though it may not have been immediately apparent.

It is further indicated that the desired practice of a uniform load policy throughout the year in the frost belt may be economically unsound. With the possible exception of limited and extremely important mileages of highways, road investments could probably be more fully utilized by seasonal changes in load limits in harmony with the ability of soils and road bases to support the loads.

In this report it was hoped to direct attention to the general nature of this research project, the objectives of the committee, and the indications of the limited data so far assembled. Most of the work still lies ahead.

The committee has so far issued two bulletins covering the scope of its meetings and details of the testing activities. If any States not already engaged in the testing program are interested in this information, it can be secured from the Highway Research Board.

FINAL REPORT OF PROJECT COMMITTEE NO. 1, MAINTENANCE OF CONCRETE PAVEMENT AS RELATED TO THE PUMPING ACTION OF SLABS

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SYNOPSIS

The purpose of the report is to summarize the findings and conclusions of the Committee in a form which will be useful to the engineer who has neither time nor inclination to read all of the reports published under the sponsorship of the Committee.

The data collected show conclusively that the repeated passage of heavy axle loads is the primary activating element in pumping at joints and cracks in concrete pavements.

Free water and fine-grained subgrade soils are the other contributing factors. Both of these elements may be present in a pavement structure indefinitely

without the development of pumping unless the deflections of the pavement slabs are increased sufficiently in number and magnitude by the passage of heavy loads to cause the subgrade soil to go into suspension and to be pumped out, thus removig the subgrade support. In dual-lane pavements practically all of the pumping occurs in the outside lanes which are used by the slower, heavily loaded trucks, while little, if any, pumping is found in the inner lanes used by the faster and lighter traffic. This is further evidenced by the instances where heavy traffic on one lane of a two-lane highway has produced pumping, while the lighter traffic on the other lane has produced none.

The speed of heavily loaded vehicles has been found to influence pumping. Pumping is more pronounced on uphill grades where truck speeds are necessarily reduced. Also deflection studies have shown that slab ends, when subjected to constant axle loads at different speeds, show less deflection at higher speeds.

In general, the results of the studies made by the Committee indicate that pumping occurs on pavements placed on subgrade soils that contain less than 55 percent retained on the No. 270 sieve (0.05 mm.), which is commonly designated as sand and gravel or in locations where granular subgrades contain plastic fines and the truck traffic is exceptionally heavy.

The consolidation or shear strength are of little value in predicting the pumping potentialities of subgrade soils. The data presented indicate that pumping may be delayed by the compaction of soil in the subgrade to the maximum density at optimum moisture content.

Sub-bases composed of granular materials placed over fine-grained or pumping soils will prevent pumping. Materials for sub-base may be divided into two classes: (1) densely-graded materials and (2) open-textured materials.

Densely-graded materials may be placed in a trench section while the open-textured types should be placed the full width of the grade or should be drained adequately by other means. The minimum thickness of sub-base required to prevent pumping is not known. Thicknesses of 3 to 12 in. of both types of material have been used and all have been reported as effective in preventing pumping.

No relation between pavement age and pumping has been found. Old and new pavements alike have been found to suffer when the factors contributing to pumping are present. Similarly, if one or more of the causes is absent, as is true on a great majority of the mileage of old and new concrete pavements, pumping has not occurred.

The data available show that neither cross section nor thickness have had any effect on pumping. Studies to date have not shown that pavement thickness in excess of that required for imposed loads and the normal supporting value of the subgrade will be either helpful or economically justified. The data obtained have been insufficient to establish the relation between deflections caused by heavy loads and the characteristics of subgrade soils. It will be necessary to establish this relation before conclusions can be drawn as to the practicability of the prevention of pumping by increasing pavement thickness.

The observations presented to the Commitee to date justify the conclusion that expansion joints should be omitted from concrete pavements or be spaced at the maximum distance permissible for keeping compressive stresses within critical limits.

Reports submitted to the Committee show that pumping has developed at both expansion and contraction joints on pavements built with expansion provisions commonly used where soil and traffic are conducive to pumping. Under similar conditions, pavements built with little or no provision for expansion, or that have otherwise been held in restraint, have developed much less or no pumping.

Expansion joints filled with premolded rubber, bituminous impregnated fiber, poured bitumen, and air-chamber filler have been examined. None has been found capable of preventing pumping.

Load transfer devices, by themselves, have not been found to be effective in preventing pumping. In New Jersey, pumping has been held to a very small amount by the use of 2-in. channel-type dowels. Load transfer devices have reduced faulting at joints which pump. Other things being equal, the dowel bar has been more effective than proprietary types of load transfer devices.

Because of the many other variables involved, it has been difficult to determine the value of joint drains in controlling pumping. No agency reports joint drains as being fully effective in preventing pumping.

Results obtained by mudjacking during the past 10 years and by bituminous undersealing during the last 4 years indicate that voids underneath the slab where free water might collect can be eliminated. However, due to deflections resulting from heavy axle loads and the depth of the unstable soil in the subgrade (caused by both free water and capillary action), the layer of slurry or bituminous material injected under the slab is not a permanent cure-all and generally does not prevent the recurrence of pumping after the pavement has been subjected to heavy loads over a long period. Eventually some of the joints and cracks stabilized by mudjacking or undersealing will resume pumping. Future maintenance must provide for frequent inspections and probably an annual mudjacking or bituminous undersealing.

It can be concluded that in addition to correcting poor drainage conditions, the proper maintenance methods for preventing and correcting the pumping of concrete pavement slabs involve two or more of the following activities: (1) mudjacking, with soil-cement-water mixtures or cement-water slurries; (2) bituminous undersealing; (3) joint and crack sealing; (4) patching full depth with concrete; (5) covering with bituminous surfacing; (6) concrete resurfacing; (7) shoulder maintenance that will insure fast run-off and thus avoid the ponding of water along the edges of the pavement.

The Committee was organized in 1942 to study the causes of pumping and to find, if possible, effective measures to correct pumping on pavements in service.

The first meeting was held at Chicago in June 1942 to discuss the details of a Wartime Road Problems Bulletin on Maintenance Methods for Preventing and Correcting the Pumping Action of Concrete Pavement Slabs. The original bulletin, Wartime Road Problems No. 4, was published in October 1942.

Meetings of the Committee were held during the annual sessions of the Highway Research Board in 1942 and 1943. In October 1945 the Committee met at Purdue University and after a one-day session, made an inspection of the concrete pavements of Indiana and Ohio in an effort to get first-hand information on the pumping problem. The final session was held in Columbus, Ohio.

In May 1946, a similar meeting was held in Missouri, Oklahoma and Kansas. One day was devoted to a meeting in St. Louis. Two days were spent inspecting the concrete pavements in Missouri, Oklahoma and Kansas where special attention was given to the success of granular sub-base as a pumping preventive measure. Attention was also given to the use of bituminous materials in undersealing and to the construction of bituminous surfaces on old pumping pavements as corrective measures.

The Committee met in Trenton, New Jersey during the period of May 5 to May 8, 1947. One day was devoted to a detailed examination of the preliminary draft of this report and three days were spent making inspections of concrete pavements in New Jersey and on Long Island, New York, with special attention being given to the volume of traffic, the use of special sub-bases, and pavement design.

The Committee has sponsored pavement surveys in Tennessee, North Carolina, Kansas, Illinois and Ohio. The survey in each of these states was conducted by the personnel of the State Highway Department and the Portland Cement Association. The reports of the investigations in Tennessee, North Carolina, Kansas, and Illinois have been published as Research Report 1-D (with supplements) by the Highway Research Board. Two surveys have been conducted in Indiana and the reports have been published under the sponsorship of the Committee. In addition, reports on various phases of the pumping problem made by representatives of the Highway Departments of Missouri, New Jersey and Ohio have been published.

This report is a summary of the data and observations submitted to the Committee by the membership.

Although pumping has occurred on a relatively low percentage of the total mileage of concrete pavements in the United States the distribution of the phenomenon is quite wide. The seriousness of the problem cannot be over-estimated. The elimination of the causes in the design of future pavements and

the correction of pumping in existing pavements are of primary importance to all highway engineers. The objective of this committee was to determine, through study of concrete pavements on which pumping had and had not occurred, the causes, methods of correction on existing pavement, and the changes in design and construction necessary to avoid occurrence of the phenomenon on new pavements. Included were studies of location, subgrade and base course materials, pavement and base course thicknesses, joint design and spacing, traffic, and all other details that must be considered in the design and maintenance of a concrete pavement and its underlying structure.

DEFINITION OF PUMPING

Pumping is defined as the ejection of water and subgrade soil through joints, cracks and along the edges of pavements caused by downward slab movement actuated by the passage of heavy axle loads over the pavement after the accumulation of free water on or in the subgrade.

CAUSES OF PUMPING

Research and observation have shown that four basic conditions must be present simultaneously to create a pumping slab. They are:

1. Frequent heavy axle loads.
2. Subgrade soils of such a nature that they may pump through open joints or cracks or at pavement edges.
3. Free water under the pavement.
4. Joints or cracks in the pavement.

If any one of these factors is absent, pumping will not occur. Continued pumping leads to the removal of sufficient soil so that lack of subgrade support results in faulting or settlement at the joints, cracking and eventual breakage of the pavement. Faulting is defined as the depression of one slab end below an adjacent slab end, usually in the direction of traffic.

Some of the visual indications of incipient pumping and of the progressive stages of actual pumping are as follows:

1. Pavement spalling along the centerline near a transverse joint or crack.
2. Ejection of water through joints, cracks and(or) along the edge of the pavement.
3. Discoloration of either the pavement surface or shoulder, or both, by subgrade soil near the joints and cracks.
4. "Plastered" hole or "mudboil" in the shoulder at edge of pavement.
5. Faulting of joints or cracks.
6. Fresh corner break or transverse crack a short distance ahead of a pumping joint or transverse crack.

Inspections should be made periodically by someone familiar with the visible indications of the early stages of pumping. Such indications serve as a warning that serious pavement distress will develop unless corrective maintenance is started immediately.

SUBGRADE CONDITIONS

The first stage of actual pumping occurs when the mixture of fine-grained soil and free water which has accumulated between the pavement slab and the subgrade is ejected. The source of free water is almost invariably surface infiltration at joints, cracks, and between the pavement edge and shoulder; however, water-bearing strata can supply water for pumping. During the spring breakup some subgrade soils may contain enough water to contribute to pumping. It has been observed that the amount of free water necessary to start pumping at a joint or crack is relatively small. Of the three variables, soil, traffic, and rainfall, affecting pumping, rainfall and the resulting free water under the pavement is the only factor that cannot be controlled.

In making subgrade surveys for pavements on which pumping has or has not occurred, many disturbed and a few undisturbed soil samples have been taken. The following tests have been made by the cooperating laboratories:

Disturbed Samples

Grain Size
Liquid Limit
Plastic Limit
Field Moisture Equivalent
Centrifuge Moisture Equivalent
Moisture-Density Relation
Permeability
Shrinkage Limit

Undisturbed Samples

Consolidation
Shear Strength

A large volume of data has been accumulated from these tests made in Tennessee, North Carolina, Kansas, Illinois, Indiana, Ohio and New Jersey and the information has been useful in the solution of the pumping problem. The following discussion is based upon an analysis of these test results.

Pumping has been most prevalent on subgrade soils in which the silt and clay sizes predominate. The data presented by five of the seven cooperating Highway Departments show that pavements placed on subgrades composed of granular materials such as sands, sandy clays, and sandy clay-loams do not pump. Data from two states indicate that a large volume of extremely heavy axle loads may cause pumping on granular soils containing highly plastic clay.

The triangular charts, Figures 1, 2, 3 and 4, show the relationship between pumping and the sand-gravel, silt, and clay content of soils. The data plotted on these charts were obtained in Tennessee, North Carolina, Kansas and Illinois. An examination of these charts shows that pumping did not occur on soils that contained more than 55 percent of combined sand and gravel. Combined sand and gravel is the fraction of the total soil sample which is larger than 0.05 mm. or will be retained on the No. 270 sieve.

Pumping did not occur on every soil containing less than 55 percent of sand and gravel even though the pavements carried traffic that would ordinarily have caused pumping. In instances where pumping was absent other factors were found to have exerted a beneficial influence. In some instances the joints were relatively watertight because of an effective seal; and in others, high subgrade density and low moisture content were responsible for the absence of pumping.

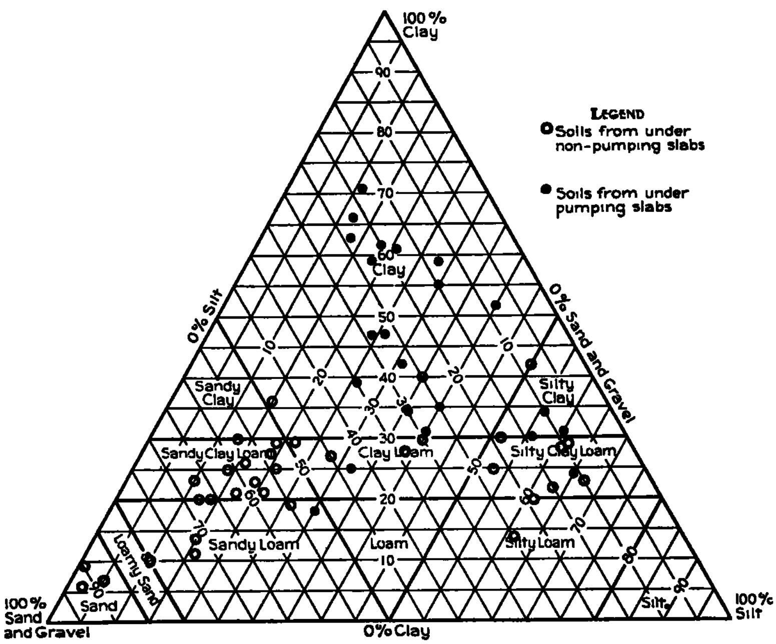

Figure 1. Textural Classification of Tennessee Soils Sampled from Under Pumping and Non-Pumping Slabs

In North Carolina all soils sampled under pumping slabs were of a plastic nature. Liquid limits and plasticity indexes ranged from a low of 32 and 17 respectively for a clay loam soil having 27 percent clay with 16 percent colloids and associated with light pumping to a high of 93 and 64 for a fat clay soil causing severe pumping. Nine of the 25 samples of soil on which no pumping was found were of a non-plastic nature. An additional eight samples were moderately plastic having

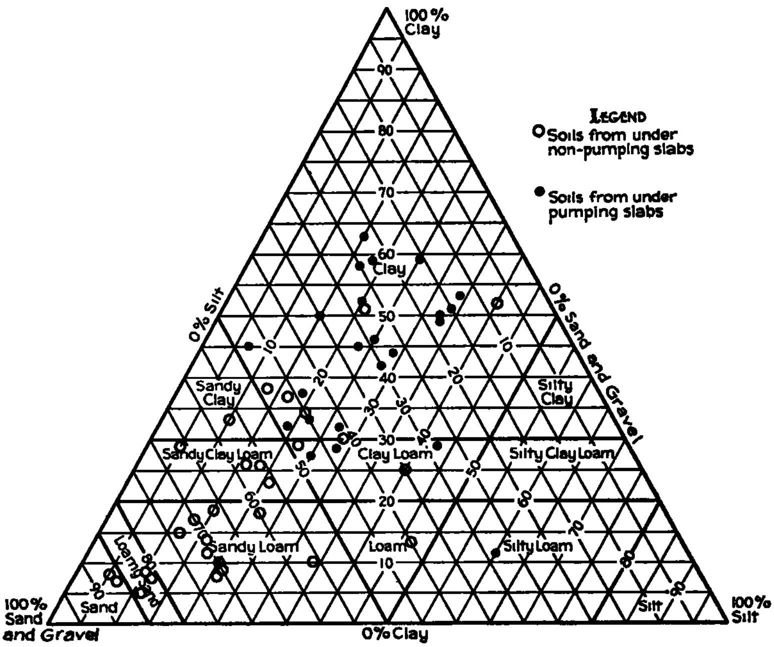

Figure 2. Textural Classification of North Carolina Soils Sampled from Under Pumping and Non-Pumping Slabs

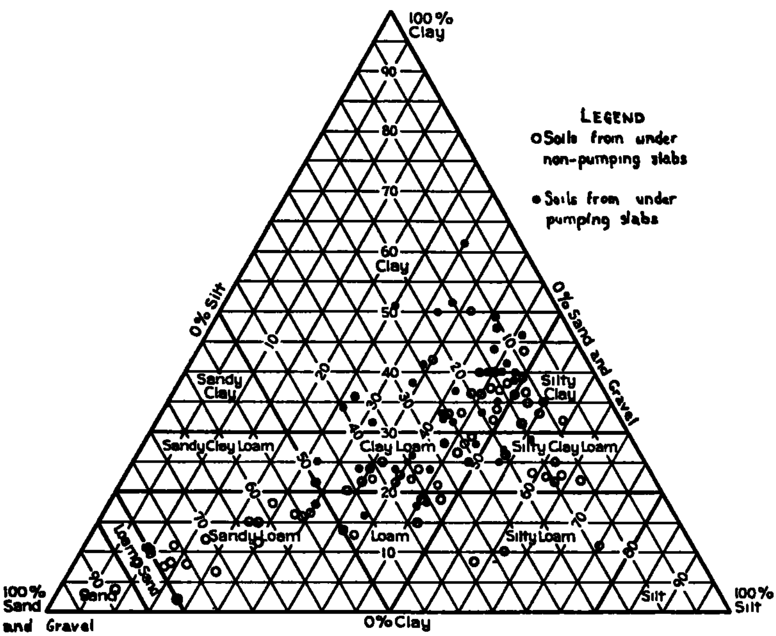

Figure 3. Textural Classification of Kansas Soils Sampled from Under Pumping and Non-Pumping Slabs

plasticity indexes of 15 or less. Eight soils had plasticity indexes in excess of 15, five of these being clay soils with indexes of 19, 20, 21, 23, and 30. No data were obtained which

explained why pumping had not occurred on these five clay soils.

In Tennessee the liquid limits of pumping soils ranged between 82 and 28, with plasticity indexes ranging between 46 and 11. The corresponding ranges for samples not pumping were between 64 and non-plastic, and 36 and non-plastic.

In Kansas samples of soils taken under pumping pavements had liquid limits ranging from 58 to 23 and plasticity indexes ranging from 37 to 9. For subgrade soils on which pumping was not observed the ranges for the 1943 survey. Data obtained from tests of soil samples taken since the 1947 survey from subgrades of pumping pavements are shown in Table 1.

Pumping in Indiana prior to 1943 was observed only on soils having liquid limits and plasticity indexes greater than 40 and 20 respectively. The data obtained since 1947 (Table 1) show that with the recent increases in traffic, pumping has occurred on soils having liquid limits and plasticity indexes as low as 20 and 7 respectively.

A survey made in Ohio in 1947 showed that

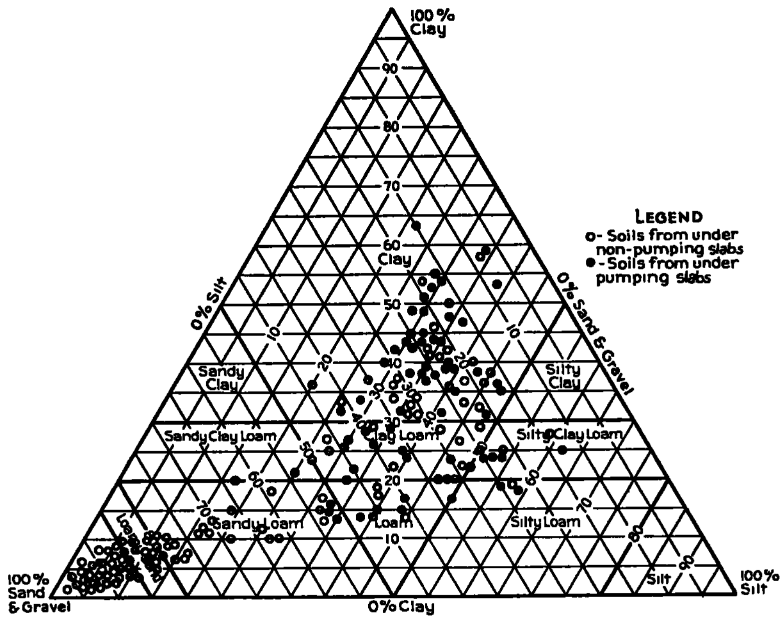

Figure 4. Texture of Soils Taken from Under Illinois Pavements During Pumping Survey—(Includes Sub-base Materials)

these constants was 57 to 15 and 31 to 2 respectively.

In Illinois the liquid limit range for pumping samples was from 54 to 21, and the plasticity index range from 29 to 7. For samples not pumping the ranges were from 57 to non-plastic and 29 to non-plastic.

In Indiana a study of the performance survey data covering both the 1943 and 1947 surveys showed that pavement pumping was spreading into soil areas in which there were few signs of pumping at the time of the 1943 survey. Information on the engineering characteristics of these new soil areas indicates that pumping has occurred on soils of lower plasticity than those affected at the time of

TABLE 1
SUMMARY OF TESTS ON HRB PUMPING SAMPLES

Sample No.	Location	LL	PL	PI	Percent Passing No. 200
2141	US 52 & SR 334—North of Indpls.	19.9	13.4	6.5	57.7
2142	US 52 & SR 334—North of Indpls.	28.6	19.1	9.5	76 5
2143	US 52—3.0 mi. N. of Lebenon, Ind	29 3	20 7	8.6	66 3
2144	US 52—5.5 mi. N. of Lebenon, Ind.	41.5	22 1	19.4	58 2
2145	US 52—Lafayette By-Pass & SR 26	26 4	16.4	10.0	93 0

pumping was confined largely, but not wholly, to fine-grained soils. Heavy traffic had pro-

duced pumping on 8 of 66 construction projects from which granular samples (containing at least 55 percent retained on a No. 200 sieve) were taken. The remaining 58 projects, or 88 percent, showed no pumping on the granular materials. Furthermore, pumping on granular materials was found to be

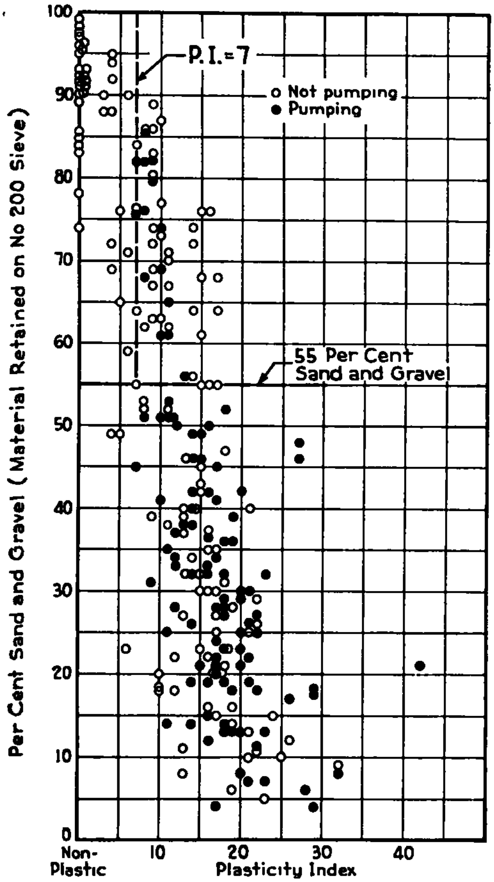

Figure 5. Relationship Between Granular Content, Plasticity Index and Pumping for Subgrade and Sub-base Samples Taken During Ohio Pumping Survey.

limited to those containing plastic fines (see Figure 5). No pumping was found on granular materials with plasticity indexes of less than 7, regardless of traffic conditions or pavement design. The entire investigation covered 160 construction projects, 75 percent of which showed pumping.

Much of the pumping on granular materials of high plasticity was in connection with pavements built during the war. These pavements have expansion joints spaced at 120 feet and contraction joints at 20 feet. No load transfer devices of any kind were used. It is now recognized that there is a progressive opening of contraction joints in pavements having a close spacing of expansion joints and that load transfer devices must be provided at all joints for adequate load transfer.

Of 87 samples of granular material taken during the survey, 14 were taken at pumping locations. Nine of the 14 were taken from under pavements having the 120-20 ft. jointing arrangement. Eight of these 9 were taken where the traffic survey, for the daylight hours of 8 AM to 4 PM, showed 437 axle loadings per 8 hr. of over 14,000 lb. The remaining sample, of a borderline sand and gravel content (56 percent), was taken where the axle count indicated 94 per 8 hr. of over 14,000 lb.

Of the remaining 5 of the 14 samples, one was of a definitely unbalanced mixture of rocks and clay. It graded from a 3-in. maximum size down through clay, but had only 3 percent between the No. 4 and No. 40 sieves, while 52 percent passed the No. 40. Heavy pumping (60 percent) occurred on this project under an indicated loading per 8 hr. of 133 axles of over 14,000 lb. Three of the 5 samples were associated with comparatively light pumping although the traffic survey indicated between 92 and 437 axles of over 14,000 lb. per 8 hr. Pumping for these projects ranged from 1.6 percent for the lightest intensity of loading to 16.8 for the heaviest. The fifth sample was taken from under a concrete pavement resurfaced with bituminous concrete, but showing a considerable amount of pumping—at 51 percent of the visible cracks and joints. This pavement, built in 1934 with expansion joints at 90-ft. intervals, was not reseated prior to resurfacing. The traffic survey indicated a loading intensity of 110 axles over 14,000 lb. per 8 hr.

As a part of the Tennessee survey undisturbed samples were taken immediately under the pavement at or adjacent to transverse joints and cracks and at locations where pumping was and was not found. Consolidation, triaxial compression and permeability tests were made on these samples. One consolida-

tion and permeability test was made on a portion of each sample as received in the laboratory and a second test was made on another portion of the sample in an inundated condition. The triaxial tests were made on the samples as received.

Nine soils from under pumping slabs and five soils from under nonpumping slabs were tested for consolidation. Greater consolidation under all loads in both the existing and inundated conditions and shorter times for maximum consolidation were found for soils taken from under pumping slabs. The data indicate a trend of greater total and residual consolidation for the pumping than for the non-pumping soils.

The values for percent reduction in height obtained in the triaxial compression test followed a trend similar to that observed in the consolidation tests. The values for shearing stress computed from the maximum differences between vertical and lateral pressures were erratic and did not show a well defined trend.

Permeability tests were made on nine pumping soils and six non-pumping soils. With the exception of one sand all were fine-grained silty-clay-loam to clay soils. No significant trends are evident from the data obtained.

In New Jersey the reconstruction in 1945 of portions of the outside northbound lane of US Route 1 over a distance of 14 miles made possible the examination and sampling of the subgrade in sections where serious pumping and faulting had occurred. The concrete pavement was 9 in. thick and of uniform cross section. It was reinforced, and had expansion joints at intervals of 35 to 38 ft. with ¾-in. round dowels 20 in. long and spaced 10 in. center to center. The daily traffic over this section was approximately 1300 axle loads of 16,000 lb. or more. Tests made on samples taken from the subgrade showed that 58 to 80 percent (average 68) of the soil was retained on the No. 200 sieve, 66 to 82 percent (average 73) was retained on the No. 270 sieve and the plasticity index ranged from 1 to 13 with an average of 9.

Studies made in Kansas, Tennessee and Illinois of the in-place density and moisture content of soils indicate that pumping occurred with greater frequency on soils compacted to relatively low densities and having low unit weights as determined by the AASHO standard compaction test. In general pumping was less frequent and less severe on soils having high density as determined by laboratory test and having relatively high in-place density. The data obtained, however, are not significant enough to warrant the use of the moisture-density (compaction tests) and relative field compaction as a basis for evaluating the pumping characteristics of soils.

Soil-water-content determinations of soils under pumping and non-pumping pavements were made by several of the cooperating agencies. In general the moisture content of the soil under pumping pavements was slightly in excess of the plastic limit.

In Kansas water content determinations made at each sampling of soil showed that

TABLE 2
RATIO BETWEEN AVERAGE FIELD WATER CONTENT AND PLASTIC LIMIT AND ITS RELATION TO PUMPING (KANSAS)

Description of Soil Group	Average Soil Water Content for Group	Average Plastic Limit for Group	Ratio of Water Content to Plastic Limit
	%		
Soils found under pumping slabs All contained less than 50 percent sand and gravel.	24.8	19.4	1.2833
Soils having less than 50 percent sand and gravel and found under non-pumping slabs.	22.8	19.2	1.198
Soils containing more than 50 percent sand and gravel, none of which pumped.	13.6	14.1	0 979

where pumping occurred the soil water contents were below the plastic limits at only four locations. One of the four soils was a lean clay of the A-4-7 group having combined sand and silt fractions of 67 percent. The other three soils were loams of the A-4 group having between 15 and 20 percent clay. All were light "pumpers." The remaining 35 samples from under pumping pavements had water contents in excess of the plastic limit. They had an average water content of 25 percent compared to an average value of the plastic limit of 20 for the corresponding soil samples.

The average soil water content, plastic limit, and their ratio are shown in Table 2 for the three groups of soils from Kansas. It will be seen that the values shown are highest for pumping soils and lowest for non-pumping

soils. Data of a similar nature were obtained in Illinois. Some relationship between water content and pumping is indicated. The data, however, are not sufficient to permit their use in predicting or designing against pumping.

No effort was made during the survey in Kansas to study the moisture gradient in the soil under the slab to determine whether the concentration of soil water was greatest in the soil immediately below the slab or at some depth below the pavement. All determinations of water content were made for the full depth of the sample taken for determination of field density and physical characteristics.

The moisture contents of the soil in the subgrade of a pavement in Ohio on which pumping occurred were found to decrease with depth, averaging 26 percent in the 0.6 ft. immediately beneath the slab, 24 percent in the next 0.9 ft. and 21 percent in the bottom 0.9 ft. in a total depth of 2.4 ft. Tests of samples taken at other locations in Ohio at different depths beneath pumping pavements indicate that in about two thirds of the cases the moisture content of the subgrade soil was highest immediately beneath the pavement and decreased with depth within the range sampled.

In Tennessee soil-water-content determinations were made at 14 locations where pumping occurred and at 15 where no pumping occurred. Water contents of less than the plastic limit were found in only two of the 14 locations where pumping occurred. The major portion of the pumping locations had water contents of 3 to 5 percentage points greater than their corresponding plastic limits. The average water content exceeded the average plastic limit by three. Five of the eleven tests of plastic soil from under non-pumping slabs had water contents below their plastic limits and six had water contents 1 to 4 percentage points greater than their plastic limits. The average water content for plastic non-pumping soils immediately under the pavement was 19.4 percent compared to an average plastic limit of 18.9 percent. Density and water-content tests showed that in nearly every instance the soil was at or near saturation.

In Tennessee the variation in soil structure and compactness of different horizons in the soil profile had little or no influence on pumping in some soils and much in others. Pumping was often equally severe in the B and C horizons of soils derived from limestones and cherty limestones. However, in soils formed from loess, the more compact and less perfectly drained B horizon of the Loring series accounted for a major portion of the pumping found on those soils. The soils of the Muskingum and Hartsells series formed from sandstones and shales sometimes had compact clay strata underlying pervious sandy soil. The less pervious compact clay strata restricted drainage, and caused the clay soils to become saturated and pump badly where the clay strata intersected the grade.

In Illinois, the topsoil used in much of the subgrade where pavements followed closely the original ground line (grade) showed considerably less pumping than did more plastic and fine-grained B and C horizon soils used in subgrades in rougher terrain.

SUB-BASES

The fact that pumping was not found on pavements in Kansas, Tennessee, North Carolina and Illinois placed over subgrade soils that contained more than 55 percent of sand and gravel lead to the study of existing sub-bases and their efficacy as a preventive measure.

In Tennessee subgrade treatments consisting of 2 to 4 in. of loose sand mixed with the existing clay subgrades to compacted depths of 4 to 8 in. were employed on three projects. The natural subgrade soils on all three projects consisted of heavy clay soils derived from cherty limestones and are representative of the worst pumping soils in the State. Some pumping occurred on all three projects. However, the analysis of soil samples taken as a part of the study showed that where the sand and gravel content (portion having particles larger than 0.05 mm. diameter) in the treated subgrade soil was greater than 55 percent, pumping did not occur. Two of these projects carry a moderate number of heavy axle loads. The third carried the greatest number of heavy axle loads encountered in the State.

Also in Tennessee there was evidence in some locations that sand-gravel used for temporary surfacing during the period between grading and paving had been effective in materially reducing pumping.

In North Carolina the materials used for

sub-base construction on the projects sampled consisted of selected soils of sand, loamy sand and sandy loam texture. With one exception all sub-base materials had combined sand and gravel contents (retained on No. 270 sieve) of 70 percent or more. Only three samples had clay contents in excess of 10 percent.

Grain-size curves of three samples which are representative of the range of sub-base materials used in North Carolina are shown in Figure 6. Sub-base soils ranged from well graded materials to gradings having as much as 50 percent of the total material between the No. 20 and 60 sieves. All had little or no volume change and all were densely graded to the degree that they restricted the downward movement of surface water and thus served to protect the underlying plastic subgrade soil.

In Indiana seven test sections with differently treated subgrades were installed in 1937 on a heavily traveled section of US Highway No. 30 in an industrial district near Valparaiso. These experimental treatments included base courses composed of granular materials, treatment of the subgrade with limestone dust, and with tar, emulsified asphalt or cut-back asphalt. Observations made in 1946 indicated that all of these treatments were effective in reducing pumping. Two base courses, one composed of three inches of crushed limestone and the other six inches of dune sand were most effective. No pumping developed in either of these sections. The materials used in these base courses contained 93 percent larger than the No. 270 sieve and were non-plastic.

Sub-bases were first constructed in Kansas in 1933. They were built to control differential volume change of highly expansive clay soils. The more recently constructed sub-bases were built to serve the combined pur poses of controlling soil shrinkage and swell providing increased subgrade support and preventing the occurrence of pumping. The survey indicated that only 1½ percent of all joints and cracks in pavements constructed on sub-base were pumping. The investigation included approximately 38 miles of pavement placed on sub-base. The pumping which occurred on these pavements was largely of a light nature, there being only a small amount of moderate pumping and no severe pumping.

The pumping which did occur on sub-bases occurred only on those having less than 50

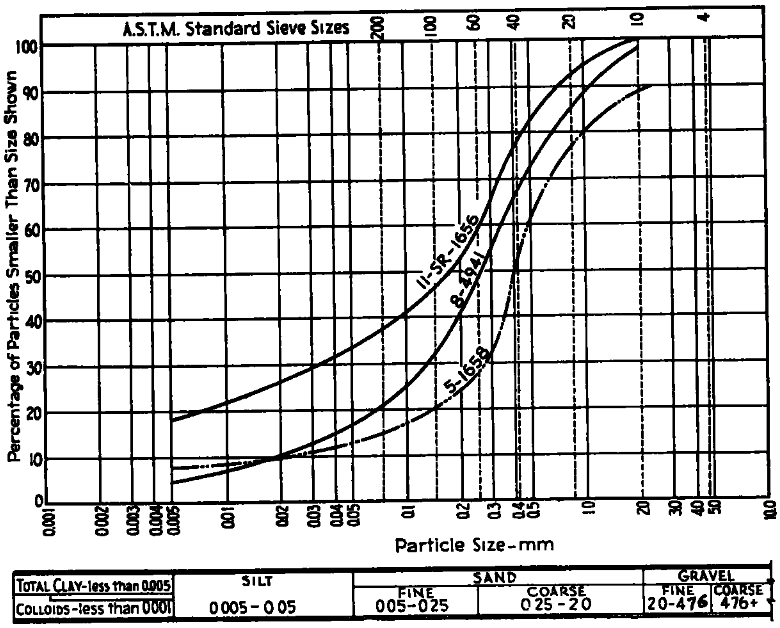

Figure 6. Grain Size Curves Indicating Range of Gradings Which Were Used in Sub-bases (North Carolina)

percent of sand and gravel in the total material. Figure 7 shows typical grain size distribution of soils used successfully in sub-bases in Kansas. Sample No. 19 is from a sub-base of crushed stone screenings.

Sub-bases built in Kansas ranged from 4 in. to 18 in. in design thickness. Widths were from 22 ft. (for 20-ft. pavement) to full roadway width. The major portion was built two feet wider than the pavement. No relation was found between thickness of sub-base and pumping. At one location where the sub-base consisted of 2½ inches of moderately open-textured limestone screenings, the underlying clay soil subgrade had become muddy at the interface with the sub-base and mud had intruded into the screenings. No pumping was found at the time of sampling and there was no evidence that pumping had occurred. However, the fact that intrusion had taken place indicates that pumping may take place under continued wet weather and heavy traffic. Neither was pumping found on sub-base thicknesses ranging from 4 in. up to 18 in. where the sub-base consisted of material of which 50 percent or more was retained on the No. 270 sieve (0.05 mm. diameter). Pumping occurred irrespective of thickness on sub-bases having less than 50 percent of material retained on the No. 270 sieve.

Pumping on heavily traveled projects in Illinois has been prevented by the use of 6 inches of densely graded granular base course. Practically all of these were built two feet wider than the pavement and were not provided with drains. The drains on one of two projects provided with them were definitely not effective.

Grain-size curves of typical sub-base materials as found in Illinois are shown in Figure 8. It will be noted that all contained sand and gravel well in excess of the 55 percent limit found to prevent pumping in Illinois.

Laboratory tests of minus No. 4 fractions of sub-base materials used in Illinois show coefficients of permeability ranging between 28 × 10^{-2} and 45 × 10^{-6} ft. per day when compacted to maximum density at optimum moisture content. It seems reasonable to expect that the total sub-base materials would be even less permeable.

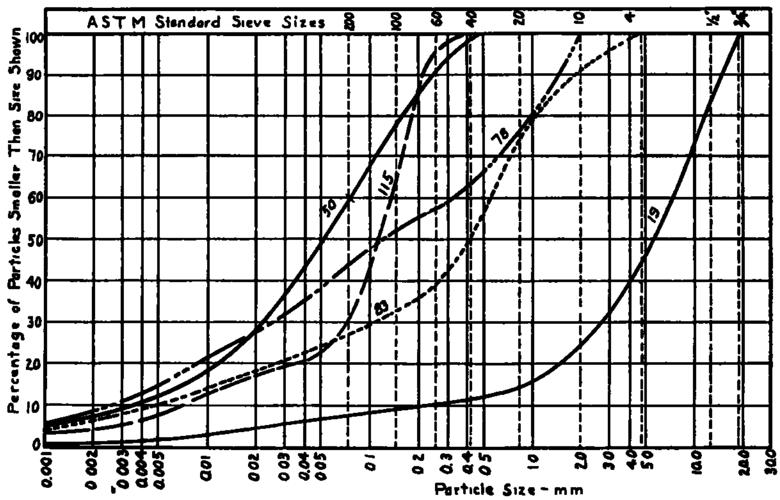

Figure 7. Grain Size Curves Indicating Range of Gradings of Non-Pumping Sub-base Materials (Kansas)

In Ohio pumping has been prevented by the use of granular sub-bases composed of open-graded granular material varying in thickness from 6 to 24 in.

New Jersey has successfully used granular sub-bases 8 to 18 in. in thickness on heavily traveled highways since 1939. These sub-bases are composed of bank-run sand, gravel or cinders.

Data as to the maximum liquid limit and plasticity index of materials suitable for ma-

terials to be used in sub-bases under concrete pavements are limited. The materials used in Illinois had a liquid limit as high as 33 and a maximum plasticity index of 13. In Kansas the maximum liquid limit and plasticity index for the densely-graded base courses were 33 and 17 respectively.

In Illinois the field water contents of subgrades under the densely-graded sub-bases were substantially the same as for similar subgrades offering direct support to the pavements, indicating the effectiveness of densely-graded materials in preventing softening of the subgrades below them.

As indicated by Figure 5 and the discussion on subgrade conditions, materials used as mass under rolling. Most of the open-graded materials are composed of aggregates having less than 5 percent passing the No. 200 sieve.

The densely-graded type of granular sub-base is usually constructed in an undrained trench somewhat wider than the pavement. To be successful, this type of sub-base must be compacted to maximum density and be of such a gradation that it is practically impervious. Only when these two conditions are satisfied will an undrained trenched-in sub-base be unaffected by the penetration of surface water. Lack of proper compaction will lead to faulting brought on by traffic causing further consolidation of the sub-base and by free water in the sub-base. Should

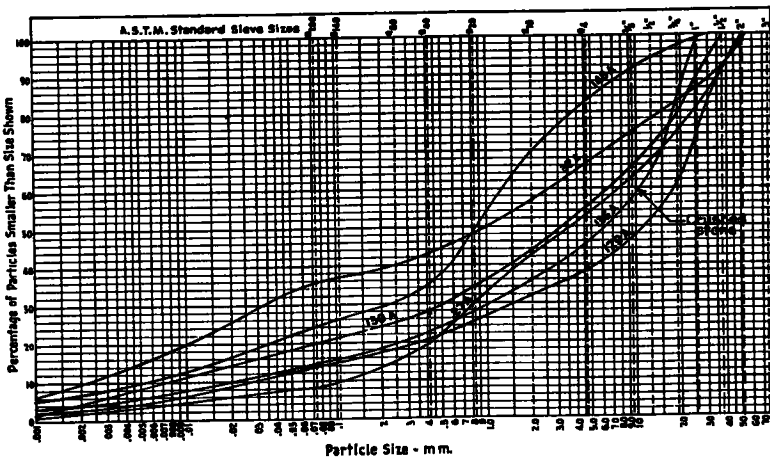

Figure 8. Grain Size Curves of Typical Sub-base Materials, Illinois Pumping Survey

subgrades and sub-bases in Ohio having more than 55 percent sand and gravel retained on the No. 200 sieve had plasticity indexes ranging from non-plastic to 18. Pumping was found at some locations where the plasticity index of the sub-base (or subgrade) material ranged from 7 to 13. Pumping was not found at any location where the plasticity index was less than 7.

Granular sub-bases found to be successful in preventing pumping have been composed of either densely-graded materials undrained, or of open-graded materials provided with adequate drainage.

The limited data on permeability now available indicate that some well-graded materials with as little as 5 percent passing the No. 200 sieve will compact into a relatively impervious the gradation be poor, the sub-base will have a high water holding capacity even though well compacted. Water in an undrained granular sub-base resulting from either improper compaction or gradation may lead to the expulsion of clear water at the pavement edge, causing a condition similar in appearance to pumping, although no subgrade material is removed from underneath the pavement.

The open-graded sub-base, must be properly compacted and of such a gradation that drainage will take place without seriously softening the subgrade. It must not be so open textured as to permit the intrusion of the subgrade and it must be provided with some system of drainage that can be maintained and kept open throughout the life of the

pavement. Such drainage is provided by using either shoulder drains or by constructing the sub-base the full width of the grade. New Jersey reports the failure of an extremely open-graded sub-base in which the clay subgrade worked up through the entire 9-in. thickness and pumped to the surface at a number of joints.

The densely-graded trenched-in type of granular sub-base has been satisfactory and is generally the most economical to construct, provided that the required material is readily available. The economy results from the fact that there are no shoulder drains to construct and keep open as are necessary when an open-graded trenched-in type of sub-base is used. Also, the quantity of material required is about half of that used when the open graded sub-base is placed the full width of the grade. The necessity for adequate and continued drainage is the chief disadvantage of an open-graded sub-base. It is doubtful if even full width construction gives complete assurance of drainage after a few years. Silting may take place in the shoulder materials as it takes place in the conventional shoulder drains and it will probably be only a matter of time until the sub-base will be improperly drained. In northern areas, shoulder drainage channels regardless of type tend to fill with ice during the fall and winter months. They then remain frozen long after the subbase under the pavement has thawed out each spring. These drains may be ineffective during a large portion of the season when pumping conditions are severe.

STRUCTURAL FEATURES OF PAVEMENTS

In the surveys made of pavements on which pumping had and had not occurred the structural features of the concrete slab were given careful consideration in an effort to determine their relation to the problem. Data on the following major items were recorded:

1. Pavement Age
2. Pavement Cross-section
3. Joint Spacing and Fillers
4. Load Transfer Devices
5. Reinforcement
6. Drains
7. Aggregates
8. Shoulders

Pavement Age—No relation between pavement age and pumping has been found. Old and new pavements alike have been affected when the four factors contributing to pumping are present.

Pavement Cross-Section—Pumping has been found on pavements varying in interior thickness from 6 to 10 in. and on all types of cross-sections built since the earliest period of concrete pavement construction. The studies have not shown that pavement thickness greater than that required for imposed loads and the normal supporting value of the subgrade will be helpful in preventing pumping or economically justified.

Pumping has occurred in New Jersey on a number of pavements that are uniformly 9 and 10 in. thick.

In North Carolina five pumping projects of 8-7-8-in. by 18-ft. cross-section and having an average age of 19 yr., a total length of 44 mi. and constructed without expansion joints, showed 2.3 percent of all cracks pumping. Five pumping projects of 9-7-9-in. by 20-ft. cross-section and having an average age of 5½ yr., a total length of 49 mi. and constructed with expansion joints at 90- or 120-ft. intervals showed 7 percent of all joints and 3.3 percent of all cracks pumping. Traffic, based only on the total number of trucks per day, was approximately the same in each case. All ten projects were on soils, a major portion of which were considered to be conducive to pumping. Here the newer, slightly heavier and wider pavements which had a shorter crack and joint interval pumped more than did the older pavements. This makes it evident that cross-section is of less significance in preventing pumping than are some other factors in pavement design.

In Tennesse of 36 projects on which pumping was studied, 26 were of 8-6-8-in. cross-section. Ten of the 36 projects were 18 ft. wide, 18 were 20 ft. wide and 3 were 22 ft. wide. Two projects were of 7-in. uniform thickness and 4 were of 9-7-9-in. by 20-ft. cross section. Pumping occurred on all pavement cross-sections where other conditions conducive to pumping were present. The 9-7-9-in. cross-section showed an average of approximately one-third as much pumping as did the 8-6-8-in. pavements, but the former carried about two-thirds as many heavy axle loads as did the 8-6-8-in. pavements.

In Kansas nearly all projects surveyed were built with a 9-7-9-in. cross-section, the transition from the 9- to 7-in. thickness being obtained in 4 ft. A large proportion were of 20-ft. width. Pumping was found on pave-

ments having 9-6-9-in. and 6-8-6-in. cross-sections but the number of projects was insufficient to obtain a significant comparison of pumping on different cross-sections. Also pavements built with 18- and 22-ft. widths as compared with these of 20-ft. width, were too few in number to justify analysis.

In Illinois, pumping was found on pavements having cross-sections of 9-6-9-in. by 18 ft., 9-7-9 in. by 22 ft., 10-8-10 in. by 20 and 22 ft., 7-in. uniform by 18 ft., and 10-in. uniform by 24 ft. No relationship was established between pavement thickness and pumping, although it was noted that thicker pavements offered somewhat more resistance to severe pumping than did thinner pavements.

Lip Curb Design—Seven projects having lip curb on hill sections and no lip curb on the flatter grades were studied in Kansas to determine the influence of lip curb on pumping. All of these pavements were placed on fine-grained residual soils derived from limestones and shales and which are considered potentially pumping soils. The lip curb was 3 in. high at the pavement edge and sloped inward for a distance of 12 in. There was a slightly higher percentage of pumping joints and cracks on the lip curb section, but the degree of pumping was less severe than on the section without lip curb. No edge pumping occurred on lip curb sections, but it should be kept in mind that these sections were all on grades that provided better surface drainage than the flatter grades on which the sections without lip curb were located.

Joints—Data collected by the Committee show that pumping at cracks and joints is greatly reduced on pavements otherwise similar but having long expansion joint spacing (300 to 800 ft.) or having no expansion joints. Although omission or longer spacing of expansion joints will not in itself prevent pumping there is no question of its value in conjunction with other preventive measures.

In North Carolina pavements without expansion joints which were placed on subgrade soils conducive to pumping showed much less pumping (only about one-tenth as much) than did pavements built on similar soils and having expansion and contraction joints both with load transfer devices. This was true although the pavement built without expansion joints is much older and carries at least as much traffic. Evidence was found that transverse cracks in the older pavements having no expansion joints were, in some instances, filled with debris and the slabs appeared to be in compression. However, there was no evidence of distress as a result of the compression.

In Tennessee studies were made at joints and cracks on 33 pavement projects having a total length of 229 miles and covering the range of subgrade soils occurring in the state. On the average, the amount of pumping at expansion joints differed but little from that at contraction joints or transverse cracks. However, very few individual projects showed the same amount of pumping at joints and cracks, the amount being influenced by the frequency of cracks, the spacing of expansion joints and resulting width of crack opening, the relative maintenance condition of the sealing material at joints as compared to cracks, and apparently whether the dowels at joints permitted free movement of the slab ends. The following examples illustrate the wide difference in pumping at joints as compared to pumping at cracks on individual projects. On one 4-lane divided highway, having no transverse cracks, 6 percent of the joints pumped. On another project pumping occurred at 1 percent of the joints compared to pumping at 21 percent of the transverse cracks. On the latter project the expansion joints were uniformly of the width constructed but the cracks had opened ⅛ to ⅜ in., indicating definitely that the dowels were restricting normal slab movements.

An analysis of the data collected in Tennessee shows a definite reduction in pumping on pavements having expansion joint intervals of 500 ft. with no contraction joints and a trend in the reduction in pumping for expansion joint intervals of 300 ft., as compared with pavements with shorter expansion joint spacing.

In Kansas 65 projects having eight different jointing arrangements and three projects built with only construction joints were surveyed. Expansion joint spacings with two exceptions, were nearly the same, ranging from 100.33 to 121.0 ft. Contraction joints resulted in original slab lengths ranging from 25.25 to 100.33 ft. Two projects out of the three built prior to 1925 having joints at construc-

tion stops only showed pumping. Pumping was found on two projects built in 1927 having expansion joints at 150-ft. intervals and no intermediate contraction joints. No pumping was found on one project built in 1940 having expansion joints at intervals of 353.75 ft. with contraction joints spaced at 25.25 ft. apart.

Of the projects representing the major jointing arrangements used in Kansas, 24 had no mesh reinforcement. Fifty-six pound wire mesh was used in the remaining 37 projects. The contraction joint intervals for the non-reinforced pavements were 29 and 40 ft. and for the reinforced slabs it was 50 ft. The omission of contraction joints in many of the mesh pavements resulted in a constructed slab length of 100.33 ft. For the two groups with mesh and the two groups without, pumping was greater in the group having the longer constructed slab length. Pumping was more severe on the reinforced pavement having the longer slab length. At the time of the survey the joint openings on the reinforced pavement were appreciably greater than those on the non-reinforced sections thus making the maintenance of a proper seal more difficult.

Jointing in Illinois consisted of the following four principal arrangements: Construction joints only, acting as contraction joints; expansion joints spaced at 800-ft. intervals with construction joints acting as contraction joints; expansion joints spaced at 90-ft. intervals with intermediate contraction joints spaced at 30 ft.; and expansion joints spaced at 50 ft. with no intermediate contraction joints. The last group was the only one having mesh reinforcement. The evidence indicated that on the sections with no expansion joints and with long (800-ft.) spacing of expansion joints pumping was considerably less than on the other sections.

Joint Fillers—Expansion joint fillers composed of premolded rubber, bituminous treated fiber, and poured bituminous material, have been completely ineffective in preventing pumping. The air core "copper seal" type was found to be even less satisfactory than other types.

Since 1942, wood filler has been installed on a number of projects in New Jersey; untreated Cypress, Redwood, Ponderosa Pine, and Spruce having been employed. Excessively rapid decay has occurred in the case of the Ponderosa Pine and Spruce. The Cypress and Redwood fillers are still in good condition. Recognizing that ordinary wood fillers will not completely fill joint spaces during cold weather, tests have been made to determine the possibilities of precompressed wood fillers. These tests indicate that most woods may be compressed to approximately 50 percent of their original thickness without suffering appreciable structural damage—provided that transverse spreading during compression is prevented—and that if kept dry the compressed wood will remain indefinitely at a thickness not exceeding 65 percent of its original thickness. When soaked in water the compressed wood will, however, swell to at least 94 percent of its original thickness, and some woods will swell to more than 100 percent. A number of different woods have been repeatedly compressed in clamps, soaked, and allowed to completely dry while clamped, in order to determine the loss in swelling capacity resulting from repeated compression, protracted periods of compression, exposure to different environments, and time. The tests indicate that over a period of time the wood suffers a certain amount of loss in swelling capacity, the rate of loss being most rapid if the wood is dried in an oven while clamped, but that even after many repetitions of compression over a period of several years the wood retains considerable swelling capacity. Because of the shortage and high price of the most suitable kinds of wood in recent years, precompressed wood has been installed in only a few joints. These installations, after two years of service, have performed satisfactorily. Periodic inspections indicate that during dry weather some shrinkage of the wood occurs near the pavement surface and that this permits the infiltration of a small amount of fine material to a depth of one or two inches. Below this depth, however, the wood appears to remain damp and in a swelled condition, and to completely fill the joint space at all times.

Load Transfer Devices—Load transfer devices have not been effective in preventing pumping. They have reduced faulting at joints which pump. Dowel bars have been as effective as proprietary types of load transfer devices.

On heavy trucking routes in New Jersey ¾-in. round dowels spaced 10 in. center to center were found to be inadequate for load transfer and the prevention of serious faulting. For this reason, dowels consisting of 2-in. channels spaced an average of 12 in. center to center were installed during the period 1934–1942. No faulting of these channel-dowel joints has occurred even on pumping-type subgrades and under unusually heavy truck traffic conditions. These dowels also appear to have been effectual in minimizing pumping. Channel dowels are no longer being installed, however, for the reason that over a period of years corrosion of the embedded surfaces of the dowels has seriously impaired their freedom to slide in the concrete. This excessive resistance to dowel slippage has in turn been reflected in excessive resistance to the normal contraction of the pavement. On some routes this has resulted in: (1) an over-stressing and final breakage of the reinforcing steel passing through transverse cracks; (2) an excessive opening of these cracks; and (3) faulting and pumping at the open cracks. Present specifications call for the installation of 1¼-in. round dowels, 18 in. long, 12 in. center to center, partly encased in Stainless steel or Monel tubing for purposes of preventing corrosion of the dowels and to insure continued free slippage. It is important to note that the 2-in. hot-rolled channel dowels that corroded, and subsequently seized as a result of corrosion, had been given a coating of white lead paint, followed by a coating of red lead paint, prior to installation, and that, immediately prior to the placement of the concrete around the dowels the dowels had been given a final coating of heavy transmission oil. Seizure due to corrosion has also occurred in the case of 2-in. channel dowels coated with cut-back tar. The behavior of dowels of various sizes in New Jersey appears to justify the following conclusions:

1. If the dowels are relatively small with respect to surface area the restraint to free slippage resulting from corrosion may be inconsequential. However, experience has indicated that small dowels lack sufficient strength and bearing area to prevent the faulting of joints in pavements subjected to a large volume of heavy trucking units. In addition, small dowels, or dowels having thin sections, that are not composed of corrosion-resistant materials, or are not in some positive way rendered corrosion-resistant, are naturally susceptible to rusting and disintegration within a few years.

2. If, on the other hand, the dowels are of sufficient size and number to fulfill their intended function, the ultimate effects of corrosion with respect to restricting their freedom to slide may have very serious consequences.

Experience indicates that in order to effectively counteract the faulting of joints in pavements which will be subjected to heavy trucking, the dowels must be substantially large, and fairly closely spaced. Experience also indicates that, especially in the case of dowels that have a large surface area, positive means must be provided to prevent their ultimate corrosion and seizure.

In addition, there are indications that joint devices that have a high load-transferring efficiency are more susceptible to seizure than joint devices that do not—because of a greater resistance to the loosening effect of traffic.

Investigations have disclosed that corrosion causes the seizure of dowels or other sliding joint parts primarily because of the expansible nature of the corrosion products. Corrosion, therefore, tends to increase rather than decrease the cross-sectional area of the embedded portions of dowels or joint parts. The corrosion products are capable of exerting a tremendous expansive effort tending to burst any confining medium. In the case of dowels or sliding joint parts the extremely high pressures resulting from the expansion of the corrosion products have a gripping effect that very greatly restrains freedom of slippage. Because of limited range of movement, corrosion products that form on embedded sliding parts have no means of escape.

Twelve projects in Tennessee on which load transfer devices were used and 30 projects without load transfer devices at joints were investigated. The percentage of pumping joints was slightly greater for the projects without load transfer devices. However, the truck traffic on the projects involving the use of load transfer devices was much heavier than on the older pavements built without load transfer devices. The load transfer devices did appear to reduce to a marked degree the percentage of pumping joints which involve faulting and breakage. However, it should be noted that more severe pumping was found

at intermediate transverse cracks where the pavements were built with load transfer devices at joints. Close inspection of transverse joints on two of the projects on which load transfer devices were used showed that the dowels did not allow free movement of the slabs when the pavement expanded or contracted. The total effect of restricted movement due to "frozen" dowels could not be determined for all projects, but it may account for the more severe pumping generally indicated at transverse cracks in pavements having doweled joints.

Similarly, load transfer devices in Illinois were found to materially reduce the faulting and breakage of pavements at pumping joints without reducing the total amount of pumping taking place. Both dowels and proprietary types of devices were used.

In Kansas pumping occurred at joints having all types of load transfer devices used at both expansion and contraction joints. Several of the older pavements had no load transfer devices but soil was found to be tightly packed in the joint space. Inspection by cutting out the tightly packed soil and by means of core holes drilled directly through the joints gave evidence that the slabs were in restraint. It seems apparent that this restraint provided some load transference without the presence of load transfer devices. A direct comparison could be made in the 100.33 ft. expansion joint spacing group (with no intermediate contraction joints) between the projects using dowels and those using a proprietary type of load transfer device. Both groups used limited extrusion rubber fillers. The data show that the total percentage of pumping expansion joints of the proprietary type was about twice as great as for expansion joints having dowels.

Reinforcement—Observations were made in Ohio, Kansas, New Jersey and Illinois of the effect on pumping of the reinforcement of the pavement slabs with steel mesh or bars. On one project observed in Ohio consisting of both reinforced and unreinforced slabs, it was found that pumping was most prevalent at the contraction joints on the unreinforced pavement and was about equally distributed between expansion and contraction joints in the reinforced pavement.

In New Jersey, in the instances where corrosion has caused the seizure of 2-in. channel dowels, longitudinal reinforcing steel consisting of $\frac{3}{8}$-in. diameter deformed bars spaced $7\frac{1}{2}$ in. center to center (slabs 9 in. thick, 56.33 ft. long) was not adequate to prevent the excessive opening of transverse cracks. Dowel seizure acted to restrain the contraction of these slabs. This restraint induced excessive tensile stresses in the steel passing through transverse cracks and resulted in: (1) the ultimate failure of the steel at some of the cracks; and (2) an excessive opening of these cracks. Failure of the longitudinal reinforcing steel, and the excessive opening of cracks, have also occurred in pavements having $\frac{3}{4}$-in. round dowels, but not so extensively. On heavy trucking routes faulting has invariably occurred at all open cracks, usually accompanied by pumping at these cracks. Faulting without definite indications of pumping has, however, occurred at open cracks in pavements laid on good quality granular sub-base material. No faulting has occurred at transverse cracks where the reinforcing steel has been capable of preventing these cracks from opening appreciably, nor has there been a very significant amount of pumping at cracks of this description.

In Kansas it was found that distributed mesh reinforcement prevented the opening of cracks between expansion and contraction joints and thereby caused the joint openings to be greater than those in un-reinforced pavements. The wider joint openings permitted the entrance of more water to the subgrade and, as a result the total percentage of pumping joints and cracks in reinforced pavement sections was greater than the total percentage of pumping cracks and joints in un-reinforced sections. As indicated elsewhere this analysis is based on expansion joint spacings of 100 to 121 ft. and contraction joint intervals of 29 to 50 ft.

In Illinois, pavements containing marginal bars, pavements with distributed mesh, and un-reinforced pavements were examined during the survey. Marginal bars did not appear to have much effect on pumping. Distributed mesh reinforcement almost eliminated pumping at intermediate cracks. However, it was indicated, as in Kansas, that expansion joints in mesh reinforced pavements were more susceptible to pumping than those in pavements without mesh.

Joint Drains—Drains have been used under expansion joints in Kansas at various times, the earliest installations having been made in 1934. Three types have been used. They are: (1) Precast concrete drains in which the upper portion is cast of porous concrete; (2) Pipe drains consisting of a 4- or 6-in. clay tile or perforated corrugated metal pipe covered with either crushed stone or gravel, a layer of sand being in immediate contact with the slab; and (3) French drains consisting of a trench backfilled with crushed stone or gravel. Nearly all installations were placed only under expansion joints. All drains extended through the shoulder and, with few exceptions, under the joint for the full width of the slab.

Because of the many other variables involved the effectiveness of these drains in the control of pumping has been difficult to evaluate. No agency reports joint drains as being fully effective in preventing pumping.

In many locations pipe drains have been placed at each edge of the pavement parallel to the centerline in an attempt to drain the water from the subgrade and thus prevent or reduce pumping. In the large majority of cases such drains have not been effective.

In Ohio early efforts consisted of attempting to drain away the free water by stone drains at the edge of the pavement either parallel with the slab or, as was more frequently the case, by French drains through the shoulder. Observation of the drains, particularly the open French drains extending through the shoulder, indicated that these drains in themselves were not sufficient to remove the water and to stop pumping which had already started.

In New Jersey, longitudinal crushed stone drains constructed immediately adjacent to the edges of the pavement were specified in most projects constructed during the period 1934–1939. The effectiveness of these drains is, however, not known because of the indeterminate influence of an improved joint device included in the design. However, in a very limited number of locations pumping has occurred despite the stone drains and improved joint devices. In these locations evidence has been found that the subgrade material has been pumped laterally into the stone drains causing them to be more or less ineffective. The stone drains were expensive and of doubtful long-range value and their installation was therefore abandoned in 1939 in favor of sub-base material. In the case of older pavements having $\frac{3}{4}$-in. round dowels at the expansion joints, the installation of longitudinal crushed stone drains in conjunction with perforated metal pipe has, at the best, merely postponed pumping and faulting. The indications are that the effectiveness of drainage of this kind is only temporary.

Aggregates—Observations on pavements in Missouri in which coarse aggregates from several different sources were used indicated that the crack interval in sections in which gravel was used was much shorter than in sections where limestone was used. As a result pumping was more frequent and severe in the gravel aggregate sections.

In Warren County Missouri a section of pavement 17 mi. in length was constructed in 1925 and 1926 in which coarse aggregate having relatively high expansive properties was used. The crack interval for this pavement was 22.9 ft. At the same time and in an adjacent location where the subgrade conditions were the same a section one-half mile in length was built in which coarse aggregate having relatively low expansive properties was used. In this section the crack interval was 76.8 ft. The difference in maintenance cost and pavement life has been very material. The pavement with the shorter crack interval has been patched with concrete, mudjacked and resurfaced, whereas only minor surface maintenance has been necessary on the section with the longer crack interval. A similar example was found in Webster County where the crack interval ranged from 21.6 ft. for the more expansive type of coarse aggregate to 92.8 ft. for the less expansive type.

Shoulders and Drainage—It has been observed that shoulders sloped to drain storm water to the pavement instead of to the ditches, or shoulders that are badly rutted, contribute to pumping. Therefore, the maintenance of smooth shoulders sloping toward the ditch will help to eliminate pumping (This seems obvious but throughout the United States high and rutted shoulders are often overlooked). Filling ruts and holes along the edges of pavements with loosely compacted materials and the use of unsurfaced widening strips composed of pervious materials may divert the flow of water toward the pavement. These

conditions contribute to pumping and such measures should be avoided in maintenance operations. All ruts, holes and trenches for widening strips should be filled with impervious material and the finished surface sloped toward the ditch.

Pumping occurred in Tennessee under conditions of good surface drainage as well as poor surface drainage. Severe pumping was observed on grades and on heavy clay soils at many locations where shoulders were lower than the pavement edge, had slopes in excess of one inch per foot, and where the runoff was not impeded by vegetation. Contrariwise, pumping occurred on some projects having loess subgrade soils only where poor surface drainage existed.

Some projects in North Carolina constructed with sub-bases also included shoulders composed of a dense sandy loam top soil. The soil supported a growth of grass—and had very little volume change. Observations showed that even when dry the material maintained close contact with the edge of the slab. The close contact did not permit water to have free access to the subgrade in the manner commonly found in shoulders constructed of high-volume-change clays which shrink away from the edge of the pavement. Visual inspection indicated that the load supporting capacity of the shoulder material was high when wet. Therefore no depressions or ruts were formed along the edges of the pavement in which water could be trapped and seep into the base course and subgrade.

TRAFFIC

As stated in the definition, pumping occurs when heavily loaded vehicles pass over cracks and joints in pavements under which free water has accumulated on susceptible subgrade soils. The deflection of a slab end depends upon the magnitude of the axle load that is applied to it, irrespective of the gross weight of the vehicle, and irrespective of the number, size and distribution of the tires. The number of heavy vehicles and the magnitude of the axle loads have increased appreciably in the last few years and as a result the severity of the pumping action and the extent of its occurrence have increased. As a part of the surveys made by the various participating agencies available traffic data were examined and some additional observations were recorded during the course of the surveys. The analyses of the available data obtained in some of the states are presented here.

No pumping of serious consequence was reported in Tennessee prior to 1937 when the first comprehensive traffic survey was made. Although no survey of pumping had been made at that time it is safe to assume that the number of truck axle loads at that time did not cause pumping except at locations of poor drainage or as a secondary effect where pavements had become damaged. Traffic counts and weighings were made again during 1942–1943. Since the 1943 count was made only a few months before this survey of pumping, the 1943 traffic data have been used. Table 3 shows the comparative 1937 and 1943 traffic count and axle weights for four projects included in the pumping survey. The projects were located near weighing stations used in the traffic survey. The 1937 traffic included only a small number of axle loads in excess of 14,000 lb., with few to none in excess of 16,000. The 1943 count showed a large increase in axle weights in excess of 14,000 lb. A large proportion of these exceeded 16,000 lb. in weight and an appreciable percent were over 18,000 lb. The pavements for which the data are shown are 8-6-8-in. parabolic cross section as are many of the pavements examined in the Tennessee survey. It appears from the data shown in Table 3 that the pumping developed from the increase in the number of axle loads of the 14,000-lb. to 18,000-lb. and over range. The weight and frequency of axle loads necessary to start pumping undoubtedly depended on the type and condition of the subgrade soil.

A correlation between traffic and pumping was found for the uniform loess soils in western Tennessee. Under average maintenance conditions the pavement built on loess soils of average water content and density did not pump until the number of 14,000 lb. axle loads exceeded 50 per day on an 8-6-8-in. pavement. A study of the projects on which slight to moderate pumping occurred showed that such pumping was associated largely with open cracks or poor surface drainage of the pavements. An over-all study of pavements built on all soil types failed to show any direct relation between the amount of pumping and the number of axle loads in the 12,000- to 18,000-lb. range.

The influence of traffic on pumping also was evident on 4-lane roads of Tennessee where nearly all pumping occurred in the outside lane which carries nearly all truck loads. Almost no pumping occurred in the inner passing lane of 4-lane divided or undivided highways.

No quantitative data were obtained on the relation between speed of traffic and pumping. It was observed, however that many of the long mountain grades in eastern and southeastern Tennessee showed a marked difference in surface condition and pumping on the uphill traffic lanes compared to the downhill traffic lanes. A very marked difference in the density of the oil streak (indicative of slow speed and tractive effort) was observed on many long grades. In some instances severe pumping occurred on the uphill lane whereas the downhill lane showed little pumping.

Surveys at locations selected to give results fairly indicative for Kansas show that truck traffic had increased considerably in 1944 over 1936. The percentage of axles weighing over 14,000 lb. increased about three times in the years between 1936 and 1944, and axle weights of 18,000 lb. or more increased about fivefold in the same period. These increases in the heavier axle loads are undoubtedly the cause of the more widespread pumping since 1936, at which time it was limited to a few miles of pavement. Traffic data were not available in sufficient detail to determine definitely the weight and volume of critical axle loads. In general, total commercial traffic was about the same on pumping and non-pumping pavements but the number of axle loads of over 14,000 and 18,000 lb. was substantially greater on projects where pumping occurred.

Detailed commercial traffic data on US 81 south of Salina, Kansas showed a significant influence of the weight and volume of axle loads on the pumping which developed on the north and southbound traffic lanes on three projects. Faulting was twice as pronounced and pumping was practically confined to the joints on the northbound lanes where axle loads of over 14,000 and 18,000 lb. were respectively, nine and three times greater than for the southbound lanes.

In Illinois the volume and weight of axle loadings were found to determine to a considerable extent the amount and severity of pumping. This was demonstrated in a number of ways. A comparison of the amount and severity of pumping of pavements placed on similar subgrade materials but carrying traffic

TABLE 3

1937 AND 1943 TRAFFIC COUNTS AND AXLE WEIGHTS ON FOUR PROJECTS IN TENNESSEE

(Located Near 1937 and 1943 Weighing Stations)

Project	Year Built	Location	Year of Traffic Survey	24-Hour Total Traffic (Number Vehicles)	24-Hour Truck Traffic (Number of trucks)	24 Hour Truck Axle Loads in Kips (Cumulative) Under 8	Over 8	Over 10	Over 12	Over 14	Over 16	Over 18	Over 22	Total Number Axles	Remarks
FAP R-8A(4) (Reop. & Ext.)	1936	3 miles north of Memphis on US 51	1937	1580	356	586	148	56	33	19	9			734	No pumping (Loess Soils)
			1943	5740	1383	2479	522	372	189	102	48	9		3001	
FAP 36DS	1929	2 miles east of Memphis on US 70	1937	3200	547	845	304	182	60	11				1149	30% of joints and cracks pumping (Loess Soils)
			1943	3740	748	1302	575	517	367	196	130	40	8	1877	
FAP 231AS	1930	10 miles north of Chattanooga on US 27	1937	2560	351	477	224	183	131	23				702	Clay soils derived from dolomitic and cherty limestones
			1943	3780	692	1124	530	457	359	262	131	25		1654	17% of joints and cracks pumping
NRH 269B	1934	17 miles east of Chattanooga on US 41 & 64	1937	1180	313	517	150	95	60	9	4			667	Clay soils derived from cherty limestones
			1943	2975	690	1054	574	481	398	282	116	23		1628	26% of joints and cracks pumping

of a different intensity showed more severe pumping on pavements carrying the heavier loadings. This is illustrated in Table 4, which shows almost twice as much pumping, and considerably more Class 2 and 3 pumping, on the pavements with the greater intensity of loading.

Pumping in Illinois was found to be confined almost exclusively to the more heavily traveled outer lanes of multi-lane pavements. And, as in Kansas, a pavement carrying a widely different intensity of axle loading in opposite directions showed considerably more pumping to have developed in the traffic lane carrying the greater number of heavy axles.

TABLE 4
THE EFFECT OF TRAFIC ON PUMPING IN ILLINOIS
(For Pavements on Predominantly Fine-Grained Subgrades)

	Miles Involved	Percent of Joints and Cracks Pumping[a]			
		Class 1	Class 2	Class 3	Total
Less than 300 Axles per day of Over 14,000 Lb	114.8	8.5	9 5	1.5	19.5
More than 300 Axles per day of Over 14,000 Lb. . .	71.4	8.6	24.2	3.4	36.2
Total . .	186.2	8.5	15.4	2.3	26.2

[a] The classes of pumping are described as follows:
Class 1. Pumping of slab ends at joints and cracks with no evidence of faulting at slab ends or breaking of slabs due to pumping
Class 2 Pumping accompanied by faulting with no evidence of breaking of slabs due to pumping
Class 3. Pumping accompanied by faulting and breaking as a result of loss of subgrade support due to pumping.

From the standpoint of violations of the 18,000-lb. axle-load law the data from Indiana show, in comparing 1936 with 1946, that the number of violations increased by some 1300 percent. Since rigid pavement pumping became a problem in Indiana at about the same time that the number of violations of the 18,000-lb. axle-load as well as gross-load limit became large, it may be concluded that trucks which violate the Indiana, state-weight law are an important contributing factor to the increase in pavement pumping in the state.

Traffic survey data in Indiana show that the percentage of vehicles having gross weights greater than 40,000 lb. increased from 0.05 percent in 1936 to 0.79 percent in 1946. Statistical analysis of the data indicates that the increase in percentage of vehicles over 40,000 lb. in gross weight and over 18,000 lb. in maximum axle load is significant and cannot be attributed to chance variation in sampling. Since vehicles with axle loads above 18,000 lb. comprise 0.7 percent of the total traffic in Indiana the data strongly indicate that less than one percent of the traffic is causing most of the pavement pumping damage.

Deflection of the pavement under axle loads of varying magnitude were measured in Indiana, Missouri and Kansas. The measurements in Kansas were made for static and moving loads, in Missouri under controlled moving loads and in Indiana under normal traffic conditions. A special device was developed and built in Missouri for measuring deflections. This apparatus is described in a report which was sponsored by the Committee (*19*).[1] The data obtained will not be presented in this report since they are available for study in the detailed report of each survey. A summary of the observations follows:

Indiana pavement deflections measured at joints emphasize the importance of vehicle weight as it affects the pavement displacement. For example, at one pumping joint, deflections of 0.002 to 0.004 in. were measured under light passenger cars, as compared to 0.14 to 0.15 in. under heavy trucks. It was found by passing a truck over the joint at varying speeds, that the slower the speed the greater the deflection. This would account for the increased pumping that is often observed on grades where the speed of heavy trucks is reduced. Many such cases can be cited where no pumping can be found on the down hill side, but where pumping is pronounced on the uphill side of the pavement. Successive repetitions of loads also aggravate pumping. For example, in observing the passage of 12 army tanks over a joint, the first two or three produced very little movement whereas the joint was pumping severely under the last two or three.

In Missouri deflections were measured before and after mudjacking or filling the voids with a soil-cement slurry. It was noted that the deflections increased for nine days after mudjacking. This was probably due to

[1] Italicized figures in parentheses refer to list of references at the end of the report.

the saturation of the subgrade by the water required for the preparation of the slurry mixture. The deflections had been reduced materially 153 days after mudjacking. In the case of the 12,000-lb. rear axle load the deflections were reduced as much as 0.007 in. whereas in the case of the 16,000-lb. rear axle load the deflections were reduced as much as 0.011 in. between the tests run 9 days after mudjacking and 153 days after mudjacking. The recorded deflections are shown in Table 5.

In Kansas data obtained in pavement deflection studies showed that under both moving and static loads vertical movements of the slab ends at both expansion and contraction joints were greater at pumping joints than at non-pumping joints. Slightly greater total deflections were observed under static loads than under loads moving at speeds up to 20 MPH. The difference was not great enough to permit the development of trends in the relationships between deflection and pumping, deflection and soil type, or in the tendency toward differential deflections with the various load transfer devices, as affected by static and moving loads. For this reason, the deflection values for static loadings have been used in analyzing the data.

Deflection measurements were made at joints where pumping was active, at joints where pumping had not started but where the soil contained less than 50 percent of sand and gravel retained on the No. 270 sieve, and at joints where the subgrade contained more than 50 percent of the sand and gravel fraction. The position of dials and wheels during load deflection studies are shown in Figure 9.

The range and average maximum measured deflections at each of the four slab corners for the joints at which deflections were measured are summarized in Table 6. Maximum deflections occurred under the loaded slab in every instance; that is, maximum deflections were observed on dials 1 and 4 when the wheels were in position A (Fig. 9) and on dials 2 and 3 when the wheels were in position C. The data in Table 6 show that the average maximum deflection at each dial is at least twice as great for pumping slabs as it is for non-pumping slabs. Also the far side of the slab in the direction of traffic deflected as much as or more than the near side (comparing deflections at dial positions 1-2 and 4-3) and that the edge deflections were greater than the center deflections (comparing deflections at dial positions 1-4 and 2-3).

In most instances lip curb was found to reduce edge deflections. Comparisons of deflections at lip curb and plain sections are

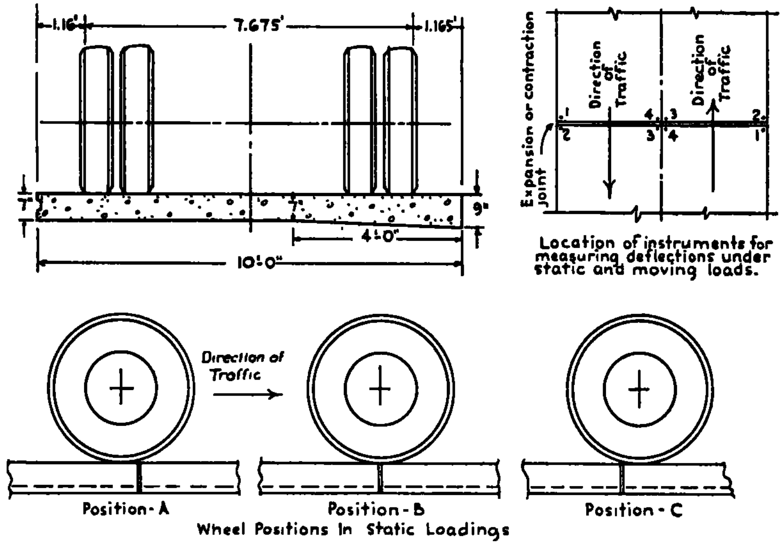

Figure 9. Position of Truck Wheels for Load—Deflection Studies

TABLE 5
Deflection Tests—Rout 40—Cooper County, Missouri

Test Slab No. 1					Test Slab No. 1A				
Run No.	Velocity	Axle Loads: Rear	Axle Loads: Front	Deflec.	Run No	Velocity	Axle Loads: Rear	Axle Loads: Front	Deflec.
	mph.	lb.	lb.	in.		mph.	lb.	lb.	in.
(Before Mudjacking)					No measurements made before mudjacking				
1	9.9	12000	3100	.018					
2	18.8	12000	3100	.014					
3	28.4	12000	3100	.013					
4	38.3	12000	3100	.009					
(Same Day—After Mudjacking)					No measurements made on same day after mudjacking				
9	9.4	12000	3100	.016					
10	19.4	12000	3100	.013					
11	28.6	12000	3100	.010					
12	38.7	12000	3100	.009					
(9 Days after Mudjacking)					(9 Days after Mudjacking)				
21	10.2	12000	3200	.020	1	10.4	16000	3000	.011
22	18.8	12000	3200	.015	2	18.6	16000	3000	.008
23	29.2	12000	3200	.018	3	28.2	16000	3000	.011
24	38.0	12000	3200	.016	4	38.0	16000	3000	.014
(153 Days after Mudjacking)					(153 Days after Mudjacking)				
29	8.3	12000	2900	.012	7	13.6	16000	3000	.000
30	9.9	12000	2900	.012	8	19.6	16000	3000	.000
31	19.8	12000	2900	.007	9	29.0	16000	3000	.003
32	29.0	12000	2900	.006	10	39.5	16000	3000	.003
33	40.6	12000	2900	.006					

shown in Table 7. The data show that the vertical movements of slab ends to the exterior corners of both expansion and contraction joints for pavements built on pumping soils are much greater on cross-sections without lip curb than they are on cross-sections with lip curb. This is true regardless of the type of load transfer device used.

Differential movements were small at non-pumping joints on potentially pumping soils and were rarely measurable at joints on non-pumping soils. Differential movements were, on the average, less at contraction joints than at expansion joints.

The deflection measurements were of particular value in showing the relative efficiency of the various load transfer devices in reducing the differential slab movements found to be generally associated with pumping. Differential movements of slab ends were found to be least at joints where plain dowels were used for transfer of load.

TABLE 6
KANSAS
SUMMARY OF MAXIMUM DEFLECTIONS
(in thousandths of an inch)

Dial Position	Static Wheel Position	Expansion Joints						Contraction Joints					
		Pumping Joints		Potential Pumping Soil		Non-Pumping Soils and Joints		Pumping Joints		Potential Pumping Soil		Non-Pumping Soils and Joints	
		Ave.	Range	Ave.	Range	Ave.	Range	Ave.	Range	Ave.	Range	Ave.	Range
1	A	30 (14)[a]	9–66	14 (18)	5–28	8 (3)	3–16	21 (15)	7–54	11 (10)	4–21	9 (10)	2–17
2	C	38 (14)	11–78	15 (18)	6–30	8 (3)	3–16	27 (15)	9–72	12 (10)	3–26	10 (10)	2–18
4	A	20 (13)	5–36	7 (18)	4–13	3 (3)	1–8	15 (15)	4–33	6 (10)	2–13	5 (10)	1–15
3	C	24 (13)	7–45	10 (18)	4–24	4 (3)	1–9	18 (15)	4–50	6 (10)	2–13	5 (10)	1–15

[a] Numbers in parentheses refer to number of joints involved.

TABLE 7
KANSAS
SUMMARY OF MAXIMUM EDGE DEFLECTIONS ON LIP CURB AND PLAIN SECTIONS
(in thousandths of an inch)

	Dial Position	Wheel Position	Expansion Joints						Contraction Joints					
			Pumping Joints		Potential Pumping Soils		Non-Pumping Soils and Joints		Pumping Joints		Potential Pumping Soils		Non-Pumping Soils and Joints	
			Ave.	Range	Ave.	Range	Ave.	Range	Ave.	Range	Ave.	Range	Ave.	Range
Lip Curb	1	A	15 (5)[a]	9–21	17 (9)	8–28	4 (2)	3–4	16 (3)	10–26	9 (6)	4–18	12 (1)	12
Plain	1	A	37 (9)	20–66	13 (11)	5–26	16 (1)	16	22 (12)	7–54	14 (4)	8–21	9 (9)	2–17
Lip Curb	2	C	17 (5)	11–21	19 (9)	9–39	4 (2)	3–4	18 (3)	13–27	10 (6)	3–26	13 (1)	13
Plain	2	C	49 (9)	26–78	15 (11)	6–26	16 (1)	16	29 (12)	9–72	15 (4)	8–22	9 (9)	2–18

[a] Numbers in parentheses refer to number of joints involved.

MAINTENANCE

The maintenance procedures necessary to correct pumping of slabs are dependent upon the condition of the pavement. If damage has not progressed to a point of breakage, adequate mudjacking or bituminous undersealing supplemented with sealing of joints and cracks have proved adequate. Where the damage has progressed to the point of pavement breakage, it may be advisable to replace broken areas of concrete with new concrete. However, if damage is extensive, and the riding surface is impaired, it may be good economy to resurface the pavement in order to prevent the entrance of excessive quantities of water to the subgrade and the continuation of serious pumping of damaged areas.

Sealing Joints and Cracks—It has been the observation of this Committee that proper filling and sealing of joints and cracks has been beneficial in minimizing pumping or in delaying its recurrence. Although beneficial, the sealing materials used to date have not been entirely satisfactory because of their failure to maintain a seal for any appreciable length of time, and because they seal only the top of the crack or joint and thus do not completely prevent the entrance of water to the subgrade. Continued research is needed to develop an economical and relatively permanent watertight material for filling and sealing joints and cracks. Rubber compounds, properly heated and poured at the proper temperature in clean joints, have been used and show considerable promise.

Mudjacking and Bituminous Undersealing Adjacent to Concrete Replacement—On pavements where pumping has resulted in damage to the extent that replacement is necessary, the areas surrounding the concrete to be replaced should be mudjacked or undersealed to properly "seat" the slab. This will prolong the life of the replaced concrete as well as that of the pavement surrounding it. This work should be done prior to the replacement of the damaged concrete.

Resurfacing—The degree of damage to the pavement which necessitates resurfacing can best be described as that condition where slab pumping has progressed to the extent that the riding surface has been definitely impaired and cannot be restored by jacking alone. When this condition exists, the best maintenance procedure is to follow the mudjacking or undersealing work with the construction of a resurfacing course. This may be a concrete resurfacing of adequate thickness or a bituminous surface one inch or more thick, the thickness depending upon the condition of the old concrete, and the traffic.

Concrete resurfacing will not only restore the riding quality of the surface but will add to the load carrying capacity and increase the stiffness of the pavement. Deflection under traffic will be reduced which will be effective in preventing further damage to the subgrade. Thickness of concrete resurfacing will usually range from 4 to 6 in., depending on condition of the old pavement and of the traffic to be carried. Joints in the resurfacing should be placed over those in the old concrete but contraction joints may be placed over expansion joints, thus using fewer expansion joints or none at all in the resurfacing. Where joints are at long intervals in the old pavement, intermediate contraction joints should be used at 15- to 20-ft. intervals in the resurfacing to form slab lengths which will control cracking.

It is desirable to prevent the cracks in the concrete pavement from continuing upward through the bituminous surfacing. The thickness of the bituminous surfacing will affect the number of cracks proceeding through it from the base. Experiments are now being carried on to determine more accurately the effect of thickness of the bituminous surfacing on the number of cracks proceeding through it from the base.

If bituminous resurfacing is used the pavement may be resurfaced almost immediately after sealing the joints and cracks, provided that they have been sealed with a low penetration asphalt. If cut-back asphalts are used for this purpose, adequate time should be allowed for curing before resurfacing in order to avoid bleeding through the new surface.

If the pavement is not to be resurfaced until the folloing season or is not to be resurfaced at all, the joints and cracks should be cleaned and completely sealed with a standard material. Too much stress cannot be placed on the regular performance of this phase of surface maintenance.

Careful and regular inspections of the bituminous resurfacing should be made to determine if any of the slabs have resumed

pumping, and if this condition is found, the slabs can be treated again through the bituminous surfacing by the mudjacking or bituminous undersealing methods.

Mudjacking—Results obtained by mudjacking during the past ten years and by bituminous undersealing during the last four years indicate that voids underneath the pavement where free water might collect can be eliminated. However, due to deflections resulting from heavy axle loads and the depth of the unstable soil in the subgrade (instability caused by both free water and capillary action), the layer of slurry or bituminous material injected under the slab is not a permanent cure-all and generally does not prevent the recurrence of pumping after the pavement has been subjected to heavy loads over a long period. Eventually some of the joints and cracks stabilized by mudjacking or undersealing will resume pumping. Future maintenance must provide for frequent inspections, and annual mudjacking or bituminous undersealing is often found to be necessary.

It can be concluded that the proper maintenance methods for preventing and correcting the pumping of concrete pavement slabs involve two or more of the following activities: (1) correcting poor drainage conditions by providing proper run-off; (2) mudjacking with cement slurry or soil-cement mixtures; (3) bituminous undersealing; (4) joint and crack sealing; (5) patching full depth with concrete; or (6) covering with a concrete or bituminous resurfacing. It is well to keep in mind that the common goal in all highway maintenance work is a safe and smooth riding surface.

The detailed descriptions of maintenance measures including mudjacking and bituminous undersealing will be found in Highway Research Board Current Road Problems Bulletin No. 4-R which was prepared by the Committee (*38*).

SUMMARY

The results of the studies made in Tennessee, North Carolina, Kansas, Illinois, and Indiana indicate that pumping has occurred only on pavements placed on subgrade soils that contain less than 55 percent of the fraction retained on the No. 270 sieve (0.05 mm.) which is commonly designated as sand and gravel. Data obtained in Indiana indicate that pumping has spread with increases in heavy traffic from soils having plasticity indexes of 20 or more to those having plasticity indexes as low as 7.

In Ohio pumping was confined largely but not wholly to fine-grained soils. Heavy traffic caused pumping on 8 of 66 locations on which the subgrade contained more than 55 percent of the sand and gravel fraction retained on the No. 200 sieve. The plasticity index of all of the samples taken on the 8 projects where pumping was observed on granular subgrades was greater than 7 indicating a relation between the plasticity of the soil fines and pumping.

In New Jersey severe pumping and pavement breakage was reported on one location where the subgrade soil had an average of 32 percent passing the No. 200 sieve and the average plasticity index was 9. The traffic on this project included approximately 1300 axle loads per day of 16,000 lb. or more.

The consolidation, or shear strength are of little value in predicting the pumping potentialities of subgrade soils. The data presented indicate that pumping may be delayed by the compaction of soil in the subgrade to the maximum density at optimum moisture content.

Sub-bases composed of granular materials placed over fine grained or pumping soils will prevent pumping. Materials for sub-base may be divided into two classes: (1) densely graded matrials; and (2) open textured materials. Densely graded materials may be placed in a trench section while the open textured types should be placed the full width of the grade or should be adequately drained by other means. The minimum thickness of sub-base required to prevent pumping is not known. Thicknesses of 3 to 12 in. of both types of material have been used and all have been reported as effective in preventing pumping.

Pavement age as such has not been found to affect pumping. Old and new pavements alike have been found to suffer when the four contributing factors to pumping are present. Similarly, if one or more of the causes is absent, as is true on a great majority of the mileage of old and new concrete pavements, pumping has not occurred.

The data available show that neither cross-section nor thickness have had any effect on the severity and frequency of pumping. In one state there were indications that thicker pavements reduced the severity of pumping but not the amount. The pavements of non-uniform thickness studied varied in cross-section from 6-8-6-in. to 10-8-10-in. Uniform thickness pavements varied from 7 to 10 in. The majority of observations were made on pavement having the 9-7-9-in. cross-section. Studies so far have not shown that pavement thickness in excess of that required for imposed loads and the normal supporting value of the subgrade will be helpful or economically justified. The data obtained have been insufficient to establish the relation between deflections caused by heavy loads and the characteristics of subgrade soils. It will be necessary to establish this relation before conclusions can be drawn as to the practicability of the prevention of pumping by increasing pavement thickness.

The observations presented to the committee to date justify the conclusion that expansion joints should be omitted from concrete pavements or be spaced at the minimum distance necessary for keeping compressive stresses within safe limits.

Reports submitted to the Committee show that pumping has developed at both expansion and contraction joints in pavements built with expansion provisions commonly used where soil and traffic are conducive to pumping. Under similar conditions, pavements built with little or no provision for expansion, or that have otherwise been held in restraint, have developed much less or no pumping.

Expansion joints filled with premolded rubber, bituminous fiber, poured bituminous, and air-chamber filler have been examined. None has been found capable of preventing pumping. The results of laboratory tests conducted in New Jersey and trial installations indicate that precompressed wood when used as a filler may form a relatively watertight joint.

Contraction joints of the dummy groove, premolded rubber, and full depth metal plate types have been investigated. None was found to have an appreciable influence on pumping. In Kansas, however a considerably greater amount of faulting took place at full depth metal plate contraction joints than at dummy groove joints. It was evident that aggregate interlock was of some aid in reducing pumping and subsequent faulting at dummy groove joints.

In general, load transfer devices have not been found to be effective in reducing pumping. These devices have, on the other hand, reduced the magnitude of faulting at joints which pump. Other things being equal, the dowel bar has been more effective than proprietary types of load transfer devices. In New Jersey, however, pumping has been substantially minimized, and faulting prevented entirely, by the installation of dowels consisting of 2-in. channels spaced an average of 12 in. center to center. On the other hand, based on difficulties experienced in New Jersey, the installation of a series of large dowels that are not adequately protected from corrosion may eventually cause serious damage to the pavement as a result of their seizure.

Because of the many other variables involved, it has been difficult to determine the value of joint drains in controlling pumping. No agency reports joint drains as being fully effective in preventing pumping.

The studies made by the Committee show conclusively that the repeated passage of heavy axle loads over joints and cracks in concrete pavements is the primary activating element in pumping at joints and cracks.

Free water and subgrades composed of fine-grained or granular soils containing plastic fines are the other contributing factors. Both of these elements may be present in a pavement structure indefinitely without the development of pumping unless the deflections of the pavement slabs are increased sufficiently in number and magnitude by the passage of heavy loads to cause part of the subgrade soil to go into suspension and be pumped out, thus removing the subgrade support.

From all the data collected, in only one instance has it been possible to determine the critical number of passages of heavy axle loads that produce pumping. There is a small amount of evidence that frequent axle loads of 14,000 lb. or more are required to start pumping. In the Tennessee surveys, an 8-6-8-in. pavement on a silty clay of loess origin was found to pump when the number of 14,000-lb. axle loads exceeded 50 per day and the number of axle loads over 18,000 lb. ranged from 7 to 51. Because of the many

variables involved, far more data must be accumulated before it can be stated that for any particular pavement design placed on a given soil type, pumping may take place when the number of axle loads of any given magnitude exceeds a certain figure per day. The general effect of traffic on pumping has been demonstrated in a number of ways. On many of the four-lane highways surveyed practically all of the pumping was found in the outside lanes which are used by the slower, heavily loaded trucks, whereas little if any pumping was found in the inner lanes used by the faster and lighter traffic. This effect is further evidenced by instances where heavy traffic on one lane of a two-lane highway has produced pumping, while the lighter traffic on the other lane has produced none. An outstanding example of this was found on US 81 near Salina, Kansas. On this road the northbound traffic was composed of loaded tank trucks from a refinery area and the southbound lane carried the returning empty trucks. Practically all of the pumping was found on the northbound lane where an average daily commercial axle count was 349 axles under 10,000 lb. and 275 axles over 10,000 lb., of which 155 were over 14,000 lb. and 10 were over 18,000 lb. Almost no pumping was found on the south-bound lane where the average daily commercial axle count was 506 axles under 10,000 lb. and only 38 axles over 10,000 lb., of which but 17 were over 14,000 lb. and 3 were over 18,000 lb.

The speed of heavy traffic loads has been found to influence pumping. Pumping is more pronounced on uphill grades where truck speeds are necessarily reduced. Deflection studies have also shown that slab ends, when subjected to constant axle loads at different speeds, show less deflection at higher speeds.

Results obtained by mudjacking during the past 10 years, and by bituminous undersealing during the last four years, indicate that voids underneath the slab where free water might collect can be eliminated. However, due to deflections resulting from heavy axle loads and the depth of the unstable soil in the subgrade (caused by both free water and capillary action), the layer of slurry or bituminous material injected under the slab is not a permanent cure-all and generally does not prevent the recurrence of pumping after the pavement has been subjected to heavy loads over a long period. Eventually some of the joints and cracks stabilized by mudjacking or undersealing will resume pumping. Maintenance planning must provide for frequent inspections and annual mudjacking or bituminous undersealing when found necessary.

It can be concluded that in addition to correcting poor drainage conditions, the proper maintenance methods for preventing and correcting the pumping of concrete pavement slabs involve two or more of the following activities: (1) mudjacking; (2) bituminous undersealing; (3) joint and crack sealing; (4) patching full depth with concrete; (5) covering with concrete or bituminous resurfacing.

FUTURE RESEARCH

An examination of the data available to the Committee to date indicates that research is needed to provide further information on the following:

1. Thickness and characteristics of sub-bases necessary to prevent pumping of concrete pavements placed over potentially pumping soils.

Definite conclusions as to the thickness of sub-base required to prevent pumping cannot be drawn from the data available. Therefore, it would be desirable to build experimental pavements at various locations throughout the United States that would include a range of sub-base thicknesses and control sections over which no sub-base would be used. Such pavements should be constructed in areas where soil, traffic and climatic conditions are conducive to pumping.

Further study should be made of the gradation of sub-base materials in an effort to develop suitable specifications. Such research should include studies of permeability, consolidation under repeated loadings, compaction characteristics, resistance to the unstabilizing effects of freezing and thawing, and in-place moisture-density.

2. The relationship of traffic and deflection of slab ends to pumping cannot be determined from the information that has been presented. Research is necessary to determine the number and magnitude of heavy axle loads required to start pumping on both fine grained and granular soils containing plastic fines. If information on this subject can be developed and future traffic can be predicted with any degree of accuracy it may be possible to predict whether or not sub-bases will be necessary on new construction.

Research should be carried on to determine the magnitude of the deflection of slab ends necessary to start pumping on any soil type. If critical deflections could be established it might be possible to weigh the cost of effectively increasing slab thickness or of providing load transfer devices of adequate load-carrying capacity against the cost of subgrade treatment necessary to prevent pumping.

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