (1.6-mm) hole and countersunk to 45 degrees to receive the points of the probe. The hand gauge was calibrated on a bar made of Invar with countersunk holes to receive the points of the probe.

Electronic Measurements

The horizontal movement was measured with linear variable differential transformers (LVDTs). The LVDT is a well-known and proven device for measuring relative displacements. It yields a voltage-time history directly proportional to the displacement-time history of its core-to-coil position. The LVDTs used had a measuring range of ±0.5 in. (±12.5 mm). To allow for the attachment of the LVDTs at each joint, the shoulder material was excavated down to the bottom of the slab. Each hole was fitted with a cutout box and made of sheet metal, complete with cover. The LVDTs were mounted on the side of the slab at mid-depth along the passing lane. Each joint was fitted with an aluminum angle on both sides of the joint: one for mounting the LVDT, the other for reference. The LVDTs were connected to a 16-channel Metrosonics Data Logger, Type DL-716, that was powered by a 12V battery. The data logger and the battery were enclosed in a watertight aluminum box that was buried off the shoulder in a waterproofed and well-drained hole.

On the base section, continuous measurements of the surface and midslab and bottom temperatures were taken in conjunction with the horizontal movement measurements. A TC 818 Type K thermocouple surface probe and two TC 8603 Type 5 thermocouples, with stainless steel sheaths 0.5 in. (12.5 mm) long, were used for the temperature measurements. Only horizontal movements were measured at the other subsections.

RESULTS AND ANALYSIS

LVDT measurements of horizontal movements on the six subsections were made for specified time durations during 16 months. The measurements were continuous for the base section (Subsection 9) and were intermittent for the other subsections, with periods that varied from 7 to 20 days. Both joints and midslab cracks were instrumented and monitored simultaneously.

During 2½ years, hand-gauge measurements were also made periodically on every joint and crack in the test section. LVDT measurements provided continuous data on the section for each inspection period, whereas hand measurements provided single-time data.

Since LVDT (electronic) measurements were continuously collected for defined intervals and manual measurement data were collected intermittently over 2½ years, both types covering all four seasons, it was possible to compare horizontal joint movements within a period of 7 to 20 days in a selected season, between seasons, between joints in the different test sections, and between cracks and joints.

During a typical 24-hr period, a joint would undergo a closing movement in the morning due to rising temperatures and an opening movement in the evening and night hours due to falling temperatures. The magnitudes of these daily cyclic movements were measured and recorded electronically. These measurements were taken over 7 to 20 days in each of the five regular test sections, and in the base section, from November 13, 1989, to March 28, 1991. Because of daily temperature changes, the joints open and close. The maximum opening and closing observed during the period of measurement was tabulated. These movements are relative and are not related to a benchmark. For example, the maximum movement in Section 3 was 0.089 in. (2.26 mm). Table 2 presents the maximum closing movement, the maximum opening movement, and the average movement over the 16 months for each joint and crack in the test sections. The average movement was calculated by finding the mean value of all measurements in the specific subsection. The absolute maximum movement for all test sections was 0.089 in. (2.26 mm), which is smaller than the electronically collected data reported from the 1970s tests (*1*). This was due to the development of more working cracks that reduced the magnitude of the maximum movement in the joints. And most of the joints and working cracks moved simultaneously, which was not so in the 1970s. As seen, the results measured on the regular test sections agreed well with those on the base section, even though the former were measured over shorter intermittent periods. Table 3 presents the periods of measurement in each section and the period during which the maximum movement occurred. As shown, the maximum movements took place between February and May, when the day-to-night temperature changes were the largest.

Because movements are influenced by temperature changes in the slab, it was necessary to determine which temperature in the slab best represented the movements: top, middle, bottom, or the average slab temperature. Plots of measured movements made against each of these temperature values showed that midslab temperature changes best represent the change in horizontal movements. Figures 1 through 9 show typical plots of measured joint and crack movements against change in midslab temperature. A specific movement is plotted against the change in temperature that caused it. Positive movements represent relative joint closings, and negative movements are relative joint openings. The solid line in each figure shows the theoretical relationship between movement and temperature using the formula

$$\delta_t = \alpha_c * \Delta T * L$$

where L = 21 ft (6.4 m). The theoretical lines show a good relationship between movements and temperature. This is

TABLE 2 Summary of Joint Movements

Section #	Length, ft	Base	Range of Movement, inch		
			Max. Closing	Max. Opening	Average
3	21	Stab.	0.0890	0.0780	0.0146
4	40	Stab.	0.0780	0.0748	0.0135
6	21	Gran.	0.0838	0.0756	0.0110
7	40	Gran.	0.0782	0.0797	0.0157
9	40	Gran.	0.0807	0.0827	0.0133
10	21	Gran.	0.0787	0.0858	0.0203

TABLE 3 Periods of Measurement and Occurrence of Maximum Movements

Section #	Dates when measurements were made	Dates when maximum movements were observed
3	9/6/90 to 9/13/90, 9/27/90 to 10/11/90, 7/24/90 to 7/31/90, 2/19/91 to 2/28/91, 4/24/91 to 5/7/91	4/24/91 to 5/7/91
4	9/27/90 to 10/16/90, 11/29/90 to 12/12/90, 3/14/91 to 3/28/91	3/14/91 to 3/28/91
6	9/13/90 to 9/20/90, 11/29/90 to 12/12/90, 2/28/91 to 3/14/91, 7/6/91 to 7/20/91	2/28/91 to 3/14/91
7	8/30/90 to 9/12/90, 9/16/90 to 9/31/90, 1/24/91 to 1/31/91, 3/28/91 to 4/8/91	3/28/91 to 4/8/91
9	11/13/89 to 3/28/91	3/14/91 to 3/28/91
10	9/13/90 to 9/26/90, 11/1/90 to 11/15/90, 1/31/91 to 2/19/91, 4/8/91 to 4/24/91	4/8/91 to 4/24/91

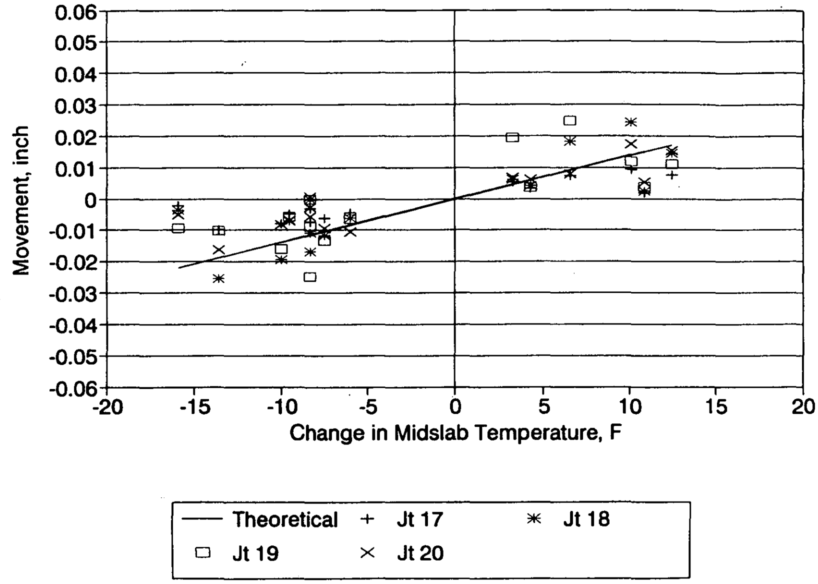

FIGURE 1 Temperature versus movement (electronic), Section 3, September 6–12, 1990.

significantly different from the results obtained on this pavement before 1981, when no correlation could be found (*1*).

As seen in Figures 1 through 9, most monitored joints moved and monitored cracks showed inconsistent behavior: some moved, others did not. For example, Cracks 27-1 and 30-1 in Subsection 4 and Cracks 75-1 and 76-1 in Subsection 9 moved like joints, as seen in Figures 3 and 9. Upon visually observing these cracks, they were found to be wide and deep, with the mesh reinforcement totally missing, rusted away. Conversely, Joints 76 and 77 in Subsection 9 appear to be frozen, as their measurements indicated no movements. So, when these joints stopped moving, the cracks next to them (Cracks 75-1 and 76-1) were forced to pick up the movement.

The theoretical line drawn in each figure (Figures 1 through 9) was based on the movements of slabs 21 ft (6.4 m) long, assuming that all cracks in the 40-ft (12.2-m) slabs were working cracks that effectively reduced slab lengths and joint movements. However, it is interesting to note that Joint 29, between two 40-ft (12.2-m) slabs, moved much more than the theoretical line (Figure 2). In fact, the measured values are closer to the theoretical movement of a joint between two intact 40-ft (12.2-m) slabs. This can be explained by looking

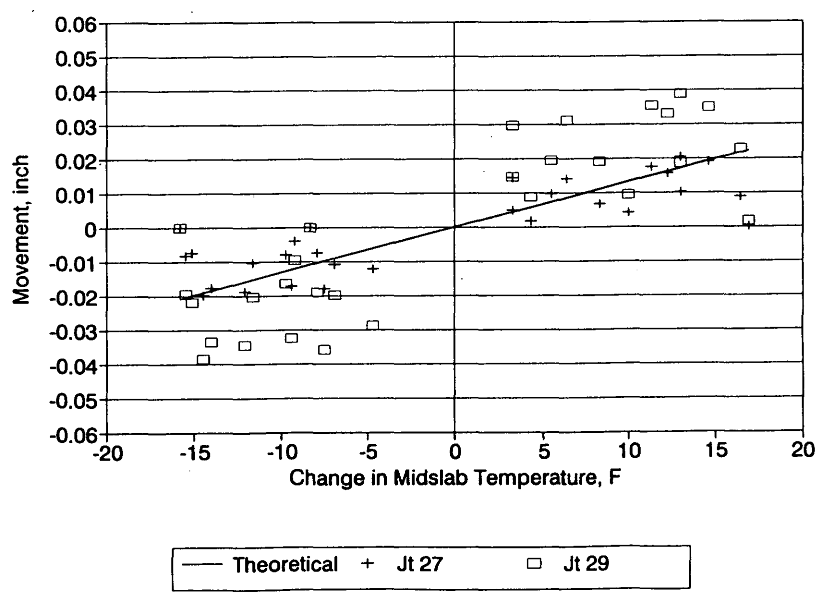

FIGURE 2 Temperature versus movement (electronic), Section 4, September 27 to October 11, 1990.

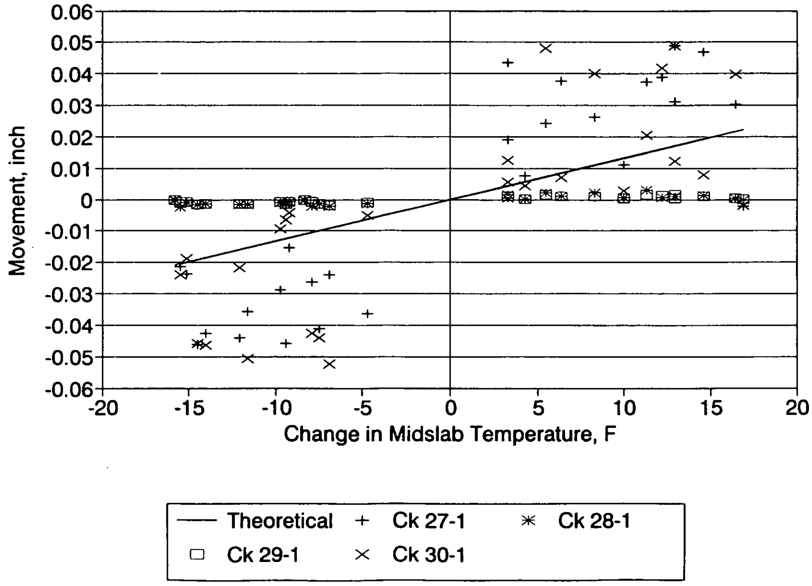

FIGURE 3 Temperature versus movement (electronic), Section 4, September 27 to October 11, 1990.

at the movements of the cracks next to Joint 29, namely, those of Cracks 28-1 and 29-1 in Figure 3. The plot shows that these cracks have not moved at all. Thus Joint 29 had to pick up all the movements, corresponding to the movement of a joint in a 40-ft (12.2-m) slab.

For another interesting observation, look at the movements of Subsection 7 in Figures 6 and 7. As seen, the joints in Subsection 7 moved less than the theoretical line would indicate. This was because most slabs had two working cracks, reducing the effective slab lengths to approximately 13 ft (3.96 m). Thus, the total movement of the slabs was distributed between the joints and the cracks.

Of considerable interest were the joint movements in the six sections over 2½ years. Figures 10 through 12 show the results of hand-gauge measurements taken from winter 1989 through summer 1991 on Sections 3 and 4. These figures show maximum joint movements ranging from the coldest months to the warmest ones. In these figures the measurements of the movements taken during summer 1989 were considered as the reference values, assuming that the measured top of slab temperature of 72°F was close to the temperature of the newly poured concrete pavement back in 1972. Also shown are the theoretical temperature–versus–joint movement curves for the appropriate joint spacings. These figures show

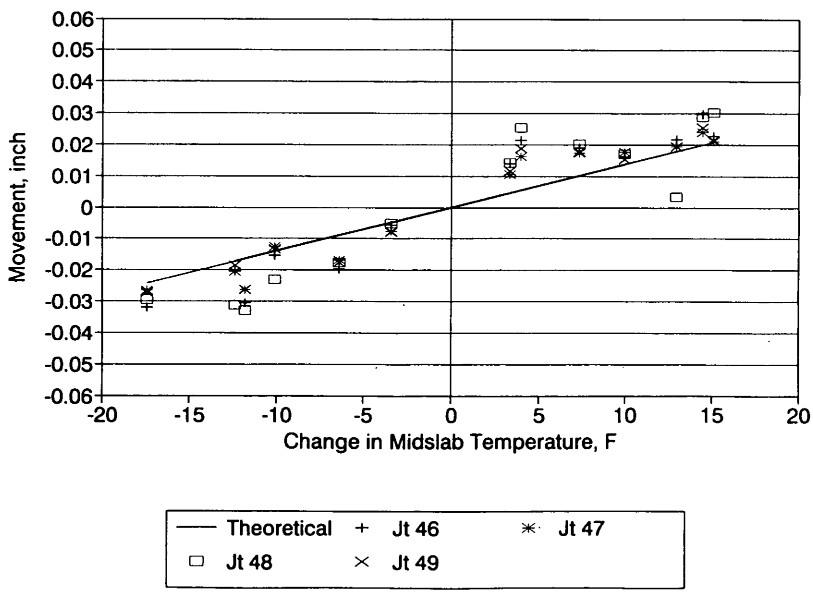

FIGURE 4 Temperature versus movement (electronic), Section 6, September 13–20, 1990.

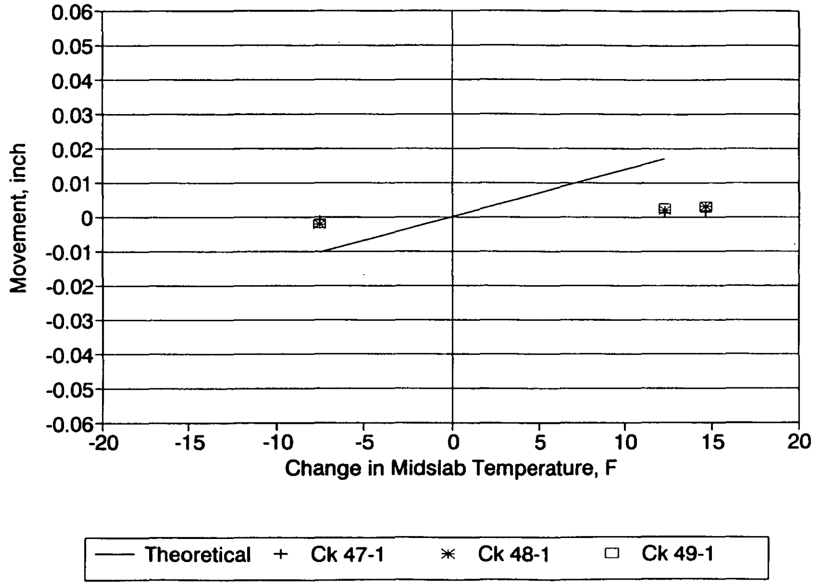

FIGURE 5 Temperature versus movement (electronic), Section 6, September 13–20, 1990.

that the absolute maximum joint movement in the two sections during the 2½ years was 0.134 in. (3.40 mm) for a maximum top of slab temperature range of 51°F. (Note that the 1990 and 1991 winters were unusually mild in the Midwest.) This range of maximum movement was not found to be dependent on joint spacing, as similar maximum values were found in joints spaced at 40 ft (12.2 m) and 21 ft (6.4 m). On the other hand, the measurements taken in the early age of this pavement (in the mid-1970s) showed a marked difference in joint movements in the two slab sizes. Namely, the 95th-percentile values of joint movements reported from manual measurements were 0.12 in. (3.0 mm) for the 40-ft (12.2-m) slabs and 0.07 in. (1.8 mm) for the 21-ft (6.4-m) slabs (*1*). This indicates that the cracks that have developed were non-working cracks back in the 1970s.

EFFECT OF VARIABLES ON HORIZONTAL MOVEMENT

Since each section is different from the others with respect to a certain variable, their comparison would reveal the effect of a chosen variable.

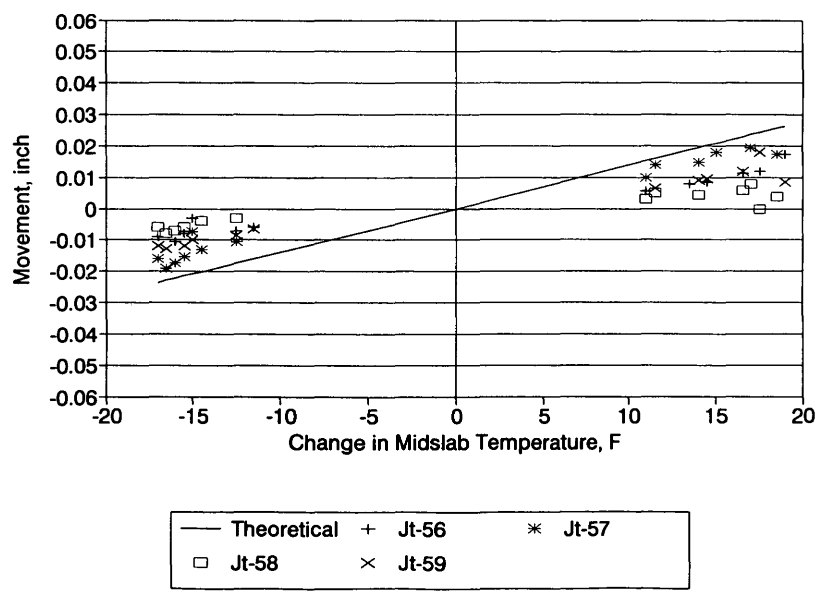

FIGURE 6 Temperature versus movement (electronic), Section 7, August 30 to September 12, 1990.

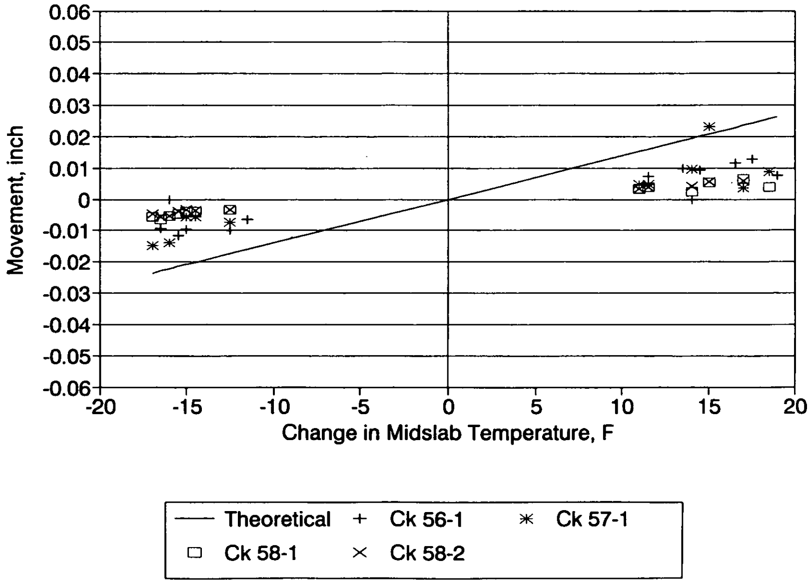

FIGURE 7 Temperature versus movement (electronic), Section 7, August 30 to September 12, 1990.

When comparing two measurements, one wants to know if the means for the two groups are different. If the mean values of measurements are significantly different, then the variable under consideration is said to have a pronounced effect. In this study, the means of maximum closing, maximum opening, and average values of horizontal movements for each section were compared. The statistical *t*-test for $\alpha = 0.05$ was used to study the effects of various design parameters on the horizontal movement of the joints of different groups, over the same period.

Sections with Different Joint Spacings

In this category, joint movements in sections with 21-ft (6.4-m) joint spacing were compared with those with 40-ft (12.2-m) joint spacing, where both sections had otherwise similar parameters.

When Subsection 3 movements were compared with Subsection 4 movements for the period September 27 to October 16, 1990, the *t*-test revealed that the results were statistically insignificant. A similar conclusion was reached when the joint

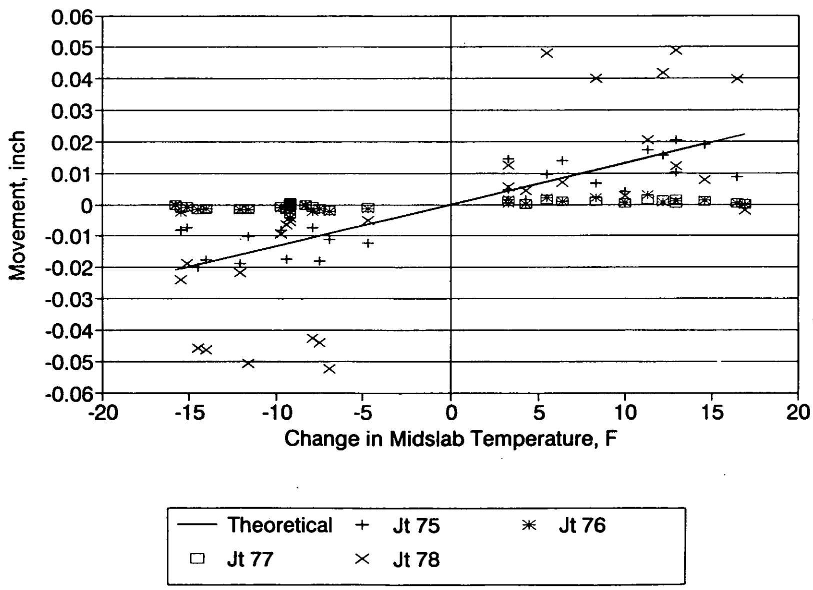

FIGURE 8 Temperature versus movement (electronic), Section 9, September 27 to October 11, 1990.

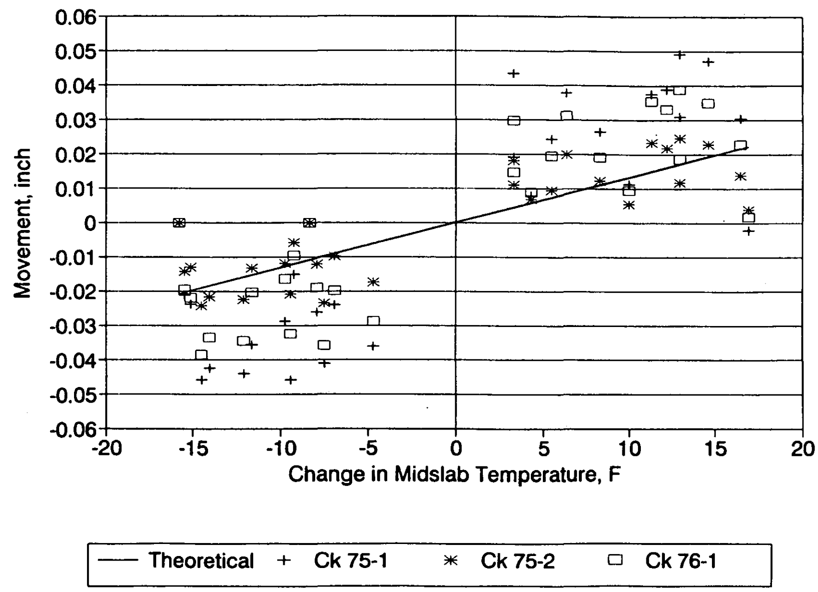

FIGURE 9 Temperature versus movement (electronic), Section 9, September 27 to October 11, 1990.

movements in Subsection 9 (the base section) were compared with those in Subsection 10 for the periods September 13 to September 26, 1990, and January 31 to February 19, 1991. From this it was concluded that the horizontal movements, including maximum closing, maximum opening, and average movement, were not affected by the difference in joint spacing. The explanation is that all 40-ft (12.2-m) slabs have developed midslab cracks. Most of these cracks are working cracks that effectively divide the slabs into approximately 20-ft (6.4-m) slabs and thereby override the effect of joint spacing.

Sections with Different Bases

To evaluate the effect of base, 12 comparisons of horizontal movements were made, using mean maximum opening, mean maximum closing, and average movement of joints. Of these 12 comparisons, 10 showed that the base had no effect on the horizontal movement. However, two comparisons yielded contradictory results. Comparison of the average movement between Subsections 3 and 10, and the mean maximum opening between Subsections 4 and 9, showed that the effect of base is significant but the level of significance was very low.

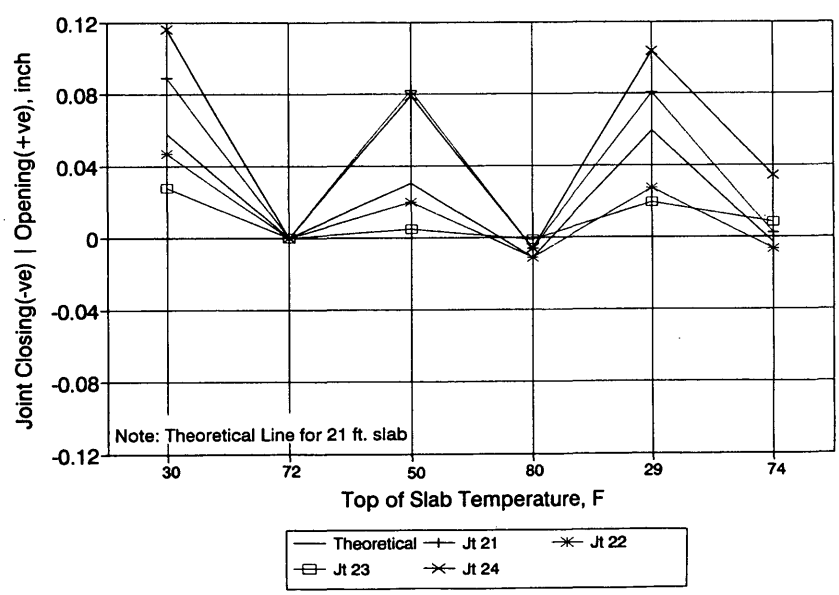

FIGURE 10 Temperature versus movement (manual), Section 3, 2½ years.

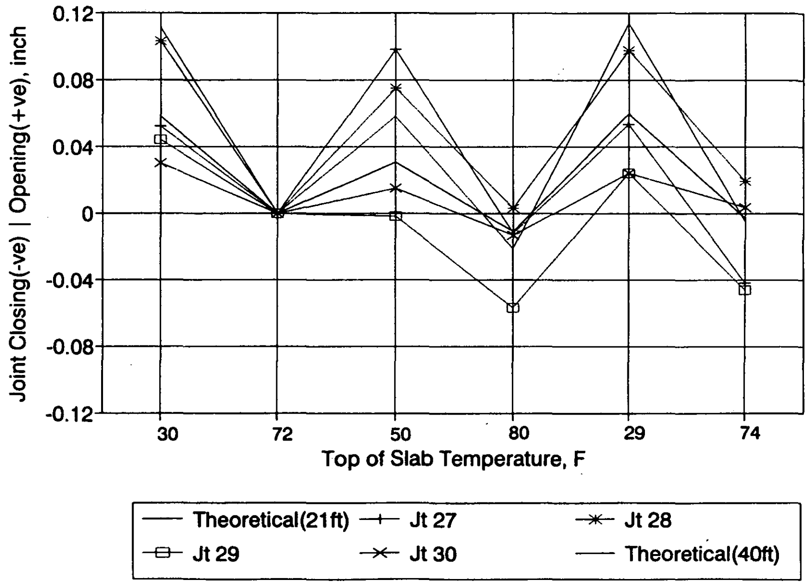

FIGURE 11 Temperature versus movement (manual), Section 3, 2½ years.

So it was concluded that overall, the base had minimal or no effect on the horizontal movements.

Sections with Different Dowels

The study showed that the type of dowel does not affect the horizontal movement. This conclusion is based on a statistical analysis of the maximum closing, maximum opening, and the average movements. This could be seen from the comparison of Subsections 7 and 9 for the periods August 30 to September 31, 1990, and January 24 to February 14, 1991. It appears that both types of dowels are allowing free movement at the joints.

COMPARISON OF PRESENT FINDINGS WITH THOSE OF 1981

This test segment of the road was continuously monitored from the start of its construction in 1972. In 1981, on the basis of the data collected up to that time, conclusions were drawn on the effect of design parameters on the horizontal movements. The details are given elsewhere (*1*). One of the primary

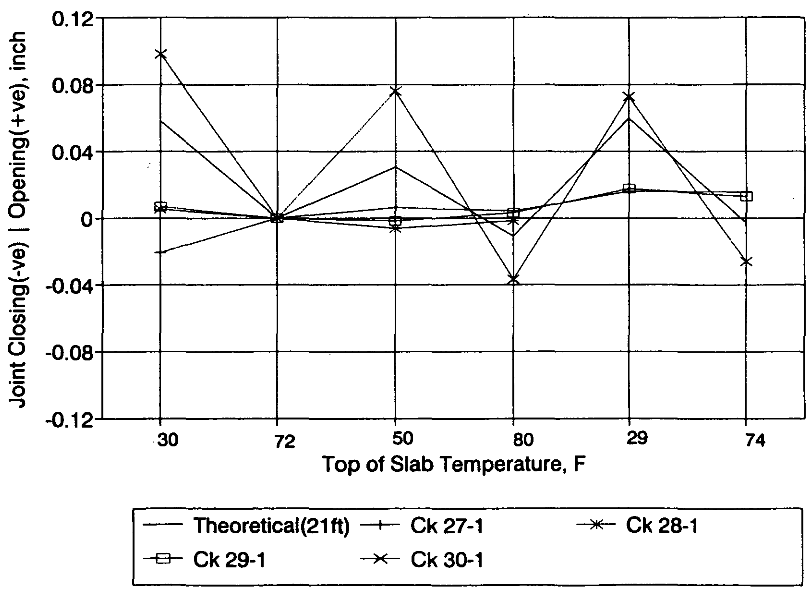

FIGURE 12 Temperature versus movement (manual), Section 4, 2½ years.

goals of the current research effort was to verify the previous findings. Thus, the conclusions from the previous studies on the same subsections were compared with the present, resulting in the following:

- From the electronic measurements of horizontal joint movements, it was concluded in the previous study (*1*) that sections with different joint spacing exhibited similar movements on a short-term basis. This conclusion was confirmed in the present research. On the other hand, the long-term movements reported in the previous study were directly proportional to slab length. This was not the case in this study because of the presence of midslab working cracks in the 40-ft (12.2-m) sections that effectively equalized slab lengths.
- Previous studies on the test pavement gave mixed results with regard to the effect of base on the horizontal movement of slabs. Statistical analysis of Subsections 3 and 10 revealed that these sections exhibited statistically different movements during 1975 and 1978. However, Subsections 3 and 6 performed differently in 1974, whereas there was no such difference in 1975 and 1978. The researchers concluded in 1981 that although the granular base offered different restraints during the early life of the pavement, it tended to behave more like the stabilized base at the later stage of service. This is further confirmed by current findings in which it appears that the type of base has little or no effect on the horizontal movement of slabs, 20 years after their construction.
- In conformance with the results of 1981, there is no significant difference in the movement of joints with standard dowels and those with coated dowels.

CONCLUSIONS

1. Horizontal movements in older pavements due to temperature changes may be calculated with confidence using the formula $\delta_t = \alpha_c * L * \Delta T$.
2. Movement data indicate that the slabs are now moving freely with temperature.
3. The maximum total movement between seasons over 2½ years in all the measured joints was 0.134 in. (3.40 mm). This was over a maximum top of slab temperature range of 51°F.
4. In slabs with intact wire mesh, the crack movements were small. The exceptions were the old and wide cracks in Subsections 4 and 9 in which the mesh reinforcement had rusted away.
5. Both the 21- and 40-ft (6.4- and 12.2-m) slabs moved as 21-ft (6.4-m) slabs. This is obvious for the 21-ft (6.4-m) slabs with no cracks. However, the 21-ft (6.4-m) slabs with cracks followed the same pattern because the cracks did not move. On the other hand, most cracks in the 40-ft (12.2-m) slabs moved and effectively subdivided the slabs into subslabs approximately 20 ft (6.1 m) long.
6. The type of dowel bar and type of base had little influence on the horizontal movements.

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