tics and physical requirements of the joint. The drawing should also show how the joint is to be placed, connected, and installed. In this way the specifying agency will relieve itself of much controversy, and at the same time they will obtain the right expansion joint at the right price through competitive bidding.

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Vertical Movement of Jointed Concrete Pavements

I. MINKARAH, J. P. COOK, and S. JAGHOORY

ABSTRACT

The vertical deflection of a concrete pavement under truck loading may be the determining factor in predicting the service life of the pavement. Consequently, it is of prime importance to know the effect of different variables on this vertical movement. To study experimentally the effects of the variables, a test pavement was constructed as part of US-23 in Chillicothe, Ohio. Data have been collected on this pavement continuously since 1972. To isolate the variables, the pavement was divided into 10 sections of approximately 10 joints each. Vertical measurements were taken by using a truck with a measured axle load. The measurements provided continuous plots of the vertical movements as the test truck traveled over the joint. Measurements were repeated at different speeds to determine the effect of truck speed on pavement deflection. Measurements were also repeated both morning and afternoon to study the effect of pavement curl. The measurements were analyzed statistically to determine the relative effects of the different variables on the behavior of the slab. The analysis indicated that there is a significant effect on slab behavior caused by difference in the subbase, location of the truck on the pavement, speed of the truck, and time of measurement (morning versus afternoon). Only a minor effect was noted due to spacing of joints, types of dowels, and a configuration of the saw cut.

The vertical movement of pavements is affected by wheel loadings and expansion and contraction caused by temperature and moisture changes. Portland cement concrete pavements are usually jointed to accommodate this movement. The results of uncontrolled pavement movement may be cracked slabs, pavement blow-ups, and bridges tilted or pushed out of skew.

Horizontal movements are usually assumed to be a sinusoidal variation of expansion and contraction, thus causing the joint to open and close. Of course, many other factors affect this movement. The vertical movement depends on both traffic loads and the curl of the pavement caused by temperature change.

STUDY OBJECTIVE

The objective of this research was to determine the actual magnitude of the vertical movements of the pavement. Because there are several factors that may affect movement, each factor was considered as a variable. The variables were then isolated to determine the effects of each. At the risk of "reinventing the wheel," even those assumptions that are commonly accepted as fact were challenged. The factors considered to be of prime importance were type of subbase, coating of dowel bars, joint spacing, configuration of the saw cut, and use of skewed joints. Combinations of these variables were incorporated into a test pavement, and were studied for a period of 8 years by actually measuring pavement movement (1-3).

TESTING PROGRAM

The test pavement is a section of the southbound lane of US-23 approximately 0.6 mile (1 km) long. The pavement is a tangent section on an easy grade. Truck loads are heavy, but the average daily truck traffic is not high.

The test section is reinforced concrete, 24 ft (7.3 m) wide and 9 in. (229 mm) thick. Most of the pavement is laid over a granular subbase, except for a 776-ft (237-m) section, which is laid over an asphalt-treated base. Spacing of the joints was set at 17, 21, and 40 ft (5.18, 6.4, and 12.2 m). The dowels used were standard steel dowels and plastic-coated dowels. The configuration of the joints also varied. There were 0.5-in. (12.7-mm) joints, 0.25-in. (6.4-mm) joints, and one set of joints with a beveled saw cut. Data about each of the variables are given in Table 1.

Instrumentation

Vertical movements were measured with a linear motion transducer and a strip-chart recorder. The

TABLE 1 Joint Groups

Group No.	Joint No.	Total No. of Joints	Type of Joint	Spacing (ft)	Type of Subbase	Type of Dowels	Remarks
1	1-7	7	0.125-in. bevel saw cut	40	Granular	Standard	
2	8-16	9	Standard 0.25-in. saw cut	40	Granular	Standard	Chlorinated rubber base cure
3	17-24	8	Standard 0.25-in. saw cut	21	Stabilized	Standard	
4	25-34	10	Standard 0.25-in. saw cut	40	Stabilized	Standard	
5	35-44	10	Standard 0.5-in. saw cut	17	Stabilized	No dowels	Right forward skew and plain pavement
6	45-53	9	Standard 0.25-in. saw cut	21	Granular	Plastic coated	
7	54-63	10	Standard 0.25-in. saw cut	40	Granular	Plastic coated	
8	64-73	10	0.5-in. sawed	40	Granular	Standard	
9	74-84	11	Standard 0.25-in. saw cut	40	Granular	Standard	
10	85-94	10	Standard 0.25 in. sawed	21	Granular	Standard	
	95-96	2	Standard 0.25 in. sawed	40	Granular	3M Coated	
	97-100	4	Standard 0.25 in. sawed	40	Granular	Standard	
	101	1	Expansion	40	Granular		

Note: 1 in. = 2.5 cm, 1 ft = 0.3 m.

transducer was an Edcliff 1500 ohm with a 1.75-in. (44.5-mm) stroke. The strip-chart recorder was a Sanborn Model B-1000 with variable amplification so that the size of the curve could be varied to suit the gradations on the chart paper for improved accuracy.

One joint in each group of 10 was selected for vertical measurements. Adjacent to the joint a small hole was dug down to the level of the base of the pavement. An 8-ft-long (2.4-m) section of No. 14 reinforcing bar was then driven vertically down into the subgrade until the top of the bar was flush with the level of the subgrade. This furnished a solid base for the movable plunger of the transducer. The body of the transducer was mounted on the side of the pavement slab. Figure 1 shows the mounting setup.

Measurements

Loads for the measurement program were supplied by the Ohio Department of Transportation (DOT). A loaded truck was weighed and then sent to the site. Because it was impossible to furnish exactly the same load for each set of measurements, all of the loads were reduced to a common base of 10,000 lb (4550 kg) before reducing any data.

For each set of measurements, the truck made three runs over the test joint at 55 mph (88 km/h) in the center of the lane, at 55 mph at the edge of the pavement (where the transducer was located), and at 10 mph (16 km/h) at the edge of the pavement.

Two sets of measurements were made on each test day. The first set was taken in the morning when the pavement was relatively cool and then repeated in the heat of the afternoon. Sets of measurements were taken during each of the four seasons of the year. Figures 2-7 are typical curves showing the vertical movement.

ANALYSIS OF DATA

The data obtained from the recorder show deflection of the joint as a function of time (i.e., the time it takes for the truck to pass over the joint). Figures 2-7 are typical time-deflection curves. The curves show two peaks, a small one corresponding to

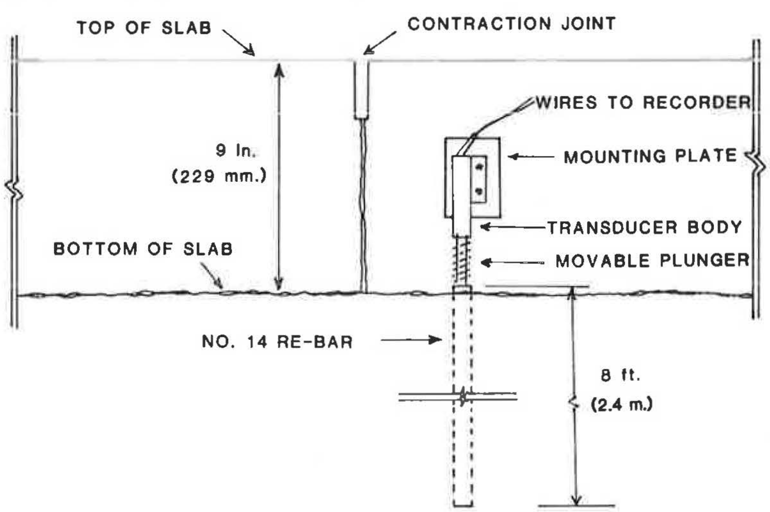

FIGURE 1 Mounting of transducer.

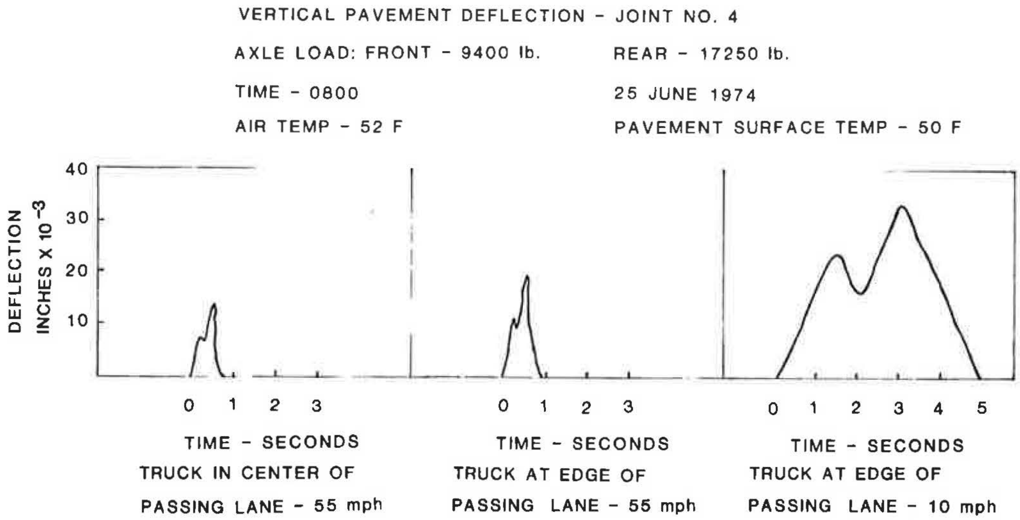

FIGURE 2 Vertical pavement deflection, joint 4, morning.

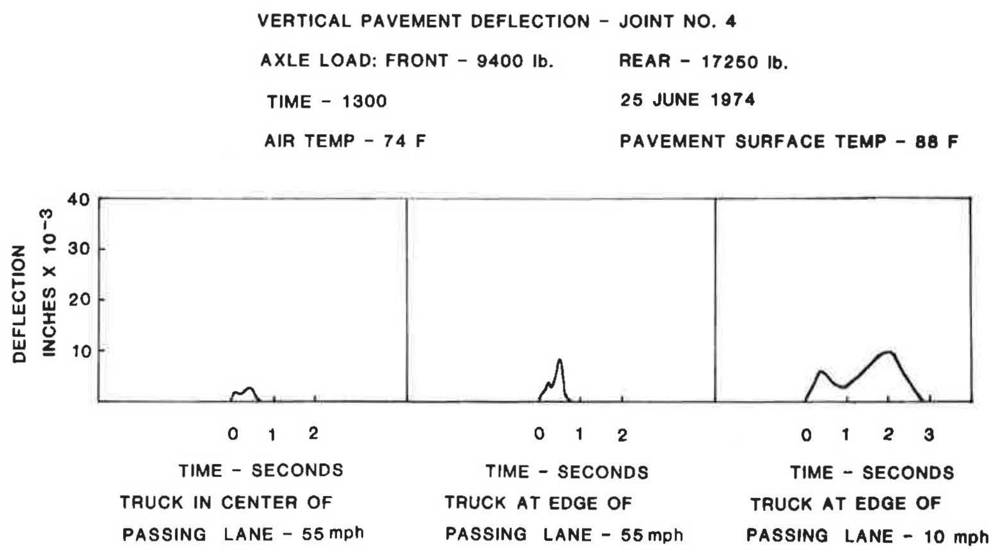

FIGURE 3 Vertical pavement deflection, joint 4, afternoon.

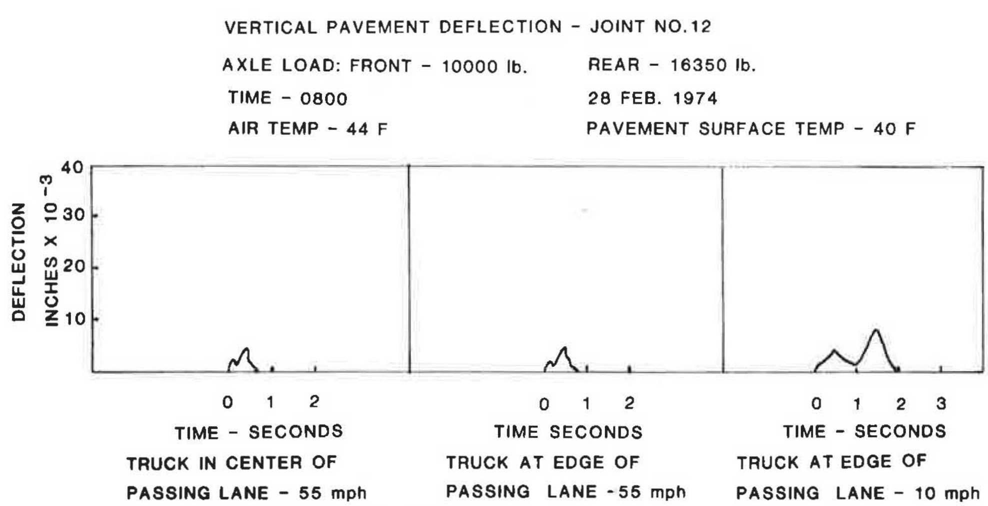

FIGURE 4 Vertical pavement deflection, joint 12, morning.

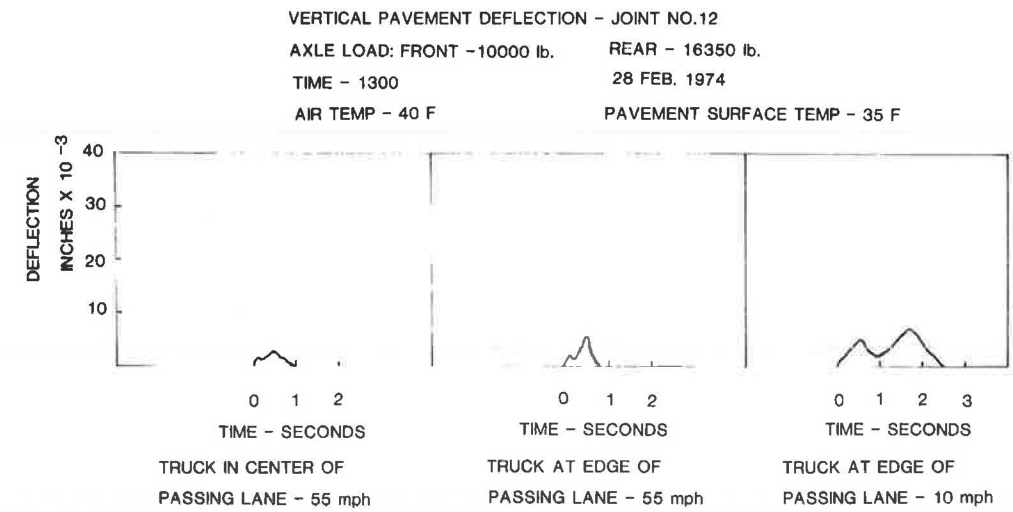

FIGURE 5 Vertical pavement deflection, joint 12, afternoon.

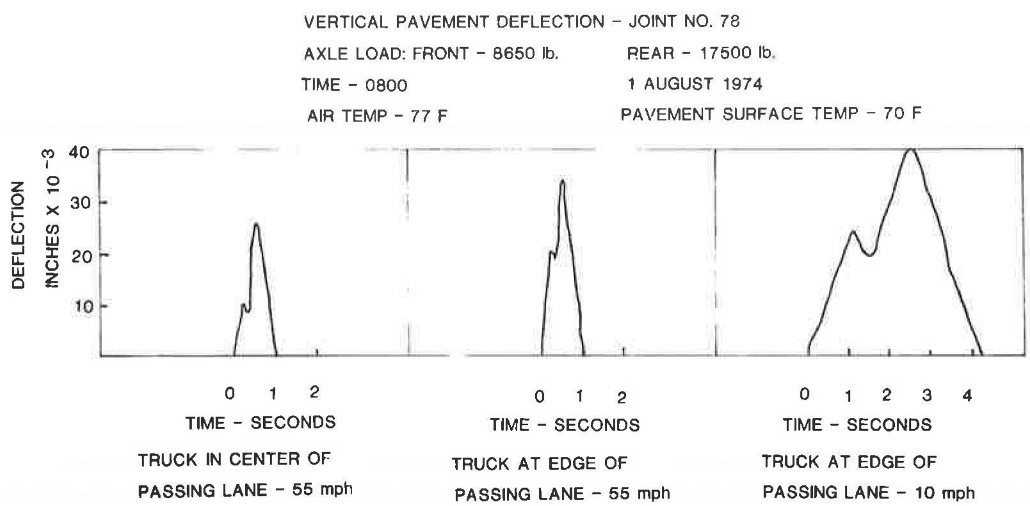

FIGURE 6 Vertical pavement deflection, joint 78, morning.

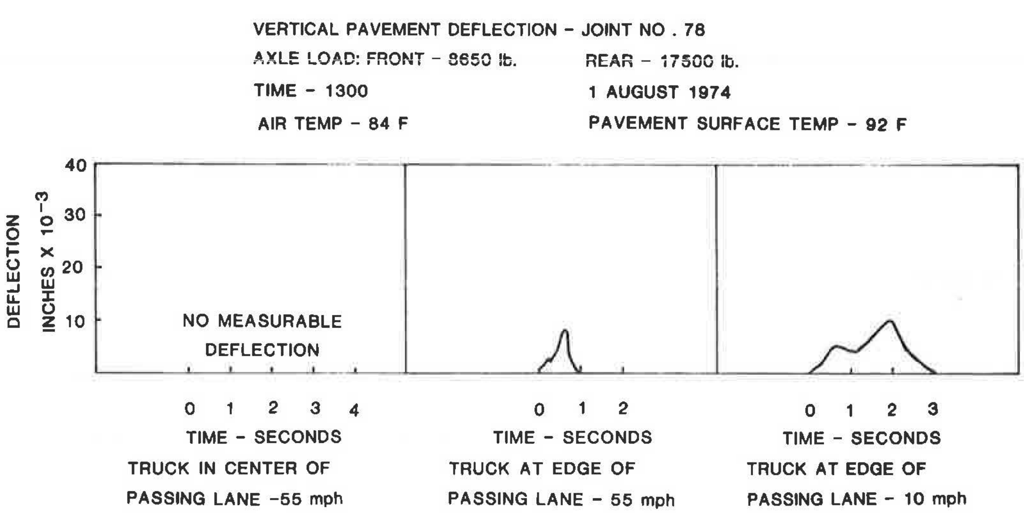

FIGURE 7 Vertical pavement deflection, joint 78, afternoon.

the front wheel passing over the joint and a larger one corresponding to the rear wheel passing over the joint. The axle weights for the truck differed slightly each time a set of readings was taken. Consequently, the measured deflection under both the front and rear axles was converted to the equivalent deflection that would be caused by a 10,000-lb (4550-kg) load. The conversion, of course, was linear. Thus the curves provided two points where both the load and the deflection are known. These points were used in the analysis.

Several variables affect the magnitude of the vertical deflections. Some variables were incorporated into the pavement in such a way that each one could be isolated by comparing two groups that are identical except for the variable under study. This comparison was then made by using a standard two sample t test. A normal distribution could not be used in this case because the sample size corresponding to one variable at a time was relatively small. The null hypothesis ($\mu 1 - \mu 2$) = 0 was tested at the level of significance $\alpha = 0.05$. The hypothesis is rejected if for (n1 + n2 - 2) degrees of freedom, t (calculated) $< -t\ \alpha/2$ or $> t\ \alpha/2$. Rejection of the hypothesis means that there is a significant difference between the pavement sections being compared. That is, the variable under study does affect the behavior of the pavement.

The effect of the location of the truck in the traffic lane and its speed became apparent from the beginning of the study. The deflection measured at the edge of the pavement with the truck in the center of the lane traveling at 55 mph (88 km/h) was always small, regardless of the season or the time of day (see Figures 2-7). Sometimes the deflection of the pavement was so small that it was not measurable. This usually occurred when the mid-slab temperature was greater than 80°F (26.5°C). However, there were cases when the movement measured 0.03 in. (0.76 mm). These movements are for a 10-kip load in the center of the lane, with the truck traveling at 55 mph.

The effect of truck speed can be observed from a comparison of the movement corresponding to a truck at the edge of the lane traveling at 55 mph to the same truck at the edge of the lane traveling at 10 mph. Figures 2-7 show that the movement is always larger for the slower speed. The means and standard deviations, converted to the equivalent 10,000-lb load, are as follows:

Truck at Edge of Lane at	X Bar	Sigma
10 mph	8.46×10^{-3} in.	8.33×10^{-3} in.
55 mph	5.98×10^{-3} in.	6.91×10^{-3} in.

The remaining variables studied were spacing of joints, type of dowels, type of subbase, time of measurement (morning versus afternoon), and temperature and seasonal effects.

Spacing of Joints

Joints in the test section were spaced at 21 ft (6.4 m), 40 ft (12.2 m), and one section at 17 ft (5.2 m) with a right forward skew. The statistical analysis indicates that joint spacing does not significantly affect the vertical deflection of the pavement. This can be seen from the data in Table 2 by comparing Group 3 to Group 4, Group 6 to Group 7, or Group 9 to Group 10. In each of these instances the isolated variable is slab length. In all cases, t (measured) is less than t ($\alpha/2$), in which α = 5 percent. This might not appear too unusual, because the weight of the slab tends to neutralize part of the lift-off due to curl of the pavement caused by temperature.

Type of Dowels

Two types of dowels were used in the project: standard steel and plastic coated. The main function of the plastic coating is, of course, corrosion control. Again, the analysis indicated no significant difference between the two types. Both types were functioning well up to the end of the project in 1981. A comparison of Group 6 to Group 10 and Group 4 to Group 7 showed no significant effect due to the dowels.

It did come as a surprise that there was no significant difference between the means of Group 3 and Group 5. The variable in this instance is dowel versus no dowel. Of course, aggregate interlock is compensating for the dowels. Unfortunately, only one section of the pavement was left without dowels, so there is not enough information to draw a relevant conclusion.

Type of Subbase

Two types of subbases were incorporated into the pavement: granular and stabilized. The analysis indicates that there is a significant difference in the vertical movements due to the subbase. This can be seen from a comparison of Group 4 to Group 9, Group 3 to Group 10, Group 3 to Group 6, and Group 4 to Group 7. In all these cases, t (measured) is greater than t ($\alpha/2$). In comparing Group 3 to Group 6 and Group 4 to Group 7, the dowels are also different, but if we accept the conclusion that the effect of dowels is not significant, then the difference is due to the subbase.

The vertical deflections of sections on stabilized bases were consistently smaller than those on granular bases. This apparently is one of the reasons why stabilized bases are superior to granular bases in controlling pumping and faulting of joints. The means and standard deviations of vertical movement of joints on granular and stabilized bases are

TABLE 2 Comparison of Means of Maximum Deflections Based on a 10-Kip Load

Comparison		Degrees of				
Group	Variable	Freedom	$t_{Calc.}$	$t_\alpha = 0.025$	$t_\alpha = 0.05$	Remarks
3 to 4	Slab length	11	−0.110	2.201	1.796	Accept hypothesis
3 to 6	Type of dowel, type of base	11	4.146	2.201	1.796	Reject hypothesis
3 to 10	Type of base	11	2.079	2.201	1.796	Accept hypothesis
3 to 5	Dowels versus no dowels	11	1.220	2.201	1.796	Accept hypothesis
4 to 5	Type of dowels, slab length	11	−1.228	2.201	1.796	Accept hypothesis
4 to 7	Type of dowel, type of base	11	−3.00	2.201	1.796	Reject hypothesis
4 to 9	Type of base	11	−3.06	2.201	1.796	Reject hypothesis
6 to 7	Slab length	11	1.373	2.201	1.796	Accept hypothesis
6 to 10	Type of dowels	11	2.183	2.201	1.796	Accept hypothesis
7 to 9	Type of dowels	11	−0.180	2.201	1.796	Accept hypothesis
9 to 10	Slab length	11	1.279	2.201	1.796	Accept hypothesis

as follows. The measurement again corresponds to a 10-kip axle load with the truck traveling at 10 mph at edge of the pavement:

Type of Base	Mean of Maximum Deflections	Standard Deviation
Granular	10.28×10^{-3} in.	10.45×10^{-3} in.
Stabilized	5.71×10^{-3} in.	5.60×10^{-3} in.

Temperature and Seasonal Effects

Vertical measurements were taken in the morning and repeated in the afternoon. The means of the maximum movements of the joints were compared. The results revealed a significant difference between the two means for most groups, with the morning deflections larger than the afternoon deflections (see Table 3). This is to be expected because the surface temperatures of the pavement are cooler in the morning than in the afternoon, thus affecting the shape of the slab and the position of the edge of the pavement with respect to the base. The sections that did not fit this pattern were those that had the short spans, that is, Group 3 and Group 10 with 21-ft (6.4-m) spans and Group 5 with a 17-ft (5.2-m) span and no dowels. This may be because the daily change in the shape of the slab for the shorter spans is not as pronounced.

TABLE 3 Comparison of Means of Maximum Deflection at 8:00 a.m. and 1:00 p.m.

Group	Degrees of Freedom[a]	$t_{Calc.}$	$t_{\alpha} = 0.025$
1 and 2	9	2.95	2.262
3	6	1.52	2.447
4	5	2.79	2.571
5	6	2.28	2.447
6	6	4.52	2.447
7	7	2.45	2.365
8 and 9	9	3.19	2.262
10	6	0.568	2.447

Note: Truck at the edge of the pavement at 10 mph (16 km/h), corrected for an equivalent load of 10 kips.

[a]Number of pairs minus one.

The surface temperature of the slab was measured at the same time as the vertical deflections. An attempt to correlate surface temperature and deflection was unsuccessful. Figure 8 is a typical plot of vertical deflection versus surface temperature. It is obvious from the plot that there is no direct relationship. Vertical deflection is a function of the shape of the slab, which depends on both top and bottom temperature of the pavement. The vertical movement is a function of the temperature gradient across the depth of the slab.

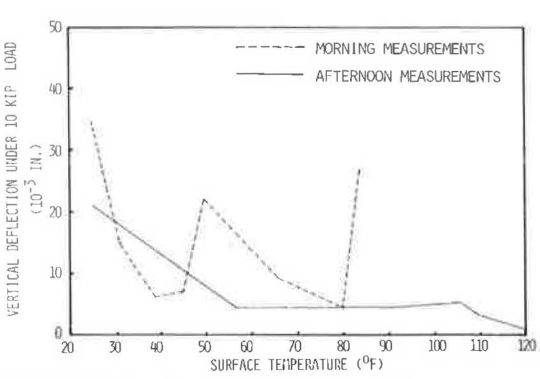

FIGURE 8 Vertical deflection versus surface temperature, group 6.

To further study the effect of temperature on the shape of the pavement, continuous measurements were taken simultaneously at three locations across the slab depth (i.e., top, middle, and bottom). These measurements were taken in both the spring and fall. Figures 9-12 show hourly temperature variation across the depth of the slab for the period of measurement. Although the data do not represent a large enough sample to have strict statistical validity, enough data are given to indicate definite patterns of variation across the slab.

1. The bottom slab temperature is seasonal and changes gradually.
2. The surface temperature fluctuates during the day, as expected.
3. The mid-slab temperature also varies a great deal and does not necessarily fall in between the top and bottom temperatures. Sometimes it is higher than both.
4. The temperature at the surface and the middle of the slab peaks early in the afternoon when the sun's rays strike the slab at more or less a normal angle. The temperature at the bottom of the slab reaches its peak value sometime in the early evening. All three temperatures hit their low points in the early morning.
5. In the spring the top and middle temperatures were within the bounds of the maximum and minimum air temperatures, whereas the bottom temperature

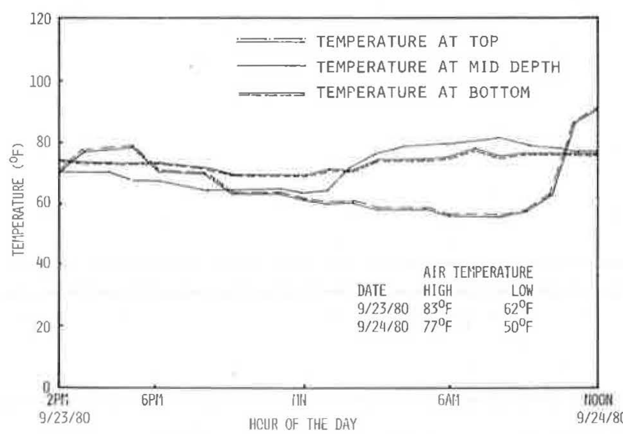

FIGURE 9 Hourly temperature variation across depth of pavement on September 23 and 24, 1980.

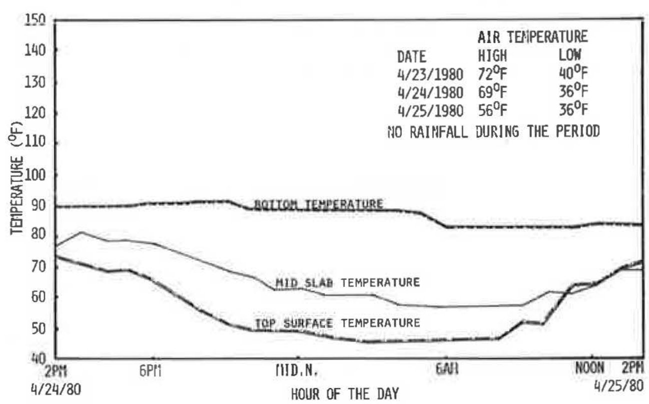

FIGURE 10 Hourly temperature variation across depth of pavement on April 24 and 25, 1980.

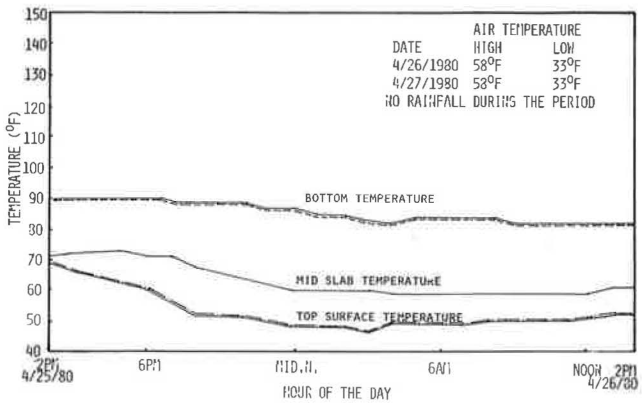

FIGURE 11 Hourly temperature variation across depth of pavement on April 25 and 26, 1980.

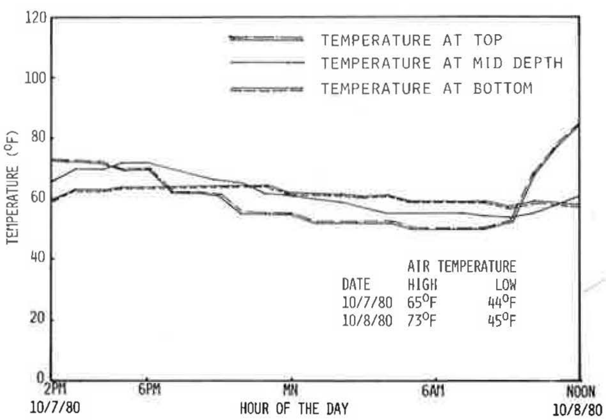

FIGURE 12 Hourly temperature variation across depth of pavement on October 7 and 8, 1980.

remained steady and unexpectedly high. In the fall all the measured slab temperatures remained within the bounds of the maximum and minimum air temperature range.

6. Surprisingly, the temperature of the top of the slab seldom exceeds the bottom temperature. Consequently, it would appear that during the summer the slab tends to remain concave, rather than changing shape from concave to convex during the day.

7. In the fall the pavement shape changed during the day. It was generally concave during the morning rush hour and convex during the afternoon rush hour. In one instance (October 8-9, 1980), the top of the slab was warmer than the bottom or almost equal to the bottom during almost the entire recording period. This indicates that the slab also may remain convex for extended periods of time.

It is apparent that it is not possible to know the shape of the slab from only one factor (i.e., air temperature, surface temperature, or time of day). Slab shape is affected by long-term as well as short-term changes in the temperature pattern. Seasonal changes affect bottom temperature more, whereas daily fluctuations affect surface temperature more. The curl, which depends on the differential between top and bottom temperature, has the largest effect on the vertical movement. Therefore, more data are needed, not only to determine the magnitude of the movement, but also to determine when this maximum movement will occur. Smaller movements in heavy traffic are more critical than large movements in lighter traffic.

CONCLUSIONS AND RECOMMENDATIONS

Analysis of the data indicate that the following factors have a significant effect on vertical pavement deflections: difference in the subbase, location of the truck on the pavement, speed of the truck, and time of measurement (i.e., morning versus afternoon).

The effect of the subbase came as no surprise. It makes sense that a stabilized base should provide more support for the pavement and be less susceptible to compaction over the years.

The effect of truck location was also expected. Because the transducer was mounted on the edge of the pavement, it stands to reason that the deflection would be more pronounced when the truck was closer to the measuring device.

It is often assumed that high-speed truck traffic is one of the major factors responsible for pavement deterioration. This study confirms recent results showing exactly the reverse. Low-speed traffic causes the greater deflection. Apparently, the truck moving over the joint at high speed simply does not give the pavement time to deflect.

Time of measurement must be studied further. In this work deflections were found to be greater in the morning than in the afternoon as a general rule. However, measurements of top, middle, and bottom slab temperatures indicate that the pavement remains concave for most of the day during the spring. In the fall, winter, and summer the temperatures would indicate that the shape of the pavement is changing during the day. This needs further study.

Spacing of joints, type of dowels, and configuration of the saw cut had only a minor effect on permanent deflection. It was expected that the configuration of the saw cut would have little effect on deflection. The same may be said for the type of dowels. However, the fact that joint spacing had little effect on deflections was somewhat unexpected. Skew joints also show virtually no effect on deflections when compared with normal joints.

All of the magnitudes of the movements appear small, if the absolute values are considered. However, it should be remembered that fatigue failure can be a major consideration. Fatigue, by definition, is repetitive loading below the yield stress of the material, and it does not take too long for the average daily truck traffic to build up to several million cycles, which would cause failure.

ACKNOWLEDGMENT

This paper was prepared in cooperation with the Ohio Department of Transportation and FHWA, U.S. Department of Transportation.

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Rigid Pavement Joint Resealing: Field Application, State of the Art

JOHN W. BUGLER

ABSTRACT

In the 1970s the New York State Department of Transportation initiated and executed field performance studies of formed-in-place sealant for future use in a statewide joint resealing program. It was determined after 3 years of service that of the six formed-in-place sealants tested, hot-poured polyvinyl chloride, conforming to ASTM D3406, performed best. A joint resealing program was initiated in Region 10 (Nassau and Suffolk counties) in 1979. There were initial field application problems. The problems are described, and the solutions used are explained.

Until 1958 New York State constructed concrete pavements with transverse expansion joints generally spaced every 100 ft. At that time the state amended the specifications to include the use of contraction joints spaced every 60 ft 10 in. The width of the joint was 0.375 in. and remained so until 1968.

Liquid formed-in-place sealants were in use until 1963, at which time the specifications were amended to require the exclusive use of 0.8125-in. (uncompressed width) preformed compression seals.

BACKGROUND

Performance of 0.8125-in. Preformed Compression Seals

The service life of the 0.8125-in. preformed compression seals was from 2 to 3 years (1). An explanation for the seal having such a short service life is as follows (2):

> Past experience had shown that due to slab contraction, transverse joints might open an additional 3/8-in. In other words, joints might be as wide as 3/4-in. during cold periods in winter. State specifications require preformed sealers to be 13/16-in. wide--1/16-in. wider than the anticipated maximum joint opening. This was in an effort to ensure that pressure against the joint faces would be maintained throughout the winter months. To consistently construct transverse joints exactly 3/8-in. wide was, of course, difficult if not impossible. Many joints were constructed slightly wider or narrower. Joints wider than 3/8-in. sometimes opened beyond 13/16-in. during winter, and thus the sealer was not in compression. When joints were too narrow, it was difficult to install the preformed sealer without stretching it. Also, in narrow joints it sometimes was subjected to more compressive stress than it was designed to withstand.

In March 1968 the specifications were amended to increase the joint width to 0.625 in. The uncompressed width of the preformed sealer was increased to 1.25 in.

This was an improvement, in that the 1.25-in. seal had to recover only 80 percent of its uncompressed width to be able to effectively seal the joint in the dead of winter, whereas the 0.8125-in. seal had to recover 92 percent.

Performance of 1.25-in. Preformed Compression Seals

After 7 years of service, 65 percent of the seals examined in the field were found to have taken a compression set of 0.375 in. (3). Also 51 percent of the joints examined were found to have moderate bottom-of-joint infiltration (3).

FIELD RESEARCH

For the purpose of effectively resealing pavement joints as the need arose, a field study involving