Magnitude of Horizontal Movement in Jointed Concrete Pavements

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A section of US-23 near Chillicothe, Ohio, has been used as a test pavement for the past seven years. Variables included in the test section are slab length, type of subbase, saw-cut configuration, type and coating of dowel bars, and skewed joints. Both hand and electronic measurements of horizontal movement have been made. The hand measurements, made monthly, gave the long-term movements. The electronic measurements were continuous readings taken for one-week periods for each set of joints. Enough data have been collected to set up a computer program on a statistical basis to interpret the results. The results show that the short-term movements are greater than the long-term movements. The short-term movements are as great as 0.25 in (6.44 mm) regardless of whether the slab length is 40 or 21 ft (12.2 or 6.4 m). The long-term movements are much smaller and are almost directly proportional to slab length. It is recommended that the preformed seal be designed for the long-term movements but be able to accommodate the larger short-term movements as an upper limit. The bond between the seal and the joint face should be able to take some tension as a further guarantee of holding the seal in place in case of large joint openings.

Jointed concrete pavements have been in use in this country for more than 100 years. Over that time span, many theories have been proposed to account for pavement movement. In recent years, a body of research has been accumulating that demonstrates that actual measurements of pavement movement in different regions of the country provide the best method for predicting movements. This paper presents data taken from 7 years of measurements on a test pavement in the midcentral region of the country (1).

The joints in portland cement concrete (PCC) pavements are usually formed by sawing a transverse contraction slot to a depth of at least 0.16T, where T is the slab thickness. This provides a weakened plane for cracking, and the drying shrinkage of the concrete causes the slab to crack through the remainder of the depth. The joint is usually bridged by a system of dowel bars that provides load transfer from one section of the slab to the next.

There are a large number of variables that may afffect the behavior of a pavement. Although it is possible to study the effect of some of these variables theoretically, the net result is that the actual in-service behavior of the pavement is quite different from its predicted behavior.

To study experimentally the effect of these variables on the behavior of pavements, a test pavement was constructed in Chillicothe, Ohio, as part of US-23. Combinations of the variables that were considered of prime importance, such as type of subbase, variation of joint spacing, type and coating of dowel bars, configuration of the saw cut, and the use of skewed joints, were incorporated into the pavement. The pavement has been monitored since 1972, and a great number of data on its behavior have been collected (2-4). This paper, however, is limited to a discussion of the magnitude of the horizontal movement of the contraction joint.

TEST PAVEMENT

The test pavement is a 3225-ft (983-m) section of the southbound roadway on US-23 in Chillicothe. It is a tangent section located between two bridges, built on fill that ranges from 20 to 35 ft (6.1-10.7 m) in depth. The profile of the highway provides an easy grade of -0.28 percent into a 600-ft (183-m) vertical curve, which is followed by a +2.0 percent grade.

The pavement is mainly reinforced PCC [24 ft (7.3 m) wide and 9 in (229 mm) thick] laid over a granular subbase [grade A, 7.5 in (190 mm) thick]. A 183-ft (55.8-m) section was left plain, with no dowels, and with right-forward-skew joints at 17-ft (5.2-m) spacing. The subbase over a 776-ft (236-m) section was changed to a 4-in (102-mm) layer stabilized with asphalt.

The spacing of the joints was set at 17, 21, and 40 ft (5.2, 6.4, and 12.2 m). Both plain steel and plastic-coated dowels were used. The configuration of the transverse joints was also varied. There are some 0.25-in (6-mm) standard joints, 0.25-in joints with 0.125-in (3-mm) bevel on each side, and some 0.5-in (12-mm) saw-cut joints. Table 1 gives the location and type of the different variables introduced in the test pavement.

FIELD MEASUREMENTS

The following types of measurements were taken on the pavement:

1. During the early life of the pavement, monthly hand-gage measurements of horizontal movement were made over the entire length of the project. These measurements were reduced later to four sets a year.
2. In 1979, selected large cracks in the pavement were instrumented for hand horizontal measurements. Readings across the cracks were taken by the hand gage at the same time as measurements were made on the rest of the joints.
3. Electronic measurements of horizontal movement were made on groups of joints. The measurements were taken continuously over a period of approximately one week during each of the seasons of the year.
4. Electronic measurements of vertical movement were made on one joint in each group during each season of the year.
5. Hand measurements of spalling and cracking were taken during each season of the year.
6. Periodically, Dynaflect readings were taken across all joints and selected cracks.
7. Electronic measurements of the temperature of the middle of the slab were made simultaneously with the electronic horizontal measurements.

INSTRUMENTATION

Hand-Gage Measurements

The hand gage consists of a base bar with two 45° pointed probes, one fixed and one movable. An Ames dial gage graduated to 0.001 in (0.025 mm) is mounted on top of the base bar between the two probes.

Brass plugs were set into the pavement on either side of each joint. These brass plugs are approximately 6 in (152 mm) apart and are set so that the top surface of the plug is just below the pavement surface. The tops of these plugs are center drilled with a 0.0625-in (1.6-mm) hole and countersunk to

Table 1. Variables included in test pavement.

Joint Group	Joints Nos.	Joints Total	Type	Spacing (ft)	Subbase Type	Dowel Type
1	1-7	7	0.125-in bevel sawcut	40	Granular	Standard
2[a]	8-16	9	Standard 0.25-in sawcut	40	Granular	Standard
3	17-24	8	Standard 0.25-in sawcut	21	Stabilized	Standard
4	25-34	10	Standard 0.25-in sawcut	40	Stabilized	Standard
5[b]	35-44	10	Standard 0.25-in sawcut	17	Stabilized	None
6	45-53	9	Standard 0.25-in sawcut	21	Granular	Plastic coated
7	54-63	10	Standard 0.25-in sawcut	40	Granular	Plastic coated
8	64-73	10	0.5-in sawcut	40	Granular	Standard
9	74-84	11	Standard 0.25-in sawcut	40	Granular	Standard
10	85-94	10	Standard 0.25-in sawcut	21	Granular	Standard
	95-96	2	Standard 0.25-in sawcut	40	Granular	Coated[c]
	97-100	4	Standard 0.25-in sawcut	40	Granular	Standard
	101	1	Expansion	40	Granular	

Note: 1 in = 25.6 mm; 1 ft = 0.3 m.

[a]Chlorinated rubber base cure.
[b]Right forward skew and plain pavement.
[c]Experimental coating being evaluated by state of Ohio.

45° to receive the points of the probe.

The hand gage has a separate calibration bar of Invar, and countersunk holes receive the points of the probe.

Electronic Measurements of Horizontal Movement

Horizontal movement was measured with 1-MΩ Bournes linear motion transducers (model 3049L), which were mounted on the side of the slab, at middepth and not on the riding surface. Each joint was fitted with a drilled and tapped aluminum plate on one side of the joint and a short section of 1.5x1.5-in (38x38-mm) aluminum angle on the other side of the joint.

The transducers were connected to double-channel Rustrak recorders (model 291) so that one recorder could serve two transducers. The recorder was powered by a 12-V battery. A resistor was connected to the recorder in series with the transducer to limit the current from the 12-V batteries to 50 μA, which is the full range of each channel.

One recorder had one channel calibrated for a motion transducer and the other channel calibrated for a temperature sensor. The temperature sensor is a model 1441 from Yellow Springs Instrument Company and is calibrated from -10° to +150°F (-23° to 66°C). This temperature sensor is mounted in a hole drilled at the middepth of the slab.

All strip-chart recorders have a chart speed of 0.25 in/h (6.4 mm/h) so that one week of continuous readings on a given set of joints is obtained in a 42-in (107-cm) length of chart paper.

The joints were arranged in the groups given in Table 1. Within each 10-joint group, the joints were wired in pairs so that one recorder could serve two joints. A short section of steel signpost was driven into the berm midway between two joints to serve as an anchoring post. At each joint, the shoulder material was excavated down to the bottom of the slab. Each joint was filled with a cutout box made of sheet metal, complete with cover. The recorder, two controls, and a 12-V battery to power the recorder served as a unit for each pair of joints. The entire unit was enclosed in a watertight welded aluminum box, which was bolted to the anchoring post and then locked. The transducers were connected to the recorders by wires threaded through a flexible rubber hose that stretched from the hole at the edge of the pavement to the aluminum box. The rubber hose protected the wires from traffic that might accidentally pass over the shoulder at that point.

Each time a set of readings was taken, either manual or electronic, both the air temperature and the pavement surface temperature were recorded. The thermometer used was a Pandux surface temperature thermometer (model 309F), graduated from -50° to +250°F (-46° to 121°C).

CALIBRATION

Very few, if any, transducers are truly linear over the entire range of the instrument. Consequently, each horizontal measuring transducer was calibrated for a particular channel of a particular recorder and was so marked. The transducers were not shuffled indiscriminately from one recorder to another.

Two serious problems were encountered during the horizontal measurements: (a) water and (b) fade in the transducer response.

Instruments often had to be moved from one joint group to another during a hard rain. Even though the test section was built on fill and was generally well-drained, there were times during a hard rain when water running down the top of the joint would fill the cutout hole faster than the underdrains could carry the water off. Consequently, there were some times when the transducer was forced to operate while actually immersed in water. For this reason, a separate calibration was carried out in the laboratory in which the transducer was immersed in water. No significant change from the dry calibration was found.

Fade in the transducer response was another problem. After a period of three months under adverse weather conditions, the data were found to be quite unreliable. Consequently, after 10 weeks in the field, the units were returned to the laboratory, fitted with all new transducers, recalibrated, and returned to the field. All calibrations, of course, were carried out by using the same battery source and controls used in the field.

Ten batteries were used on the project. There were, at all times, five batteries in the field powering the units and another five back in the laboratory for recharging.

RESULTS

The electronic measurements of horizontal movement gave a continuous reading of the movement of the joint, plus or minus from a given zero setting. For purposes of data analysis, discrete points were needed. Consequently, the magnitude of the movements at 6:00 a.m., noon, 6:00 p.m., and midnight were chosen for use all through the analysis.

The hand-gage horizontal measurements also provided, over the years, a large number of readings.

The values used to plot the frequency curves were obtained from the difference between the readings of two consecutive months taken at the same joint.

The frequency curves of both types of measurements are shown in Figures 1-4. Figures 1 and 2 show the electronic measurements of the movement of a pavement with 21- and 40-ft (6.4- and 12.2-m) slabs. Figures 3 and 4 show these movements as measured by hand. Positive values indicate expansion of the slab or closing of the joint.

It is easily seen by comparing Figures 1 and 2 with Figures 3 and 4 that the magnitude of the movement is virtually the same. A statistical F-test was conducted to compare the movement for the 40-ft (12.2-m) spacing of joints with that for the 21-ft (6.4-m) spacing. The results show no significant difference in movement due to joint spacing. The main reason for this behavior is that, over time, a midslab crack developed in most 40-ft spans. A detailed joint-by-joint study of the movements shows that, within any particular group, most of the movement is taking place at one joint and the joints before and after it are moving very little.

The distribution curves for the measurements show

Figure 1. Frequency curve for horizontal movement in 21-ft spans: electronic measurement.

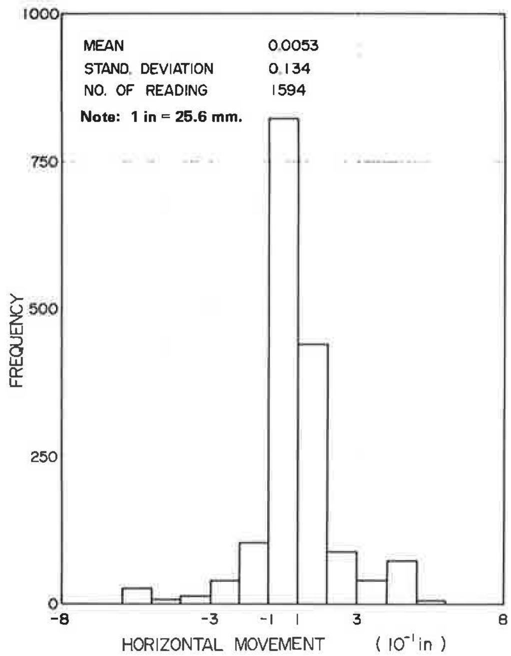


Figure 2. Frequency curve for horizontal movement in 40-ft spans: electronic measurement.

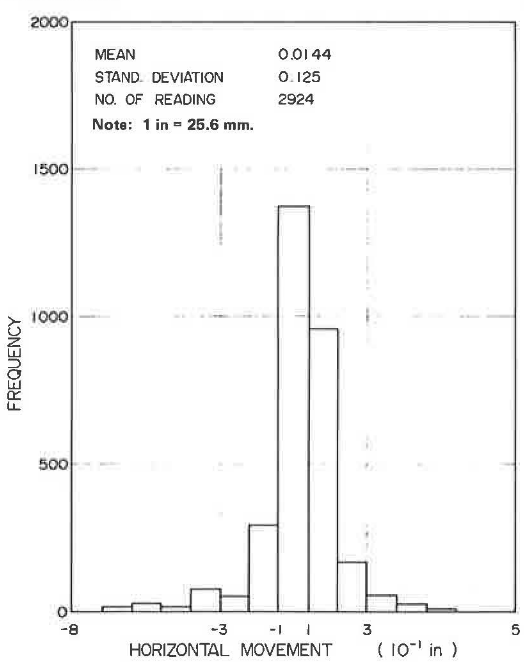


Figure 3. Frequency curve for horizontal movement in 21-ft spans: hand measurement.

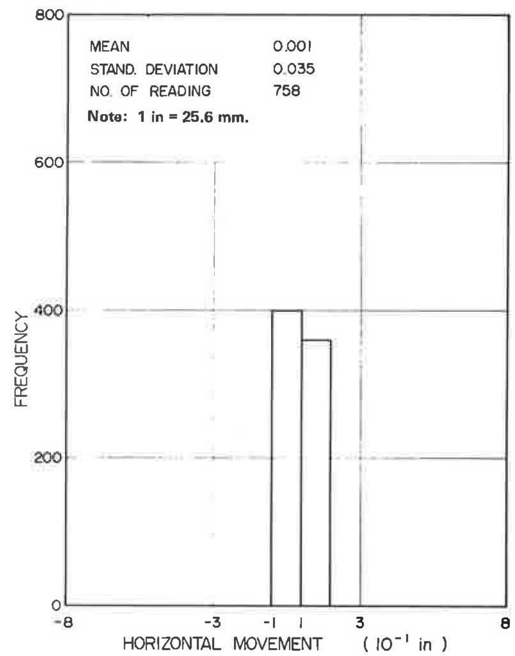
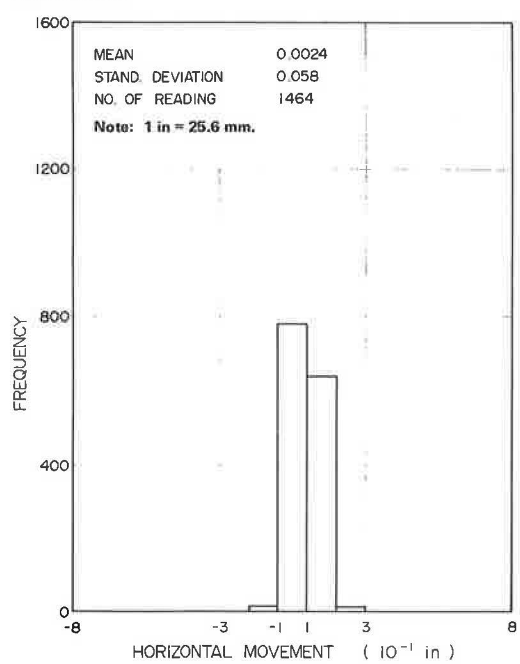


Figure 4. Frequency curve for horizontal movement in 40-ft spans: hand measurement.



that the movement of 97 percent of the joints lies between ±0.1 in (±2.5 mm) when movement is measured by hand whereas only 78 percent of the movement is within this band when movement is measured electronically. It is important to note, however, that the movement of most of the joints within this band is close to zero.

Joints that show little or no movement at a particular time are not necessarily frozen into a fixed position. Any particular joint may show little or no movement at one time and then later show a large movement. This point is currently being double-checked by spot measurements of both the joints that show large movements and the two or three joints that precede and follow them.

For analysis of the data, normal distribution curves have been superimposed on the frequency distributions. Figures 5 and 6 show the normal distribution curves for the 21- and 40-ft (6.4- and 12.2-m) slabs. Figure 7 shows the normal distribution curves for a combination of all the movements.

The magnitude of the movement at a joint is of extreme importance in the design of the jointing material, whether this material is premolded or field molded. To determine the magnitude of the movement, 90 and 95 percent confidence limits (C_1 and C_2) were calculated by using the normal distribution curves corresponding to the frequency distributions of hand and electronic measurements. Figures 8-13 show the normal curves and the values of C_1 and C_2 for all cases under study. The values are also given in Table 2. The nomenclature used in the statistical analysis is based on the work of Miller and Freund (5). The calculations are

Figure 5. Superposition of normal curve for 21-ft spans: electronic measurement.

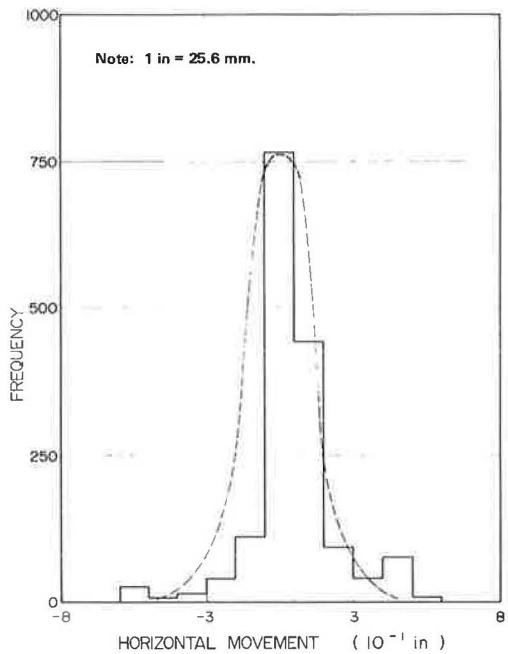


Figure 6. Superposition of normal curve for 40-ft spans: electronic measurement.

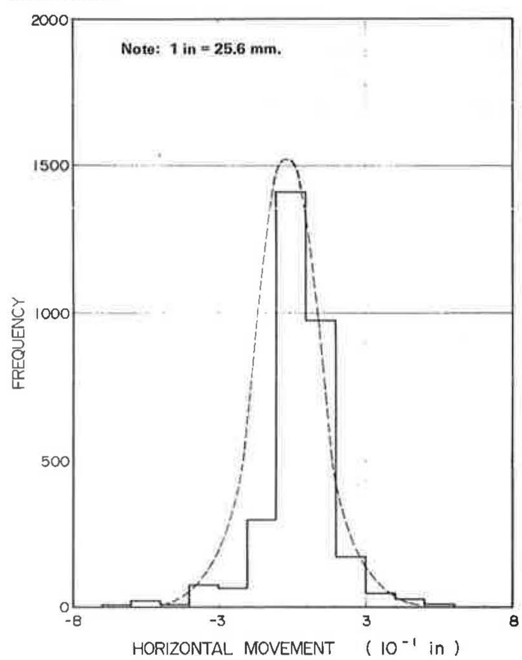


Figure 7. Superposition of normal curve for all spans: electronic measurement.

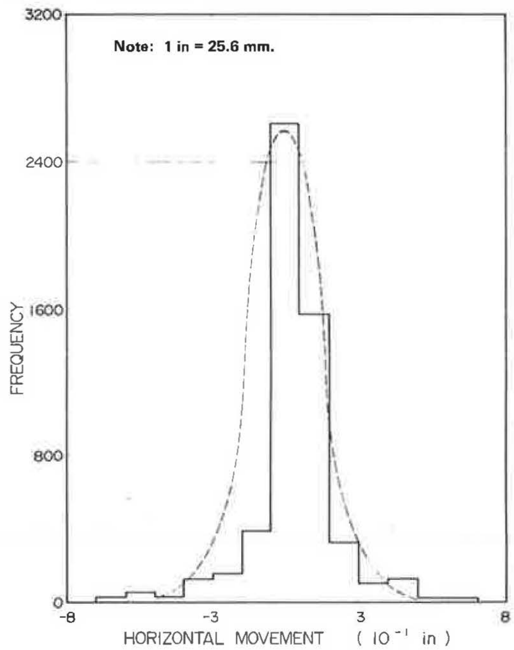
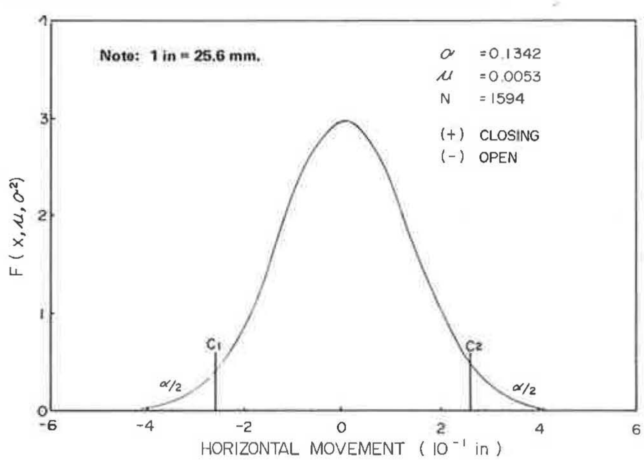


Figure 8. Normal distribution curve for 21-ft spans: electronic measurement.



based on the following formulas:

$$C_1 = \mu - (Z_{\alpha/2})\sigma \quad (1)$$

$$C_2 = \mu + (Z_{\alpha/2})\sigma \quad (2)$$

Figure 9. Normal distribution curve for 40-ft spans: electronic measurement.

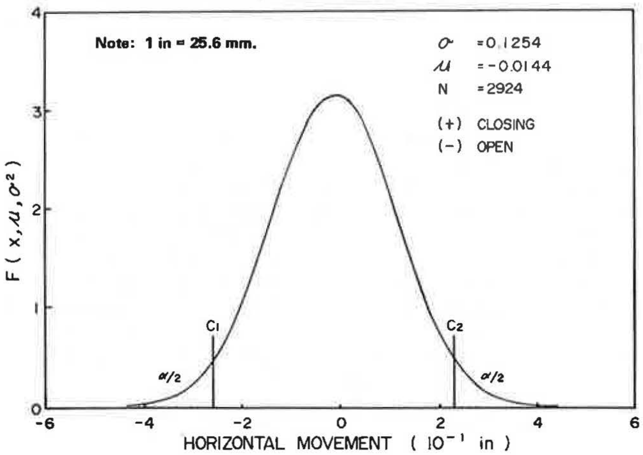


Figure 10. Normal distribution curve for all spans: electronic measurement.

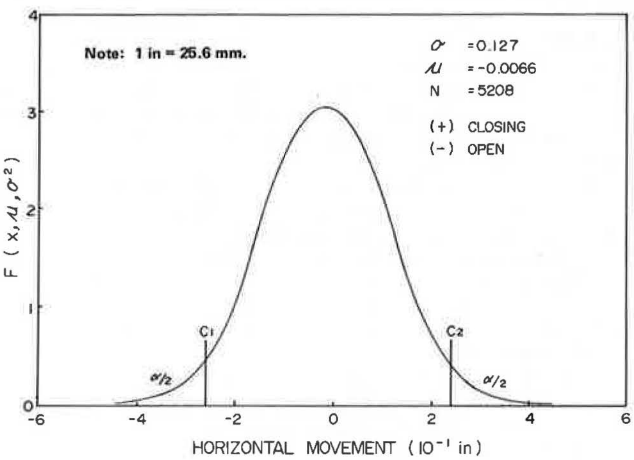
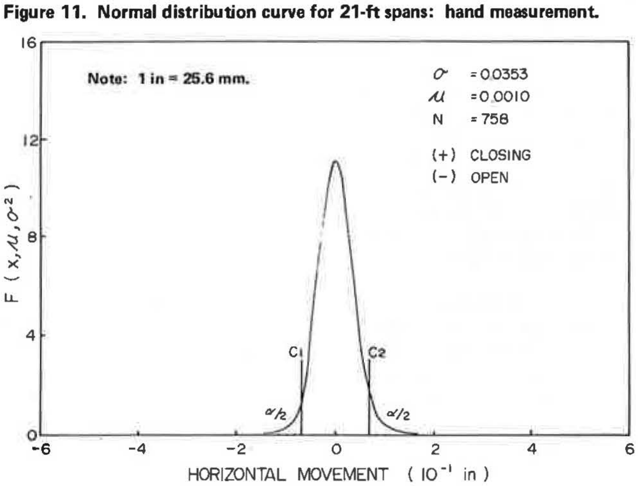


Figure 11. Normal distribution curve for 21-ft spans: hand measurement.



where

μ = mean of the normal distribution,
σ = standard deviation,
$z_{0.025}$ = ± 1.96, and
$z_{0.05}$ = ± 1.645.

It is apparent that the value of C_1 and C_2 for electronic measurements can be taken as ± 0.25 in (6.4 mm) and is the same for 40- and 21-ft (12.2- and 6.4-m) slabs. The electronic measurements give the short-term movements, since they were taken by continuous recording. The hand measurements show the aggregate movement obtained over a long period

Figure 12. Normal distribution curve for 40-ft spans: hand measurement.

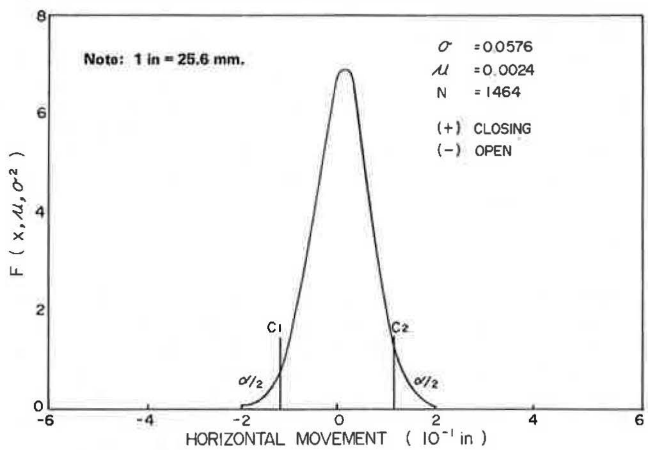


Figure 13. Normal distribution curve for all spans: hand measurement.

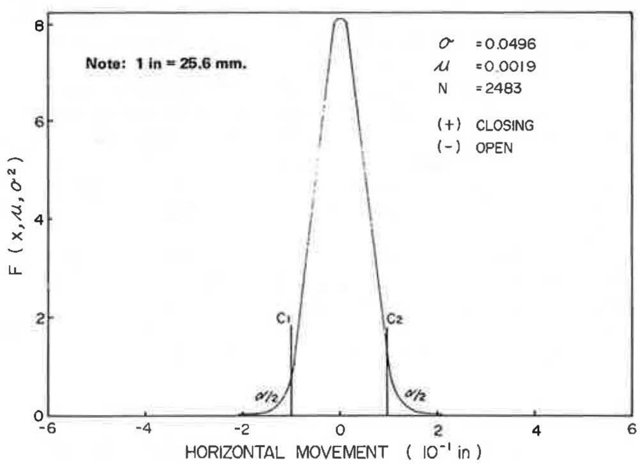


Table 2. Probable magnitude of joint movements.

Measurement Type	Joint Spacing (ft)	Movement (in): 95 Percent Confidence Limits C_1	C_2	90 Percent Confidence Limits C_1	C_2
Electronic	40	-0.26	0.23	-0.22	0.19
	21	-0.26	0.27	-0.22	0.23
		-0.26	0.24	-0.22	0.20
Hand	40	-0.12	0.11	-0.10	0.10
	21	-0.07	0.07	-0.06	0.06
		-0.10	0.10	-0.08	0.08

Note: 1 in = 25.6 mm; 1 ft = 0.3 m.

of time, since they were based on a monthly difference in the movement. Over this longer time span, the slabs had time to adjust themselves to the temperature and moisture change and more of the slabs took up their share of the movements. It is interesting to note that the long-term movement of a 40-ft slab is almost double that of a 21-ft slab, whereas the short-term movements are almost equal.

The midslab temperature was also measured at one joint in every group. This measurement was taken simultaneously with the horizontal movement. The temperatures include not only hot summers but also some of the worst winters Ohio has seen in many years.

INTERPRETATION OF RESULTS

In the experimental pavement, the jointing material used was a standard 0.7-in (17.5-mm) premolded seal inserted into a 0.25-in (6.4-mm) saw-cut groove. The pavement was cast and the joints were sawed under almost ideal weather conditions. Enough shrinkage had occurred to crack all joints through before sealing. Neither the vertical edges of the pavement nor the longitudinal pavement shoulder joint was sealed.

Short-Term Movements

Many of the joints, on a short-term basis, have shown movements as great as 0.25 in (6.4 mm). However, it is not always the same joint that repeatedly shows these large movements. A statistical analysis of the data shows a probability of only 2.5 percent that a particular joint will move this much.

In general, the joints after seven years are still in excellent shape. Close inspection shows no joints completely closed and no joints in which the jointing material has slipped completely to the bottom of the saw-cut groove. However, there are joints in which the seal has lost contact with the joint face over a portion of its length and has slipped, which results in a "scalloped" effect.

The preformed seal will slip if contact with the concrete face of the joint is lost and vibration due to traffic causes it to migrate downward. Tire pressure on compacted snow may cause the same effect. This will happen if the preformed seal opens completely and the adhesive between the seal and the concrete fails.

Therefore, the short-term movement of ±0.25 in (6.4 mm) could be considered as the ultimate movement of a joint. The jointing material should be capable of resisting an occasional extension and compression of 0.25 in without failure.

Long-Term Movements

It is apparent from Table 2 that long-term movements are appreciably smaller than short-term movements: i.e., C_1, C_2 = ±0.12 in (3.0 mm) for a 40-ft (12.2-m) slab, and C_1, C_2 = ±0.07 in (1.8 mm) for a 21-ft (6.4-m) slab. These values should be considered as the actual movements of contraction joints in the midcentral region of the United States (1). If the jointing material is designed to sustain a short-term maximum movement of 0.25 in (6.4 mm), the factor of safety ranges from 2.08 for a 40-ft slab to 3.57 for a 21-ft slab. Similar values can be obtained for different slab lengths and different environmental regions of the United States. The values given above correspond very closely with the values obtained in a 1956 Michigan study (6) for pavements with similar contraction joints and a similar spacing between expansion joints. The tabulated measured values take into account the combined effects of temperature, moisture, and shrinkage.

Although the short-term movements are appreciably larger than the long-term movements, experience has shown that it takes a large number of these cycles to cause a preformed seal to fail. The Ohio study shows that, although these large movements have occurred, the probability of these movements occurring repeatedly at any given joint is less than 3 percent.

Present Practice

In most areas of the country, the following well-known formula is used to calculate movement:

$$\text{Movement} = \alpha_c (\Delta T) L \tag{3}$$

However, actual measurements do not verify the formula and its use is not recommended. Note that the formula contains three variables, none of which can be estimated with sufficient accuracy. The coefficient of expansion (α) varies with different concretes. The temperature range is indeterminate because it has not been shown whether movement varies with air temperature, slab surface temperature, or midslab temperature. Even the slab length is indeterminate because measurements show that, in the short term, two or three slab units may act together. In addition, the formula does not take into account the change in slab length due to moisture.

CONCLUSIONS AND RECOMMENDATIONS

From the discussion in this paper, it becomes obvious that the present practice of using the temperature-change formula in the calculation of the horizontal movement at a joint in order to design a sealant is not adequate. Neither the length nor the change in temperature nor the coefficient of thermal expansion can be determined with any degree of accuracy. The best approach is to physically measure the movement and get a statistical value of the probable movement.

There are two different types of movements to be considered: short term and long term. The short-term movement, which is large and does not seem to be dependent on the spacing of the joints, is equal to ±0.25 in (6.4 mm) for 21- and 40-ft (6.4- and 12.2-m) spacing. The long-term movement is dependent on joint spacing and is much smaller than the short-term movement. It is recommended that the long-term movement be used in the design of the seal in spite of the fact that it is smaller. The short-term movement can be considered as an upper limit or ultimate value that has to be allowed for rather than being used for design.

Values of long-term movements can be determined for different regions in the United States and other countries by using a statistical analysis of hand measurements similar to the method reported in this article. There is no need for expensive electronic measurements when the same result can be obtained by taking hand measurements at closer intervals--say, every 6 h. Such a measurement could be undertaken on a pavement with 60- or 80-ft (19.2- or 25.6-m) spacing of joints to conform the insensitivity of short-term movements to joint spacing.

In view of the above, the following recommendations are made:

1. A movement of 0.07 in (1.8 mm) should be used as a basis for the design of seals with 20-ft (6.1-m) spacing of joints or less in the midcentral region of the country (1).
2. A movement of 0.12 or 0.125 in (3 or 3.2 mm) should be used for the design of seals with 40-ft (12.2-m) spacing of joints in the midcentral region (1).

3. A similar study should be undertaken in other regions to determine the value of the movement to be used as a basis for the design of seals. These values could be tabulated and used in lieu of Equation 3.

4. A check should be made on short-term movements to confirm that they are in the order of ±0.25 in (6.4 mm) for longer spans.

5. A seal should be designed to accommodate the long-term movement and to resist the short-term movements as an upper limit.

6. The bond between the seal and the face of the joint should be able to take some tension as a further guarantee of holding the seal in place in case of a large opening of the joint.

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REFERENCES

1. P.J. Nussbaum and E.C. Lokken. Portland Cement Concrete Pavements: Performance Related to Design-Construction-Maintenance. FHWA, Rept., FHWA-TS-78-202, Aug. 1977, revised Nov. 1978.
2. J.P. Cook and I. Minkarah. Development of an Improved Contraction Joint for Portland Cement Concrete Pavements. Ohio Department of Transportation, Columbus, Aug. 1973.
3. I. Minkarah and J.P. Cook. A Study of the Field Performance of an Experimental Portland Cement Concrete Pavement. Ohio Department of Transportation, Columbus, May 1975.
4. I. Minkarah and J.P. Cook. A Study of the Effect of the Environment on an Experimental Portland Cement Concrete Pavement. Ohio Department of Transportation, Columbus, Aug. 1976.
5. I. Miller and J.E. Freund. Probability and Statistics for Engineers. Prentice-Hall, Englewood Cliffs, NJ, 1977.
6. H.C. Coons. Report on Experimental Project in Michigan. HRB, Res. Rept. 17-B, 1956, pp. 35-88.

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Design for Minimizing Detrimental Vibrations from Construction Blasts

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Effects of ground vibrations on structures and people in the vicinity of construction blasts have become a major environmental concern and problem to engineers and contractors as well as to the general public. Understanding of the propagation characteristics of stress waves produced by blasting and structural response to ground vibration is essential in planning and design for safe blasting operations to minimize or eliminate legitimate damage claims and complaints. Both the theoretical and empirical propagation laws for ground motions resulting from blasting are analyzed; by this means, the intensity of ground vibration can be predicted on the basis of weight of explosives, distance from point of detonation, dynamic properties of transmitting medium, and other variables. Existing damage criteria by which the damage to a structure can be related to the intensity of ground vibration are reviewed to show that, although dynamic analysis (such as the response-spectrum technique) may provide the most rational approach, peak particle velocity appears to be the best and most practical criterion for use in design of safe blasting operations. However, the currently recommended design criterion of 50-mm/s (2-in/s) peak particle velocity, applicable uniformly to all types of structures, is found to be inadequate. Revised design criteria based on the type, age, and stress history of the structure are proposed. Structures are classified into four categories, and the safe design value is recommended for each. Human response to vibration is found to be very critical and sometimes a controlling factor in the design. A case study is presented to illustrate a design based on the revised design criteria.

With the expansion of construction activities and a growing public awareness of and demand for improved environmental quality in recent years, the problem of detrimental vibrations resulting from construction activities has become increasingly important to engineers and contractors. The problem is normally associated with surface activities such as quarry operations and construction projects in residential areas. Specifically, the problem of the effect of vibrations on structures and people becomes most acute when explosives are used in rock excavation for foundations and transportation facilities (tunnels and highways), quarry operations for construction materials, and the mining of natural resources. On the other hand, as Figure 1 (1) shows, operation of construction equipment causes less vibration unless the distance from the source to the affected point is extremely close.

Because the general public is directly involved in the problems of blasting vibration, many investigations have been conducted, both in this country and abroad, on the effects of air and ground vibrations on residential and other structures. Although many of these studies focused on quarry operations, construction blasting raises many of the same problems. There are, however, problems unique to construction blasting that have not received special attention.

To minimize or eliminate legitimate damage claims and complaints, the engineer needs a reliable basis on which to plan and conduct blasting operations. To ensure an environment free from nuisance and annoyance, the engineer must, therefore, be able to determine the maximum weight of explosives that can be detonated without causing damage to adjacent structures and, at times, without having detrimental effects on the human beings in those structures.

The design for minimizing detrimental vibrations