PAVEMENT BLOWUPS CORRELATED WITH SOURCE OF COARSE AGGREGATE

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SYNOPSIS

This paper reports, in part, the results of a study of the performance of 3300 miles of rigid pavements constructed in Indiana from 1921 to 1943. The study was made by the staff of the Joint Highway Research Project, Purdue University, for and in co-operation with the State Highway Commission of Indiana.

The data were obtained primarily from field performance surveys made over a period of some two years, together with records of construction and materials obtained from the construction and testing departments of the Commission and from blowup reports obtained from the maintenance department. Those data pertaining to the influence of materials on the performance of pavements—particularly data indicating a correlation between coarse aggregate and blowups—are included in this report. Additional data covering other features have been reported previously or are still being analyzed. Furthermore, since expansion joints were not generally employed in the design of pavements in Indiana until 1935 and after, and since the susceptibility of a pavement to blowing up is not generally indicated until the pavement is from 7 to 10 yr old, the data herein reported are confined largely to the 2623 miles of pavements constructed between the years of 1921–1935 which are still in service

In analyzing the data it was found that there were 2404 blowups in the 2623 miles without expansion joints and that 851 miles contained no blowups, while 1715 miles (65 per cent) constructed from 82 coarse aggregate sources contained only 203 blowups. In contrast, 1188 blowups were found in 284 miles of pavements constructed with coarse aggregates from only five different sources Furthermore, 97 1 miles of pavement constructed with material from one of these sources contained 707 blowups (29.6 per cent of the total blowups in the State). These data were considered important, since it was observed generally that map cracking, serious disintegration, and a relatively short pavement life accompanied the blowup failures.

It was concluded, on the basis of a statistical analysis of these blowup data, that:

(1) An outstanding correlation existed between certain coarse aggregates used in the concrete mix and the blowup performance of the pavements.

(2) No correlation existed between the cement, fine aggregate, traffic, or subgrade soils used and blowup performance.

(3) Extensive laboratory research is indicated as necessary to determine the basic reason for the variation in performance between aggregate sources and to develop new and better methods of tests by which those aggregates which produce concrete of an unsatisfactory quality can be identified before they are incorporated in the concrete pavement.

For the past 20 years or more, many State highway departments, including the State Highway Commission of Indiana, have encountered an increasingly serious problem in the susceptibility of certain rigid pavements to "blowing up." Associated with this phenomenon is map cracking and subsequent disintegration of large sections of the pave-

ment. Experience has shown, even at an early date, that blowups result from pavement expansion and that this expansion is most pronounced during periods of exceptionally high temperatures which follow a period of precipitation, even of low intensity.

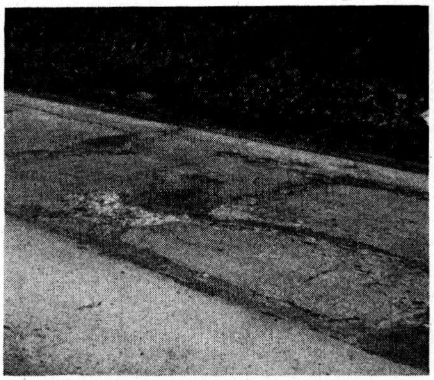

Figure 1. Excessive Map Cracking and Disintegration of One of the Pavements Constructed with Coarse Aggregate 82-1G, One of the Five Very Poor Aggregates in the State.

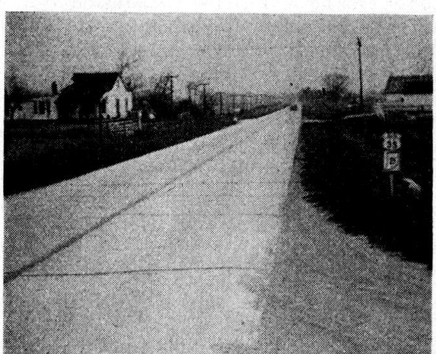

Figure 2. A Typical Example of One of the many Indiana Pavements Showing Excellent Performance. This road was constructed without joints in 1933, with a good performing aggregate.

Since the susceptibility of a pavement to excessive expansion under certain conditions of temperature and moisture is not generally indicated until the pavement is 7, 8, or even 10 years old, it can be readily understood why the problem was considered lightly until possibly in the late twenties or even the early thirties. Research in particular has suffered because of this fact, and also because of the further complication of differential performance—some pavements may have had numerous blowups after a period of several years (Fig. 1), while others of comparable age show no signs of serious distress (Figs. 2, 3, 4, and 5).

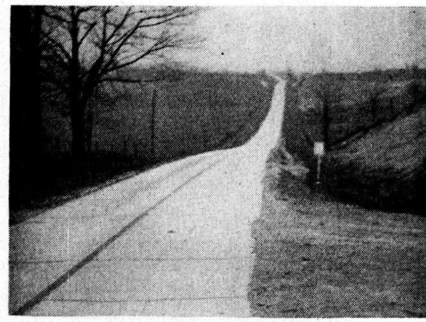

Figure 3. Excellent Performance on S.R. 1, Constructed Without Joints in 1931 with Aggregate 21-1G.

Figure 4. A View of S.R. 3, Constructed with Good Aggregates in 1935. The pavement has no joints and the average transverse crack interval is over 100 ft.

Likewise, the evaluation of materials in the concrete mix has been exceedingly difficult despite the fact that it has long been known that the so-called standard methods used for acceptance testing are frequently inadequate. In fact, these extreme variations in pavement performance have been responsible, at least in part, for the large-scale endeavors to evaluate materials with greater refinement by the use of tests such as the autoclave, freezing and thawing, sodium and magnesium sulphate, and others.

Design of the pavement slab must be considered also in connection with this problem. Here again, several hundred miles of pavement may be built before the problem is recognized and a "cure" can be incorporated in the new designs. In addition, the new design may introduce new problems—sometimes of greater magnitude than the original one. The expansion of concrete pavements and the subsequent susceptibility of certain ones to blowing up is one of the major reasons for the almost standard use of expansion joints since about 1935. However, it remains to be proven that blowups are eliminated by the types of joints used extensively to date, and it has been well established that the expansion joints most frequently employed contribute to pavement pumping under certain conditions of traffic, subgrade soil, and climate.

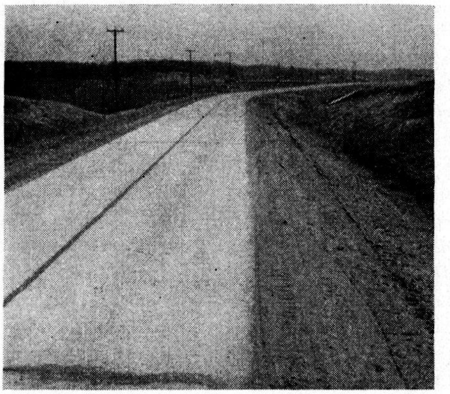

Figure 5. S.R. 62, One Mile East of Dale, Illustrating a Pavement with Exceptionally Long Crack Interval (42 ft and no blowups). The pavement was constructed in 1930.

In Indiana, as in Illinois, Ohio, Missouri, and other states, pavement blowups have made trouble for many years. The maintenance superintendent stated in the 1925 Annual Report, State Highway Commission of Indiana that "Quite a few 'blow-ups' have taken place in concrete roads due to expansion caused by extreme heat and moisture on hot days. Although these blow-ups disturb the pavement temporarily, they are not usually difficult to repair, the cracks and breaks are usually filled with a bituminous mixture, or, if only small, with the pure asphalt or tar and coated with the ordinary covering materials. It is noted that these blow-ups occur much more frequently on some roads than others." Ten years later (1935) expansion joints were incorporated in the State Highway Department designs for rigid pavements. Although various types and spacings have been employed, practically all rigid pavements constructed on the State system have had these joints until in 1944.

Research was initiated on this problem in 1942 in connection with an analysis of blowup records obtained by various districts. These records have proven valuable in establishing the variation in susceptibility of various pavements to this action and in determining the the climatic conditions—temperature and moisture—which are necessary to cause blowups. At about the same time large-scale performance surveys were initiated to study such problems as blowups, pavement pumping, scaling and frost damage, and to evaluate soils, materials, traffic, and other factors as they influence pavement design.

Although additional data and analyses are required before all the important paving factors can be evaluated, these surveys have already been particularly useful in analyzing specific problems, including scaling, pavement pumping (27),[1] and soils (26). This paper reports the data collected on blowups and shows the correlation established between this type of failure and the coarse aggregate used in the concrete mix.

PREVIOUS INVESTIGATIONS

One of the earliest references to the occurrence of blowups was in the Engineering News-Record (1) in 1925, which states: "The causes of blowups are something of a speculation. There is expansion longitudinally of the paving slab. This causes it to hump up or arch at some weak point, generally a transverse joint. The rise is from a fraction of an inch to 18 in., and there is an amount of cracking and shattering depending upon the extent and character of the expansion movement and on other conditions, as slab strength. Blowups are most common on long flat tangents and on a sand subgrade. On clayey subgrade the greater bottom friction appears to hold

[1] Numbers in parentheses refer to list of references at the end of the paper.

the slab. Where there are frequent vertical or alignment curves, they appear, like bends in a steam pipe, to take up the expansion without disruptive movement. The most frequent occurrence of blowups is when a hot day is followed by a rainy night succeeded by another hot day, causing both temperature and moisture expansion "

As early as 1925 varying performance of different roads with respect to blowups was observed Although blowups in themselves do not appear to be a serious problem since they are "not usually difficult to repair," they assume importance because of two factors (1) they have led to the widespread incorporation of expansion joints in pavements; and (2) their occurrence is associated with other manifestations of pavement deterioration such as map cracking.

Regarding the first factor, Hewes (9) states "the expansion corresponding to increased temperature requires sufficient relief, which is provided by elastic fillers in the transverse joints Without such relief, buckling or blowups may occur in extreme cases, such as sudden hot weather following prolonged moisture, particularly on low-friction subgrades " On the other hand, Reagel and Gotham (18) concluded that· "Under average conditions in Missouri expansion joints are not necessary but, in fact, are detrimental in pavement built with the commonly used crushed-limestone aggregate, provided contraction joints are installed at suitable intervals to provide efficient crack control Under average conditions the use of expansion joints causes increased transverse cracking in pavements built with either chert aggregate or crushed limestone However, in pavement built with chert aggregate some provision for expansion is probably necessary to provide the degree of control of blowups generally considered desirable."

The comments of Mr E F. Kelley (13) are of interest in this respect: ".. a rise in temperature as great as 100 deg. F. would create a compressive stress of only 2500 p s i (assuming a modulus of elasticity of 5,000,000 p s i and a thermal coefficient of 0 000005 per deg F.). A direct compressive stress of this magnitude should cause no distress in concrete of the quality commonly used in pavements. . . . Also, such a large change in temperature generally can be expected to take place only over a relatively long period of time and therefore, it may be expected that the indicated stress will be reduced somewhat by the plastic flow of the concrete However, the slab undoubtedly acts to some extent as a long column and its ultimate strength as a column is considerably less than its compressive strength as measured by tests on short specimens It is believed that compressive failures are due primarily to column action rather than to direct compression and observations of pavement failures support this conclusion." Kelley also showed that the shrinkage from the tendency to dry out during the summertime would tend to compensate for the expansion due to increased temperature. He noted the manifestation of "slow growth" of concrete and ascribed it to the failure of the concrete to return to its original length after expansion from moisture had occurred.

Also pertinent in this respect are the observations of Cashell and Benham (5) on an experimental pavement on U.S. 40 in Indiana They note. ". . . the sections were able to expand more freely each succeeding year Specifically the length change of the 1310-ft. sections for the first year was only 41 per cent of the expected length change of an unrestrained section This percentage value for the second, third, and fifth years respectively increased to 53, 61, and 62 per cent. Thus, it appears that the sections encountered less subgrade resistance each successive annual expansion period until, by the end of the third period, a condition of stability was attained." However, they also observed that the sections up to and including 140 ft. long showed "no definite indication of a permanent change in length . . . the 335-, 600-, 1070-, and 1310-ft. sections show a progressive increase in expanded lengths each August but every succeeding February they return so closely to their base length of February 1939 that, up to the present time, permanent growth is not manifested."

In the projects upon which the foregoing observations were made, the reinforcing varied from light-weight (0.19-in. diameter) welded wire fabric to 1-in diameter rail and billet steel bars at 6-in centers In the long sections under consideration, the extremely heavy reinforcement was used.

These observations suggest a possible design procedure; the use of heavy reinforcement

in cases where abnormal expansion is to be anticipated, assuming that this action could be duplicated in projects where expansive aggregates were to be incorporated.

Oregon engineers (17) concluded that: "Expansion joints in portland-cement concrete highway pavements in western Oregon are unnecessary, in fact they are a detriment to the smooth riding qualities required in a modern highway." Their conclusions were based on observations of experimental sections constructed in 1939 and 1940. It should be noted that these concrete pavements were, however, comparatively youthful.

It is evident from the foregoing references that blowups occur more frequently on some roads than on others and, indeed, in many cases they do not appear even though there may be no expansion joints. Obviously, if the causes of the excessive expansion which occurs in some cases can be determined and the situation corrected, expansion joints can be eliminated. The advantages consequent to this may be enumerated briefly as: (1) Saving in cost, (2) Improvement in riding quality, (3) Minimizing of pumping and faulting at expansion joints (due to malfunctioning of load-transfer devices); (4) Minimizing, at least in some instances, of the total amount of transverse cracking

Regarding the map cracking associated with blowups, Jackson and Kellerman (10) noted: "The primary cause (of map-cracking) appears to be excessive and abnormal expansion of the concrete. Evidence of this is found in the closed expansion joints which usually accompany the appearance of map-cracking." Many other investigators have observed that "excessive" expansion usually accompanies map cracking and similar forms of concrete disintegration. Included among these are T. E. Stanton (21), who concluded "Excessive expansion sufficient to rupture a concrete mass may occur when certain minerals are present." Such action is to be expected from siliceous magnesium lime rocks which occur in upper Miocene sedimentary deposits in California. He further states that: "The chemical reaction producing excessive expansion (occurs) only when the portland cement component contains an appreciable percentage of alkali in the form of sodium and potassium oxides. Blanks and Meissner (3), in an investigation of deterioration of concrete dams, also noted "excessive expansion" and "expansive deterioration" apparently due to alkali aggregate reaction.

In investigating the problems of blowups, warping, curling, map cracking and other failures of concrete pavements, several investigators have studied coarse aggregate as a possible source of trouble. W. H. Johnson and W. H. Parsons (11) outlined a method for determining the mean thermal coefficient of linear expansion of aggregates and pointed out that aggregates containing the following expansivity characteristics might be detrimental to concrete: "(a) materials having a uniform coefficient of thermal expansion markedly different from the normal value of concrete; (b) aggregate composed of single crystalline fragments with different expansivity in various crystallographic directions, (c) aggregate (gravel or crushed coarse grained rock) composed of two or more fractions which are present in considerable amounts and have widely different expansivities; and (d) material with irregular expansion." In 1936, J. H. Griffith measured the coefficient of thermal expansions of various rocks and came to the conclusion that "the expansion appears to be dependent upon the amounts of free silica in the rocks"

In considering thermal conductivity and diffusivity (time rate of change of temperature) with regard to aggregates, W. T. Thomson (24) developed a method for measurement of the two characteristics. He states "Since a difference in diffusivity would result in different rates of diffusion of heat through the aggregate and cement, it is believed that such a combination would result in additional thermal stresses over that of homogeneous bodies" This might also be true of thermal conductivity.

Considering only geological characteristics, F. R. McMillan and G. W. Ward (16) state that, in general, igneous rock aggregates have not been traced to any concrete failure. However, considering sedimentary rocks, "Limestones that break with a smooth conchoidal fracture, particularly if the porosity is low, are usually good aggregates. Uneven fractures that tend to follow planes, the presence of many closely spaced bedding lamellae and high unsoluble matter, especially if clay minerals can be microscopically detected, are danger signs." "In addition," they state,

"some danger points, such as bedding planes, concentrations of clay minerals, mica seams, sulfides, etc , may occur and one should be on the watch for them." With regard to chert, McMillan and Ward add "it must be stated that many cherts are not unsound or unstable. The two factors which seem to contribute most to the instability of certain cherts are the microscopic irregularities of texture and the presence of firmly embedded crystals, such as pyrite, with their different physical properties." Additional information on chert in coarse aggregate is contained in reference 22.

In Kentucky, failures attributed to the coarse aggregate led to a study by Curtis Cantrill and Louis Campbell (4). They traced the failures of concrete in western Kentucky to the use of a gravel "obtained from the Tennessee and Cumberland Rivers in Western Kentucky" Their study also showed that the deleterious chert gravel could be eliminated by the following two requirements· "(a) Coarse aggregate shall not show an absorption greater than 3 per cent when subjected to ASTM standard test C95-36; (b) Concrete in which any aggregate is incorporated shall not show a reduction in flexural strength greater than 30 per cent when subjected to 40 cycles of freezing and thawing in the presence of water."

ANALYSIS OF BLOWUP REPORTS

Since 1925 the Maintenance Department of the State Highway Commission of Indiana has collected detailed data on blowups by requiring reports from the field men covering each failure These records show the location of the road with the failure, the location of the failure on the road with reference to grade and alignment, time of day of occurrence, air temperature, age of pavement, and materials incorporated in the pavement. In analyzing these data, some field checks were made and the blowup locations, as indicated by pavement patches, were checked. The age of pavement and materials used was checked against similar data compiled in connection with the initiation of the performance survey program. The weather data were checked against records available at variously located weather stations. The data for 1940, 1941, and 1942 are believed to be representative. During this period 517 blowups were reported —239 in 1940, 162 in 1941, and 116 in 1942.

Records of the maximum temperatures on the days each blowup occurred were obtained from the weather station nearest the

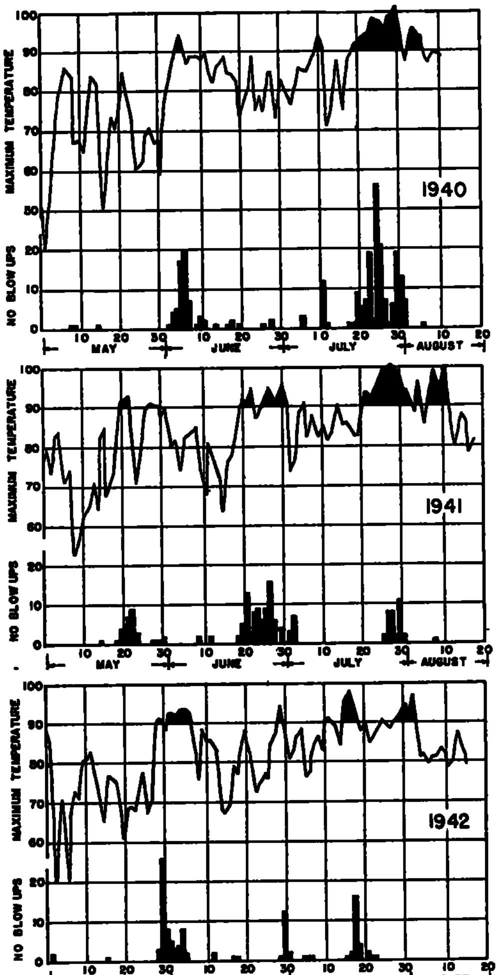

Figure 6. Maximum Temperature vs. Number of Blowups.

location of the blowup. These data are shown in Figures 6 and 7. The maximum temperatures on the days blowups occurred ranged from 65 to 105 F. with an average of 93.7 F. Data were also obtained for maximum temperatures on the four days preceding the blow-

ups. The average maximum temperatures on these days were the following:

One day before	91.7 F.
Two days before	88 4 F.
Three days before	87.0 F.
Four days before...........	86.5 F.

Figure 6 shows the blowup occurrence and the maximum temperature for each day of the summer months in 1940, 1941, and 1942. The relationship of blowups to periods of high temperature is striking. It may be noted from these curves that a tendency is shown toward a greater number of blowups when periods of high temperature occurred in the earlier months; high temperature in August has lesser effect. This tendency could be accounted for by probable decrease in moisture in the pavement In the spring months it is logical to expect a higher moisture content than in the summer. (Lang's (15) test results showed that the moisture content of a concrete pavement in Minnesota varied from 8 per cent in March to 4 per cent in August.)

The number of blowups at each hour of the day is shown in Figure 7. The earliest occurrence noted was at 8:00 A M and the latest, 11:00 P.M Afternoon was the time of the greatest number of occurrences with a median time of approximately 3:00 P.M. This represents, in general, the maximum heat of the day.

Analysis of rainfall data showed that, in general, the precipitation was greater on the days preceding the blowups than on the days blowups occurred. Total precipitation for the 5 days including and preceding the day of the blowups averaged 0.23 in., while on the day of the blowup the precipitation averaged 0 025 in. These figures represent the average of weather conditions for the occurrence of 517 blowups.

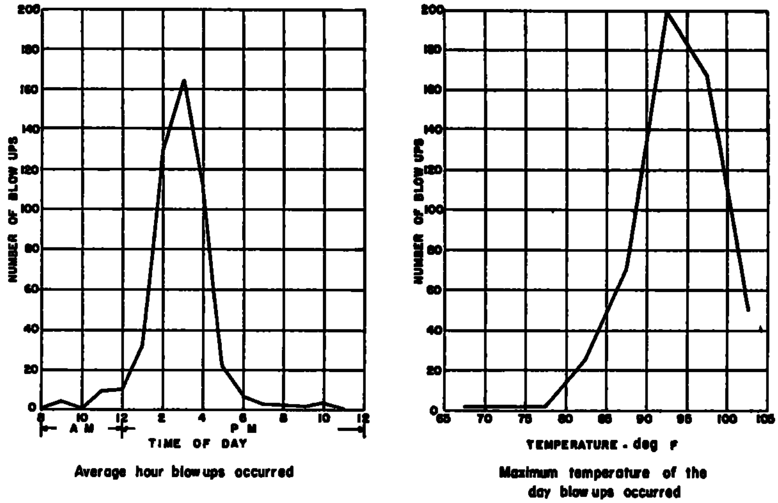

Figure 7. Summary for Three Years

PERFORMANCE SURVEY PROCEDURE

In examining the blowup reports, it was observed that many more blowups occurred on certain sections of pavement than on others. As a result of this observation detailed performance surveys were undertaken in an attempt to establish the reason for this wide variation in pavement performance.

As a first step in the survey, construction records were obtained from the Indiana State Highway Commission on all state-constructed, concrete-pavement projects. Data regarding location of road, length, dates of contract award and completion, design features, and source of materials were transcribed from these records.

The performance surveys were made during the latter part of 1943 and early part of 1944. The survey was conducted by driving over the road at a slow rate of speed and logging, for each construction project, the number of blowups, the average crack interval, and the presence or absence of such defects as pitting, pop outs, scaling, map cracking, and pumping.

Figure 8. Pavement Blowup Patch on U.S. 41, One-half Mile South of S.R. 68, on a 7-8-7 in. Section, Constructed in 1924 (Agg. 82-10).

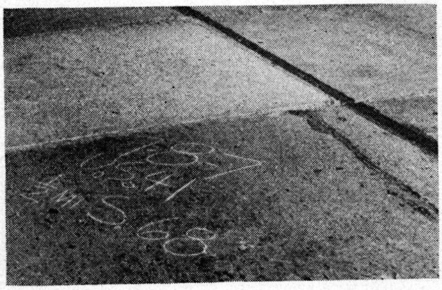

Figure 9. Close-up of Blowup Patch Shown in Figure 8.

The crack interval was determined by counting the number of cracks in several representative 1000-ft. sections.

The method of recording blowups is of special interest since it is obvious that only a very limited number of the total blowups were seen during or immediately following their actual occurrence. Here again, the Maintenance Department's reports were of great help in locating the area where a blowup had occurred. After inspecting several hundred such repairs the blowup areas were readily recognized by such features as narrowness and shape of the patch (Figs. 8 and 9) and their rhythmic occurrence at remarkably consistent intervals. Since the repair of other types of pavement distress such as frost heaves and settlements over culverts, other drainage structures, peat bogs, and bridge approaches might be confused with blowup patches, extreme care was used in classifying the failures. Furthermore, it was found early in the performance survey work that map cracking, particularly at cracks and joints, was almost invariably associated with blowups. This observation was useful in the detection of blowups, since more than average caution could be employed in their location when the pavement showed map cracking.

TABLE 1
BLOWUPS IN PAVEMENTS CONSTRUCTED BEFORE 1935

No. of Blowups per Mile	No. of Miles
0	851.1
.01 to 0.10	223.3
0.11 to 0.50	641.1
0.51 to 1.00	384.0
1.01 to 2.00	182.4
2.01 to 4.00	213.4
4.01 to 6.00	55.6
6.01 to 10.00	44.4
10.01 to 26.00	27.5
Total	2622.8

Total number of blowups 2404
Average number of blowups per mile 0.924
Percentage of miles of projects without blowups ... 32.4

Five hundred projects comprising 3300 miles, or 78 per cent of the concrete pavement in the State were examined. The survey was confined almost entirely to rural 2-lane pavements. Of the pavements surveyed, 2623 miles were constructed prior to 1935 without expansion joints. It is the information regarding these pavements that is considered in the analysis of data. In these pavements, all older then 8 yr. at the time of the survey, the performance varied from 25.3 blowups per mile on one project to no blowups on 130 projects comprising 851 miles. Table 1 summarizes the performance of these pavements.

ANALYSIS OF DATA

The following variables which might effect blowup performance were recognized in analyzing the data:

1. Pavement design
2. Age of pavements
3. Traffic

4. Subgrade soil
5. Cement used in pavement
6. Fine aggregate used in pavement
7. Coarse aggregate used in pavement

Pavement Design

The following resume of design practice in use for the Indiana concrete pavements built before 1940 was made by M. R. Keefe (12): "During 1919 and 1920 the pavement design provided for 6-8-6 in. plain concrete using a 2-in. crown and a mix of 1.1½:3 .... In 1922, the concrete-pavement design was modified to a 7-8-7-in. section using a 2-in. crown and a concrete mix of 1:2.3. In 1923 the concrete-pavement design was again changed, this time going to an 8-in. uniform thickness, still retaining the same 2-in. crown. ... In November, 1923, a new design for concrete pavements was adopted that involved more radical changes than had been made in any of the numerous sections used up to that time This design provided for a uniform thickness of 7 in. with one ¾-in reinforcing bar along each edge of the pavement 6 in. in from the edge. One-half inch transverse bars were spaced 4 ft. center to center. The pavement width still remained 18 ft. and the crown 2 in. Up to this time none of the several designs provided for any type of joint, and the pavement thickness had either been uniform or thickened at the center.. ."

A sixth change was made in 1925 whereby a 9-7-9-in. cross-section, with a ¾-in. marginal bar along each edge and a longitudinal joint were required. The pavement crown was reduced from 2 in. to 1¼ in This design was used until late 1934, at which time expansion joints spaced at 105 ft, with two intermediate contraction joints, were employed The 9-7-9-in design was retained for heavy traffic and, in addition, two lighter cross sections, 9-6-9 and 8-5-8, were developed. The concrete mix was also changed, lowering the cement content from 1.72 to 1 5 bbl. per cu. yd. Mesh reinforcement was provided for crack control.

Subsequent changes included variations in expansion-joint spacing between the limits of 80 and 120 ft. and the use of load-transfer devices at both expansion and contraction joints

In addition to the numerous changes in design, improvements have been made from time to time in the control of quantity, quality, and composition of materials as well as in construction methods. For example, in November 1928, weight proportioning of aggregates was specified instead of proportioning by volume On March 10, 1930, the specifications were revised, fixing the percentage of sand between 35 and 40 per cent. Also the cross-section yield test was specified for cement content determination On September 22, 1933, the specifications were revised permitting the use of bulk cement and specifying more accurate water-measuring equipment and requiring an auxiliary tank on the mixer. In addition to the reduction in cement content in 1934 (already noted), the coarse aggregates were split into two sizes "U" and "L", to permit more accurate control of the aggregate gradation Also, the bucket yield test was employed for cement-content determination. For the first time (1934) a soundness requirement was specified for aggregates used in the concrete mixture.

Prior to 1935 concrete highways in Indiana were constructed by the State without expansion joints They have been included in practically all concrete pavement projects built since that time. Of the concrete pavements, 2623 miles were constructed without expansion joints and were older than 8 yr. A total of 2404 blowups was observed in these pavements, an average of 0 92 per mile. However, 2099 miles or 80 per cent of these pavements had less than one blowup per mile, while 851 of the 2099 miles had no blowups. In contrast, 4 per cent of the total miles without joints contained 40 per cent of the total blowups in the state.

Included in the survey were 595 miles of pavements with expansion joints Five blowups were observed in these pavements. In considering this record it should be recognized that the pavements with expansion joints were all constructed in 1935 and later years.

On the basis of the performance surveys which showed that pavements could be constructed successfully without expansion joints, these devices were largely eliminated on pavements designed since late 1944.

Age of Pavement

The pavements surveyed were constructed between 1921 and 1943 Figure 10 shows graphically on a cumulative basis, the number of miles constructed in each year. Also plotted in this figure are the miles of projects

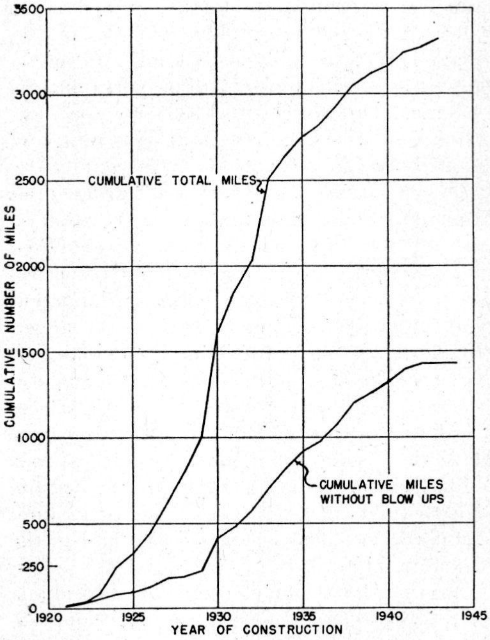

Figure 10. Ages of Concrete Pavements Surveyed

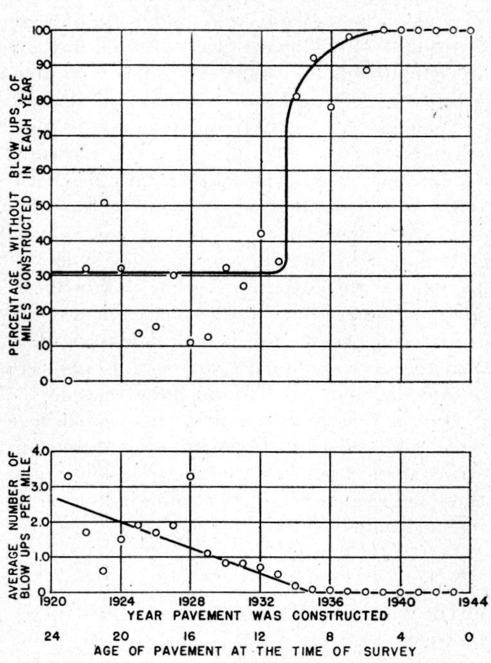

Figure 11. Effect of Age on Blowup Occurrence

with no blowups. The number of projects without blowups are shown in Figure 11 as a percentage of the total number of miles constructed each year. The average number of blowups per mile for pavements of different ages is also plotted in Figure 11.

The curve of average blowups per mile shows a trend toward fewer blowups per mile in the younger pavements, considering even those without expansion joints. As previously noted, no joints were employed in pavements constructed prior to 1935. Most, but not all, projects completed in 1935 were also without joints.

Traffic

The effect of traffic has been observed to be secondary. Blowups have occurred on both lightly- and heavily-traveled roads. Conversely, many roads, built before 1935 and subjected to wide ranges of traffic conditions, are without blowups. However, it has been observed that on highways where blowups are prevalent, accompanying concrete deterioration is more severe on the heavily-traveled roads. See Figure 12.

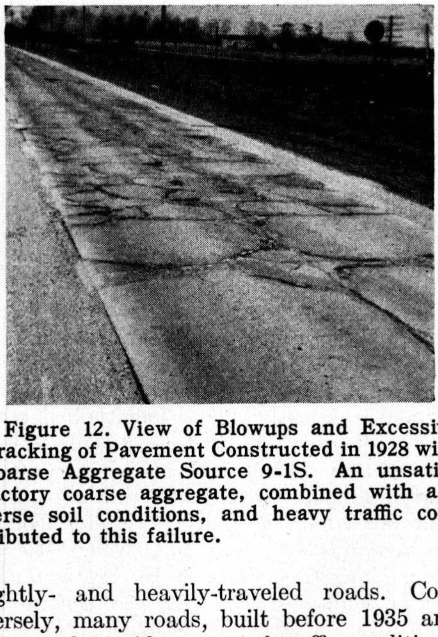

Figure 12. View of Blowups and Excessive Cracking of Pavement Constructed in 1928 with Coarse Aggregate Source 9-1S. An unsatisfactory coarse aggregate, combined with adverse soil conditions, and heavy traffic contributed to this failure.

Subgrade Soil

The effect of type of soil upon which the pavement was laid has not been completely evaluated. It was observed, however, that

blowups occurred on all types of subgrade soil, although there was some evidence to indicate that subsequent deterioration was much accelerated in those instances where the pavement was located on plastic, poorly-drained soils (Fig. 13.) Further, detailed studies of the effect of soil type are indicated as desirable.

Figure 13. The excessive map cracking on this section of pavement is probably due in part to adverse soil and drainage conditions.

Figure 14. Excellent Performance of a Portion (17 miles) of S.R. 53 Constructed in 1930 Largely with Aggregate from Source 79-1G.

The following example is of interest in considering the effect of soil type: On a 19.4-mile section of concrete pavement built without expansion joints in 1930, 17 miles were constructed using coarse aggregate 79-1G, and 2.4 miles using coarse aggregate 9-1S. The other materials incorporated in the concrete were the same. The entire section of road was in very gently undulating topography on a till plain of Wisconsin drift; soil types were the same between the two sections. The 17-mile section had no blowups (Fig. 14); the two-mile section had eleven blowups (Fig. 15).

In this case, where the soil types were the same, the difference in performance between the two coarse aggregates is striking. Numerous other examples of the same nature were noted, leading to the tentative conclusion that subgrade soil is not a major factor in the occurrence of blowups.

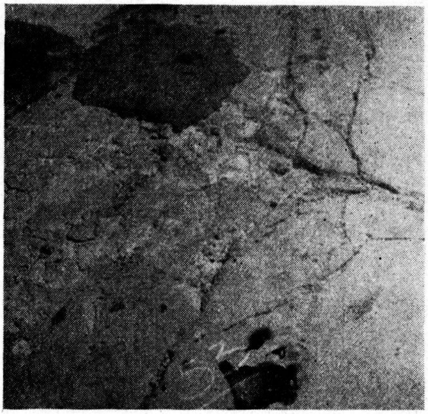

Figure 15. Severe Disintegration of a Portion (2.4 miles) of S.R. 53 Constructed at the Same Time as the Pavement Illustrated in Figure 14, but with coarse aggregate 9-1S.

Effects of Materials in the Concrete

For comparison of the effects of materials used in the concrete, only the highways constructed before 1935 were considered. This distinction served to eliminate all projects with expansion joints. The effect of age was also minimized, since the curves in Figure 11 show an abrupt change in the blowup performance in pavements constructed after 1934. Although the curve for average blowups per mile showed a steady decline for newer pavements, the curve representing the percentage of miles of projects without blowups appears to be constant at approximately 31 per cent until the year 1934 when a decided break occurs.

In evaluating the performance of the different cements, fine aggregates, and coarse aggregates, the indices used were average blowups per mile and miles of projects without blowups, expressed as a percentage of the total

mileage. The performance of aggregate or cement from each source, was determined in these terms by grouping all the projects in which each particular material was used. Some difficulty was encountered in those projects in which cement, fine aggregate, or coarse aggregate were from more than one source. In the case of cement and fine aggregate, it was impossible to determine, in the field, in which section of the project a particular material was incorporated. This was also the case where two or more different gravels had been used as coarse aggregate. Where stone and gravel were both used as coarse aggregate, it was possible to differentiate visually between the two, and the performance of each section was determined separately. Where no better information was available it was assumed, arbitrarily, that an equal length of road had been constructed with each material and that each material had the same performance (i e., the mileage in the project under consideration was divided by two, the total blowups in the project were divided by two, and one-half were assigned each material). In the over-all analysis, this approximation would introduce little error.

The performance rating of each material was then analyzed for significance. An adaptation of the method given in the A S T.M. Manual on Presentation of Data (28) was employed. The percentage of miles of projects without blowups for each source was compared with the percentage without blowups of total miles of projects. This was done to determine whether or not these percentages differed by an amount greater than should be attributed to chance. The difference in percentage was considered to be significant if it was greater than the value computed from the following formula:

$$\Delta p = 3 \sqrt{\frac{\bar{p}(1 - \bar{p})}{\bar{n}}}$$

where

- Δ p is the difference in the percentages to be considered
- $\bar{p}$ is the percentage of the total miles that are without blowups (32.4 per cent)[2]
- $\bar{n}$ is the miles of projects constructed with material from the source in question.

[2] In computing the total miles without blowups, the smallest unit employed was the construction project.

If the difference in percentage proved to be greater than the value of p computed from the formula, this indicated a 99.7 per cent probability that the observed difference was not attributable to chance.

The number of miles of pavement constructed with material from the different sources varied widely. In order to apply the significance test, the curve shown in Figure 16 of $\bar{n}$ versus percentage of miles without blowups was drawn. Using this curve, the material sources with performance significantly different from the average were determined. These sources were then examined in detail since a strong probability was indicated that something other than chance was govening the performance of these materials.

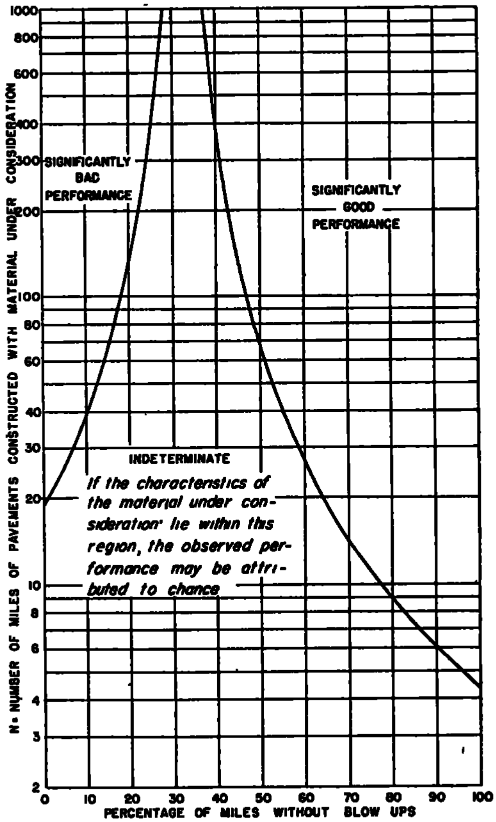

Figure 16. Curve for Determination of Significance

This significance test rated the material on

the basis of consistency of performance. It was deemed advisable to distinguish further between the materials on the basis of the average number of blowups per mile. Since the entire group of pavements averaged 0.92 blowups per mile, any material with a record close to this was not analyzed in detail.

Fine Aggregate

Fine aggregate for the concrete pavements constructed before 1935 came from 138 sources The performance of these sources in terms of percentage of miles of pavements without blowups is shown on the curve in Figure 17. Each point plotted represents one fine aggregate source.

Since the performances of some of the fine aggregates differed significantly from the average, further analysis of these materials was undertaken In this analysis, an attempt was made to discover whether the cause of the performance indicated was assignable to some other factor—coarse aggregate, soil, traffic, etc.—or whether it was due to a characteristic of the material itself.

The indicated significantly-bad-performing fine aggregates were listed first in Table 2 These were considered to be those shown to be bad by the significance test and averaging more than 1.5 blowups per mile Material from five sources fell in this category, representing 231 miles of pavements with 557 blowups. As noted in the "discussion" column, detailed examination of the performance records showed that, with one exception, differentiation between performance of fine and coarse aggregate could not be established. The records of material 27-3, the exception, showed a striking relationship between coarse aggregate and performance This case is particularly interesting because the two sections were let under one contract of 22.7 miles, the only known construction variable between the two sections being the coarse aggregate. One section of 11.4 miles, in which 9-1S was the coarse aggregate, contained 80 blowups (Fig. 18). The other section of 11.3 miles, with 9-2S as the coarse aggregate, contained one blowup.

Also shown in Table 2 are those fine aggregates having performance classified as poor. These failed to show significance statistically but were examined in detail because their performance might, at the least, be considered suspicious. All sources, except those already listed, with performance averaging greater than two blowups per mile were included. Eleven sources were included in this category representing 136 miles of pavements containing 349 blowups No definite distinction between coarse or fine aggregates was possible from the records of these materials

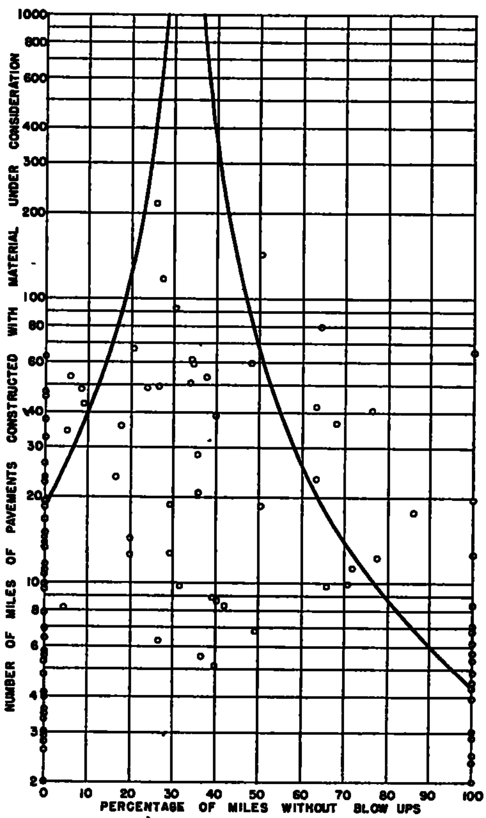

Figure 17. Performance of Fine Aggregates

Materials with performance averaging less than two blowups per mile and not differing significantly from the average of all pavements were grouped together in Table 2 Fine aggregate from 106 sources is included representing 2050 miles of pavements with 1497 blowups. Also shown in the table are the 16 sources with significantly good performance representing 206 miles of pavement with one blowup. In considering the performance of the latter it was recognized that, in projects with strikingly good performance, all ma-

TABLE 2
SUMMARY OF FINE AGGREGATE PERFORMANCE

Source	Probable Geological Origin	No. of Proj	Total Miles 1921–1934	No of Miles without Blowups	No of Blowups per Mile: Avg	No of Blowups per Mile: Min	No of Blowups per Mile: Max	Total No of Blowups[a]	Primary Factor in Blowup Perform[b]	Discussion
Significantly Bad Performance										
27-3	Glacial Gr	2	22 70	0	3 57	0 09	7 00	81	C A	In these two projects the cement used, soil, traffic, and age were the same for each, the C A differed In one, C A was from 9-1S, 80 blowups occurred in 11 4 mi In the other, with material from 9-2S, 1 blowup occurred in 11 3 mi
62-1	River Gr.	6	45 58	0	3 11	0 57	4 27	142	C or F A	In every case this material was used with C A from 62-1G, i e , the performance of coarse and fine aggregates cannot be differentiated
82-1	River Gr	10	54 57	3 67	2 35	0	5 52	126	C or F A	C A 82-1G was combined with 82-1 F A in every project
52-2	Glacial Gr	10	46.96	3 98	2 09	0	9 40	98	Indeterminate	See Note 1
73-1	River Gr.	9	62 37	0	1 77	0 71	3 83	110	C or F A	Used with coarse aggregate 73-1G in every project
Group summary.		37	232 18	7 65	2 4	0	9 4	557		
Poor Performance										
95-5	Glacial Gr	2	10 33	0	6 77	6 56	7 45	70	C or F A	C A 95-5G was combined with 95-5 F A in both projects
94-2	Glacial Gr	1	2 86	0	5 60	5 60	5 60	16	C or F A	Used with 94-2G only—no differentiation possible
36-7	Glacial Gr	1	1 03	0	5 50	5 50	5 50	5 67	C or F A	Used with 47-4S and 45-5S in one project—the only one in which these coarse aggregates were used
50-2	Glacial Gr	1	1 45	0	5 50	5 50	5 50	8	C or F A	Used only with 9-1S C A, a material with consistently bad performance.
76-3	Glacial Gr.	4	9 66	3 04	4 14	0	11 50	40	Indeterminate	With 76-3G, a C A used only with 76-3, the performance was 0 to 1 7 blowups per mi With 35-2S as C A, perf was 9 4 to 11 5 blowups per mi.
84-2	Glacial Gr.	1	4 66	0	3 22	3.22	3 22	15	C or F A	Used only with 84-2G
36-5	Glacial Gr	1	0 82	0	3 26	3 26	3 26	2 67	C or F A	Used only with 36-5G
84-1	Glacial Gr	7	35 83	6 27	2 70	0	8 13	97	C or F A	Used predominantly with 84-1G
94-12	Glacial Gr.	1	6 37	0	2 51	2 51	2 51	16	C or F A	Used only with 94-12G
55-1	Glacial Gr.	1	1 89	0	2 12	2 12	2 12	4	C or F A	Used only with 55-1G
43-1	Glacial Gr.	13	60 61	12 37	2 08	0	9 4	75	C or F A	Used with a number of coarse aggregates, but most often with 43-1G, in which case performance was fair, ranging from 0 to 1 27 blowups per mi With 9-1S the record varied from 1 9 (for a section constructed in 1934) to 20 3 blowups per mi
Group summary .		33	135 51	21 68	2.6	0	11 50	349.34		
Indeterminate Performance										
106 Sources		273	2049.5	625.3	0 73	0	2 0	1496.7		
Significantly Good Performance										
14-1	Glacial Gr.	4	40.13	30 98	0 02	0	0.11	1		
55-8	Glacial Gr	1	4 20	4 20	0	0	0	0		
43-4	Glacial Gr	2	4 29	4′29	0	0	0	0		
30-3	Glacial Gr	1	4 51	4 51	0	0	0	0		
94-3	Glacial Gr.	1	4 81	4 81	0	0	0	0		
93-5	Glacial Gr	1	5 37	5 37	0	0	0	9		
57-2	Glacial Gr	1	5.60	5 60	0	0	0	0		
6-1	Glacial Gr.	1	5 68	5 68	0	0	0	0		
93-18	Glacial Gr.	1	5.80	5.80	0	0	0	0		
93-1	Glacial Gr.	1	6 15	6 15	0	0	0	0		
29-3	Glacial Gr.	1	6.82	6 82	0	0	0	0		
10-8	River Gr	1	7 09	7 09	0	0	0	0		
24-2	Glacial Gr	2	8 27	8 27	0	0	0	0		
28-2	Glacial Gr	1	12.52	12 52	0	0	0	0		
27-1	Glacial Gr	4	19 90	19 90	0	0	0	0		
67-7	Glacial Gr	9	64 44	64 44	0	0	0	0		
Group summary.		32	205 58	196 43	0 004	0	0 11	1		
Grand total, 138 sources		375	2622 77	851 06	0 92	0	11 50	2404		

Note 1 The following coarse aggregates were combined with 52-2 fine aggregate
- 9-1S (very bad performance whenever used)
- 9-2S (variable performance)
- 35-2S (variable performance with other fine aggregate)
- 43-1G (variable performance with other fine aggregate)
- 52-1G (variable performance with other fine aggregate)
- 52-2G (variable performance with other fine aggregate)

[a] The figures showing the apparent occurrence of a fractional number of blowups were obtained because it was necessary to divide the number of blowups occurring in a given project by the number of fine aggregates used in that project.

[b] C A and F A represent Coarse and Fine Aggregate, respectively

terials and possible variables should be classified as good performing. Therefore no distinction between fine and coarse aggregate could be obtained except indirectly. In general, it was found that those coarse aggregates combined with the significantly good fine aggregates also had good performance records when used with other fine aggregates.

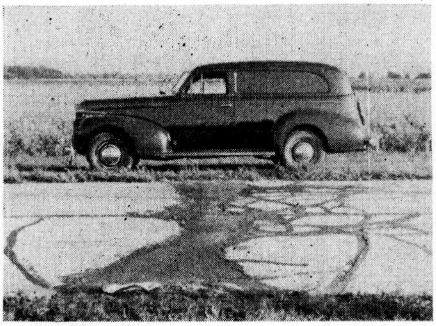

Figure 18. A typical Illustration of a Blowup in one of the Pavements Constructed with Coarse Aggregate 9-1S in 1932. Eighty such blowups were found in 11.4 miles of this road. An adjacent section, 11.3 miles long and constructed at the same time with aggregate 9-2S, had one blowup.

Coarse Aggregate

Coarse aggregates from 155 sources were incorporated in concrete pavements constructed between 1921 and 1935. The performance of material from these sources was rated in terms of percentage of miles without blowups and plotted on Figure 19. Each material is represented by a point.

An analysis similar to that discussed under "fine aggregate" was made of the records of those coarse aggregates with performance differing significantly from the average. The results of this analysis are shown in Table 3.

Five coarse aggregates showed outstandingly bad performance. These five materials were used in 284 miles of pavements (10.8 per cent of the mileage in the period considered) in which 1168 blowups occurred (49 per cent of all the blowups observed). Detailed examination of the service records of these pavements showed that material 9-1S gave very poor performance in every project in which it was incorporated. This material was used in 23 projects in combination with six different cements and eight different fine aggregates. Every project contained blowups, ranging from 0.17 to 25.3 per mile with an average of 7.28. The project with 0.17 blowup per mile consisted of a 5-mile length with one blowup. Two other coarse aggregates were used in addition to 9-1S and

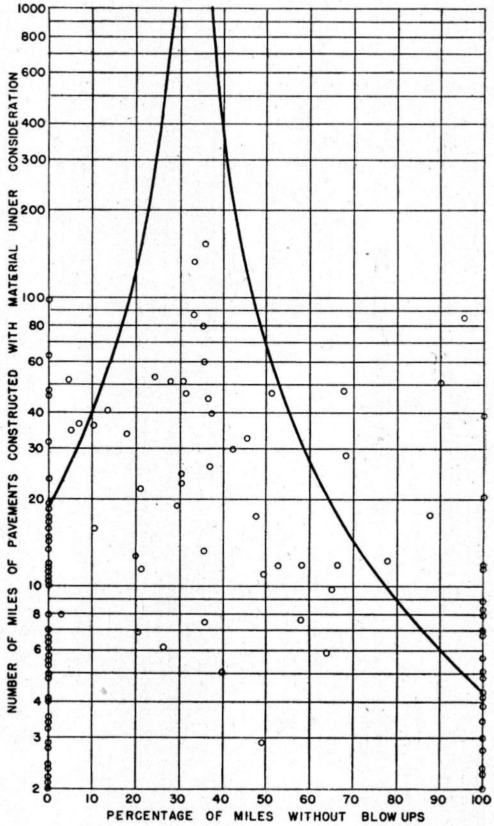

Figure 19. Performance of Coarse Aggregates

may have predominated. Two additional projects containing 9-1S material and with less than two blowups per mile also contained other coarse aggregates to an unknown extent. Material 35-2S, a limestone from the Huntington formation of the Silurian system, likewise gave bad performance in each of six projects in which it was incorporated.

The other three bad-performing materials in this group were each used in combination with only one fine aggregate so that differentiation between coarse and fine aggregate performance was not possible.

TABLE 3
SUMMARY OF COARSE AGGREGATE PERFORMANCE

Source	Probable Geological Origin	No of Proj.	Total Miles 1921–1934	No of Miles without Blow-ups	No of Blowups per Mile			Total No Blow-ups[a]	Primary Factor in Blowup Perform-ance[b]	Discussion
					Avg	Min	Max			
Significantly Bad Performance										
9-1S	Devonian-Silurian	23	97 10	0	7 28	0 17	25 30	707	C A	For discussion, see Note 1
35-2S	Silurian	6	28 27	0	3 12	0 62	11 50	88	C A	Used with 7 F A which had variable records with other C A
62-1G	River Gr.	6	45 58	0	3 10	0 59	4 27	141	C or F A	Used with 62-1 F A in every case—differentiation is possible
82-1G	River Gr	10	51 00	2 45	2 40	0	5 52	122	C or F A	Used with 82-1 F A in every project
73-1G	River Gr.	9	62 37	0	1 77	0 84	3 83	110	C or F A	Used with 73-1 F A in every project
Group summary.		54	284 32	2 45	4 11	0	25 30	1168		
Poor Performance										
95-5G	Glacial Gr.	2	10 33	0	6 77	6 56	7.45	70	C or F A	Used with 95-5 F A in both projects.
94-2G	Glacial Gr	1	2 86	0	5 60	5 60	5 60	16	C or F A	Used with 94-26 F A
47-4S	Mississippian	0 5	1 55	0	5 50	5 50	5 50	8 5	C or F A	Both 47-4S and 47-5S used with F A 36-7, 42-6, and 84-4 Material 36-7 was used only in this project The other two showed variable performance with other C A
47-5S	Mississippian	0 5	1 55	0	5 50	5 50	5 50	8 5	C or F A	See discussion for 47-4S, above
23-2G	Glacial Gr	1	3 15	0	3 65	3.65	3 65	11 5	C or F A	Used with 23-2 F A which showed variable performance in other projects
84-2G	Glacial Gr	1	4 66	0	3 22	3 22	3 22	15	C or F A	Used only with 84-2 F A
36-5G	Glacial Gr	1	0 82	0	3 26	3 26	3 26	2 67	C or F A	Used only with 36-5 F A
84-1G	Glacial Gr.	6	33 42	5 99	2 80	0	8 13	90	C or F A	Used only with 84-1 F A
93-12G	Glacial Gr	1	6 37	0	2 51	2 51	2 51	16	C or F A	Used only with 94-12 F A
82-3G	River Gravel	2	5 27	0	2 18	1 58	3 36	11 5	C or F A	Used with 82-3 F A In another project of 2 mi, 82-3 was used with a different C A without blowups.
72-4G	Glacial Gr	0 5	1 72	0	2 33	2 33	2 33	4	C or F A	Used only with 72-4 F A
72-5G	Glacial Gr	0 5	1 72	0	2 33	2 33	2 33	4	C or F A	Used only with 72-5 F A
55-1G	Glacial Gr	1	1 89	0	2 10	2 10	2.10	4	C or F A	Used only with 55-1 F A
83-1G	Glacial Gr	5	11 41	2 44	2 02	0	5 55	23	C or F A	Used with 83-1 F A in every project.
Group summary		23	86 72	8 43	3 28	0	8 1	284 67		
Indeterminate Performance										
119 Sources		236	1934 99	541 24	0 49	0	2.00	948 83		
Significantly Good Performance										
93-19S	Silurian	5	28 24	19 22	0 05	0	0 20	1		
60-1S	Mississippian	10	50 67	45 85	0 01	0	0 07	0 5		
67-1S	Mississippian	17	84 65	80 69	0 01	0	0 29	1		
43-4G	Glacial Gr	2	4 29	4 29	0	0	0	0		
94-3G	Glacial Gr	1	4 81	4 81	0	0	0	0		
67-5S	Mississippian	2	5 03	5 03	0	0	0	0		
6-1G	Glacial Gr	1	5 68	5 68	0	0	0	0		
29-3G	Glacial Gr	1	6 82	6 82	0	0	0	0		
10-8G	River Gravel	1	7 09	7 09	0	0	0	0		
1-1S	Silurian	1	7 92	7 94	0	0	0	0		
51-1S	Mississippian	3	8 22	8 22	0	0	0	0		
93-18G	Glacial Gr	2	8 90	8 90	0	0	0	0		
18-7G	River Gr	1	11 41	11 41	0	0	0	0		
24-2G	Glacial Gr.	2	11.79	11 79	0	0	0	0		
59-1S	Mississippian	3	12 04	12 04	0	0	0	0		
67-7G	Glacial Gr	2	20 46	20 46	0	0	0	0		
67-2S	Mississippian	8	38 76	38 76	0	0	0	0		
Group summary.		62	316 80	299 00	0 007	0	0 29	2 5		
Grand total, 155 sources		375	2622 83	851 12	0 92	0	25 30	2404		

Note 1 The following fine aggregates were used with 9-1S coarse aggr
- 8-3 (used with no other coarse aggregate)
- 9-3 (with other course aggregates this material showed variable performance, including 54 miles without blowups)
- 9-4 (variable performance with other coarse aggregates, including 20 mi without blowups)
- 27-3 (good performance with coarse aggr 9-2S—see discus of F A performance)
- 43-1 (variable performance with other coarse aggr, including 12 mi. without blowups)
- 50-2 (used with no other coarse aggr)
- 52-3 (variable performance including 4 mi without blowups)
- 79-1 (variable performance including 71 mi without blowups)

[a] The apparent occurrence of a fraction of a blowup was caused by the necessity for dividing the number of blowups occurring in a particular project by the number of coarse aggregates incorporated in that project This occurred only when it was not feasible in the field to distinguish between the sections containing each type of aggregate.

[b] C A and F A indicate coarse and fine aggregate, respectively

The coarse aggregate sources with non-significant performance but with an average of more than 2.0 blowups per mile were grouped and considered in detail. These are listed in Table 3 as materials having poor performance records. Fourteen materials fell in this category, totaling 86.7 miles with 285 blowups. Materials with a performance not significantly different from the average of all pavements and with less than 2.0 blowups per mile comprise the next group shown in Table 3. Included are coarse aggregates from 119 sources incorporated in 1935 miles of pavement with 949 blowups. Many of the coarse aggregates included in these two groups were used on an insufficient number of miles of pavement to afford accurate evaluation and is the primary reason for the materials not falling in the significantly good or bad groups. In other instances, variable performance of an aggregate may be attributed to changing plant operations or changing source of supply for a given company.

Figure 20. Excellent Performance of a 1928 Pavement Constructed with a Good Coarse Aggregate.

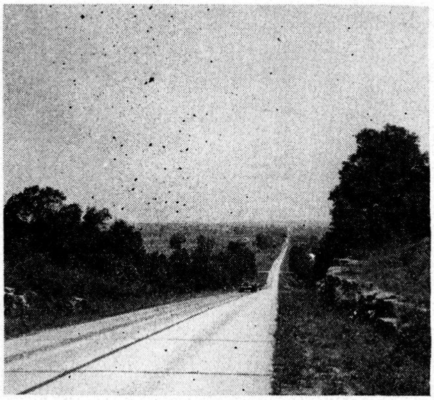

Figure 21. A view of a portion of U. S. 50 in Southern Indiana Constructed in 1934 Without Joints.

The coarse aggregates with significantly good performance (Figs. 20 and 21) are listed individually in Table 3. Seventeen sources are listed from which materials were used in 317 miles of pavement with only two blowups. However, when the significantly good performing aggregates are added to those in the indeterminate group which contained less than 0.5 blowup per mile, it is important to note that there are represented, 82 sources, 232 projects, 1715 miles (65 per cent of the total) with only 203 blowups (8 per cent of the total). In contrast, 73 sources were used in 143 projects totaling 908 miles and containing 2201 blowups.

The significance of the coarse aggregate component in regard to its effect on blowup occurrence was suspected early because of the cases, some of which already have been described, where performance was vastly different between adjacent sections of highway in which the only known variable was the coarse aggregate. The statistical analysis of all the accumulated data substantiates this early suspicion.

Cements

Cements used in the construction of concrete pavements between 1921 and 1935 were obtained from 17 sources. The number of miles constructed with each cement and the number and percentage of miles of projects without blowups were determined. The performance of each source, in these terms, was plotted on the significance curve, Figure 22. Each point on the graph represents one cement source. It is evident from the curve that no significantly bad performance records were obtained, the variation in performance of all but one of the cements being of a magnitude which may be attributed to chance. One source, No. 7, was used only once and in this instance the cement was used in conjunction with two other cements, 1 and 3, in a 14.68-mile project which had no blowups. In accordance with the system established, one-third of this mileage, 4.89 miles, was assigned to cement 7. Since no blowups occurred on this project, the performance of cement 7

was shown by the significance curve to be significantly good.

In order to evaluate further the cement performance, the projects in which the significantly bad coarse aggregates were used were eliminated from consideration. This changed the performance figures on six of the 17 cements. With these projects eliminated (387 miles) 2235 miles of pavement remained for consideration with 851 miles (38.1 per cent) without blowups. The comparison of the revised cement performance data with the new average is shown in Figure 23. The graph shows that elimination of the projects with poor performance improved the general performance rating However, even though the deleterious effect of the significantly bad aggregates on the apparent performance of the cement was removed, the performance rating of every cement source remained underneath the significance curve. Since each cement was used, in general, with many different aggregates—good, indeterminate, and bad performing—the average performance of any one cement was not significantly different from the average performance of all pavements.

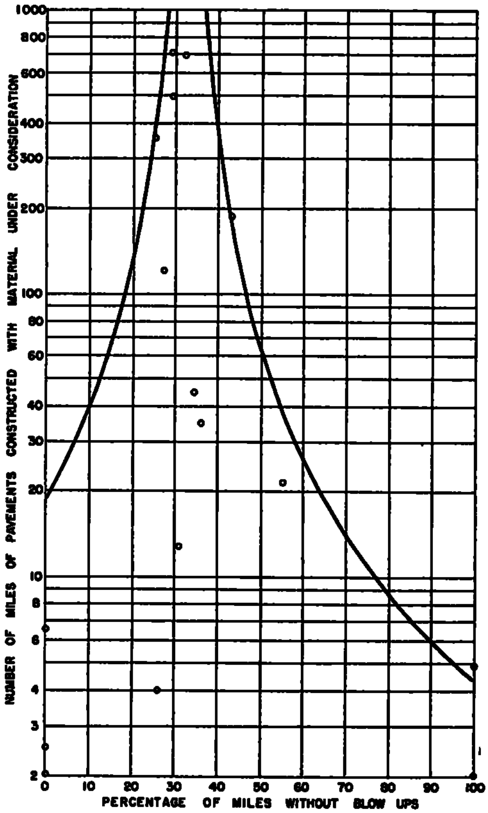

Figure 22. Performance of Cements

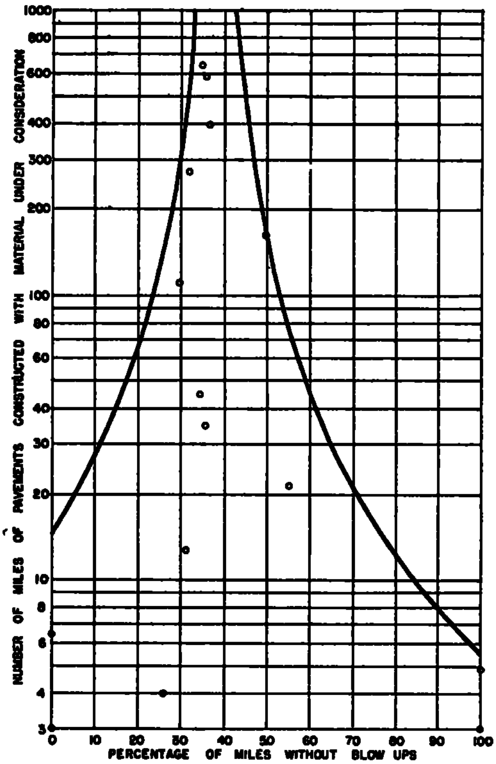

Figure 23. Revised Cement Performance (Projects containing bad aggregates have been deleted from the analysis.)

This analysis, although showing no cements to be significantly good, is strikingly important in that none is indicated as being bad. These data show definitely that none of the cements used was the controlling variable in the Indiana projects with bad performance. On the other hand, it is obvious that the cement performance, as well as that of the other materials, was good in the projects with good performance. It is recognized that interaction between the cement and other materials incorporated in the concrete may occur and cause distress However, the data indicate

that, if such were the case, this possibility was latent in all the cements in use at the period considered.

Relation of Blowups to Map Cracking

The association of map cracking and blowup occurrence is indicated in Table 4. Only three projects without blowups contained map cracking, while 47 out of 64 projects with over two blowups per mile showed map cracking. Figures 24, 25, and 26 illustrate this type of failure.

TABLE 4
RELATION OF MAP CRACKING TO BLOWUP OCCURRENCE

Blowups per Mile	No. of Projects			Percentage of Projects With Map Cracking
	With Map Cracking	Without Map Cracking	Total	
0	3	127	130	2.3
0.01-0.50	16	86	102	15.7
0.51-1.00	11	36	47	23.4
1.01-2.00	13	19	32	40.6
2.01-4.00	23	15	38	60.5
Over 4.01	24	2	26	92.5
Total........	90	285	375	24.0

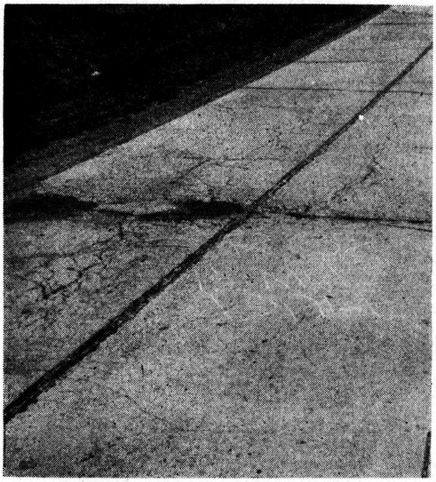

Figure 24. Severe Map Cracking of Pavement on S.R. 62, 1½ mile East of Dale. (Constructed in 1930.)

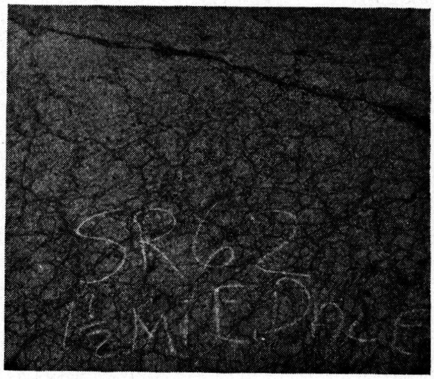

Figure 25. Close-up of Severe Map Cracking of Pavement Shown in Figure 24.

Figure 26. View Showing Extensive Cracking in Pavement Constructed in 1927 with Coarse Aggregate from Source 9-1S.

DISCUSSION

The analysis of performance survey data showed that 2404 blowups occurred in 2623 miles of concrete pavements constructed before 1935. These pavements had a number of different design characteristics; they were alike in the respect that they contained no expansion joints. The blowups occurred in all parts of Indiana, on all types of soils, and on roads with all degrees of traffic. In considering the possible effects of the materials in the concrete, it was found that the cement (as classified by source) could not be considered as a primary factor in the occurrence of blowups.

Certain sources of fine aggregate proved to have significantly bad performance. However, it was determined that each of these materials, in all but one case, was used in combination with the gravel coarse aggregate produced at the same source In the exception, the fine aggregate was used in two projects in combination with a different stone coarse aggregate in each. In one project 80 blowups occurred in 11 miles; on the other, 1 blowup occurred in 11 miles, indicating that the performance of this fine aggregate was apparently bad only because of the influence of the one deleterious coarse aggregate. This same coarse aggregate was a bad performer in every one of the 23 projects in which it was used, having as many as 25 blowups per mile.

The outstanding correlation observed in the analysis was that between the coarse aggregate source and the pavement performance as indicated by the number of blowups Five sources of coarse aggregate were shown to have significantly bad performance and produced almost half the total blowups in the State in only 10 per cent of the total mileage of pavements constructed before 1935 In the case of three of these sources, differentiation between the coarse and fine aggregate was difficult because the coarse aggregates were combined in every case with fine aggregate from the same source. In the other two cases the coarse aggregates were combined with a number of fine aggregates, but showed consistently bad performance. Of possibly greater significance is the fact that only 203 blowups (8 per cent of the total) occurred in 1715 miles of pavements (65 per cent of the total), thus indicating that the coarse aggregates in Indiana are predominantly satisfactory.

It was observed that map cracking and general concrete deterioration usually existed in pavements which were also subject to blowing up. This condition was more related to soil and traffic, however, than was the actual occurrence of blowups On concrete pavements with what might be called "excessive" blowups, the associated concrete deterioration was more extensive in pavements carrying heavy traffic and/or on those constructed on plastic soils.

It should be noted that these aggregates, toward which suspicion is now directed, conformed to the specification requirements existing at the time of their use and that material from the same sources is satisfactory according to present aggregate specifications in use in Indiana (29).

It may be concluded that existing standard test procedures and specifications are inadequate to differentiate between the coarse aggregate having good and bad performance with respect to blowups, map cracking and general deterioration. Research is needed, and is contemplated, to establish the causes for the performance observed and to develop a test procedure that will enable prediction of the performance of the material when it is incorporated in concrete pavements.

SUMMARY OF RESULTS AND CONCLUSIONS

The following conclusions are drawn primarily on the basis of performance surveys covering 3300 miles of concrete pavements in Indiana, 78 per cent of all concrete pavement constructed between 1921 and 1943. Of this mileage 2623 miles were constructed prior to 1935 without expansion joints including 851 miles without blowups. Eighty per cent (2099 miles) of those constructed prior to 1935 had less than one blowup per mile A total of 2404 blowups was observed in these pavements constructed before 1935, an average of 0 92 per mile

1. Performance surveys constitute the best preliminary method available for evaluating materials, soils, and pavement design They do have definite limitations in determining the ultimate solution to a problem since they can be used only to establish performance facts—such data must be supplemented by laboratory research to determine the reasons for the specific performance recorded.

2. An outstanding correlation has been established with Indiana pavements between certain sources of coarse aggregate incorporated in the concrete mix and the lack of blowups in the resulting pavement.
   A. 316 8 miles of pavements constructed prior to 1935 from 17 sources of supply had a total of only two blowups
   B 1715 miles (65 per cent of the total) constructed from 82 sources of supply contained a total of only 203 blowups (8 per cent of the total).

3. An outstanding correlation has been established with Indiana pavements between certain sources of coarse aggregate incorporated in the concrete mix and the susceptibility of the pavement to blowups.
   A. 284 miles of pavement (10.8 per cent of

the total miles) constructed from five sources of supply contained 1168 blowups (49 per cent of the total blowups).

B. One of the five sources was used in the period from 1926 to 1934 to construct 97 1 miles of pavement (3 7 per cent of the total surveyed) containing 707 blowups (29 4 per cent of the total blowups).

C. Considering the significantly bad sources together with those indeterminate sources which produced one-half blowup per mile or more, 73 sources were used to construct 908 miles of pavement which contained 2201 blowups

4 On pavements containing more than two blowups per mile map cracking predominated, occurring in 47 out of 64 projects in this category. In contrast 127 projects out of 130 with zero blowups contained no map cracking

5 Blowups, as such (when their occurrence is not too extensive) do not constitute a serious problem, since they can be repaired easily. They assume importance because their occurrence has led to the widespread use of expansion joints in pavements and because of the map cracking and general concrete deterioration associated with them

6 Since blowups occur only to a limited extent in Indiana, being primarily restricted to pavements constructed with coarse aggregate from a limited number of sources, it appears that the use of expansion joints can be largely abandoned.

7 In regions of the state where only poor performing aggregates prevail and where it may be economically expedient to import better performing materials, special design procedures are to be recommended. These may include the continued use of expansion joints to relieve at least some of the stress created by excessive expansion, the possible use of granular base courses to improve concrete durability; and the possible use of an extra amount of reinforcing steel to restrain some of the abnormal expansion associated with the use of these aggregates in concrete pavements.

8. New methods for quickly evaluating materials and design are urgently needed since by the present methods these evaluations cannot be made until pavements are at least 10 years of age. Likewise, after changes in material and design are made to correct a given problem, there is no assurance that new problems will not arise as a direct result of the changes made

9. No definite correlation of fine aggregate with blowup occurrence was indicated

10. None of the cements used was the controlling variable in the Indiana projects with bad performance The cement performance, as well as that of the other materials, was good in the projects with good performance.

11. Soil is not a significant factor in the susceptibility of a pavement to blowing up, this failure having occurred on a wide range of soil textures However, deterioration of those pavements susceptible to blowups was more rapid on plastic soils than on the more granular types.

12 Traffic in Indiana is not a significant factor in the susceptibility of a pavement to blowing up, this failure having occurred on roads with a wide range of traffic conditions. However, it is true that the heavier the traffic, the more accelerated is the deterioration on those pavements which are susceptible to blowups

13 On the basis of the blowup reports obtained from field offices covering primarily 1940, 1941, and 1942, it was determined that blowups occurred predominantly in mid-afternoon at a temperature above 90 F, which period was usually preceded by varying amounts of precipitation.

14. Blowups occurred in pavements with a wide range of ages but it was found that they were generally not observed until the pavement age was between 7 and 10 years However, many miles of pavements never blow up, there-being, for example, 100 miles of pavement over 20 years of age and without expansion joints still in service with no indication of blowups.

REFERENCES

1. "Repair of Concrete Blowups in Delaware," *Engineering News-Record* v. 95, n 11, p 432, September 10, 1925
2. Allen, Harold, "Report of Committee on Warping of Concrete Pavement Slabs," *Proceedings*, Highway Research Board, Vol 18, p. 306, 1938.
3. Blanks, R F , and Meissner, H. S., "Deterioration of Concrete Dams Due to Alkali Aggregate Reaction " *Proceedings*, A.S.C E , January 1945
4. Cantrill, Curtis, and Campbell, Louis, "Selection of Aggregate for Concrete Pavements Based on Service Records," *Proceedings*, American Society for Testing Materials, Vol. 40, p. 937, 1939
5. Cashell, H. D., and Benham, S W., "Experiments with Continuous Reinforcement in Concrete Pavement—A Five-Year History," *Proceedings*, Highway Research Board, Vol. 23, 1943.
6. Clemmer, H F., "Rigid Type Pavement Joints and Joint Spacing," *Proceedings*. Highway Research Board, Vol. 23, p. 45, 1943.

7. Gibson, W E , "The Study of Map Cracking in Sand and Gravel Pavements," *Proceedings*, Highway Research Board, Vol. 18, p. 227, 1938.
8. Griffith, J. H , "Thermal Expansion of Typical American Rocks," Bulletin 128, Iowa Engineering Experiment Station, October, 1936
9. Hewes, Laurence Ilsley, American Highway Practice, Vol. II, 1942, John Wiley and Sons, Inc , p. 282.
10. Jackson, F. H., and Kellerman, W. F., "Volume Changes in Sand-Gravel Concrete," *Proceedings*, Highway Research Board, Vol. 22, 1942.
11. Johnson, W H , and Parsons, W. H , "Thermal Expansion of Concrete Aggregate Materials," *Journal of Research*, Bureau of Standards, March, 1944.
12. Keefe, M R., "Pavement Design," *Proceedings*, 26th Annual Road School, Purdue University, Ext. Series No. 47, p. 47, July, 1940.
13. Kelley, E. F , "Application of the Results of Research to the Structural Design of Concrete Pavement," *Public Roads*, July and August, 1939.
14. Kellerman, W F., "Designing Concrete Mixtures for Pavement," *Public Roads*. Vol 27, No 7, p. 121, September 1940,
15 Lang, F C., "Temperature and Moisture Variations in Concrete Pavements," *Proceedings*, Highway Research Board Vol 21, p 260, 1941.
16. McMillan, F R., and Ward, George W., "Influence of Coarse Aggregate on the Durability of Concrete," *Proceedings*, American Society for Testing Materials, Vol. 29, Part II, pp. 816–829. 1929
17. Oregon State Highway Department, "Expansion Joints Unnecessary in Pavements," *Engineering News-Record*, Vol. 134, p. 100, March 22, 1945.
18. Reagel, F. V., and Gotham, Don E., "Field Observations on Effects of Joints on Cracking and Other Deterioration in Concrete Pavements," *Proceedings*, Highway Research Board, Vol. 21, p. 179, 1941.
19. Reagel, F. V., "Freezing and Thawing Tests of Concrete," *Proceedings* Highway Research Board, Vol 20, p. 587, 1940.
20. Scholer, C. H., and Dawley, E R., "Volume Change of Concrete," *Proceedings*, American Society for Testing Materials, Vol. 30, p. 751, 1930.
21. Stanton, T. E , "Expansion of Concrete through Reaction between Cement and Aggregate," *Transaction* A S.C E , Vol. 68, No. 8, Part 2, p. 54, 1942.
22. Sweet, H. S., "Chert as a Deleterious Constituent in Indiana Aggregates," *Proceedings*, Highway Research Board, Vol. 20, 1940.
23. Teller, L. W., and Sutherland, E. C., "Observed Effects of Variations in Temperature and Moisture on the Size, Shape, and Stress Resistance of Concrete Pavement Slabs," *Public Roads*, Vol 16, n 9, November, 1935.
24. Thomson, W. T., "A Method of Measuring Thermal Diffusivity and Conductivity of Stone and Concrete," Bulletin No. 40, Kansas State College, May, 1941.
25. Withey, M. O., et al. "Progress Report, Committee on Durability of Concrete," *Proceedings*, Highway Research Board, Vol. 24, 1944.
26. Woods, K. B., and Gregg, L. E., "Pavement Performance Related to Soil Texture and Compaction," *Proceedings*, Highway Research Board, Vol 24, p. 426, 1944.
27. Woods, K. B , and Shelburne, T. E., "Pumping of Rigid Pavements in Indiana," *Proceedings*, Highway Research Board, Vol. 23, 1943.
28. "A S.T M. Manual on Presentation of Data," Sponsored by Committee E-1 on Methods of Testing, American Society for Testing Materials, March 1941.
29. "Standard Specifications for Road Construction," State Highway Commission of Indiana. October 1939.