DEPARTMENT OF MAINTENANCE

Pumping of Highway and Airfield Pavements

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This paper presents the results of a study of pumping of rigid pavements. A literature search was conducted on present and past experiences of state highway departments and various governmental agencies relative to the pumping problem.

A study was made of the mechanics of pumping of rigid pavements. Surveys were made of highway pavements in Indiana constructed with and without granular bases, as well as of 15 air bases.

The report is divided into three parts; namely, (a) a review of pumping of highway pavements built directly on natural subgrades, (b) performance of rigid highway pavements built on granular bases, and (c) a study of pumping of airfield aprons, taxiways and runways.

Data obtained from this study indicate that performance of rigid highway pavements built with granular bases is greatly influenced by gradation of the granular base as well as amount of traffic. Correlations are presented which show that pavement distress as evidenced by restraint and transverse cracks is due to "blowing" of bases and that this in turn results on roads carrying high volumes of truck traffic and where poorly graded bases are used. Base courses with drains have shown better performance than those without drains, although constructing poorly graded bases through the shoulder for drainage was found to be ineffective for those roads surveyed.

Pumping on airfield pavements was found to be restricted primarily to taxiways. The action is particularly apparent in areas of channelized traffic on airfields supporting wheel loads in excess of the design and when pavements are built directly on plastic clay-like materials. Pumping on airfields appears to be a minor problem. It was concluded that the primary difference between highway and airfield pavements, when comparing extent of pumping, is in the repetition of load the pavements will receive during their lifetimes. Also, airport pavements are not subjected to edge loading conditions to the same extent as highway pavements.

● THIS REPORT presents the results of a field and office correlation study of the factors affecting pumping of rigid pavements and the requirements for base courses for controlling pumping.

Pumping of rigid pavements was recognized as a serious problem during the late years of World War II. As a result, field studies were made by many state highway departments to determine the cause and extent of pumping. These early studies dealt primarily with the factors which resulted in pumping, although some attempt was made to evaluate procedures by which it could be corrected. In 1946 a special committee was formed by the Highway Research Board to study the pumping phenomena and to make recommendations for correcting pumping.

Several methods have been used for correcting pumping. These include (a) use of a granular subbase under the pavement, (b) heavy load transfer across

joints, (c) mudjacking and bituminous undersealing, and (d) resurfacing. Each method has proven at least partially successful. The last two methods listed deal primarily with maintenance, whereas the first two are positive methods that have been used with great success during the design phase. The most economical and widespread method of controlling pumping has been the use of granular bases under the pavement. However, this method, although highly successful, has in turn created several new problems.

Although granular materials do not pump in the normal sense, they are affected by a damaging process known as blowing. Though differing in some respects from ordinary pumping, blowing is basically a form of pumping which occurs in granular materials. Pavement distress resulting from blowing has been somewhat less dramatic than that resulting from pumping. Nevertheless, many miles of rigid highway pavements constructed on granular bases have shown considerable distress that can be attributed to blowing.

It is significant that the literature contains no data regarding pumping of rigid airport pavements. This is because pumping has not seriously affected airports, due to the relatively low repetition of loads during the pavement life. The records of the different governmental agencies indicate that pumping has occurred only in isolated cases on airport pavements in the past. In more recent years, however, the pumping of rigid airport pavements has increased considerably because of the extremely heavy loads presented by some military aircraft. Data are meager at the present time regarding the similarities of highway and airport pavements. Certainly the frequency and number of applications of loads on airports are much less than on highways.

In the fall of 1953, the Engineering Experiment Station of Purdue University entered into a contract with the Arctic Construction and Frost Effects Laboratory, Corps of Engineers, U. S. Army, to study the pumping problem, particularly as it affects the design of rigid airfield pavements. As a result, studies have been made of highway and airport rigid pavement pumping in an attempt to evaluate all the factors which cause pumping. As a part of the study an evaluation has been made of the present design criteria in order to make recommendations for future design.

PURPOSE AND SCOPE

The present Corps of Engineers criteria for design of granular base courses under rigid pavements, as stated in Chapter 4, Part XII of the Engineering Manual, require full depth frost protection over F_4 soil and a base equal in thickness to the slab over F_1, F_2, and F_3 soils. When the design freezing index[1] is less than 1,000 degree-days, or when depth to uppermost water table is greater than 10 ft, a base course 4 in. thick is permitted over F_1, F_2 or F_3 soils. As an added requirement this 4-in. base course must be designed as a filter against intrusion of the underlying subgrade. For rigid pavements, the 85 percent size of the filter or regular base course placed directly under the pavements shall be equal to or greater than ¼ in. in diameter. The purpose of this requirement is to prevent loss of subgrade support by pumping of soil through the joints of the pavement.

The purpose of this study is to collect data to either modify or substantiate these criteria for thin bases.

It was recognized at the outset of the research program that the largest amount of data available is that gained from past experiences of pumping on highway pavements. Few data were available regarding pumping of airport pavements. Therefore, the first objective of the research program encompassed an extensive review of available literature. Also, a study of highway performance was initiated. Concurrently, inspections were made of several airfield pavements to evaluate their performance.

Thin base courses have been used for many years as a foundation under high-

[1] Design freezing index is the freezing index of the coldest winter in a 10-year period of record or the average of the 3 coldest in 30 years of record.

way pavements to control pumping. A study of the performance of these highways was included in the over-all investigation. It was recognized that loading conditions on airfields are vastly different from those on highways; however, it was postulated that the factors affecting the structural integrity of the pavement base structure of highways and airports must be the same. Therefore, as a part of the study, basic data were collected dealing with the performance of these highways to evaluate the causes and effects of pumping and the effectiveness of relatively thin bases for controlling pumping.

A laboratory study dealing with repeated loads on base-subgrade combinations was also included as part of the over-all investigation. These data, however, are not included in this report, but constitute a separate report.

REVIEW OF PUMPING OF FINE-GRAINED SOILS

An article by Poulter (*17*) was one of the first in which pumping was mentioned. From 1939 to 1942 some work was done on methods of mudjacking pavements, but little on the basic features of pumping. Later, the HRB Committee on Maintenance Methods Related to Pumping Action of Soils published a report (*11*) in which pumping action and corrective methods were described.

This report stated that pumping action resulted from a combination of soil, water, and heavy loads. It was pointed out that free water must be present at a joint or edge of the pavement for pumping to result. Preventive measures mentioned in the report included (a) visual classification of soils, (b) sealing of joints, (c) proper surface drainage, (d) French drains, and (e) proper maintenance of shoulders. It was recognized that granular materials are not susceptible to pumping, but no mention was made of using granular bases for controlling pumping.

The corrective measures recommended at that time consisted of filling the voids under the pavement. The primary method of filling consisted of mudjacking, although the Ohio State Highway Department reported some use of asphaltic materials. For the most part, use of mudjacking or bituminous underseal materials was found to be effective in controlling pumping.

It was recognized from the start that the factors resulting in pumping were as follows:

1. Plastic soils.
2. Free water under the slab.
3. Heavy traffic loads.

Woods and Shelburne (*25*) studied each of these factors in great detail. They made a survey of pumping pavements in Indiana, and found positive correlation between soil type and extent of pumping.

Pumping was reported to be most severe in plastic lacustrine deposits and plastic moraine deposits, with less pumping found on Wisconsin and Illinois drift materials and residual soils. The predominance of pumping in cuts was noticed, particularly in deep cuts where bad ground water conditions were encountered.

It was found that pumping was most prevalent during the wet seasons of the year, and that the source of pumping water was largely surface infiltration at joints, cracks, and pavement edges. Slow-moving traffic, such as that which occurs on steep grades, was found to produce far more pumping than fast traffic. The severest pumping was found at expansion joints.

In 1938 the Indiana State Highway Department constructed a series of test sections on US 30 through the plastic shale moraine territory. The test sections included 6 in. of sand backfill and 3 in. of crushed stone backfill, as well as several sections treated with various bituminous materials. At the time of the 1943 survey a pronounced difference between the performance of the granular backfill sections and the remaining sections was noted. No pumping was found on these granular sections, although adjacent untreated sections pumped severely

and the bituminous sections pumped to varying degrees.

The highway system of New Jersey was one of the first to be affected by pumping. Van Breemen (*21*) reported that granular bases were used in that state as early as 1939 for correcting pumping. Most states have discontinued the use of expansion joints due to the severity of pumping at this type of joint, but New Jersey still uses expansion joints extensively, utilizing heavy load transfer systems at the transverse joints to minimize pumping. At present pumping is practically nonexistent in this state, due primarily to the extensive use of the state's abundant high-quality granular material in bases.

Because the water which produces pumping is a film of free water existing immediately under the pavements, efforts have been directed to correcting pumping by installation of drains. Vogelgesang (*23*) mentions how this particular method was successful in some cases, but not in others. The reason given for the general failure of this method of correction was that the drains easily became clogged by the soil slurry which is developed under the pavement.

Henderson and Spencer (*10*) reported on a survey of the aforementioned experimental sections on US 30 in Indiana. Severity of pumping of each of the sections was evaluated by means of joint fault measurements. These authors recognized that factors other than pumping can result in joint faulting, but felt that for this particular road pumping would be the primary source.

The measurements indicated that performance of the pavements was improved by treatment of the subgrade soil or use of a granular base course. The best results were obtained on two sections constructed with granular bases, one a 6-in. dune sand base, the other 3 in. of crushed stone. These sections showed excellent performance and were still in very good condition in August 1956, whereas all other sections have required undersealing and resurfacing. On several sections bituminous stabilizers were mixed with the subgrade soil. Tar, emulsified asphalt, and MC liquid asphalt were used, each improving the performance slightly.

An exception to the generally improved performance caused by subgrade treatment was noted on the one section in which the subgrade soil was saturated with water before construction. This section showed serious pavement distress almost immediately after construction.

Immediately after World War II, Woods, Green and Sweet (*24*) presented a correlation between pumping and traffic in Indiana. The pertinent results of this study are as follows:

1. In 1940 pumping was practically non-existent, whereas in 1943 and 1947 about 6.0 percent and 12.0 percent, respectively, of rigid pavement mileage was affected.
2. Pumping in 1947 occurred on soils of lower plasticity than in 1943.
3. Some pavements built on sand bases showed considerable faulting. (Note: The majority of these pavements were constructed during war periods and with no load transfer devices).
4. Pumping had started at about the same time as violations of axle load requirements.
5. An excellent correlation was shown between overload and extent of pavement pumping.

In 1945 the HRB Committee on Maintenance of Concrete Pavement as Related to the Pumping Action of Soil issued a series of reports dealing with pumping in Kansas and North Carolina. In 1948 a final report was made in which studies in these states, as well as in Illinois, Ohio and Tennessee, were used to formulate final design recommendations. Pumping is defined in the 1948 report as follows:

> 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.

The conditions necessary for pumping to occur, as given in this report, are:

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

Many statements were made from the results of the study, some of which were not conclusive but rather of a tentative nature. The more important conclusions were as follows:

1. Repeated passage of heavy vehicles was the most important factor.
2. Slower vehicles caused more pumping than faster ones.
3. Free water and fine-grained subgrade soil contributed to pumping, but not unless slab deflections were increased sufficiently both in magnitude and in frequency.
4. Compaction of subgrade soil to maximum density at optimum water content delayed pumping.
5. Granular subbase placed over fine-grained soils prevented pumping. The exact thickness required was not determined, but 3 to 12 in. was found to be effective.
6. Pumping was not affected by the age of the pavement.
7. The thickness and the cross-section of the pavement did not appear to influence pumping.
8. Owing to insufficient data, relation between deflection caused by heavy axle loads and subgrade soil characteristics was not determined.
9. Pumping developed both at expansion and contraction joints if soil and traffic conditions were conducive to pumping. Pavements without expansion joints or with restrained ones developed much less or no pumping under similar conditions. Therefore, it was recommended that expansion joints should be omitted or spaced at the maximum distance permissible.
10. Filling expansion joints with premolded rubber, bituminous fiber, poured bituminous, or air-chamber type of filler did not prevent pumping. Precompressed wood filler, however, may form a relatively watertight joint and prevent pumping.
11. Load transfer devices failed to reduce pumping, but the magnitude of faults at pumping joints was reduced. Dowel bars were more effective than proprietary types.
12. The value of joint drains in controlling pumping could not be determined definitely.
13. Mudjacking or bituminous undersealing eliminated the voids below the pavement, but generally did not prevent recurrence of pumping. Hence, it was believed that future maintenance must provide for inspections and periodical mudjacking or undersealing.
14. The proper maintenance to prevent and correct pumping was said to include:
    - (a) Correcting poor drainage, including shoulder maintenance to avoid ponding of water along edges.
    - (b) Mudjacking or undersealing.
    - (c) Joint and crack sealing.
    - (d) Patching full depth with concrete.
    - (e) Covering with bituminous surfacing.
    - (f) Concrete resurfacing.

In 1949 a research project was initiated by the International Council on Highway Transportation under the direction of the Highway Research Board to conduct a series of controlled field tests on pumping (*13*). The tests were made on US 301 south of LaPlata, Md. Trucks of varying weights were driven over the pavement and observations of pumping distress, as well as many deflection and strain measurements, were made. Axle loads used for the study included 18,000-lb single-axle, 22,400-lb single-axle, and 32,000-lb tandem-axle. A summary of the major findings is as follows:

1. The predominating soil type encountered on the road was a silty clay with some sections on a granular soil.

2. No pumping occurred on the granular soil after 238,000 applications of the 18,000- or 22,400-lb single axles when the soil contained less than 9 percent passing a 200-mesh sieve. Slight pumping occurred under the 22,400-lb axle when the soil was granular and contained more than 9 percent passing a 200-mesh sieve.

3. Pumping resulted under all classes of loads on the fine-grained soil.

4. More than four times as many passes of the 18,000-lb axle load were required to produce pumping than of the 44,800-lb tandem load.

5. Occurrence of cracking was definitely attributed to pumping.

6. More cracking occurred at expansion joints than at contraction joints.

7. Cut and fill sections were about equally susceptible to pumping, but more cracking occurred in cuts than on fills.

8. Magnitudes of pavement stresses and deflections increased with magnitude of load.

9. Stresses in slabs on non-pumped fine-graded soil were about 12 percent higher than on corresponding granular soils.

10. Pumping, with accompanying loss of subgrade support, caused an increase in pavement stresses.

11. Deflections on non-pumped fine-grained soil were but 65 percent greater than on granular soil.

12. The studies indicated that tandem axles spaced 50 to 55 in. apart did not act as two single axles.

Several observations in the final report reflect the thinking of the authors regarding mechanics of pumping as well as the effect of base courses. Regarding the cause of pumping the report says (*13*, p. 54):

> . . . . the following order of related events will occur: (1) When the first heavy axle load is applied, there will be a deflection of the slab and the subgrade will be deformed in proportion to the magnitude of the downward movement of the slab. (2) After the removal of the applied load, the deflected slab returns to its original alignment and a certain degree of loss of subgrade contact will occur at the critical deflection points. (3) This loss of subgrade contact with the pavement creates a space under the slab which, if given access to free water, quickly becomes filled and softening the top layer of subgrade soil begins. (4) Subsequent deflection of the slabs, under successive application of load, increases the size of the area of non-subgrade contact with the slab and at the same time develops the soil water slurry which is ejected in increasing amounts during the downward bending of the slab under applied loads. (5) As the subgrade action is repeated, the deflection for the same intensity of load application increases in proportion to the loss in subgrade contact and the stress in the slab increases until a point is reached where the developed stress results in cracking of the pavement. After the slab cracks, faulting and settlement occur, with further repetition of load.

Mention is made in the report of the "surging" action of pumping water. It is also brought out that in the early stages the escape of clear water between the shoulder and edge of the pavement is confined to within several feet of a joint or crack, but as pumping increases, escape channels may develop well under the slab.

During the later 1940's most state highway departments began extensive use of granular base materials under concrete slabs to control pumping. Widespread use of granular subbases did stop most pumping quite effectively; however, due probably to an increasing shortage of supply of high-grade granular materials, several rigid highways built on base courses began showing a new type of distress. This distress was defined by Vogelgesang (*22*) as "blowing," which for all intents and purposes is just another form of pumping. The primary difference is that the action first becomes noticeable by the occurrence of small holes in the shoulder resulting from expulsion of water from under the slab under action of heavy loads. This action, if permitted to continue, soon results in some cases in ejection of granular material. Chastain (*4*) also recognized blowing in Illinois.

Blowing apparently results in "restraint" cracks, which are longitudinal cracks occurring at the joints. These cracks are reasoned to be due, in part at

least, to a restraining action at the joint when a portion of the joint is filled with granular material.

Pumping of airport pavements has not generally been a serious problem in the past. A few cases of pumping have been reported on military airfields, but these were generally due to severe overloading. However, due to channelized traffic and a general speedup of activity on military airfields in recent years, severe pumping has begun to occur, and may become a major problem in rigid airport pavement design.

BLOWING OF BASE COURSE MATERIALS

As defined by Volgelgesang (*22*), blowing is caused by the high-velocity ejection of water that lies immediately under a rigid pavement and on top of the base course. As this water is forced from under the pavement, it may erode the base material. He classified this action as first- and second-stage blowing. First-stage blowing was evidenced by the formation of "blow holes" at the edge of the pavement; second-stage blowing was evidenced by accumulations of sand around the edge of the blow hole at the pavement edge.

Data obtained from this study have substantiated the foregoing definition. It is believed, however, that a third stage of development also exists. This third stage appears as restraint and, in some cases, transverse cracks in the pavement. Some question exists regarding the true mechanics of restraint crack formation; however, the data indicate very strongly that these cracks do constitute a third stage of development.

The first step in blowing is the accumulation of free water immediately under the slab. For this to result, an initial void must be present. This may result from inadequate compaction of the subbase and or subgrade, or from an accumulation of fines in the subbase with resultant excessive permanent deformation of the upper layer of base course. Next, water enters the void, and if the granulation of fines in the subbase with remain under the slab until ejected by the deflecting slab. If the base is open-graded, the water will percolate through it and blowing will not result.

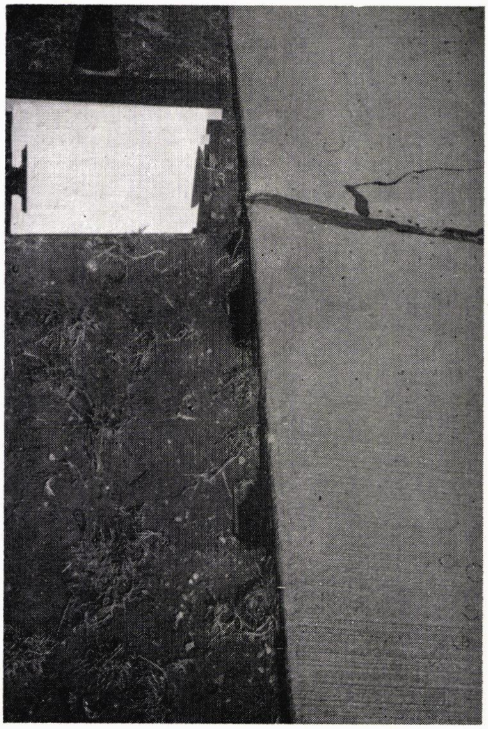

Figure 1. First-stage blow hole on a crushed stone base.

The next step results when the layer of water under the pavement is ejected at the pavement edge, forming holes as shown in Figure 1. This is termed first-stage blowing. Second-stage blows may or may not develop (Figure 2), depending on whether the base can be eroded. Crushed stone bases rarely erode and form second-stage blows, but gravel and sand bases frequently do.

If blowing occurs when the slab is contracted, some of the base course material will enter the joint. In some cases this material will clog the joint sufficiently to form a joint spall, as shown in Figure 3. These spalls nearly always occur in the slab towards traffic. This is probably due to the bending action of the forward slab which tends to break off the lower half of the backward slab at the point where the material is lodged in the joint.

Figure 2. Second-stage blow on a gravel base.

Severe second-stage blowing is nearly always followed by restraint cracks and transverse cracks. Restraint cracks (Figure 4) are due in part to a restraining condition at the joint when the slab expands, and in part to bending of the slab upon removal of support by blowing. Transverse cracks are caused by bending or by tension due to temperature changes.

The principal difference between the effect of pumping of fine-grained soils and blowing of base course materials is the type of defect that will occur. In the case of pumping of fine-grained soils, pumping in the advanced stages results in transverse cracking and faulting, whereas blowing results in joint spalls, restraint cracks, and transverse cracks.

At the start of this research project, personnel of the Arctic Construction and Frost Effects Laboratory sent a questionnaire to most of the state highway departments regarding the pumping problem. The results indicated several significant trends, but in many cases the answers reflected opinions rather than actual data.

Of the 31 states replying to the questionnaire, only 5 reported that pumping

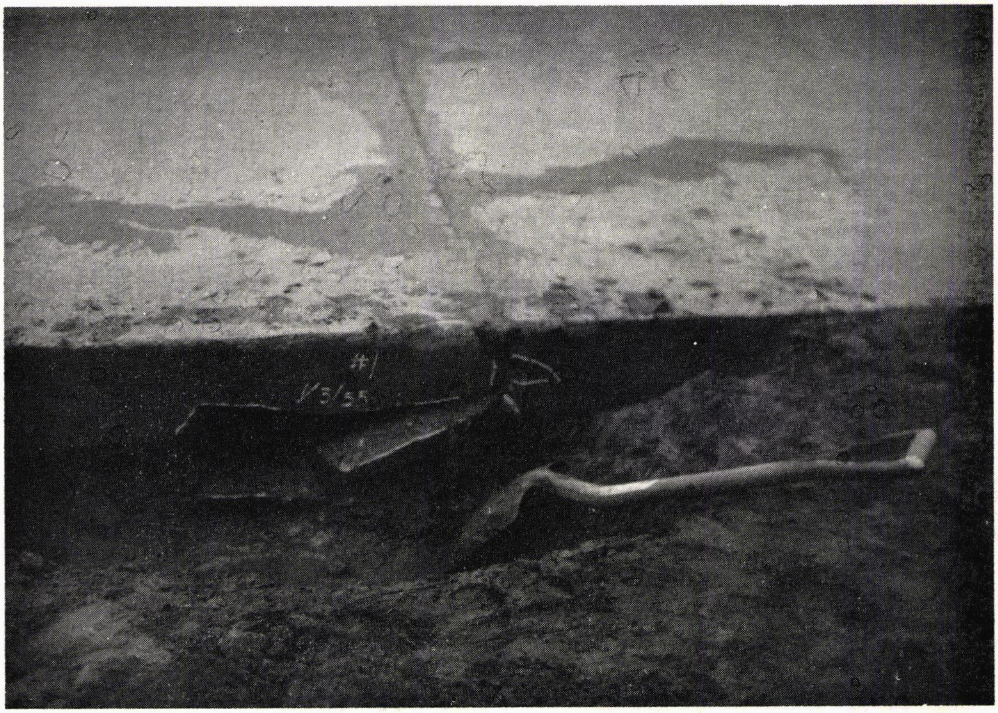

Figure 3. Joint spall resulting from second-stage blow. Note that spall is at left of joint; traffic moves to right in picture.

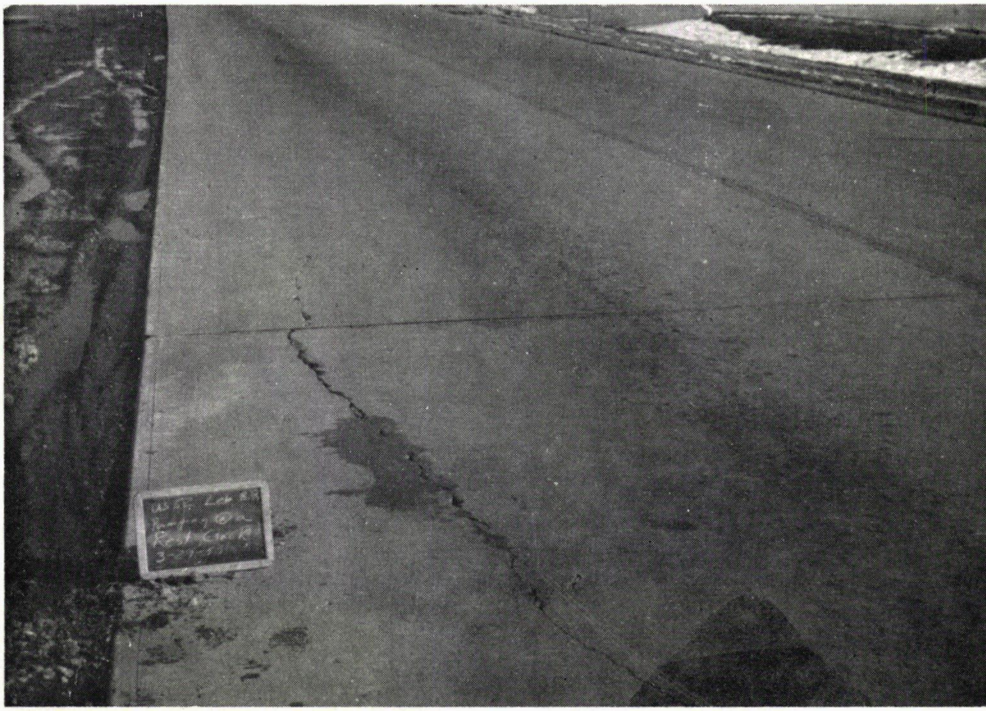

Figure 4. Restraint cracks. Note that the cracks start near the edge at the joint and tend to swing in towards the center of the pavement.

of rigid pavements had never become a problem. Nineteen other states reported that pumping had at some time occurred with varying degrees of severity, although only two felt that the problem was still a major one on highways built to their revised design specifications. The general feeling was that proper design, including base courses, will eliminate pumping, although the proposed remedial design showed a wide variation from state to state.

Six states reported that failures had occurred within the base course itself. It is significant that the majority of the base courses in which pumping occurred were of the dense-graded variety (more than 7 percent passing a 200-mesh sieve permitted by specification), although others commenced blowing only when the percentage of fine-grained soil in the base course was increased by entrance of the subgrade material or degradation of the base course aggregate.

Performance of base course materials has received increasing attention in recent years. Notable is the work done under the sponsorship of the Bureau of Public Roads (*1*) (*19*).

Because the data appearing in the literature are relatively new, it was necessary to devise a detailed pavement performance survey to isolate the variables affecting performance of rigid pavements built on relatively thin bases. To accomplish this, a field study was initiated of highways constructed in Indiana.

At the outset of this survey is was known that many factors influence the performance of pavement-base structures. Although pumping and blowing were principally considered, it was felt that to gain a true quantitative as well as qualitative idea of performance other factors also should be considered.

The factors believed to affect rigid pavement performance are as follows:

1. Base type and gradation.
2. Traffic.

3. Climate.
4. Drainage.
5. Subgrade type.
6. Pavement cross-section.
7. Geometric design.

The purpose of the field study was two-fold. First, it was proposed to make a state-wide condition survey of concrete pavements in Indiana which had been built with granular bases. This phase of the work dealt with a general over-all evaluation of these pavements, with emphasis on blowing and structural cracking. Second, it was proposed to make a study of the conditions which resulted in pavement distress and to evaluate qualitatively the factors affecting the performance of the pavements.

To accomplish this, a systematic sampling plan based on statistical procedures was adopted to rate the pavements on a state-wide basis. Several pavements were studied in great detail, others were not. The first and second objectives of the work were accomplished simultaneously.

Procedures For Indiana Survey

The detailed step-by-step procedure used is outlined in the following. It is significant to note that all variables were considered and studied in a minimum of time.

General description of the survey

A. Purpose of the survey
   1. To determine the number of defects per mile for certain portland cement concrete pavements in Indiana which were constructed on subgrade treatment. The types of defects to be counted were:
      (a) Transverse cracks.
      (b) Restraint cracks.
      (c) Corner breaks.
      (d) Blow holes.
      (e) Pumping.
   2. To study the relations which existed between the previously listed variables and others which were measured in connection with digouts at the site of defects.

B. Definition of the universe (scope of sampling program)
   The survey universe consisted of the 74 stretches of pavement designated in Figure 5. These stretches cover a total of approximately 381 miles of pavement. Eight of the stretches were required to be in the survey and were more extensively studied than were the others. The remaining stretches were sampled on a probability basis in accordance with the sampling procedures described in the following.

C. Stratification of the universe
   In order to group together those stretches which may have more uniformity in the measured variables and in order to make the comparisons which are implied by the second purpose of the survey, the 75 universe stretches were stratified into 18 subgroups in accordance with the following classifications:
      Type of subgrade treatment: Gravel, sand, stone.
      Volume of traffic per day: High (over 5,000), Low (under 5,000).
      Year of construction: Before 1945, 1945-1949, after 1949.
   Although there were 18 possible strata, only 12 of these were represented among the universe stretches.

D. Definitions of the survey units
   1. The primary sampling units in each strata were the stretches given in Figure 5. In many cases two or more stretches were contiguous parts of the same road, but received separate designations by the nature of the stratification. In the case of divided highways, each lane was given a separate stretch designation.
   2. The secondary sampling units were successive quarter-mile sections of pavement in each stretch, starting 0.5 miles from the origin.

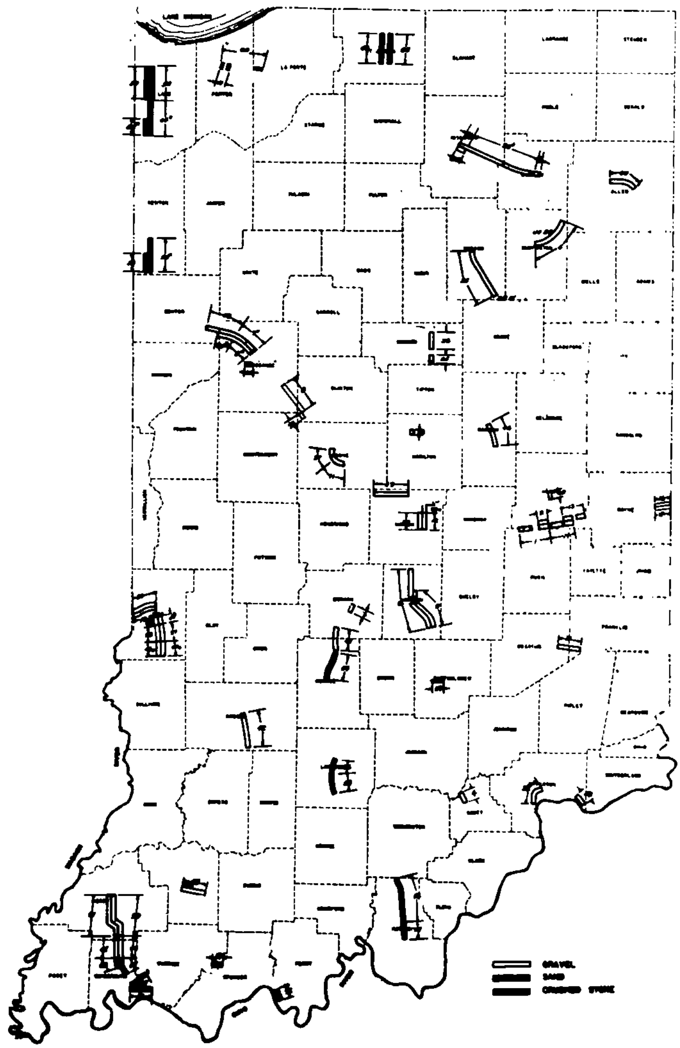

Figure 5. Universe for defect survey.

3. The elementary units of the survey were pavement joints. There were approximately 35 elementary units in each of the quarter-mile sections.

E. Sampling plan of the survey
   1. *Sampling of primary units (stretches to include in survey)*. In each stratum (that is, base type, traffic, etc.) several stretches of road were required to be in the survey. The other stretches were sampled using a random procedure with probability proportional to the stretch mileage.
   2. *Sampling of secondary units.* Each stretch of road was subdivided into quarter-mile sections. The program was set up such that only four of these quarter-mile sections were actually surveyed. The sections to be sampled were again de-

termined using a random procedure.

3. *Sampling of elementary units (joints) within a section.* Base course materials were sampled at two joints showing blowing and cracking distress, as well as at two joints showing no distress.
4. *Survey procedure.* For each quarter-mile section of highway surveyed, a map was drawn to scale showing all cracking and blowing distress.

In all, 32 stretches of road were sampled. Within each stretch, just 4 sections were surveyed, each a quarter mile in length. Thus, 32 miles of pavement were surveyed. This 32 miles of pavement was representative of about 500 miles of pavement. The data obtained from the field study were evaluated in light of traffic, base type and thickness, subgrade type, and climate. Each of these is discussed in subsequent paragraphs.

Correlation of Defects

The principal objective of this investigation was to study the effect of blowing of rigid pavements and to study the base course requirements of rigid pavements. To accomplish this, data were collected relative to the general performance of rigid pavements built on granular bases, as well as data regarding blowing.

As mentioned previously, edge holes are generally an indication of blowing activity. It is believed, however, that blowing exists at the interiors of some slabs as well as at the edges. This is indicated by the formation in recent years of restraint cracks at interiors of the traffic lanes as well as in passing lanes. As is illustrated later, however, this activity is generally restricted to the pavement edges.

The data on hand at present indicate that pumping of the subgrade soil through the base course is not a problem. However, the possibility has been suggested of upward movement within the base of sandy fractions and fines of the base itself whenever blowing occurs. This possibility is supported by grain-size distribution curves of base materials in service, which indicate a general distribution from fine to coarse depth.

It is believed that blowing of base courses *per se* may or may not constitute a serious problem. This appears true even though the formation of blow holes is rather dramatic and has received increased attention in recent years. In fact, several pavements built on crushed stone bases which have sustained serious first-stage edge blows are still in excellent shape after many years of service.

Data obtained from field observation indicate that good correlation exists between number of joints and cracks affected by blowing and the formation of transverse and restraint cracks. In several cases, however, serious cracking has occurred where little or no blowing exists at the present time. Notable among these cases are stretches 7 and 8 on US 52 north of Lafayette, which although they are not blowing at present, have blown extensively up until recent years. These stretches suggest that it may not be unusual for blowing to stop after a time. Table 1 gives a summary of the performance data. Figure 6 shows detailed data for two stretches of highway constructed on dense-graded gravel bases which were carried through the shoulder for drainage purposes. These particular bases are relatively impermeable, and it is therefore doubtful that drainage is accomplished through the shoulder.

These data illustrate that pavement distress as evidenced by crack formation is preceded by blowing activity. Also where blowing is not evidenced soon after the pavement is constructed, little or no cracking develops at a later date.

Transverse cracks develop primarily during the cold season; restraint cracks develop during summer months. It is important to note, also, that blowing was not encountered at road turnouts and that little cracking exists at these locations.

A definite time lag exists between blowing and the formation of cracks (see Figure 7). Furthermore, blowing

TABLE 1
SUMMARY OF BASE COURSE PERFORMANCE DATA IN INDIANA

Stretch	Year Built	Load Rep. x 10^5	Cracks per Mile				Blowing per Mile			
			Restraint	Center 1/3 of Slab	Transverse Forward 1/3 of Slab	Transverse backward 1/3 of Slab	1st Stage Joint	2nd Stage Joint	1st Stage Edge	2nd Stage Edge
(*a*) Gravel Base (Trench)										
11	1949	27.2	97	91	23	28	15	37	1	3
7	1949	26.4	131	92	18	23	6	19	1	1
8	1949	25.3	130	91	10	9	3	24	1	6
45	1947	23.3	58	43	10	14	15	0	3	0
33	1949	21.6	88	42	9	9	6	40	76	63
50	1950	17.4	25	40	2	0	28	0	3	0
6	1946	16.2	15	67	7	8	4	0	0	0
48	1951	4.9	14	4	0	1	0	4	1	3
42	1947	3.2	1	16	7	3	0	0	0	0
(*b*) Gravel Base (Through-Shoulder or Tile Drained)										
1	1939	50.6	0	30	10	17	0	0	0	0
36	1949	26.2	4	19	7	5	0	0	0	0
3	1938	12.6	3	33	12	10	0	0	0	0
23	1952	10.7	11	7	0	0	19	29	7	10
24	1952	10.7	70	10	0	2	68	36	20	2
(*c*) Sand Base (Trench)										
64	1946	41.1	4	143	10	37	6	30	0	0
15	1947	40.6	27	75	30	7	0	0	0	0
65	1949	30.6	6	83	9	12	0	4	0	0
69	1949	6.4	0	3	1	1	2	0	1	0
27	1953	4.5	2	3	0	1	7	8	1	0
71	1949	2.3	9	1	0	0	0	0	0	0
57	1953	1.2	0	0	0	0	0	0	2	0
(*d*) Crushed Stone Base (Trench)										
53	1949	20.7	0	60	15	15	39	3	0	0
52	1949	20.7	0	52	18	12	43	8	7	0
54	1949	10.7	17	13	2	3	8	4	7	2
55	1950	3.1	15	0	0	0	0	0	0	0
56	1948	1.6	0	0	0	0	0	0	0	0
56	1953	0.6	0	1	0	0	0	0	0	0
(*e*) Crushed Stone Base (Through-Shoulder or Tile Drained)										
52	1952	10.3	0	3	1	0	0	0	0	0
53	1952	10.3	0	0	1	0	0	0	0	0
69	1949	3.3	0	6	1	1	3	0	2	0
(*f*) Gravel Base (20-Ft Slabs)										
1	1943	51.9	0	28	0	0	9	2	1	0
30	1944	5.4	0	8	2	3	3	1	1	1

does not increase appreciably after the action has started. In fact, as previously mentioned, evidence indicates that blowing activity decreases and in some cases completely stops after several years (Table 2).

It is apparent from Table 2 that cracking distress occurred during the first five years of pavement life and that the severest cracking occurred on stretches that showed serious blowing activity during the 1950 survey. Stretch 7-3 did not blow during its early life and likewise has shown little cracking distress. Stretches 7-12, 7-14, and 8-14 showed early distress from blowing and cracking,

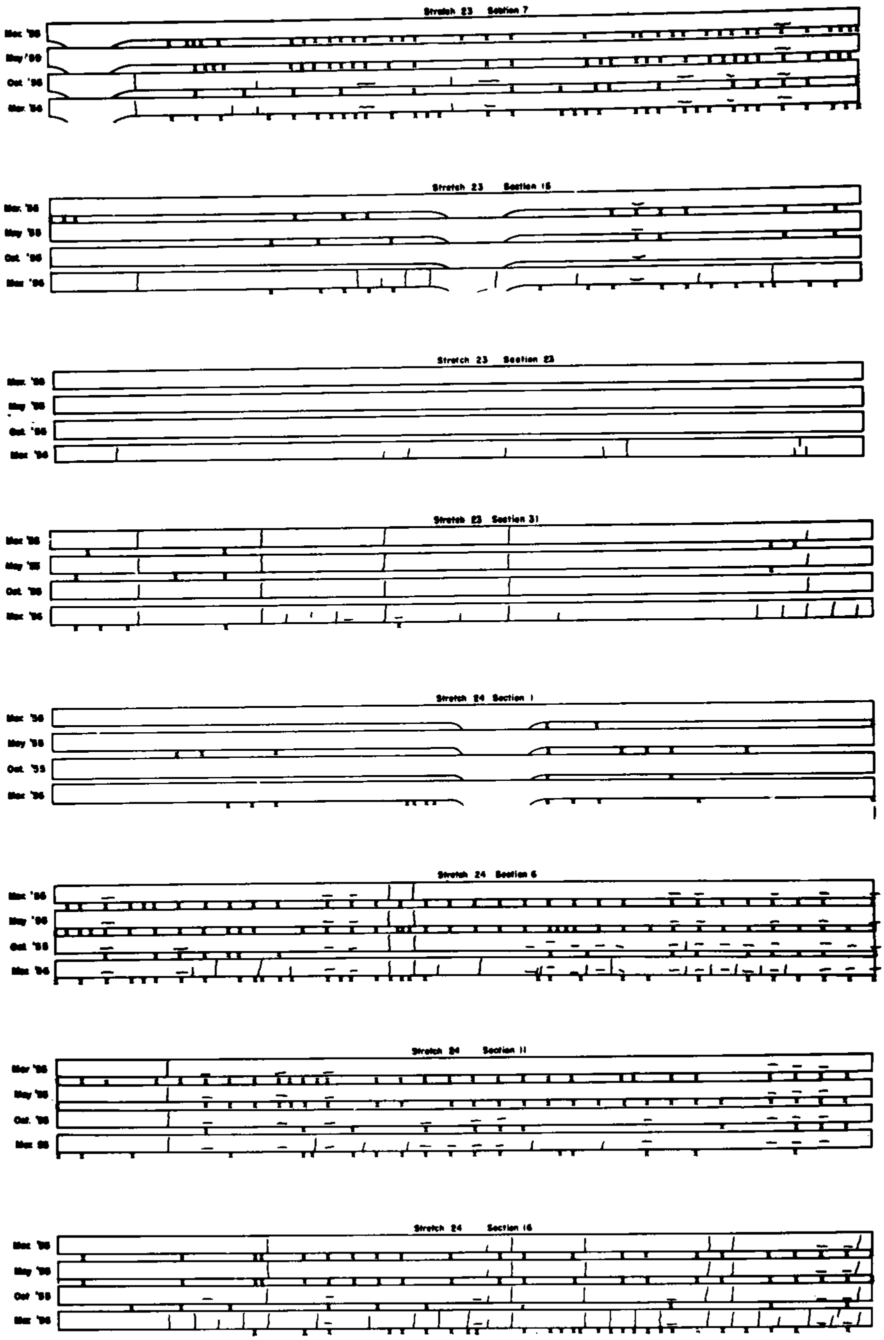

Figure 6. Progression of blowing and cracking on US 52 north of Lafayette; dense-graded gravel, through-shoulder construction, Sept. 1952.

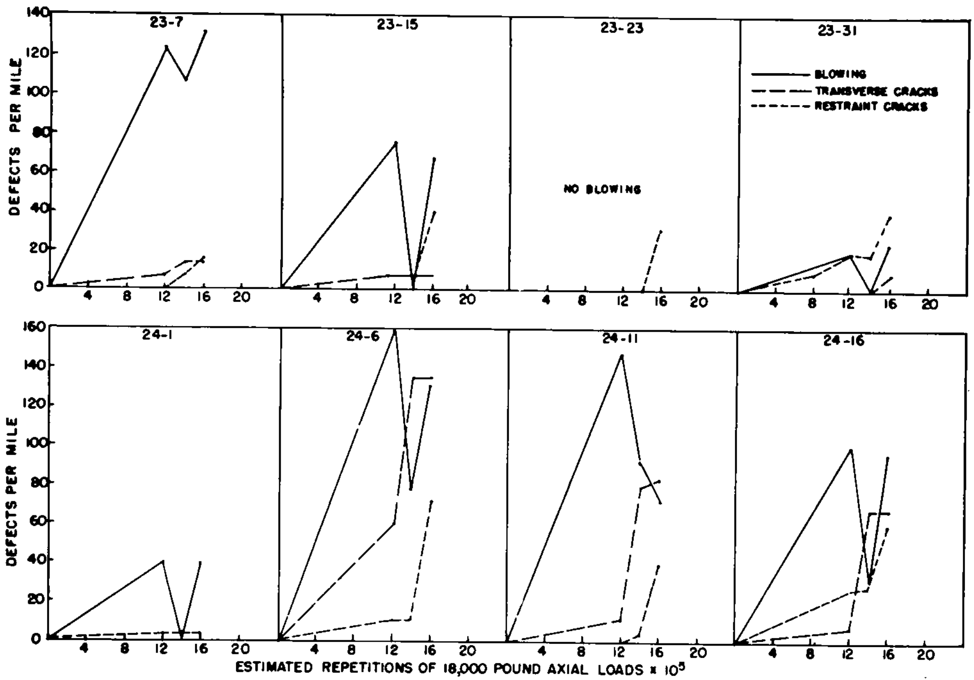

Figure 7. Correlation of defects, US 52, dense-graded gravel.

but additional cracking has not taken place after 1954 and blowing has practically stopped.

This suggests that the decrease in blowing may be due to cracking and subsequent settlement of the pavement slabs. In other words, as long as the pavement is intact and not in intimate contact with the base course, blowing will result, but if the pavement cracks and faults, the severity of blowing will decrease.

Figure 8 shows the relationship of blowing to performance as measured by number of cracks in the concrete pavement. The upper curves show data for restraint cracks; the lower are for transverse cracks occurring in the end 1/3 of the slabs. These data indicate that cracking is not necessarily associated with first-stage blows, and that more cracks occur when blowing has progressed to the second stage. The numbers beside the curves represent the survey stretch numbers. Therefore, each line represents data for a particular highway, but for different sections on that highway. It is significant that the sections of a given highway showing greatest distress on the basis of crack formation also show greatest second-stage blowing activity.

Type and Quality of Base

According to this survey, bases which result in the highest degree of blowing distress are those constructed of poorly graded materials. Figures 9, 10, 11, 12, and 13 present average grain-size curves for the materials tested. These curves are averages of several tests made on base materials from each stretch of road surveyed and do not present curves for each individual section of pavement sampled. For purposes of analysis these data have been organized according to type of base, type of construction (trenched or drained), and length of slab. Unless otherwise noted, the slab length is 40 feet and all joints are dummy groove contraction joints.

Curves for Fuller's maximum density

TABLE 2
HISTORY OF BLOWING AND CRACKING, US 52, DENSE-GRADED GRAVEL, TRENCH CONSTRUCTION, CONSTRUCTED JUNE 1949

Stretch and Section	Restraint Cracks, no./mile					Transverse Cracks, no./mi										Blows (All Type), no./mi				
						End 1/3 of Slabs					Center 1/3 of Slabs									
	11/50	5/54	10/54	8/55	8/56	11/50	5/54	10/54	8/55	8/56	11/50	5/54	10/54	8/55	8/56	11/50	5/54	10/54	8/55	8/56
7-3	0	0	0	0	0	0	21.2	21.2	21.2	21.2	0	79	79	79	79	0	0	26	20	
7-12	21	280	280	280	280	0	32	32	32	32	0	69	69	69	69	52	22	84	32	4
7-14	73	196	196	196	196	0	11	11	11	11	6	95	95	95	95	95	0	74	20	8
8-24	69	238	238	238	238	0	27	27	27	27	0	74	74	108	108	110	6	95	0	0
8-15	48	115	115	144	144	0	32	32	32	—	11	90	90	90	—	22	36	85	85	—
8-13	0	69	69	69	69	0	16	16	16	16	0	43	43	43	43	22	6	11	0	4

are superimposed on each of these grain-size curves. Fuller's curves were calculated by means of

$$\text{Percent Passing} = 100 \sqrt{\frac{d}{D}} \qquad (1)$$

where d is the sieve size in question and D is the maximum size of aggregate. The materials which blow most severely are poorly graded gravels containing an excess of sand and fines. Crushed stone bases which are relatively well graded have shown little or no blowing. Likewise, well-graded sand bases have shown only a slight amount of blowing. Some of the older gravel bases were constructed using well-graded materials and have shown very little distress.

For a given gradation of coarse material, the percent of fines (material passing a 200-mesh sieve) used appears to affect the performance of the base. The joints associated with blowing have nearly always been situated on material containing from 3 to 4 percent more fines than those with no blowing. The permissible quantity of fines, however, is a function of the maximum grain size of the aggregate. This is illustrated, when comparing the sands with the gravels, where sands containing up to 14 percent fines are showing satisfactory service although gravels prove unsatisfactory if they contain more than 10 percent fines. For comparable coarse aggregate bases more fines can apparently be permitted in stone bases than in those of gravel. This may be due to a higher coefficient of permeability of the stone bases. Also, grain shape certainly plays a part.

These curves indicate several significant trends. First, the lower half of each of the bases sampled, almost without exception, contained fewer fines than the upper half. Second, a layer of fine sandy material nearly always existed on top of each of the bases. The origin of this fine sandy material is not presently known, but, as is brought out later, this layer appears to influence the pavement behavior as much as any other factor.

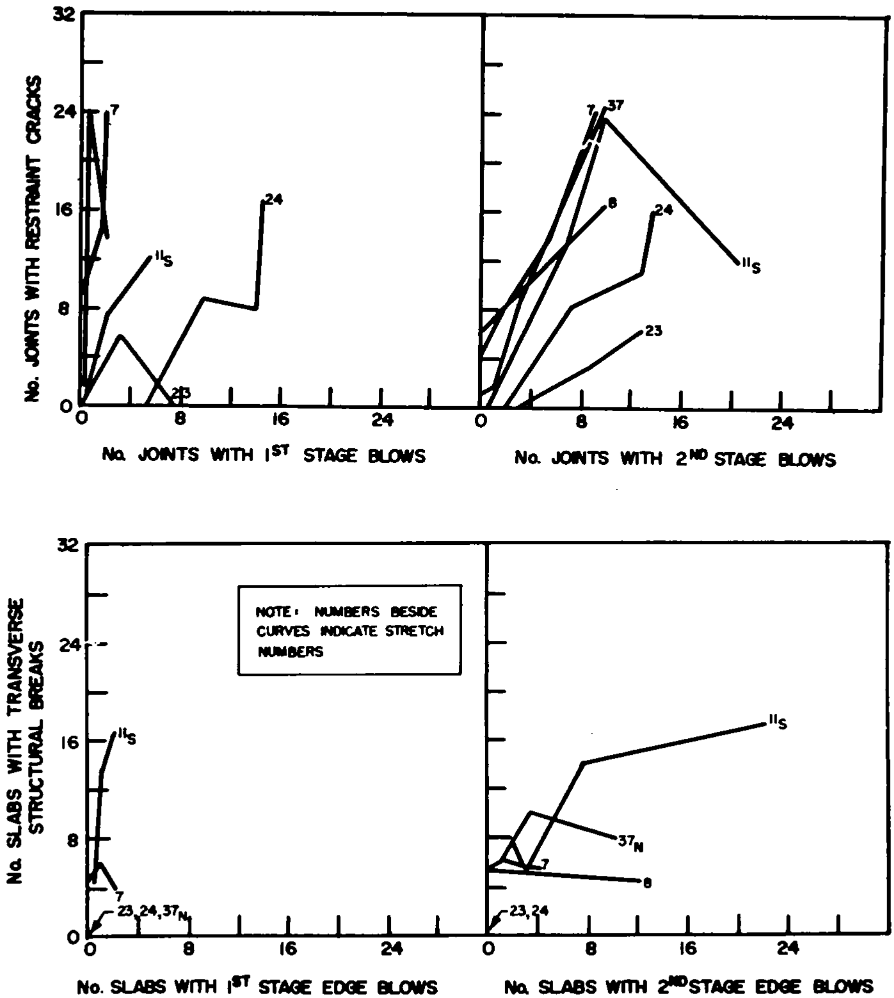

Figure 8. Variation of structural defects with blowing (gravel, trench construction, traffic lanes).

There are several possible reasons for a layer of this type to occur under a slab: (a) it may have been placed on top of the base as a leveling course (see Figure 14); (b) it may result from rolling the aggregate base during construction; (c) it may result from the finishing operation on the base; or (d) it may represent an accumulation of fines due to pumping action. Regardless of the source of this material, its effect on blowing is at once apparent. Figure 9 reveals that this material as encountered in this study is primarily sand containing an average of 17 percent by weight passing the 200-mesh sieve at joints showing no blowing. Figure 15 reveals that on the newer pavements (those constructed after 1950) the upper ½ in. of the bases contained an average of 27 percent fines at joints showing second-stage activity. However, when considering the older pavements it is seen that this layer contains an average of 21 percent, suggesting that the material pumped out from under the pavement comes from this layer. If the foregoing is a correct hypothesis, it follows that the material which enters the

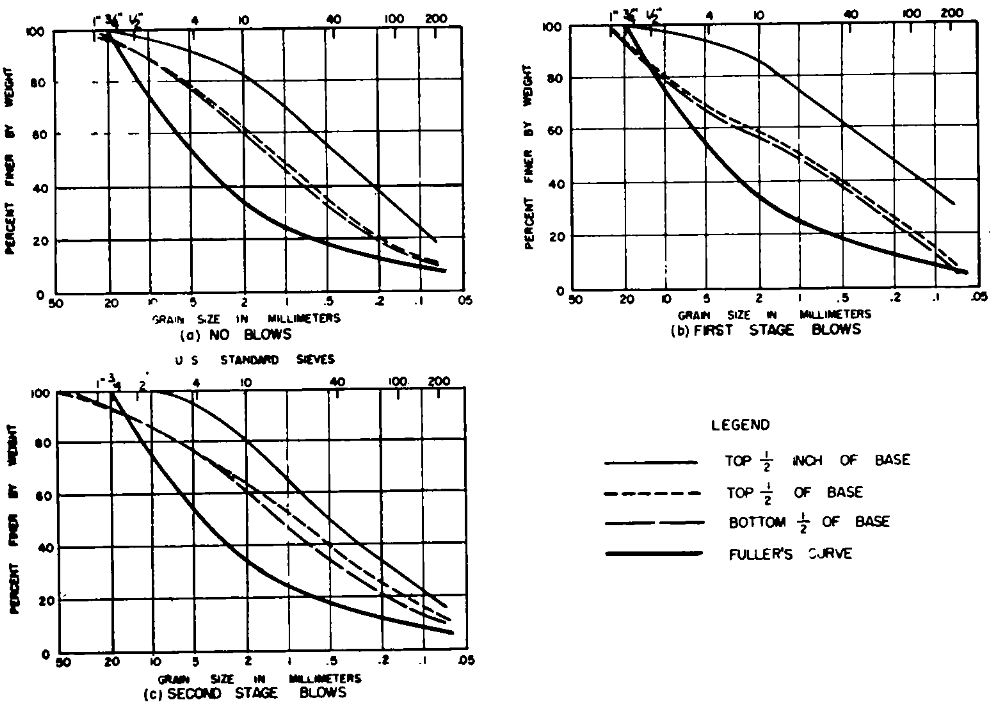

Figure 9. Grain-size distribution curves, gravel base course, trench construction.

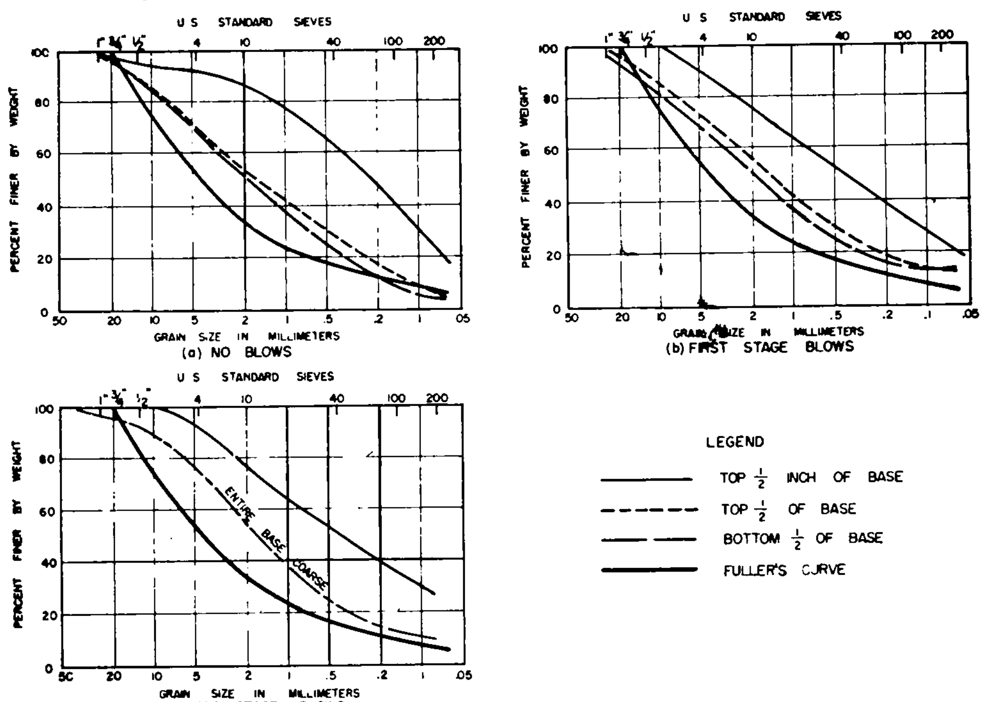

Figure 10. Grain-size distribution curves, gravel base course, through-shoulder on tile drainage.

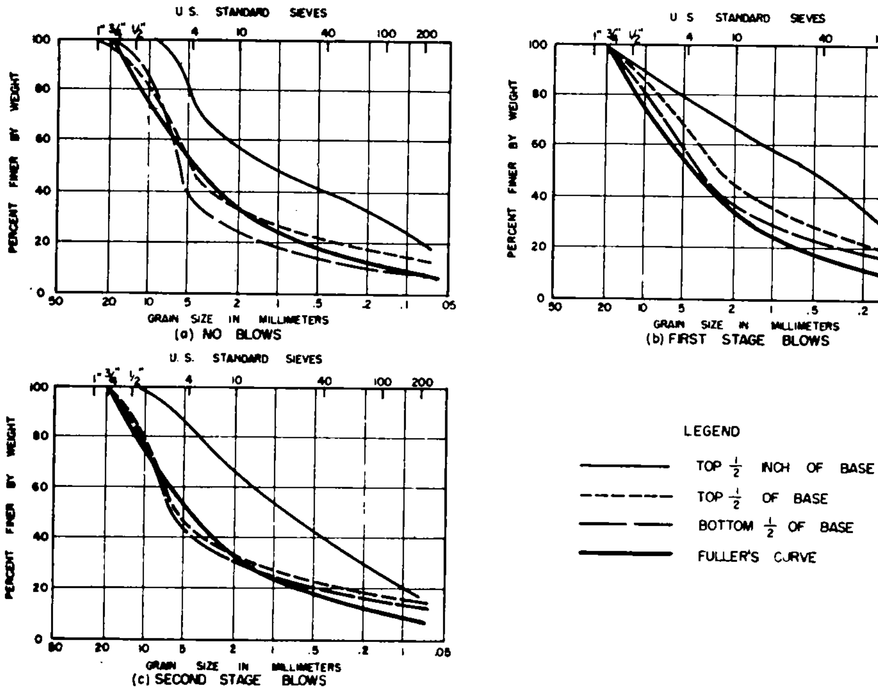

Figure 11. Grain-size distribution curves, crushed stone base course, trench construction.

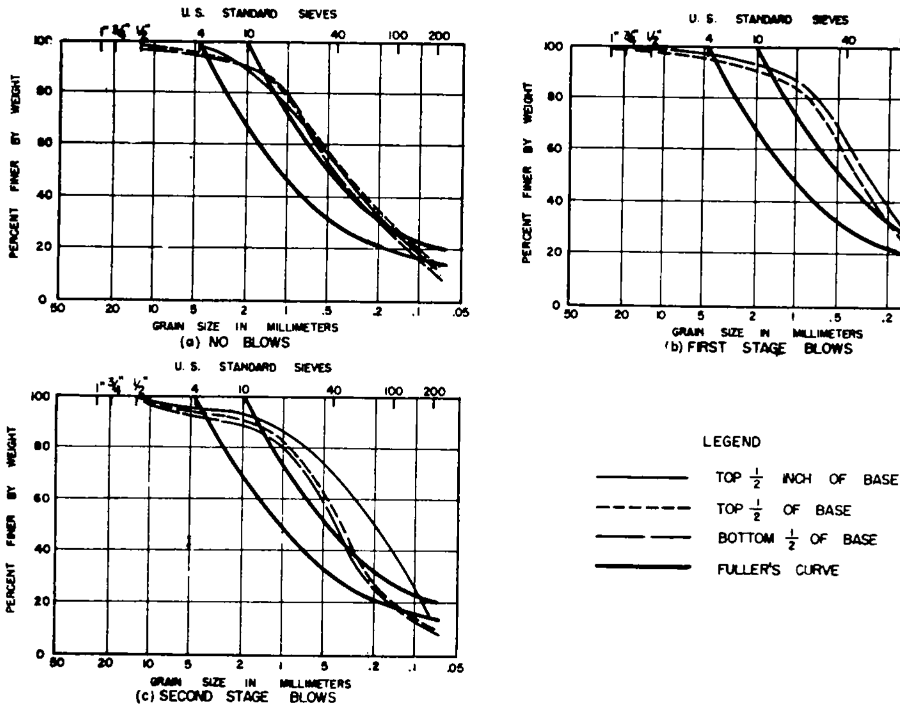

Figure 12. Grain-size distribution curves, sand base course, trench construction.

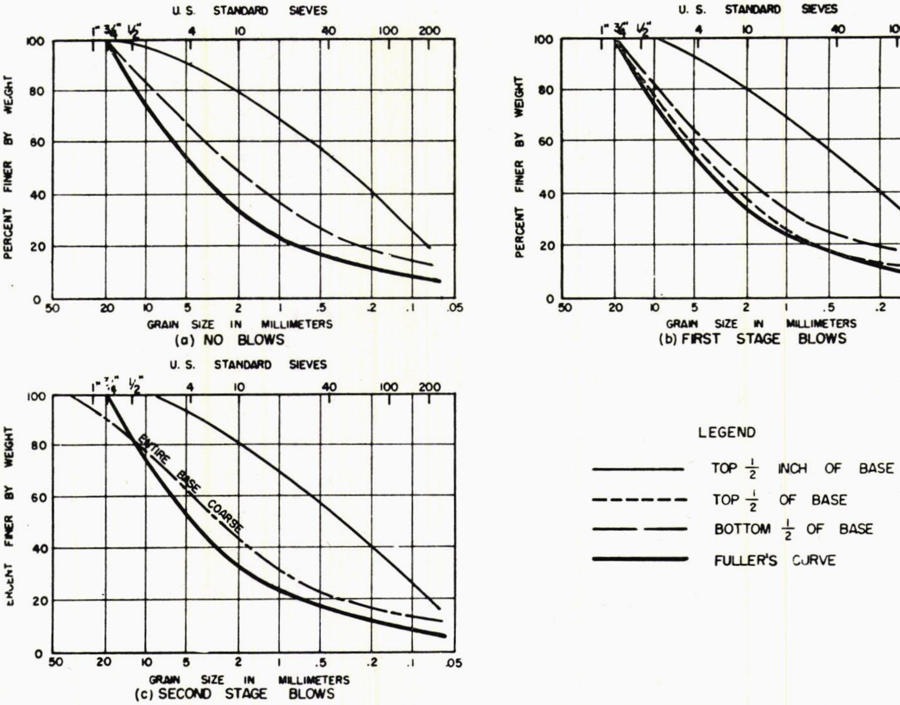

Figure 13. Grain-size distribution curves, gravel base course, 20-foot slabs.

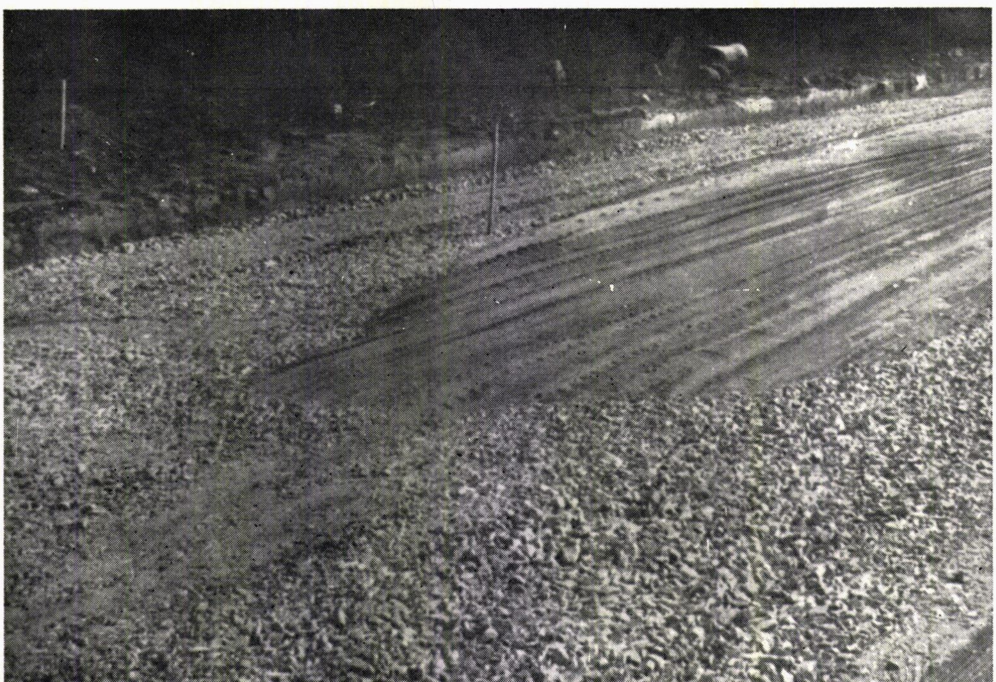

Figure 14. Leveling course on open-graded base.

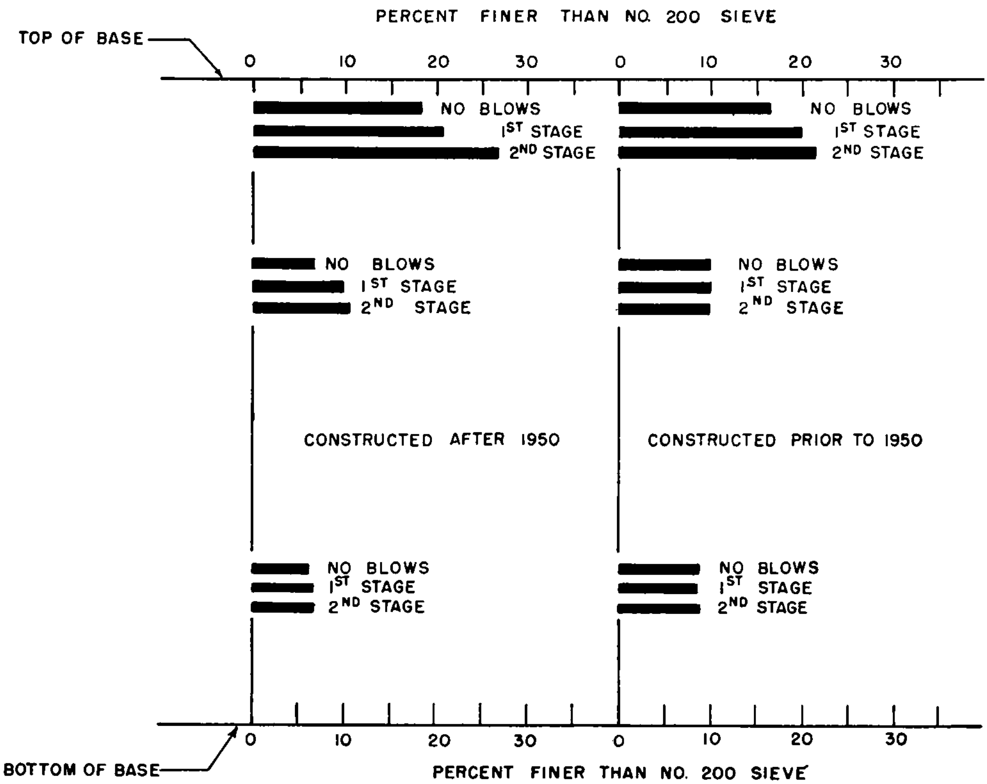

Figure 15. Variation of fines with depth, gravel base courses.

joint and causes restraint cracks comes from this layer.

It will be noted that in the more open-graded bases, such as crushed stone and sand, this layer is either relatively clean or missing entirely. Because the gradation curves for these bases consistently show more fines in the upper half of the base than in the lower half, it is believed that there is little movement of subgrade material up and through the base material.

Data obtained from this study have indicated that second-stage blowing activity is associated primarily with gravel base courses and that the source of the sandy material found at pavement edges in the vicinity of second-stage blow holes is the extreme upper layer of the base.

It has been definitely shown that a perched water table condition between the base and pavement is necessary for blowing to occur. No evidence exists that water is caused to move through the subgrade due to repetition of load. The depth to water table has no apparent effect.

The data do not suggest that one type of base material gives more satisfactory service than another as long as the gradation is satisfactory. Results from two test roads, one in Indiana, the other in Ohio (*1*) (*19*), indicate that soil cement results in increased blowing, pumping, and cracking distress.

For both test roads mentioned, open-graded base materials have resulted in less blowing than have the dense-graded materials. Because blowing apparently decreases or stops after a time, it is possible that it will be reduced by increased compaction.

Repetition of Load

Figure 16 shows a summary of the performance data on the basis of traffic.

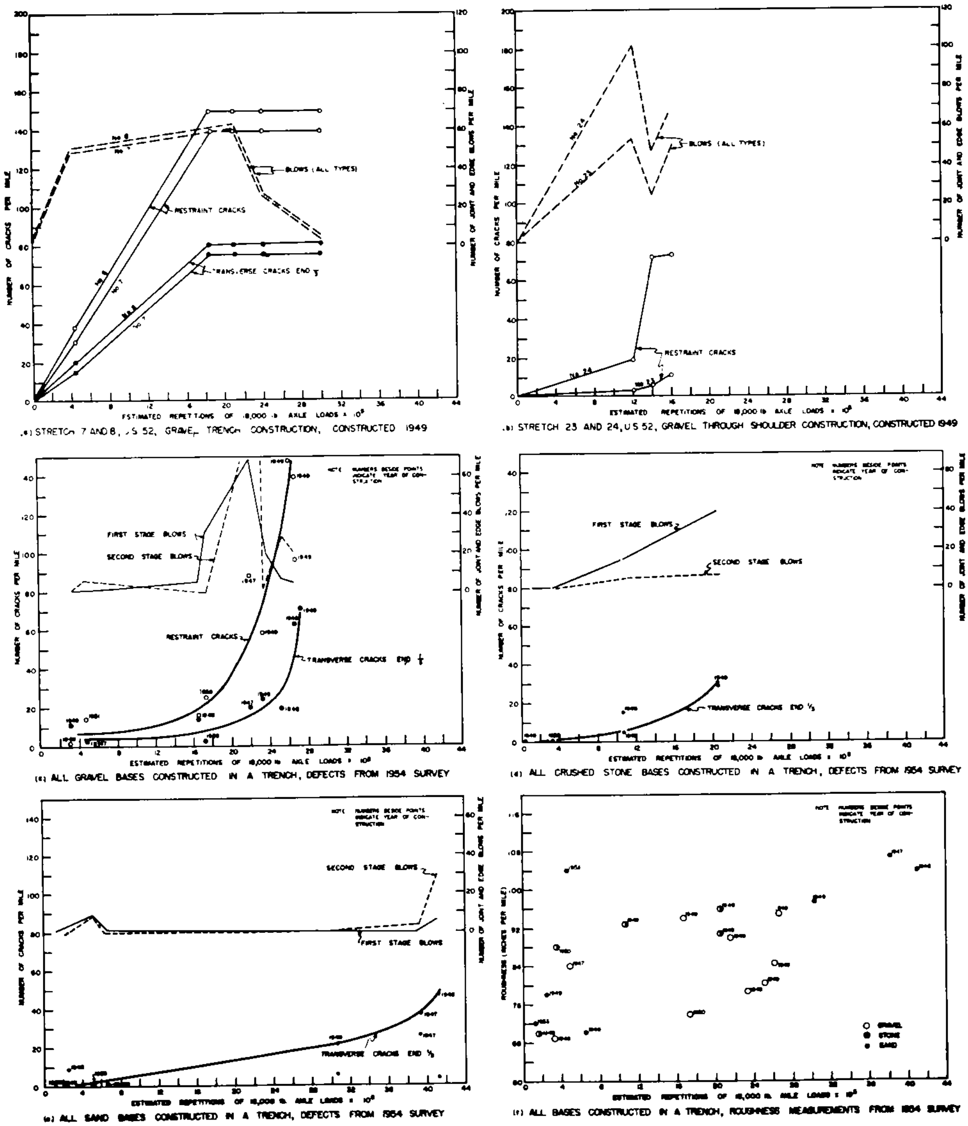

Figure 16. Variation of performance with repetition of load.

For these curves an estimate was made of the total number of repetitions of 18,000-lb axle loads from the date of construction to the time of the survey. These data were calculated using equivalent wheel load procedures.

Figure 16 shows that the occurence of restraint and transverse cracks is greatly influenced by traffic. It is recognized that distribution of traffic with time is important and that this factor is not taken into account when considering equivalent wheel loads. For example, on some roads heavy truck traffic is concentrated during the early morning hours. This is the time of day when the pavement slab is warped upward at the corners and edges. As a result, the pavement is stressed to a higher degree (for comparable loads) at this time of the day than during the

late afternoon. It appears reasonable, however, to assume that distribution of traffic throughout the day will be the same for most roads and that the only variable entering into this type of analysis will be number of load applications.

Continuous surveys have been made on US 52 north of Lafayette, Ind. Figure 16a shows data for a section of road constructed in 1949; Figure 16b, for a section built in 1952. The former road was constructed using trenching procedures; the latter was constructed with the base extending through the shoulder. It is apparent from these data that the stretches of roads showing greatest blowing activity also have shown the greatest number of structural defects. Also, blowing activity has been decreasing on stretches 7 and 8.

The effect of repetition of load is apparent from Figures 16c, d, and e. Pavements built using identical designs and constructed during the same year have shown distress proportional to the number of heavy axle loads using the road. A discrepancy can be noticed when comparing Figures 16a and 16c. No additional cracking has been found on stretches 7 and 8 after about three years of traffic, although Figure 16c indicates that cracking continues for an indefinite period. Therefore, it must be reasoned that the curve in Figure 16c should be much steeper for lower traffic values than is shown. Nevertheless, the correlation of defects with number of load repetition is unmistakable.

Second-stage blowing has been active primarily on gravel bases. Stone bases have resulted in very little second-stage blowing, but in extensive first-stage activity. Likewise, restraint cracks are rare on pavements built on crushed stone. On the basis of transverse cracks the sand bases are apparently showing the best performance (for a given number of repetitions of load), whereas the gravel bases have shown poorest performance.

Figure 16f shows roughness data for pavements built on all types of bases. Sand and stone bases have resulted in slightly greater roughness values, for comparable traffic, than gravel.

The data indicate that traffic is one of the more important variables affecting performance of pavements built on granular bases. All pavements carrying light traffic have shown good performance for all types of base materials. This point deserves increased attention from the standpoint of design.

Thickness of Base

Thickness of base course has very little effect insofar as blowing is concerned. Table 3 gives data relative to this from Indiana surveys. In some cases thicker bases have shown greater blowing than thinner bases. This can be presumed to be due to greater consolidation of the

TABLE 3
SUMMARY OF PERFORMANCE OF SAND BASES*

Road No.	Repetitions of All Classes (x 10⁵)	3″, or 3″ - 2½″ Base		6″ -5″ -6″ Base		7″ or 8″ Base		9″-6″-3″-6″-9″, or 9″-8″-9″ Base	
		1st-Stage Blows	2nd-Stage Blows	1st-Stage Blows	2nd-Stage Blows	1st-Stage Blows	2nd-Stage Blows	1st-Stage Blows	2nd-Stage Blows
662	0.88	0	0						
66	4.74	0	0						
37	4.64			0	0				
41	8.47							7.78	0
41	8.47							45.53	0
37	8.76							1.10	0
37	11.47			0.16	0				
41	12.30							0	0
41	12.30							0.61	
31	20.10					0	0		
31	20.10					0	0		
40	25.03			4.43	0				
30	78.85			14.03	0				

* Vogelgesang (*19*).

deep sand layers, which in turn creates a larger space into which water can accumulate under the pavement. A survey of performance records indicates that these thick bases showed severe blowing immediately after construction, but that it diminished after about two years and practically stopped after seven years.

Data from the Indiana and Ohio test roads (*1*) (*19*) indicate that depths of 3, 5, and 8 in. give about the same performance, the 3-in. depth showing only slightly more blowing than 5 in. of base.

From these data it is strongly indicated that relatively thin bases will give satisfactory results if the material is properly graded.

Drainage of Base

Drainage of the base is very important and is closely associated with permeability. Table 1 illustrates that open-graded stone bases with drainage have shown excellent performance. Likewise stretch 1 on US 40, one of the most heavily traveled roads in Indiana, has shown very little distress. This section of road has transverse drains spaced every 100 to 200 ft.

Water accumulates in open-graded materials constructed in a trench if the underlying soil lacks permeability (see Figure 17). The principal source of this water is surface infiltration. However, the subgrade does not show any appreciable increase in moisture content of soil where trench construction is used over drained sections. Figure 18 shows moisture data for all CL subgrades sampled.

Figure 19 shows blowing data for a dense-graded gravel with some sections drained and the remaining ones built through the shoulder. Although blowing and subsequent distress by cracking are markedly decreased by installation of drain tile, it should be remembered that many stretches of roads built in a trench and without drains have shown excellent

Figure 17. Water running from open-graded base constructed in a trench on a 50-ft fill on Ind 37.

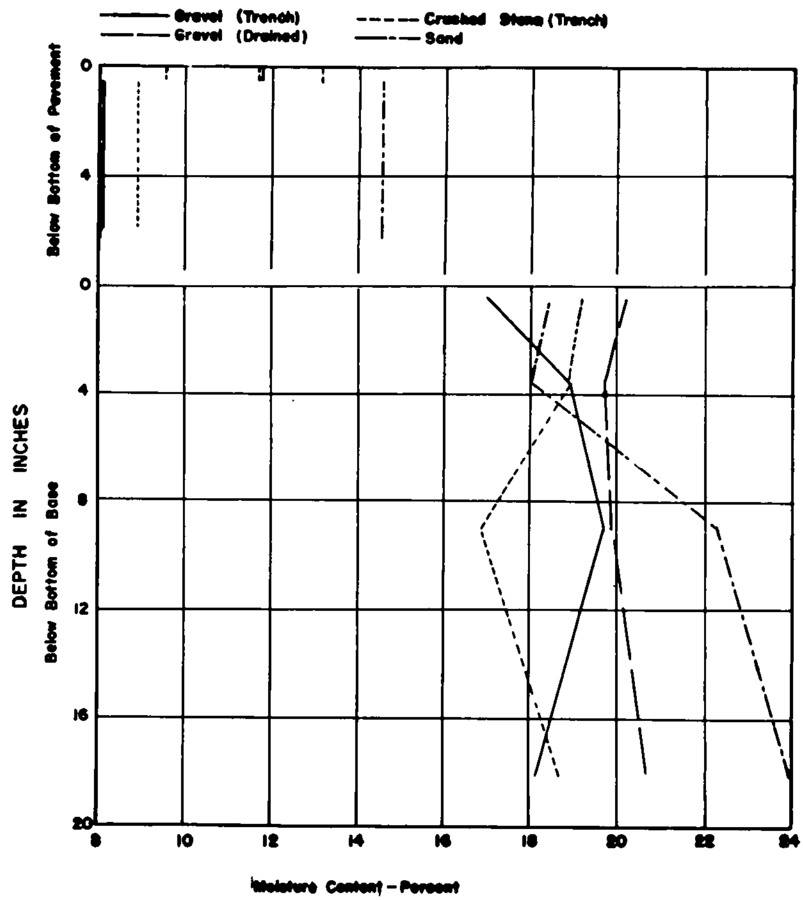

Figure 18. Variation of moisture content with depth, all CL subgrades.

performance. The data in Figure 19 suggest that drainage of poorer quality materials is quite effective. However, Table 1 shows that good quality base materials will function equally satisfactorily, even without drains.

The data further show that extending the base through the shoulder is very effective if the base is open-textured. However, poorly graded materials will not drain effectively through the shoulder.

Structural Capacity

Data regarding this factor are meager at present, because most pavements have been built from a standard design. Performance of 9-in. uniform highway pavements is generally no better than the 9-8-9-in. pavements.

It should be mentioned that some of the war-time pavements constructed with a 20-ft joint interval and no load transfer have shown little blowing distress, but have faulted considerably. This is true of stretches 30 and 1. Stretch 30 has received little heavy traffic, but stretch 1 has received very heavy traffic.

Although pavements included in these surveys have been of about the same thickness, it is reasonable to assume that increased thickness would at least minimize cracking of the pavement slab.

Figures 20 and 21 show distribution and length of restraint cracks and the

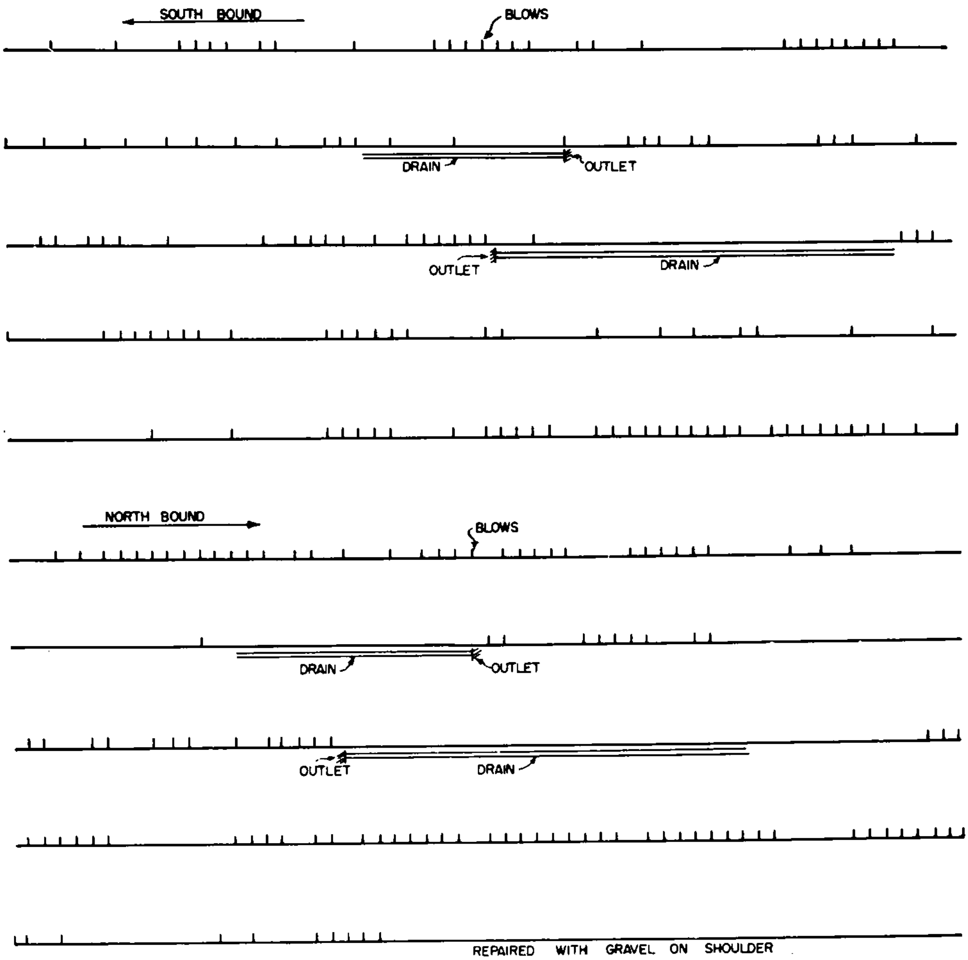

Figure 19. Effect of tile drains on blowing, US 52 (dense-graded gravel through-shoulder base except as noted).

longitudinal distribution of transverse cracks. Transverse cracks are largely located in the centers of the slabs, but the longest restraint cracks occur when the distance to the nearest transverse crack is less than 8 ft.

It is believed that occurrence of restraint cracks is influenced by the pavement cross-section. In Figure 22 it can be seen that by far the most restraint cracks occur at the transition from the thickened edge. Also, most trucks travel inside the thickened edge. These facts indicate that the thickened edge is not warranted as used on these pavements.

Restraint cracks are largely a result of shearing stresses during the expansion cycles. These stresses are caused by infiltration into the joints of base material from below due to blowing action. Restraint cracks generally occur during the summer months (see Figure 6). They are no doubt also influenced to a degree by bending action of the slab. Figure 23 indicates the percentage of cracks which are diagonal and those which are longitudinal.

Since both 9-7-9-in. and 9-in. uniform pavements have shown considerable blowing and restraint crack distress when

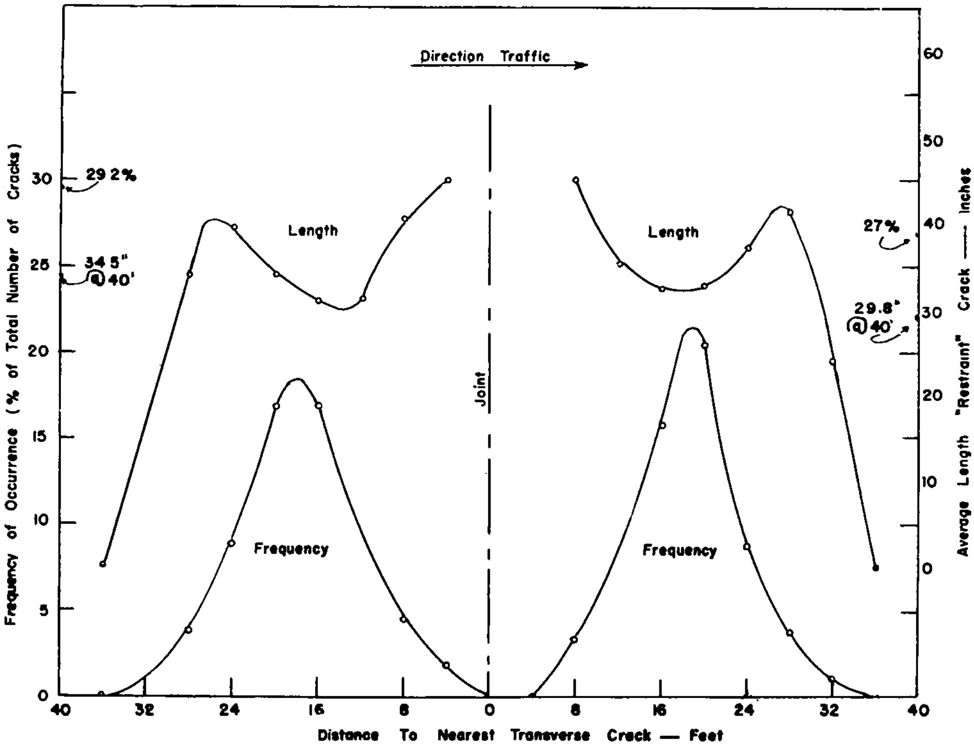

Figure 20. Distribution and length of restraint cracks.

constructed on poorly graded gravels, it follows that any significant difference in performance for comparable traffic of pavements ranging in thickness from 7 to 9 in. is obscured by the quality of the base.

Adequate load transfer is extremely important. Data from the US 41 Indiana Test Road indicates that by far the greatest blowing and subsequent faulting occurred on the plain concrete sections. Spencer, Allen, and Smith (*19*) have shown that cumulative roughness is about twice as great for plain concrete as for reinforced concrete. The plain concrete sections built on natural subgrade have all failed, but the reinforced pavement is still in good condition. Also, Woods, Green, and Sweet (*24*) reported that many pavements in Indiana constructed on sand bases have shown considerable faulting. These pavements were largely war-time pavements built with no load transfer across the joints.

Subgrade Type and Climate

Climate has an immediate effect on blowing of bases, in that surface infiltration is blamed for its severity at any one time (Table 4). When considering the over-all effect of climate on performance, however, no noticeable difference is seen.

In general, the pavements in the northern portion of the state have undergone more distress than those in the southern portion. This northern area is also where most of the traffic is concentrated. Thus, the effect of soil type and climate is obscured by the variables of traffic and base course type. For comparable traffic and base course type all subgrades appeared to function equally well, with one exception. This exception is SR 37, which has a crushed stone base course and is built on a highly plastic limestone residual soil. This pavement has shown considerably more distress

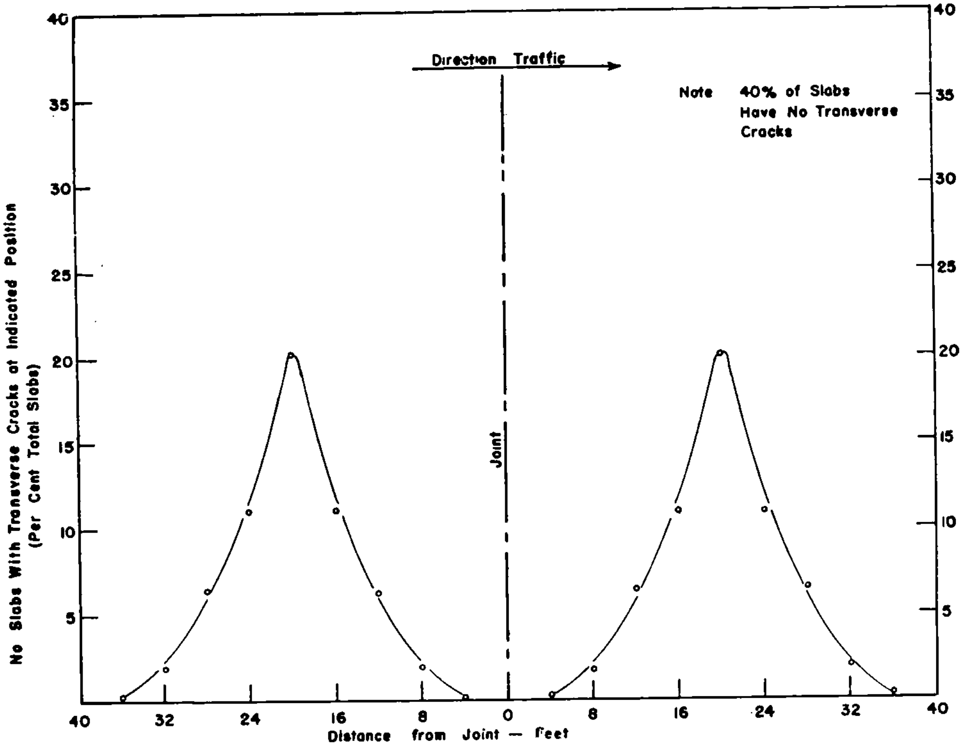

Figure 21. Distribution of transverse cracks (gravel base, trench, traffic lanes only).

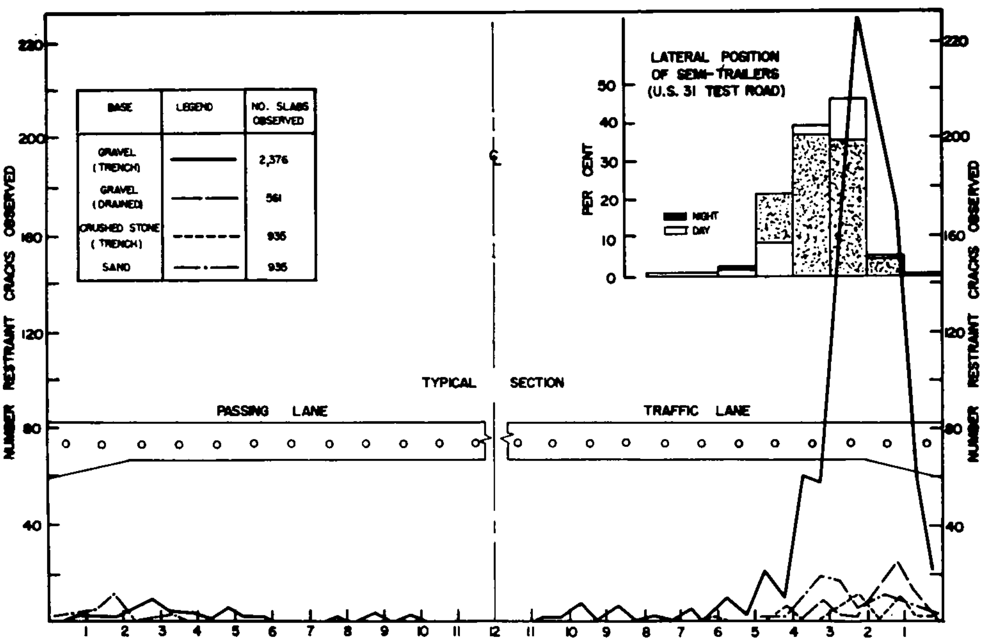

Figure 22. Lateral position of restraint cracks.

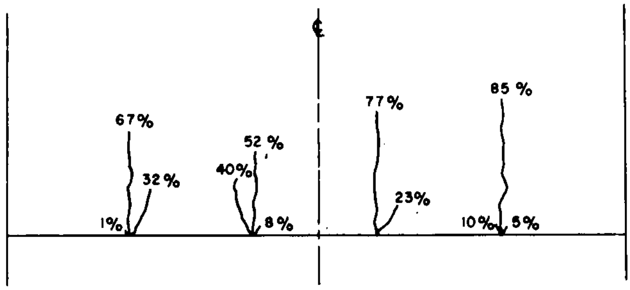

Figure 23. Percentage of restraint cracks that are diagonal and longitudinal.

with less traffic than those built on silty clay subgrade.

The data in Table 4 suggest that precipitation has a great effect on blowing. For this one section of road, blowing was just as severe during the fall season as during the spring of the year. The intensity of rainfall a week prior to the inspection appeared to influence the extent of blowing which was logged. Based on the limited data available, severity of the preceding winter has little effect on the extent of blowing during the spring.

Grade, Alignment, and Geometric Design

As shown in Table 5, cut sections show considerably less blowing than sections which are on grade, and slightly less blowing than fill sections. This is probably due to utilization of more base course drains on the cut sections than on the fill sections and sections which are on grade. The frequency of pavement cracking, however, is generally considerably greater on the cut sections than on those sections which are on grade or in fill.

Horizontal and vertical curves also appear to influence the pattern of blowing of highway pavements. On horizontal curves blowing is the most serious on the inside of the curves. This is probably due to traffic moving closer to the inside edge of the pavement on curves. On vertical curves blowing is the most severe at the low points of the curves, although some serious blowing also occurs at the high points.

Blowing and pavement cracking are most severe at the free edge of the pavement. This is shown by Table 6, which is a summary of data obtained on heavily traveled highways. It is significant that of the 135 road intersections and deceleration lanes observed, none showed any blowing and only about 10 percent showed evidence of structural failure. Some cracking is apparent, but generally to a lesser degree than on pavements with turf shoulders.

The effect of a free edge as compared to a paved shoulder is illustrated in Figure 24. This section of road is on US 52 (Lebanon By-Pass). In this case the deceleration lane is a rigid concrete pavement. This additional paving apparently has considerably reduced blowing and restraint cracking, but has had little effect on transverse cracking. Although in this case the reduction in blowing and restraint cracking is probably due to both the prevention of surface infiltration at the edge of the pavement and to the additional load support provided by the rigid turning lane pavement, in most cases the reduced blowing and restraint cracking are primarily due only to the prevention of surface infiltration. This is because most of the turnouts and intersections have been paved with bituminous materials and are not rigid pavements with load transfers. For example, on stretch 7 (Table 6) only 10 of the 89 intersection and turnout pavements observed were concrete; on stretch 8, only 12 of the 94 slabs observed were concrete.

This improved performance due to protection of the pavement edge is com-

TABLE 4
SUMMARY OF BLOW HOLE COUNT, US 52 NORTH OF LAFAYETTE (CONSTRUCTED FALL 1949)

Stretch	Section	No. of Joints or Cracks with Blows and Slabs with Edge Blows													
		11-14-50		5-11-54		9-7-54		10-15-54		10-20-54		10-26-54		3-11-55	
		Joint and Crack	Edge	Joint and Crack	Edge	Joint and Crack	Edge	Joint and Crack	Edge	Joint and Crack	Edge	Joint and Crack	Edge	Joint and Crack	Edge
7	3	0	0	0	0	0	0	5	1	0	0	1	1	0	0
7	12	9	0	5	2	5	1	16	1	7	1	7	1	1	0
7	14	18	0	0	0	4	1	12	3	6	1	7	2	1	1
8	24	20	1	0	0	7	5	16	5	10	2	9	1	0	0
8	15	4	0	7	3	2	1	15	7	8	4	9	4	7	6
8	13	4	0	1	0	0	0	2	1	1	1	1	0	1	0
Preciptation, day prior		0		0		0		0.72		0		0.18		0	
Precipitation, week prior		1.17		0.11		0.85		3.74		3.74		0		0.07	
Preciptation, month prior		1.38		3.49		4.58		5.59		6.19		6.00		1.05	
Degree days, day prior		—		18		60		23		10		21		27	
Degree days, week prior		—		94		309		206		120		138		55	
Degree days, month prior		—		660		1200		960		951		950		—120	
Freezing index, winter prior		—		170		170		170		170		170		205	

TABLE 4 (Continued)

Stretch	Section	No. of Joints or Cracks with Blows and Slabs with Edge Blows									
		3-30-55		5-17-55		10-3-55		3-5-56		3-26-56	
		Joint and Crack	Edge	Joint and Crack	Edge	Joint and Crack	Edge	Joint and Crack	Edge	Joint and Crack	Edge
7	3	0	0	0	0	0	0	0	0	0	0
7	12	7	2	8	1	0	0	0	3	3	3
7	14	4	1	6	1	0	0	0	0	—	—
8	24	0	0	0	0	0	0	0	0	0	4
8	15	15	10	8	2	0	0	—	—	16	4
8	13	1	0	0	0	0	0	1	0	—	—
Precipitation, day prior		0.00		0		0		0.11		0	
Precipitation, week prior		0.14		2.41		0.65		0.29		0.27	
Precipitation, month prior		1.05		3.29		4.67		2.33		1.23	
Degree days, day prior		7		30		27		9		12	
Degree days, week prior		—11		182		209		19		28	
Degree days, month prior		180		720		1020		—120		150	
Freezing index, winter prior		205		205		205		556		556	

TABLE 5
NUMBER OF SLABS SHOWING RESTRAINT AND TRANSVERSE CRACKS AND BLOWING IN CUT, FILL, AND ON GRADE (EXPRESSED AS PERCENT OF NO. OF SLABS OBSERVED IN CUT, FILL, OR GRADE)

	Cut		Fill		On Grade	
	Traffic Lane	Passing Lane	Traffic Lane	Passing Lane	Traffic Lane	Passing Lane
Restraint cracks	10.6	4.1	8.2	2.1	7.1	0.2
Transverse cracks-center 1/3	38.6	28.8	25.2	24.5	27.4	20.7
Transverse cracks-forw'd 1/3	71.1	2.9	7.3	2.3	3.9	1.2
Transverse cracks-backw'd 1/3	71.1	3.9	8.2	3.8	4.5	2.3
Blowing (all types)	14.7	0	18.9	0	52.0	0
No. slabs	835	—	2,435	—	187	—

patible with results obtained from the WASHO Test Road, where the data indicated that adequate shoulder construction and maintenance effectively improved flexible pavement performance.

The foregoing observations carry implications which may be applied to airfields. Because traffic on taxiways, aprons, and runways does not occur at the pavement edges, blowing and subsequent pavement distress are reduced.

AIRFIELD SURVEYS

Field inspections were made of 15 military airfields and a literature search was conducted of the pumping history of 12 additional airfields. The purpose of these surveys was to determine the severity, amount, and location of pumping on rigid airfield pavements. Emphasis was placed on air bases situated in the northern half of the United States, although inspections were made of several southern fields as well.

The Rigid Pavement Laboratories, U. S. Corps of Engineers, furnished condition survey reports which indicated the extent of pumping in the various Corps of Engineers Districts. These data were compiled and analyzed to determine the cause of pumping.

Pumping was found to be minor in extent, considering the total amount of pavements inspected. In most cases pumping was found to be due to overload. Pumping and resulting failure has been confined primarily to pavements which carry loads in excess of the design value.

Highway surveys have shown that pumping is due to high repetition of heavy loads, fine-grained soils, and free water under the slab. The airfield data were analyzed in light of these variables. The following paragraphs present a portion of these data.

Subgrade Type

As in the case of highways, some variation exists regarding types of soils which result in pumping. Table 7 shows soil data obtained during the Air Base surveys.

The data shown are those which have a known pumping (or non-pumping) history. If reasonable doubt existed as to the pumping history of a particular fea-

TABLE 6

DEFECTS AT FREE EDGES AND AT TURNOUTS, ROAD INTERSECTIONS, ETC.

Stretch	Base	Free Edge				Road Intersections, Etc.			
		No. Slabs Observed	Slabs* Blowing	Trans.* Cracks	Rest* Cracks	No. Slabs Observed	Slabs** Blowing	Trans.** Cracks	Rest** Cracks
23	Gravel	126	38.1	5.6	8.3	6	0	0	16.0
24	Gravel	128	81.4	9.4	52.5	4	0	0	0
5-33	Gravel	464	10.0	12.9	19.0	32	0	6.3	9.9
11-37	Gravel	434	12.0	32.8	22.3	47	0	12.9	7.8
7	Gravel	133	18.9	100.0	99.0	89	0	82.0	13.5
8	Gravel	133	20.3	83.0	97.8	94	0	61.6	38.1
52	Stone	62	38.3	61.6	0	4	0	12.5	0
53	Stone	59	30.8	67.6	0	7	0	57.2	0
64	Sand	125	28.8	152.0	3.2	7	0	71.4	0
65	Sand	125	3.2	83.2	4.8	7	0	28.6	0

* Percent of slabs with free edge.
** Percent of slabs in intersections.

ture, the data for this feature were completely ignored. It is noted in Table 7 that an overlap exists between pumping and non-pumping soils. However, there is an unmistakable tendency for the plastic clays to result in more pumping distress than the less plastic silty clays and silts. The fact that some overlap exists suggests that most of the soils occurring within the group of pumping soils would pump if all conditions were conducive to this action. Data from highway surveys also indicate an overlap of pumping and non-pumping soils. Some silts and fine sands have resulted in pumping on air fields.

Data from this study indicate that subgrades which result in pumping on airfields are of the same general type as those which result in pumping on highways. Most airfield pavements which have resulted in pumping have been overloaded according to the Corps of Engineers design criteria. There are instances, however, where soils within a certain soil group have shown no evidence of pumping, although other soils in the same group have shown serious pumping distress under identical loading conditions. This fact indicates that under favorable moisture conditions most soils would not pump under considerable overload.

Type and Quality of Base

Airfield pavements constructed on granular base materials resulted in pumping on only five of the 27 air bases surveyed. In every case the pavements which resulted in pumping were overloaded. In addition, the base courses which resulted in pumping in every case contained excessive amounts of fines. In other parts of this report the effect of base course type on pumping and blowing of highway pavements was discussed at great length. It was brought out that granular bases which are poorly graded result in pumping under conditions of heavy traffic. Data show that this applies also to airfield pavements.

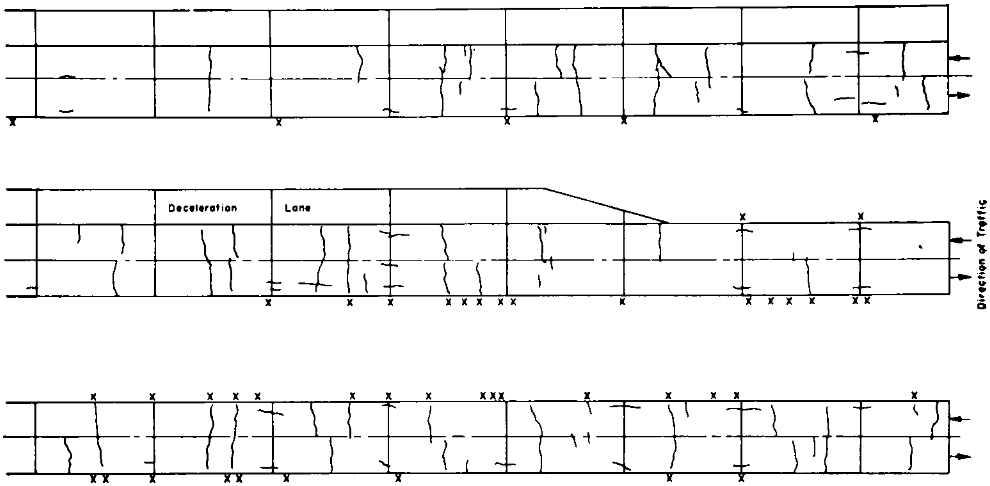

Figure 24. Effect of deceleration lane on pavement performance, US 52, Lebanon by-pass (dense-graded gravel, trench construction).

Structural Characteristics

Data obtained during this study have indicated that for airfields, gross load, and in particular overload, is the predominant factor which causes pumping. Table 8 shows a summary of pumping and overload. In all but two cases where pumping was ever active on a pavement feature, this feature was overloaded according to the Corps of Engineering design criteria.

Even though pumping can be correlated with overload it does not follow that overload will always result in pumping. Many of the pavements included in this survey were overloaded without pumping action resulting. By the same token, loads less than the design will cause pumping where improper compaction, warped pavements, percolating ground water, or other factors permit water to accumulate immediately beneath the pavement.

It is of interest to note that in several cases pavements situated on natural subgrade soils have resulted in pumping under overload conditions, although other paving features built on granular bases at the same field did not result in pumping.

Highway And Airfield Pumping Compared

Performance of highway and airport pavements regarding pumping has been vastly different. Highways which carry high volumes of heavy traffic nearly always result in pumping distress if built directly on clay subgrades. On the other hand, many airfield pavements built over plastic soils have shown little or no pumping. Data presented in this report have indicated that pumping at the present time is minor on these latter pavements. Pavements which have shown pumping distress have been subjected to loads as much as two to three times the design value.

To determine the factors which may be different for the two cases it is necessary to evaluate the factors affecting performance of rigid pavements. Some of these factors are as follows:

1. Total weight.
2. Tire pressure.
3. Gear configuration (that is, duals, tandem, etc.).
4. Repetition of load.

The total weight of an airplane is usually greater than that of a truck, but on the other hand the number of repe-

TABLE 7
COMPARISON OF PUMPING AND NON-PUMPING SOILS (AIR FORCE BASE SURVEYS)

Air Base	Pumping							Non-Pumping						
	Feature	Phsy'phy	L.L.	P.L.	% Finer		Class	Feature	Phys'phy	L.L.	P.L.	% Finer		Class
					No. 40	No. 200						No. 40	No. 200	
			(%)	(%)	(%)	(%)				(%)	(%)	(%)	(%)	
Andrews	Apron	Great Plain					CL	RW, TW	Great Plain					SF&CL
Ardmore	RW	Coastal Plain						RW, TW Apron	Coastal Plain	27 31 24 28	19 16 NP 18 NP 16	99 98 94 99 100 99	90 71 40 64 72 62	CL CL SM CLML ML CL
Barksdale	Apron TW	Alluvium	34 29 65	19 18 25			CL CL CH	RW, TW Apron	Apron RW, TW	29 36 40 38 43 27 34	18 18 20 20 22 16 18			CL CL CL CL ML CL CL
Brookley	RW	Coastal Plain	Nonplastic		92 98 99 86	27 29 43 34	SMd SMd SMd SMd	RW, TW Apron	Coastal Plain	Nonplastic				SMd
Carswell	Apron TW	Coastal Plain	36 27 35	17 14 19			CL CL CL	TW RW	Coastal Plain	Visual Classification indicates soils identical to those pumping				CL
Ellsworth	RW	Great Plain			90	76	CH	Apron TW	Great Plain					
Forbes	RW&TW	Old Drift	49 53 53 42	23 27 13 21	100 98 95	98 94 88	CL CH CH CL							

(TABLE 7 Cont.)

COMPARISON OF PUMPING AND NON-PUMPING SOILS (AIR FORCE BASE SURVEYS)

Kearney	Apron	Loess	36	20			CL						
Lincoln	TW	Flood Plain	48 45 42 50 46 56	23 20 20 22 21 30	98	92	CL CL CL CL CL CH						
Lockbourne	TW RW	Young Drift	46 61 30	23 26 19	95 100 86	86 72 74	CL CH CL						
Lowry	TW Apron	Shale	35	18	92 82 72	69 46 32	CL	RW, TW	Shale	29 34 31 33	17 17 19 18			CL CL CL CL
McConnell								TW	Great Plain	38 42 48 53 59	19 22 22 23 23		90 94 95 96 98	CL CL CL CH CH
Scott								Apron TW, RW	Young Drift	39 41 42 43 31 25 33 32	23 26 18 25 20 22 23 20	99 98 99 99 99 100 99 99	98 96 98 97 98 99 98 98	CL ML ML CL CL ML ML CL
Sedalia								Apron TW, RW	Loess	44 40 45 49 40 44	23 22 24 25 22 22			CL CL CL CL CL CL
Smokey Hill	RW		57	22	100 100 93	98 94 60	CH	Apron TW, RW		42 53 51 52 52	21 23 21 23 22	93	90	CL CH CH CH CH

TABLE 8
SUMMARY OF PUMPING AND GROSS LOAD

Air Base	Base Course Pumping	Overload	Subgrade Pumping	Overload
Andrews	Yes	No	—	—
Barksdale	—	—	Yes	Yes
Brookley	Yes	Yes	Yes	Yes
Carswell	Yes	Yes	Yes	Yes
Ellsworth	Yes	Yes	—	—
Forbes	No	No	Yes	Yes
Kearney	Yes	Yes	—	—
Lockbourne	No	Yes	Yes	Yes
Lowry	—	—	Yes	Yes
Maxwell	Yes	Yes	—	—
McConnell	No	No	Yes	Yes
Selfridge	Yes	No	No	Yes
Smokey Hill	No	No	Yes	Yes
Ardmore	No	No	No	No
Chanute	No	Yes	No	Yes
Clinton Co.	—	—	No	No
Connelly	No	Minor	—	—
Grandview	No	No	—	—
Grenier	No	Minor	No	Minor
Lake Charles	—	—	—	—
Lincoln	No	No	—	—
Offutt	No	No	No	—
Scott	No	Yes	No	Yes
Sedalia	—	—	—	—
Westover	No	Yes	No	Yes
WrightPatterson	No	Yes	No	Yes
Youngstown	No	No	No	—

titions of loads is much greater on highways than on airports. The design load for a major highway is generally in the vicinity of 9,000 lb on dual tires and the expected repetition may be as much as 1,000 to 2,000 trucks per day. In contrast, a heavy bomber may have wheel loads in excess of 100,000 lb, but only 20,000 to 40,000 coverages may be considered for the life of the pavement. Tire pressures on jet aircraft may be as high as 200 psi; for the conventional truck tire, the pressures will be in the vicinity of 60 to 70 psi.

Results of the present study have indicated that the B-47 type planes may result in pumping if fine-grained soils are encountered. All of the severe pumping noted during these surveys can be attributed to channelized B-47 or B-36 traffic.

According to recent studies made by the Corps of Engineers, 75 percent of the B-47 type of traffic on channelized taxiways falls within a strip 7.5 ft in width. From this it is calculated that for this type of traffic 2.14 operations are required for one coverage. A coverage occurs when each point in a pavement area is traversed one time by an aircraft wheel. For features of non-channelized traffic the traffic is distributed over about 38 ft of the pavement.

Lateral placement of traffic on highways has indicated that nearly all truck traffic occurs within 6 to 7 ft of the pavement edge. More than 95 percent of the truck traffic is concentrated within a width of about 3 ft.

From the foregoing discussion it is seen that a major difference between highway and airfield pavements is that of repetition of load and distribution of traffic over the pavement width. In turn, this is affected by pavement width and type of aircraft. Gross weights as well as tire pressures associated with aircraft are much higher than for trucks; however, these factors are minimized when pavement thickness is taken into account.

The number of repetitions of load causing pumping on airfield pavements is extremely difficult to determine, due to lack of data. The exact date on which pumping started, as well as the true number of planes in each weight category, are not known for most of the fields studied.

The geometry of the pavement is extremely important. Severest pumping and subsequent failures on airfields occurred

where the traffic line followed a longitudinal joint. Very little pumping was found on aprons or in the center portion of runways.

SUMMARY

The following briefly summarizes the data presented in this report:

1. Blowing of base courses occurs mainly in states which utilize dense-graded aggregates as bases. However, a few states utilizing dense-graded bases report satisfactory use of these materials.
2. General pavement distress, evidenced by cracking, accompanies blowing of bases after this action progresses into the second stage, where removal of fines occurs. Pumping and blowing of clear water from under the pavement does not necessarily indicate that pavement distress will occur.
3. Blowing starts soon after the pavement is opened to traffic, but decreases or completely stops after about 4 to 6 years. When the pavement begins to crack, blowing decreases.
4. Blowing is a direct result of a layer of free water between the slab and base course. This free water accumulates if the pavement is not in firm contact with the base due to warping of the slab or consolidation of the base of subgrade.
5. The principal factors affecting performance of rigid pavements on thin bases are load repetition and quality of the base.
6. Crushed stone, gravel, or sand bases function equally well as long as they are well graded and contain a minimum of fines. Bases giving good to excellent performance are at least as open-textured as materials which conform with Fuller's maximum density curve.
7. Those bases which show blowing distress nearly always have a layer of sandy material on top which contains an excess of fines. When this layer is absent, gravel or crushed stone bases containing as much as 10 percent passing a 200-mesh sieve function satisfactorily.
8. Use of leveling courses on top of open-textured bases should be very closely controlled and this material should be free of all fines.
9. Restraint cracking results when poorly graded gravel bases are used. Sand bases and crushed stone bases rarely develop this type of distress.
10. Bases ranging in thickness from 3 to 9 in. are equally resistant to blowing.
11. Through-the-shoulder drainage is effective for open-textured bases, but not for dense-graded bases.
12. Tile drainage systems are effective for both dense- and open-graded bases.
13. Use of either tile drains or through-the-shoulder drainage is not warranted as long as the quality of the base is controlled. This is true inasmuch as dense- or open-graded bases built in a trench function nearly as well as drained bases if the layer of fines previously mentioned is not present between the pavement and base.
14. Pavement thicknesses ranging from 9-7-9-in. to 9-in. uniform have no apparent effect on the performance of the pavements surveyed.
15. Restraint cracks in concrete pavements occur principally at the transition from thickened edge to uniform pavement. These cracks, however, also occur on some 9-in. uniform pavements after second-stage development of blow holes. Restraint cracks result from infiltration of the base material into joints during blowing, and occur during expansion of the concrete due to warm weather.
16. Subgrade type has little effect on performance of pavements built on thin bases.
17. Severe blowing occurs in the spring, but does not start during the frost melt period. Rather, it appears to build up its intensity, reaching a climax several weeks to a month after the base and subgrade thaw. Severest blowing occurs after rainfall.
18. The geometry of pavement design should be given consideration. Pavements show less blowing and cracking distress where the shoulder is paved with either concrete or bituminous materials.

19. Blowing is slightly more prevalent on fills than in cuts, due probably to extensive use of base drains in cuts. Cracking is more severe in cuts than on fills.

20. No evidence exists that subgrade soils pump up and through the base courses surveyed. More attention should be directed toward this matter.

21. The factors which cause pumping of airfield pavements are identical to those for highway pavements. These include fine-grained soils, high repetition of heavy loads, and water immediately under the pavement slab.

22. In general, pumping of airfield pavements was found to be minor in extent.

23. Plastic clay subgrades show more pumping distress on airfields than less plastic silty clays and silts. Performance records show, however, that some sands and silts have pumped.

24. Base course materials under airfield pavements which have pumped were for the most part poorly graded and contained excessive amounts of material passing a 200-mesh sieve. These pumping base courses had as much as 35 percent passing the 200-mesh sieve. In contrast to this, and with but one exception. bases which have given satisfactory performance have contained from 2 to 15 percent fines.

25. Major pumping occurs on taxiways, runway ends, and other areas of channelized traffic. Very little pumping exists in parking areas of aprons or in the central portion of runways.

26. The principal cause of pumping of airfield pavements is overload. However, overload does not always result in pumping. All factors conducive to pumping must be present before this action will occur.

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DISCUSSION

PHIL FORDYCE, *Highways and Municipal Bureau, Portland Cement Association, Chicago, Ill.* — Mr. Yoder has presented much valuable information on the performance of subbases under concrete pavements. The purpose of this discussion is to supplement his report with information from another source. That source is a study of Indiana concrete pavements built on granular subbases, which is currently under way as a cooperative undertaking between the Indiana Highway Department and the Portland Cement Association.

The purpose of this, and similar studies in other states, is to determine subbase designs, materials, and construction methods which will give sustained, good pavement performance for present and projected traffic. The method is to observe and analyze pavement behavior in terms of traffic, soils, climate, subbases, and pavement designs. This analysis of observed performance is supplemented

by more intensive studies of sections of projects to find out why some sections perform better than others.

One important objective in Indiana is to correlate the current subbase study with a similar study made by Carl E. Vogelgesang in 1949-50. To this end the definitions used in the present study are the same as those given by Mr. Vogelgesang (*22*). To further insure valid comparisons between the two surveys, observers on the current study were trained by engineers who worked on the former survey, and field observations were checked periodically.

In his earlier paper, Mr. Vogelgesang defined and analyzed several types of performance phenomena. Among these were first- and second-stage blows and restraint cracks. Mr. Yoder has also described these conditions and shown examples. Additional illustrations can be found in the Vogelgesang paper.

It is important to know whether a relationship exists between blowing activity and the occurrence of restraint cracking. If a relationship is found, it is equally important to learn whether the restraint cracks are caused by the blowing or whether blowing and restraint cracking have common or unrelated causes. The author has presented data which are of value in finding the answers to these questions. The present subbase study in Indiana has also yielded information bearing on these questions.

Data are available from 75 projects, 3 to 10 years old, which have identical joint designs and similar pavement designs. All 75 projects have contraction joints spaced at 40 ft, with ¾ x 24-in. plain round dowels spaced at 12 in. Expansion joints are used only at bridge ends or other fixed objects. Distributed steel is used between joints. Lane widths are either 11 or 12 ft, and all projects have thickened edge cross-sections. Sixty-four of the 75 projects have a 9-7-9 section, three have a 9-8-9 section, and eight have a 9-6-9 section.

Relationships between blowing and restraint cracking on these 75 projects are shown in Figures 25 and 26. Projects have been grouped by subbase type and design, and have been further subdivided into age groups of 3 to 5 years and 6 to 10 years. Projects less than 3 years old do not have restraint cracks and were omitted. Within the age groups, projects increase in age from left to right. Each bar graph represents data from a single project. The lower half of each graph shows restraint cracks and the combined total of first- and second-stage blowing. The upper half shows restraint cracks and second-stage blowing only.

Study of Figures 25 and 26 fails to reveal any consistent relationship between restraint cracking and blowing activity. This absence of relationship is more pronounced for second-stage blows than for combined first- and second-stage blows.

The largest single group of projects are 6- to 10-year old pavements which have a trenched-in sand-gravel sub-base (Figure 25). All 45 projects have restraint cracking in various degrees. Fourteen of the 45 projects (29 percent) were free of both first- and second-stage blows, and 20 projects (45 percent) were free of second-stage blows. On those projects not exhibiting both restraint cracking and blowing, there is no relationship between the extent of restraint cracking and the extent of blowing. The behavior of these 45 projects indicates that blowing is probably not responsible for the restraint cracking.

It is also notable that although the most severe restraint cracking occurred on projects with trenched-in sand-gravel subbase, there were wide variations in severity, with seven projects showing less than five restraint cracks per mile. It is known that differences in truck traffic will account for some, but not all, of these variations. It is planned to make detailed investigations which may uncover the cause or causes for these variations.

The second largest group of projects have trenched-in sand subbases, and are also 6 to 10 years old (left side Figure 26). These subbases are dune sands and other uniformly graded sands. They have uniformity coefficients[2] of 1½ to 3, and from 6 to 14 percent of their material content will pass the 200-mesh sieve. All

[2] Ratio of D70 size to D20 size.

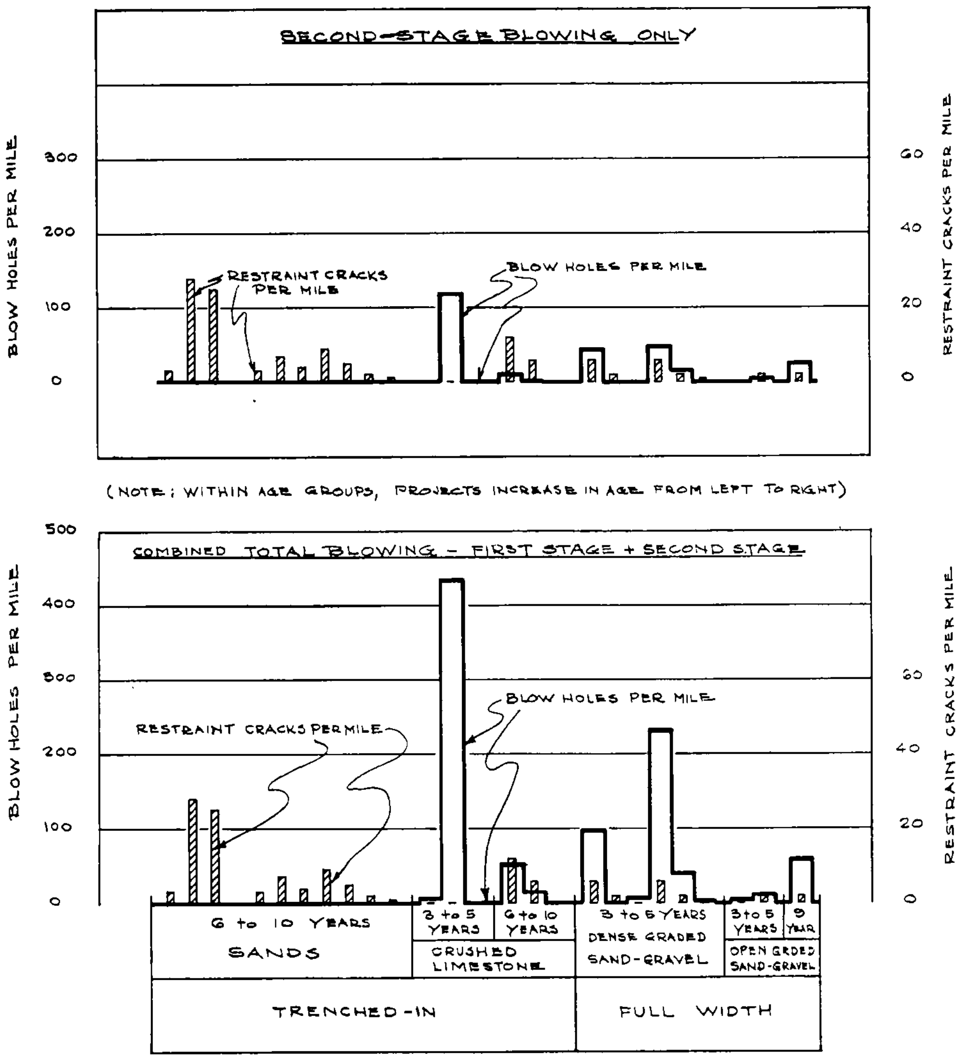

Figure 25. Relationship between blowing and restraint cracking.

but one of these projects exhibited restraint cracking in various amounts. None of these projects exhibited either type of blowing. It is known that the absence of blowing on these projects is not due to the absence of truck traffic. It is also true that uniformly graded subbases, similar to those used in Indiana, are found to be free of blowing whenever and wherever they are observed—and regardless of whether they are built trenched-in or full width through the shoulder. Two Indiana projects with these sand subbases have been observed under a variety of weather conditions over a period of several years. Both are located on routes which carry large numbers of heavy trucks. Neither has exhibited any evidence of blowing activity. It is considered probable that all eleven projects have always been free of blowing; hence, that blowing is not responsible for the restraint cracks.

The remaining five groups of projects

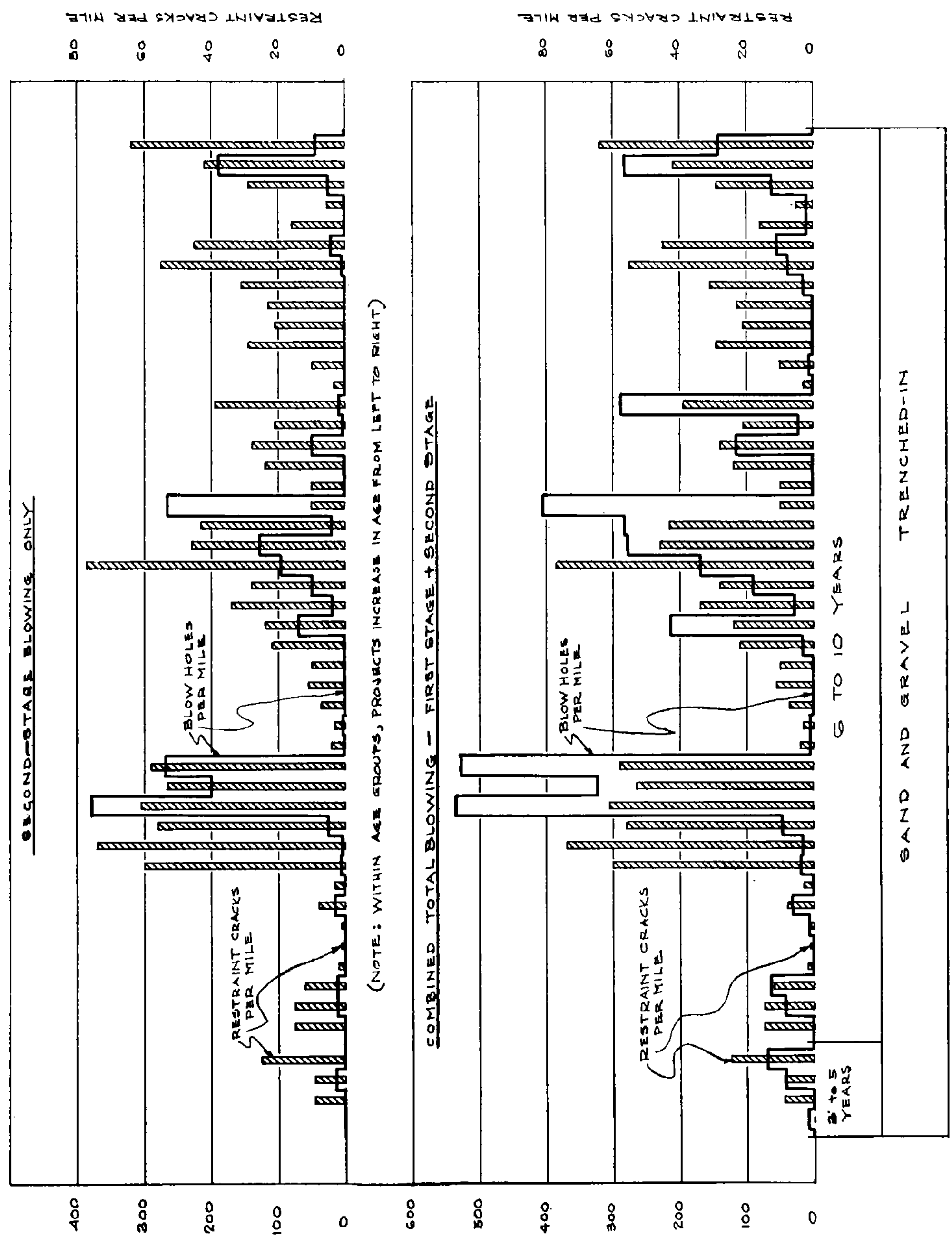

Figure 26. Relationship between blowing and restraint cracking.

differ too much in age or in numbers of projects per group for reliable comparison with the two larger groups of projects previously discussed. However, there is no important difference in behavior between these five smaller groups and the two larger ones.

If absence of blowing is taken as a performance criterion, the eleven projects with trenched-in sand subbase are outstanding. If absence of restraint cracks is taken as the performance criterion, the six projects with trenched-in crushed limestone subbase, and the nine projects with either dense- or open-graded full width sand-gravel subbases are superior.

In his presentation, Mr. Yoder observed that blowing tends to decrease after pavements reach an age of about 6 or 7 years. The data on blowing shown in Figure 25 for 6- to 10-year old projects bears out this fact, with notable exceptions on individual projects.

It should be emphasized that the Indiana subbase study is incomplete. It is expected that additional detailed field studies and further analysis of data will help to uncover the causes and significance of blowing and the causes of restraint cracking.

E. J. YODER, *Closure* — The author wishes to express his appreciation for the interesting data presented by Mr. Fordyce. Particular interest is found in the inconsistent relationship found by him between blowing and restraint cracks. The reasons for this apparent inconsistency can perhaps be found by considering the data, which show lack of blowing of sand base courses on projects that have shown some distress from restraint cracks.

Regarding eleven projects which had restraint cracks but no blowing at the time of his survey, Mr. Fordyce states that it is considered probable that all eleven have always been free of blowing and that blowing is not responsible for the restraint cracks.

Data from the Purdue surveys have shown that blowing will decrease and in some cases completely stop after the pavement has cracked. That this is true is not

TABLE 9

SUMMARY OF BLOWING[1] AND RESTRAINT CRACKING,[2] US 52, DENSE-GRADED GRAVEL, TRENCH CONSTRUCTION

Stretch and Section	November 1950		May 1954		October 1954		March 1955		March 1956	
	Blows	Restraint Cracks	Blows	Restraint Cracks	Blows	Restraint Cracks	Blows	Restraint Cracks	Blows	Restraint Cracks
7-3	0	0	0	0	26	0	20	0	0	0
7-12	52	21	22	280	84	280	32	280	4	280
7-14	95	73	0	196	74	196	20	196	8	196
8-24	110	238	6	238	95	238	0	238	0	238
8-15	22	48	36	115	85	115	85	144	—	144
8-13	22	0	6	69	11	69	0	69	4	69

[1] All types of blows expressed as number per mile.
[2] Number of restraint cracks per mile.

surprising if one considers the mechanics of blowing. Mr. Fordyce has also observed this and remarks on this point by referring to the data in Figures 25 and 26, which indicate that blowing has decreased for the 6- to 10-year old projects.

This latter point tends to explain why in some cases no apparent correlation can be found between blowing and restraint cracking. Table 9 gives the data from a continued survey made on US 52 just north of Lafayette, Indiana. This particular road was built utilizing a trenched gravel base course.

If just one survey had been made and a correlation attempted using the data for March 1956, it would be necessary to conclude that blowing and restraint cracking were unrelated. However, if a correlation would be made using the data for all surveys as a group, the reverse would be true. It is thus apparent that one survey may not give adequate results, and that it may be necessary to make continued surveys at different periods of the year.

Considering all the data accumulated during this study an excellent degree of correlation has been found between second-stage blowing and restraint cracks. As pointed out in the paper, first-stage blows have no apparent serious effect regarding formation of this type of cracking.