known, but its value in preventing incipient cracks which might develop during hardening of the concrete and later into failure of the slab is not generally appreciated.

CONCLUSION

In the present-day design of pavements, proper design and installation of joints is recognized as the most important factor influencing rigid pavement performance. However, the variations in spacing of transverse joints are as great as at any time, and range from 15 feet to none. It is believed, however, that results from the experiments now being conducted and the study being made of pavements constructed under varying design principles will bring about more uniform practice and it is the belief of this department that practice will specify short slabs with well distributed reinforcement and with well constructed and well maintained joints. The cost of such construction is small in comparison to the insurance provided. Post-war building is going to demand careful consideration of our spending to guarantee the greatest possible economy—not merely low cost.

TRANSVERSE JOINTS IN THE DESIGN OF HEAVY DUTY CONCRETE PAVEMENTS

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SYNOPSIS

This paper is an account of experience with concrete pavements in New Jersey. The situation of New Jersey is such that it is an ideal laboratory for the purpose of quickly and thoroughly testing designs of concrete pavements. Transverse joints, cracks, and pavement design are discussed as relating to ability to sustain the amount of heavy traffic using the State Highway System. Main conclusions reached are:

(1) Heavy duty pavements require designs that provide load distribution at all joints and cracks.
(2) Joint structures should be designed to reduce dowel restraint to the lowest practicable limit.
(3) Surface water should be excluded from access to subgrade in so far as practicable
(4) The surface on which the pavement is laid should be non-erodible, have high bearing value, and preferably be somewhat porous.
(5) Earth infiltration in open joints and cracks leads to spalling, blow-ups, and destruction of load transfer often accelerated by pavement growth.
(6) Joint fillers should fill the joint space at all times.
(7) The use of precompressed wood should be tried extensively for joint fillers.
(8) Contraction joints are unsuitable for heavy duty concrete pavements and warping joints appear to be undesirable.
(9) Concrete sills may be a better load distributing device than steel dowelled structures.
(10) Consideration toward the early abandonment of the free end theory in construction of concrete pavements and adoption of the controlled compression theory, in which pavements are kept under compression at all times by the use of spring dowelled joint structures, is suggested as being more in accord with concrete's inherent characteristics

The material for this paper has been drawn largely from experience gained in studying the performance of concrete pavements on New Jersey's state highway system

New Jersey's location in a densely populated area, between two of the Nation's largest cities, accounts for the heavy traffic on its highways. Average daily traffic was 6300 vehicles on the state highway system in 1940; on many parts of the system it was 10,000 to more than 60,000 vehicles. The heavy traffic has disclosed some of the weaknesses of heavy duty concrete pavements. Normally, such traffic would include from 300 to 2000 vehicles carrying loads in excess of 7½ tons. Although no information is at hand to indicate how many loads of this weight require heavy duty designs, 100 has been selected as a tentative figure Between 1930 and 1940 all traffic on the system increased 35 per cent; the heavy truck traffic probably increased more than this; in the future greater increases are likely. This is why small troubles observed on today's horizon should be analyzed and anticipated in the design of tomorrow's highways.

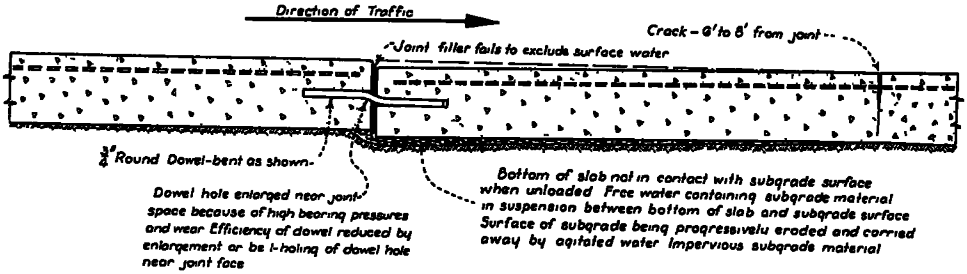

Figure 1. Typical Conditions at a Stepped-Off Joint

This information as to the nature of, and reasons for these weaknesses in so far as they are known, and thoughts on improved designs contributed to the common effort of building more durable pavements Because of the incompleteness of data some of the conclusions reached and speculations made herein point all too clearly to the need for better organized research in the complex problem of joint design. Pavement life is limited by adequacy of joints. An appreciation of this will lead to a larger return on the investment of public funds in concrete pavements

JOINT FAULTING

Joint faulting—also described as stepping off in the direction of traffic—occurred in New Jersey in 1930 on 9-in uniform section reinforced concrete pavements two years old. Six ¾-in round dowels, grouped in threes 12 in. apart near the corners, had been installed in the perfunctory manner usual at that time The dowels were found to be badly bent and the dowel holes enlarged Impact increased the faulting in extreme cases to as much as an inch. Many of the slabs were cracked 6 to 8 ft. beyond the joints and the ends were bent down on the subgrade. Many of the cracks did not appear to extend the full depth of the pavement. The joint filler, which consisted of pre-moulded bituminous impregnated felt sheets, was partly squeezed out of the joint space, affording surface water easy access to the subgrade After rains, free water underlay the depressed slab ends; nevertheless a few feet away the subgrade was hard and there was no free water. This condition existed in cuts and fills alike where the subgrade was partly clay. The faulting was accompanied by subgrade erosion, also called mud pumping, which has since become so familiar to highway engineers. (See Fig. 1).

CAUSES OF FAULTING

While faulting can be attributed to impact of the load on the concrete slab end beyond a joint the nature of the process in the early stages and the exact causes of its beginning are obscure and must be partly surmised Breaks in the continuity of a rigid pavement change the application of forces and their distribution over the subgrade As the load approaches the joint the slab end on the near side of the joint assumes the load gradually, reaching its maximum deflection with the load at the end. Without load transfer across the joint the far slab end has not deflected and is subject to impact as the load passes on to it This impact causes a larger deflection and a higher unit pressure on the subgrade. The increase in the unit subgrade pressure has a

tendency to deform the subgrade by compaction or rearrangement of the soil particles to a greater extent on the far side of the joint. Because this inequality of forces on the slab ends, accompanied by the inequality of support on either side of the break, is repeated many times the far slab end tends to be depressed permanently below the near slab end. A small start in this process, as evidenced by a small difference in elevation, adds a small increment to the larger force and, unless counteracted by special means, tends to accelerate the progress of depression In dry weather many subgrades effectively resist appreciable deformation, in the presence of free water those with large percentages of clay soften, aided by agitation of soil and water under frequent heavy loads During rains free water tends to collect on the subgrade in the joint area, entering through the joint space and at the pavement edge Water lies in the thin spaces created by warping and subgrade compaction Each heavy load drives the water forward and the accumulated pressure expels some of it with a few of the finer soil particles Gradually a layer of soil under the end of the concrete slab is washed away, leaving the end suspended over the eroded subgrade As subgrade support decreases, still greater deflections increase the tension in the top of the slab until the slab end finally bends down on the eroded subgrade.

Without load transfer this process is fairly rapid under the far slab end In weak load transfer devices, small round dowels bend and then work loose under the heavy loads The bending of the dowels produces high unit pressures on the dowels at the face of the joint, crushes the supporting concrete, and enlarges the dowel holes. This in turn lengthens the span of the dowels and further decreases their resistance to bending By reason of the bending and loosening the greater impact on the far side of the joint accelerates the erosive action, and slowly drives the far slab end below the near one Faulting, as borne out by some observations, may occur very slowly in the absence of free water, but it is accelerated by free water in the joint area on erodible subgrades. This faulting at the joint is proof of the loss of load transfer Thereafter evenness of surface can be restored by mudjacking whenever faulting and refaulting reach a critical stage

As long as load transfer devices are fully effective faulting is prevented, but the same tendencies exist, and erosion may bring about a sagging of the slab ends on both sides of the joint Load transfer reduces the deflection at the corners by about a half Even so these deflections are about three times as much as at the pavement edge several feet away from the joint area With these greater deflections go higher unit subgrade pressures and the same tendency toward subgrade deformation. Load transfer, at best, does not provide uniform continuity of structural behavior nor uniform support for rolling loads but rather a series of weaknesses that have been bolstered up by the load transfer device Whether or not these weaknesses are sufficient, even with an adequate load transfer device, to cause ultimate failure is not known but experience over a period of ten years records no signs of failure.

EXTENT OF FAULTING

Early joint faulting was limited to those pavements laid on clayey subgrades and carrying many heavy trucks Faulting occurred somewhat later on other roads where heavy trucks were less frequent and subgrades were better Roads having non-erodible subgrades and light traffic have been little affected as yet

It has been noted that wider slabs, having more rigidity and subgrade support, faulted less than the narrower 10-ft slabs Heavy loads travelling along a narrow slab pass over the corners more often than on a wide one As the corners are the weakly supported portions of the pavement, the destructive process leading to faulting is delayed by keeping the heavy loads off the corners as much as possible. Thus wider slabs have important structural advantages in addition to those of traffic operation and saving of shoulder maintenance, advantages that may well be sufficient to extend the life of the pavement several years.

PROPOSED REMEDIES

Prevention of faulting and sagging is accomplished by (1) excluding free water from the subgrade in joint area in so far as practicable, (2) selecting porous subgrade materials or those not affected by erosive action, and (3) making the load transfer device adequate.

The effectiveness of each of these measures

by itself is not known. Some pavements in New Jersey with good subgrade but without adequate load transfer devices showed no sign of faulting for many years under fairly heavy traffic, economic changes in the area brought a greater number of heavy loads with moderate but increasing faulting Perhaps any one of these measures would be sufficient for a time with infrequent heavy loads, and any two should still further postpone faulting. However, all of them are used in New Jersey because the saving made by omission of any effective measure that costs so little additional was considered as gambling unnecessarily with the life of pavements Although future causes of failure may be discovered that are not covered by these measures, each of them contributes to prevention of failure by known causes and may provide insurance against failure by undiscovered causes.

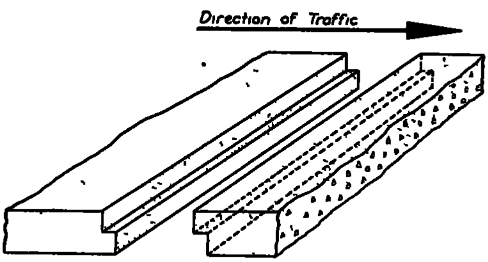

Figure 2. Ledge Joint

CONSTRUCTION OF TEST ROAD

Immediately after the first faulting the development of suitable joint structures with provision for excluding surface water was thoroughly explored. In 1932 a circular test road was constructed to learn the effect of heavy loads on the designs suggested Two of these are shown in Figures 2 and 3. All slabs were 10 ft. wide. The subgrade was clayey and represented the worst condition likely to be found in the State. Formed metal sheets (Fig 6) called flashings, covered the standard filler in some joints For purposes of comparison, plain butt joints, the standard 6-dowel, and the hastily revised standard 12-dowel joints of ¾-in round bars were included in the test All dowels were installed very carefully. Loads varied but were as high as 16 tons on a single axle. After an initial dry period run the pavement was sprinkled with water to accelerate the test

RESULTS AND CONCLUSIONS

Some of the results of the partial destruction of the test road and conclusions drawn were as follows

The plain butt joint without any load transfer started to fault soon after the subgrade was thoroughly saturated. Later both slab ends sagged, accompanied by top cracking about six feet from the joint Because of the large quantity of water used in accelerating the test, the erosive action was extremely rapid and affected the area under all slab ends laid on earth On the highway generally, the erosive action is less rapid and is confined mostly to the slab end beyond the joint

Joints of six ¾-in dowels showed early signs of looseness. Looseness was measured during the test by the differences in deflections of slab corners as the load passed over the joint; it was associated with offset bending of the dowels. With this was a gradual crushing of

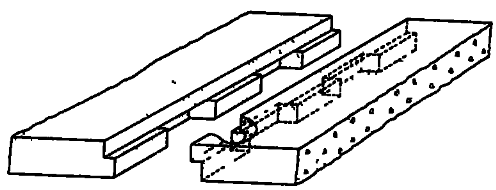

Figure 3. Alternate Ledge Joint

the concrete at the joint faces. The enlargement of the dowel holes was evidence of the necessity of decreasing the unit pressure at these points Soon after the dowels became loose, metal flashings used with some of these joints cracked at the top because of bending fatigue

Joints of twelve ¾-in dowels spaced only 10 in. apart were affected similarly to joints with six dowels but the rate of deterioration was much slower, indicating a possible sufficiency under favorable conditions of subgrade and traffic (However, recent observations disclosed much faulting of this design, even after mudjacking, on heavy traffic highways built about 12 years ago.)

Joint structures with rectangular dowel bars placed on edge, and flanked top and bottom by small channels to distribute the load and decrease wear at the joint faces, showed practically no looseness nor any offset bending of the dowels Metal flashings incorporated with these joints showed no signs of fatigue.

The ledge joint (Fig. 2)—the ledge being a continuous right angle offset in the direction of traffic supporting the far slab end on the projection of the near slab end—acted in the test similarly in many respects to the plain butt joint but somewhat better. As the load crossed the joint the impact on the far side quickly depressed the slab end just when the supporting ledge was returning to its normal position after deflection. The meeting of these two projections was accompanied by increasing noise rather early in the test. The unsupported slab end (on the near side of the joint) deflected about the same amount as the corresponding slab end at the plain butt joint, indicating high tensile stresses on the top of the slab about five or six feet back from the joint. Rather early, a top crack occurred at this location, followed by sagging of this slab end and, later, by cracking and sagging of the slab end beyond the joint. Despite the rather unsatisfactory performance of this type in the test it is thought to possess advantages for light traffic roads, especially where frost heaving is not a factor. It is simple to construct, inexpensive, and free from restraint. Although it is subject to impact, as is the plain butt joint, the ledge serves as a fairly effective preventive of faulting. (Recent observations of this type laid 12 years ago on a heavy traffic road disclosed faulting of ½ to ¾ in.)

The same type of joint laid on concrete sills neither faulted nor sagged. After a long time there was some erosion outside the sill area. Later a bottom crack occurred over the eroded area. The sills gave every indication of being able to carry heavy loads under very adverse conditions.

The alternate ledge joint (Fig. 3)—also described as a concrete interlocking joint in which five ledges (two on one side and three on the other, formed alternately on the bottom half of each slab end) extended into recesses under and supported the other slab end—acted like a true hinge under load. Some of the ledges were reinforced by ½-in. bars. One of the two ledges on one side that were without bars broke off. In this design two of the four corners (on the slab end having three ledges) lacked direct support by ledges. A high bending moment, produced by the load on the unsupported corner several inches away from the support of the nearest ledge, caused the break. Even with this design defect the type generally performed well in the test. The design could be greatly improved by more ledges of less width. As yet no satisfactory method of installation has been devised that provides the degree of accuracy required for uniformly good results in construction. Perhaps a design with precast reinforced ledges about a foot wide would be satisfactory for medium traffic. (Recent observations of the type used in the test laid 12 years ago on a heavy traffic road disclosed moderate faulting—where the ledges were not reinforced.)

As the testing progressed mud pumping was present in the vicinity of every joint and crack. In a general way its beginning and severity corresponded to the inadequacy of the devices used in distributing the load over the subgrade in the joint area.

As should be expected, when deprived of subgrade support some of all types of hinged joints sagged down on the eroded subgrade without faulting, the stiff dowel joints with rectangular bars sagging less than those with concrete ledges. This sagging was accompanied by top cracking in one or both slabs.

Although the subgrade was not uniform, several duplicates of the joint types were so well distributed in the test road that inequalities in subgrade appeared to have no marked effect on joint behavior nor on conclusions reached. The test furnished a somewhat better understanding of the process of failure. Also a general idea of the relative load supporting value of each joint type was obtained. Roughly, they could be listed in this order beginning with the weakest: plain butt, six ¾-inch round dowels, ledge, twelve ¾-inch round dowels, alternate ledge, rectangular dowel bars on edge, and ledge on sills.

The effect of some factors ordinarily contributing to pavement failure during normal life was distorted in the accelerated test. Other factors had no influence on the results of the test. For instance, the test did not extend through a yearly cycle of expansion and contraction nor a period of freezing and thawing. Observations supplementing those of the test influenced the conclusions used in later design.

NEW STANDARD JOINT DESIGN

As a result of this test and other observations a new standard joint design was adopted in 1933. It consisted of twelve 2-in. channel

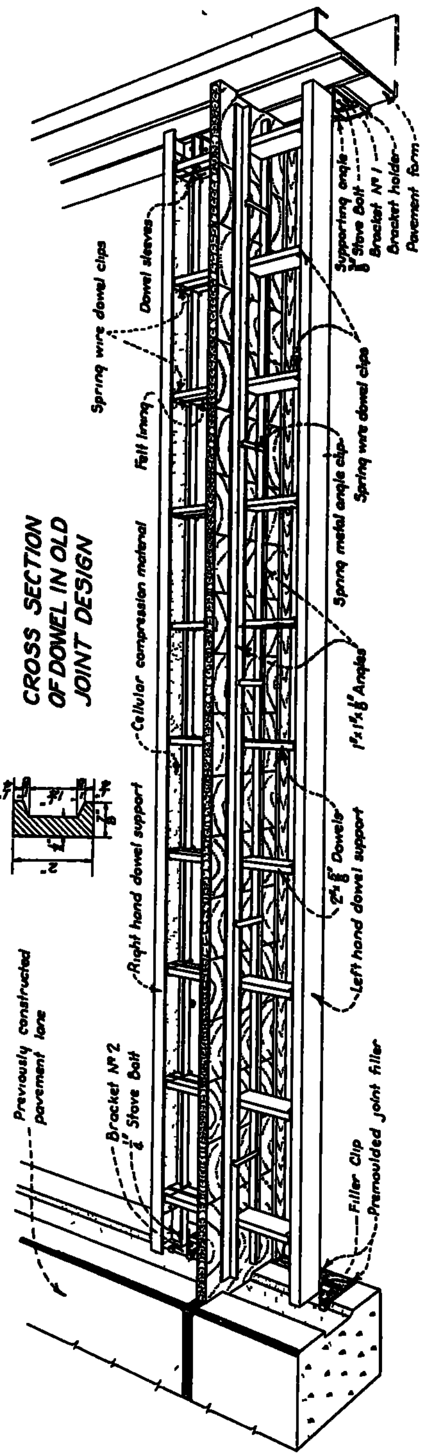

Figure 4. Perspective View of Revised Design of Joint Assembly

dowels with variable spacings of 6 in at the corners to 19 in at the center. The dowels were flanked top and bottom by 1 by 1-in. angles at the joint faces. The pavement forms supported the ends of the dowels by means of auxiliary cross channels, brackets, removable bracket holders, and clamps attached to the form base All means of support were left in place until the pavement forms were removed. (See Figs 4 and 5) The slab length was increased from 35 to 56 ft Unusual attention to details was given in the design to assure accuracy of assembly and certainty of correct installation Neglect of this is not only waste of the joint material but is detrimental to the pavement Subgrade support, aided by driven pins, was rejected as being inaccurate and too uncertain of stability and uniformity Top support on the forms was rejected to allow the finishing

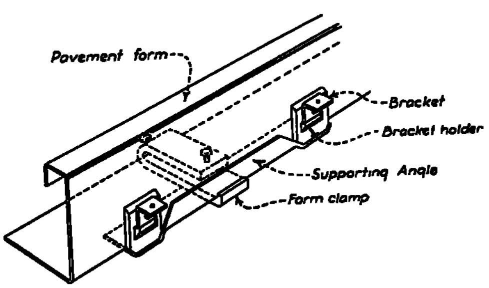

Figure 5. View of Attachments to Form

machine to travel uninterruptedly over the joint without removing the supporting device. One-half inch premoulded bituminous impregnated felt was used as a joint filler The upper part of the joint filler was covered by metal flashing formed of pure iron sheets. The flashing was anchored in the concrete at the top of the dowels and extended up to within ½ in of pavement grade. Its function was to provide a roof over the joint space against the entrance of water and earth The metal flashing was adopted reluctantly because of the possibility of corrosion and the impracticability of replacement, but no better means were known at that time.

SUBGRADE IMPROVEMENT

Subgrade improvement was made slowly, as it was not then too clear what means would be most effective At first, stone filled shallow longitudinal trenches were constructed under the shoulder just outside the pavement edge to drain away any free water that might collect on the subgrade Apparently these were rather effective but costly Later, for about the same cost, a granular and somewhat porous subbase under the pavement and shoulders, supplemented by intercepting drains, was substituted for the stone drains. It was hoped that in addition to providing a non-erodible and a well drained surface for the pavement the subbase would be an insulating blanket against frost entrance, some good effects in this respect were realized and there is a tendency to increase the thickness of subbase material Such a subbase may not be as unyielding as one with more clay but it is firm enough if efficient load distributing devices are used. Although subgrades can be built that are capable of sustaining the heavy loads without benefit of load transfer and with no resulting deformation, a combination of a reasonably good subgrade with a good load distributing device is believed to be more economical

SOME DESIGN DEFECTS AND REMEDIES

The new joint structure and subgrade improvement prevented faulting and subgrade erosion But, like all new products that depart so radically from usual practice, a few unexpected defects have been disclosed in 10 years' use

Restrained Joints

In some of the early installations dowels were restrained from sliding by insufficient lubrication of the coatings Bonding strengths on poorly coated dowels ranged from 100 to 600 lb per sq. in at the time of investigation, which sometimes was several weeks after construction. Many joints were "frozen," causing some serious cracking. Apparently, much of this cracking occurred when the temperature dropped several degrees while the concrete was still weak, perhaps during the first night. Despite the later use of better coatings selected after many tests, sliding restraint was still thought to cause cracks, and dowel coatings were abandoned after several years' trial The use of metal sleeves, which are automatically adjusted to maintain top and bottom contact with the dowel, were adopted as the best preventive for

restraint from this source Even with extra precaution in design, good sliding surfaces are difficult to attain in every case

Dowel coatings should do more than break the bond with the concrete When the bond is broken restraint does not disappear. Assumption that restraint decreases with age does not appear to be borne out by measurements on some dowelled joints 12 years old Although some joints have less restraint with age others, for some unknown reason, appear to have greater restraint with age. Expansion forces restrained joints to partly close; contraction cannot open them as wide as before. In a series of dowelled joints some of which are partly restrained, the slabs creep toward the restraint. Consequently, joint widths become variable; an extra strain is imposed on reinforcing steel. Some wide cracks in slabs are undoubtedly caused by dowel restraint; used to reduce restraint in the early life of the pavement.

The reduction of all known causes of dowel restraint in joints to a practical minimum is very worthwhile It is well to remember that joints are assembled usually by those who do not know the reasons for every requirement In handling of parts, placing and consolidating concrete, seldom is much care given to protecting the joint structure from harm. Designs that are completely foolproof against incorrect installation are not possible, but the nearest practical approach to them will go far to prolong the life of the pavement.

Flashing Infiltration and Spalling

The metal flashing spanning the joint space led to trouble about two years later The flashing was shaped in cross section like an inverted U having a width of ½ in and depth

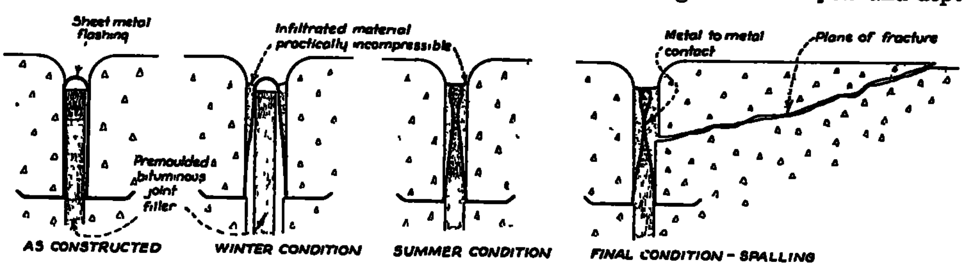

Figure 6. Progressive Infiltration of Foreign Materials, Flashing Collapse and Ultimate Spalling

the joints opened and closed the first year but not so freely as others in the series Several of these cracks had faulted as much as ½ in

Another source of restraint is misalignment of dowels Dowels that are not parallel restrain joints from opening in a somewhat direct relation to the amount of their divergence and their stiffness While there was no definite evidence of pavement cracking from this cause, the probability of it was considered—especially after a few tests indicated that even a small divergence might cause restraint. Possible divergence in the standard design was 1 in 300; probable divergence, much smaller.

Shearing of the dowels deformed the ends so that the cross section was not uniform. As this contributed to restraint sawed ends were required Sleeve linings of compressible paper on the sides of the dowels further reduce sliding resistance With this a lubricant about the consistency of gear oil should be of 3 in. (See Fig 6). The ends of the U were bent outward and anchored in the concrete under the flanking angles 3½ in below grade As the pavement expanded the rounded top was bent to conform to the narrower joint space Subsequent contraction, producing a wider joint space, spread the flashing at the bottom, but the rounded top and the right angle bends at the bottom resisted change The sides of the flashing then flexed in the form of reversed curves, leaving spaces between the flashing and the faces of the joint. Sand and other soil gradually filled these spaces, even when the bituminous material over the top appeared to afford a perfect seal Subsequent pavement expansion compacted the infiltrated material, moving the sides of the flashing closer together Repeated contractions and expansions of the pavement, accompanied by progressive distortions of the sides of the flashing, further infiltrations of earth, and compactions soon

forced the sides of the flashing together. Summer pressures compressed the infiltrated earth into solid masses.

This process gradually built up high pressure on certain small areas of the joint faces about two inches below the top of the pavement. Obviously the expansion of the pavement was resisted by relatively small portions of the cross sectional area. The force at the peak of the expansion cycle grows with resistance to free movement. Each year further infiltration in the same area increases the force to be resisted. This concentration of force and resistance at successive points produced unit pressures exceeding the strength of the concrete. Spalling of successive portions of the top edges of the pavement at the joint followed. The larger of these spalls had a width of about 2 ft., extended several inches from the joint, and were as much as 2 in. in depth.

A warning of the imminence of such spalling was sent to us by Mr. Clifford Older in September 1934, after the joint structure became standard. Had this been given more prompt and thorough consideration at that time some of this spalling might have been prevented. Investigation started shortly after but a suitable alternative was not developed before spalling occurred on pavements laid previously.

As a part of the investigation, the process of flashing distortion by infiltration was repeated in the laboratory at an accelerated rate on a model. Seeking further information, sand was squeezed between heavy steel horizontal plates. At first the sand was squeezed out easily, but when the plates were about $\frac{3}{8}$ in. apart the pressures exceeded 5000 lb. per sq. in. and distorted the steel plates, apparently without further compression of the sand layer. Later, clayey soil resisted in excess of 5000 lb per sq in. when compressed to 0 28 in. Other materials tested gave different thicknesses. Unfortunately, such tests do not afford very definite indications of the pressures that might be found in practice. On the road, such variables as the area under compression, the kind of infiltrated material, the conditions of confinement in the joint space, time, and moisture might give many different results. Upon reflection, and in the light of later information, these tests seem to be indicative of the process leading to spalling but not necessarily of the magnitude of the pressures that might cause it.

Wider Joint Space

Nevertheless, these tests led to the hope that a wider joint space would check the consolidation of infiltrated material and extrude the loosened material. Probably some minimum dimension could be found to accomplish this The joint space was increased $\frac{1}{4}$ in. and the joint edges were tooled deeper and wider, but it is still not known if the change was enough. The widened joint may spall in future; when this is indicated, removal of the infiltrated material is facilitated by the extra width. So far, no widened joint has spalled, although some of them are six years old The wider joint space is not objectionable other than that it creates some noise and slight shock.

New Jersey's experience with metal flashings has proved somewhat unsatisfactory; still their use in a wider space was continued while searching for a good substitute. Their use creates a future problem of substitution—solvable but expensive.

Infiltration of Old Joints and Cracks

Infiltration troubles have not been limited to designs using flashings. Investigation of old joints disclosed many infiltrated spaces where premoulded bituminous impregnated felt had been used as a joint filler. When the filler was squeezed out by pavement expansion the following contractions left free spaces into which earth entered. Since this process is intermittent throughout the year no ordinary maintenance can be depended on to keep a joint of this type free from infiltration. New pourings of bitumen usually cover rather than penetrate or bypass infiltrated materials. The bitumen, being of the nature of a viscous liquid, cannot replace solid materials such as earth, but earth can replace the bitumen, perhaps displacing it by slow penetration under certain conditions. There is a progressive interchange; the earth is found at the bottom of the space, and the bitumen at the top; in between there may be a mixture of the two A casual inspection of the surface may indicate no defects but a careful investigation reveals the cause of future trouble.

Cracks that open frequently during the year can hardly be kept free from infiltration by pouring them with bitumen once a year. Bituminous seals often do not stick to the sides of concrete surfaces for long, particularly in prolonged wet weather. Pouring joints

and cracks with bitumen, if done carefully and at the right time, greatly retards infiltration but it is no sure preventive.

Narrow spaces may not infiltrate so rapidly as the wider spaces but the wider spaces appear to have a better chance to check consolidation of infiltrated material and may loosen and extrude it. At joints without effective load transfer the independent deflection of slab ends under load may tend to loosen and extrude the material. Thus, an occasional heavy load on light traffic roads may do more good than harm.

Inasmuch as infiltration occurs more rapidly at the shoulder line, because of greater availability of material and, whereas only the top, and not the sides, of the cracks and joints are poured, small outside corner breaks are likely to occur at open cracks. In the wider spaces at joints more extensive infiltration may

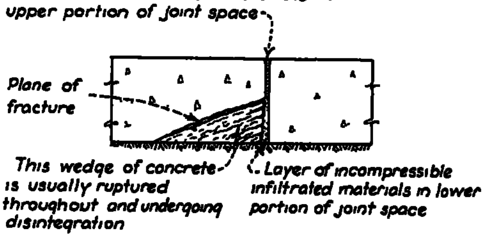

Figure 7. Bottom Corner Fracture at Infiltrated Expansion Joint.

account for longitudinal cracks starting at the joint; later, under heavy loads and increased pressure, these may cause large corner breaks. So long as free expansion space nearby is preserved relief is afforded; but with further infiltration in successive years the free space is diminished.

Spalling and Blow-Ups

At some of the old joints the bottom edges near the corners had spalled opposite infiltrated areas; gradual extension of the spalling toward the center was indicated, a few spalls reached a height of half the pavement thickness. (See Fig. 7). Ordinarily, they remain unnoticed for several years Progressive bottom spalling often formed inclined wedges, raising one slab end. As the slab restraint was relieved by the spalling, the joint space closed, the faces touching at the top, presenting smaller areas to absorb the expansive force. As the spalling continued these areas became still smaller until spalled off by a blow-up. (See Fig. 8).

CAUSES AND PROCESS OF BLOW-UPS

The evidence of the contributing causes and the process of blow-up are seldom complete after the occurrence. The difference in appearance of old bottom spalls, former disintegration, and the final breakage may not be readily distinguished. It may be a natural assumption, on inspection, that all of the breakage occurred at the time of blowing up. Nevertheless, the evidence leads to this belief: *blow-ups are the final products in a process of progressive disintegration over a period of years, the principal causes being infiltration, consolidation, and repeated concentration of the entire expansion force of the pavement successively on small areas, resulting in*

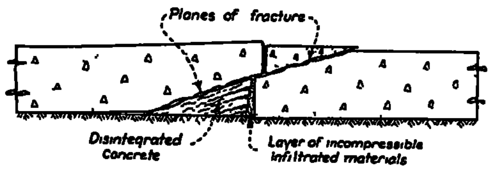

Figure 8. Blow-Up at Infiltrated Expansion Joint.

unit stresses higher than the strength of the concrete.

Blow-ups do not occur until the pavement is several years old. It takes some time for infiltration to build up resistance sufficient to produce high compressive stresses. Initial spalling may occur in a period of a year or two but may be deferred for several years. As one area is relieved of pressure by spalling, the pressure is concentrated on new areas in subsequent years; the spalling is progressive.

Many blow-ups have occurred in early summer, when the pavement moisture content is still high, In a series of concrete pavement slabs under pressure longitudinally, the location of the blow-up seems likely to be at the point of greatest eccentricity of pressure. While this could be at a crack, reports usually place it at joints. The element of chance or luck is evident in the occurrence of blow-ups because of the distribution of infiltration, the character of materials, time of laying concrete and abnormal weather.

On light traffic roads, without load transfer, blow-ups may be regarded as an inconvenience and a maintenance expense that is perhaps lower in cost than the preventive measures. On heavy duty pavements blow-ups make the load transfer device in joints worthless. The maintenance expense is much higher and hastens the time of reconstruction.

Infiltration General in Concrete Pavements

Evidently infiltration takes place in all concrete pavements. There must be a difference in rate, because of differences in maintenance, differences in pressure of material, and differences in direction and velocity of wind and water, which carry material to the free spaces The building up of eccentric pressures at nearly every free space is believed to be proceeding during every expansion cycle. If this is true, it seems likely that concrete pavements where infiltration accumulates and consolidates are gradually approaching a condition leading to a blow-up. However, infiltration distribution over an area of cross-section large enough to keep the compressive stresses below the breaking point probably would avoid blow-ups. A review of present and past designs, supplemented by field investigation by digging out the shoulder opposite several consecutive joints and cracks would disclose the extent of infiltration and suggest remedies to extend the life of pavements seriously affected. Apparently, some designs used in the past may bring about their own partial destruction, even though the pavements were never subjected to a single wheel load of traffic.

Pavement Growth

Although there is difference of opinion regarding a general tendency of concrete pavement slabs to grow longer, the fact of growth in some pavements has been verified by many observers And, in others, the frequency and extent of blow-ups can be accounted for only by pavement growth, accompanied by infiltration. However, it is important to distinguish between actual growth of concrete and apparent growth due to infiltration

Where blow-ups had occurred in one stretch of pavement several slabs were cut off to relieve the pressure. While one slab end was being cut off, the space closed just before the cut was quite completed and the small part of the slab that was not yet cut off was shattered as the slabs moved together The whole pavement was under pressure. A rough calculation of joint space originally provided and then existent, after allowances for the length cut off and the difference in temperature, indicated a growth of several feet in a distance of two miles. The constructed length of slabs was about 34 ft.; the joint space was ½ in.; the pavement was 15 yr. old. Wherever concrete pavements grow, the effects of infiltration are accelerated.

Results of past and continuing investigations into the causes of growth together with possible design changes lead to the thought that slab growth will not affect future pavements as it has some old pavements. If growth can be counteracted by plastic flow, it is only necessary to prevent eccentricity in pressures of such magnitude that would cause spalling. Joint fillers that fill the joint space all the time and can absorb high pressures should distribute the expansive force over the larger part of the cross section area and should reduce harm from slab growth However, if it is necessary to maintain free expansion space for concrete slabs to grow, the joint space would need to be quite wide.

Prevention of Free Spaces

Possibly some infiltration can be removed; but apparently the more certain way to avoid its effects is to prevent the formation of free spaces in both joints and cracks Free space in cracks can be prevented by adequate steel reinforcement; free space in joints is inevitable unless the joint filler fills the joint space at all times.

PRECOMPRESSED WOOD AS A JOINT FILLER

In the search for suitable joint fillers, the use of wood was suggested It has been used for many years with excellent results in some places The desire to learn what happens to wood, when subjected to such treatment as joint fillers must withstand, led to testing the effects of water and compression. Some woods withstood a great deal of pressure without any noticeable deterioration They compressed to half or more of their initial thickness, and when the pressure was removed, they recovered a small amount—usually about ten per cent of the initial thickness This com-

pressed wood stayed in that condition in the air for long periods, but when put in water returned very quickly to its initial thickness.

This behavior suggested that certain dry compressed woods could be used to form a joint space when the pavement is laid, or could be inserted in a preformed joint space when the pavement is contracted, and later, by giving water access to the wood, it would exert a small pressure in tending to return to its initial thickness. After water absorption, compressed wood has the property of being spongy. In an effort to learn what might eventually happen, a few pieces were put through many cycles of compression, wetting and drying, each cycle being of at least 48 hr. duration Specimens kept continually wet, after 97 cycles of compression to half thickness, shrank about 24 per cent, others with oven drying for 50 cycles and warm air drying for 37 cycles, a total of 87 cycles of compression to half thickness, shrank 28 per cent. The shrinkage appeared to have stopped before completion of all the cycles, no further loss in the recovery of the wood in water occurring as yet However, other information indicates that heat affects the cell structure and, if completely dried by heat, all recovery may be lost eventually

In some respects such accelerated tests are believed to be more severe than service conditions In service the high heat would be absent, there would be fewer cycles of compression to half thickness, but of longer duration. Except for the top surface, the wood probably would remain damp To replace water that may evaporate or be squeezed out, more is available from rains, and possibly from subgrade moisture long after rains. Examination of precompressed wood in joints one year old, showed the wood just under the top surface to be moist and spongy, even after a long dry spell The whole story of what might happen over a long period cannot be told in so short a time but in the meantime decisions as to its use must rely on careful estimates based on known information

As for durability there seems to be no reason to expect any difference in precompressed and uncompressed wood, unless the cell structure is injured by the initial compression Possibly the effect on the cell structure of any particular wood varies with the rate and amount of the initial compression and the amount of moisture in the wood. Preservatives did not appear to change the recovery characteristics of compressed wood.

The year-old experimental installations of precompressed wood as a filler in joints in New Jersey indicate a superior joint filler, when properly used within its range of recovery. All other materials tested have fallen short of the performance of precompressed wood up to this time—principally because they do not expand as the pavement contracts, and thus leave free spaces at the joints; many materials do not recover appreciably after a relatively short period of compression

One peculiarity of precompressed wood is that during compression of a long piece—such as a plank—it has a tendency to assume an irregular shape when the pressure is released. This is probably caused by a lack of uniformity of grain structure throughout its length. This irregularity is overcome by using laminated wood, plywood, or short pieces To maintain a constant height in the joint for better riding, a large part, or all, of the wood should be placed with the grain vertical, because there is no change of dimension with the grain.

As the compression of wood approaches half its initial thickness, it builds up resistance to further compression rather rapidly. Such resistance would increase the compression in the concrete Inasmuch as this compression is spread nearly uniformly over the entire cross section, it is believed to be more beneficial than harmful

UNCOMPRESSED WOOD AS A JOINT FILLER

In the future, precompressed wood, on the basis of present knowledge, promises to fill the joint space at all times longer than other materials While carrying on further experiments with it, uncompressed wood appears to offer promise for the immediate future, its properties are known better and it has been used successfully Ordinarily, the swelling of wood is limited to about 4 or 5 per cent, and it cannot fill the joint space during all of the contraction cycle As the joint space opens it is expected to infiltrate with earth In the following expansion cycle the infiltrated material would be consolidated and the wood compressed As infiltration proceeds it is expected to build up partial layers of incompressible material on one or both sides of the wood In

these circumstances, during expansion the wood must compress an additional amount, because of the thickness of the layer of consolidated earth The wood becomes, in effect, the same as precompressed wood.

In this process some inequalities of pressure would be expected because of the localization of infiltration. However, considering the time it takes for these forces to attain sufficient magnitude, the tendency for them to spread progressively over larger areas with further infiltration in each contraction cycle, and the large recovery of the wood during its early life because of the slow rate of compression shrinkage these pressures are thought to be well below those causing spalling.

Some of the very hard woods are compressed initially a considerable amount only by pressures higher than concrete can withstand. Conceivably, these might give trouble, but some of the softer woods, having the right kind of cell structure, would be more suitable. As infiltration proceeds, it should stop successively at different places, because of the tendency of the compressed wood to recover and fill the remaining space. The final condition after a few years may be one or two layers of incompressible earth and a layer of compressed wood, the whole filling the joint space thereafter. Some of this is, of course, speculation; there can be no definite assurance that the process would proceed as outlined. In fact, some reports of blow-ups, where wood was used in joints, cast doubt on the expectation of perfect results. No information accompanied the reports as to the kind of wood used, or conditions in connection with its use. The surrounding conditions are very important in judging the merits of any material for the purpose

Woods having a low percentage and a slow rate of compression shrinkage would be most suitable for joint fillers, whether precompressed when used or not Until their limitations are better known, safeguards should be employed in connection with wood joints. For instance, an extra joint, involving a short slab, can be inserted at frequent intervals, this slab, if pressures become dangerous, can be removed and replaced by a shorter one. Or, perhaps nearly the same result can be attained by making the wood in each joint thicker in proportion to the length of slab; this allows a margin of safety in not utilizing the full indicated range of wood recovery. Since the compression and recovery properties of woods differ greatly, their characteristics should be determined by tests preceding experimental installations. In no case should knots be allowed in wood joint fillers. A few war time projects in New Jersey, in which uncompressed wood has been used, should furnish information on some of these points over future years. And, doubtless, information on this subject is available from other sources.

SPRING JOINTS

Another way to prevent infiltration in cracks is to keep the entire pavement surface tightly closed by compression. Probably many existing pavements are under compression a large part of the year—especially after earth has infiltrated cracks and joints So long as spalling and blow-ups are avoided this compression is effective in decreasing the warping stresses in the summer time. In

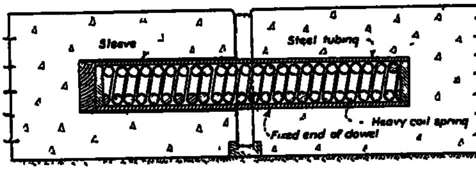

Figure 9. Sketch Showing Possible Method of Utilizing Heavy Compression Springs in Combination with Tubular Dowels.

the winter, however, this benefit is lost. Engineers have long recognized the benefits of compression to counteract tension in concrete pavements For nearly the entire period of building concrete pavements, much theorizing has been devoted to the subject of decreasing the effects of tension. Whether the compression should be a small amount during the coldest weather, so as to avoid high pressures during summer, or a larger amount, to attain a material decrease in any normal tension is a matter for further study.

There is the question as to the manner of putting the pavement under pressure. Besides utilizing the expansive force of the pavement, which is limited to the summer time, probably the most practical means is spring steel incorporated in the joint structure. A little study indicated that coil springs could

be used, were available in the desired sizes, and were not too expensive. The springs, inserted in a closed metal cylinder that takes the place of the customary dowel, would be installed in a fully compressed state. (See Fig. 9). One experiment was tried with a small spring of 3300 lb. capacity; war time requirements for steel checked further experiments. Just now, there seem to be no insuperable obstacles to building compression in pavements by the use of steel coil springs. At first the installation was a problem, but two apparently practicable methods of spring release after pavement hardening have been devised.

As a practical matter, the forces exerted by springs may not greatly exceed 100 lb. per sq. in. in the pavement During contraction, this would be less in the middle of the slab while overcoming subgrade friction Perhaps all tension, except that caused by local settlements and differential frost heaves, can be kept within safe limits by compression. Consequently, cracking would be reduced. Should cracks occur they would be pressed together by the springs. Even a small pressure may be enough for load transfer and to exclude infiltration. Bituminous pouring would not be needed. Steel reinforcement would not be needed because the steel coil springs would perform every function now performed by reinforcement and others in addition.

Present practice in concrete pavement construction is at variance with the inherent properties of concrete, it makes little use of concrete's great compressive strength, but accepts the weakness in tension and endeavors to avoid its effects Its survival and extension as a paving material for heavy duty pavements may depend on designs that make more use of its strength The use of springs would be in accord with concrete's inherent properties. Studies have been carried far enough to justify further experiments to fix the scope of suitable designs.

CONTRACTION JOINTS

Pavements with built-in compression are a promise for the future; meanwhile improvements for the immediate future should be discussed These center mostly about the joints Past troubles with expansion joints led to the desire to use as few as practicable Following the omission of expansion joints, contraction joints were introduced to control cracking. The view that cracks cause less trouble than joints is ostensibly supported by some observations. Contraction joints, according to some opinion, are acceptable substitutes for some of the expansion joints.

Support for contraction joints evidently is based partly on the assumption of load transfer through the interlocking of the fractured faces. A recent examination of a new contraction joint, before the pavement was opened to traffic, showed the fractured face to be rather smooth to the feel of the hand. Manifestly, only perfect closure would effect full load transfer. According to observation, a temperature drop of about 30 deg. would separate the fractured faces sufficiently to allow a deflection of ⅛ in. before meeting resistance from the adjacent slab. Any independent deflection would add appreciably to the load stresses, would produce higher subgrade unit pressures, and would cause impact on the slab end beyond the joint.

Even with a rough fracture, all points of roughness cannot be utilized simultaneously to transfer load when the joint is slightly open. Initially only the points that break on a horizontal plane provide load transfer. The distribution of these points depend on accident and partly on the slope of fracture. When the joint is not tightly closed the load is sustained separately on each side only by these points that break on a horizontal plane Wider openings utilize fewer points and these few must bear the whole load. As the joint opens these are so few they would be likely to break off under heavy load, causing some loss in load transfer. Then the load is carried successively by points having steeper slopes. The progressive breaking of these and the rubbing together of the joint faces with each load passage would gradually lessen the load transfer present when the crack formed. After the joint is open and subjected to crushing of the points of fracture and to infiltrated earth it seems doubtful that the fractured faces ever regain the original contact As for the probability of load transfer from the friction or bearing on consolidated infiltrated material, this would obtain, if at all, only when the pavement is under great pressure from expansion.

In several series of six contraction joints

spaced 15 ft apart the joints cracked at different times The early tendency was to form slabs 45 and 60 ft long, later, intermediate joints cracked However, some of the openings in the first winter were as wide as 0 15 in These did not decrease in width until the summer expansion equalized the openings Early in the second winter these openings averaged 0 10 in —partly due to the decrease in the expansion space as the joint filler did not recover from summer compression. Some of the contraction joints were opened ⅛ in Such openings preclude load transfer and are subject to infiltration On old pavements moderate faulting has occurred at openings of this width

One reinforced concrete pavement in New Jersey laid in 1934 cracked very badly where several expansion joints in succession were frozen, these were the standard channel dowel joints Apparently contraction was the primary cause Gradually many of these cracks became quite wide despite the ⅜-in reinforcing bars 7½ in apart The cracks infiltrated and spalled; many of them faulted causing additional cracking All the joints in this pavement are in excellent condition but the pavement, which is only nine years old, needs replacement in the near future

If load transfer devices of the sliding type are constructed at the contraction joints, apparently the only sources of trouble are those caused by infiltration of water and earth Closely spaced and well maintained joints might delay trouble for a long time Inevitably earth infiltration during the contraction cycles would progressively prevent the joints from closing. The effects of infiltration probably would escape detection until blow-ups occur; these may be at the expansion joints rather than at the contraction joints although the contraction joints may contribute to the cause as much or more than the expansion joints All things considered, the economic justification of such a design is doubted

The inclination of fractured faces operates to open cracks under the action of heavy loads Each vertical force imposed on a sloping surface has a horizontal component tending to push the slabs apart This is resisted by the subgrade friction and the steel, if reinforced Sometimes this is not enough to prevent wide opening and faulting As the slope of the fractured faces varies in amount and direction in different contraction joints in a series, this tends to open some joints wider than others, the wider ones being susceptible to greater faulting. Free expansion space allows cracks and contraction joints to open wider. Altogether, heavy loads and contraction with infiltration tend to make the slabs creep toward free spaces.

The place of contraction joints in roads not needing load transfer is not certain A combination of excellent subgrade and well maintained contraction joints might support many heavy loads for a long time without faulting However, heavy duty pavements should have load transfer throughout their length at all times, both at joints initially installed and at cracks subsequently formed anywhere. Contraction joints cannot meet these requirements, and have no proper place in the design of such pavements

DUMMY (OR WARPING) JOINTS

If adequate steel reinforcement holds the fractured faces together, there is full load transfer and no infiltration The reinforcement eliminates the function of the contraction joint and converts it into a dummy joint, with the single function of relieving warping stresses

The introduction of dummy (warping) joints, which are preformed cracks, may have the effect of adding to the number of cracks that otherwise might form in the pavement Although many New Jersey pavements are cracked, hundreds of slabs of all ages up to 25 years are not cracked The justification of the dummy joint is that it is better than a crack caused by warping This is debatable, as such cracks usually are so fine as not to disfigure the pavement and may require no maintenance and probably will not infiltrate and become wider—always provided the reinforcement is adequate. If on the other hand, the evidence does not indicate a great number of such cracks, the use of dummy joints would not seem to be justified. If the pavement is strong enough to withstand warping stresses in addition to the load stresses, the extra breaks in continuity of structure are not beneficial, because all such breaks, whether in the form of cracks or joints, are weak points and are thought to bring closer the ultimate need of reconstruction The causes of all

cracks in New Jersey pavements cannot be identified but more evidence is needed to attribute the cause to warping Present indications are that heavy duty pavements would be better without dummy joints. It seems almost axiomatic that heavy duty concrete pavements would last longer with the least practicable number of breaks in their continuity. Eventually each break contributes to a rougher profile, a weakening of subgrade support, and possible pavement spalling. Each break that is necessary should be designed to resist deterioration and to preserve as much continuity of structure and surface as is practicable.

CONCRETE SILLS

Most of the thought about load transfer devices centers on dowels because they provide economy in material by functioning in both directions. Nevertheless, one load distrib-

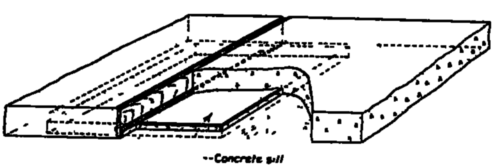

Figure 10. Expansion Joint with Inset Concrete Sill.

uting device may prove worthy of more consideration, that is, a concrete sill under the pavement slab ends. Its behavior in the test road was entirely satisfactory. As this was an accelerated test, it may not have told the whole story During warping and in periods of alternate freezing and thawing earth might infiltrate over the sill; consequently, the slab ends may not return to their original or to the same relative elevation, with resultant impact at the joint and uneven bearing of slab ends In a war time use of the sill these contingencies were anticipated by making the sill extend to within 9 in of the edge of pavement and raising the top of it 2 in. above subgrade. (See Fig. 10). That is, the upper half of the sill was surrounded by the bottom of the pavement It was hoped this design, by enclosing the top of the sill, would exclude infiltration coming from the shoulder and the subgrade. The only protection against infiltration from above was the wooden plank used as a joint filler

On three later contracts this design and two others were used. On one contract the sill was raised up 2 in. but extended the full width of the pavement On the third contract the sill was set flush with the subgrade and extended the full width of the pavement, no provision being made to exclude infiltration from either the side or the bottom. Comparison of these three designs in future years may indicate if protection from infiltration over the sill is needed To afford further comparisons with these designs, a few of the channel dowel joints were incorporated in this work.

The sill derives its principal value from two advantages over steel dowelled joints: the surface is non-erodible, and there is no metal to rust away and thereby lose the load distribution essential to heavy duty pavements.

SLAB LENGTHS AND JOINT SPACE WIDTH

Allied to the subject of joints is that of slab lengths. One basis of determining the length of slab of reinforced pavement with load transfer devices is that of least cost for the reinforcement and the joint, computed by assuming a coefficient of subgrade friction and making allowances for joint restraint and the horizontal component of the vertical force of heavy loads However, slab lengths should not be determined on this basis alone. Length of slab should be related to width of joint space Narrow joint spaces are preferable because wide joint spaces cause noise unless the joint material is flush with the pavement surface This is annoying to motorists; even on a smooth pavement there is a sensation of bumpiness—perhaps partly induced by hearing the noise Also there may be slight vibration from the shock of the tires hitting the far side of the joint space The width of joint space is a function of the properties and limitations of the filler used—especially its range of resiliency in filling the joint space—and the permissible toleration of noise and shock.

If the filler is able to resist compression so that the pavement can absorb some of the expansive force, obviously less change of slab length need be taken into account than indicated by the temperature range and the coefficient of expansion. While information is insufficient to determine slab lengths on this basis, such as is available can be used by resort to trial and error methods. Using that available in New Jersey, a tentative ratio of

wood thickness to concrete length of about 1 to 600 has been fixed.

BASIS OF DESIGN OF THE NEW JERSEY JOINT STRUCTURE

Returning to the standard joint structure used in New Jersey, the reasons governing the selection of design, and some of the questions raised, from time to time, in the nature of criticisms should be discussed. The first question was that of justifying a higher cost; low cost is an asset not lightly dismissed. The whole joint cost is about one dollar per foot—amounting to about 6 per cent of the total pavement cost. There has been no way of knowing what a joint should cost; other than what has been accepted and become customary over a period of years, no valid criterion for justifiable cost has been evolved. The weakness of concrete pavements is the lack of continuity of structure. Except for scaling and similar disintegration the ultimate failure of the pavement probably will take place at those points where continuity has been broken. The joint may measure the life of heavy duty concrete pavements. If this is so, then reluctance to pay the price of adequacy reduces the return on the investment in the pavement

To some engineers and contractors the blueprints were rather formidable; on paper the structure appeared complicated to assemble. Simplicity of structure and ease of installation are alluring arguments to engineers and contractors alike, but they are not essentials. A demonstration of the joint assembly and a short experience in its use provided the answer to this question of complexity. No measurements were required; no adjustments had to be made; procedure became standardized quickly; assembly could be made in but one way—the right way.

It was questioned if the dowels were not heavier than they needed to be. While this may be true no one could tell how heavy dowels needed to be. It is rather difficult for theoretical analyses and laboratory test with static loads to take into account the wear on steel and concrete, and some unknowns about millions of moving traffic loads over inequalities of subgrade during variable weather conditions that may include long rainy spells and periods of thaw after a prolonged freezing spell. Since actual tests were made under heavy loads, the careful observance of the testing, supplemented by the observance of the behavior of pavements carrying heavy traffic, furnished the most practical criteria of requirements. Evidence of corrosion reducing the cross section of old dowels at the joint space by more than half was not without its effect in determining dowel dimensions. For instance, the thickness of the web was increased from $\frac{1}{4}$ to $\frac{3}{8}$ in. on this account.

The length of dowel needed was not known. A long dowel can be aligned better but adds to the cost and may add to dowel restraint. Most of a long dowel's work is done by a small part of the length. On the other hand, very short dowels or studs have eight points of high pressure on the concrete, at each end and at each joint face both top and bottom Pressure at these points may be more concentrated because of the short length. Twenty inches was selected as a trial in the absence of more knowledge of the required length.

The depth of 2 inches was selected to afford stiffness, in view of past offset deformation of the $\frac{3}{4}$-in. round dowels Shear is less a measure of dowel adequacy than bending. The ability of the concrete at the face of the joint to withstand the high pressures imposed by bending of the dowel is a critical condition of design. These pressures are dependent on the width of joint space or the span between points of positive support The stiffness reduced the concentration of pressure at the joint faces, by making more of the dowel resist bending At one time it seemed desirable to replace the stiffness the pavement lost in breaking its continuity. Later, it was realized that this was not practicable because more steel would be required than could be held by the surrounding concrete. For instance, one of several 3-in. I-beams included experimentally in a 9-in. pavement joint broke out the concrete under it. Ideas of stiffness were modified; it was concluded that enough stiffness to avoid permanent dowel bending was the primary requirement.

Measurement of differences in deflection and in warping between the stiff and hinged structures on an existing pavement and on the test road showed these differences to be unimportant. This was disappointing at the time, but when the question was raised later, it indicated that the stiff structure would not add

substantially to the warping stresses. A little reflection on the relative stiffness of the pavement and of the joint structure led to the same conclusion. Surveys of roads in service several years show few cracks in the pavement near the joint; most cracks are in the middle third of the slab. What was regarded as a very stiff joint structure proved to be almost as flexible as any true hinge joint within the limits of slab bending found in practice.

Before adoption of the design, concern was felt lest the cross channel supporting device might create a plane of weakness at the ends of the dowels, because it extended across the pavement and occupied about a fourth of the cross-sectional area. (See Fig. 11). Consideration was given as to how this "hole through the concrete" might affect the functioning of the pavement in practice. Stresses in shear, contraction, and bending were considered—those in shear and contraction were not thought to be critical. In bending, the slab ends act as cantilevers, the critical point of stress, as evidenced by cracks, being about 5 to 8 ft. from the end. At the dowel support, which is less than a foot away from the joint, more than sufficient cross-sectional area is available to support the load. When in the first year some cracks did appear over the dowel supporting device it was ascertained that the dowels were tightly bound to the concrete because of inadequate lubrication. Even then, often the cracks occurred in other parts of the slab. Since then better lubrication is believed to have eliminated frozen joints and all possibility of structural weakness due to this method of supporting dowels.

Notwithstanding rather satisfactory experience with this structure for 10 years, much still is unknown about required dimensions of design. Rule of thumb selection has been necessary. For instance, the 1 by 1 in. angles extending across and contacting the dowels above and below decrease wear at the joint faces and transmit load from the dowels to the concrete; but definite knowledge is lacking as to the proper size or shape for these purposes. No effort has been made to vary the size and spacing of parts to determine experimentally the most desired dimensions. The first problem was to make the structure adequate to preserve the investment in the pavement. To accomplish this it was believed only a rugged and rigidly held structure could withstand the rough treatment usually encountered in construction operations and assure correct installation, and only a structure with a minimum tendency to develop looseness would transmit load effectively for a long period. Whatever it has cost, it has prevented faulting, provided load transfer, and minimized subgrade erosion. It is estimated that three to five million heavy loads have passed over many of these joints without any noticeable deterioration.

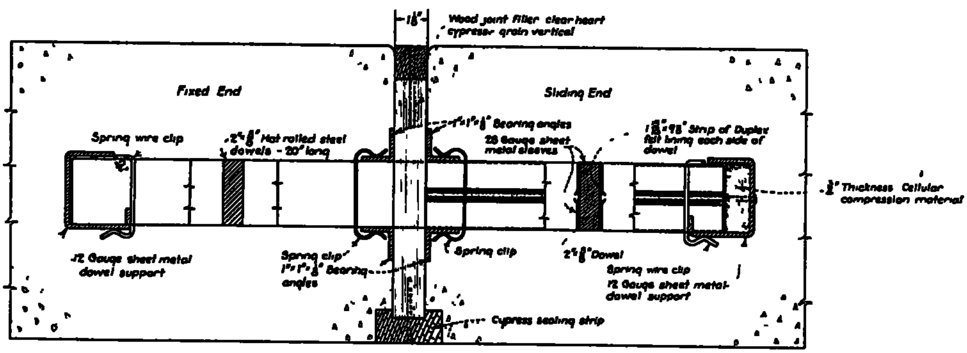

Figure 11. Cross Section of Expansion Joint as Recently Revised for Future Use.

The possibility of a lighter weight design proving satisfactory is admitted. At best, this would save a few pounds of steel—steel that may extend the life of the pavement many more years. Granted a possible saving of 2 to 3 per cent in the first cost of the pavement; the saving, in terms of the total investment it might jeopardize, is rather like the insurance premium. Only when it can be shown that the design is overweighted in any respect should such revisions be made.

This design appears to satisfy the conditions found in New Jersey. It is not intended to imply that other designs would not satisfy these conditions, nor that this design will satisfy the conditions found in other places. These principles of design apply to all heavy duty concrete pavements, though the application may differ with local conditions. A long observance of light traffic roads does not support the need for the same design requirements. Nevertheless, similar designs may extend still further the life of light traffic roads, and guard against failure if the character of the traffic should change greatly within the life of the pavement. For heavy duty roads the necessity of better designs is clear and the extra cost is justified.

SUMMARY OF REQUIREMENTS

The requirements of design of heavy duty concrete pavements include:

1. A non-erodible subgrade—preferably somewhat porous—capable of withstanding the high unit pressures in the vicinity of the joint without deformation
2. A sturdy load distributing device, free from restraint, and with a slow rate of deterioration.
3. Adequate steel reinforcement to hold cracked slabs together, assuring always a full measure of load transfer and no space for infiltration.
4. Joint fillers that always fill the joint space

Fulfillment of these requirements not only builds but also preserves load transfer in the whole length of pavement for a long time

In addition it is suggested that the allowance for expansion can be less than sufficient to provide for all expansion, because summer pressures, if controlled and uniformly distributed, are beneficial, especially in decreasing high summer warping stresses. Possibly, in the future, steel reinforcement in the pavement can be replaced by steel springs in the joint, and some of the winter tension can be offset by controlled compression as a permanent feature of design.

If joint fillers cannot always fill the joint space, and if infiltration is not removed, joint spaces should be wide enough to prevent consolidation of infiltrated material; or a filler should be used that will avoid high eccentric pressures. The potentialities of wood, both precompressed and uncompressed, give the best promise of filling the above requirements of joint fillers and wood should be tried extensively with, however, such safeguards as are thought necessary to prevent any unexpected bad results If then, wood does not prove equal to present expectations, the results, considering its replaceability, can hardly be less satisfactory than present practice.

Finally, it is a regrettable situation that at this time the scarcity of data requires evidence to be supplemented so much by speculation and inadequately supported conclusions in the consideration of improvement of joint and pavement design. It is hoped that this account of failure, success, hope, and probabilities may direct closer attention to present shortcomings and lead to better designs for the future If only it prompts questioning of the accepted way, it is useful

The author desires to acknowledge the work of William Van Breemen of this Department in contributing generously of his time and thoughts to making this account more complete and accurate All the details of designing, testing, and observing mentioned have been done by him or under his personal supervision