PERFORMANCE OF MICHIGAN'S POSTWAR CONCRETE PAVEMENT

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SUMMARY

This study was conducted to determine the general level of performance of postwar pavements and, if possible, to statistically relate performance and certain design, construction, materials, and environmental factors. It was realized from the outset that many factors play a part in determining performance; that many of these factors are difficult to quantify, other factors difficult to measure or control. However, with the amount of data available (520 construction projects representing 1,880 miles of pavement) it was felt that the more significant variables which affect performance might emerge from a multiple-regression type of statistical analysis. In addition, the study was made to determine specific points of weakness of design or construction procedures and to recommend possible means of improving future pavement performance.

Initial, 5-, 10-, and 15-year condition surveys, as well as roughness measurements taken with less regularity, were available to define performance of these postwar pavements.

It was found that information obtained by condition surveys, that is, transverse and longitudinal cracking, corner breaks, spalling, joint blowups, mud-jacking and patching, etc. were much more useful indicators of performance and remaining useful life of the pavement than roughness measurements. The general level of performance of these pavements after 10 and 15 years of service (1946-1954 construction), is given by the tabulation below indicating the medium performance level.

	Performance		
	10 years	15 years	
Transverse cracking, (99 foot slabs)	1.5	2.49	- cracks per slab
Longitudinal cracking	10	11.5	- feet per mile
Corner breaks, exterior corners	0.3	0.46	- percent of corners
Corner breaks, interior corners	0.2	0.2	- percent of corners
Spalling, exterior corners	12	29	- percent of corners
Spalling, interior corners	6	19	- percent of corners
Spalls along joint, not at corner	3.1	8	- per 100 joints
Joint Blowups, percent of projects with none	64	10	
Mud-jacking, percent of projects with none	78	----	
Patching, percent of projects with none	45	14	
Patching, median performance	less than 50	75	- sq ft per lane-mile

It should be stated that for most of these types of deterioration there was a tremendous spread in performance among the construction projects

studied. In general, most projects performed quite well but a small number of projects performed quite poorly. The most serious type of deterioration from the point of view of frequency was joint spalling, particularly corner joint spalling. One type of deterioration that was infrequent in the early life of the pavements, but became quite serious by the end of 15 years, was pavement joint blowups. It should be noted that there was a good correlation between percent of internal and external corner spalls at 5 years and blowups per 100 joints at the end of 15 years. Thus, early joint spalling is a good indicator of later more serious joint repair problems.

Three pavement performance models, Present Serviceability Index (PSI, from the AASHO Road Test), Performance Rating Factors (RPF) and Structural Deterioration Index (SDI) were used to evaluate the effect of seven possible causal factors in a multiple regression statistical analysis. Two of these seven factors were found to have a significant effect on pavement performance. These two factors were the percent of soft, non-durable content in the coarse aggregate and the average daily commercial traffic.

Since most projects performed satisfactorily, and the same basic design was used for all projects, it is apparent that causal factors for the poor performance of a few projects are much more likely to be related to materials, construction factors, or environmental factors of climate and traffic loading. All condition survey indicators of performance (transverse cracking, longitudinal cracking, external or internal corner spalls, deterioration, and patching) showed that the traffic lane (the lane with the most and heaviest traffic) had 65 percent poorer performance than the passing lane as measured by the Depreciation Index.

The report shows that performance indices, of either the subjective or objective type, based on condition surveys are much more valuable in indicating structural deterioration than is the Present Serviceability Index which is based primarily on roughness. Moreover, performance indices based on condition surveys serve to measure the "remaining useful life" of pavement while the Present Serviceability Index is nearly useless in this respect. Signs of short service life appear in the five-year condition surveys. These early signs are significantly correlated with later structural performance as measured by the ten and fifteen year surveys. Thus, after five years of service, it should be possible to determine which projects will fail prematurely.

Pavement joint blowup frequency is considerably higher for aggregates containing greater amounts of soft, non-durable material than it is for aggregates with lower amounts, thus blowups can be causally related to this type of deleterious content in the coarse aggregate.

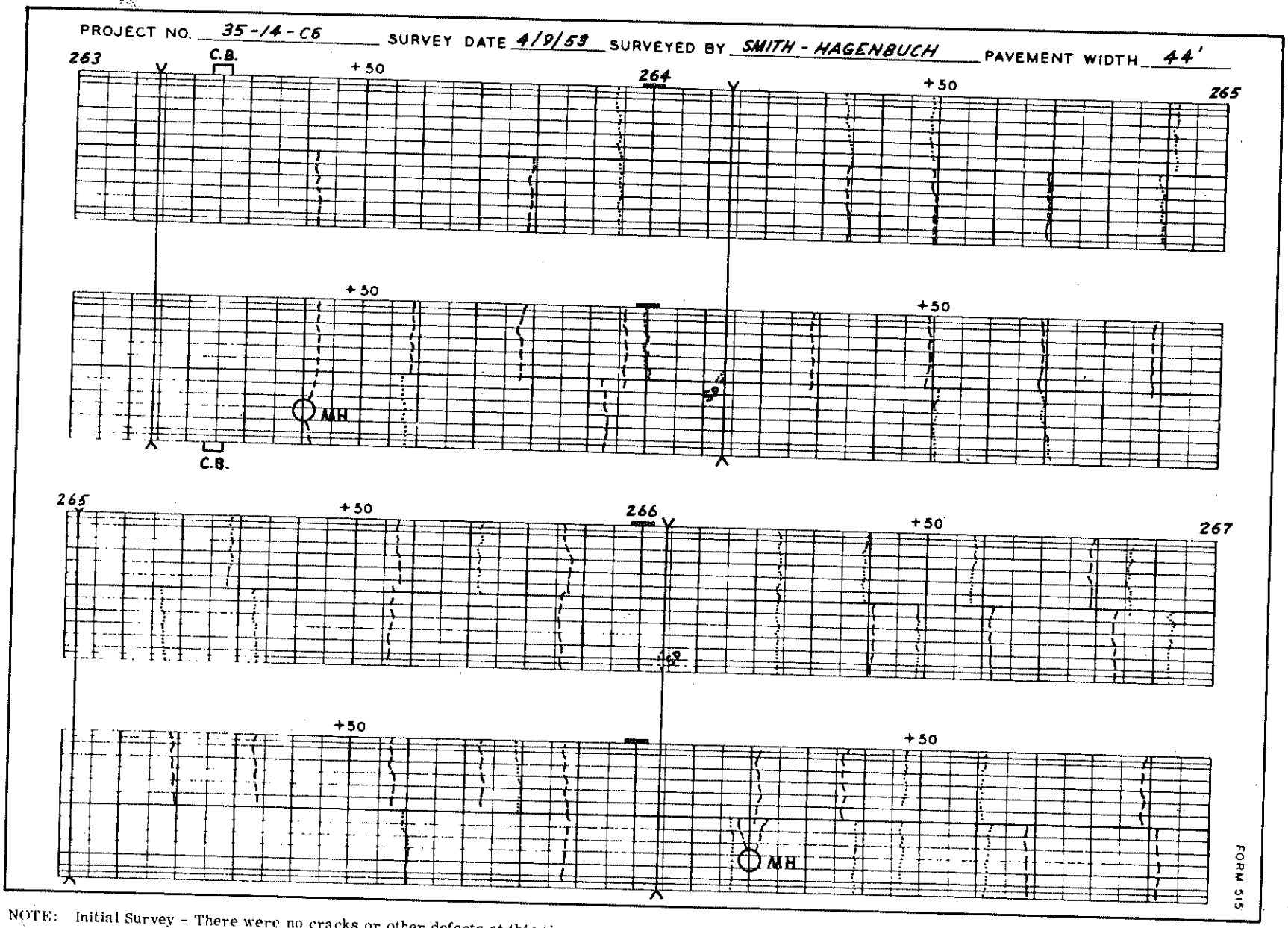
INTRODUCTION

This study was started in July 1963 in cooperation with the Bureau of Public Roads under the Highway Planning and Research Program. However, collection of the condition survey data which made evaluation of performance of all Michigan's postwar concrete pavements possible began in 1946, and initial roughness measurements of concrete pavements in 1949 after constructing a roughometer patterned after the Bureau of Public Roads model.

The primary purpose of this study is to obtain comprehensive information on the performance of pavements constructed since 1946, the beginning of Michigan's "postwar design" construction; a design that remains fundamentally the same today. It was anticipated that this detailed performance study would suggest certain changes in design or materials that could effect improvement in future pavement construction.

These postwar pavements were subjected to surveys shortly after construction and at five-, ten-, and fifteen-year periods in as systematic a pattern as scheduling limitations would allow. As mentioned in the "Scope" of the Proposal, the records and compilations of pertinent construction and materials information, along with condition and roughness surveys for a total of approximately 520 construction projects (1,880 miles) contain the essential ingredients for a comprehensive statistical analysis on pavement performance and the factors that may influence this performance.

The proposal outlined two phases; a cause and effect study of pavement performance, followed by a second phase which would include analytical and experimental studies of the effect of certain design innovations on pavement performance. These innovations were to consist of various design improvements with a determination of whether improved performance as measured by durability, riding quality, and reduction in maintenance warranted the expected increase in initial construction costs. This second phase was also to include certain laboratory model studies to resolve design issues for conventional concrete pavements, and to determine if there were inherent performance advantages to prestressed concrete or continuously reinforced pavements for high-volume heavy axle-load situations.



NOTE: Initial Survey - There were no cracks or other defects at this time.
5-Year Survey - Cracks and other defects shown by ----------
10-Year Survey - Cracks and other defects shown by

Figure 1. Typical condition survey sheets (Colo

The first phase was to run for twelve to eighteen months, and the second phase for fifteen months. The second phase was never started, since it was not possible to attain the research effort in two years of the program which had been scheduled for the first year. This was due to the necessity of assigning personnel to projects that presented more immediate demands.

However, with this curtailed program most of the objectives of Phase 1 have been met and will be discussed within the report. As stated in the Proposal, the specific objectives of Phase 1 were:

I - To determine the general performance of all postwar pavements.

II - To determine specific points of weakness of design methods or construction procedures.

III - To determine the effect of various sources of materials used in the projects on the performance characteristics of the pavement.

IV - To determine the relationship between pavement performance and quality of the subgrade support.

V - To investigate in detail the cause of certain specific types of pavement distress.

Condition surveys are made on each newly completed concrete pavement project as soon after completion as possible, within the limitations of scheduling. The survey data were collected by walking along the edge of the pavement in the direction of increased stationing, which is embossed in the pavement at 100-ft intervals. A measuring wheel recorded the distance of items to be noted between the 100-ft stationing points. The markings placed on the survey sheets in the field are made to scale for cracking, corner breaks, spalling, etc. (Fig. 1). Certain symbols are used to denote the type of condition. Definitions of terms for pavement condition surveys are given in Appendix I. Appendix I also illustrates photographically the typical types of deterioration that were observed. Periodic resurveys are generally made for most projects after five, ten, and fifteen years of service. The same survey sheets were used for subsequent surveys but the condition changes at these periods were noted by using a different colored pencil marking for each survey, making it possible to tell on which survey the first indication of deterioration was observed. Extensions of cracks are noted by elongation of the crack in the appropriate color.

In studying and comparing the condition of pavements in service it was decided to compare performance at the end of five, ten, and fifteen years. At the time the condition survey data were tabulated, it was possible to use the projects constructed during 1946 through 1948 for fifteen-year performance and the 1946 through 1958 projects for the five-year performance. However, preliminary study and analysis indicated that more significant results appeared possible after ten and fifteen years of service. Thus, it was decided to study only the five-year performance on those projects (1946 through 1953) which also had ten- or fifteen-year service records in order to determine the rate of pavement deterioration that had occurred. The condition survey data remain available but in untabulated form for the five-year surveys of projects constructed between 1953 and 1958. Initially, the general analysis was confined to 50 projects with fifteen-year service records representing 193.1 project miles and 207.9 miles of equivalent two-lane pavement; and 148 projects representing 510.1 project miles and 563.4 miles of equivalent two-lane pavement with both five- and ten-year service records. However, as the project progressed, additional surveys became available and, where possible, were incorporated in those aspects of the analysis not already completed.

The condition survey data were tabulated such that the performance of all projects could be evaluated on a common and equitable basis. This entailed a good deal of study for some performance variables. For example, the number of interior and exterior corner breaks cannot equitably be compared per mile of pavement for two-lane or four-lane undivided roadway. Also, such variables as the number of spalls at transverse cracks cannot be compared without also taking into account the variation in the number of cracks from one project to another.

Another source of basic data for this study was Research Laboratory Report No. R-235, "Compilation of Design and Construction Data for Concrete Pavements on the State Trunkline System," printed in October 1955. This book--in coded form--contains the essential design and construction data pertaining to concrete pavements constructed from 1919 through 1953. Some additional data pertinent to pavement performance were required for this study which were not as readily available, e.g., the quality of subgrade soil. These additional data had to be obtained by searching Department records on a project-by-project basis.

Another source of data was the annual roughometer survey of newly constructed concrete pavements. These roughness measurements have been made, since 1951, with a Research Laboratory roughometer patterned after the Bureau of Public Roads design. In addition to the initial roughness sur-

vey, measurements were taken of pavements in service. However, a regular pattern of such roughness measurements to tie-in with the condition surveys was not made until the last few years, when the matter of associating pavement roughness with performance as determined by condition surveys was planned in this study. All available prior roughness data were used, however, and where possible, roughness measurements were made on projects after ten or fifteen years of service in this latter period. All projects with fifteen years of service had roughness measurements taken between fourteen and sixteen years of service. However, initial roughness measurements for these projects were not available. For projects with ten years of service, those constructed since 1951 had initial roughness values and 57 of the total of 148 projects had roughness measurements between nine and eleven years of service.

Preliminary Analysis Studies

As mentioned previously it was not possible to obtain the pavement roughness history for the projects under study as completely as would have been desired. However, certain roughness data were available in terms of measurements taken at odd years rather than after five, ten, or fifteen years of service. Therefore, an analysis was conducted to determine if it was possible to interpolate or extrapolate roughness values from measured intervals, to intervals that would match those where condition survey records were obtained. If, with reasonable accuracy, the rate of roughness increase could be correlated with years of service, then such projections might increase the amount of valid data that could be analyzed. The relationship turned out to be completely unsatisfactory for such projection purposes since the variation in roughness increase was large. Another attempt was made, on the supposition that perhaps the absolute increase in roughness was related to some extent to the initial roughness value. The relationship between the absolute increase in roughness for five- or ten-year periods was compared with the initial roughness value. The maximum increase is 45 inches per mile for five years and 85 inches per mile for ten-year periods with average increases of 25 to 44 inches per mile, respectively. The average increase in roughness per year for the five-year period is 5.0 inches per mile and 4.4 inches per mile for the ten-year period. However, again the variation in the rate of increase of roughness is so great that interpolation or extrapolation of roughness data to other periods is hazardous. The best correlation, although not sufficiently good for projection, was obtained with respect to the relationship of increase in roughness as a percent of the initial roughness values. As a result of this preliminary analysis it was decided that if a roughness measurement was available for a project which was taken within one year of the time of the

condition survey, it would be used in the analysis. The roughness measurement data for pavement projects taken between nine and eleven years of service were grouped with ten-year condition survey data and fourteen to sixteen years of service with fifteen-year condition survey records.

OBJECTIVES I AND II

GENERAL PERFORMANCE OF ALL POSTWAR PAVEMENTS AND SPECIFIC POINTS OF WEAKNESS OF DESIGN METHODS AND CONSTRUCTION PROCEDURES

One of the primary objectives of this study, and a foremost consideration at the time this pavement condition survey program was initiated in 1946, was to obtain a comprehensive measure of pavement performance. As a result of the Report, "The Design of Concrete Pavements for Postwar Construction," Research Laboratory Report No. R-68A, and the preliminary evaluations of experimental test roads built in Michigan, California, Kentucky, Minnesota, Missouri, and Oregon, a new design for concrete pavements in Michigan was adopted in 1946. Using this design concept, the pavement consisted of long reinforced slabs and contraction joints only. The need for expansion joints to prevent undue compression and pavement Blowups was no longer apparent as a result of the performance of these test roads where, in the case of Michigan's, the expansion joint spacings varied from 90 to 2,700 feet. Prior to this, various joint combinations had been used in Michigan, viz: 1) The exclusive use of 1-in. expansion joints spaced at 100 ft, 2) The use of contraction joints at close intervals, and 10, 20, and 30 ft and expansion joints at varying intervals, 3) The use of expansion, contraction and hinged or warping joints in a 120-60-30 combination (expansion joints spaced at 120 foot intervals, contraction joints midway between the expansion joints, and hinged joints midway between the expansion and contraction joints), thus resulting in 30-ft slabs.

Since 1946 the primary design features have been unchanged or changed only slightly. These features are as follows:

Pavement thickness - 9 in. uniform thickness.

Contraction joint spacing - 99 ft. In 1963 this was changed to 71 ft 2 in. but all projects under this study were constructed with a 99-ft slab length.

Expansion joint spacing - Used only at special locations, or when placing concrete before April 15, or after September 15, and then at 396-ft intervals.

Subbase - 12 in. of granular material.

Load Transfer - 1 in. diameter by 15-in. dowels at 12-in. centers.

Reinforcement - Mesh, bar mat, or expanded metal at approximately 76 to 88 lb per 100 sq ft, depending on lane width and type of reinforcement.

In 1953, the load transfer dowels were changed from 1 in. diameter to 1-1/4 in. diameter and the assemblies for supporting the dowels were upgraded to permit only those that held the dowels rigidly in position in order to eliminate dowel misalignment problems.

Since 1955 a selected subbase has been used directly beneath the concrete pavement to provide a smooth, durable, and firm surface for concrete and to provide better support for the load transfer assemblies. This has consisted of 3 in. of selected material in addition to 11 in. of regular subbase material resulting in a total subbase thickness of 14 in. Since 1963 the selected subbase has been 4 in. with 11 in. of regular subbase for a total thickness of 15 in.

PERFORMANCE OF POSTWAR PAVEMENTS AFTER 10 AND 15 YEARS OF SERVICE

While condition surveys were available for five-, ten-, and fifteen-year service periods, preliminary analysis indicated that performance differences were less distinct or significant at five years and, therefore, the reported performance will be confined to service periods of ten and fifteen years only.

Ten Year Service

The performance of pavements after ten years of service will be discussed in terms of the physical manifestations of deterioration that could be noted by periodic condition surveys.

1. Transverse Cracking

The number and percent of pavement slabs which had 0, 1, 2, 3, ..., n, transverse cracks per slab was tabulated for each project. Frequency distributions of the percent of slabs with 0, 1, 2, 3, ..., n transverse cracks per slab were graphed to determine the variations encountered for 76 projects. The range in performance can be clearly noted in Figure 2 where the average of the ten best and ten worst performing projects with respect to transverse cracking are plotted. The extreme difference in performance is very apparent. The transverse cracking for these ten best and ten poorest performing projects indicates that the extreme differences between good and bad performance is not due to isolated "flukes" but that the normal performance distribution simply covers a tremendous spread. The distribution of the average number of cracks per slab of all two-lane projects after ten years of service is illustrated in Figure 3. For these 82 projects the average varied from 0.03 to an average of 5.17 cracks per slab. The median performance was 1.50 cracks per slab, and approximately 80 percent of the projects had less than 2.8 transverse cracks on the average per slab. For the same 82 projects with ten years of service the frequency distribution, by project, of the percent of slabs of that project with no transverse cracks is also shown in Figure 3. The median performance project had 38.6 percent of its slabs uncracked while 13 percent of the projects had more than 70 percent of their slabs uncracked after ten years of service.

Figure 2. Histogram of transverse cracks per slab for two-lane pavement; 10 years of service.

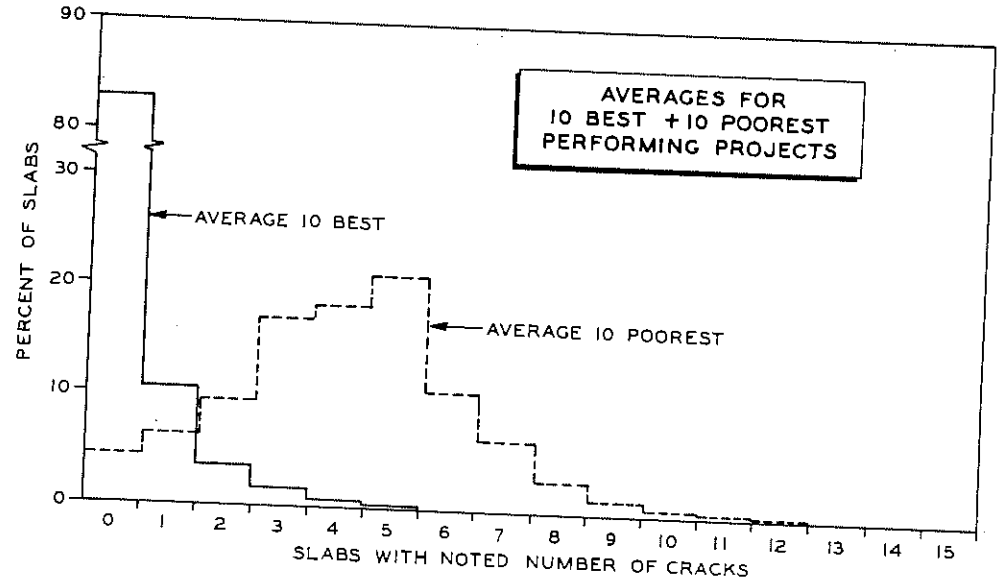
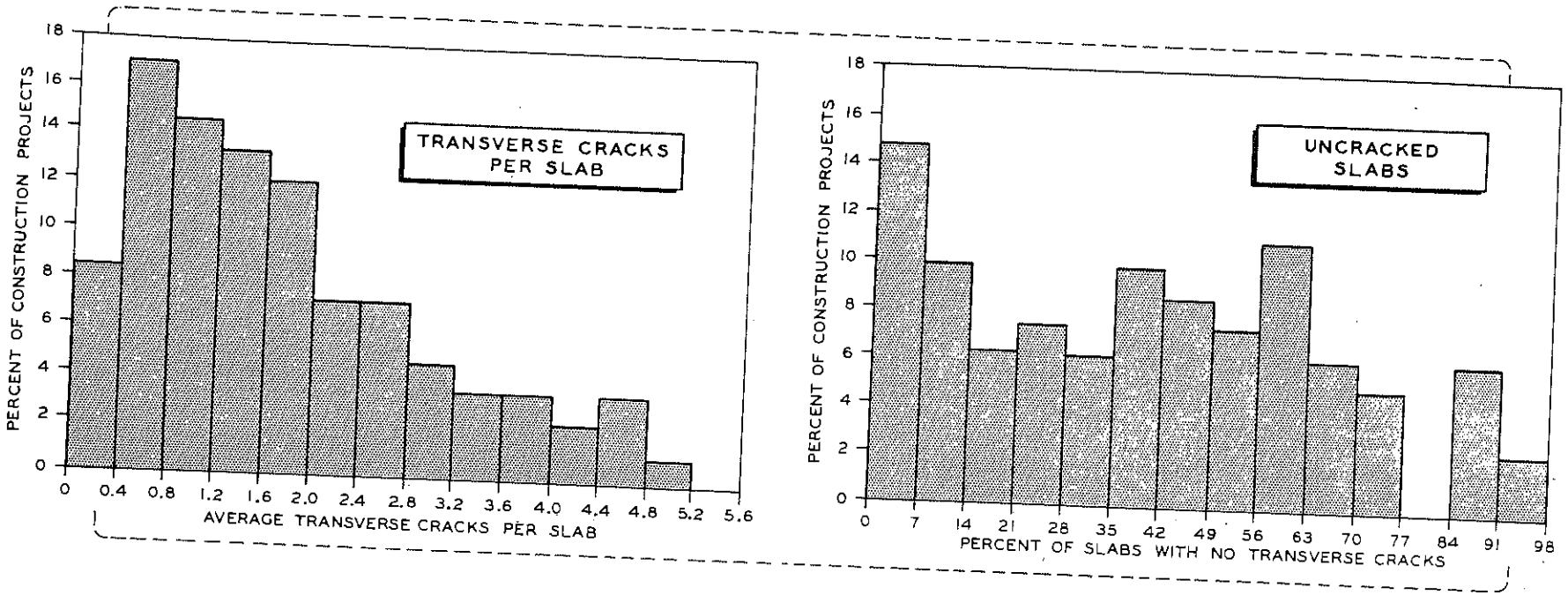


Figure 3. Histograms of transverse cracking for 82 two-lane pavement projects; 10 years of service.



2. Longitudinal Cracking

The distribution of longitudinal cracking among 124 construction projects with ten years of service for two-lane, or four-lane divided pavements, is shown in Figure 4. Construction specifications called for 1/4- by 2-in. bituminous filler strip to form the plane-of-weakness for the centerline crack on standard construction projects from 1946 through 1954. Since 1954, the centerline construction joint has been sawed a minimum of 1/8 in. wide to a minimum depth of 2 in. For all projects studied with ten years of service the bituminous filler strip was used to form the centerline. A wide difference in performance can be noted in Figure 4; for 49 percent of the projects the longitudinal cracking is between 0 and 9 ft per mile of equivalent two-lane pavement, but for seven projects, or approximately 5.5 percent of the total, the cracking was 100 ft or more per mile of pavement. The worst performing project had cracked at the rate of 266 ft per mile, or approximately 5 percent of its length.

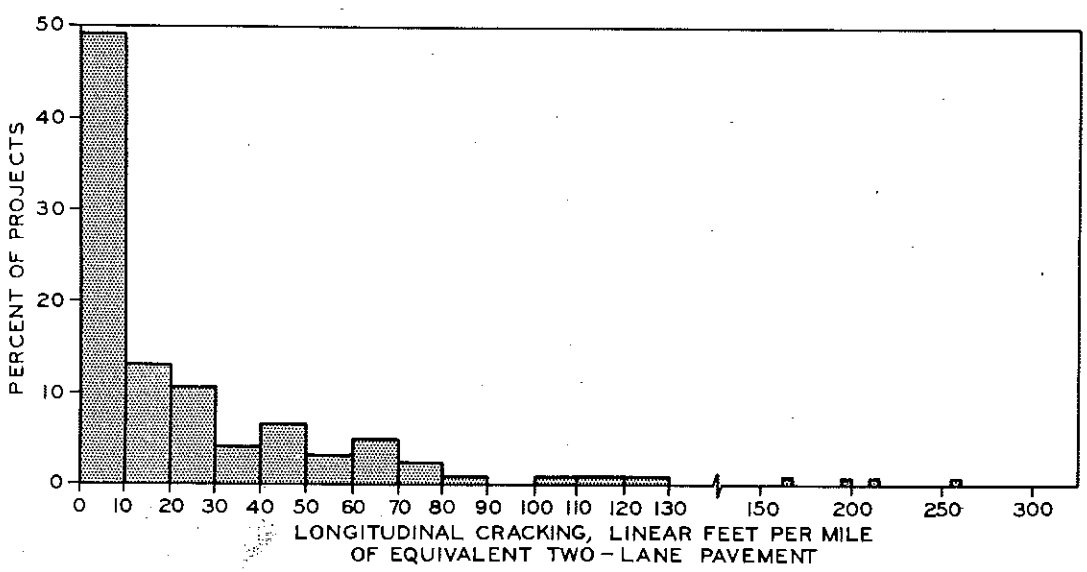


Figure 4. Histogram of longitudinal cracking for two-lane and four-lane divided highway construction projects with 10 years of service (124 projects).

During 1953, on one construction project, short stretches of pavement (between 1,000 and 2,000 ft) were sawed to depths of 1, 1-1/4, 1-1/2, or 1-3/4 in., instead of the standard depth (a minimum of 2 in.) to determine the effect of this on longitudinal cracking. This experiment indicates that when the depth of cut is reduced to 1-3/4 in., the longitudinal cracking as

a percentage of pavement length increased approximately four times, and that for a 1-in. cut the longitudinal cracking is approximately 25 times as great as for the standard 2-in. minimum cut (Fig. 5).

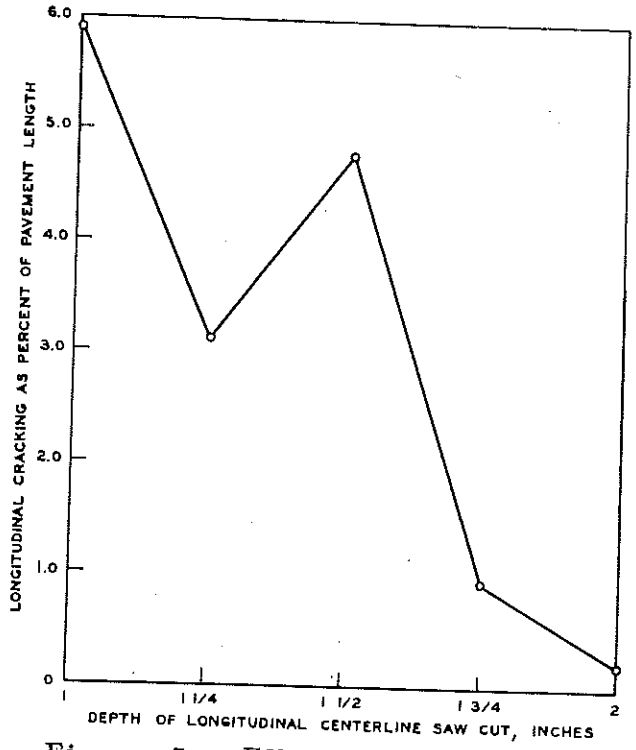


Figure 5. Effect of longitudinal centerline saw-cut depth on subsequent formation of longitudinal cracking; 10 years of service.

3. Corner Breaks

Figure 6 is a histogram showing the distribution of exterior and interior corner breaks for 82 two-lane construction projects with ten years of service. Twenty-nine percent of the projects had less than 0.1 percent of the possible exterior corners broken and forty-six percent of the projects had less than 0.1 percent of the possible interior corners broken. This good performance, however, is offset by 17 projects, or slightly more than 20 percent, where more than 1 percent of the exterior corners were broken, and eight projects (approximately 10 percent) with more than 1 percent of the interior corners broken. The extreme of poor performance was 44.8 percent of the exterior corners broken for one project and 13.9 percent of the interior corners for another. This is a serious problem for a few individual projects but the vast majority of the projects are performing quite well.

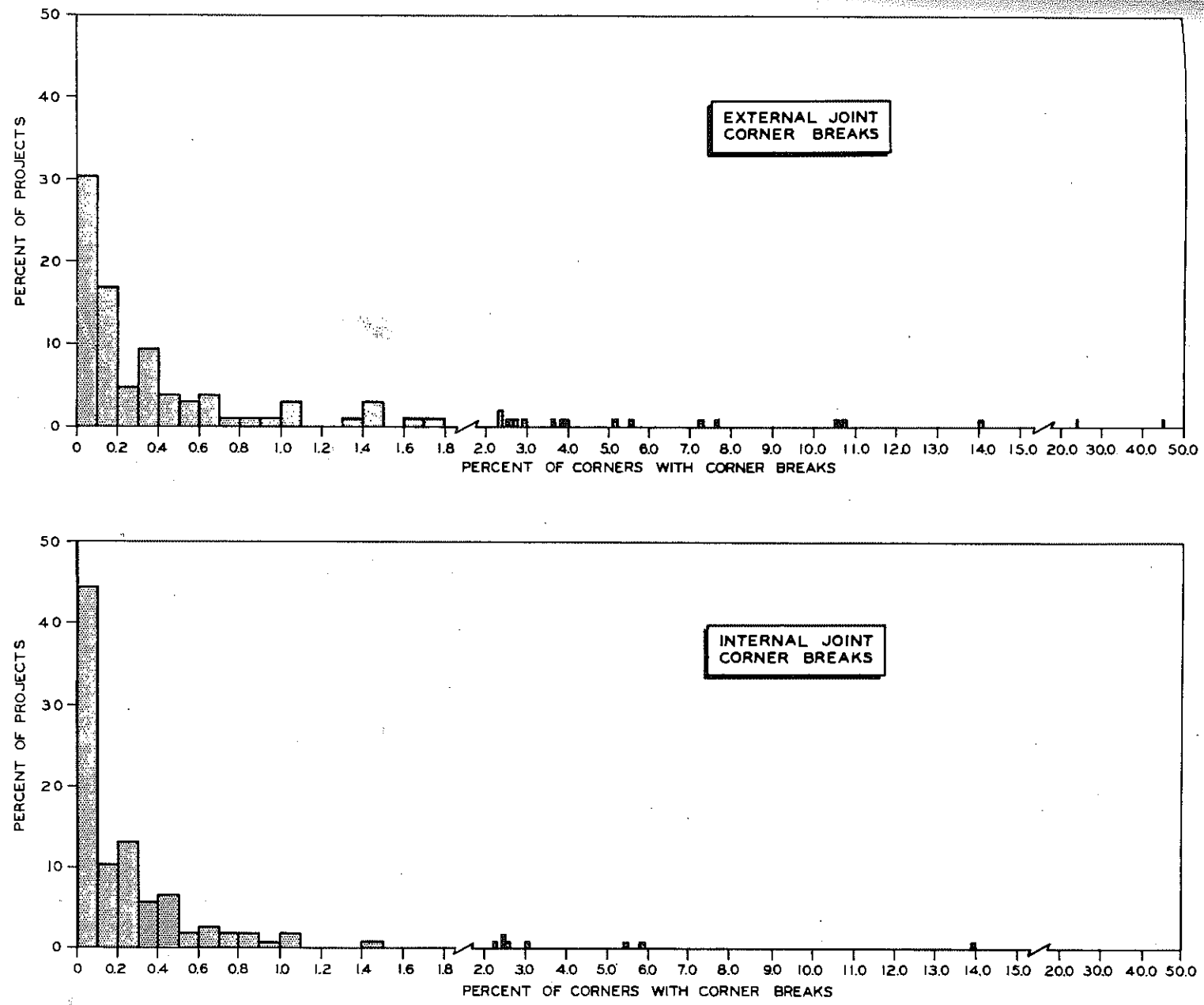


Figure 6. Histogram of corner breaks for 82 two-lane pavement projects; 10 years of service.

The distribution of corner breaks at both exterior and interior corners at transverse cracks is shown in Figure 7. Thirty-four percent of the projects had no corner breaks at transverse cracks and 86 percent had less than one corner break at a transverse crack for 100 cracks. The poorest performing project had 3.8 corner breaks at transverse cracks per 100 cracks.

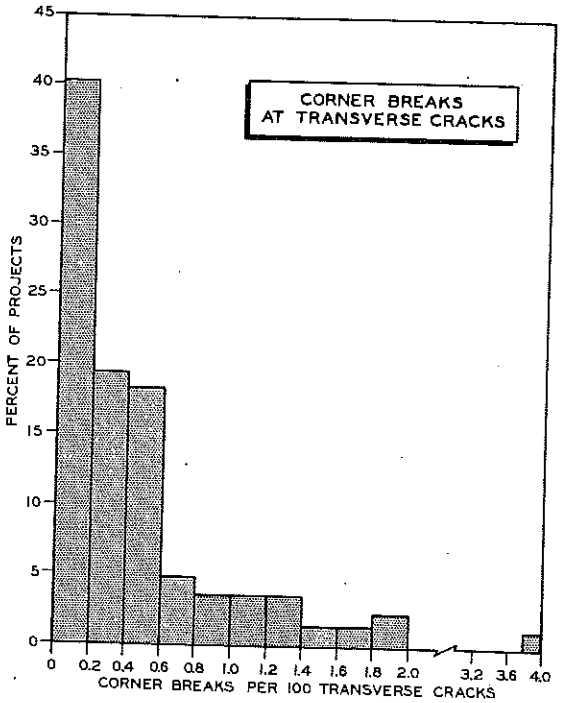
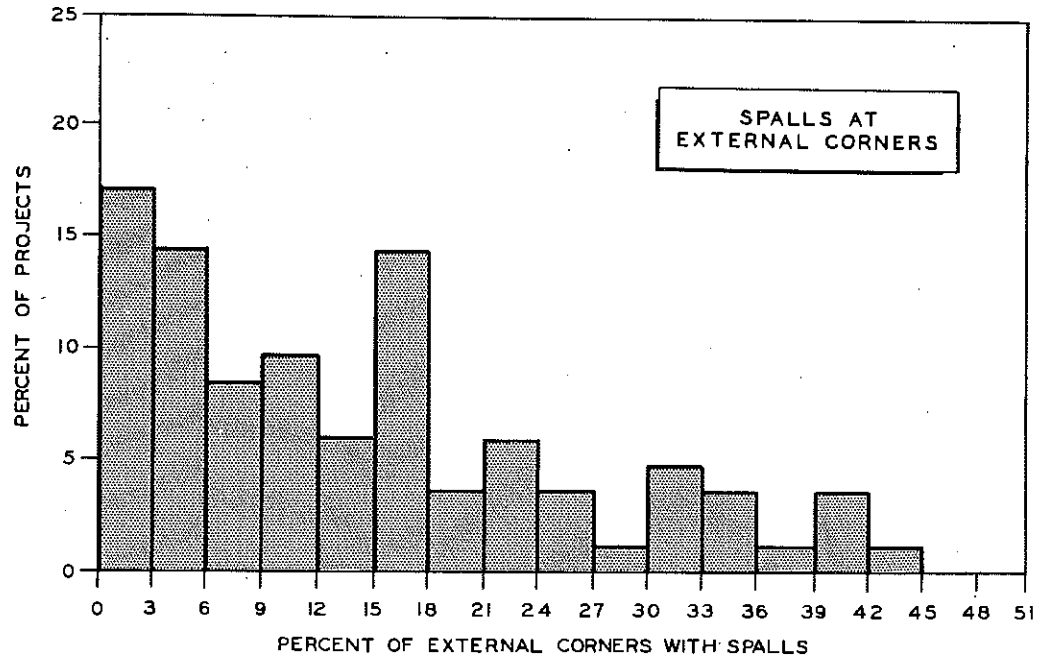


Figure 7. Histogram of corner breaks at transverse cracks for 82 two-lane pavement projects; 10 years of service.

4. Spalls

Spalling has been characterized in the following ways: 1) spalls at external corners, 2) spalls at internal corners, 3) spalls along transverse joints (not at joint corners), 4) spalls along transverse cracks, 5) spalls along longitudinal centerline joint, 6) spalls along outside longitudinal edge of slab, and 7) spalls in interior surface of slab. The distribution by construction projects of spalls at external and internal joint corners is shown in Figure 8. Pavement performance has not been particularly good for this indicator of pavement deterioration since 36 projects (44 percent) had more than 15 percent of the possible external corners spalled after ten years of service and the poorest performing project had 43.3 percent spalled. As might be expected, spalling at interior corners is generally not as severe as at external corners. Slightly over 30 percent of the projects had less than 3 percent of the possible internal joint corners spalled, but approximately 20 percent had more than 15 percent spalled and the poorest performing project had 48.4 percent spalled.



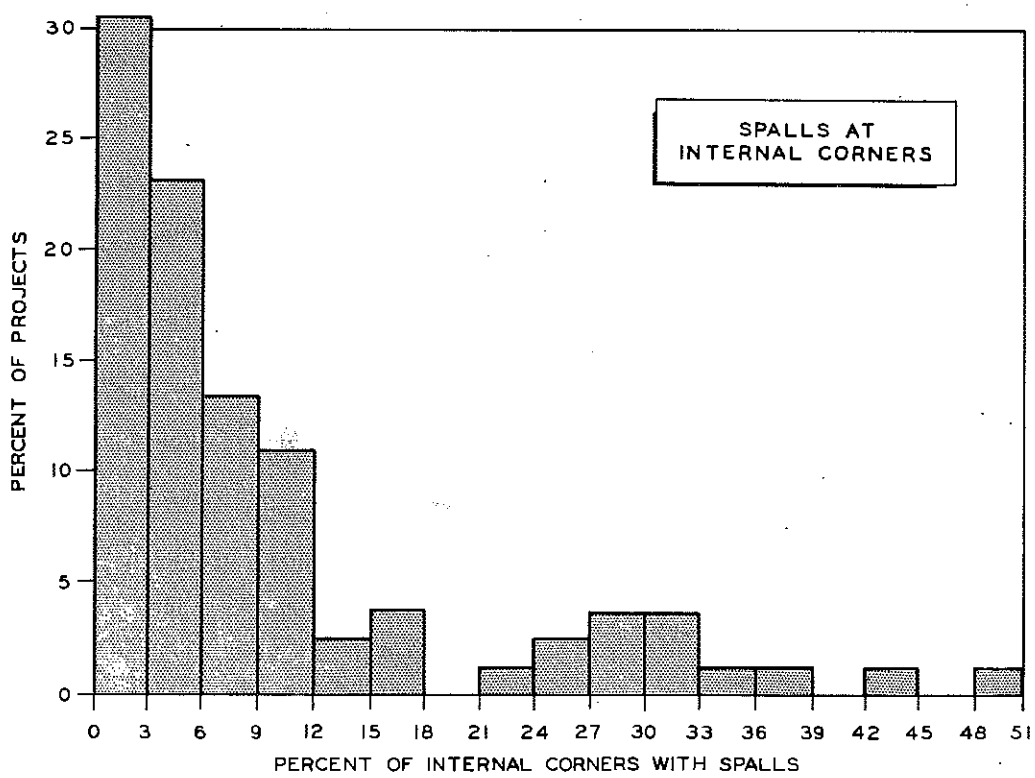


Figure 8. Histograms of corner spalls for 82 two-lane pavement projects; 10 years of service.

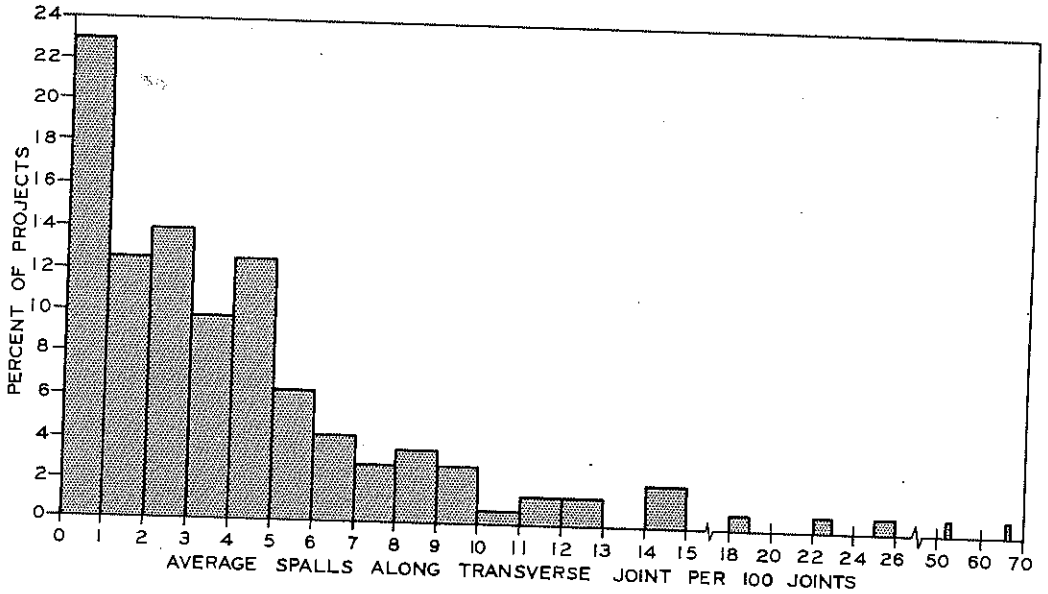


Figure 9. Histograms of average number of spalls along transverse joints for 144 construction projects; 10 years of service.

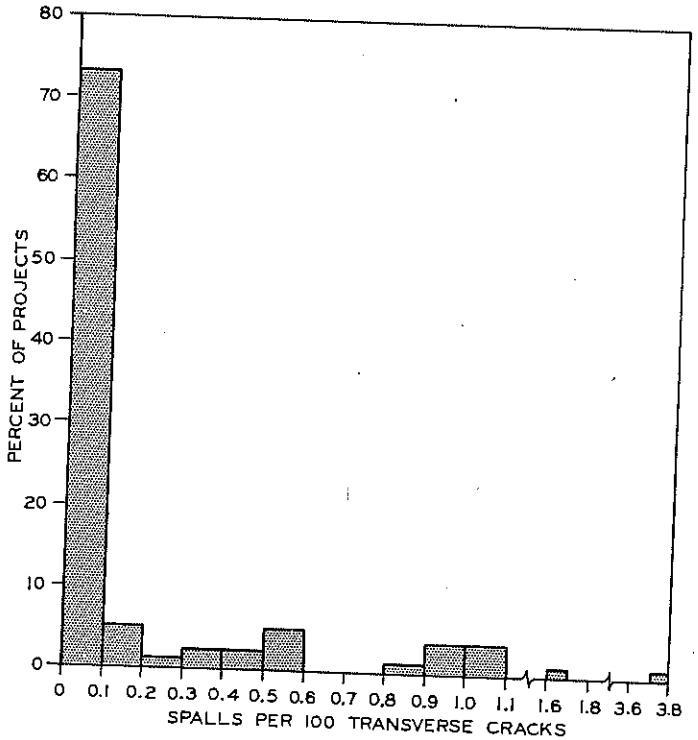


Figure 10. Histogram of spalls at transverse cracks for 82 two-lane projects; 10 years of service.

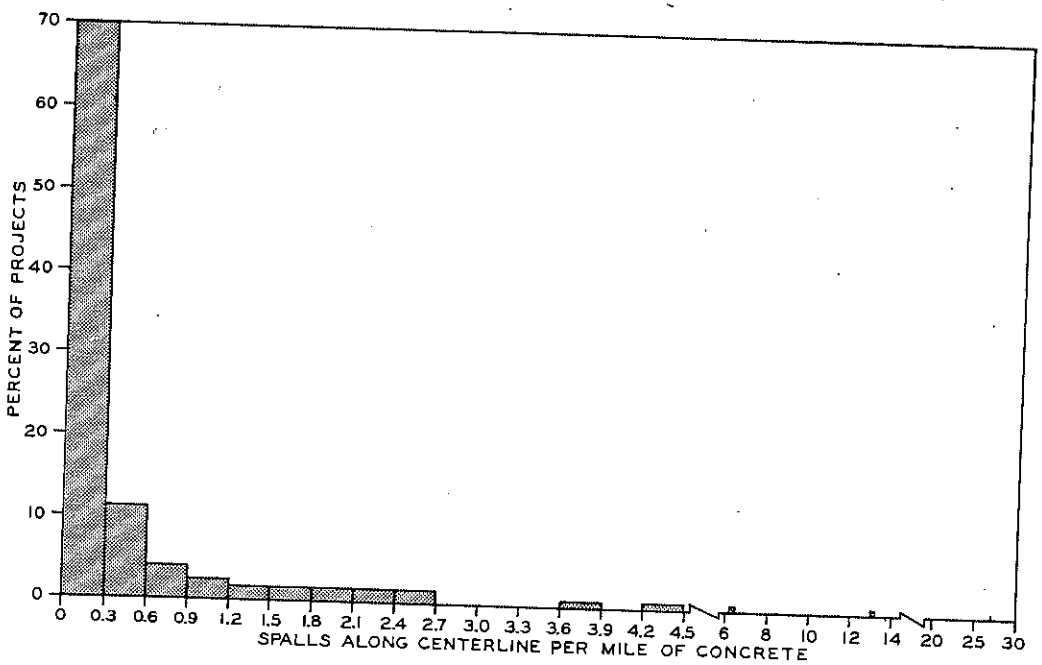


Figure 11. Histogram of spalls along centerline for two-lane and four-lane divided pavement; 10 years of service.

Spalling along the interior portion of transverse joints is shown in Figure 9. The distribution is again extreme, from 22.9 percent of the 144 projects with an average of less than one spall along the interior portion per 100 transverse joints to an average of 70 such spalls per 100 transverse joints or nearly one for every joint. The median performance was 3.11 interior spalls along the joint per 100 transverse joints. Spalling along transverse cracks appears to be no serious problem for most projects, with 73 percent of the projects having no spalling at transverse cracks and 98 percent of the projects have on the average one or less spalls per 100 transverse cracks (Fig. 10). The poorest performing project had an average of 3.8 spalls along transverse cracks per 100 cracks.

Spalling along the centerline joint is indicated by the frequency distribution in Figure 11. Over sixty percent of the projects had no spalling of this type and 88 percent had less than one such spall per mile of pavement. The poorest performing project had 27 spalls per mile of pavement or one approximately every 200 ft.

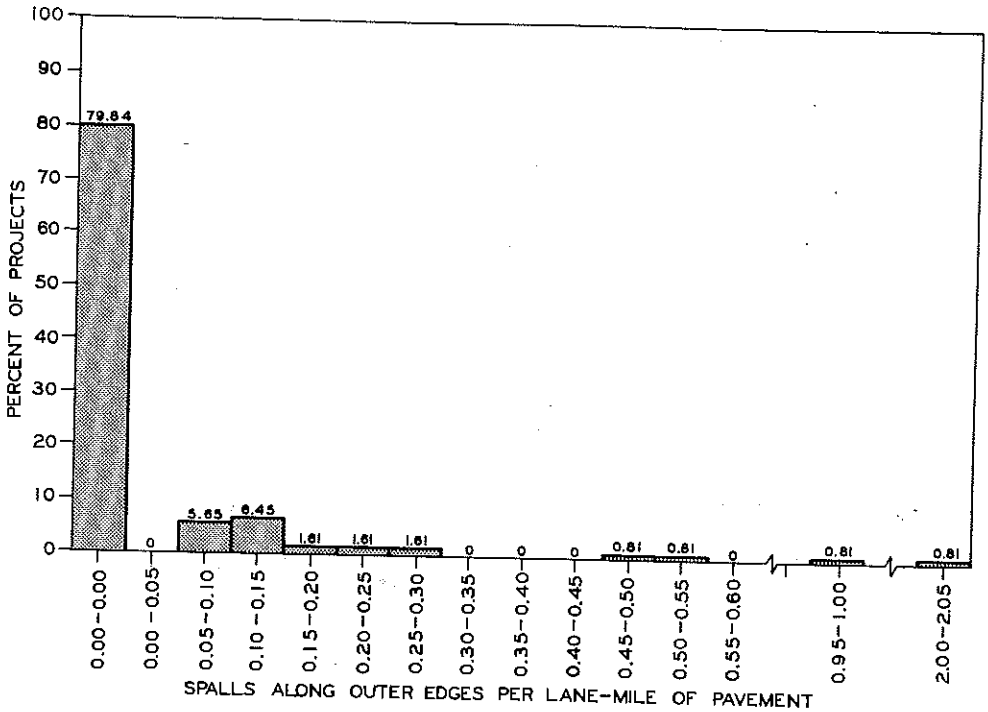


Figure 12. Histogram of spalls along the outer edge of slab for two-lane and four-lane divided highway construction projects; 10 years of service.

Spalling of the longitudinal edge of the pavement is shown in Figure 12. Approximately 80 percent of the projects had no spalling of this type and

only one project of 124 had an average of more than one such spall per lane-mile of pavement. This project had approximately two such spalls per lane-mile.

The frequency of spalling of the interior of the pavement slab surface is shown in Figure 13. Seventy-seven percent of the projects had no spalling of this type and only one project had more than one spall per lane-mile. The poorest performing project had 2.9 spalls per lane-mile.

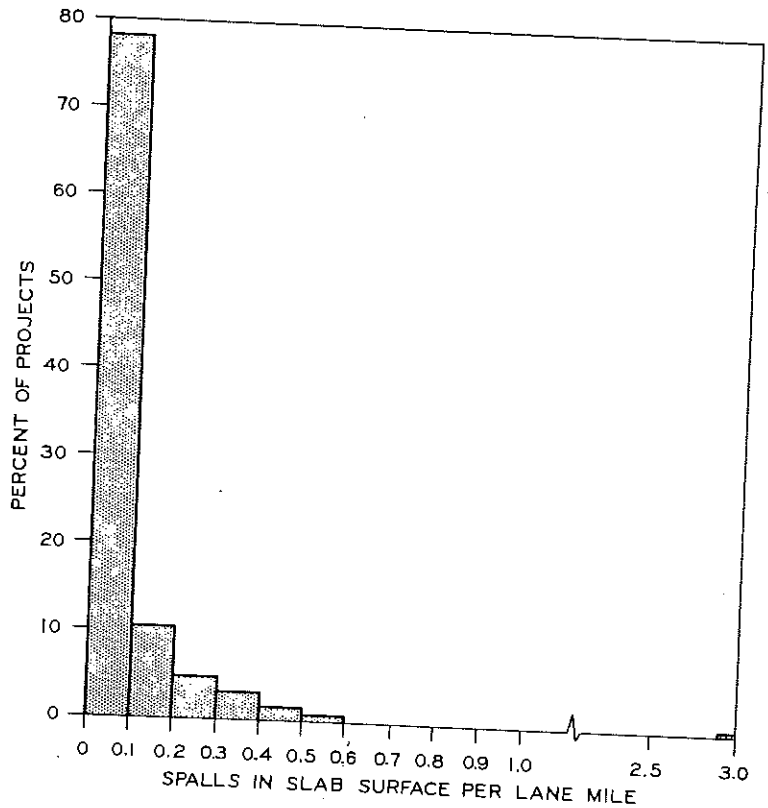


Figure 13. Histogram of spalls in slab surface per lane mile for 124 construction projects; 10 years of service.

5. Joint Blowups

A study of the number of pavement blowups in postwar roadways is of interest since postwar pavements in Michigan were the first to omit expansion joints except at special locations such as bridge approaches, street intersections, railroad crossings, etc. Further, if the pavements were placed prior to April 15 or after September 15, expansion joints were placed at intervals of 396 ft, or every fourth joint, in place of a contraction joint.

For a large part of the pavement projects under study no expansion space was provided. During the late spring, the moist subgrade conditions, along with occasional warm temperatures, does lead to pavement blowups. As these are reported Research Laboratory personnel attempt to visit the site and determine if some construction irregularity, such as improperly centered or misaligned dowels, etc., might have contributed to the blowup at this particular location. A study of two-lane and four-lane divided highways indicated that 63 out of 98 (64 percent of the projects) had no joint blowups at the end of ten years of service. A frequency distribution of blowups is shown in Figure 14. While the largest portion of the projects performed well in this respect, six projects had five percent of the joints blown by the end of ten years of service. The ten poorest projects (10.2 percent) had 62 percent of the pavement joint blowups. This extreme spread in performance has been studied in detail later in the report and causally associated with various material variables.

6. Mud-Jacking

Mud-jacking is required when the pavement settles due to non-uniformity and lack of compaction of the subgrade or subbase prior to the paving operation. Usually the need for mud-jacking is apparent after small amounts of traffic and, therefore, this corrective measure is generally applied early in the service life of the pavement. Two-lane and four-lane, divided and undivided, construction projects (a total of 144) with ten years of service were studied. Of this total 113, or 78 percent, required no mud-jacking. The frequency distribution of mud-jacking as a percent of the original pavement is illustrated in Figure 15. In addition to the 78 percent with no mud-jacking, another 16 projects (11.1 percent) had less than 1 percent of the pavement surface mud-jacked. Seven projects or 4.9 percent had 2 percent or more of the pavement surface that had been mud-jacked and the poorest performing project required 22.8 percent of the pavement surface to be mud-jacked.

7. Patching

After ten years of service, 66 of the 146 projects (45 percent) had no patching and 66 percent had less than 50 sq ft per lane-mile of patched pavement (Fig. 16). Two projects had more than 400 sq ft per lane-mile, and the worst performing project in this category had more than three times as much patching as the next highest project or 1,320 sq ft per lane-mile of pavement (approximately 2.3 percent of the pavement surface).

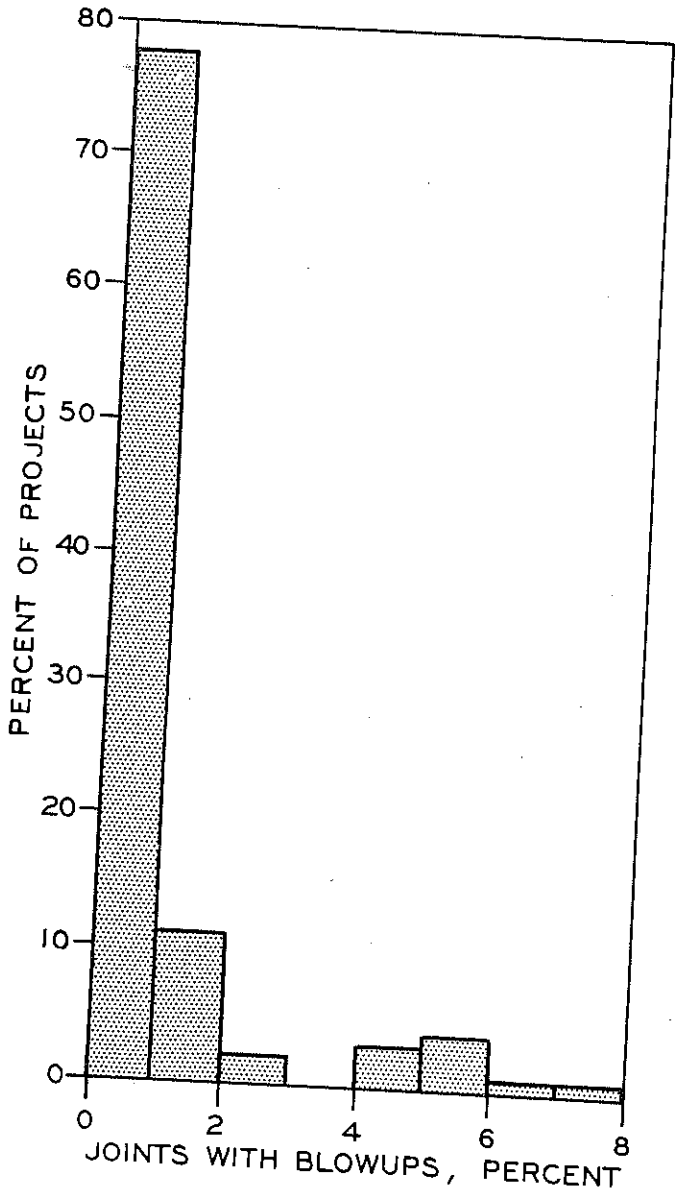


Figure 14. Histogram of joint blowups for 98 projects; 10 years of service.

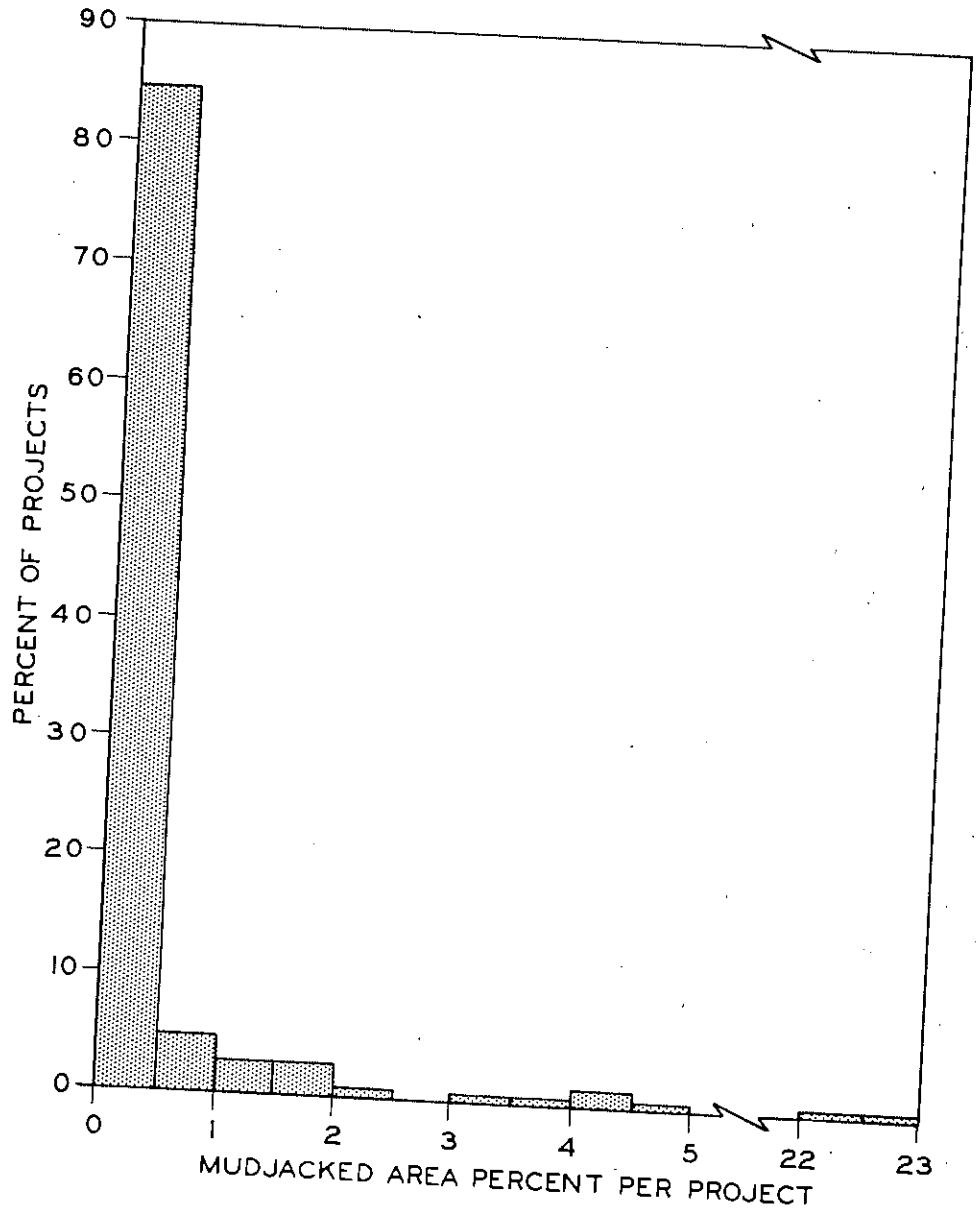


Figure 15. Histogram of percent of pavement requiring mudjacking (144 projects); 10 years of service.

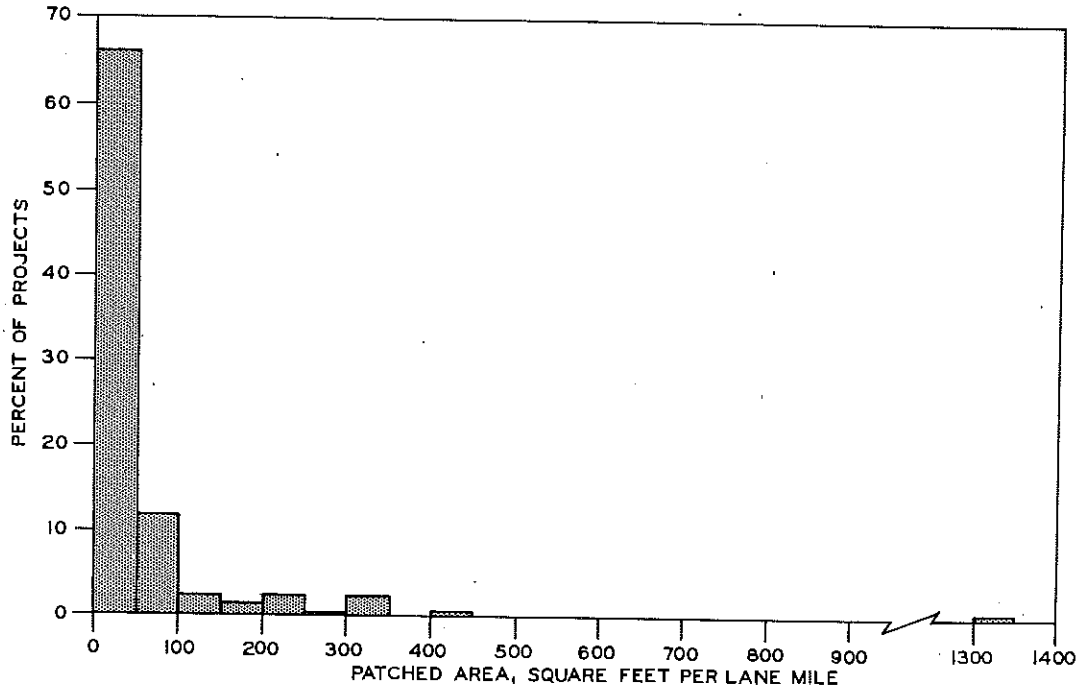


Figure 16. Histogram of patched area for 144 construction projects; 10 years of service.

8. Infiltration Cracks

Infiltration cracks at joints or cracks are short cracks following a course approximately parallel to the centerline and starting from a transverse joint or transverse crack. Figure A4, Appendix I illustrates this type of cracking. Frequency distributions of these two types of cracking are given in Figure 17. For the 82 two-lane projects with ten years of service, 23 had no infiltration cracks at joints and 66 had no infiltration cracks at transverse cracks. At the other extreme, the poorest performance was obtained on two projects where there were 218 and 231 infiltration cracks per 1,000 joints. Infiltration cracks at transverse cracks were not as severe; the two poorest performing projects having 0.42 and 0.47 cracks per lane-mile of pavement.

Fifteen Year Service

Fifty postwar projects had fifteen-year service records. These 50 projects are part of the 144 projects where performance was analyzed on the basis of ten years of service.

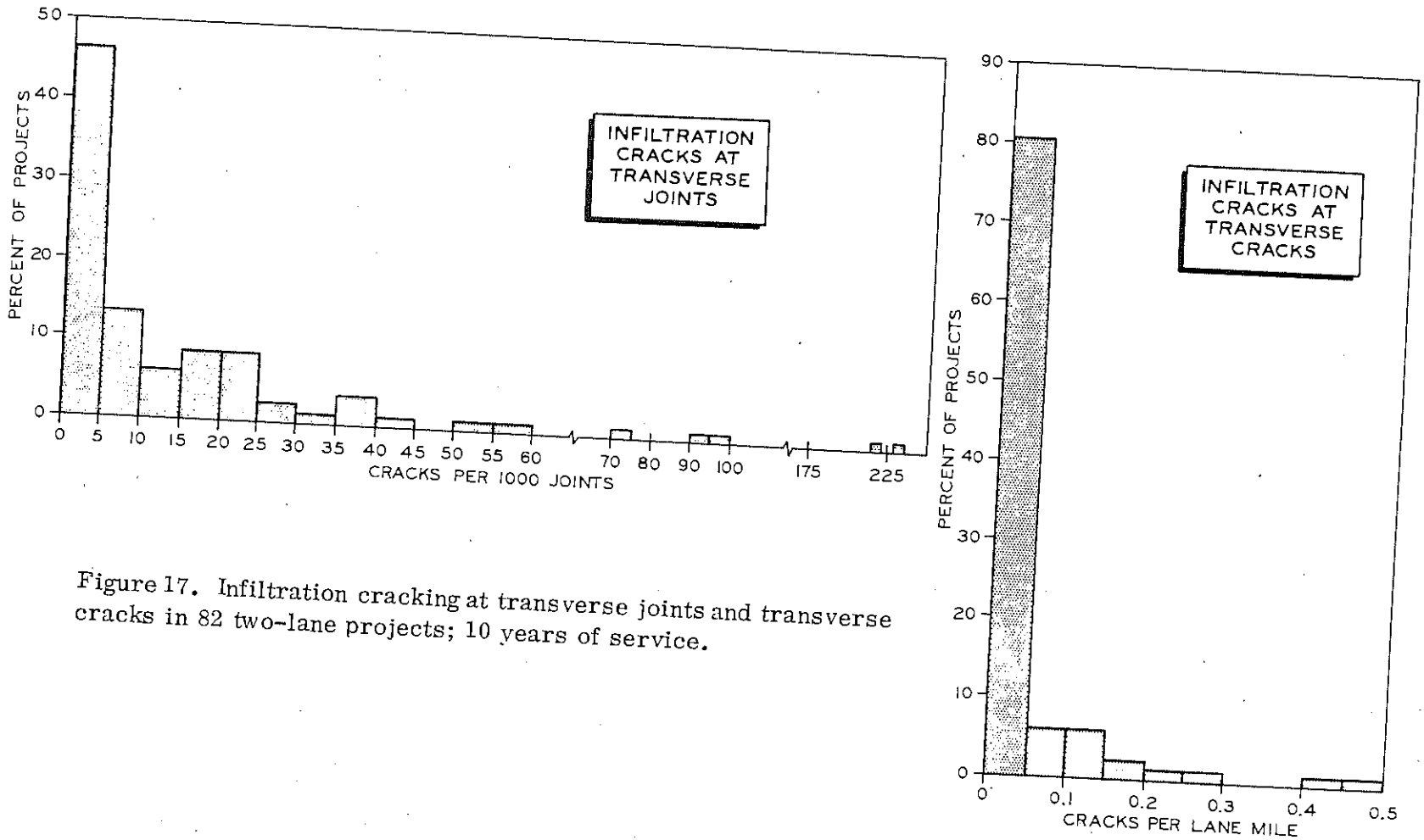
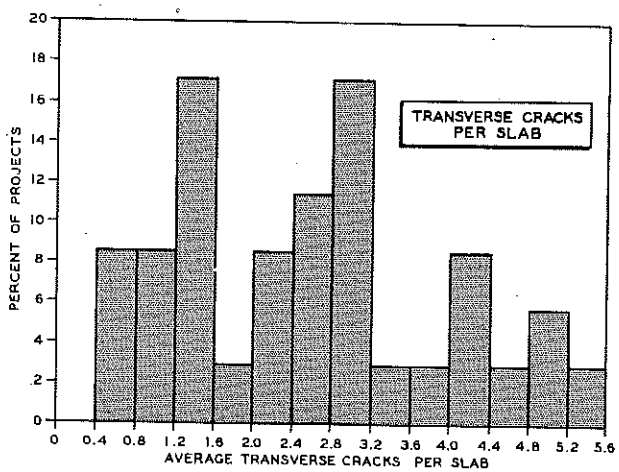


Figure 17. Infiltration cracking at transverse joints and transverse cracks in 82 two-lane projects; 10 years of service.

1. Transverse Cracking

Figure 18 shows the frequency distribution of transverse cracking. Median performance was 2.49 cracks per slab. This compares with 1.50 cracks per slab for projects with ten years of service. The four best projects averaged 0.77 cracks per slab, while the four poorest projects averaged 5.0 cracks per slab.

The frequency distribution of projects with various percentages of uncracked slabs is also shown in Figure 18. The median project had 19.1 percent of the slabs uncracked at the end of fifteen years; the worst performing projects had all slabs cracked and the best performing project had 67.5 percent of the slabs uncracked after fifteen years of service.



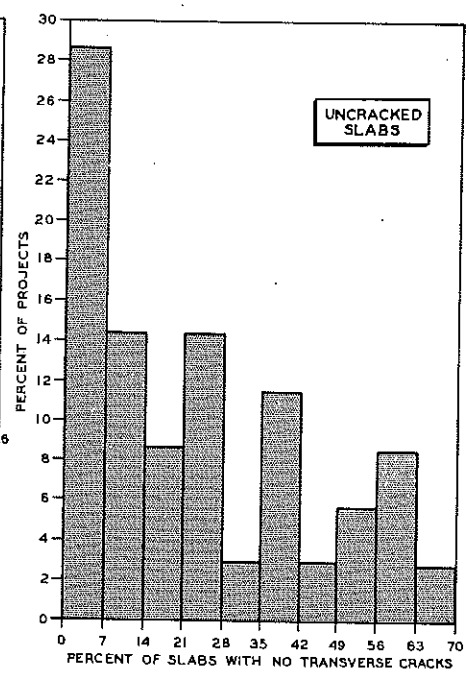


Figure 18. Histograms of transverse cracking for 35 two-lane pavement projects; 15 years of service.

2. Longitudinal Cracking

Variations in the amount of longitudinal cracking for the 44 construction projects are shown in Figure 19. Seven projects (15.9 percent) had no longitudinal cracking, the median performing project had 11.5 ft of longitudinal cracking per mile of pavement and the two performing the poorest had 133 and 136 ft per mile, or approximately 2.5 percent.

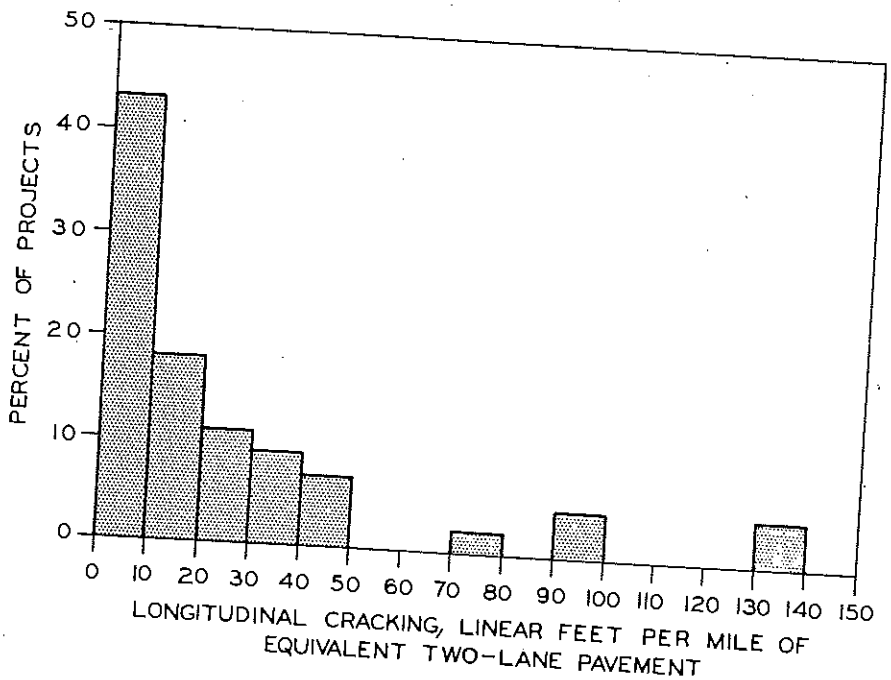


Figure 19. Histogram of length of longitudinal cracking for 44 projects; 15 years of service.

3. Corner Breaks

The distribution of external and internal corner breaks among 35 two-lane construction projects is shown in Figure 20. In five projects (14 percent) there were no external corner breaks and in 12 projects (34 percent) there were no internal corner breaks. Median performance was 0.46 percent of the external corners with corner breaks and 0.18 percent of the internal corners. The four poorest performing projects had 2.14, 2.16, 23.39, and 42.94 percent of the external corners broken. With respect to internal corner breaks, the four poorest projects had 0.88, 1.13, 4.42, and 13.45 percent of the corners broken. It is hardly a coincidence that the same project was the poorest with respect to both types of corner breaks. This project was intensively studied about ten years ago in an attempt to determine the cause of this poor performance.

The distribution of external and internal corner breaks at transverse cracks of pavement with fifteen years of service is shown in Figure 21. Seven of 35 projects had no corner breaks of this type and the median project had 0.27 corner breaks per 100 transverse cracks. The four poorest projects had 1.20, 1.32, 1.34, and 1.70 corner breaks per 100 transverse cracks.

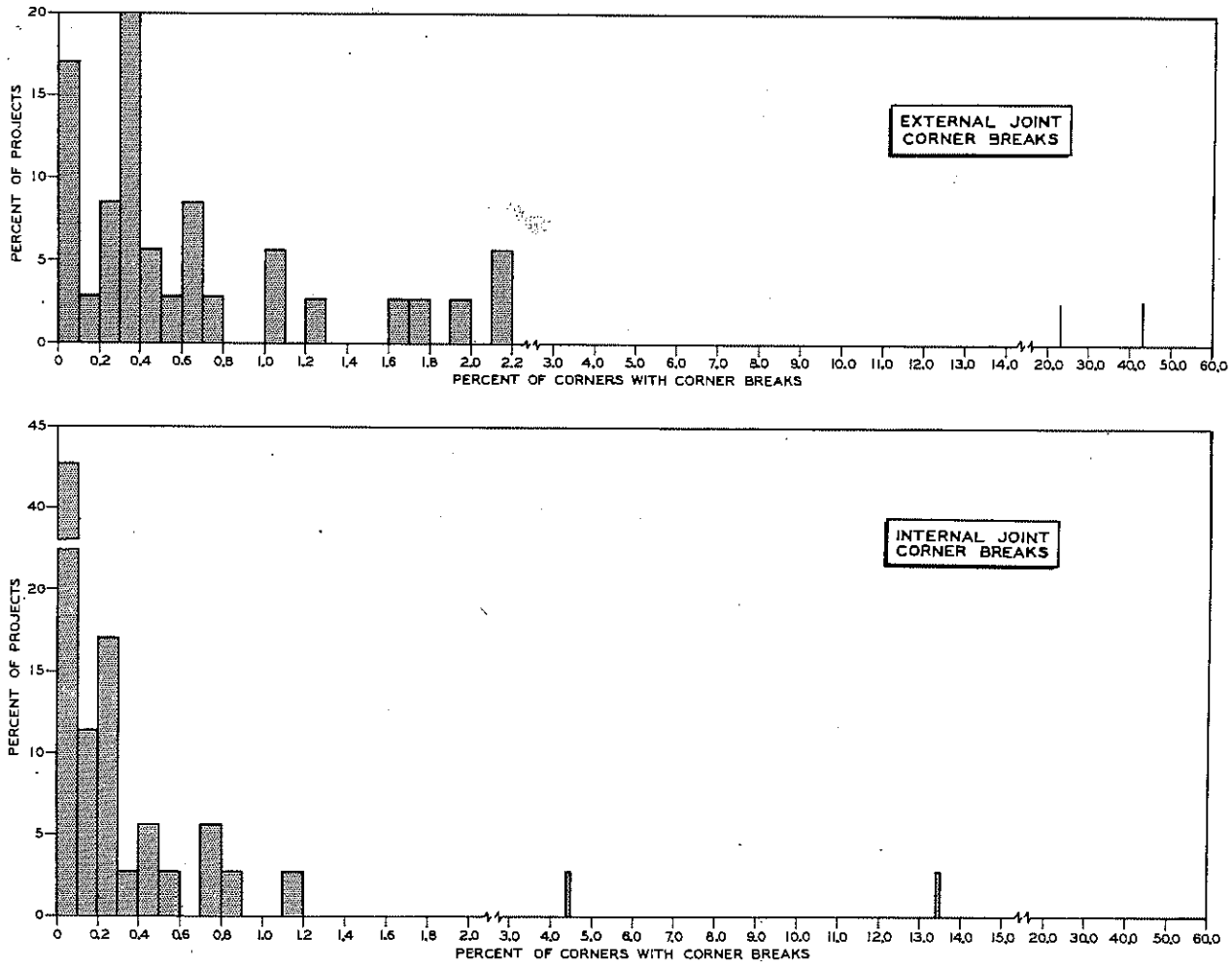


Figure 20. Histograms of corner breaks for two-lane pavement projects; 15 years of service.

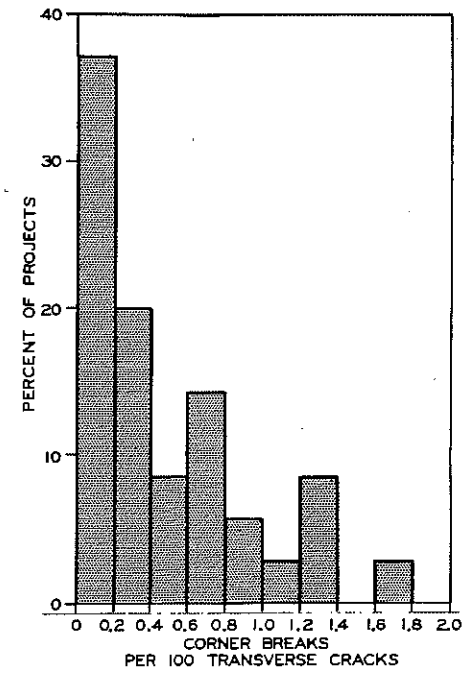
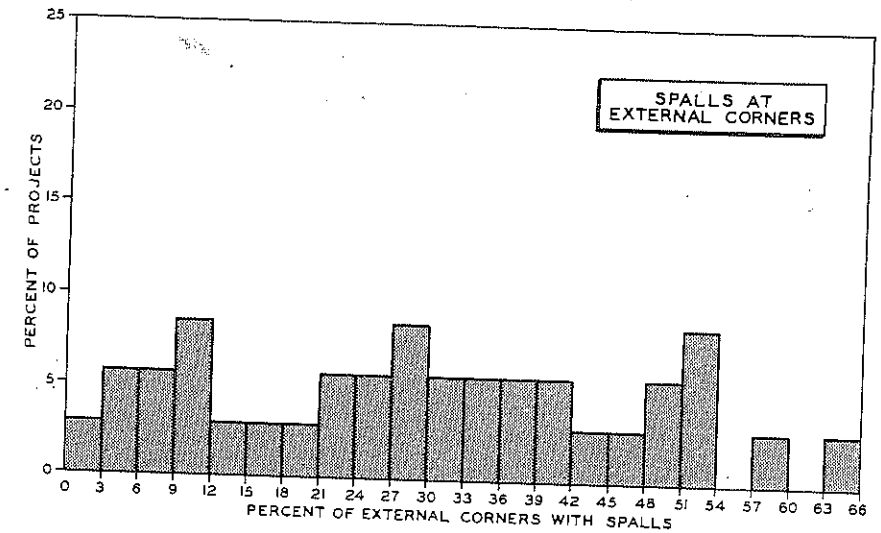


Figure 21. Histogram of corner breaks at transverse cracks for 35 pavement projects; 15 years of service.



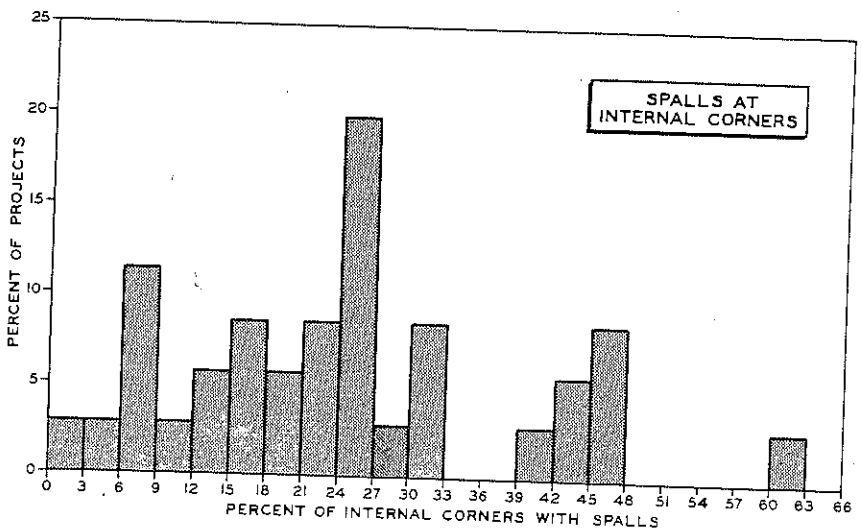


Figure 22. Histograms of corner spalls for 35 two-lane pavement projects; 15 years of service.

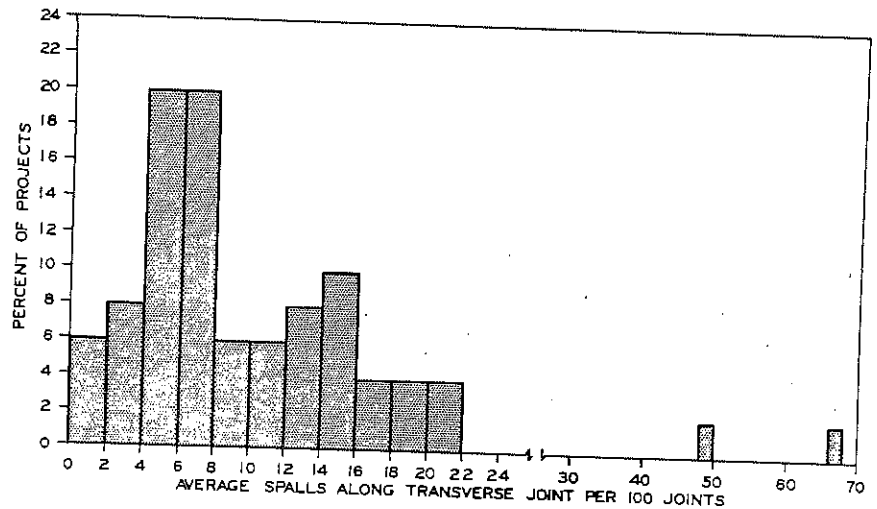


Figure 23. Histogram of average total spalls along transverse joints for 35 construction projects; 15 years of service.

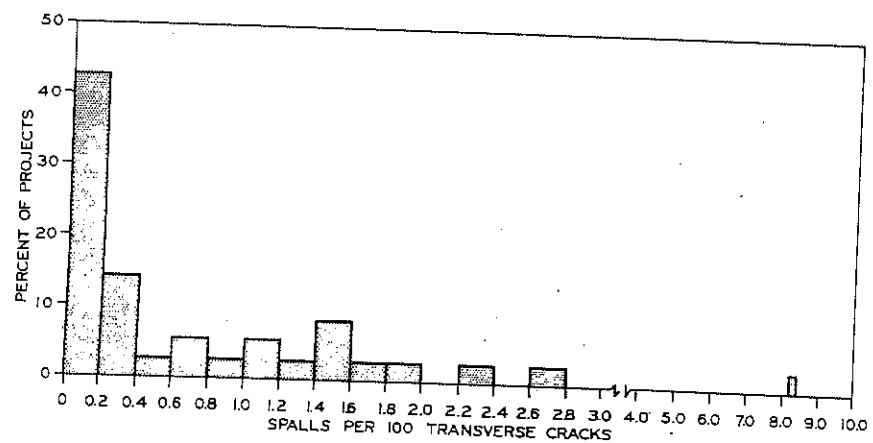


Figure 24. Histogram of spalls at transverse cracks for 35 two-lane projects: 15 years of service.

4. Spalls

The severity of external and internal corner spalling is shown in Figure 22. Median performance for the 35 projects with fifteen years of service was 29.2 percent of the external corners with spalls and 18.7 percent of the internal corners. The four poorest projects in each category had 53.3, 53.6, 58.6, 65.2 percent of the external corners with spalls and 46.9, 47.2, 47.9, and 60.1 percent of the internal corners with spalling. In comparing the frequency distribution of corner spalls for ten (Fig. 8) and fifteen years of service it is apparent that a large increase in this type of deterioration takes place in this period. This aspect of pavement performance warrants design improvement to reduce future maintenance. However, one design change introduced in 1964 should markedly reduce the amount of joint spalling. In the 1964 construction season, the Department began using preformed neoprene joint seals in transverse joints. Since that time, annual inspections have shown an absence of soil or stone infiltration into the joint groove. The hot-pour rubber-asphalt seals used before this time became impregnated with solid materials after a few years of service and thus became incompressible. We feel this was the primary cause of the large amount of joint spalling previously discussed.

Spalling along transverse joints not at the joint corners is illustrated in Figure 23. The four best projects had an average of 1.65 percent of the joints with spalling of this type while the four poorest performers ranged from 20.2 to 66.0 percent of the joints and averaged 38.8 percent. The frequency distribution among projects of spalling along transverse cracks is shown in Figure 24. Ten of the 35 projects had no spalling of this type, while median performance was 0.3 spalls per one hundred cracks. The poorest performing project had 8.2 spalls per one hundred cracks.

Spalling along the longitudinal centerline joint ranged from none for 22 projects out of 44 to 6.3 spalls per mile of pavement for the poorest performing project. The frequency distribution among projects for this type of spalling is shown in Figure 25.

Performance was even better for spalling along the outside edge of the pavement where 31 of the 44 projects had no spalling of this type and the poorest performer had only 0.85 spalls per mile of pavement (Fig. 26). Spalling on the interior of the slab surface was non-existent for 26 of the 44 projects and the maximum on a project was 0.9 spalls per lane-mile of pavement, as illustrated by the frequency distribution in Figure 27.

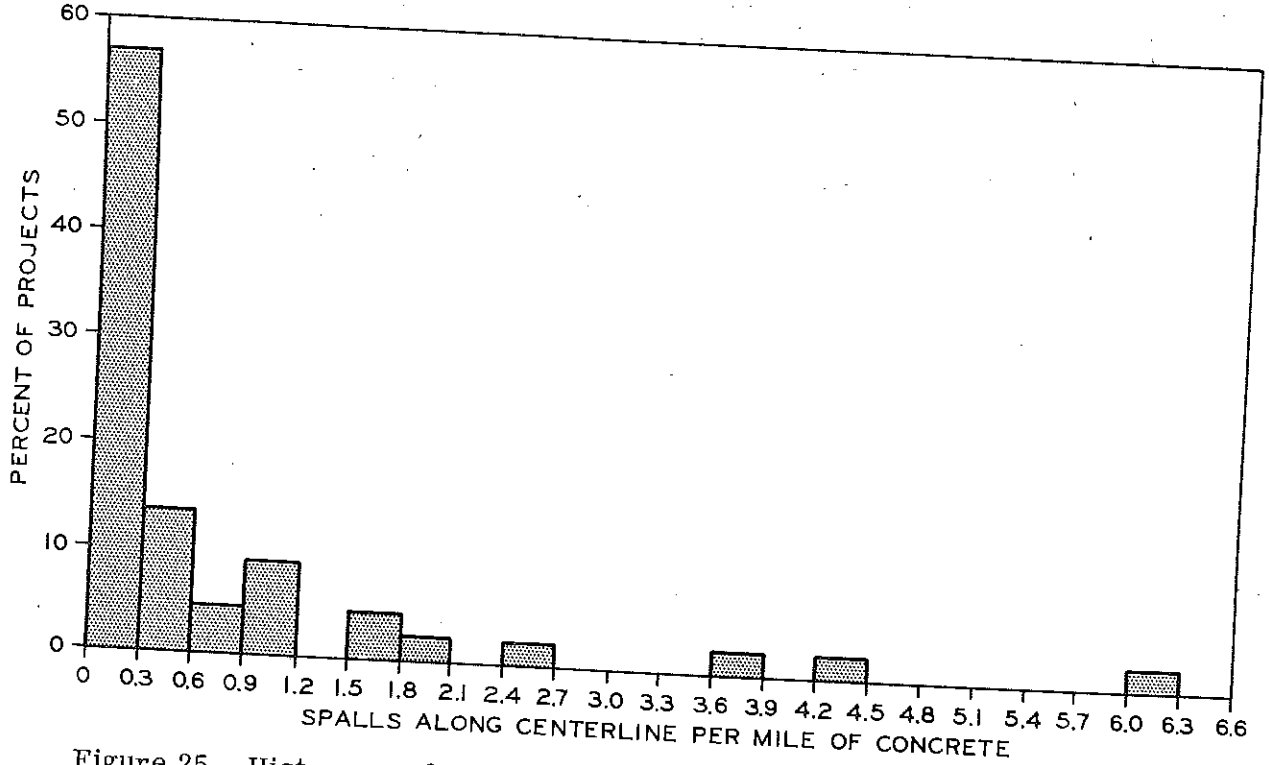


Figure 25. Histogram of spalls along center line for two-lane and four-lane divided pavement; 15 years of service.

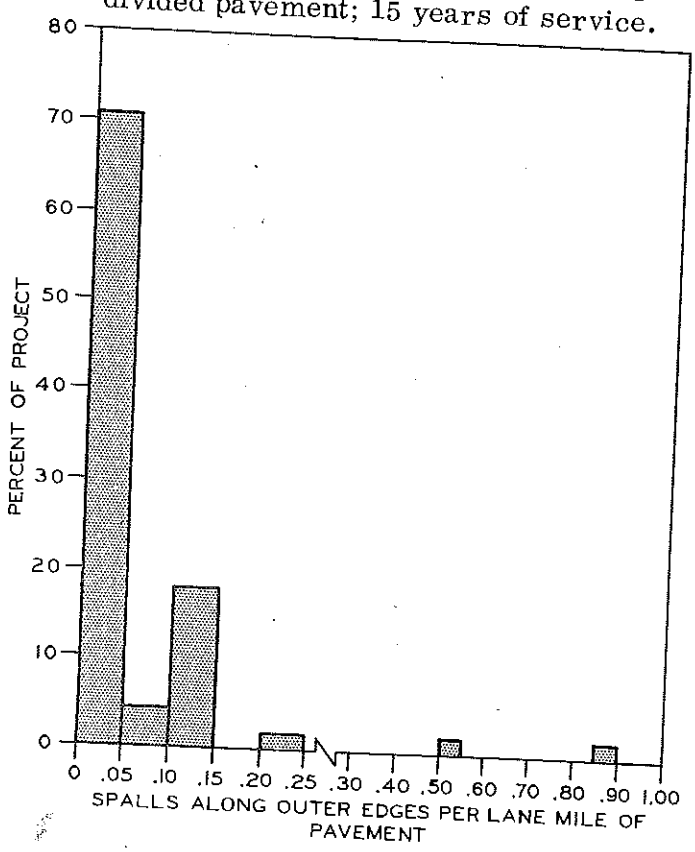


Figure 26. Histogram of spalls along the outer slab edges for two-lane and four-lane divided construction projects; 15 years of service.

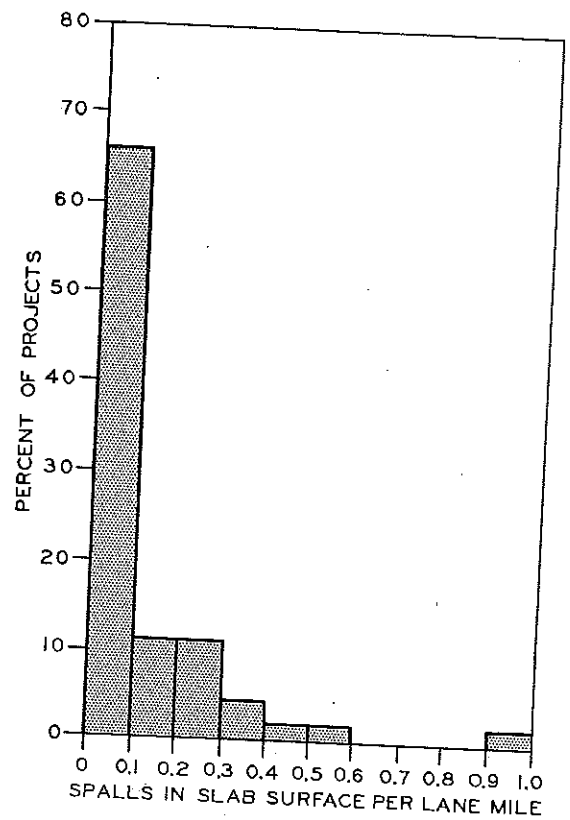


Figure 27. Histogram of spalls in slab surface per lane mile for 44 construction projects; 15 years of service.

In summary, it appears that the most serious type of spalling after fifteen years of service is the spalling of external and internal corners at transverse joints, followed by spalling along transverse joints away from joint corners. If spalling could be controlled at the transverse joint the remaining spalling would be relatively negligible.

5. Joint Blowups

Pavement joint blowups for projects with fifteen years of service are shown in Figure 28. Six of 38 projects had none, the median performance project had 1.4 percent of the joints with blowups and the four poorest projects had 11.5, 17.3, 23.4, and 31.0 percent of their joints with blowups.

6. Mud-Jacking

The prevalence of mud-jacking is shown in Figure 29. Forty-one of 50 projects had no mud-jacking but the four poorest projects in this respect had 2.1, 2.3, 4.7, and 5.0 percent of the pavement surface which had been mud-jacked in order to improve riding quality.

7. Patching

Seven of 50 construction projects had no patched areas after fifteen years of service (Fig. 30). The median performance project had 75 sq ft of patching per lane-mile of pavement (0.13 percent) and the four poorest performing projects in this respect had 830, 910, 1,260, and 1,500 sq ft per lane-mile of pavement or 1.4 to 2.6 percent of the pavement surface (Fig. 30).

8. Infiltration Cracks

The severity of infiltration cracks at joints is shown in Figure 31. Eleven of 38 two-lane projects with fifteen years of service had none of this type of cracking. Median performance was approximately five infiltration cracks per 1,000 joints but the four poorest projects had 18, 36, 47, and 93 such cracks per 1,000 joints. Infiltration cracking at transverse cracks is also shown in Figure 31 as distributed for 35 construction projects. Twenty-one of the projects did not have this type of cracking and the four poorest performing projects had 0.27, 0.43, 0.81, and 2.79 infiltration cracks per lane-mile of pavement.

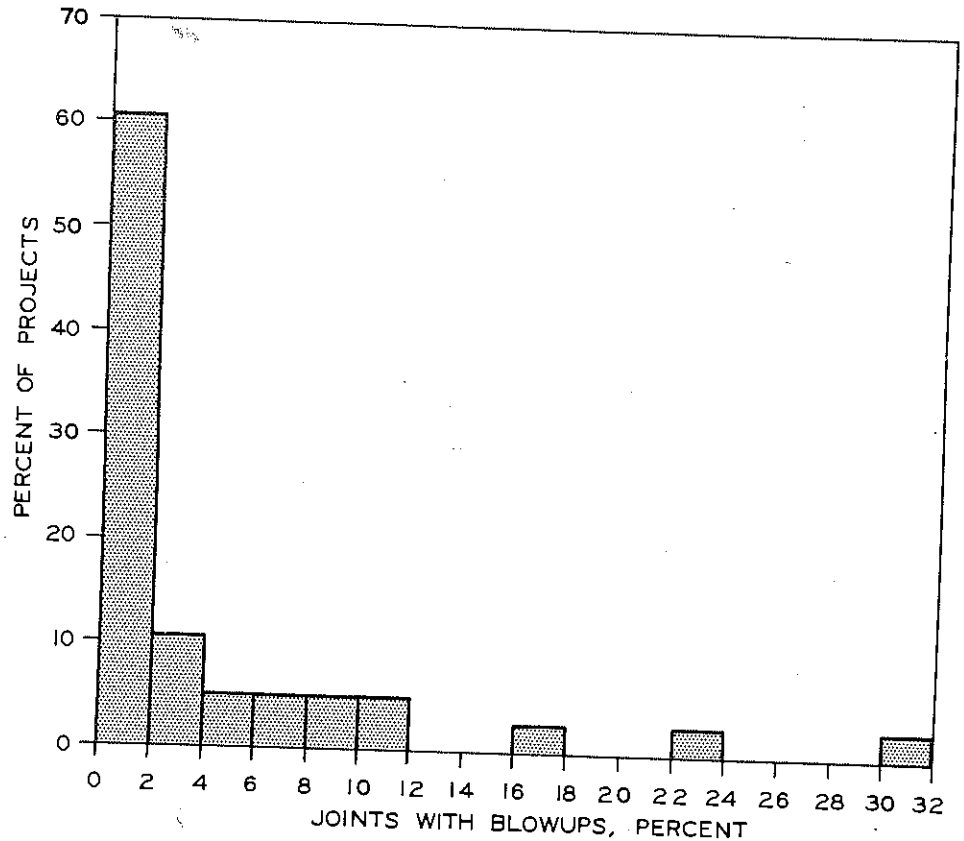
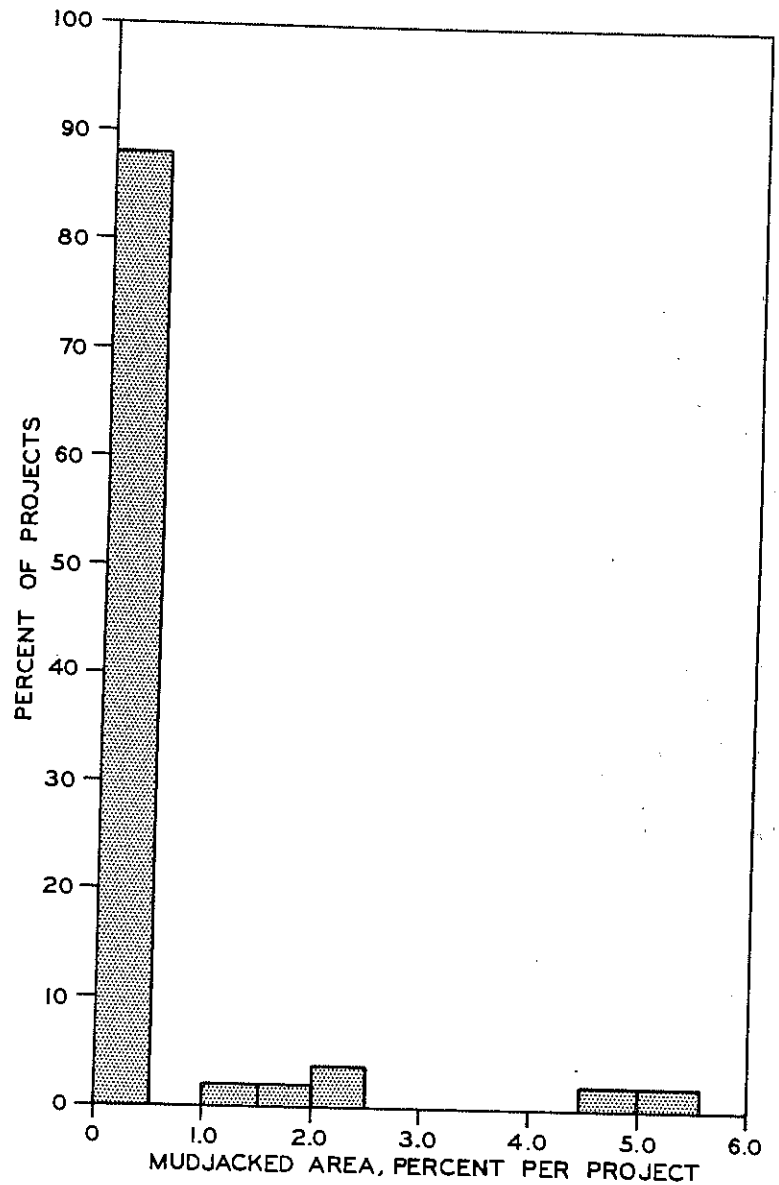


Figure 28. Histogram of joint blow-ups for 38 projects; 15 years of service.

Figure 29. Histogram of percent of pavement requiring mud-jacking (50 projects); 15 years of service.



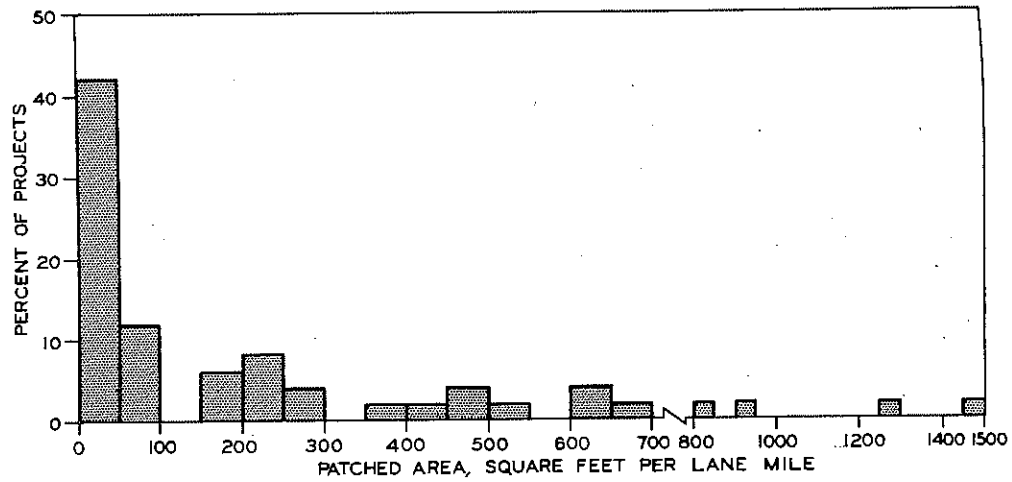
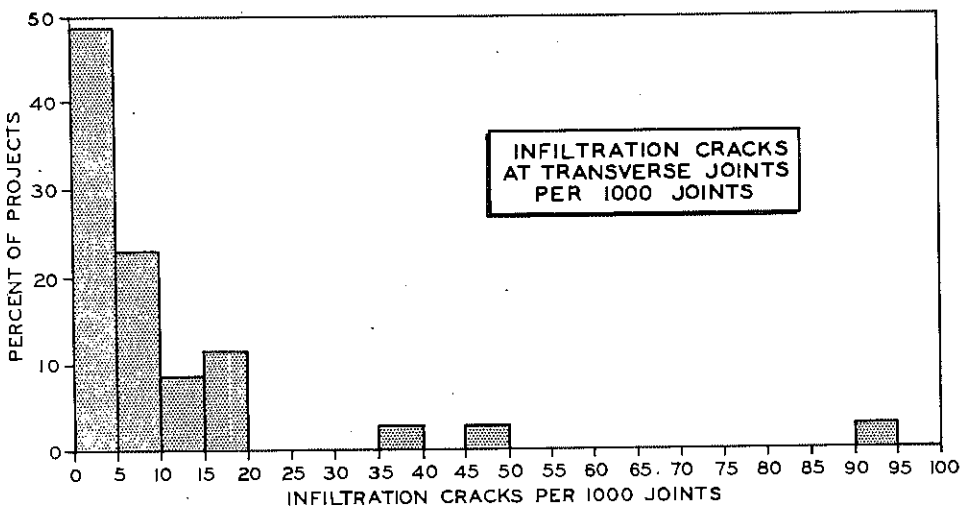


Figure 30. Histogram of patched area for construction projects; 15 years of service.



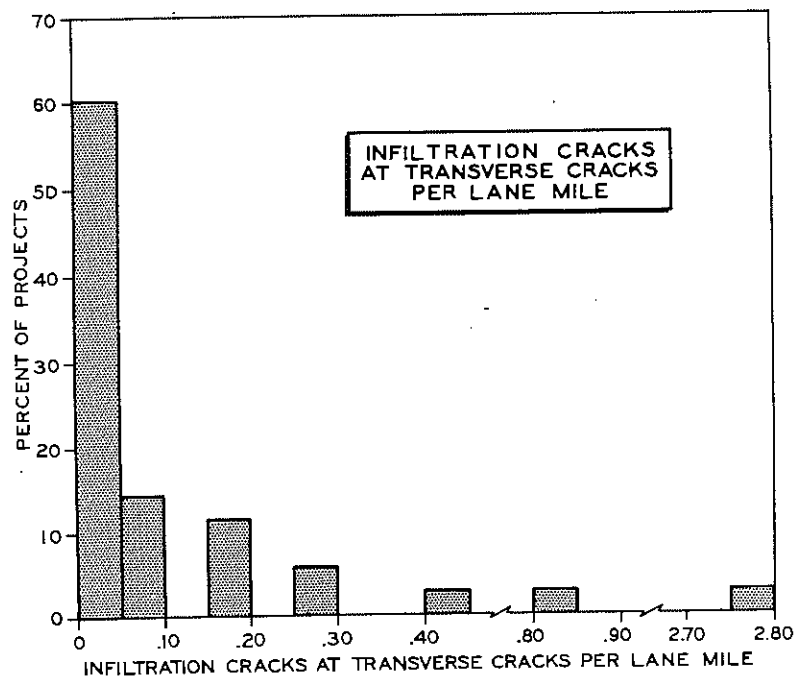


Figure 31. Histogram of infiltration cracks for all two-lane projects; 15 years of service.

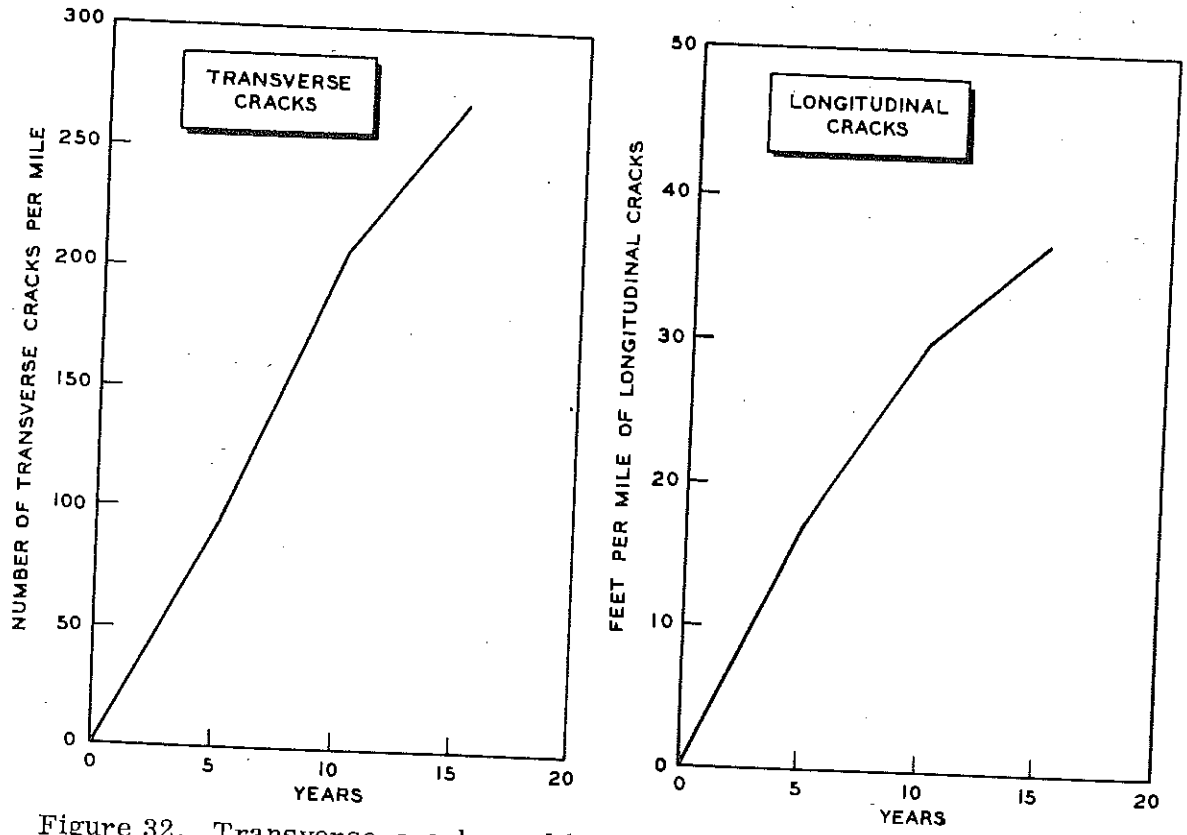


Figure 32. Transverse cracks and longitudinal cracks per mile of two-lane pavement, based on 28 projects with 5, 10, and 15 years of service.

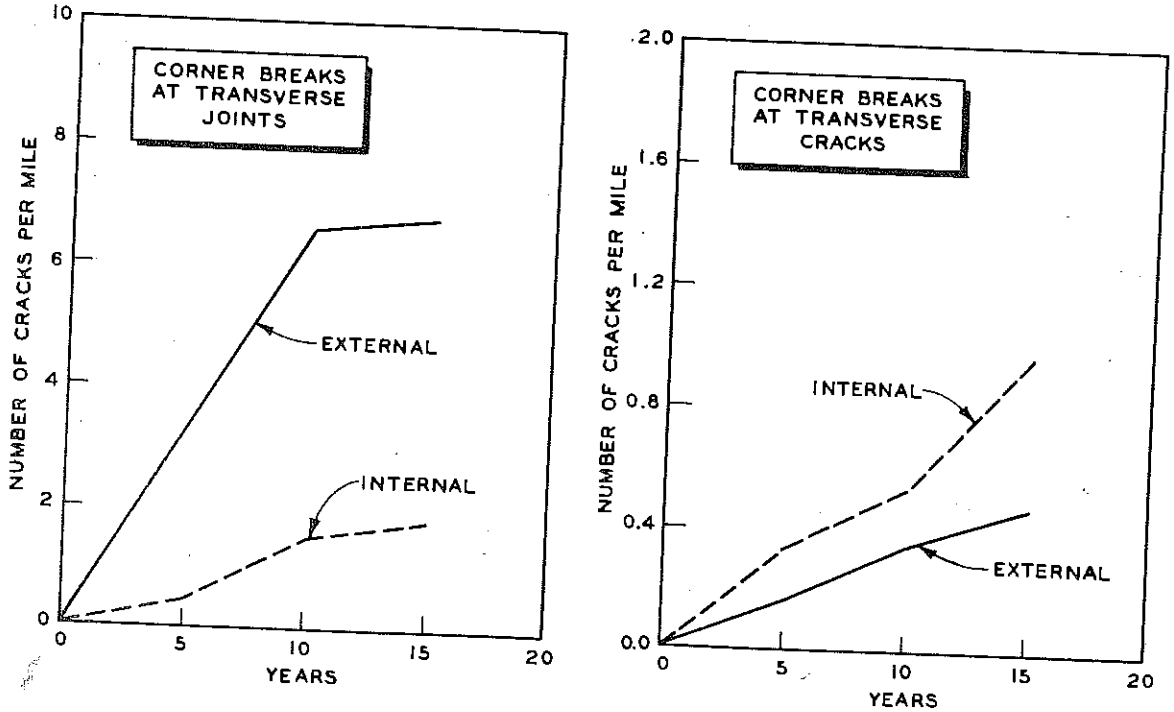


Figure 33. Number of corner breaks per mile of two-lane pavement. This was based on 28 projects, with service checks taken at 5, 10, and 15 years.

Progressive Deterioration

From the condition surveys available for this study it was decided that a study of performance after ten and fifteen years of service would be most rewarding. However, five-year service records were also available for study. In order to determine the rate of change over the fifteen years of service, it appeared most feasible to study the same projects during this span. Figures 32 through 37 illustrate the average progressive deterioration for various types of pavement distress for 28 construction projects built in 1947, 1948, and 1949. Throughout the service period the average number of transverse cracks for the 28 projects increased rather linearly. Although not shown, it is interesting to note that the poorest project with respect to transverse cracking was the same for all three periods of service.

The rate of increase for longitudinal cracking tends to decrease with time. This might be expected since two primary causes of longitudinal cracking, premature traffic loading and subgrade settlement, have their greatest effect at an earlier age. The progressive nature of corner breaks at transverse joints and transverse cracks is shown in Figure 33. Except for external corner breaks during the ten- to fifteen-year period the increase is generally quite linear. In contrast, spalling at transverse joint corners and at transverse crack corners increases at an increasing rate with service life, with very large increases noted in the ten- to fifteen-year service period (Fig. 34). Spalling at other locations also increases very rapidly in the ten- to fifteen-year service period (Fig. 35).

Another form of pavement distress, joint blowups, shows a rapid and progressive increase during the ten- to fifteen-year period (Fig. 36). However, spalling is an earlier distress phenomenon in the life of the pavement and a blowup is a more mature one. During the first five years, only one project out of 28 had any blowups, but by the end of ten years, 11 projects had blowups, and by fifteen years only four projects had no blowups. For those four projects without blowups, the coarse aggregate came from pits with either high 80-100 percent carbonate or very low 0-20 percent carbonate. However, the project which had a blowup by the end of five years was also the worst performer at the end of fifteen years, showing that the character of a bad performing project is indicated early.

Pavement deterioration, resurfacing due to deterioration, and patching are three more pavement distress conditions which progressively become more severe with time as shown in Figure 37.

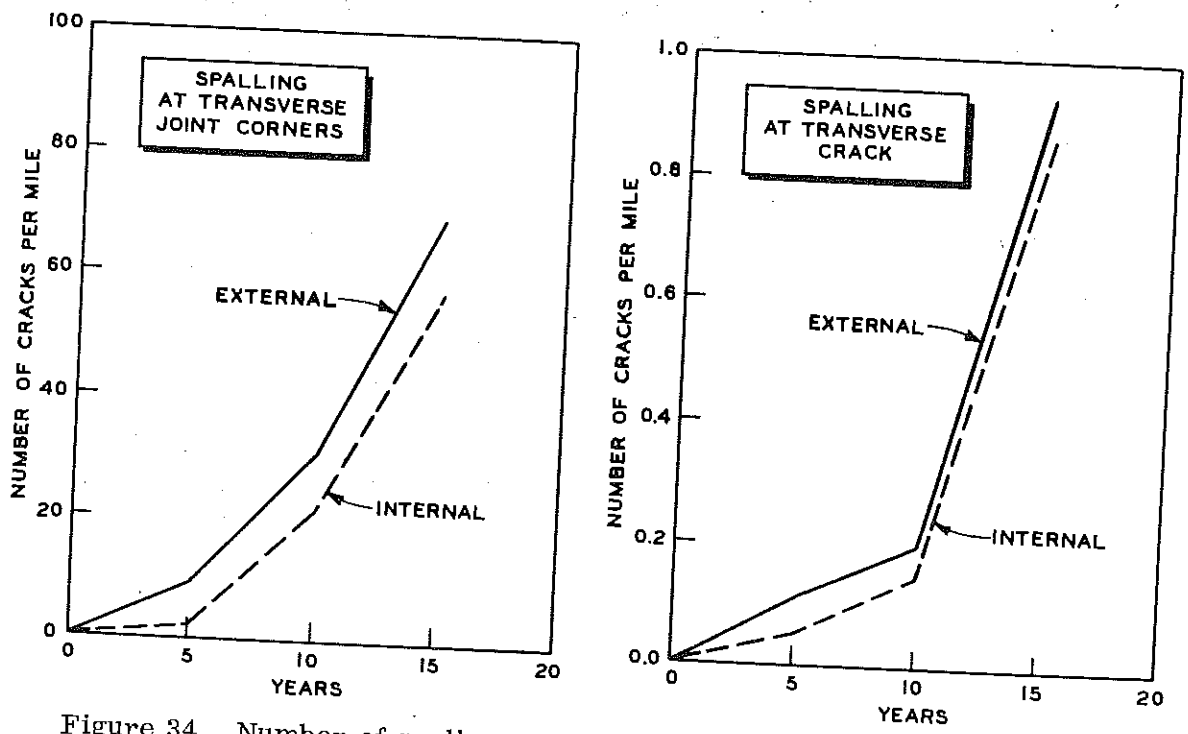


Figure 34. Number of spalls per lane of two-lane pavement, based on 28 projects with service checks at 5, 10, and 15 years.

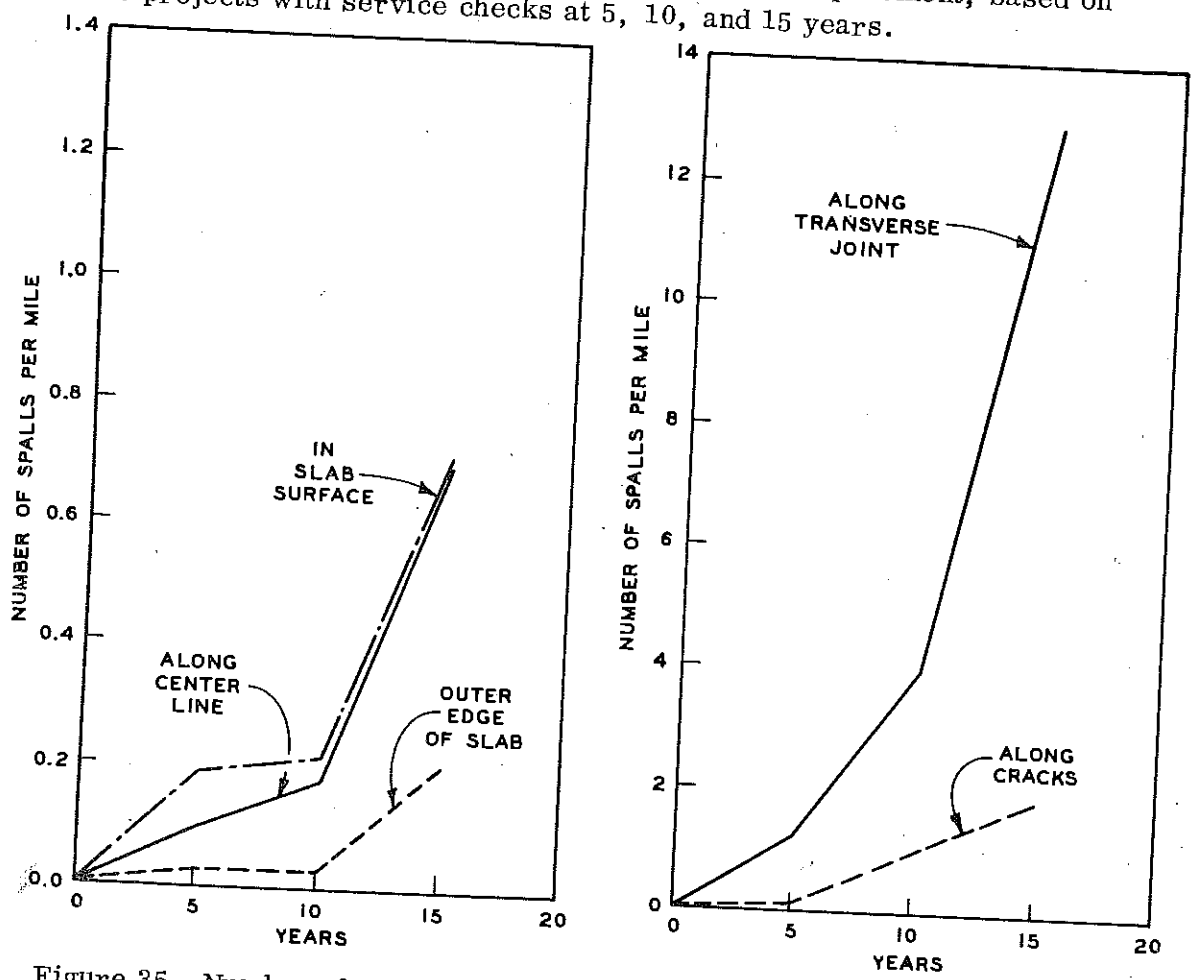


Figure 35. Number of various types of spalling per mile of two-lane pavement, based on 28 projects with service checks at 5, 10, and 15 years.

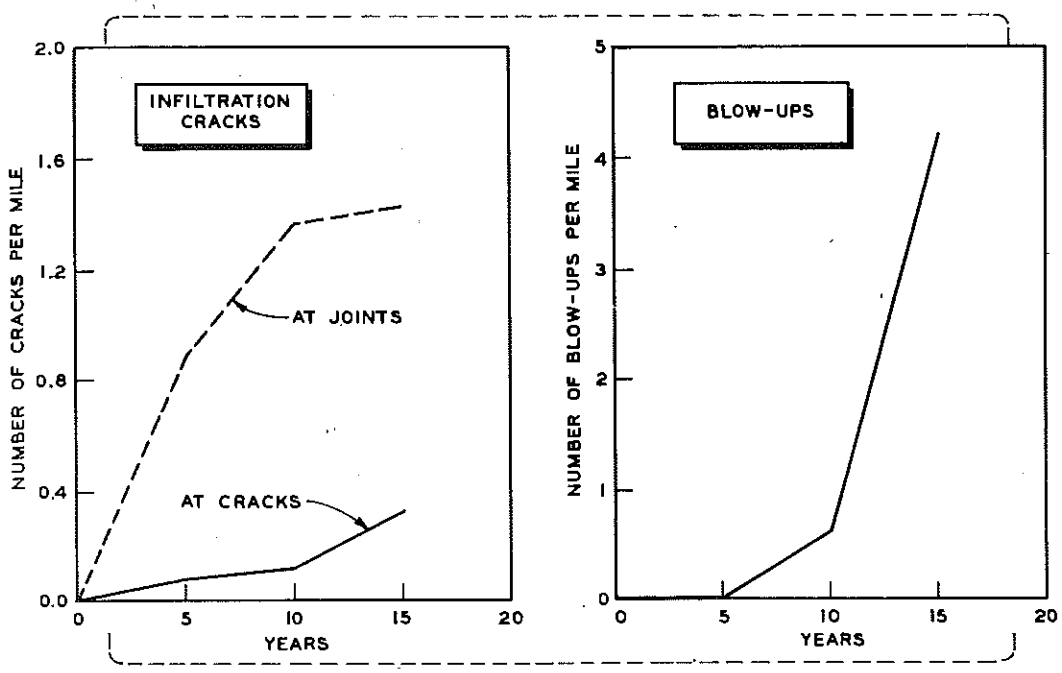


Figure 36. Number of infiltration cracks per mile and number of blowups per mile of two-lane pavement, based on 28 projects after 5, 10, and 15 years of service.

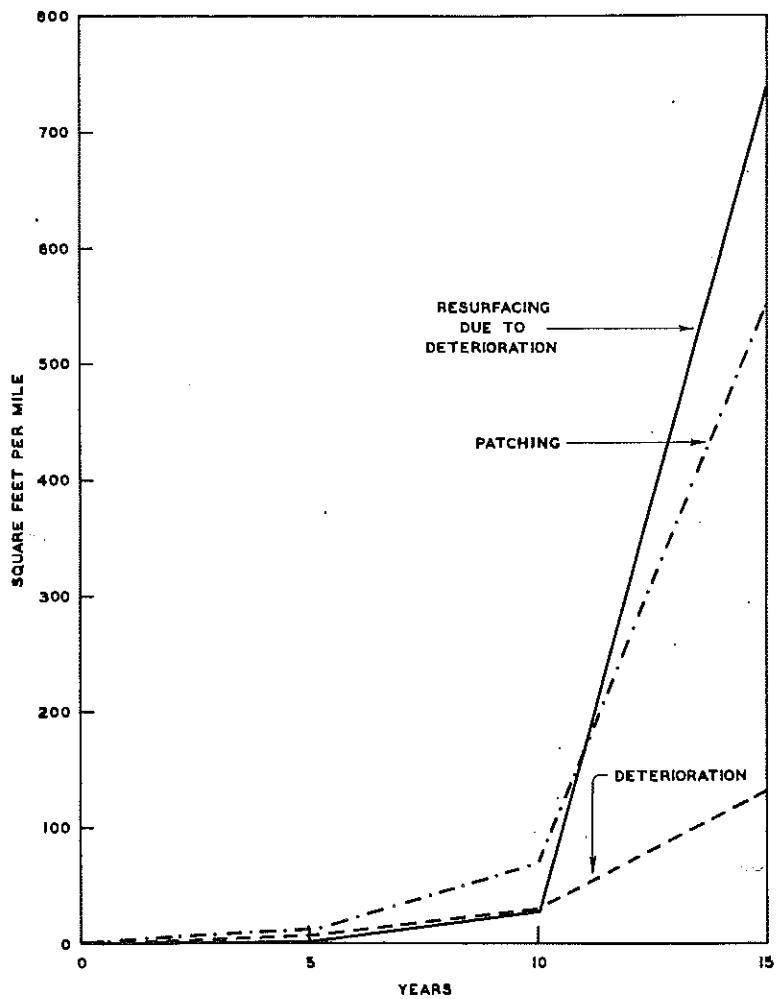


Figure 37. Resurfacing due to deterioration and patching based on 28 projects of two-lane pavement with service checks at 5, 10, and 15 years.

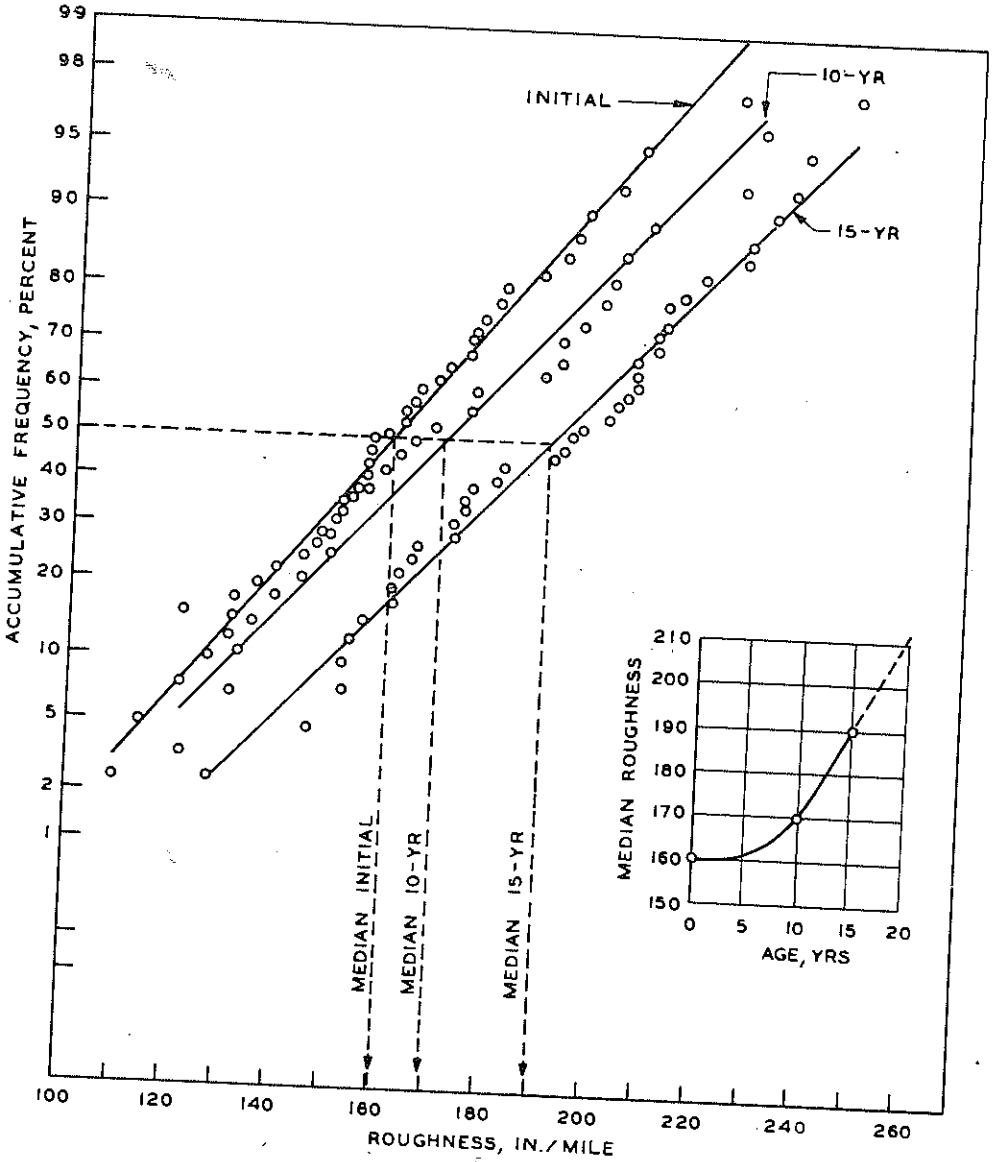


Figure 38. Progressive roughness increase with service.

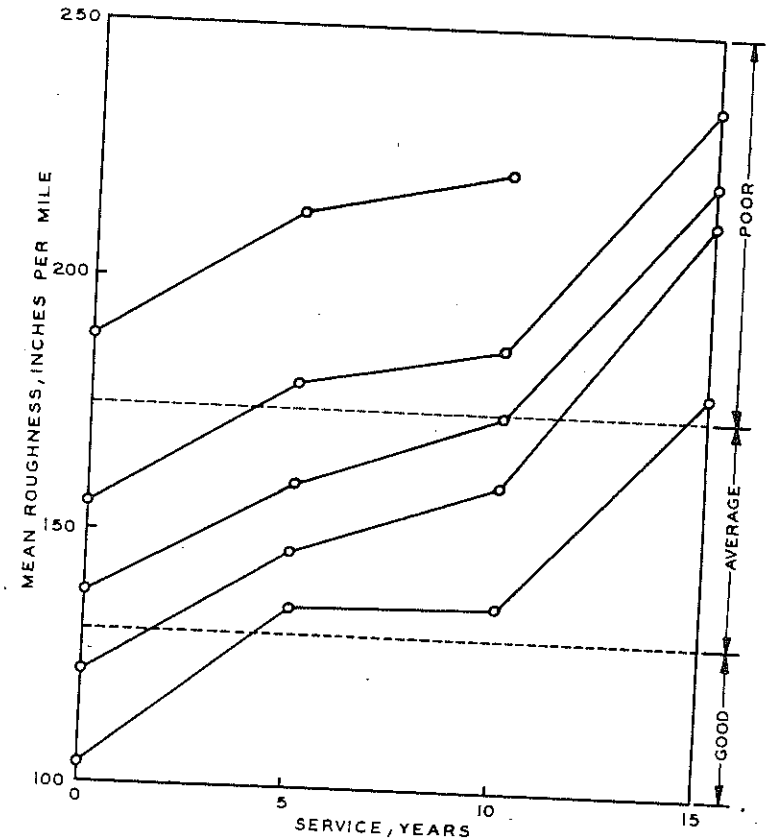


Figure 39. Progressive increase in roughness with service for five initial roughness categories.

Roughness

In addition to the specific survey variables described earlier, measurements of roughness were obtained for a number of projects when completed, and at one or more of the service periods of five, ten, or fifteen years. From one point of view, roughness may be considered as a summary of the information found in the other survey variables. A pronounced degree of deterioration as expressed in almost any of the condition survey variables could conceivably be reflected in roughness as measured by the Michigan roughometer. However, the usefulness of roughness as a general measure of performance is greatly diminished by the extreme variation of initial values. To be sure, if initial roughness were more uniform, this might possibly be used to measure structural deterioration. Michigan's experience, however, precludes this use, as shown in Figure 38. These cumulative frequency distributions show that initial roughness varies across almost the entire range of values obtained after ten and fifteen years of service. Many fifteen-year old pavements are smoother than many new pavements. The conclusion from Figure 38 is inescapable--a project's "roughness" depends more on its initial profile than its age or service. Only the median performance can be used to indicate roughness increase with service, where the median roughness for these projects with initial ten- and fifteen-year roughness surveys increased only 10 in. the first ten years of service and 20 in. the next five years. However, the overall variability of roughness values at each survey level is too large to permit the use of roughness as a research tool.

Considering roughness by itself, and bearing in mind its extreme variability, one can make some very crude comparisons. Figure 39 shows the progression of mean roughness for five arbitrary categories of initial values to the final fifteen-year determination. The general form of each curve suggests a plateau in the five- to ten-year range. Again it must be stressed that the values presented are averages and, consequently, represent general trends.

The differences in the rate of roughness increase may be attributed to the rate of increase of several condition survey performance variables. The more rapid increase in the first five years may be due to minor settlement which may or may not require mud-jacking. During the five- to ten-year period the roughness increase is less rapid but increases more rapidly in the ten- to fifteen-year period which correlates with the more rapid increase in pavement deterioration as reflected by a large increase in spalling, patching, blowups, and surface deterioration.

GENERAL PERFORMANCE PHILOSOPHY: THE NEED FOR A STRUCTURAL INDEX

It is often found that basic field or research variables are not directly and simply related to the property for which causal information is sought. The information contained in each basic variable may be totally lost because of the influence of other variables either not measured or controlled. Under these conditions, the use of a general index may be helpful. General indices are designed to amplify the desired information weakly expressed in the more basic and specific field variables. By a suitable weighting of these highly specific variables, it is hoped that an index can be constructed that will serve as a more powerful research tool in the investigation of more general properties. The structural performance of highways is an example of this problem: each condition survey variable measures a particular type of pavement distress, and therefore is not a complete measure of overall structural performance. In short, structural performance is a concept we cannot physically measure directly, but would like to define.

The manner in which condition survey variables are used in performance definition depends on the kind of performance considered important, as well as the methodological preferences of the investigator. Thus, there can be considerable disagreement concerning the proper formulation and use of these composite variables. Nevertheless, the simplicity and utility of a single, overall performance index justifies most any approach, provided its composition and assumptions are in clear view.

A pavement structural performance index can be used for the following purposes:

1. To summarize the essential information contained in the condition survey variables, thereby effecting a simplified measure of performance. While the index equation may be complex (i.e., some linear equation of the condition survey variables), once it is calculated, the structural performance of a length of highway is characterized by only one figure rather than a dozen or more.

2. To serve as a convenient tool in the search for possible "causes" of structural deterioration.

3. To anticipate the pavement's ability to continue in service.

4. To indicate the need for maintenance or improvements to forestall excessive deterioration.

Each condition survey variable is unique, and ideally could be uniquely associated with the relevant variables of design, materials, construction, or environment provided they were all known and measured with precision at the proper time. Because this amount and quality of information is usually not available, it is expedient to take the view that most condition survey variables express varying degrees of the same information, and this redundancy makes the complicated, tedious, and probably impossible consideration of each variable by itself unnecessary.

While indices can be computed for almost any length of pavement, computations for this study are for complete construction projects. Thus, the computed performance is considered general, in that it pertains to an entire project and not to a smaller subsection. This is not to say that short stretches of light or excessive deterioration associated with local conditions such as subbase, drainage, joint construction, etc., are of no interest. These factors, while affecting the general index, may not be linked with the overall conditions such as climate, materials, traffic, etc., set aside as possible determinents of performance. Consequently, these stretches are best investigated by the "case history" approach where all relevant local conditions are examined in depth. To this end, general performance indices conceivably may be used to spot extremes of deterioration, thereby reducing the number of projects requiring intensive investigation.

Performance indices used to measure highway structural deterioration[1] will display the same advantages and shortcomings encountered with their use in other areas of research. If one wishes to measure standard of living, economic activity, intelligence, or cardiac condition, he must decide on some abstract criterion of indirect measurement. What one usually finds available are many direct and specific measures, no one of which uniquely expresses the more general property subject to definition. Notwithstanding each measure's uniqueness, there is often good reason to relate these variables to the fundamental, more general property, with the presumed degree of relationship determining each variable's ultimate influence on the overall criterion.

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[1] Performance is generally considered to be a positive concept, and deterioration its polar opposite. The emphasis of this paper will be on the negative of performance, i.e., deterioration.

Subjective Rating Approach

The measurement of many highway properties should depend on subjective evaluations. These include aesthetic appeal, rideability, and even structural condition. In these cases a value judgment will be required that will not be identically made by all individuals. The AASHO Road Test, PSR (Present Serviceability Rating) is a case in point. Using a graphic rating scale of 1 to 5, professional and lay panels judged the general "serviceability" of a variety of pavements. By including persons of varying backgrounds on the lay panel, it was hoped that a stable evaluation approximating that of the general public could be produced by the averaging of individual responses. While an index so designed could be used for a variety of purposes (e.g., design or materials research) there are several disadvantages which limit its usefulness:[2] 1) no overt attempt was made to emphasize the relative seriousness of the various types of structural deterioration, and 2) it appears that both lay and professional panels are strongly influenced by longitudinal roughness; a highway property imperfectly correlated with structural condition.

In the Michigan study, it was considered worthwhile to design a rating index that would take into account the differential importance of the several survey variables. Admittedly, these differences are largely subjective--based on the professional judgment of an individual engineer. However, such an approach has the advantage of recording important conditions that may not enter into panel evaluations. Even if these conditions do not critically affect public acceptance at the time of rating, they may portend more serious deterioration and result in premature failure.

Subjective Rating Model

The form of this equation developed from a desired range of 0 to 10, with zero indicating a very poor pavement condition and 10 a perfect condition. All types of pavement deterioration obtained by condition surveys subtract from the perfect condition. Thus, it was a matter of subjective judgement to determine if a certain amount of longitudinal cracking was comparable in reducing the Performance Rating Factor (PRF) with another amount of deterioration, say, corner breaks or joint spalling. From the outset it was determined that the magnitude in the PRF reduction for one type of deterioration must be limited by an arbitrary maximum limit. The coefficients assigned to each term in the equation below do not directly represent weighting factors, influenced by the seriousness of the type of deterioration, but are a combination of this judgement factor and a scaling

[2] A complete list of problems with the PSI as seen from the psychological scaling view point can be found in reference (1).

factor to bring the various units of measurement (percent or average number) into a logical relationship.

The original intuitive equation (Model 1) was developed on the basis of pavement evaluation experience and with only a general review of the observed range in performance for each of the measured variables which collectively compose the rating. To study and adjust the coefficients and the maximum limits for each type of deterioration, 30 construction projects were used which had service records for five-, ten-, and fifteen-year periods. The distribution of the PRF values for these projects were studied as well as the changes in the distribution with service life.

$$PRF = 10 - A\,[a_1\,(TC) + a_2\,(LC) + a_3\,(CB) + a_4\,(SP) + a_5\,(BU) + a_6\,(PT) + a_7\,(MJ) + a_8\,(RS) + a_9\,(SC) + a_{10}\,(DT)]$$

where:

TC = average number of transverse cracks per slab

LC = percent of linear length of pavement with longitudinal cracking

CB = average number of corner breaks (exterior and interior) per mile of equivalent two-lane pavement

SP = average number of spalls per mile of equivalent two-lane pavement (This includes all spalls along transverse joints, longitudinal joints, cracks, or the interior of the slab.)

BU = percent of joints with blowups

PT = percent of pavement area with patches or structural replacement

MJ = percent of pavement area where mud-jacking was required

RS = percent of pavement area that had been resurfaced

SC = percent of pavement surface area with scaling

DT = percent of pavement surface area showing disintegration

MODEL 1			FINAL MODEL		
A =	1.0		A =	0.8	
a_1 =	1.0	TC term limited to max. of 4.0	a_1 =	1.00	TC term limited to max. of 5.0
a_2 =	0.25	LC term limited to max. of 1.0	a_2 =	0.060	LC term limited to max. of 1.5
a_3 =	0.25	CB term limited to max. of 0.5	a_3 =	0.04	CB term limited to max. of 1.0
a_4 =	0.03	SP term limited to max. of 2.5	a_4 =	0.008	SP term limited to max. of 2.0
a_5 =	0.015	BU term limited to max. of 1.0	a_5 =	0.08	BU term limited to max. of 2.0
a_6 =	0.60	PT term limited to max. of 2.5	a_6 =	2.5	PT term limited to max. of 2.5
a_7 =	0.30	MJ term limited to max. of 1.5	a_7 =	0.40	MJ term limited to max. of 2.0
a_8 =	0.20	RS term limited to max. of 4.0	a_8 =	0.10	RS term limited to max. of 10.0
a_9 =	0.10	SC term limited to max. of 1.0	a_9 =	0	SC term limited to max. of 0
a_{10} =	0.60	DT term limited to max. of 1.0	a_{10} =	4.00	DT term limited to max. of 2.0

Five models were tried, four of these were of the form shown above and the fifth used the log values of the terms representing deterioration in the equation. It should be noted that pavement scaling as a term in the rating was dropped in the final equation. This final model equation for the Performance Rating Factor was used as a single measure of project performance in various studies and analysis in later parts of this report.

Objective Rating Approach

In contrast with the AASHO Road Test's PSR (and therefore PSI) and PRF, an attempt will be made in this paper to devise a structural performance rating index on "objective" rather than "subjective" grounds (2). The technique of factor analysis (3) does not utilize either the differential subjective importance of the survey variables, nor public or professional subjective evaluation of serviceability. Rather, the empirical intercorrelations found among the survey variables provide the only basis for a performance equation. The key methodological assumption is that if the survey variables linearly measure in varying degrees general structural performance, they will be intercorrelated accordingly. The degree to which a

given variable is correlated with the others in a group reflects the extent to which it expresses the "common" performance characteristic. Because this method of performance fabrication does not utilize any form of subjective evaluation its chief contribution is in delineating basic, non-judgmental categories of pavement deterioration which simplify the search for assignable causes. For the present study, the survey variables are "reduced" first to a single, more general category of performance (deterioration) from which is developed a single performance index. While more specific categories can be subsequently extracted, their generality will decrease and they will account for diminishing amounts of survey variable intercorrelation.

By stressing the subjective aspect of performance, the PSI and PRF approaches could weight the survey variables disproportionately to the effects of the underlying "causes" of structural distress. While the same argument could be advanced against an index derived from factor analysis, one should remember that statistical association provides the investigator with a necessary, though not sufficient, condition for the assumption of "casual" relationship. The association assumed by the factor analysis approach is simple linear correlation.

Another advantage of "objective" rating is that the sets of intercorrelations for the five-, ten-, and fifteen-year survey periods can be considered separately. Consequently, the changing pattern of intercorrelations reflecting the evolutionary or retrogressive importance of each variable in respect to the underlying causes of deterioration can be acknowledge in different rating equations for each survey period. This is not usually possible with any of the subjective approaches. Both the PRF and PSI equations are invariant with time, thereby disallowing corrections for changes in each variable's relationship to general performance or to the underlying system of causes. On the other hand, there are occasions when strict continuity of performance is desirable, requiring a uniform performance measure. PRF and PSI can be computed at any time in a project's life and, taken sequentially, can provide a historical record of performance. Consequently, projects can be compared on the basis of their performance time histories. This latter advantage was considered important, and the present analysis was conducted accordingly using a single performance equation for all survey periods. The various types of indices are compared in Table 1 and Figure 40.

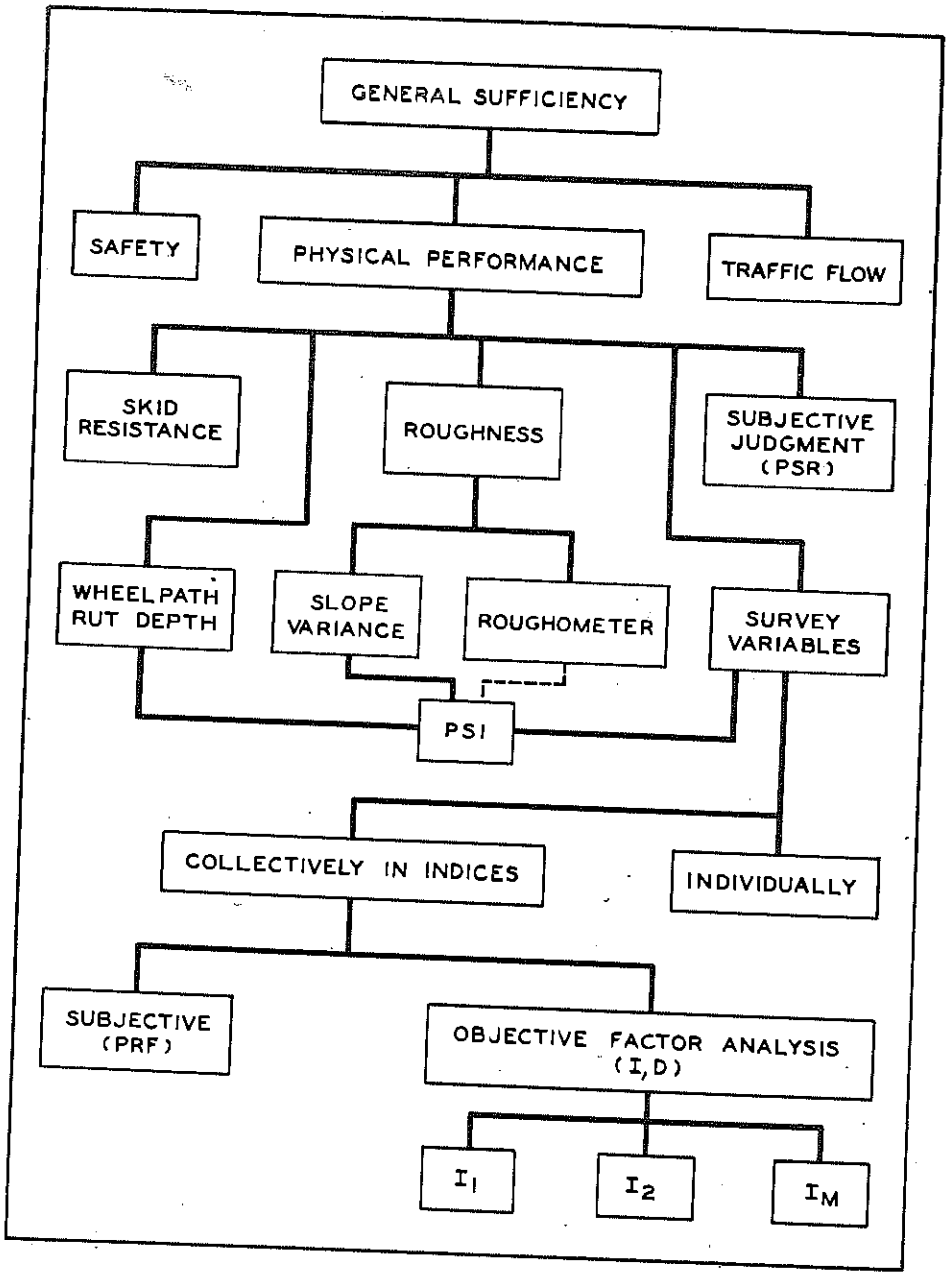

Figure 40. Alternative methods of rating pavement performance.

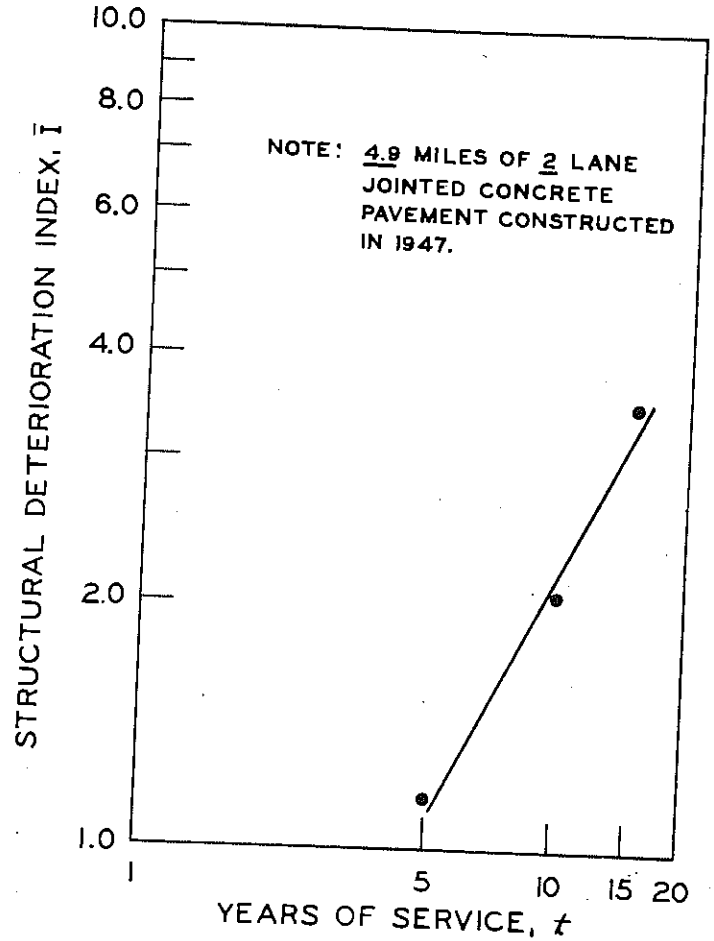

Figure 41. Time index history for construction project 17-7-66.

Objective Rating Model

The principal axis method of factor analysis based on the survey variable intercorrelation matrix yielded the following structural deterioration index (I):

$$I = [\,.004\ (LC) + .005\ (TC) + .006\ (D) + .106\ (BU) + .011(CBJ) + .410\ (CBTC) + .013\ (SJ) + .359\ (STC) + .043\ (SE)\,] \ldots\ldots \quad (1)$$

where:

LC	=	longitudinal cracks per mile
TC	=	transverse cracks per mile
D	=	disintegration in square feet per mile
BU	=	blowups per mile
CBJ	=	corner breaks at transverse joints per mile
CBTC	=	corner breaks at transverse cracks per mile
SJ	=	spalls at transverse joints per mile
STC	=	spalls at transverse cracks per mile
RS	=	remaining spalls per mile

While a pavement in perfect structural condition would have an index value of zero, there is no limit to the degree of deterioration measurable with the scale. Unlike the PSI, the structural index has ratio scale status, and therefore can be mathematically manipulated without attention to scaling assumptions.

Index values can be computed for any year for which a condition survey is available. Substitution of a series of surveys taken during a project's service life, in equation (1), will show the structural deterioration trend as well as the project's relative condition at any service period. Figure 41

shows the structural deterioration index history for a project for which the five-, ten-, and fifteen-year surveys are available. It is characteristic of this project, and others in general, that the index history plot is nearly linear when plotted on log-log coordinates. Therefore, it is assumed that a close approximation to the index history could be made with the following power function:

$$\log \hat{I} = A \log t + \log B \qquad \text{or}$$

$$\hat{I} = Bt^{A} \qquad \text{(2)}$$

where:

$\hat{I}$ = structural deterioration index estimate

t = service time in years

A, B = fitting constants unique to each project, and determined by least squares

TABLE 1
PROPERTIES OF VARIOUS PERFORMANCE INDICES

Property	Present Serviceability Index (PSI)	Performance Rating Factor (PRF)	Structural Deterioration Index * (I)	Structural Depreciation Index (D)
Based on Engineering Judgement as to Seriousness of Deterioration	No	Yes	No	No
Based on Public Evaluation of Serviceability	Yes	No	No	No
Allows Rating of Progressive Deterioration	Yes	Yes	Yes	Yes
Coefficient Weights Proportional to Intercorrelation	----	No	Yes	Yes
Allows for Separate Indices for Different Types of Deterioration	No	No	Yes	Yes
Unique-Not Dependent on Investigator	Yes	No	Yes/No*	Yes/No*

* The approach is unique if each investigator uses the same mathematical techniques. However, there is a variety of approaches with variety of solutions.

The structural deterioration index I, and its estimate $\hat{I}$, can be computed by equations (1) and (2) for any specific time, t. However, condition at a point in time is generally of minor interest; one usually wishes information on the rate of deterioration so that performance can be evaluated. In the present case, the negative of performance will be called "depreciation." To evaluate total depreciation, D, over each project's service life, deterioration was summed over time as follows:

$$d\hat{D} = \hat{I}\,dt = Bt^{A}\,dt \qquad \text{and}$$

$$\hat{D}_T = B\int_0^T t^A\,dt = \frac{B}{A+1}\,T^{A+1} \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (3)$$

where:

$\hat{D}_T$ = estimate of structural depreciation from time of construction to terminal rating

T = elapsed time in years to terminal rating

Using equation (3) one can evaluate each pavement's structural depreciation from construction to any time up to fifteen years.[3]

The structural depreciation index, D, accomplishes first the pooling of correlated information (survey variables) on deterioration into a time-dependent measure of pavement condition, and second, the summarization of deterioration over service life. Thus, the deterioration index I, and the depreciation index D, provide single measures of negative structural condition and performance, respectively. It was hoped that these very general measures would facilitate the search for associated materials, environment, and construction variables.

Certain fundamental properties of the three performance indices previously discussed are compared in Table 1. In the development and use of performance rating indices, and before attempting to select one of these indices to compare with material and construction variables in a cause and effect relationship, it is of interest to determine if these different factors correlate. Thirty projects with fifteen years of service and 55 projects

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[3] Survey data beyond fifteen years were not available; therefore, equation (2) can be applied only to this period.

with ten years of service were compared on the basis of PRF and PSI values. The values of PRF varied from 1.75 to 9.1 for fifteen-year projects and from 4.8 to 9.7 for ten-year projects. Corresponding values of PSI were from 2.1 to 3.7 and 2.0 to 3.8, respectively. Although the graphs are not shown, the resulting scatter of points for each service period was so broad that it was apparent no correlation of these two rating methods was possible. This is not unexpected for, as discussed previously, these rating systems are measuring different aspects of performance: the one physical indications of pavement deterioration and the other, primarily, roughness.