perimental project is not subject to the
lume increase with age noted in many
her pavements. Joint movements follow
mperature changes fairly consistently, but
e correlation between joint movement and
infall, while probably present, is masked
the greater temperature movement.
ere has been a progressive opening of
ntraction joints. With each successive
mperature maximum, the joint closure
s been less complete.

Concrete temperatures follow air tempera-
res with a considerable lag in time. Tem-
ratures at the top of the slab show much
der fluctuations than at the bottom. The
mperature gradient is steeper when the top of the slab is hotter than the bottom than when the gradient is reversed. There is some evidence that the bottom part of the slab had not dried out to any great extent during the first year. There also seems to be a concentration of moisture at the plane between the slab and the subgrade.

Spalling at contraction joints has taken place due to displacement of the felt strips by the finishing machine. The need for great care in placing these strips and maintaining them in position during the placing and finishing of the concrete is emphasized. The two cracks that have occurred in the project do not appear to be related to any particular joint spacing or joint type.

STRUCTURAL EFFICIENCY OF TRANSVERSE WEAKENED-PLANE JOINTS

By Earl C. Sutherland, *Senior Highway Engineer* and Harry D. Cashell, *Associate Highway Engineer, Public Roads Administration*

SYNOPSIS

As part of the cooperative studies of the effects of varying the spacing of expansion joints in pavements containing closely spaced weakened-plane contraction joints, the Public Roads Administration conducted some special tests to determine the ability of the joints of the weakened-plane type to reduce critical load stresses These tests were made on six concrete test sections, each 30 ft long, 20 ft. wide and of 8-in. uniform thickness. Each section was divided longitudinally by a deformed metal center joint having ⅝ in diameter tie-bars at 60-in. intervals and transversely by a weakened-plane joint of a specific design. The technique of testing to determine the efficiency of the various joints was similar to that used in previous studies, that is, the critical strain was measured for a load of given magnitude acting successively at selected points at the joint edges, free edges and interiors of the panels of a section

Information was obtained on the structural behavior of weakened-plane joints as affected by. (1) type of coarse aggregate, (2) maximum size of coarse aggregate, (3) presence or absence of dowel bars, (4) method of producing fracture at the joint, (5) compressive forces acting to close the joint, and (6) width of joint opening

Briefly, the data obtained from this study indicate that (1) on the whole, all of the joints were more effective in controlling critical corner-load stresses than they were in controlling critical edge-load stresses, (2) in the presence of compression between the joint faces, all of the joints were effective in reducing critical stresses at both the edges and the corners, (3) without compression between the joint faces, aggregate interlock is an uncertain means of stress control regardless of type and size of coarse aggregate, (4) the presence of dowels improved the control of critical edge stresses to a limited extent but very definitely aided the control of of corner stresses, and (5) the presence of dowels greatly improved uniformity in stress reduction from point to point along the joint edge

For some years it has been recognized that the formation of transverse cracks in concrete pavements can be eliminated only by the introduction of closely spaced transverse joints. Consequently, there has been a gradual trend toward decreased slab lengths and, in the past 15 years, toward the use of transverse weakened-plane or dummy joints as a means of dividing the pavement into slabs of short lengths.

Early in 1940 the Public Roads Administration sponsored a comprehensive, cooperative experimental investigation for the primary purpose of studying the effects of varying the spacing of expansion joints in pavements containing closely spaced weakened-plane contraction joints. Incidental to this investigation, some questions arose regarding the ability of joints of the weakened-plane type to transfer load and thus to control critical stresses caused by loads acting in their immediate vicinity. Previous research on the subject indicated that aggregate interlock as it occurred in such a joint separating two 20-ft. slabs could not be depended upon to control load stresses.[1] For example, the efficiency of the joint, as determined by strain measurements, was negligible in the winter when the maximum annual width of joint opening existed as a result of contraction of the abutting slabs. Furthermore, even in the summer when the width of opening was a minimum, the stress-reducing ability of the joint was questionable, varying from point to point along its edges due to the irregular and sloping manner in which the pavement fractured beneath the parting groove. Similar tests on a weakened-plane joint containing ¾-in dowels spaced at 18-in. intervals showed a rather high average efficiency for all seasons of the year.

Inasmuch as the preceding tests were of limited scope and left unanswered certain questions, it was decided to include, as part of the cooperative investigation, a study of the structural efficiency of weakened-plane joints Specifically, the research was planned to determine the structural behavior of joints of this type as affected by. (1) type of coarse aggregate; (2) size of coarse aggregate, (3 presence or absence of dowel bars; (4) metho of producing fracture at the joint; (5) com pressive forces acting to close the joint; an (6) width of joint opening.

Referring to the previously-mentioned ea lier research on joints,[1] it was found tha deflection relations are not a measure of th stress conditions that accompany them Therefore, measurements of strain in th concrete are necessary in order to evaluat joints on the basis of their ability to reduc critical stresses caused by applied load Since these strain measurements are time consuming and because the pavement at th test site should be protected from change in temperature and moisture, this part of th investigation was conducted on test slab that were not subjected to traffic. How ever, data obtained from the study shoul furnish exact information relative to the initia efficiency of similar weakened-plane joint incorporated in pavements in actual servic The influence of traffic and other facto acting over a period of time to change th initial effectiveness of joints of this typ cannot, of course, be ascertained from thes tests

THE TEST SECTIONS

These special tests were made by the Publi Roads Administration on the concrete tes pavement shown in Figure 1. The pavemen was divided into six sections, each bein 30 ft. long, 20 ft. wide and of 8-in unifor thickness. Each section was definitely sep arated from those adjoining it, and wa divided longitudinally by a deformed meta center joint having ⅝-in diameter tie-ba at 60-in. intervals and divided transverse by a weakened-plane joint of specific desig Thus, each section was subdivided into fou panels, each 10 by 15 ft

At one end of every section, anchor bo assemblies, such as shown in Figure 2, we embedded symmetrically in the concrete, o on either side of the longitudinal joint, provide a means for attaching the apparatu used to control the opening of the weakene plane joints. Between sections 1–2, 3– and 5–6 a concrete block or deadman was co structed to provide the reaction whenev direct compression was applied to the sectio or whenever the joints were opened.

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[1] The Structural Design of Concrete Pavements, Part 4 By L W Teller and Earl C Sutherland *Public Roads*, Vol 17, Nos 7 and 8, September and October 1936

Figure 3 is shown the reaction block together with the apparatus comprising the push-pull system. When closing a joint the jacks exerted pressure directly on the end of the section containing the joint. When opening a joint the jacks were moved to the other side of the reaction block and exerted tension in rods attached to the anchor bolt assemblies of the section in question. The four hydraulic jacks employed in the system were equipped with pressure gages in order to measure the forces applied to the section and, also, to insure uniform forces on both sides of the longitudinal joint.

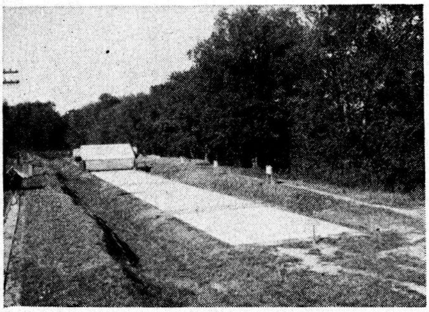

Figure 1. The full-size pavement slabs in which the weakened-plane joints were incorporated.

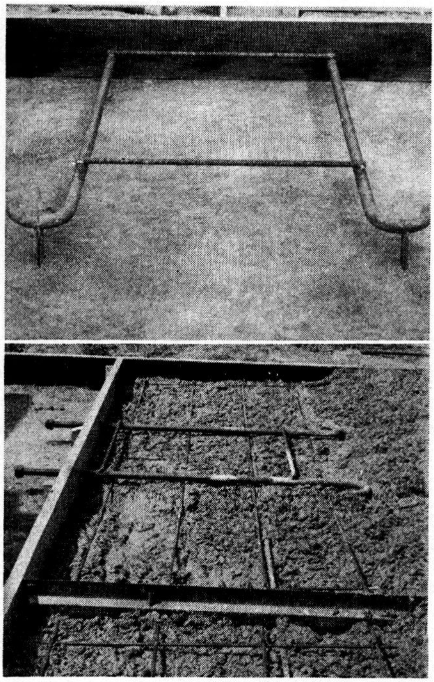

Figure 2. Anchor-bolt assembly for attachment of apparatus used in controlling the width of joint opening.

THE SUBGRADE

The test sections were laid in the late summer of 1940 on the site of an earlier experimental concrete pavement.[2] The soil underlying the earlier pavement was classified as a uniform brown silt loam (Class A-4). For these later tests, the character of the subgrade immediately beneath the new sections was altered by thoroughly mixing 4 in. of clean sand with the top 4 in. of the original soil. After blending, the material was then

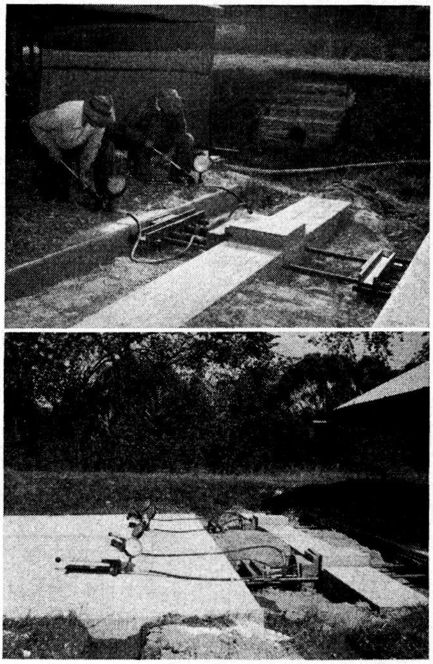

Figure 3. Apparatus used for applying compression and controlling the width of joint opening.
Upper—Closing a joint.
Lower—Opening a joint.
The section under test is covered by straw in each case.

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[2] "The Structural Design of Concrete Pavements," Part 1. By L. W. Teller and Earl C. Sutherland. *Public Roads,* Vol. 16, No. 8, October, 1935.

compacted at optimum moisture to an average dry density of 136 lb. per cu. ft. This modification of the subgrade soil had the effect of increasing the value of the modulus of subgrade reaction, as determined from load-deflection tests at the interior of the pavement, approximately 10 per cent.

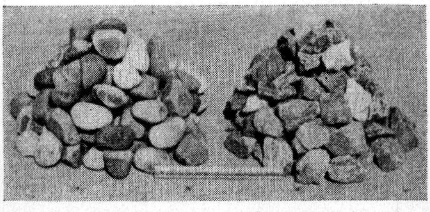

Figure 4. Larger size of coarse aggregate ($2\frac{1}{2}$-inch maximum size). Left, gravel. Right, crushed stone.

THE CONCRETE

In order to investigate the influence of type of aggregate on the structural efficiency of the joints, two coarse aggregates having widely different characteristics were used. One of the coarse aggregates was a siliceous gravel obtained from the Potomac River and the other was a crushed limestone obtained from near Frederick, Maryland. The gravel was typical of river gravels in that the edges of the individual pieces were well rounded and the surfaces were very smooth. The stone fragments had rather sharp angular fractures and relatively rough surfaces. The difference in character of the two aggregates is shown in Figure 4.

The effect of aggregate size was studied for both types of coarse aggregate. This was accomplished by limiting the maximum size of coarse aggregate to 1 in. in some sections and to $2\frac{1}{2}$ in. in others.

The program required the designing of four concrete mixes. For each, the cement was from the same source, the cement factor was approximately 6 sacks per cubic yard and the fine aggregate was a Potomac River sand having a fineness modulus of 2.7. In Table 1 are given data on the mix proportions, strength and other properties of the concrete. The average slump (17 tests) was $2\frac{1}{2}$ in. The flexure tests were made on 8- by 8- by 40-in. beams, the load being applied at the third points of a 24-in. span. Compression tests were made on 6- by 12-in. cylinders. All specimens were cured in the same manner as the test sections (as nearly as possible) and, until a few days before testing, were stored in the ground adjacent to the pavement. The modulus of elasticity values were determined from 6- by 12-in. cylinders which had been stored in the ground for 16 months.

TABLE 1
MIX CHARACTERISTICS AND STRENGTH PROPERTIES OF THE CONCRETE

Type of concrete	Coarse aggregate		Proportions by dry weight	Modulus of rupture		Crushing strength	Modulus of elasticity
	Type	Max. size (sq. opening)		28 days	17 months	28 days	16 months
		in.	*lb.*	*lb. per sq. in.*	*lb. per sq. in.*	*lb. per sq. in.*	*lb. per sq. in.*
I	Gravel	1	94:200:330	557	627	4,620	4,868,000
II	Gravel	$2\frac{1}{2}$	94:190:340	517	632	4,850	4,650,000
III	Stone	1	94:232:308	611	725	4,640	5,407,000
IV	Stone	$2\frac{1}{2}$	94:222:318	530	673	4,520	5,725,000

FEATURES OF THE WEAKENED-PLANE JOINTS

The details of the three types of weakened-plane joints incorporated in the six sections are shown in Figure 5. Types A and B are conventional joints. Type C is of special design having, in addition to a shallow surface groove, a bottom metal parting strip which is supposed to fracture the concrete in such a manner that load transfer will be developed to a more positive degree than is possible with the usual type of weakened-plane joint.[3] Figure 6 shows the bottom parting strip in place on the subgrade ready for the concrete to be cast.

In Table 2 are listed the features of each of the six weakened-plane joints. Examination of the table indicates certain comparisons in which only one variable is present. These are as follows:

1. Type of coarse aggregate.

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[3] This joint was developed by Messrs. L. I Hewes and William Bertwell.

   - A. Small gravel versus small crushed stone (joint 2 versus joint 5).
   - B. Large gravel versus large crushed stone (joint 3 versus joint 6).
2. Size of coarse aggregate.
   - A. Small gravel versus large gravel (joint 2 versus joint 3).
   - B. Small crushed stone versus large crushed stone (joint 5 versus joint 6).
3. Presence or absence of dowel bars.
   - A. Joint 4 versus joint 2.
4. Method of fracturing pavement.
   - A. Joint 1 versus joint 3.

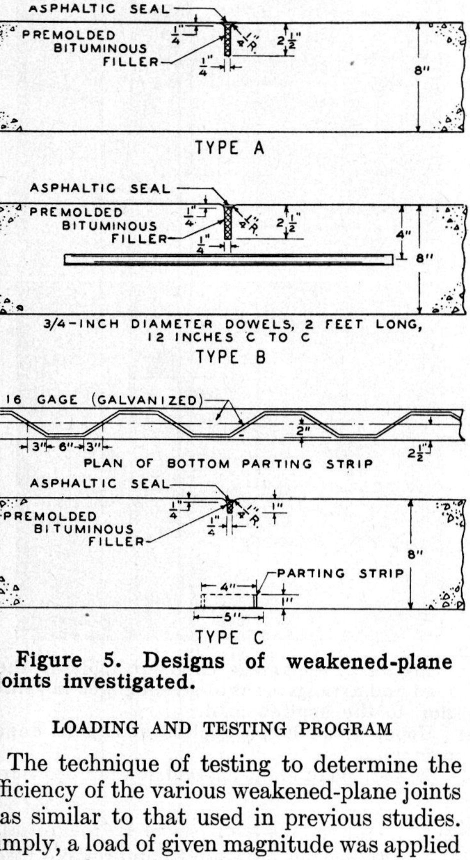

Figure 5. Designs of weakened-plane oints investigated.

LOADING AND TESTING PROGRAM

The technique of testing to determine the ficiency of the various weakened-plane joints as similar to that used in previous studies. mply, a load of given magnitude was applied ccessively at selected points at the interiors nd free edges of the panels of a section coniining a specific joint and at points along the lges of the joint. While this load was ting, the critical strain was measured in the pper surface of the slab. Critical strains cur directly under the contact area in the se of interior loading and, also, when a load is applied at the edges of a joint and at the free edges of a panel (but away from the corners). For a load acting at or near the outside joint corners and the free corners of a panel, critical strains occur along the bisector of the corner angle at some distance from the load.

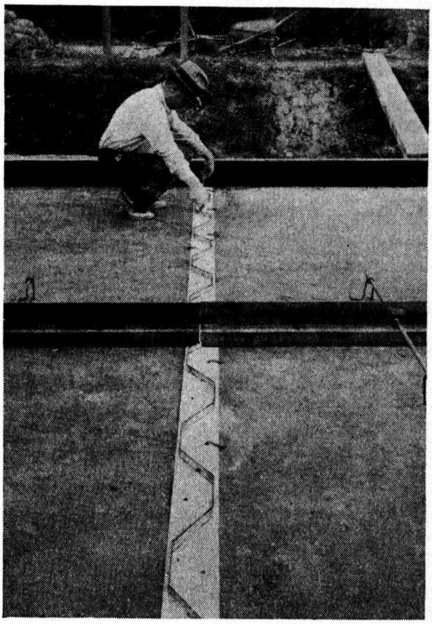

Figure 6. Base plate and bottom parting strip of Type C joint in place on the subgrade.

TABLE 2
FEATURES OF THE WEAKENED-PLANE JOINTS

Joint No.	Type of joint (see Fig. 5)	Coarse aggregate in adjacent slabs	
		Kind	Size
1	C	Gravel	Large
2	A	Gravel	Small
3	A	Gravel	Large
4	B	Gravel	Small
5	A	Crushed stone	Small
6	A	Crushed stone	Large

The points at which the loads were applied and the positions of the strain gages in relation to the load points are shown in Figure 7. At each of the indicated points, a load of given magnitude was applied to the surface of the pavement through an 8-in. steel circular bearing plate, the load being maintained for 5 min. before making strain measurements.

The magnitude of the load was measured by means of a dual-beam dynamometer. A sponge-rubber pad ½ in. thick was placed between the rigid plate and a previously prepared smooth surface. This surface was formed at each load point by seating the plate in a thin layer of plaster of Paris and then removing after the plaster had set. A large, cylindrical steel tank that transversely spanned the section provided, when partially filled with water, the necessary reaction for the vertical loads. Strains were measured at the positions indicated in the figure with a recording type of strain gage[4] installed between brass posts set into the upper surface of the concrete. The loading equipment and the method of measuring strains are described in detail in an earlier study of the structural behavior of concrete pavement slabs at the Arlington Experiment Farm.[2]

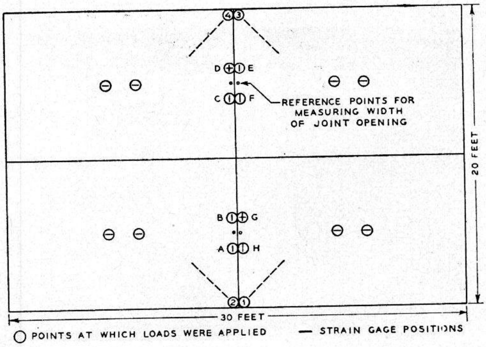

Figure 7. Plan of a 20- by 30-ft. test section, showing points at which loads were applied and strains measured.

Figure 8 shows the load being applied and the strain gages in place at the joint edge (upper) and the joint corner (lower) of one of the test sections. In the case of edge loading, it will be noted that the bearing plate is grooved to accommodate the strain gage. The straw covering observed in the figure extended over the entire section and remained in place during the testing period. In addition, the section was sheltered from rain and direct sunlight. These protective measures minimized moisture changes in the subgrade and temperature warping of the slab.

TESTING SCHEDULE

Testing of the various joints was conducted between June and October of 1941, or 10 to 14 months after the pavement was laid The testing schedule was essentially the same for each of the joints. Briefly, this schedule consisted of:

1. Measurement of the critical strain at the interiors of the 4 panels of a given section for a load of selected magnitud
2. Application of a total compressive forc of 120,000 lb. to one end of the section anc with the force acting, measurement of th critical strains at the joint edge points an at the joint corners.
3. Release of compressive force and mea urement of the critical strains at the joi for successive controlled widths of opening 0.037, 0.055, 0.073, 0.092, 0.110 and 0.220 i

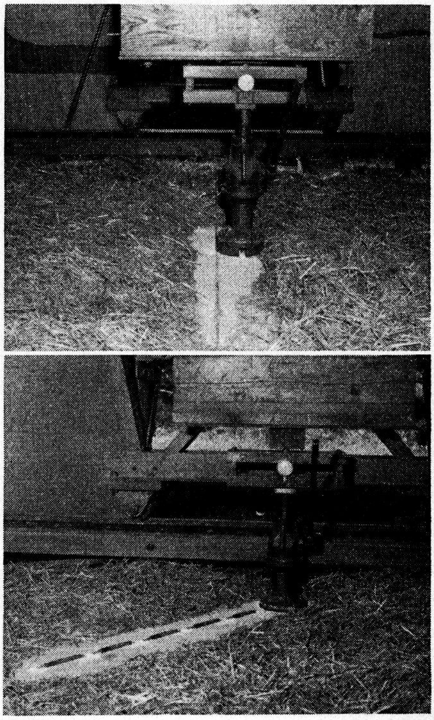

Figure 8. Apparatus used for applying the load and arrangement of strain gages in rela- tion to the applied load.

Upper—load being applied at a joint edge point.

Lower—load being applied at a joint corner

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[4] "An Improved Recording Strain Gage," by L. W. Teller. *Public Roads*, Vol. 14, No. 10, December 1933.

These are computed maximum joint openings which might occur during the annual cycle of temperature and moisture variations for slab lengths ranging from 10 to 60 ft. Initially, it was intended to measure strains both at the edge points and corners of the joints for each of the preceding openings; but, because of a time limit imposed by the necessity for vacating the site, the original schedule was curtailed. The schedule was reduced by obtaining strains at the edges of the joints for openings of 0.037, 0.055, 0.073 and 0.092 in.; and, with the exception of joint 2, at the corners for openings of 0.037, 0.073, 0.110 and 0.220 in.

4. Opening of the joint to a width of ½ in. and measurement of the critical strains at the edge points and corners. For this opening all effects of aggregate interlocking had disappeared and the edges of the joint were acting as free slab ends. In the case of the doweled joint, all dowels were cut before testing at this opening.

5. Remeasurement of the critical strains at the interiors of the panels.

Before presenting the results of this study, attention is called to the fact that the zero widths of the joints are the widths established when the joints were closed by the 120,000-lb compressive force. Prior to the application of this force, it was observed that, with the exception of joint 1, the joints were opened about 0.015 in. Under the compressive force the joints closed approximately 0.010 in.; thus, at the zero width there existed a residual opening of about 0.005 in. The base readings at the zero joint width and subsequent determinations of the widths of joint opening were obtained with a vernier caliper by measuring between gage plugs cemented into the surface of the slab (see Fig. 7).

EFFICIENCY OF THE JOINTS WITH A LOAD ACTING AT THE JOINT EDGE

Previous research has established that, for a slab of uniform thickness, the magnitude of the critical stress produced by a given load is minimum at the interior and maximum at the free edge. Consequently, in this investigation, the ability of the various joints to reduce stresses caused by a load acting at the joint edge, but away from the corners, will be determined by comparing the critical stress at the joint edge with that produced by the same load acting at the free end and at the interior of the slab.

From critical strains measured with the load acting at the aforementioned points, the efficiency of a joint may be computed by the equation:

$$E = \frac{\sigma_f - \sigma_j}{\sigma_f - \sigma_i}$$

in which E = joint efficiency,
σ_f = critical stress for a given load applied at the free end,
σ_j = critical stress for a given load applied at the joint edge;
σ_i = critical stress for a given load applied at the interior of the slab.

It will be noted that this equation indicates an efficiency of 100 percent if the critical stresses at the joint edge and at the interior are equal and, conversely, a joint efficiency of zero if the critical stress at the joint edge is equal to that of the free end.

In Figures 9, 10 and 11 are shown the relations between edge efficiency and width of joint opening for each of the six weakened-plane joints listed in Table 2. These relations are grouped in accordance with the comparisons given in connection with the discussion of Table 2. Referring to the efficiency formula, the value of σ_i for a given section is based on the average of the strains measured (both before and after testing the joint) at the eight interior points of the slab units (see Fig. 7). Similarly, the σ_j values and the value of σ_f for each joint are established from the strains measured successively at the eight joint edge points, A to H inclusive, the strains for σ_f being measured after the joint had been pulled apart ½ in.

The relations just presented show that efficiencies within the approximate range of 70 to 100 per cent were attained by the various joints at the zero width of joint opening or, in other words, when the 120,000-lb. compressive force was acting. If it is considered that the total force, used to close the joints, was uniformly distributed over the 5-½in. depth of the joint face below the parting grooves of joint types A and B, the average compression would be only 91 lb. per sq. in. This value might even be reduced slightly if the subgrade resistance were taken into account. Hence, it appears that all of the weakened-plane joints studied in this investigation attained high efficiency in the presence of interfacial pressure much less than might develop in pavements under conditions of restrained expansion.

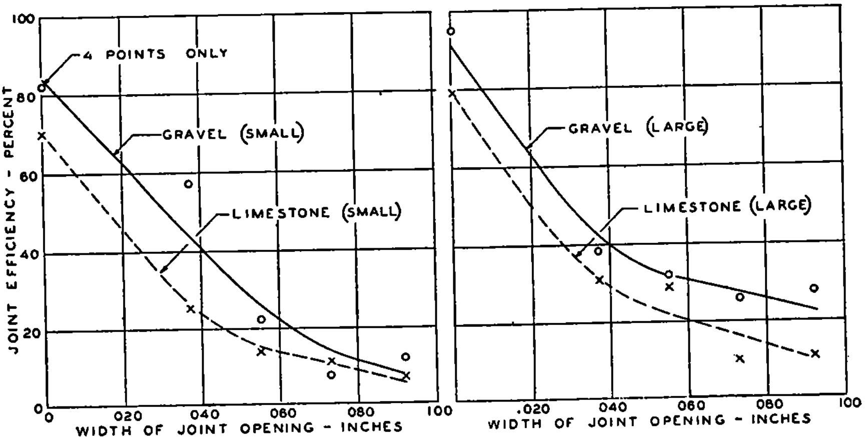


Figure 9. Effect of type of coarse aggregate on the relation between joint opening and joint efficiency as determined with edge loading. Each value is an average from tests at points A to H, inclusive.

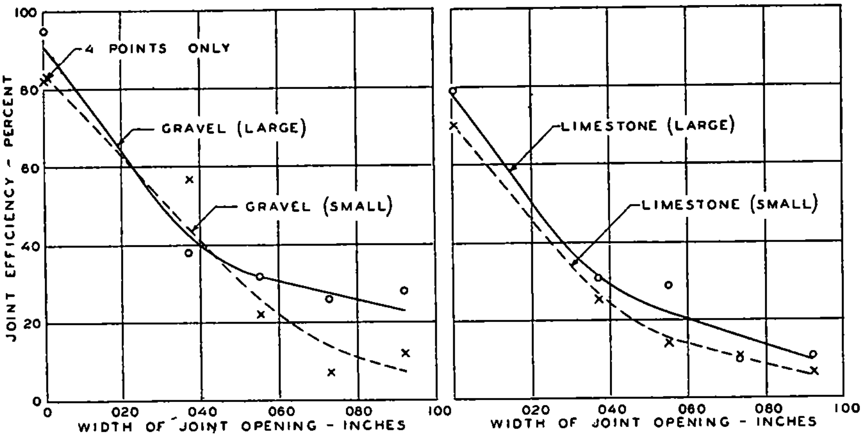
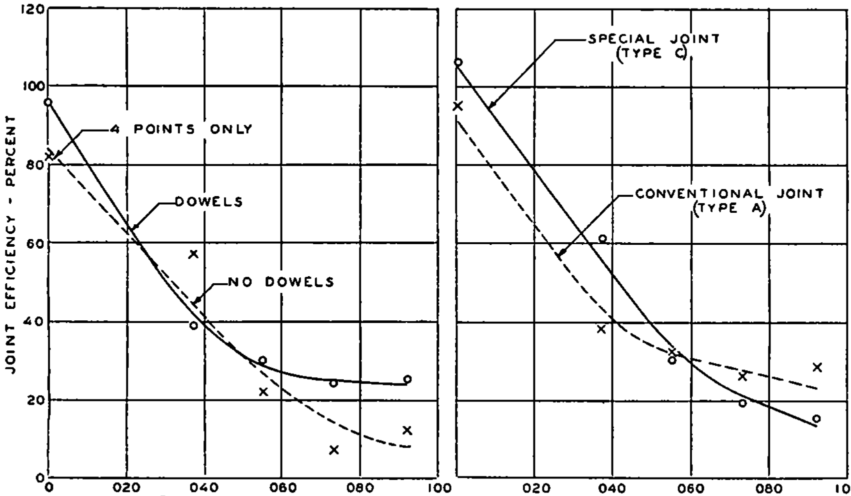


Figure 10. Effect of size of coarse aggregate on the relation between joint opening and joint efficiency as determined with edge loading. Each value is an average from tests at points A to H, inclusive.

As previously mentioned, there was a residual joint opening of about 0 005 in. when the joints were tested while under compression. After completion of the regular schedduled tests, joints 3 and 6 were closed and again tested while subjected to the 120,000-lb. compressive force. Because of slight changes in the relative elevation of abutting slabs, the rough joint faces did not match as perfectly as before and the residual joint openings generally were much greater than those that existed at the time of the initial tests. In the case of joint 3, a separation of 0 14 in. remained after application of the compressive force while for joint 6 the separation was 0 02 in Of interest is the fact that the efficiencies of joints 3 and 6, which were initially 95 and 79 per cent respectively, were still 61 and 49 per cent respectively when retested under the rather severe conditions just described. These data indicate that weakened-plane joints when subjected to direct compressive forces are able to maintain fair efficiencies, even if the fractured faces are not perfectly matched.

Another observation made during the testing of the joints was that, in the presence of the 120,000-lb. compressive force, the stress directly under the applied vertical load in a direction perpendicular to the edge of the joint was about one half of the stress in a direction parallel to the edge of the joint. As the stress for a comparable load acting at a free end is virtually zero in the perpendicular direction, the tests indicate that the compressive force makes it possible for the joint to transmit appreciable moment in addition to shear.



A - DOWELS VERSUS NO DOWELS (LOAD MIDWAY BETWEEN DOWELS) SMALL GRAVEL AGGREGATE

B - CONVENTIONAL VERSUS SPECIAL METHOD OF FRACTURING PAVEMENT LARGE GRAVEL AGGREGATE

Figure 11. Effect of design details on the relation between joint opening and joint efficiency as determined with edge loading. Each value is an average from tests at points A to H, inclusive.

Again referring to the relations of Figures 9, 10 and 11, it will be observed that the efficiencies of the joints decreased progressively as the width of joint opening was increased. At an opening of 0.037 in., the efficiencies for the various joints, as established by the curves, ranged from 27 to 56 per cent. At an opening of 0.092 in., none of the joints had an efficiency greater than 25 per cent.

From Figure 9 it is evident that the joints in sections containing the gravel coarse aggregate developed higher efficiencies than similar joints incorporated in sections having comparable sizes of the crushed stone coarse aggregate. At some of the joint openings the difference was as much as 15 per cent.

In an attempt to determine the cause of this difference in efficiency, a portion of one of the panels forming the joint was removed from each section so that the faces of the joints could be examined. This examination showed that in the sections having gravel coarse aggregate the joint faces were rougher than those of sections containing crushed stone coarse aggregate due to the fact that when the crack occurred at the joints, the crushed stone aggregate fractured whereas the gravel aggregate, in most instances, pulled out through loss of bond This contrast in the surfaces of the fractured faces is shown in Figure 12. The rough faces of the joints in sections containing gravel aggregate apparently were better able to transmit shear than were the relatively smooth faces of the joints in sections having crushed stone aggregate.

In connection with the preceding discussion of the relative roughness of the joint faces, it is of interest to refer to the previously-mentioned widths of opening that existed at joints 3 and 6 after they were closed upon completion of the regular scheduled tests. It will be recalled that the residual opening of joint 3 (large gravel aggregate) was 0.14 in. but that of joint 6 (large crushed stone aggregate) was only 0.02 in.

Figure 10 offers a comparison between the efficiency relations of the two sizes of gravel aggregate and of the two sizes of crushed stone aggregate. In the case of the gravel aggregate, the two efficiency curves are practically coincident for a width of joint opening up to 0.05 in., after which the joint in the section containing the large-size gravel definitely was more efficient. This greater efficiency was probably due to the greater projections of the larger size of gravel aggregate. In the case of the crushed stone aggregate, the joint in the section having the large-size stone was slightly, but only slightly, more efficient than a similar type of joint in the section built with the small-size stone. The probable reason for this condition is that both the large- and small-size crushed stone aggregate fractured as the crack formed, thereby producing in both instances equally smooth joint faces.

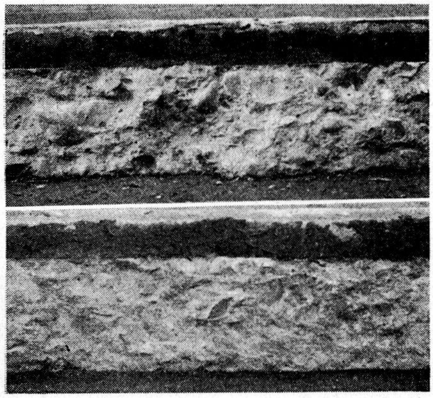


Figure 12. Exposed faces of weakened-plane joints. Upper, section containing large gravel coarse aggregate (Section 3). Lower, section containing large crushed stone coarse aggregate (Section 6).

In order to evaluate the effect of dowels on the relation between joint efficiency and joint opening, comparative efficiency data were established for two joints which were similar in every respect except that one contained dowels. These are shown in Figure 11-A. Both of the joints were in sections having small gravel aggregate. As observed in Figure 5, the dowels were $\frac{3}{4}$-in. in diameter, 24 in. long and were spaced at 12-in. intervals. The load was applied midway between dowels or at the weakest locations along the joint edge. Any departure of the efficiency curve of the doweled joint from the curve of the undoweled joint is presumed to be caused by the action of the dowels.

The general coincidence of the two curves at openings between zero and 0.05 in., inclusive, indicates that in this range the dowels aided but little the natural aggregate interlocking ability of the joint faces. However, after an opening of 0.05 in. the dowels had a marked effect on joint efficiency.

It will be recalled that earlier in this report mention was made of a previous study of a weakened-plane joint containing dowels spaced at 18-in. intervals. This study showed the joint to be 65 to 70 per cent efficient for both summer and winter. As shown by the curve of Figure 11-A, the doweled joint of the present investigation was only 25 per cent efficient at openings greater than 0.06 in. With our present knowledge derived from experimental studies of the structural behavior of dowels in transverse joints, this difference in efficiency cannot be fully explained. When more data are available a definite reason may be forthcoming. For instance, future research may shed some light upon the influence of subgrade stiffness and of pavement thickness on the structural performance of dowels. In the case of the two doweled joints in question, attention is directed to the fact that the test pavement of the investigation being reported was not only constructed upon a somewhat more rigid subgrade; but was of 8-in. uniform thickness as compared to an approximate 7-in. thickness that existed at point of test in the earlier study.

The efficiency relations of Figure 11-B provide some measure of the effectiveness of the Type C joint as compared with the conventional type of joint. Both of the joints in this comparison were in sections containing large gravel aggregate. The relations indicate that a clear-cut advantage of one type of joint over the other does not exist. At a joint opening of about 0.06 in., both are equally efficient. At openings less than 0.06 in., the special type of joint is more efficient than the conventional type; but at openings greater than 0.06 in., the reverse is true.

Just prior to the testing of each of the joints, the earth shoulder was removed for the purpose of examining the crack that had formed. As remarked before, the crack that occurred at the special joint (No. 1) was unlike those that developed at the other five joints. Specifically, this crack was extremely fine and was visible for only one-half the depth of the slab; whereas, the cracks at the other joints were very definite, being open about 0.015 in. Moreover, when the 120,000-lb. compressive force was applied, the special joint closed only 0.003 in. as compared to a closure of 0.010 in. that was measured at the other joints. Besides the differences just mentioned, the special joint could be pulled apart only 0.006 in., even by a total force of 110,000 lb. which, incidentally, started the 20- by 30-ft. section slipping as a whole over the subgrade. As a consequence, wedges in conjunction with the pulling force were used to effect a complete separation.

The difference in the behavior of the special joint as compared with that of the other joints is an indication that the bottom parting strip failed to fracture the pavement as planned. Figure 13 shows the exposed joint edge of the special joint after a section of the pavement adjacent to the joint had been removed. This figure shows rather conclusively that the bottom parting strip did not function in the intended manner.

The efficiencies of the various joints have thus far been discussed on the basis of relations determined from the averages of strains obtained at a number of load points. Figure 14 shows the amount of stress reduction found at individual points along the edges of the joints. These reduction values are expressed as percentages and are based on the stress determined at the points when the joint edges were acting as free slab ends. Since strains were measured at the same load point for all widths of joint opening and, also, for the basic free end condition, the reduction values at the individual points, as shown in Figure 14, should be affected but little by variations in the condition of the concrete and in subgrade support.

An estimate of the abilities of the joints to reduce the critical stresses at the individual load points is provided by comparing their stress-reduction values with a similar value determined for the interiors of the sections.

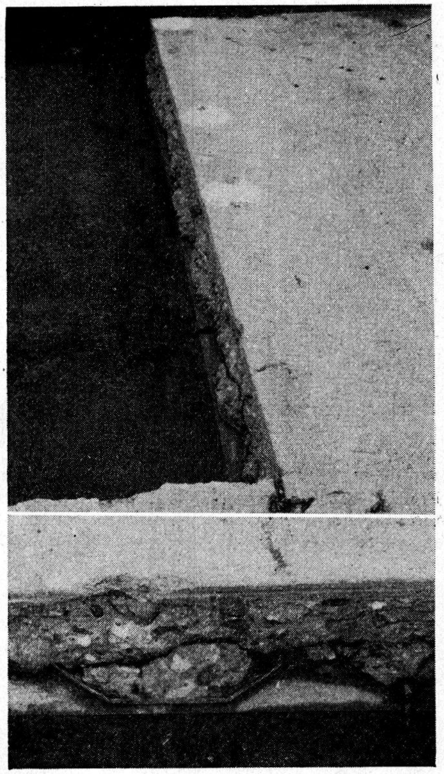


Figure 13. Exposed edge of special type of weakened-plane joint (Type C).

This interior stress-reduction value was found to be 33 per cent, being established from the average of all of the critical strains obtained at the free ends and at the interiors of the panels of the 6 sections. Thus, if a reduction of 33 per cent is attained at any point along the joint edge, then the joint at that point is assumed to be 100 per cent efficient.

Referring to Figure 14, it is observed that considerable variation in stress reduction was found at the individual points along the edges of the joints. Nevertheless, in spite of these variations, when the joints were closed and the compressive force acting, a relatively high degree of efficiency was developed at all of the points. At a joint opening of only 0.037 in., however, the individual stress-reduction values indicate that aggregate interlock was not very dependable in reducing critical load stresses. When the joints were opened to a width of 0.073 in., their stress-reducing ability diminished to such an extent that no reduction in stress was found at one-third of the points. In this respect all of the joints, with the exception of joint 4 which contains dowels, show a zero efficiency at two or more of the individual load points. The non-uniformity of the stress-reduction values is not surprising when one considers the irregular manner in which cracks formed at joints of this type. Figure 15 shows the fractured surfaces at two of the test joints.

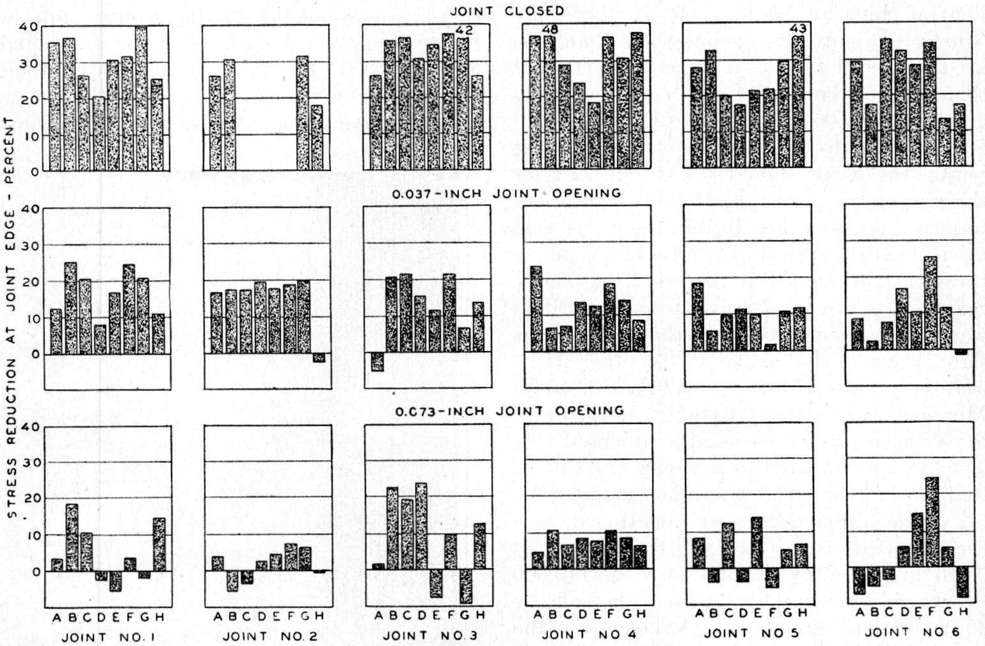


Figure 14. Variation in the amount of stress reduction at individual points, A to H inclusive, along slab edges at weakened-plane joints. The joint-closed condition is that created by a compressive force of 120,000 lb. applied at one end of the section.

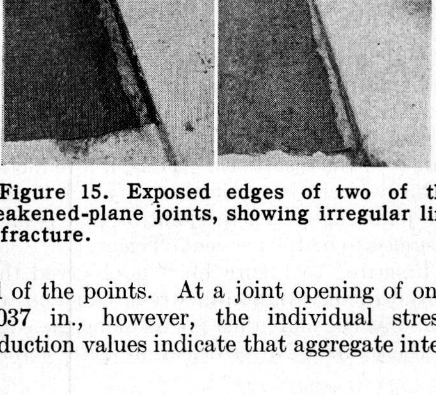


Figure 15. Exposed edges of two of the weakened-plane joints, showing irregular line of fracture.

Summarizing the preceding data on the effectiveness of the various joints in controlling critical stresses originating from loads acting at some distance from the joint corners, it is concluded that: (1) in the presence of interfacial pressure, all of the weakened-plane joints were effective, even at relatively large residual joint openings; (2) without interfacial pressure, aggregate interlock was found to be an uncertain means of stress control regardless of the type and size of coarse aggregate; (3) the doweled joint showed a rather low average efficiency (about 25 per cent) at widths of joint opening greater than 0.06 in., but the presence of the dowels improved the uniformity of stress reduction at individual points along the edge of the joint; (4) in general, the rougher the joint face the greater the ability to reduce the critical load stress; and (5) roughness of joint faces depends in part upon whether or not the aggregate fractures or pulls out through loss of bond at the time the crack is formed.

EFFECTIVENESS OF THE JOINTS WITH A LOAD ACTING AT THE JOINT CORNER

The ability of the various weakened-plane joints to reduce critical stresses caused by loads acting at their edges has, heretofore, been confined to a discussion of the stresses that occur when the loads are applied at some distance from the joint corners. Under such a loading the critical stress is directly beneath the load and in a direction parallel to the joint edge. When loads are applied at or near the free corners of constant-thickness slabs, critical tensile stresses, as remarked before, develop in the upper surface of the slabs along the bisectors of the corner angles at some distance from the load.

As mentioned earlier, strains were measured along the bisectors of the outside corners of the six weakened-plane joints. These strains afford a means of determining how effectively the joints functioned in reducing the critical stresses for the condition of corner loading. Typical data obtained from tests at one of the joints are shown in Figure 16. It is indicated that, for a given width of joint opening, the strains remain nearly constant over the distance between 16 and 32 in. from the corner, the maximum variation within these limits being less than 10 per cent.

The data for zero width of joint opening were obtained with the joint under compression which explains why values for this condition are so much smaller than those found with the joint open a small amount.

The effect of type and size of coarse aggregate and of other variables on the reduction in the corner stresses at the various joint openings is given in Figures 17, 18 and 19. Comparisons between the different joints in these three figures are the same as those previously described for the corresponding figures in the discussion of the edge condition of loading. The stress-reduction values shown in the graphs are expressed as percentages and were obtained by the following method: The average strains measured at the four corners of a given joint were first plotted in the manner shown in Figure 16. From these curves the maximum average strain value for each joint opening was obtained. Using the maximum average strain value for a joint opening of 0.500 in. as a base, the amount of stress reduction effected by the joint at each of the lesser joint openings was then computed for each type of joint.

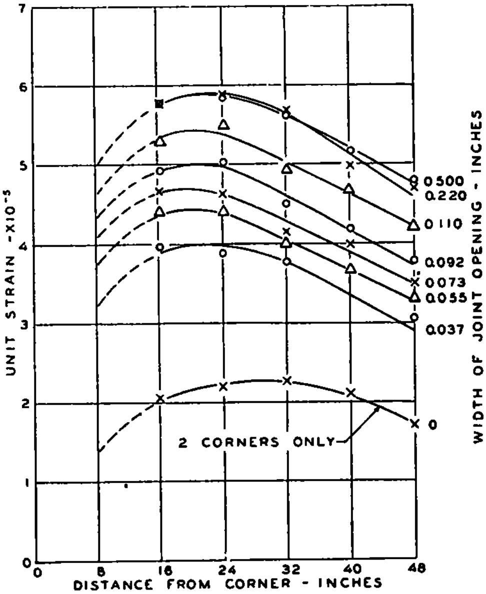


Figure 16. Effect of width of joint opening on the magnitude and distribution of strain along the bisector of the corner angle as determined with corner loading. Each value is an average from tests at four corners of joint No. 2.

It is observed that the stress reduction at zero opening, or with the joints under compression, generally exceeded 50 per cent of the stress for the free corner condition. Theoretically, the maximum amount of load that can be transferred by any joint is slightly less than 50 per cent. Thus, with a load acting at a joint corner, the maximum reduction in stress that might be expected by load transfer is about 50 per cent. However,

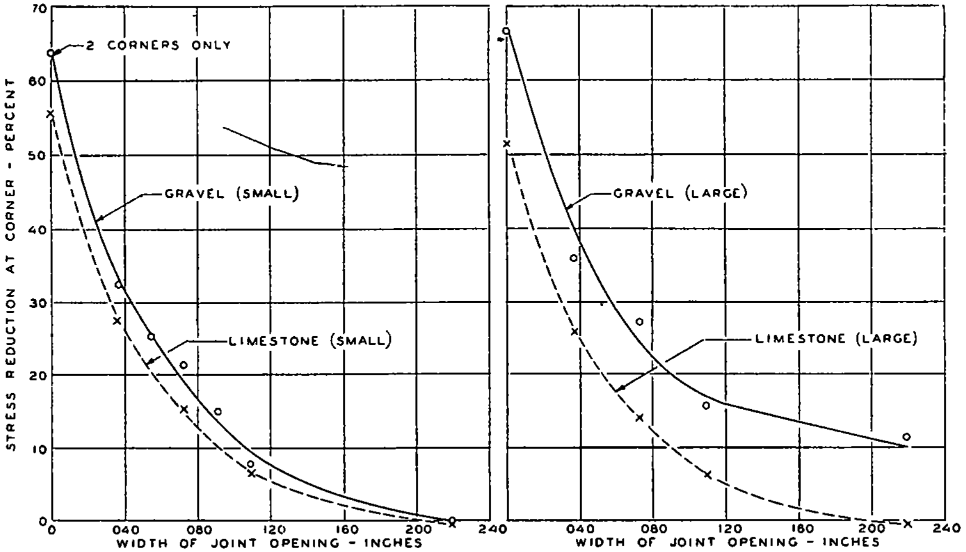


Figure 17. Effect of type of coarse aggregate on the relation between joint opening and stress reduction as determined with corner loading. Each value is based on the maximum average stress as determined by tests on corners 1 to 4, inclusive.

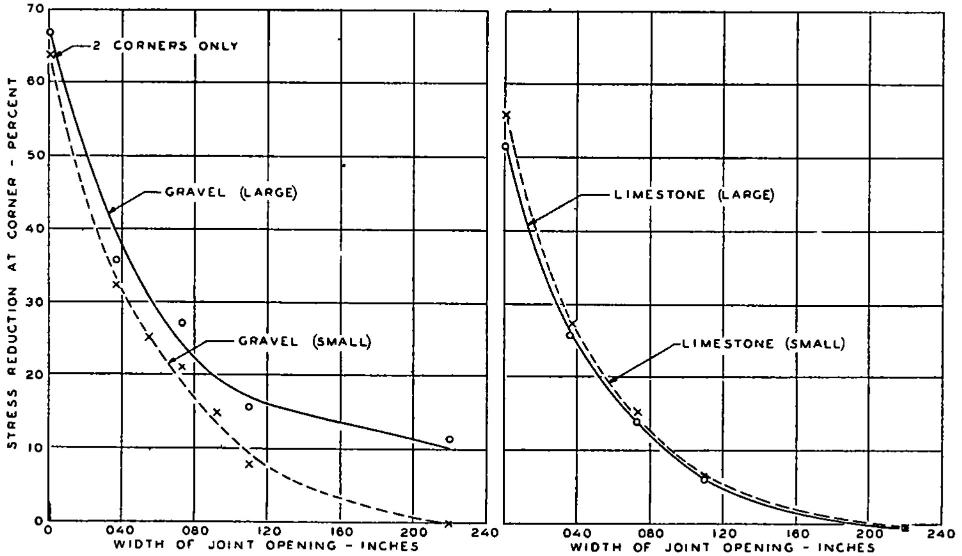


Figure 18. Effect of size of coarse aggregate on the relation between joint opening and stress reduction as determined with corner loading. Each value is based on the maximum average stress as determined by tests on corners 1–4, inclusive.

if the joint is capable of exerting a moment which resists bending as well as transferring load through plain shear, it is possible that it might cause a reduction in stress greater than 50 per cent of that for the free corner condition Apparently, therefore, the reductions in stress above 50 per cent found at the zero width of joint opening were due to the resistance to bending caused by interfacial pressure at the joint.

It will be recalled that the residual opening of joint 3 (large gravel aggregate) was 0.14 inch and that of joint 6 (large crushed stone aggregate) was 0.02 in when these joints were retested while under compression after completion of the scheduled tests These separations had the effect of respectively reducing the average corner stress-reduction value (joint under compression) of joint 6 from 67 to 25 per cent and the value of joint 3 from 52 to 47 per cent.

The relations presented in Figures 17, 18 and 19 indicate that there was a sharp reduction in the effectiveness of the joints as the compression between the joint faces was released. Also that there was a progressive reduction in their effectiveness as the widths of the joints were increased beyond 0.037 in.

Figure 17 was constructed to show the effect of the type of coarse aggregate on the reduction in stress caused by aggregate interlock It is indicated by this figure that the gravel gave a more effective interlock than the crushed stone. The difference between the two aggregate types was not great for the small-size coarse aggregate, but was appreciable in the case of the larger coarse aggregate.

In Figure 18 is shown, for both types of coarse aggregate, the influence of the size of aggregate on the effectiveness of the aggregate interlock It is observed that the large gravel gave a more effective interlock than the small gravel, but the size of the aggregate appeared to have little influence in the case of the crushed stone aggregate.

It is believed that the reason for the more effective interlock shown by the gravel aggregate, particularly the large size, in these corner tests is the same as that discussed earlier in the presentation of the data for the edge condition of loading.

Comparisons are shown in Figure 19 between similar weakened-plane joints with and without dowels and between the special weakened-plane joint, Type C, and one of a conventional type. The coarse aggregate in the joints of the first comparison was small gravel while that in the joints of the second comparison was large gravel

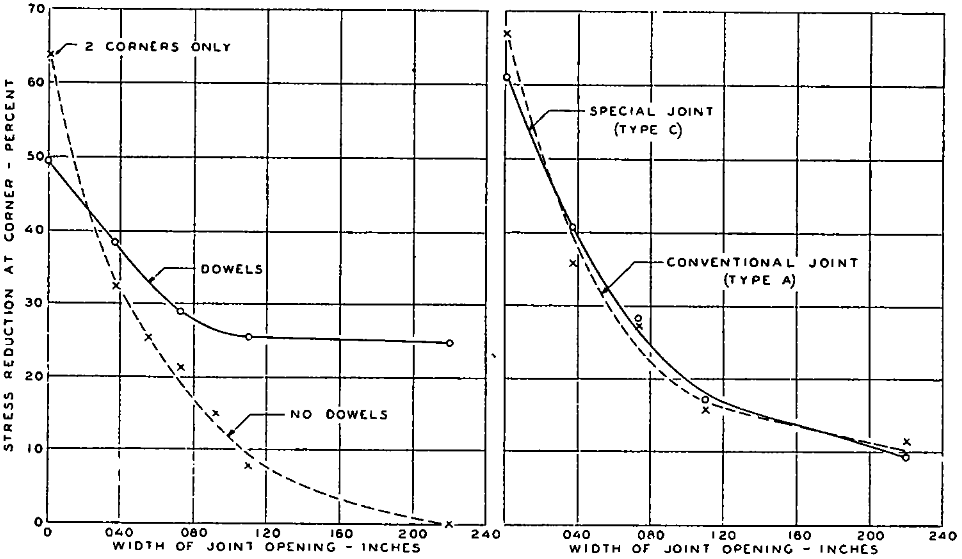


Figure 19. Effect of design details on the relation between joint opening and stress reduction as determined with corner loading. Each value is based on the maximum average stress as determined by tests on corners 1 to 4, inclusive.

It will be noted that at the zero width of joint opening (joint under compression), the stress reduction for the joint without dowels was greater than that of the joint with dowels. This may be the result of a difference in the effectiveness of the aggregate interlock in the two joints since the dowels have little or no opportunity to act while the joint is under compression or until some relative displacement between the two sides of the joint has developed The stress reduction of the doweled joint exceeds that of the comparable undoweled joint at openings greater than approximately 0 02 in., the difference being considerable at the larger openings.

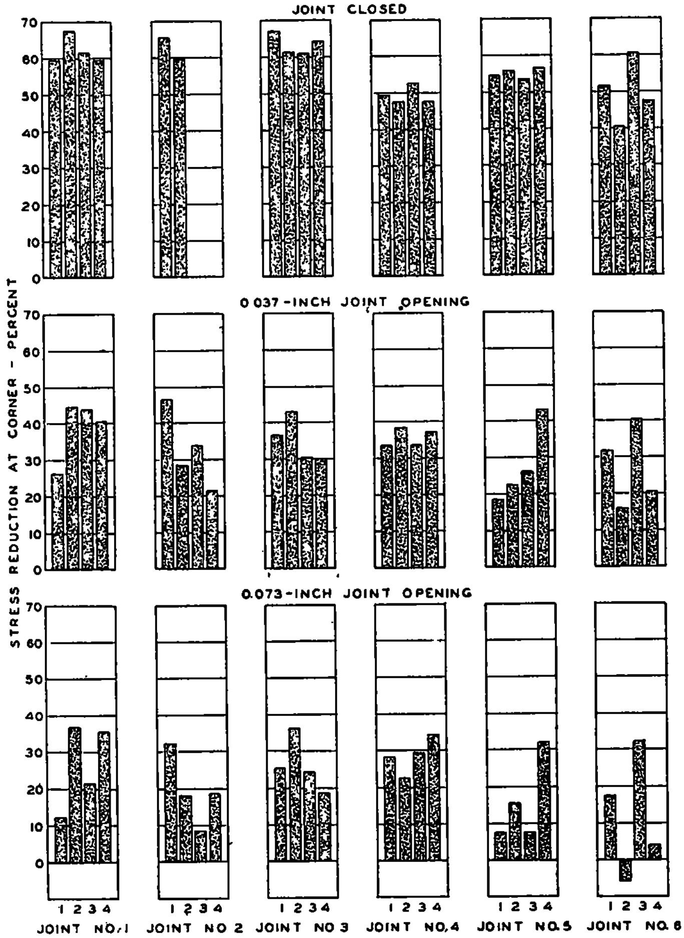


Figure 20. Variation in the amount of stress reduction at individual corners, 1 to 4 inclusive, at weakened-plane joints. The joint-closed condition is that created by a compressive force of 120,000 lb. applied at one end of the section.

There appears to be little or no difference in the effectiveness of the aggregate interlock in the special weakened-plane joint, Type C, and the conventional weakened-plane joint, Type A.

The stress-reduction values at the four individual corners of each joint are shown for three different joint openings in Figure 20. With the joint in a closed condition (under compression) the stress-reduction values at the four corners were found to be quite uniform at all of the joints, although at joint 6 there was somewhat more variation than at the corners of the other five. However, as the joints were opened, appreciable variations were found in the amount of stress reduction among the four corners of each of the individual joints. At the 0.037-in. opening, the maximum variations occurred at joints 2, 5 and 6 where the stress-reduction values at the individual corners ranged as much as 25 per cent and the amount of stress reduction at the corner showing the maximum was more than double that at the corner showing the minimum. The doweled joint (No. 4) showed the most uniform stress reduction, the range in reduction values being approximately 5 per cent.

At the 0.073-in. opening the stress-reduction values at some of the individual corners of several of the joints were so low as to indicate that, at this opening, aggregate interlock is not dependable. A possible exception to this is joint 3 with the large gravel aggregate. However, this joint would, without question, lose its effectiveness at only a small increase in opening or, perhaps, by the action of traffic gradually destroying the projecting aggregate.

The doweled joint at the 0.073-in. opening showed the greatest uniformity in stress-reduction values (23 to 34 per cent) and the highest average stress reduction (29 per cent). A special test was made of this joint at an opening of 1 in. and it was found that, at this opening, the stress reduction at the four corners ranged between 20 and 25 per cent and averaged 22 per cent. Thus, even at an opening of 1 in , this joint not only maintained a high degree of uniformity in stress reduction but the difference in the average of the reduction values was only 7 per cent when the width of the joint was changed from 0.073 to 1 in. The efficiency of this doweled joint in controlling the corner stresses was not as high as might be desirable on the basis of perfect transmission of shear, but this was probably due to the fact that the dowels were not of sufficient diameter to be highly effective in an 8-in. pavement.

In the preceding discussion it was assumed that a joint acting in shear only should, if it is 100 per cent effective, cause a reduction in the critical load stresses at the corners of 50 per cent. It might be contended that it is only necessary for a joint to cause a sufficient reduction in the critical corner stresses to make them equal to those caused by an equivalent load acting at the interior of the slab.

Comparison of the average of all of the critical free-corner strains with the average of all of the critical interior strains obtained from the six sections of this study indicated that a reduction in the corner strains of approximately 27 per cent is necessary if the load stresses at the interior and corners of the slab are to be equalized. Thus, if it is desired to reduce the corner stresses only enough to make them approximately equal to the interior stresses, it might be considered that all of the joints with gravel aggregate were sufficiently effective at an opening of 0 037 in. At this opening the stress reduction of a number of the individual corners with crushed stone aggregate fell appreciably below 27 per cent.

At the 0 073-in. opening the stress reduction at one or more of the individual corners was appreciably less than 27 per cent in all of the joints except joint 4, which contained dowels.

It is concluded from the preceding data on the corner loading tests that: (1) on the whole, all of the joints were more effective in reducing critical corner stresses than they were in reducing critical edge stresses; (2) in the presence of interfacial pressure and small residual openings, all of the joints were not only extremely effective but a high degree of uniformity of stress reduction was indicated among the individual corners; (3) in the presence of interfacial pressure and a relatively large residual opening (0.14 in.) the reduction in the critical corner stress was sufficient to make the stress approximately equal to that caused by a load of the same magnitude acting at the interior; (4) without interfacial pressure, all of the joints depending solely upon aggregate interlock to reduce critical stresses indicated a wide variation in the stress-reduction values; (5) the effectiveness of aggregate interlock was improved by roughness of the joint faces; and (6) the dowels improved the uniformity of stress reduction among the individual joint corners and, even at large openings, reduced the critical corner stress to a value approximately equal to that caused by a load of the same magnitude acting at the interior.

SIGNIFICANCE OF THE RESULTS

In concrete pavements the amount that closely-spaced contraction joints may open during the winter when the concrete is in a contracted condition depends primarily upon the following factors: (1) the temperature of the concrete at the time it hardens, (2) the thermal coefficient of the concrete and the range in temperature to which the pavement is subjected, (3) the spacing of the joints, (4) the amount of shrinkage that occurs when the concrete hardens; and (5) the change in volume of the concrete due to seasonal moisture variation.

In a pavement laid without expansion joints, the expansion beyond the length at which it hardens is restrained; hence the maximum change in the widths of the contraction joints, due to volumetric changes in the concrete, is dependent upon the changes which occur from the time the pavement hardens to the time it reaches its minimum length. In a pavement with sufficient expansion space to permit full expansion, the maximum change in the width of the joints is dependent upon the volumetric changes during the annual cycle of moisture and temperature variations Thus, to compute the maximum opening of the joints it is necessary in the case of pavements without expansion joints to assume the hardening temperature of the concrete and the minimum temperature which might occur. For pavements with expansion joints, it is necessary to assume the maximum and minimum temperatures which might occur in the concrete. It should be possible, with the help of published temperature data on concrete pavements, to assume these temperatures with reasonable accuracy A number of determinations have been made of the thermal coefficient of concrete and while it varies with different aggregates it has been found to average approximately 0 000005 per deg F. Unless the spacing of the joints is known, it will be necessary to assume a value for purposes of computation

A limited amount of data are available on the shrinkage of concrete pavement slabs during the hardening period and, also, the change in length caused by seasonal moisture variations. In the Minnesota project measurements were made of the shrinkage in a number of slabs over a period of several years It was found that during the early hardening period the amount of shrinkage was equivalent to that which would be caused by a reduction in the average temperature of the concrete of approximately 16° F, but that the amount of shrinkage increased appreciably later. Observations have been made of the changes in length of several full-size concrete pavement slabs from seasonal moisture variations. These observations indicate that the change in length depends upon the weather conditions, but is generally equivalent to that which might be caused by a change in the average temperature of the concrete of 20° to 30° F. Thus, within the limits of these data, it appears that the seasonal change in length of a pavement slab caused by seasonal moisture variation, from summer to winter is approximately equal to the shrinkage which occurs when the concrete hardens.

To permit the measurement of the opening that is expected to occur later at contraction joints in concrete pavements, it is necessary to make the basic measurement before the joints fracture This was done in the case of the project in Michigan and in the central part of the section without expansion joints and a contraction joint spacing of 20 ft. it was found that, during the second winter, that is, the first winter after the pavement had expanded to its maximum length, the average joint opening was 0 06 in. The opening should be correspondingly greater or less for other contraction joint spacings.

In pavements laid with expansion joints there is a tendency for contraction joints to open progressively until all available expansion space is dissipated. Because of this, the actual opening of the joints may, after a period, greatly exceed the computed openings or those observed during the first or second winter after the pavement is laid. In pavements without expansion joints there is little opportunity for progressive changes in the widths of the contraction joints It has been observed, however, that where contraction joints are spaced at close intervals fracture may occur at some of the joints soon after the pavement is laid yet be delayed as much as a year or more at others Under these conditions for a given average opening some of the joints would open correspondingly more and others less than the normal amount. Should the open joints become filled with foreign matter they are apt to maintain a large part of this abnormal opening throughout the life of the pavement

It was shown by the tests of the weakened-plane joints in this investigation that aggregate interlock was effective in stress control when the joints were closed or under compression, but that it was not dependable when the joints were open 0.037 in. or more, irrespective of the type or maximum size of the aggregate in the concrete. Thus, it must be concluded that aggregate interlock cannot be depended upon to give effective stress control thoughout the full yearly temperature cycle in pavements with contraction joint spacings such that the joints can open an amount greater than approximately 0.04 in.

Aggregate interlock may, during the early life of the pavement, be of some benefit in reducing the critical load stresses at weakened-plane joints which open less than this amount. The elimination of expansion joints might be expected to increase the length of the period over which the joints would retain their initial effectiveness, but it is doubtful if it would make them permanently effective. It has been found that joints which permitted a relative deflection, between the two sides of the joint, of approximately 0.008 in. or more under critical loads were ineffective in stress control, so that a joint to be effective must become fully engaged at very small deflections. Heavy, high frequency traffic causes a severe hammering action in weakened-plane joints when they are open even small amounts and it is only natural to expect that, over a period of several years, this hammering action would break down the aggregate interlock sufficiently to permit the small relative deflection necessary to make the joint ineffective in stress control.

In pavements where stress control at the joints is desirable it, therefore, appears necessary to use some more effective type of load transfer. The doweled joint tested in an open condition in this investigation, although more effective than the plain weakened-plane joints, did not show the structural efficiency that had been expected. Other tests on doweled joints made by the Public Roads Administration indicate that ¾-in. dowels at 12-in intervals are quite effective in stress control in slabs 7 in. or less in thickness. This suggests that the size of the dowels should be progressively increased with the thickness of the pavement.

One of the most serious conditions that has developed in concrete pavements in recent years is faulting and pumping at expansion joints, open cracks and open weakened-plane joints. This condition is probably aggravated by a greater frequency of heavy loads on the pavements during the war period than has been common in the past. Faulting generally follows pumping, but may occur without pumping. The type of faulting not associated with pumping has been found on subgrades of both fine-grained and granular soils, but seems to be most common and serious with silt and clay subgrade soils. Pumping is definitely associated with fine-grained subgrade soils and observations indicate that the water which is pumped to the surface from benath the slabs is largely surface water that has leaked through the joints, open cracks and along the edges of the pavement. Hence, defective sealing of joints and cracks is a condition contributing to pumping and the type of faulting associated with it.

Aggregate interlock at weakened-plane joints and cracks that are not permitted to open too widely seems to have been generally effective in preventing faulting of the type not associated with pumping. In pavements laid without expansion joints and closely spaced contraction joints (15 to 20 ft.) aggregate interlock probably will be effective in preventing serious faulting of this type. If conditions are such as to permit an appreciable progressive opening of the weakened-plane joints, however, it is thought that an additional means of load transfer should be provided.

Adequate load transfer acts in two ways to prevent or reduce the amount of pumping and the accompanying faulting at joints in concrete pavements. First, it reduces the total deflection that occurs when the loads pass over the joint, thus causing a reduction in the amount of water and soil pumped to the surface with each repetition of load. Second, it reduces the relative deflections of the two slab ends when the loads pass over the joint thus helping to preserve the seal of the joints and to prevent the infiltration of surface water. Tests have shown that the total deflections at joints may be reduced nearly 50 per cent and the relative deflections nearly 100 per cent by adequate load transfer installations.

It has been found that aggregate interlock may be very helpful in reducing the total deflections and relative deflections at joints if they are not allowed to open too widely. However, it must be recognized that heavy, high frequency traffic may in time seriously reduce the effectiveness of aggregate interlock. From load-deflection studies on slabs not subjected to traffic, it has been observed that the performance of weakened-plane joints with dowels was definitely better than those without dowels. Also, it might be expected that the doweled joints would retain their effectiveness at wider openings and over a longer period of time.

Since aggregate interlock is of definite value in preventing or reducing the amount of pumping and faulting in weakened-plane joints when they are not allowed to open too widely, it is desirable that some provision should be made in the design of the pavement to limit the opening of the joints. This would involve the adjustment of the spacing of such joints to limit the magnitude of the seasonal opening from temperature and moisture variations in the concrete, and the limiting of available expansion space to prevent appreciable progressive opening of the intermediate joints, either by actually eliminating the expansion space or by using an expansion joint filler which will offer appreciable resistance to compression.

It is desirable that further studies should be made to determine the effectiveness of aggregate interlock and other methods of load transfer in preventing pumping and faulting and the conditions under which other corrective measures might be necessary.