Aggregate Interlock at Joints in Concrete Pavements

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Load transfer across joints in concrete pavements through shear developed by interlocking aggregate was investigated in the laboratory by simulating the repetitive motion of tandem truck wheels across a joint.

Effectiveness of load transfer was found to depend on load magnitude, number of repetitions, slab thickness, joint opening, subgrade bearing value, and aggregate angularity. A summary statistic called "endurance index" is used to relate the significant variables to test performance.

•TRANSVERSE contraction joints are constructed in concrete pavements to relieve tensile stresses, and when properly spaced they control the location of transverse cracks. Proper spacing is determined principally by three factors: (a) the presence or absence of steel, (b) the environment, and (c) the properties of the aggregates.

Contraction joints are most frequently constructed by sawing or forming a narrow groove in the pavement to the depth required to produce a plane-of-weakness. For highway pavements the minimum depth of the groove is generally one-sixth the slab thickness; sawed joints should meet the additional requirement that the depth be not less than the diameter of the maximum size aggregate. At the plane-of-weakness, restrained contraction forces produce a crack below the groove.

Load transfer across the crack is developed either by the interlocking action of the aggregate particles at the faces of the joint (aggregate interlock) or by a combination of aggregate interlock and mechanical devices such as dowel bars. When load transfer is adequate, load stresses and deflections in the vicinity of a joint are low, and the riding quality of the pavement is maintained.

To analyze the factors that influence the load transfer characteristics of aggregate interlock joints, a research program was inaugurated in the laboratory with equipment that permitted control of significant variables. Laboratory results were compared with data from field tests on highway pavements.

The objective of the program was to evaluate the effectiveness and endurance of load transfer developed by aggregate interlock under loading conditions simulating in-service concrete pavements.

Five variables considered significant to the performance of joints were selected for study: (a) width of joint opening, (b) thickness of concrete slab, (c) magnitude of load, (d) foundation support, and (e) shape of aggregate. For this investigation, maximum size of aggregate was held constant. Future studies will consider this important aspect of joint design.

FACILITIES AND INSTRUMENTATION

Facilities for Laboratory Study

A testing device was developed to apply repetitive loads of known magnitude in a manner closely simulating the action on a pavement as a vehicle passes over the joint.

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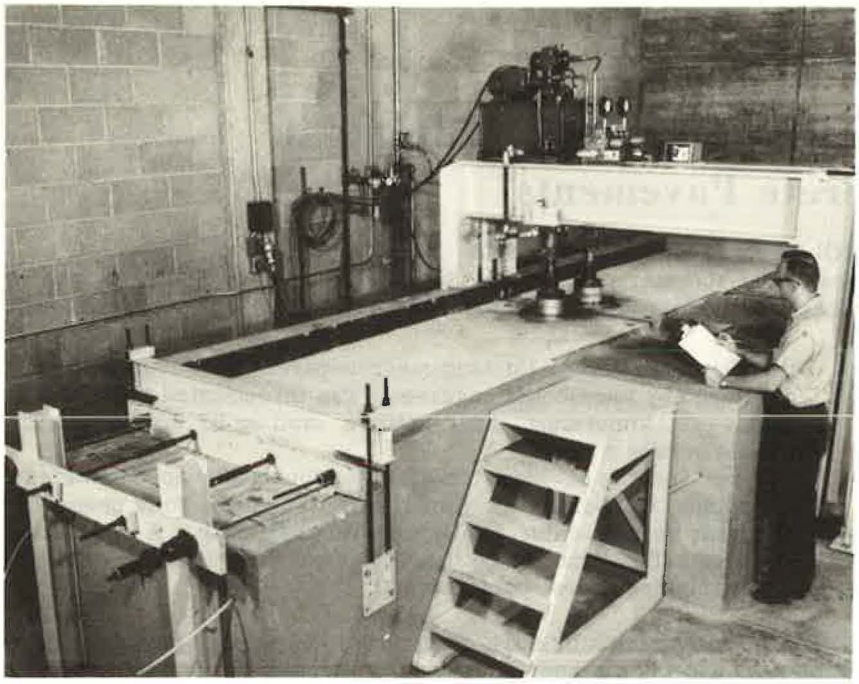


Figure 1. Load transfer test equipment.

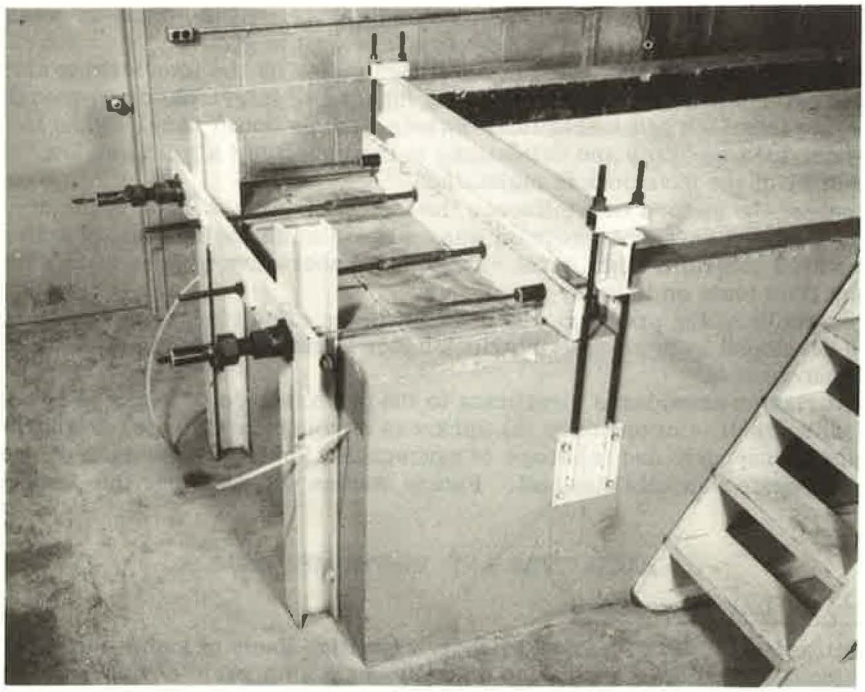


Figure 2. Joint-width control system.

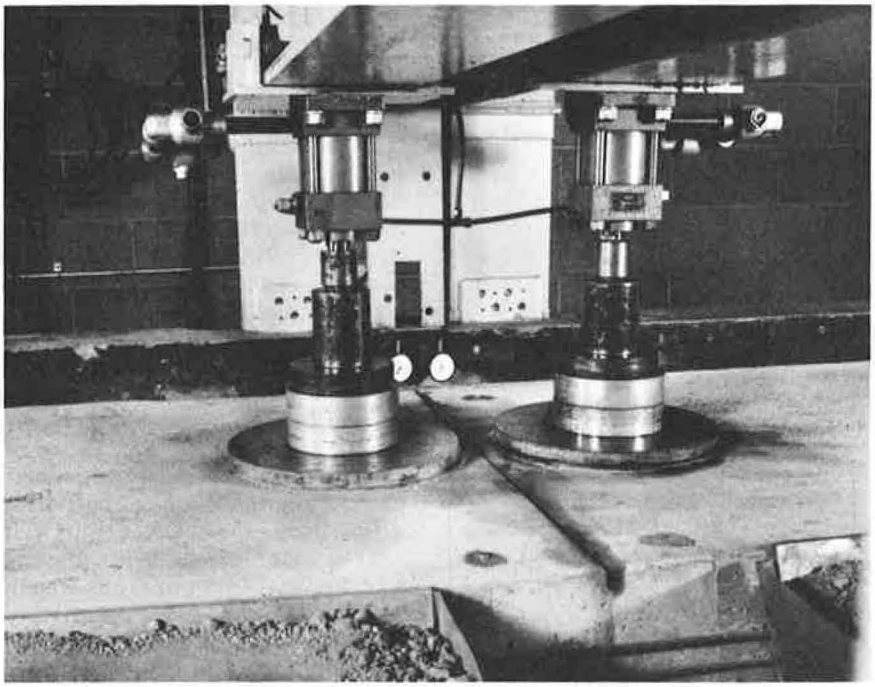


Figure 3. Load application equipment.

Two devices were constructed. They are housed in an air-conditioned area where the temperature is maintained at 72 F throughout a test to permit the joint width to be held constant while the effects of other variables are studied.

The device shown in Figure 1 consists of three basic components: (a) a base box which contains the subgrade, subbase, and concrete slab and also acts as support for the load application equipment; (b) a joint width control system; and (c) the repetitive loading apparatus and reaction frames.

Base Box—The base box of reinforced concrete is 4 ft high, 6 ft wide, and 22 ft long. The center section of the box is wider on one side to provide an area 3 ft wide and 8 ft long for future studies of the performance of shoulders. The walls and floor of the box are waterproofed to prevent excessive loss of moisture from the subgrade and subbase materials. Silty-clay soil was compacted in the box to a depth of $2\frac{1}{2}$ ft to serve as a subgrade upon which various combinations of type and thickness of subbase and pavement slabs are constructed and tested.

Joint Opening Control—The system for controlling joint opening permits adjustment of the width and maintenance of that width for the duration of the test. Equipment developed for this operation is shown in Figure 2. To open the joint, two steel rods anchored in the concrete are connected through threaded couplings to crossbars at the ends of the box. By tightening the couplings the slabs are pulled apart, thus opening the joint. To close the joint, two steel strands are employed along each side of the slab. One strand on each side is anchored to the left end of the slab and the right crossbar. The other strand is anchored in a similar manner to the right end of the slab and the left crossbar. By applying tension to the four strands the slabs are pulled together, thus reducing the opening. The combined use of these systems and control of the temperature maintained joint openings to within 0.001 in. of the desired value throughout a test.

The transverse beam shown on the end of the slab in Figure 2 prevents upward movement of the slab ends when the joint is loaded. With the slab restrained, the movement of a joint under test is similar to that of a transverse joint between full length slabs.

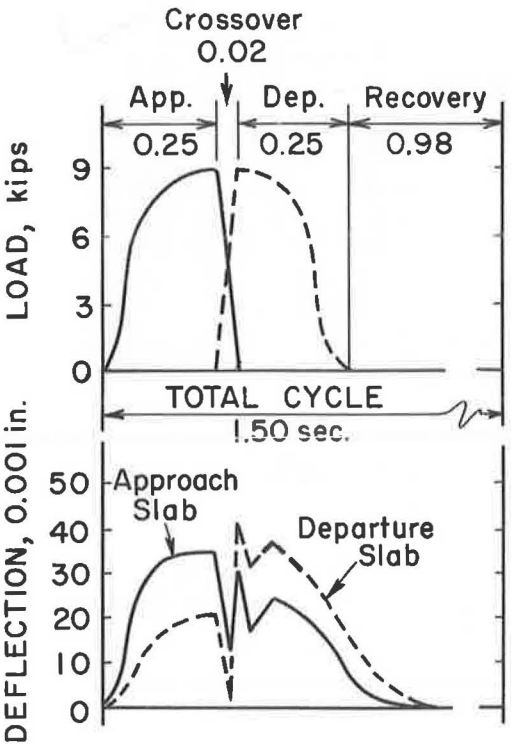


Figure 4. Loading cycle.

Repetitive Loading Apparatus—The hydraulic rams shown in Figure 3 react against a steel frame that is fastened to the base box. Loads are transmitted to the pavement by a pair of 16-in. diameter steel bearing plates resting on ¼-in. solid rubber pads. The plates are positioned on each side with their centers 9 in. from the joint and on the longitudinal centerline of the slab. Between each plate and the hydraulic jack are a series of spacer plates and a load cell.

The load application equipment is an electrically operated air-hydraulic system that alternately pulses the rams on either side of the joint to produce loads up to a maximum of 12,000 lb. Details of the controls for the sequence of loading and rate of load application have been described in a previous report (1).

The loading sequence closely simulates a continuous train of truck wheels traveling across the joint at approximately 30 mph. The magnitude of load, sequence and rate of loading may be varied to represent load patterns imposed by different types of traffic.

The rate of loading together with the corresponding joint deflection for a loading cycle are shown in Figure 4. To simulate a wheel approaching a joint, the load applied to the approach slab is increased from zero to full load in ¼ sec. The load on the approach slab is then released to zero and simultaneously the load on the departure slab increased from zero to full load in 0.02 sec. This interval would permit a tire making a 10-in. print and traveling 30 mph to move completely across the joint. To simulate a wheel moving away from the joint the load on the departure slab is reduced to zero in

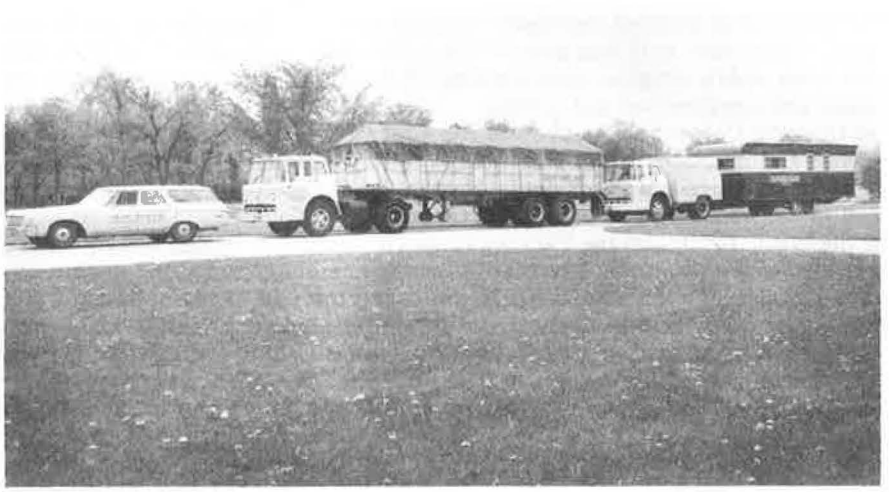


Figure 5. Field test equipment.

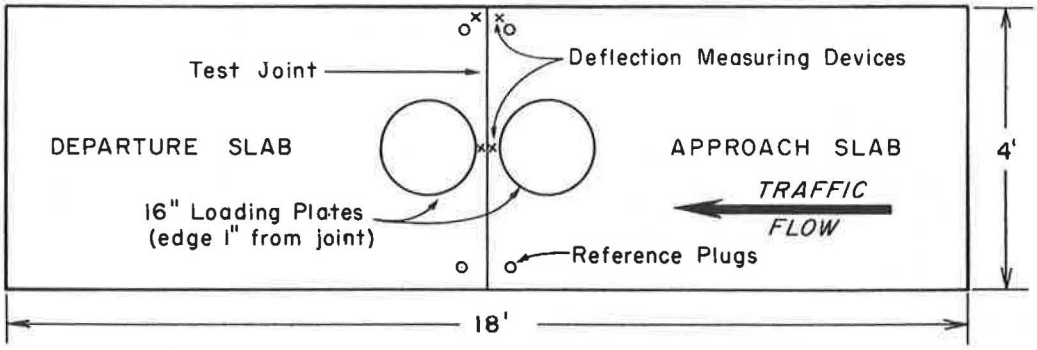


Figure 6. Plan of test slab and instrumentation.

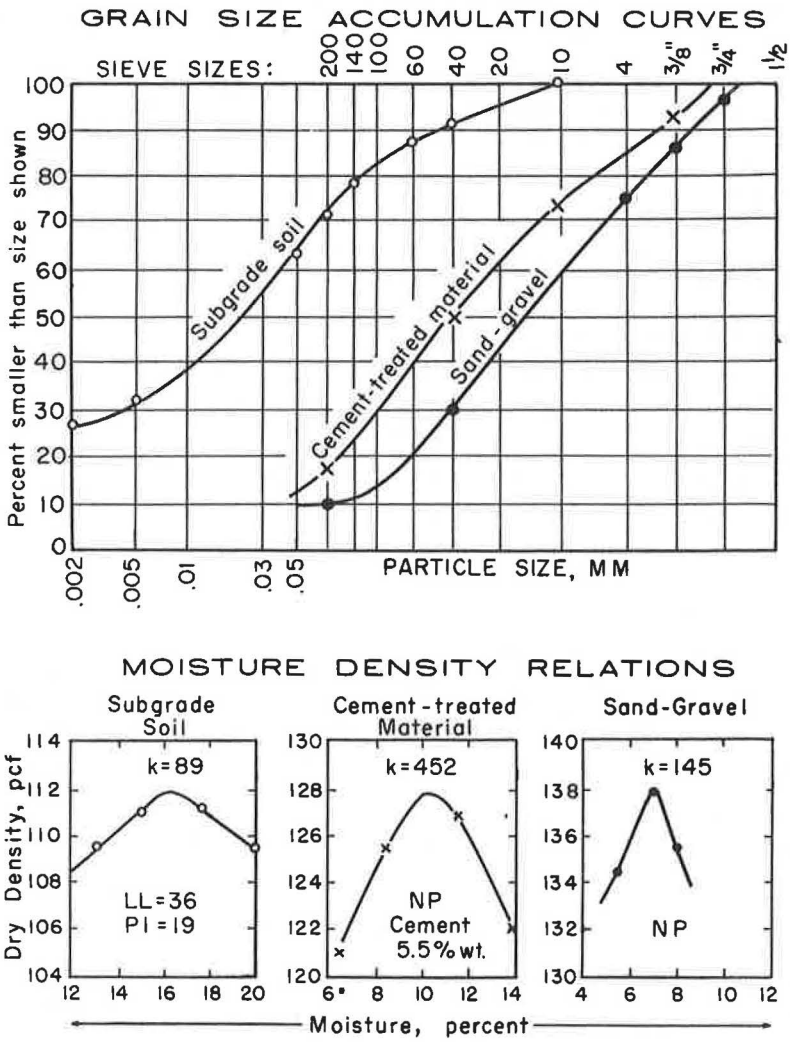


Figure 7. Foundation materials.

¼ sec. This action is followed by an interval of approximately 1 sec. when there is no load on either ram and the slabs return to a no-load position. A joint under test receives about 50, 000 of the 1. 5-sec loading cycles per day.

Facilities for Field Tests

Tests on existing pavements were made with moving loads of known weight in assigned paths across selected joints. The control vehicle was a tractor-semitrailer with variable wheelbase. Auxiliary equipment included a utility vehicle and house-trailer type mobile laboratory (Fig. 5). A more complete description of the equipment and its potential is given by Nowlen (2).

Instrumentation of Laboratory Slabs

Test slabs were instrumented for measurements of joint openings and deflections. In addition, devices were installed to measure the magnitude and rate of load repetitions. Automatic recordings of slab deflections and load magnitude were obtained at regular intervals. The instrumentation plan is shown in Figure 6.

Joint opening was measured using brass reference plugs and a Whittemore strain gage. Initial measurements were made before the slab was cracked to form the joint, so that reported joint openings are actual distances between the fractured faces of the concrete.

To evaluate load transfer, deflections on each side of the joint were measured with 0. 001-in. dial indicators for static loading, and with electronic deflectometers for dynamic loading. The dials and deflectometers were supported by brackets attached to the base box.

The magnitude of load applied to the slab was measured with load cells placed below each ram. These strain-sensed cells were connected electrically to a strain indicator for static measurements, and to an automatic recorder to measure the rate of load application and magnitude of repetitive load.

Instrumentation of Field Pavements

Pavement joints were instrumented in a manner similar to the laboratory slabs to measure deflection as the vehicle approached, crossed, and departed from the joint. Pavement joint openings were measured in the manner described for laboratory slabs. On pavements that had been in service before testing, the first caliper measurement between joint plugs was not made at zero opening. Distances between joint faces at this initial reading were determined by an optical comparator.

MATERIALS

Foundation for Laboratory Slabs

Subgrade—To provide a subgrade for the specimen pavement slabs, a silty-clay soil was compacted in each base box to a depth of 2½ ft. Gradation and moisture-density relations of the subgrade soil are shown in Figure 7. The soil was compacted in 6-in. lifts to standard conditions, as determined by AASHO Method T99 or ASTM Method D 698. Each time a new subbase and slab was placed, the subgrade was reprocessed, thus assuring a uniformly low bearing value subgrade for each test. The average bearing value, k, measured with a 24-in. diameter plate at 0. 05-in. deflection, was 89 lb/sq in. /in. (pci). The prepared subgrade was covered with a sheet of polyethylene to restrict loss of moisture.

Subbase—Two types of subbase were used, a sand-gravel and a cement-treated material. The gradations and moisture-density relations of these materials are shown in Figure 7.

The subbase materials were mixed in a pug mill. The nonplastic sand-gravel was placed at standard conditions as specified by AASHO Method T99 or ASTM Method D 698. The cement-treated material was mixed with 5. 5 percent cement by weight and 11 percent water. The cement requirement was determined using ASTM Procedures

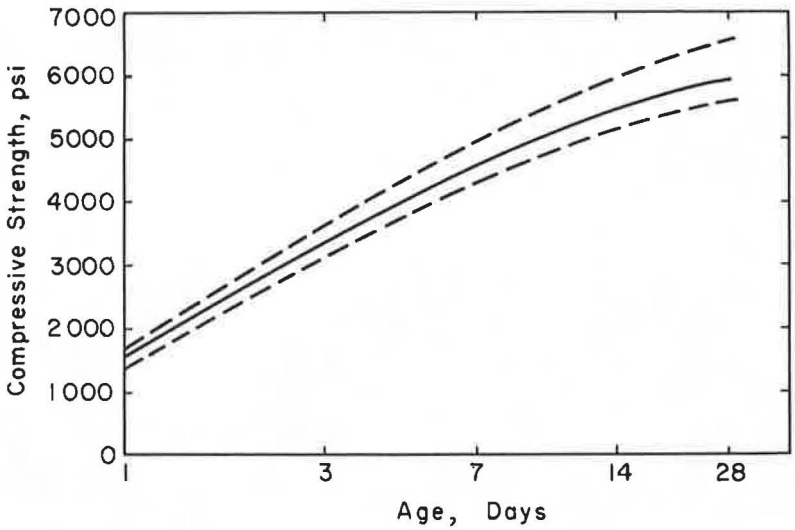


Figure 8. Concrete strength.

D 559 and D 560 and the Portland Cement Association criteria for weight loss (3). The moisture-density relationship was determined using ASTM Method D 558.

The subbase materials were compacted to 100 percent of standard density using a mechanical tamper and a vibrating sled. All subbases had a compacted thickness of 6 in. and, to restrict moisture loss, were covered with a sheet of polyethylene. This also reduced friction on the foundation and aided in adjusting joint width.

The bearing value, k, was measured using a 24-in. diameter plate. The average bearing value of the sand-gravel subbase was 145 pci and that of the cement-treated subbase measured at age seven days was 452 pci.

Laboratory Pavements

Concrete Slabs—The slabs were 46 in. wide and 18 ft long with a transverse joint at the midpoint. The maximum aggregate size in the concrete was 1½ in., the cement factor was 6 sk per cu yd, water-cement ratio 0. 50, slump 2. 5 to 3. 5 in., and air content 4 to 5 percent. Prior to load testing, the concrete was cured for 14 days under polyethylene sheets. The 14-day compressive strength of the concrete averaged 5, 500 psi. In Figure 8 the average age-strength relationship of the concrete is shown by the solid line and the dashed lines represent the range of extreme values.

Two aggregates were used in the concrete. One was a natural gravel with subrounded to rounded particles. It consisted of about 55 percent siliceous materials that

TABLE 1

PHYSICAL CHARACTERISTICS OF CONCRETE AGGREGATES

Test	Natural Gravel	Crushed Stone
Absorption (24 hr), percent	2. 0	2. 4
Bulk, specific gravity (s. s. d.)[a]	2. 67	2. 65
Unit wt (dry rodded), lb/cu ft	107	105
Abrasion (L. A. method)[b], percent	28	24

[a]Saturated, surface dry.
[b]ASTM designation C 131.

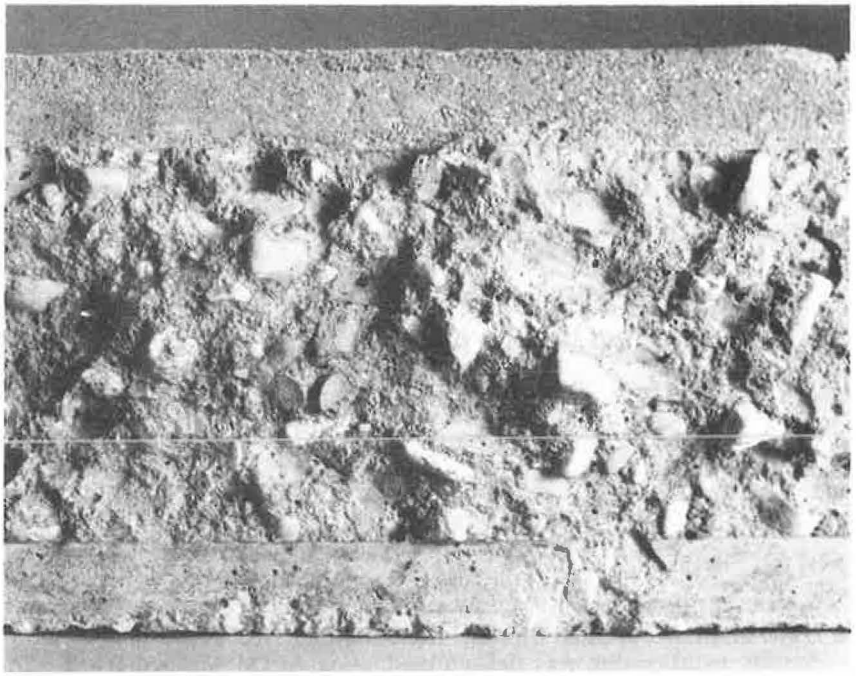


Figure 9. Joint interface.

include quartzite, feldspar, and a variety of igneous and metamorphic rock types. This material was crushed and recombined to the same gradation as the natural gravel for a study of the effect of particle shape.

The second aggregate was a crushed stone with angular particles that consisted of 65 percent dolomite and 35 percent siliceous materials. Both aggregates had the same gradation. Physical characteristics of the aggregates are given in Table 1.

Test Joints—Joints were of the plane-of-weakness type where load transfer is achieved solely by aggregate interlock. A removable parting strip of 20-gage galvanized metal of 1-in. height was supported transversely on the foundation at the joint location. While the concrete was plastic, a groove 1 in. in depth was formed in the surface of the slab directly over the metal strip. Thus a vertical joint was assured and angle of fractured face was not a variable. The slab was cracked in the weakened plane to its full depth with minimum disturbance to the foundation the day after casting by loading at the joint while applying tension to the slab ends. This method of making a joint produced a roughened interface depth of 5 in. for the 7-in. thick slabs, and 7 in. for the 9-in. thick slabs. The depth of fractured face was slightly less than that usually formed in highway pavements. The texture of a joint interface after completion of testing is shown in Figure 9.

TEST PROCEDURES

Program and Measurements for Laboratory Study

Specimens were prepared for testing by setting the selected joint opening, seating the rams on the loading plates, and programming the load application equipment to apply the desired repetitive load. Data obtained prior to the start of repetitive loading and at regular intervals throughout the test were: (a) joint opening; (b) deflections of both the loaded and unloaded slabs produced by a static load of 9 kips applied successively to the approach and departure slabs; and (c) deflections of the slabs produced by applying a dynamic loading cycle of the programmed magnitude.

TABLE 2

FIELD MEASUREMENTS OF JOINT OPENINGS

Location	Joint Spacing (ft)	Maximum Opening (in.)
Michigan	10	0.06
Michigan	20	0.08
California	15	0.03
Oregon	15	0.06
Kentucky	20	0.05
Missouri	25	0.07
Minnesota	15	0.07

Repetitive loading was initiated 15 days after the concrete slab was cast. About 50,000 loads were applied daily in a 22-hr period. During the remaining 2 hr, static load test data were obtained and routine maintenance was performed on the equipment. The program of repetitive loading and data recording was continued until deflection data showed no load transfer or until one million cycles had been applied.

A series of special tests was conducted on several of the joints after completion of routine testing. Load-deflection tests were made as the joints were progressively closed in increments of 0.005 in. with 1000 cycles of repetitive load applied at each joint opening. This was continued until no further reduction of joint opening could be obtained.

The tightly closed joint was then progressively opened in increments of 0.01 in. and the sequence of repetitive loading and load-deflection tests repeated at each joint opening. This was continued until effectiveness was reduced to zero or until the width of joint opening was 0.10 in.

The laboratory test procedure subjected a joint to loading conditions more severe than those encountered in the field. The action of the specimen slabs, though similar, did not duplicate the action of concrete pavements in service; deflections measured in the laboratory exceeded deflections measured at similar joints in the field. Principal reasons for the differences were: (a) the specimen slabs, being only 46 in. wide, did not have as large a resisting cross section; (b) the height of roughened interface was about 0.5 in. less for the 7-in. slabs and 0.25 in. less for the 9-in. slabs; (c) joint opening was held constant in the laboratory, whereas in the field there are cycles of opening and closing; (d) laboratory loads were applied at a rate of 40 applications per minute, so that the pavement and foundation had little time to recover between load applications; (e) the age of concrete was less than 60 days for these tests and strengths may have been slightly less than those for pavements of much greater ages; and (f) the subgrade k-value was deliberately low to represent a poor field subgrade condition. Because of these factors it is considered that the laboratory data were conservative.

Evaluation of Load Transfer

Ability of a slab to carry load is normally evaluated by computing stresses from measured strains. Other suitable responses are subgrade pressure and slab deflection.

When a wheel load at a slab end is resisted in part by an adjacent slab there is asymmetric loading. The slab under the wheel is loaded by direct bearing, while the adjacent slab is loaded by shear in the load transfer mechanism. Therefore, corresponding areas of the two slabs do not experience similar stresses, and readings from symmetrically placed strain gages are not comparable.

Pressure comparisons are likewise unsatisfactory. In addition to the need for meter installation at the time of construction, valid readings can be made only during periods when the slab ends are flat on the subgrade to preclude any downward movement not sensed by the meter.

Ability to transfer load across the joint in this study was evaluated by comparing deflections of the two slabs. As these slabs were in identical environments, temperature and moisture affected each similarly and subgrade reaction modulus also was essentially

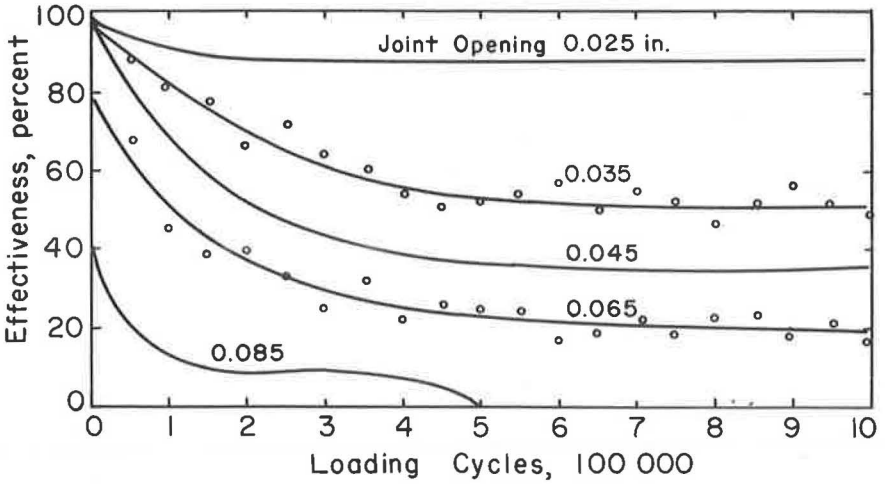


Figure 10. Influence of joint opening on effectiveness, 9-in. concrete slab, 6-in. gravel subbase.

the same. Lack of complete transfer or, in this study, looseness of interlock resulted in larger deflections of the slab under plate load than those of the adjacent slab.

Load transfer effectiveness was rated using a method devised by Teller and Sutherland (4). In this method, joint effectiveness, E, is computed using the formula

$$E\ (\%) = \frac{2\,d_j'}{d_j + d_j'}\,(100) \qquad (1)$$

where d_j' is the deflection of the unloaded slab and d_j is the deflection of the loaded slab. If load transfer at a joint were perfect, the deflections of the loaded and unloaded slabs would be equal and the effectiveness would be 100 percent. If, however, there were no load transfer at a joint, only the loaded slab would deflect and the effectiveness would be zero. All effectiveness values are computed from measured deflections obtained with a 9-kip static load applied to the approach slab.

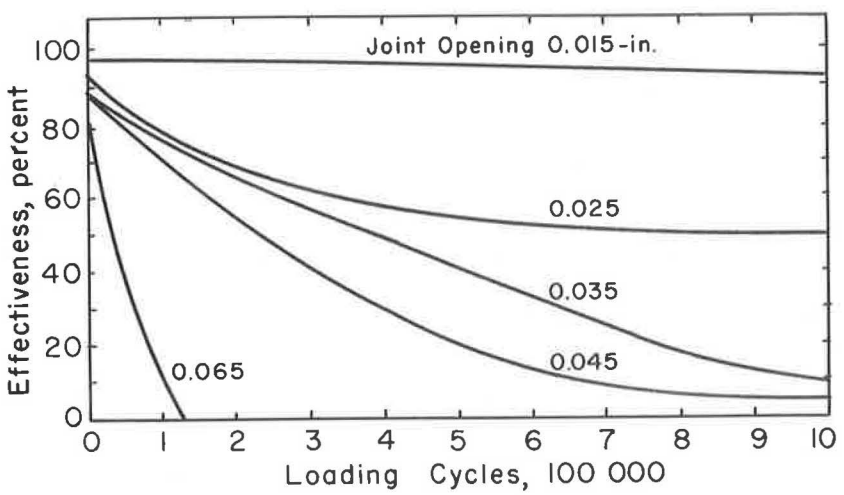


Figure 11. Influence of joint opening on effectiveness, 7-in. concrete slab, 6-in. gravel subbase.

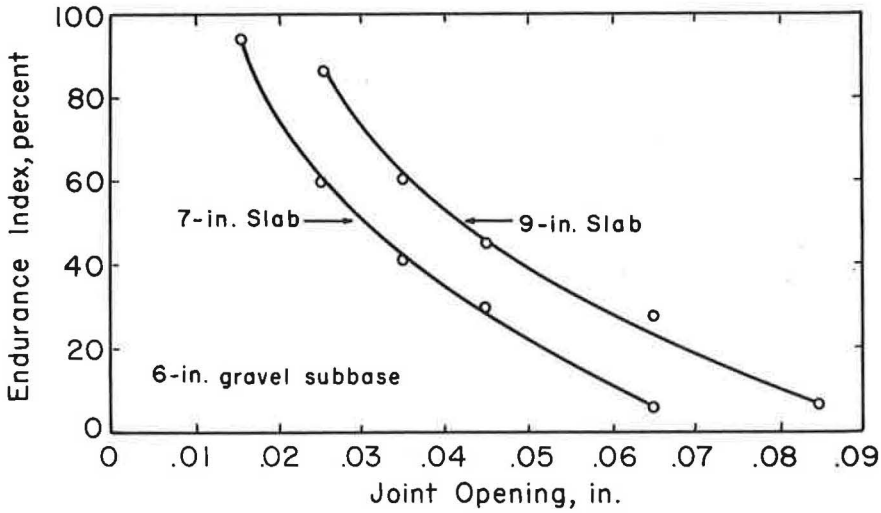


Figure 12. Influence of joint opening on endurance index.

Tests to determine effectiveness were made at intervals of 50, 000 load applications. Data are reported in plots of computed joint effectiveness against number of load cycles. A summary statistic of joint performance called the endurance index (EI) was developed. This index is expressed in percent and is obtained by dividing the area under the curve of effectiveness vs cycles by the area that would be developed if the joint retained an effectiveness of 100 percent throughout one million load applications.

PRESENTATION AND DISCUSSION OF DATA

Data are presented on the effectiveness and endurance of aggregate interlock as a means of providing load transfer at a joint. Variables evaluated independently are joint opening, strength of foundation, load, and shape of aggregate. The effect of slab thickness on load transfer is included as a portion of the discussions under joint opening and strength of foundation.

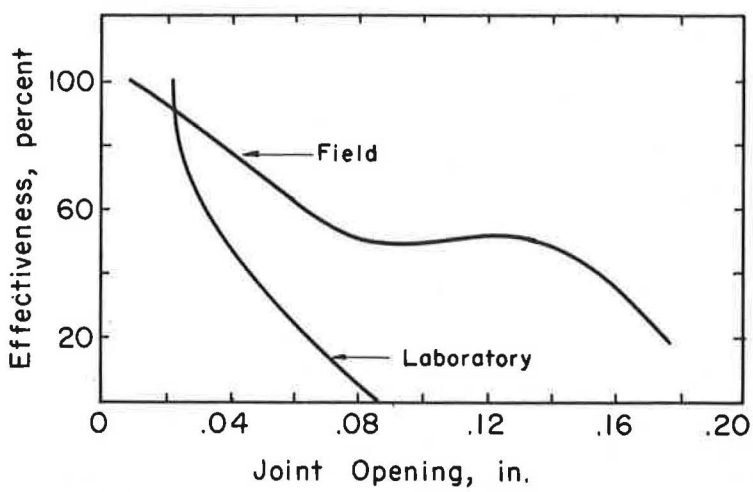


Figure 13. Comparison of field and laboratory data.

Influence of Joint Opening

When expansion joints are used only at structures or are widely spaced, the opening of a contraction joint depends primarily on spacing between joints and environment. Data in Table 2 are measurements on pavements in service of joint openings over a 10-year period (5) showing the relationship between maximum opening, spacing, and geographical location. Based on these data, joint openings selected for test in the laboratory ranged from 0.015 to 0.085 in.

A 9-kip repetitive load was used to evaluate the influence of joint opening on effectiveness. Curves for 9-in. slabs on 6-in. gravel subbases are shown in Figure 10. Data points are shown on the curves for joint openings of 0.035 and 0.065 in. There was only minor scatter in the data and for simplicity the points for remaining curves are omitted. It is seen that effectiveness decreased as the joint opening became wider. Effectiveness also decreased with additional load applications, although more than 90 percent of the decrease occurred during the first 500,000 repetitions. A similar trend is observed for the data in Figure 11 obtained for 7-in. slabs. In Figure 12, these data are summarized as a plot of endurance index vs joint opening. It is seen that the EI decreased as joint opening increased. The effect of slab thickness on effectiveness can be observed by comparing joint openings at equal EI values. For example, at an EI value of 60 percent the openings in the 7- and 9-in. slabs were 0.025 and 0.035 in., respectively, and at an EI of 5 percent the openings were 0.065 and 0.085 in., respectively. This tendency for the difference between openings to increase as the EI decreased was noted throughout the range of testing and demonstrates the advantage of a thicker slab at wider openings.

Deflection data obtained from tests on in-service pavements using the PCA mobile laboratory equipment were reduced in the same manner as those from laboratory studies. The field pavements were from 4 to 21 years old and were located in six states with climatic features varied from Wisconsin to Florida. The pavements were 9 in. thick with joint spacing ranging from 15 to 30 ft and were placed on granular subbases, with k-values ranging from 120 to 190 pci. A comparison of effectiveness ratings between laboratory and field is shown in Figure 13.

The laboratory effectiveness values were taken from Figure 10 at 500,000 load cycles. It should be noted that the plot would not vary significantly if the values selected had been for one million load cycles. Complete traffic records were not available for the field projects but it is reasonable to assume that the pavements had carried between 300,000 and two million applications of a 9,000-lb wheel load. The field data showing openings larger than 0.08 in. were obtained on pavements with 30-ft joint spacing located in an area having large variations in temperature.

The comparison shows that laboratory effectiveness values were considerably less than those obtained from field data. Previously it was indicated that the laboratory loading procedure was more severe than field loading. A portion of the difference in performance is due to daily and seasonal changes in joint openings. For example, a joint that is open 0.08 in. on a winter day may be open only 0.02 to 0.05 in. for a large portion of the year. In this case only a small percentage of the loads would be applied to the joint when the opening was maximum in contrast to the laboratory loading procedure where all loads were applied at the same opening. This aspect of joint design can be considered by applying proper weight factors to traffic and joint opening data for the geographical area under consideration.

The effect of joint opening and closing on the fit between worn aggregate particles in the fractured faces of the joint is also important to load transfer. This factor was investigated by special tests on several laboratory slabs after completion of routine loading. The data in Figure 14 were obtained from a 9-in. slab on a gravel subbase. The slab had received one million 9-kip load applications at a joint width of 0.065 in. At the end of routine testing, joint effectiveness was 19 percent. At this time the opening was closed in increments of 0.01 in. to the smallest width that could be obtained. To aid closing and create wear at the joint, one thousand load applications were applied after each increment of closure. At the smallest opening, effectiveness had increased to 100 percent.

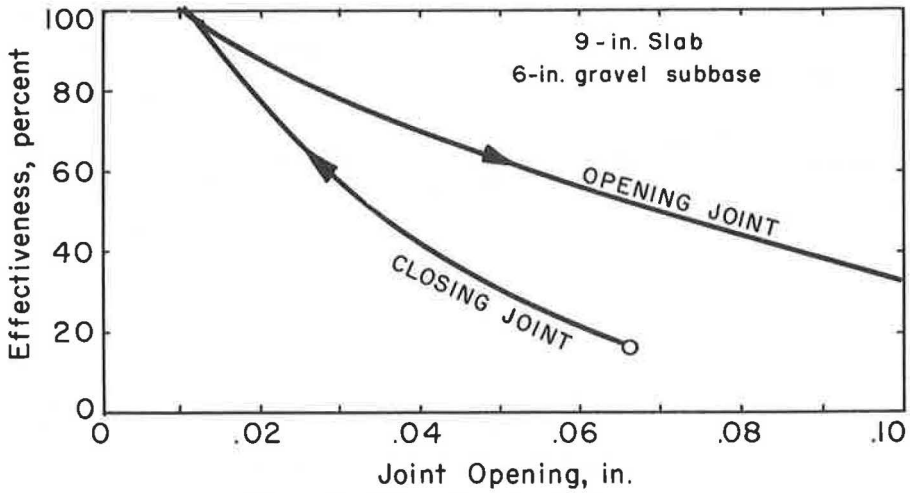


Figure 14. Effect of varying joint opening.

After reaching minimum closure, the same technique was followed as the joint was reopened in increments to a maximum width of 0.1 in. Although effectiveness decreased during reopening, the rate of decrease was low and at an opening of 0.065 in. effectiveness was 52 percent. This is in contrast to 19 percent at the end of routine testing. Furthermore, at an opening of 0.1 in. effectiveness was 32 percent.

Influence of Foundation Support

Three materials were used to investigate the influence of foundation support on load transfer effectiveness and endurance. The materials were: (a) a clay subgrade with k = 89 pci; (b) a gravel subbase with k = 145 pci; and (c) a cement-treated subbase with k = 452 pci. All slabs were tested with a 9-kip repetitive load. Effectiveness data are shown in Figure 15 for 7- and 9-in. slabs with joint openings of 0.035 in. on clay subgrades. Effectiveness at the end of one million load cycles was 5 and 29 percent, respectively. As a basis of comparison, effectiveness values at this opening on the granular subbases,

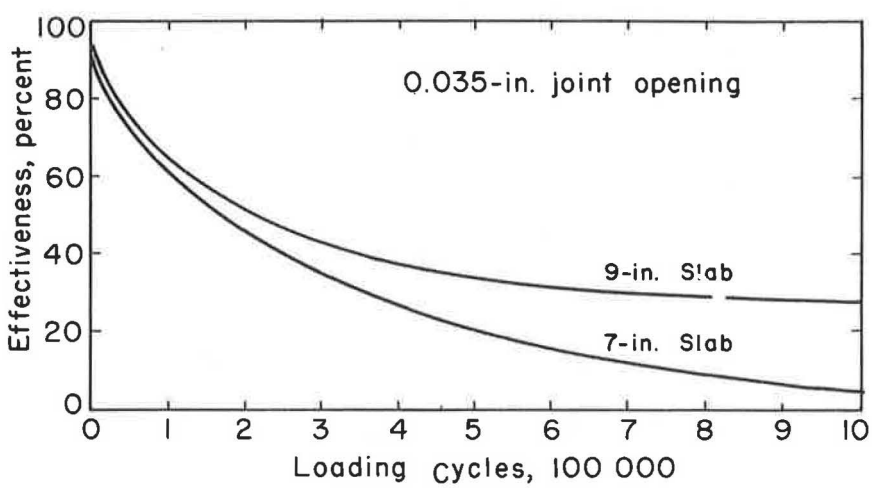


Figure 15. Effectiveness of joints in slabs on clay subgrade.

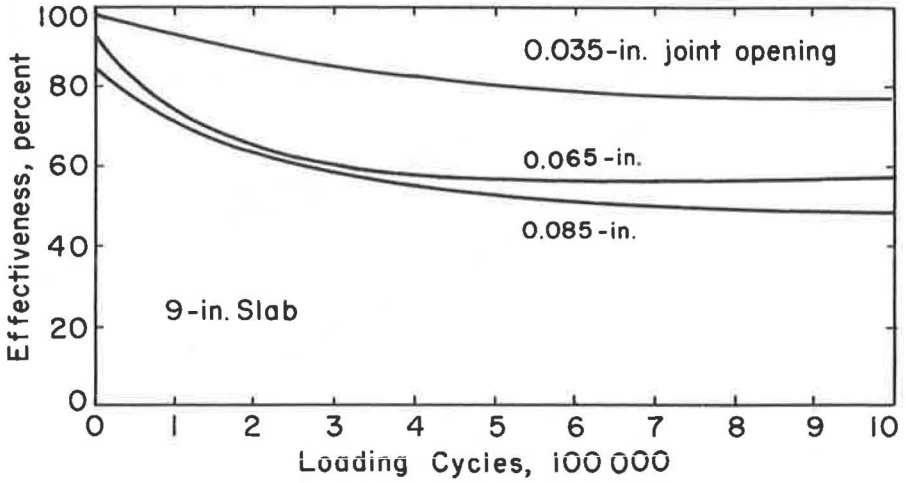


Figure 16. Effect of cement-treated subbase.

reported in Figures 10 and 11 for 7- and 9-in. slabs, were 9 and 50 percent. It is apparent that the added stiffness of the 9-in. slab contributed significantly to the aggregate interlock of the slab on a clay subgrade.

Joint effectiveness was further increased when slabs were placed on a 6-in. cement-treated subbase. This is demonstrated by test results shown in Figure 16. These data are for 9-in. slabs with joint openings of 0.035, 0.065, and 0.085. End values of effectiveness corresponding to these openings were 77, 57 and 50 percent. In contrast, effectiveness values on the granular subbase were 50 and 19 percent, respectively, for the 0.035- and 0.065-in. openings. Furthermore, effectiveness for the 0.085-in. joint opening tested on the gravel subbase was zero after only 500,000 load cycles.

The test results are summarized in terms of the endurance index in Figure 17. All data are for joint openings of 0.035 in. It is seen that as the k-value of the foundation was increased from 90 to 450 pci, the endurance index was increased about 2.6 times for the 7-in. slabs and about 2 times for the 9-in. slabs.

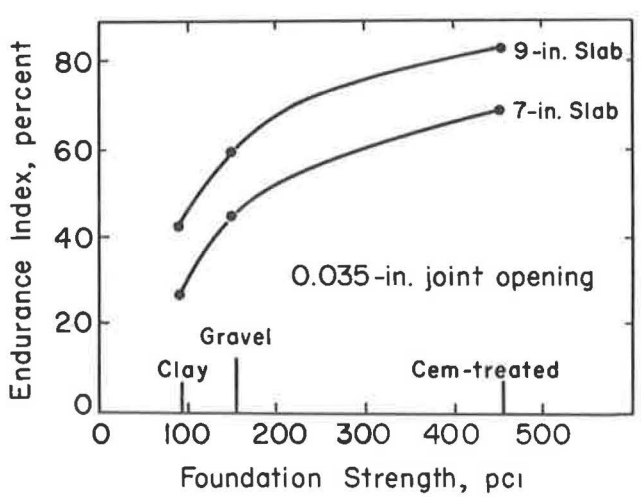


Figure 17. Effect of foundation strength on endurance index.

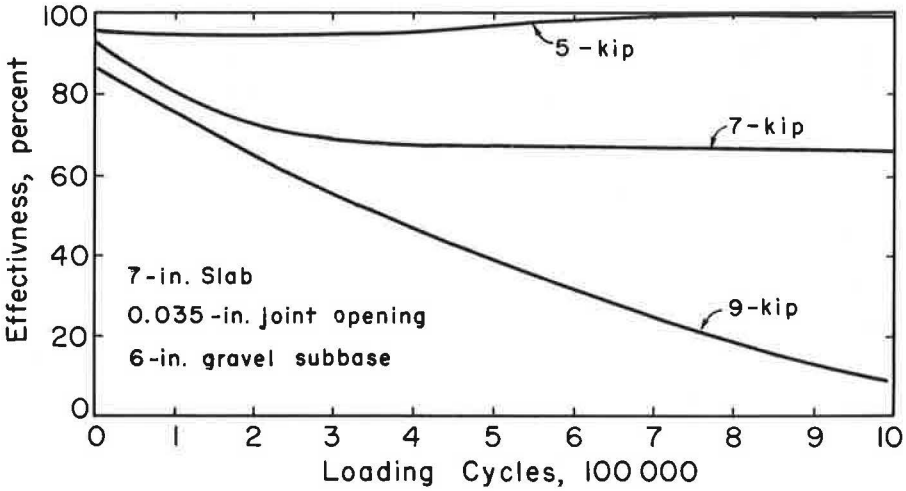


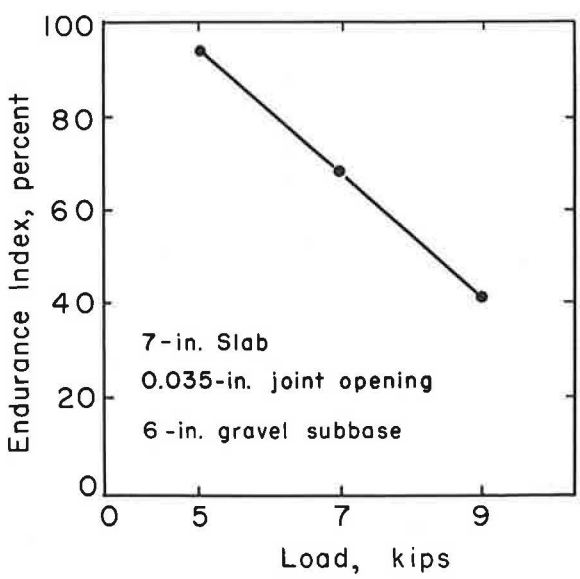
Figure 18. Influence of load on effectiveness.

Influence of Load Magnitude

The influence of load on joint effectiveness is shown in Figure 18. The data are for 7-in. slabs on gravel subbases with joint openings of 0.035 in. Prior to repetitive loading the effectiveness of the three joints was about the same, ranging from 87 percent to 95 percent.

Significant differences in effectiveness developed under the action of repetitive loading and became more pronounced as the test continued. After 500,000 loading cycles, the effectiveness of the joints tested with the 5-, 7-, and 9-kip repetitive load was 96, 68, and 39 percent, respectively. After one million loading cycles the effectiveness values were 98, 65, and 9 percent. These data indicate that effectiveness decreased as the magnitude of load was increased. At the end of routine testing, one million additional load cycles were applied to the slab tested with the 5-kip load and there was no further change in effectiveness. This is significant as it suggests that light loads cause little or no wear and probably do not need to be considered.

Figure 19. Effect of load on endurance index.



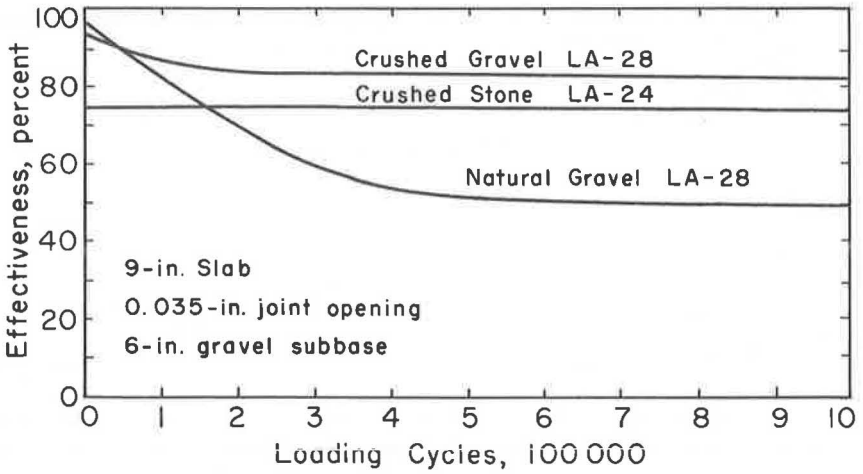


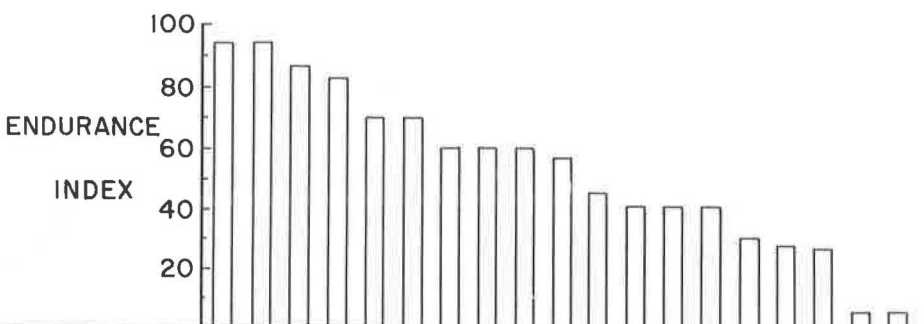
Figure 20. Influence of aggregate shape on joint effectiveness.

As shown in Figure 19, the effect of load on endurance index was linear. The endurance index decreased as the load was increased.

Influence of Aggregate Shape

The influence of aggregate shape on effectiveness is shown in Figure 20. These curves were obtained from tests on 9-in. slabs with 0.035-in. joint opening placed on gravel subbases.

The data shown in the bottom curve were taken from Figure 10. The coarse aggregate used in this test slab was a rounded natural gravel with a Los Angeles abrasion value of 28. The data shown in the middle curve were obtained from a slab cast with crushed stone coarse aggregate that had a Los Angeles abrasion value of 24. The gradation of the crushed stone was the same as the gradation of the natural gravel. Comparing these data, it is seen that joint effectiveness values for the crushed stone were larger than values for the gravel. Although the two aggregates had slightly different



Joint Opening	15	35	25	35	35	35	35	65	25	85	45	35	35	65	45	65	35	65	85
Slab Thickness	7	7	9	9	7	7	9	9	7	9	9	9	7	7	7	9	7	7	9
Foundation	G	G	G	CT	CT	G	G	CT	G	CT	G	C	G	CT	G	G	C	G	G
Repetitive Load	9	5	9	9	9	7	9	9	9	9	9	9	9	9	9	9	9	9	9

Figure 21. Equivalence of performance.

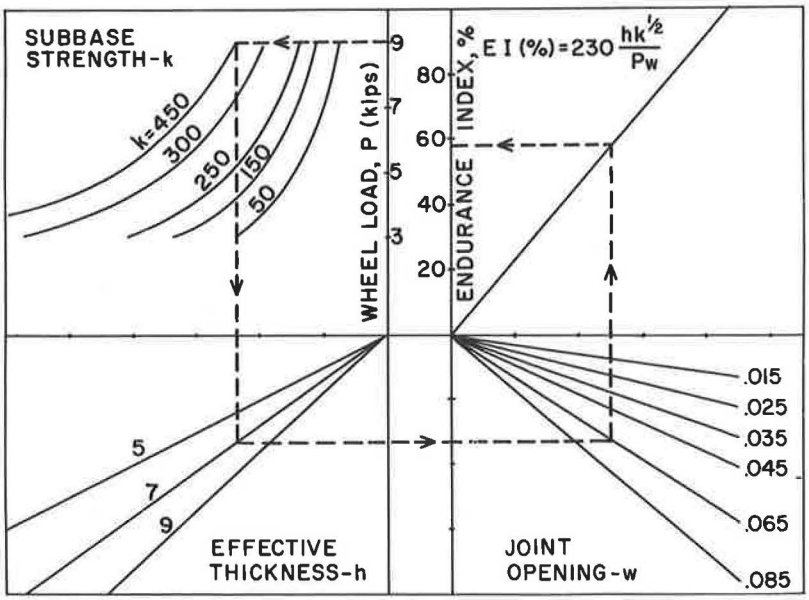


Figure 22. Endurance of joints.

properties, the higher effectiveness of the crushed stone was attributed to its angularity. To check this observation, effectiveness data were obtained for a third slab shown by the top curve. The coarse aggregate for this slab was the natural gravel after being crushed and recombined to its original gradation. In this case the only variable was the shape of the coarse aggregate and joint effectiveness was increased from 50 to 84 percent. Thus, for the same hardness, effectiveness was increased with increased angularity of the coarse aggregate.

EQUIVALENCE OF PERFORMANCE

Data summarized in Figure 21 can be used to show equivalence of performance. It is seen that bars of equal height indicate slabs with equal endurance index values. The variables are joint opening, slab thickness, type of foundation, and magnitude of load. Under the heading of foundation, designations are G for gravel subbase, CT for cement-treated subbase, and C for clay subgrade.

Two designs were equivalent at an endurance index of 70. Each was a 7-in. slab with a joint opening of 0.035 in. However, one slab was supported on a cement-treated subbase and the other on a gravel subbase. It is seen that the additonal foundation strength provided by the cement-treated subbase increased the load capability of the joint by 2 kips.

Numerous other comparisons can be made; however, to summarize the test results, an equation was developed by regression analysis. This equation relates endurance index to the significant variables included in the test program. It includes only data obtained from the rounded natural gravel. The equation is

$$EI = 230 \frac{h}{Pw} \sqrt{k} \qquad (2)$$

where

h = depth of roughened interface, in.,
k = foundation modulus, pci,
P = wheel load, lb, and
w = joint opening, in.

Figure 22 is a nomograph developed from Eq. 2. A solution by the use of the nomograph is illustrated by following the arrows. Starting with a 9,000-lb wheel load and proceeding horizontally to a k of 450 pci, vertically to an effective thickness of 7 in., and horizontally to a joint opening of 0.065 in., it is seen that the endurance index is 58.

The equation has a standard error of estimate of 9.2 percent and a coefficient of correlation of 90 percent.

SUMMARY

Load transfer across transverse joints in concrete pavements through shear in the aggregate interlock was investigated. Two laboratory devices applied repetitive loads alternatively on the two slabs separated by the test joint. Load interval and frequency were programmed to simulate the movement of tandem axles of highway vehicles. Validity of simulation was established by field tests with the PCA mobile laboratory.

The ability of a joint to transfer load was established by its effectiveness. The ability to retain this effectiveness under load repetitions was labeled the endurance index.

The following trends were observed:

1. When test load, slab thickness, and subbase were held constant, joint effectiveness decreased as the joint opening was increased.
2. When these conditions prevailed and joint width was held constant also, effectiveness decreased with load applications but the rate of decrease became less with continued repetitions. Usually 90 percent of effectiveness loss occurred during the first 500,000 applications.
3. Effectiveness of a joint at a given opening was improved by closing the joint incrementally while subjecting it to limited repetitions before restoring the width to the stipulated value. This operation to study the effect of aggregate fit and attrition explains in part the good effectiveness values obtained for in-service highway joints that develop wide winter openings.
4. Joint effectiveness improved with foundation bearing value, k. Effectiveness of joints in 7-in. slabs on cement-treated subbases was 2.6 times that for slabs on clay subgrades. Cement-treated subbases doubled the joint effectiveness for slabs on clay subgrades when the concrete was 9 in. thick.
5. Experiments with 7-in. slabs on gravel subbases showed that the effectiveness values at 0.035-in. openings decreased continuously under 9-kip loading, reached a pleateau at 65 percent under 7-kip loadings, and remained close to 98 percent under 5-kip loadings. This is significant as it suggests that for each joint design, effectiveness is not influenced by loads less than a critical value.
6. For the same aggregate or for aggregates of the same hardness, effectiveness increased with increased particle angularity.

Endurance index was established as a suitable criterion for equivalence of joint performance. An empirical relation relating endurance index to slab thickness, subgrade k, load, and joint opening was developed and placed in nomograph form.

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