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Pavement Performance

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Contents

Types and Causes of Failure in Highway Pavements

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● A DESCRIPTION or discussion of failures in highway pavements presents some difficulty because in many cases there is no agreement on terminology; furthermore, the same type of distress may be variously described by engineers in different areas of the country and in different engineering organizations. Among those who use language for communication, engineers are not the most meticulous in their choice of terms, and it is at times difficult clearly to understand just what is being discussed. In addition to the use of different phrases and expressions to describe types of pavement construction and types of failure, there is lack of distinction between "failure" and the evidence of some condition that makes the pavement less than perfect. It appears that there is a too prevalent tendency to use the one word "failure" to describe all manner of phenomena, some of which are, strictly speaking, not failures at all and may be only warnings of possible future adverse developments, or may be nothing more than a minor defect. For example, pumping of water through the joints in concrete pavements is generally viewed with alarm, but if this never progressed beyond the pumping of water, there should be little cause for concern. The same may be said of many forms of cracking in pavements of all types. It is certainly a moot question whether or not a crack in any type of pavement should be regarded as a failure. It often seems that if a crack is placed in a concrete pavement by the engineer, that is "design," but if the pavement cracks where it wants to, that is a failure, although the traveling public may use the road with satisfaction for years without being aware of such fine distinctions. In any event, it seems that some grouping and classification of so-called failures is necessary for discussion purposes.

The types of pavement distress are first logically divided into two primary groups, depending upon the type of pavement. Certain characteristic defects develop in asphaltic pavements and others are typical of portland cement concrete types. It also appears that there is a greater variety in the distress patterns developed in bituminous pavements compared to portland cement concrete. This is partly attributable to the fact that there are a great many more variations and varieties of bituminous types of road surfacing. Also, under-design is far more frequent in the "flexible" types, prompted by the urge for economy in first costs.

Considering the bituminous or so-called flexible types first, failures may be grouped under three headings depending upon the primary cause or source of the trouble. First, are the types of failure or unsatisfactory performance that are attributable solely to the quality of the pavement itself. Deficiencies of this type may be in the form of stripping, raveling, disintegration, cracking and instability (or plastic distortion) of the road surface which may develop regardless of foundation support. The second group is represented by several manifestations but represents only one type of failure; that is, slippage caused by lack of bond between the top course of the pavement and the underlying leveling course or base layer. In the third group are the pavement failures attributable to deficiencies in the base or the underlying support. Chart A is an attempt to classify failures characteristic of bituminous pavements. This chart separates the failures into those caused by qualities of the surface layer alone, those that are due to improper relationship between the surface course and the next layer, and finally those that are chargeable solely to weak, yielding or unstable foundations. Chart B (see "Concrete Pavements") represents a similar arrangement of the failures characteristic of concrete pavements.

It is difficult to describe each of these failures clearly so that everyone will recognize the distinguishing characteristics of each. Attempts have been made to secure photographs representing typical examples. The following series have been selected to illustrate the most common types of failure and are shown accompanied with a brief explanation in an attempt to diagnose the cause and to assign reasons for the particular development. Due to space limitations, no detailed discussion of preventive measures or proper maintenance repair has been undertaken.

ANALYTICAL CHART
Classification of Failures in Bituminous Road Surfaces

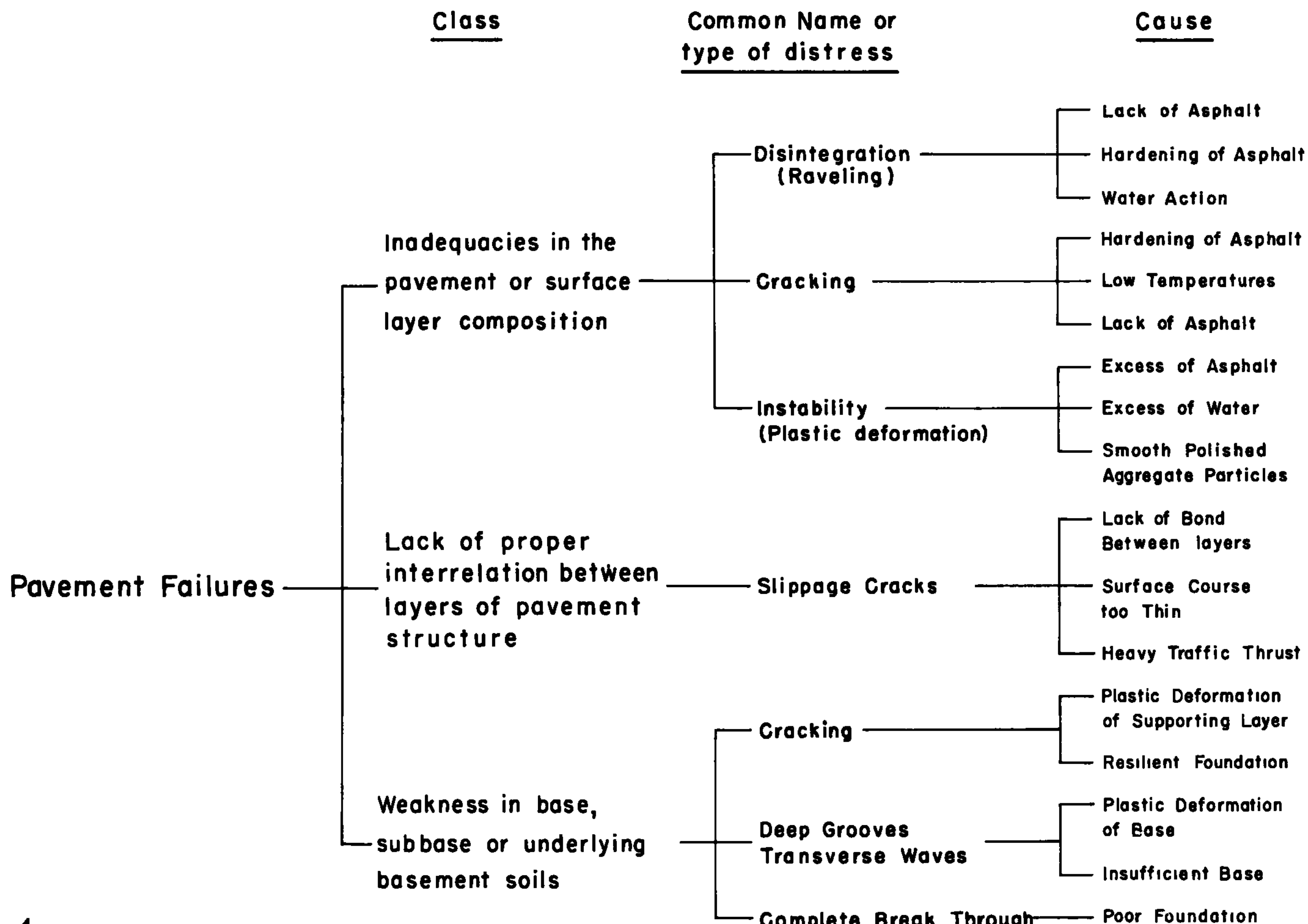


Chart A

BITUMINOUS PAVEMENTS

Failures and Distress

Figures 1 to 12, inclusive, show types of failure or unsatisfactory performance that are attributable solely to the quality of the pavement itself.

Figures 13 to 17, inclusive, show types of distress caused by lack of bond or lack of friction between layers of surface and/or level course or base.

Figures 18 to 36, inclusive, show failures and distress appearing in the surfacing, but primarily due to weakness and instability in the base or underlying soil.

Figure 1. Raveling of a pavement in grooves corresponding to the alternate strips of light and heavy application left by an asphalt distributor.

Cause: Poor adjustment of the distributor sprays causing application in streaks; or insufficient asphalt in the mix to prevent raveling where unprotected by the surface application.

Figure 2. Screenings (or stone chips) whipped off from a seal coat leaving right hand lane almost bare in contrast to the left hand lane which shows good coverage and retention of stone cover.

Cause: Failure of emulsified asphalt binder to dehydrate and set up properly because work was done on right hand side in cold, damp weather.

Figure 3. Disintegration of a level course consisting of hot plant mix using 120-150 pen asphalt.

Cause: Hydrophilic fine material in a mixture subjected to rain shortly after construction. Traffic whipped out fine material leaving the mosaic of coarse aggregate particles.

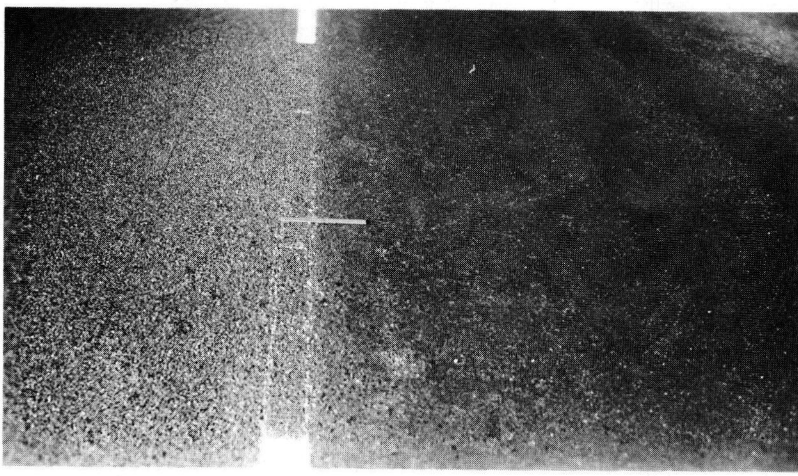


Figure 4. Extensive deterioration of new plant mixed dense graded bituminous surface. Hot mix material with 85-100 pen asphalt.

Cause: Surfacing was spread and compacted with steel tired roller in October but was not open to traffic until a month later and was subjected to a heavy rain and heavy high speed traffic on the opening day before a "traffic seal" could be developed by the pneumatic tires; or aggregate particles were coated with fine clay-like material. Total amount passing No. 200 was within specification limits but material would not pass the Sand Equivalent Test.

Note: Aggregates from same quarry have given no trouble since washing required at plant.

Figure 5. Extensive raveling in oil mix surfacing in the Mojave desert. A dense graded plant mix with SC oil constructed in 1929.

Cause: Insufficient amount of asphalt aggravated by a coating of colloidal clay on all sand grains. An initially high percentage of moisture caused the mix to appear well oiled when first laid down.

Note: Aggregate was hydrophilic and would not have passed the present day Sand Equivalent Test.

Figure 6. Extensive raveling of a dense graded mix using liquid asphalt placed as resurfacing over an existing pavement.

Cause: Insufficient quantity of asphalt in the mix.

Figure 7. Unstable pavement. Deformation evidenced by distortion in traffic stripe. Surface scarred by attempts to blade off the bumps.

Cause: Too much asphalt in the mix.

Figure 8. Somewhat unusual irregular pattern of an unstable road mixed surfacing.

Cause: Primary cause—excess amount of asphalt. Lack of uniformity in pattern of distorted surface probably due to scattered pieces of large stone in the mixture.

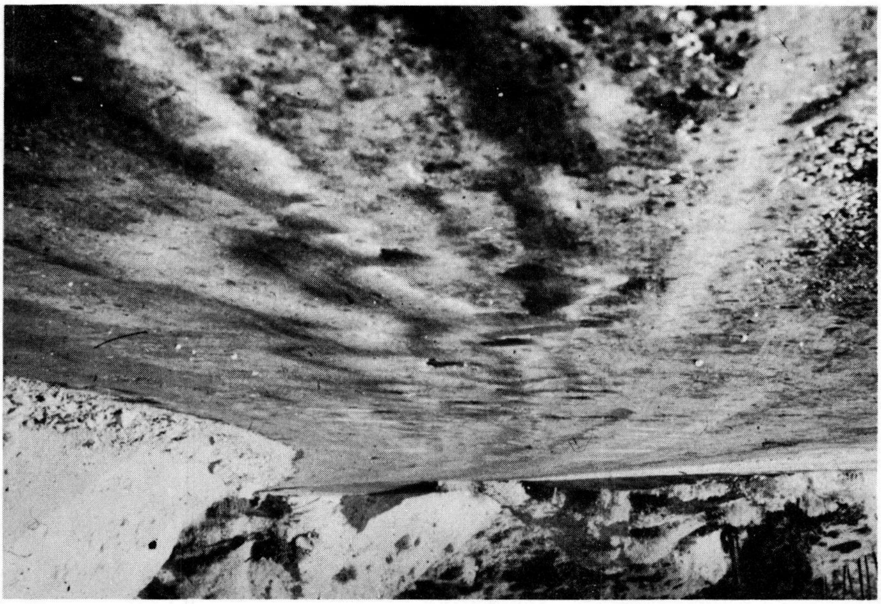


Figure 9. An unstable surface, distortion evidenced by substantial grooving in the wheel path.

Cause: Moisture entering from the subgrade and flushing the relatively liquid asphalt to the surface.

Figure 10. An unusual example of an unstable distorted surface which is also raveling under the action of traffic.

Cause: Same project as Figure 5. Aggregate contained a high percentage of colloidal clay of the montmorillonite type and from 3 percent to 4 percent moisture. The total liquid content of asphalt plus moisture was too high for a stable mix and surface developed transverse waves and grooving under the initial traffic. As moisture on exposed surface was dried out under the hot desert sun, surface began to ravel due to deficiency in amount of binding agent.

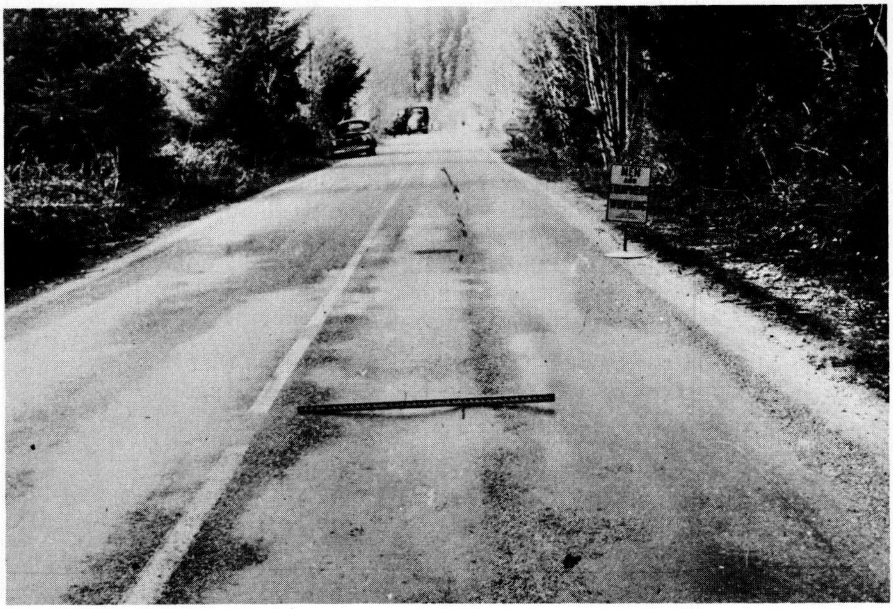


Figure 11. Shrinkage cracks in a sheet asphalt pavement characteristic of mixtures containing a relatively high content of low penetration asphalt and subject to little or no traffic.

Cause: Shrinkage due to the volume change characteristics of the asphalt. Shrinkage cracks are usually distinguished by the primary and secondary sequence of crack formation and by the shape of the polygons which tend to have sharp corners and angles—many of which approach 90 degrees.

Note: Asphalt has about four times the thermal coefficient of expansion of the average stone or sand particle. Such cracks are characteristic of rich mixtures subjected to insufficient traffic to close the cracks and to offset thixotropic hardening.

Figure 12. Another example of shrinkage cracks in a mixture containing coarser aggregates. Even though separated into small blocks, such road surfaces may remain quite smooth with little signs of distortion indicating that the cracking is not caused primarily by poor foundation, or heavy loads.

Cause: Shrinkage and drying out of the mix.

Figure 13. Crescent shaped cracks in a stable surfacing over a sound base.

Note: The larger cracks have been patched.

Cause: Slippage of the surface course on a smooth textured asphalt base or level course. Lack of bond between the two layers frequently caused by a layer of fine dust, moisture or both.

Figure 14. Another example of slippage. Movement of pavement is indicated by distortion in transverse paint stripes. Traffic moves to the left in the far lane and to the right in the lane just beyond the longitudinal stripe.

Cause: Vehicle wheels form a depression however slight in all pavements. Wheels tend to push a wave before the wheel in the direction of travel. Surface may slide if bond is too weak. Braking and deceleration of heavy loads may also cause slippage.

Note: An unstable sand mix may also flow in direction of traffic.

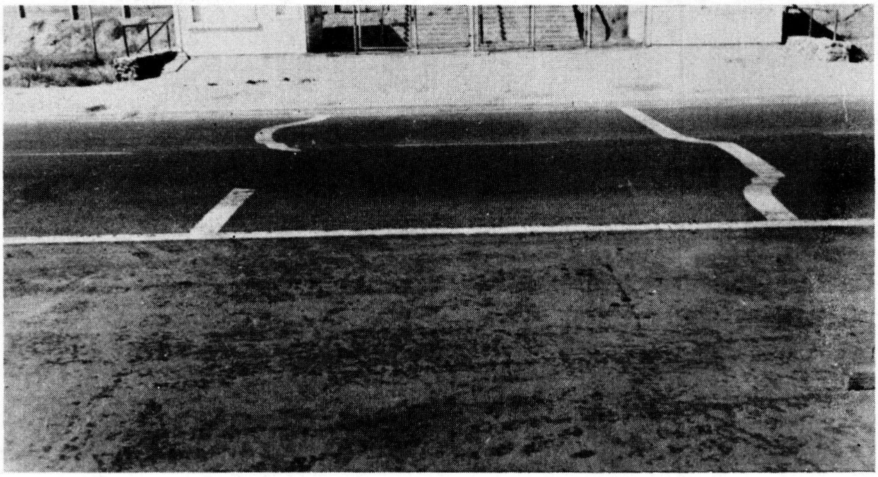
Figure 15. Another example of slippage failure illustrating the lateral movement that frequently occurs where shoulder support is weak or non-existent.

Cause: Primary cause same as for Figure 12.

Note: The thrust is in the direction of travel and toward the low side of the cross-section.

Figure 16. Another example of slippage failure.

Cause: In this case, under heavy truck traffic on a steep downgrade. Loose sandy surface on the cement treated base.



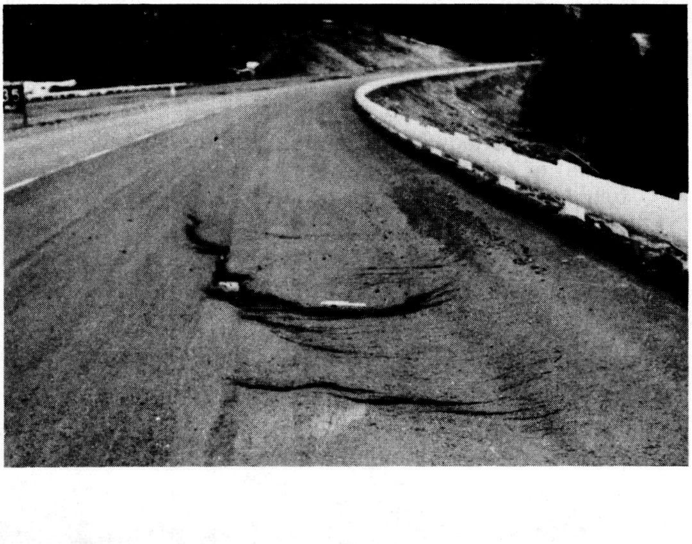


Figure 17. A close-up view of large cracks caused by slippage.

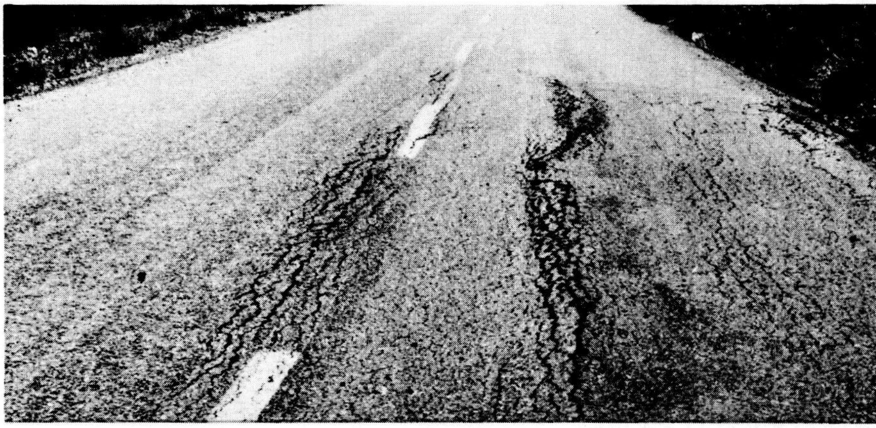
Note: It is useless to seek to prevent this type of failure by changes in the surface mix design or composition.

Figure 18. Depressions in the wheel path and upheavals along-side causing breaking and rupture of the asphalt surfacing.

Cause: An unstable base and poor foundation saturated with water.

Figure 19. Failures in the outer wheel lane on WASHO test track showing depression and breakup of surfacing accompanied by upthrusts of the uncemented granular material on the shoulder.

Cause: Inadequate thickness (for the wheel loads) of pavement and base over plastic foundation soil; or lack of lateral support in shoulder material.



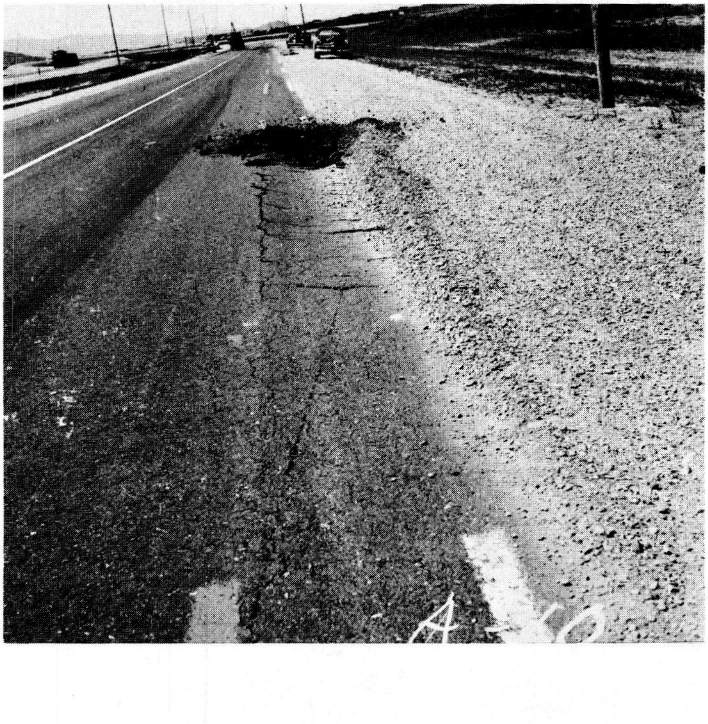


Figure 20. Failure in the wheel path on the Brighton test track.

Cause: Lateral and upward movement of the gravel base which was not sufficiently stable to resist the heavy truck loads on the thin bituminous surface.

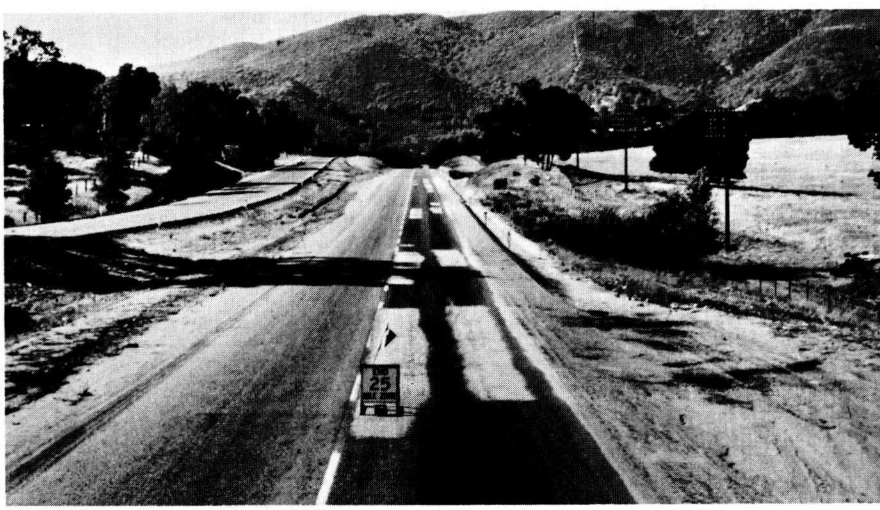
Note: Gravel base had a CBR of 90 at 0.1 in. pen and a "minimum CBR" of 54.

Figure 21. Extensive patches over areas of distress in an outer traffic lane which carries virtually all of the heavy vehicle loads.

Cause: Springy or resilient foundation. Pavement shows high deflection readings under the Benkelman beam; or heavy vehicle loads.

Figure 22. Typical "alligator" type crack pattern characteristic of failures in a stable asphalt pavement when subjected to heavy wheel loads over yielding foundations.

Note: Foundation may be unstable (plastic) or resilient (springy).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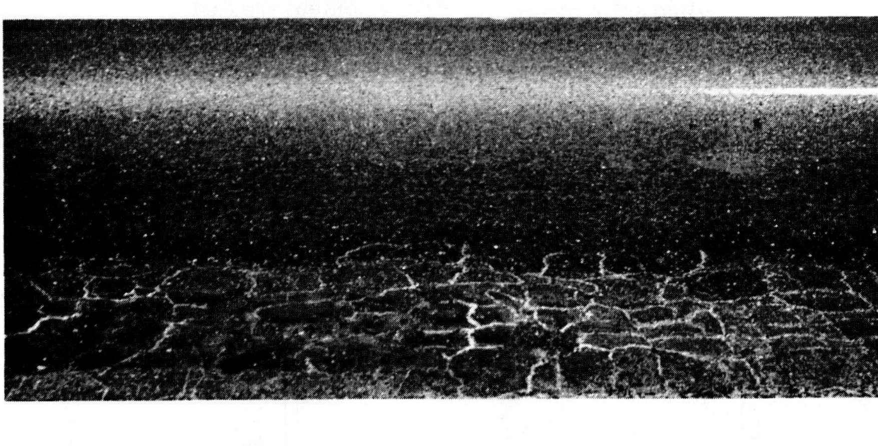


Figure 23. Close-up of an alligator crack pattern in a heavy asphaltic concrete pavement. (4 in. of A.C. over 13 in. of stable granular base and subbase.)

Cause: Springy or resilient soil beneath the subbase; unusually hard and brittle asphalt; or heavy traffic.

Figure 24. Block type cracking in an asphalt surface over a cement treated base.

Cause: Base was of insufficient thickness and strength to sustain the heavy truck loads over a local area of poor basement soil; or heavy truck traffic.

Figure 25. Examples of local spot failures in bituminous surfacing over a cement treated base on a 6 percent grade.

Cause: Water being forced upward through cracks in the base.

Note: Water is standing about 3 in. deep in hole in surfacing.

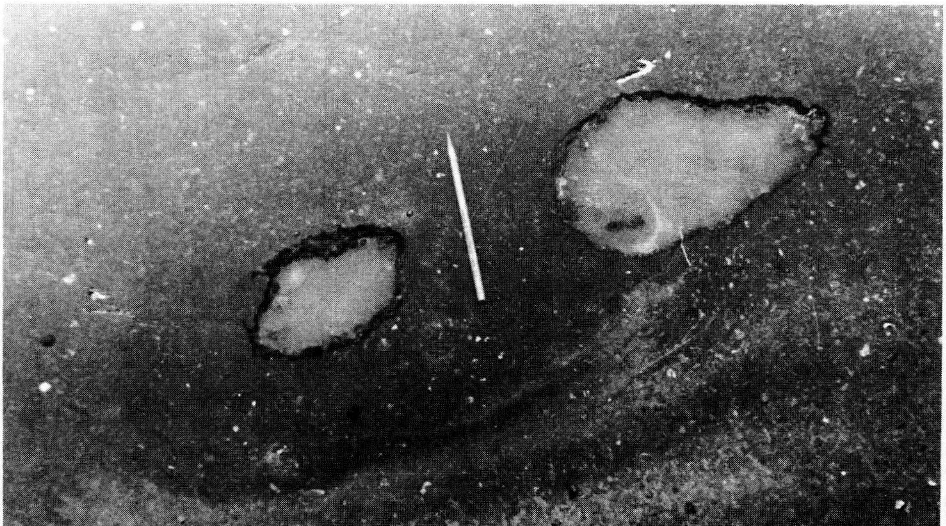


Figure 26. Same as Figure 25. Local failure in a bituminous surface at right of photo.

Note: Water flowing out through a core hole cut through the bituminous surface and cement treated base.

Cause: Water under pressure beneath the base due to impervious soil beneath base and a steep grade with superelevations.

Note: Water pressure actually lifted the base and surface in certain areas.

Figure 27. Longitudinal crack in the outer shoulder parallel to the pavement.

Cause: Fill settlement involving both downward and lateral movement.

Note: No traffic loads on this area.

Figure 28. Longitudinal cracks in the outer traffic lane.

Cause: Deep seated movements involved in fill settlement.

Figure 29. Alligator cracking and extensive distress in a thin bituminous surface over a cement treated base in an arid region subjected to irrigation.

Primary Cause: Alkali attack which weakened and destroyed the slab strength of the cement treated base.

Secondary Cause: Insufficient thickness of surface and weakened base over a poor basement soil.

Figure 30. Wide double cracks near edge of pavement over cement treated base. Surface has been sealed and material in cracks has settled slightly.

Cause: Cracking in a cement treated base which was of insufficient thickness and strength to support heavy traffic over a weak foundation.

Figure 31. Typical crack pattern in a bituminous surface reflecting cracks in a cement treated base.

Cause: Shrinkage of cement treated base.

Note: Cracks in this area are more numerous in the passing lane than in the outer lane that is subjected to heavy traffic. Obviously, this cracking is not due to heavy loads or lack of support.

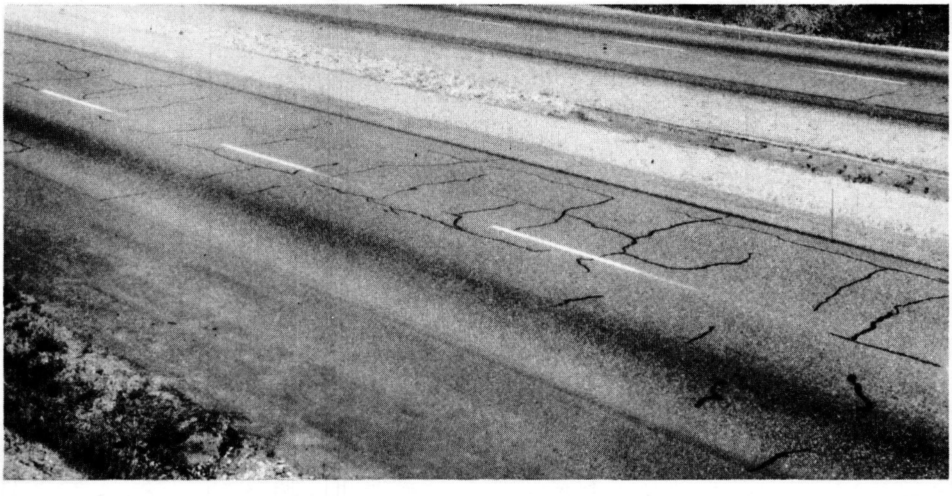
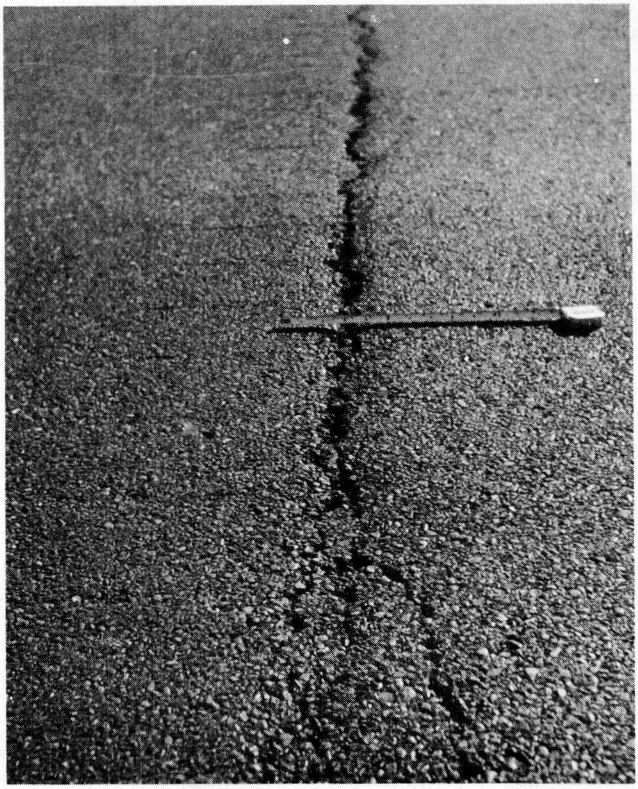


Figure 32. Longitudinal crack in asphalt pavement coinciding with longitudinal construction joint in cement treated base.

Cause: Weak vertical plane created by a juncture of two spreads of cement treated base material. Neither base nor surfacing had sufficient tensile strength to prevent separating along this line. Could be prevented by better construction techniques.

Figure 33. Core from same pavement as shown under Figure 32 showing that crack in the surfacing coincides with wide crack in the base.



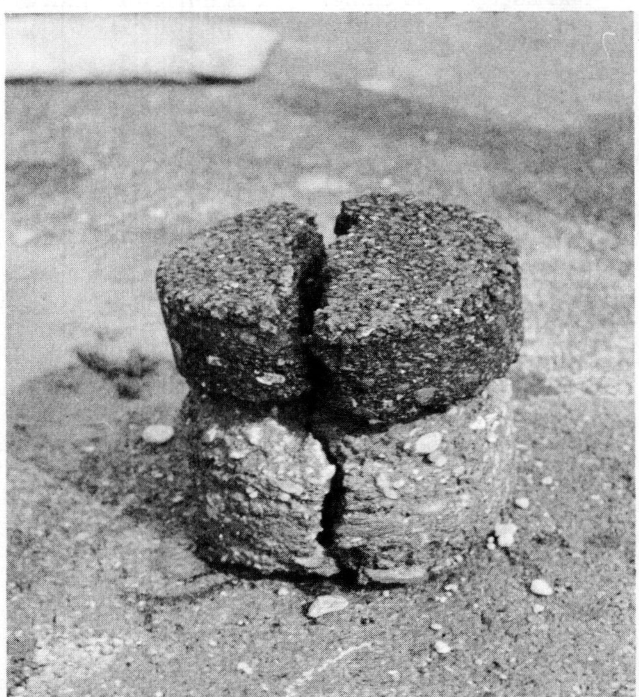


Figure 34. Localized distortion of patching material used to resurface a trench excavation across pavement.

Cause: Unstable mix containing too much asphalt.

Figure 35. Poor repair of a pavement failure.

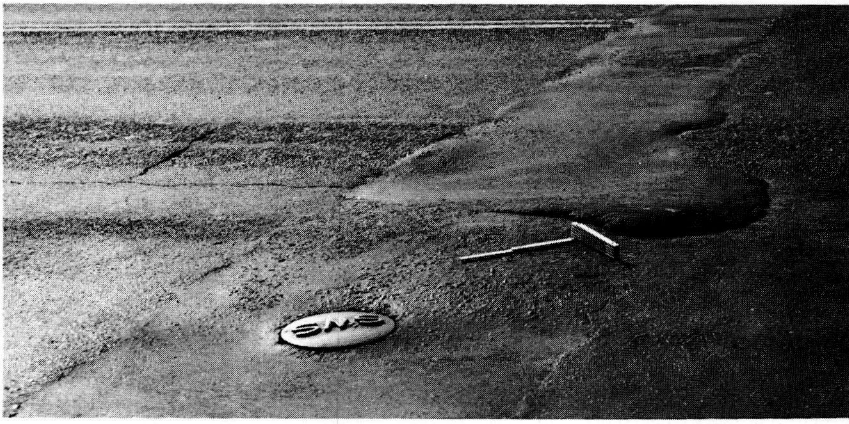
Primary Cause: Trying to correct a base failure with a thin surface patch.

Secondary Cause: Over-rich unstable material used for patching. (An example of an all too common bad maintenance practice.)

Figure 36. A pronounced bump accompanied by cracking of a newly constructed bituminous pavement.

Cause: Localized expansion of subgrade material.

Note: Material was secured from waste piles of a magnesium plant. Expansion developed slowly and was not detected in preliminary tests. See Figures 57 and 58 for effect on concrete pavement.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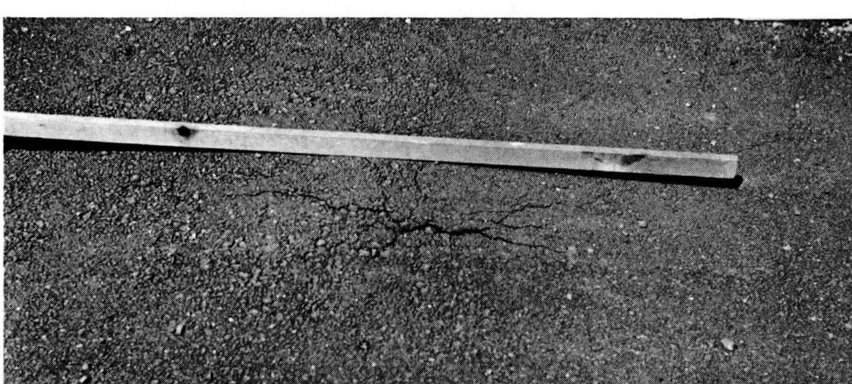


ANALYTICAL CHART

Classification of Failures in Portland Cement Concrete Pavements

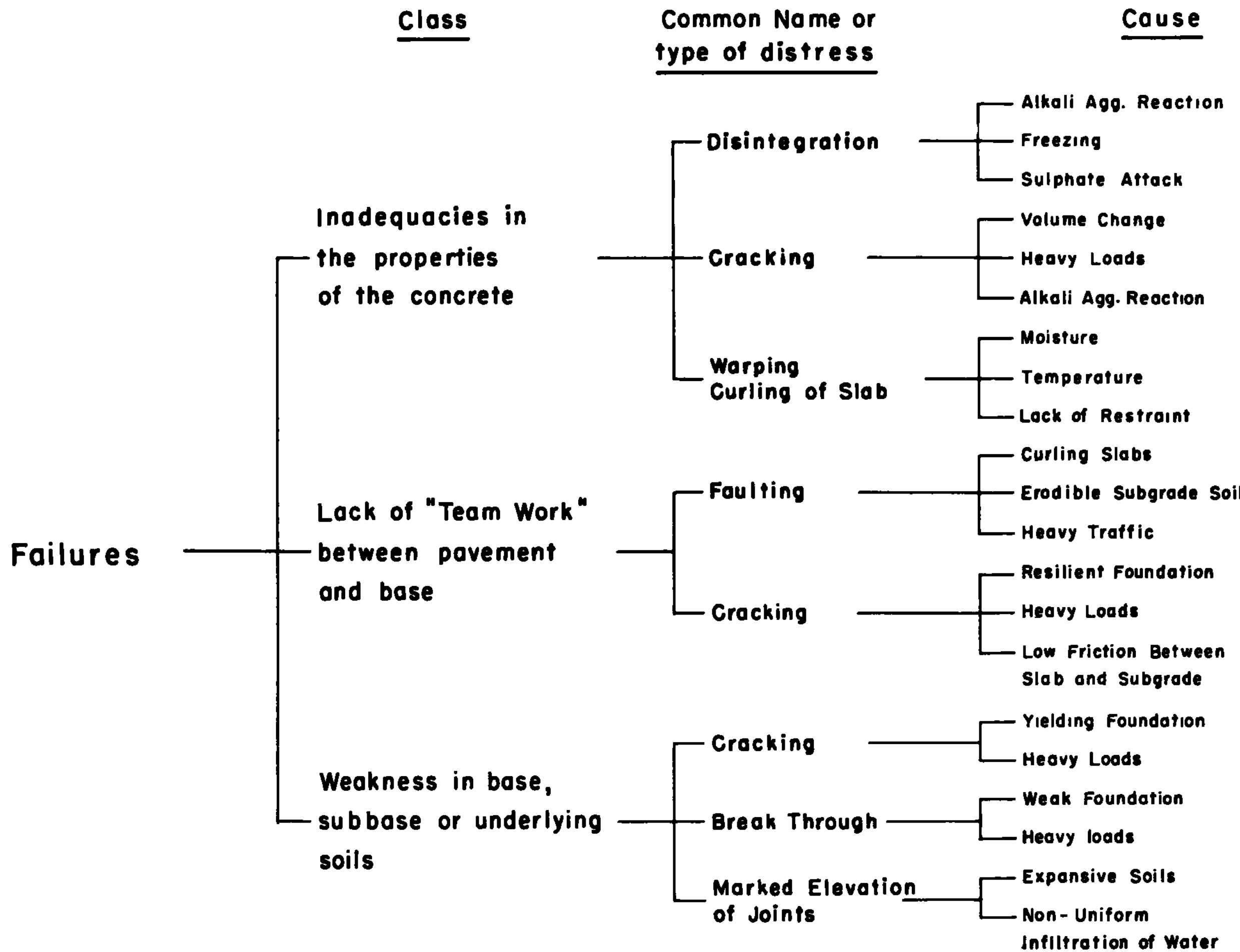


Chart B

CONCRETE PAVEMENTS

Failures and Distress

Chart B classifies failures in portland cement concrete pavements by distress type and cause.

Figures 37 to 43, inclusive, show types of failure or conditions developing primarily because of qualities of the concrete pavement slab.

Figures 44 to 55, inclusive, show types of distress largely caused by failure of slab and foundation to act in unison or to afford mutual protection and support.

Figures 56 to 62, inclusive, show failures and distress appearing in the concrete pavement which are primarily due to weakness and instability of the base or underlying soil.

Figure 37. A random crack showing slight spalling.

Cause: The primary cause for such cracks is shrinkage and expansion of the concrete. Whether or not such a crack is serious is debatable. Its unsightly appearance is probably the chief reason why engineers insist on cutting contraction joints at close intervals. Cracks of this type are probably more annoying to the engineer than to the traveling public. Many old concrete pavements have given excellent performance over a long period of years where all "joints" were of the type shown here.

Figure 38. Badly cracked pavement nearing the stage of disintegration.

Cause: Expansion of the concrete due to reaction between alkalies in the portland cement and opaline silicate particles in the aggregate.

Figure 39. Striking contrast in appearance of adjacent lanes of concrete pavement. The aggregates, foundation conditions and traffic are the same on both slabs.

Cause: Right hand slab—although all of the aggregates contained reactive material, the cement used in the right hand side was high in alkali while that used in the left hand slab was not. A clear example of alkali aggregate reaction in the right hand slab.

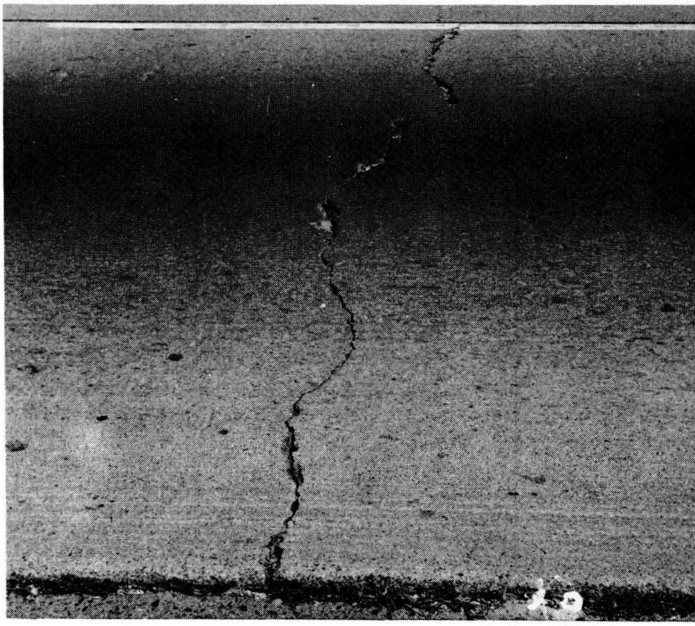


Figure 40. Advance deterioration in a concrete floor slab. While not a "pavement failure" it demonstrates that such failures can develop in slabs submitted to no load heavier than pedestrians.

Cause: High alkali cement and reactive aggregate.

Figure 41. Contrasting performance of adjacent pavement slabs subjected to freezing conditions. Foreground shows slab in good condition; upper portion is slab showing surface scaling. Both subjected to chemically treated abrasives for traffic safety.

Cause: Action of salt and freezing temperatures.

Note: Concrete in lower slab is protected by an air-entraining agent, upper slab is not.

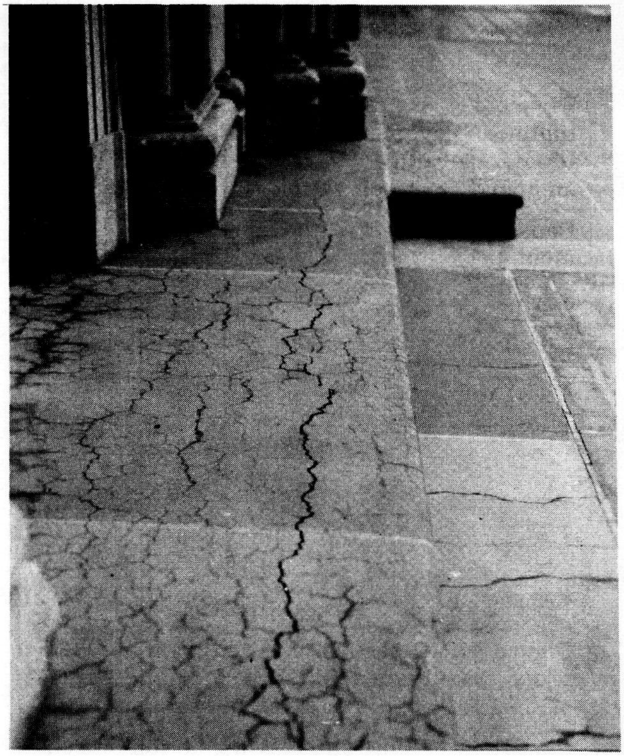


Figure 42. Extensive patching of a thin bituminous pavement "second story" subject to low temperatures in northern California at an approximate elevation of 3,000 ft.

Cause: Failures in the old concrete pavement beneath.

Figure 43. Close-up of failed highway. Same project as Figure 61 showing disintegration of concrete beneath a bituminous surface.

Cause: Freezing and thawing action on concrete without air-entrainment.

Figure 44. Water being ejected through a joint in a concrete pavement. This is the phenomenon called pumping. Strictly speaking, it is not a failure. It simply indicates a condition which may lead to distress or failure of a pavement.

Cause: Under the influence of differential moisture and/or temperature pavement slabs curl upward in the vicinity of a joint leaving a void space between pavement slab and subgrade for the accumulation of water. Entrapped water is subjected to considerable pressure with each passage of heavy axle loads. Water flows laterally at high speed and exerts considerable erosive action upon subgrade; muddy water is ejected with considerable force through transverse cracks and along edge of slab. Characteristics of both subgrade and concrete slabs contribute to this condition.

Figure 45. View through a core hole showing space (about ¼ in.) beneath the underside of the slab and the subgrade.

Cause: Curling of the slab due to expansion of the underside from moisture. Curling also varies with changes in temperature of the upper surface of the slab.

Note: The existence of this void space "sets the stage" for pumping. There is reason to believe that the so-called pumping action would never start if the slab were firmly in contact with the subgrade at all times. Furthermore, pumping action would not be serious if the subgrade layer were not eroded away.

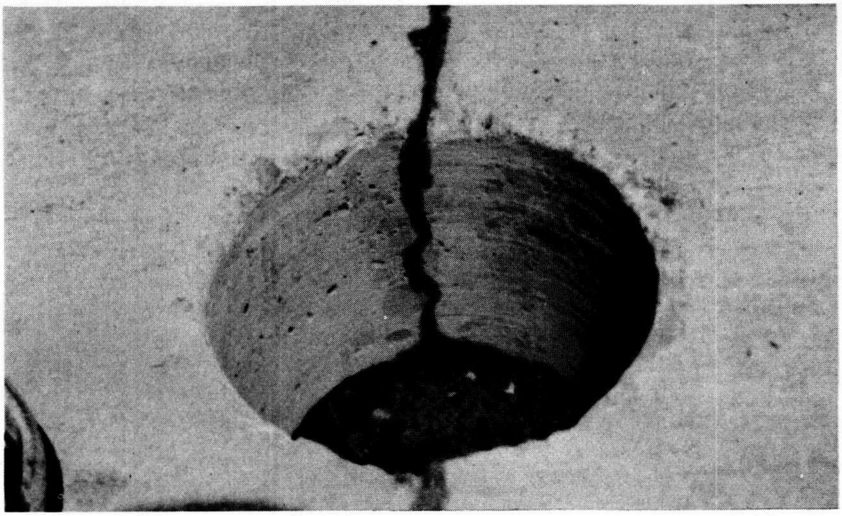
Figure 46. A badly faulted joint or "step-off."

Cause: Usually a development from the pumping action of the slabs that results in the removal of some subgrade material and the transfer from the low side to the higher. Although it is commonly assumed that the low side of the joint has been "pounded" down, there is much evidence to support the theory that in many cases the higher side may have been elevated above its original position. Faulting has also been observed in pavements over clean granular material with no evidence of pumping.

Figure 47. Characteristic transverse break that develops under heavy axle loads just beyond a transverse joint. These cracks are generally from 5 to 7 ft beyond the joint.

Cause: Long continued pumping action of a slab erodes and removes subgrade material leaving a deep void space beneath the slab. Pavement slab becomes an unsupported cantilever which finally breaks under load.

Note: The end of the slab approaching the joint is often supported or bolstered in its elevated position by the accumulation of coarser particles pumped from beneath the slab beyond the joint.



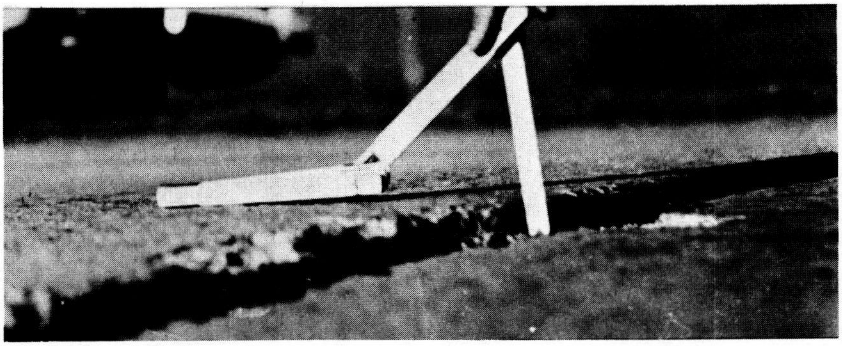



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Figure 48. Second stage of slab failures at a pumping joint. Second crack develops as traffic approaches the joint.

Cause: Primarily, curling of the slab. Secondarily, removal of subgrade support by erosion from the pumping slab.

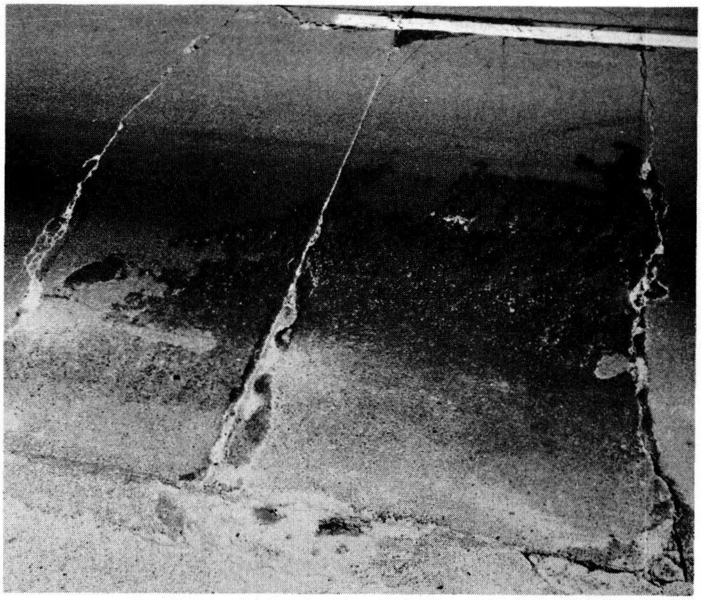
Note: Slab end on approach side is less susceptible to being broken as the sequence of action under one-way traffic tends to transfer the coarser sand particles from the far side of the joint to the approach side, thus tending to support the slab in its uplifted condition; hence, reducing the length of the cantilever arm.

Figure 49. A third stage of failures in the vicinity of a transverse joint showing longitudinal cracks through the short slabs adjacent to the joint.

Cause: Continued repetition of heavy loads on the poorly supported short slabs.

Figure 50. A corner break at the junction of a longitudinal and transverse joint.

Cause: Probably due to the effects of heavy load on an unsupported corner of the curled or warped slab.



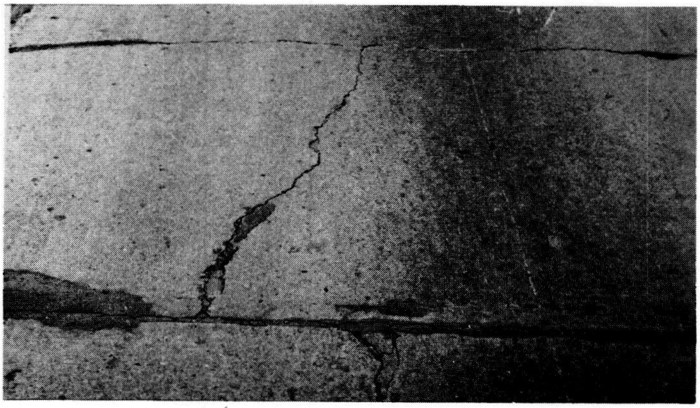


Figure 51. A more extensive corner break.

Cause: In this example, it appears that there is a local weak spot of poor soil beneath the pavement as evidenced by failure in the bituminous shoulder alongside.

Figure 52. Diagonal cracks that have developed in the vicinity of a pavement joint.

Cause: Slab curling followed by pumping out of the subgrade support soil. Slabs broken by heavy truck loads on the unsupported slab ends. Photograph from report on Test Road One-MD.

Figure 53. Spalling of the slab at an expansion joint.

Cause: In this case coarse gravel or uncompressible material in the upper levels of the joint subjected the concrete to heavy local pressures when pavement expanded.

Note: It should be recognized that movement at the joint usually involves wider opening and closing at the top of the pavement due to the warped condition of the slab and the combination of horizontal and vertical movement.

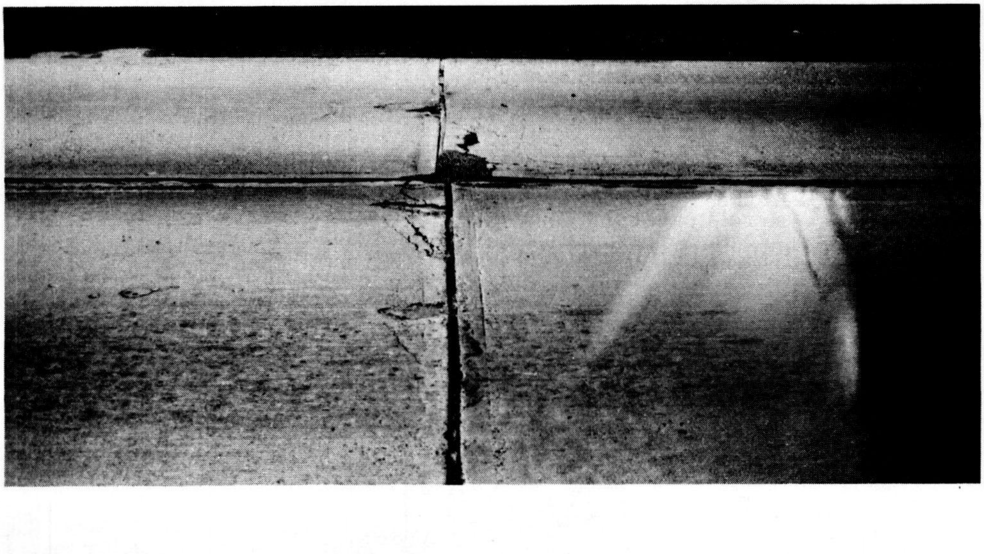


Figure 54. A "blow-up" in a concrete pavement. Photograph taken a few minutes after pavement broke. Loose material is still lying on the surface.

Cause: Expansion of the concrete exceeding the available joint space.

Figure 55. Badly spalled random crack close to and approximately parallel to a contraction joint 2 in. in depth. Crack occurred before pavement was subjected to traffic.

Cause: Expansion and contraction of the concrete due to temperature changes. It must be inferred that the strength of the full 8-in. slab along the irregular line of the crack was less than the 6-in. net section under the contraction joint. The spalling appeared to follow "planes" of weakness along the surfaces of the coarse aggregate. Bond between the cement paste and the siliceous, glassy, coarse gravel is relatively poor: or movement possibly facilitated by bituminous treated sand subgrade with low friction. Cracks ultimately opened 1 or 2 in.

Figure 56. Longitudinal crack in a thin concrete pavement constructed in 1917.

Cause: Vertical and lateral alternate expansion and shrinkage of a heavy clay soil.

Figure 57. Longitudinal and transverse cracks in a modern 8-in. concrete slab constructed in 1955.

Cause: Abnormal expansion of imported borrow material secured from waste piles at a magnesium plant.

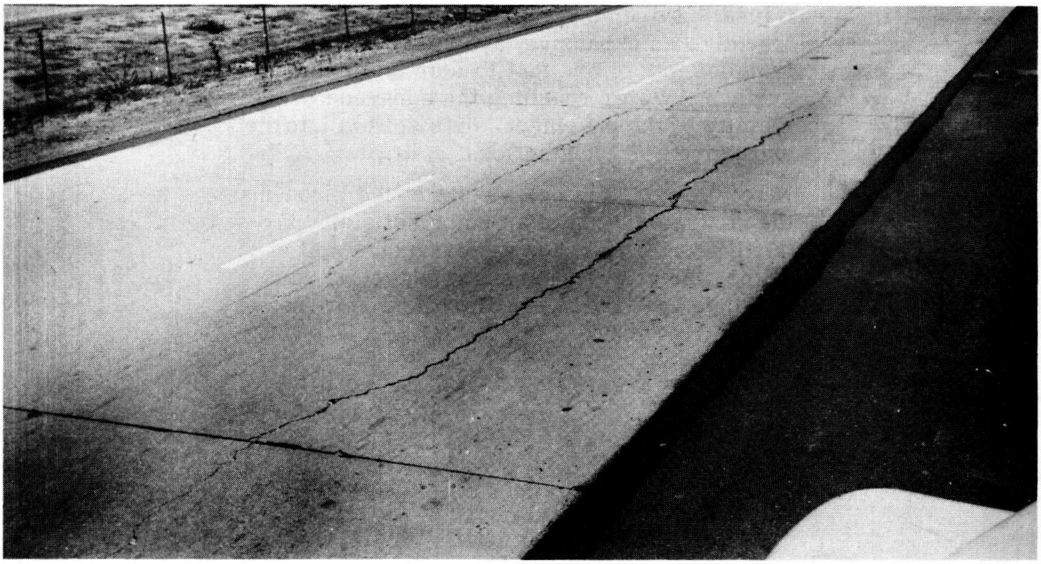
Note: Expansion of this material developed slowly; hence, was not detected in preliminary tests, but expansive action has continued to develop after being placed on the roadbed. (See Figure 36 for effect on asphaltic pavement.)

Figure 58. A more recent view of the cracked pavement shown in Figure 57.

Cause: Same as Figure 57. Note two approximately parallel cracks and greater width of opening.

Figure 59. Transverse cracks, corner breaks and general distress in a concrete pavement.

Cause: Very poor soil beneath the pavement as further evidenced by the marked alligator cracking of the bituminous border which is normally subjected to little traffic.



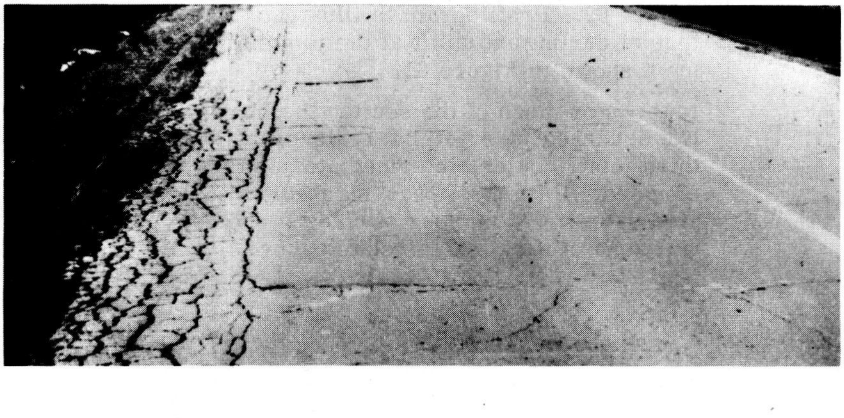


Figure 60. Distress and serious breakup of an airfield pavement used as a test track.

Cause: Heavy wheel loads and poor subgrade support.

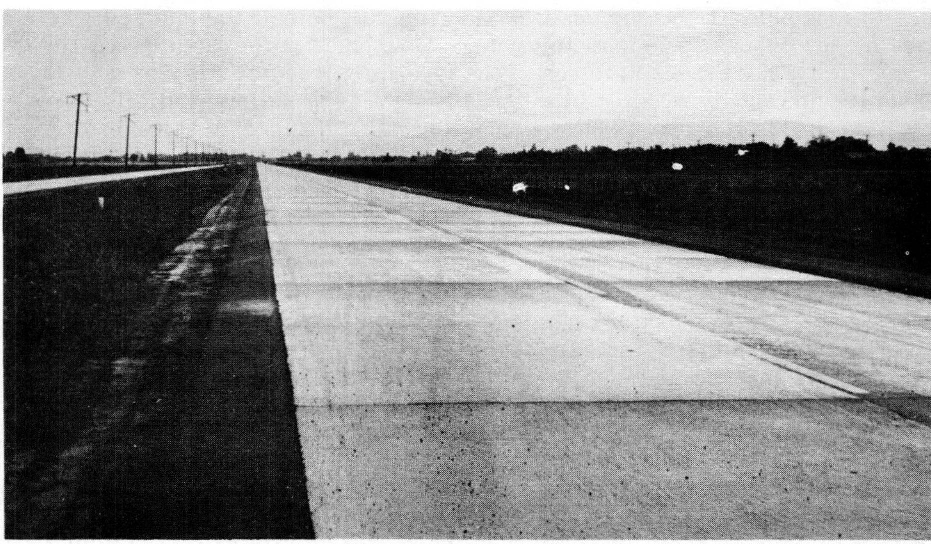
Figure 61. Badly curled or warped slabs in a new concrete pavement approximately one year old.

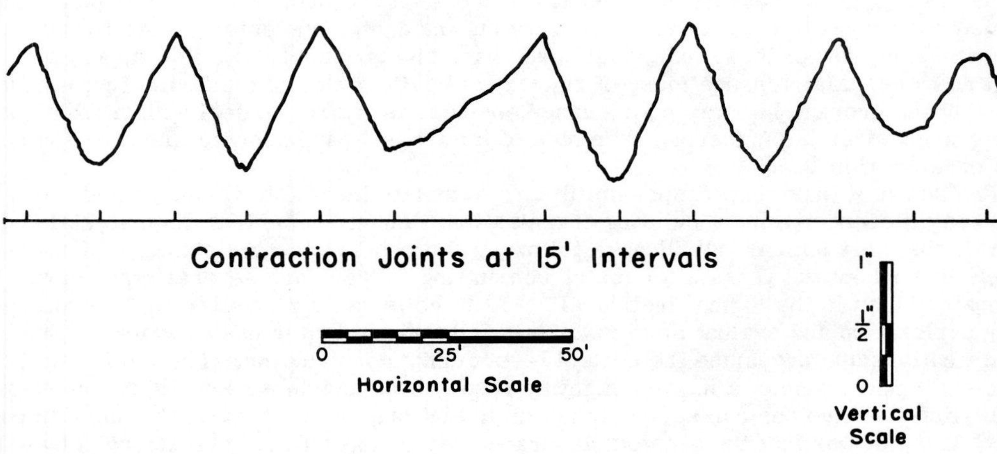
Cause: Extreme upthrust at the joints was traced to an expansive layer of soil ranging from a depth of one foot to four feet below the surface. Water reaching the subgrade in the vicinity of the pavement joints soaked into the expansive soil causing local uplift.

Note: A series of holes were bored through the central portion of a number of slabs permitting water to reach the expansive soil at all points. The roughness was greatly reduced as the slabs were lifted to a more nearly uniform plane.

Figure 62. Profilogram to illustrate magnitude of curling and uplift at the joints of pavement shown in Figure 61.

Note: For much of the section the initial uplift occurred at 45-ft intervals or at every third joint. Later, intermediate joints were elevated. Roughness was markedly alleviated by boring a number of holes in the central zone of each slab as stated above.




Contraction Joints at 15' Intervals
0
25'
50'
Horizontal Scale
1"
1/2"
0
Vertical Scale

It is hoped that the foregoing catalog and brief description of the various types of failure will be of interest to engineers responsible for rural highways, city streets and airfield pavements. However, it is pertinent to point out that highway engineering today has been sub-divided into a number of specialties and there is inevitably a difference in viewpoint and motivation between design engineers, construction engineers and maintenance engineers, to say nothing of materials engineers. Many of the failures shown could have been prevented only by a more adequate design which, in turn, can only result from a better understanding of the properties and limitations of materials. Another group of failures may be charged to faulty construction practices. Of the failures shown, only those in Figures 34 and 35 could properly be charged to faulty maintenance.

Having been in turn a construction man, a maintenance superintendent, and a member of the materials department, the author can sympathize with the problems and viewpoint of each. Although the burden of responsibility for providing durable pavements rests jointly with the materials, design, and construction departments, the maintenance engineers cannot escape the responsibility for many poor or inadequate repairs. It is hoped that a study of highway failures will encourage greater cooperation between the "specialists" in the several departments represented in most organizations constructing pavements. It is also hoped that maintenance engineers will have a greater tendency to look beneath the surface when repairs are being contemplated and that they will have money enough to do something more than place a thin "skin patch" over a failure caused by a weak base. Failures of the type illustrated by Figures 1 to 12, inclusive, may be corrected or halted by relatively light applications; but all of those covered by Figures 13 to 36 will require something more than a thin surface patch or surface treatment to effect a permanent restoration.

From the viewpoint of the materials engineer, there is an unfortunate and all too widespread tendency for many engineers engaged in design or planning to regard detailed quality specifications as nuisances. The materials engineer is often somewhat taken aback to find that his adverse test results and rejection of materials sources are not always appreciated as a timely warning of probable troubles and failures in the finished construction. A laboratory man often is made to feel that he is an unpopular obstacle and handicap to those who are "trying to get things done." There also is the fear in many quarters that too restrictive requirements will "frighten" contractors into higher bids. Construction engineers or resident engineers have many things to think about and often are inclined to leave the control testing to the youngest and least experienced men on the resident engineer's crew.

Although individuals may differ, no one can seriously maintain that there is any generic difference in the abilities or conscientious devotion to the job between materials engineers, design engineers, or engineers in any other departmental grouping. There is, however, a definite difference in the opportunities to observe the results and performance of completed pavements under traffic over a long period of time. In most large organizations, design departments continue to design and plan and construction men administer the contracts and attempt to carry out the design and enforce specifications. Nevertheless, few of these individuals ever have an opportunity to follow up and see what happens. Maintenance men, of course, are fully aware of the facts of pavement life, but the average highway maintenance engineer is trained to deal with trouble and is apt to consider the numerous examples of failure and pavement weakness as the normal order of things.

The scope of individual responsibility and authority inevitably varies considerably between different pavement building organizations, but it seems that the materials engineer is the most logical individual to follow up and observe the performance of pavements throughout the years after the ribbon cutting. There are several reasons why the laboratory man is the logical individual. First, he is usually involved in the preliminary exploration and evaluation of materials. He should be the one to write materials specifications and prescribe the control tests during construction. The intelligent and efficient construction of a modern highway requires the combined efforts of a number of specialists, and no one can seriously maintain that one or the other is the more important. It is obvious that the greatest assurance of success will only be achieved by teamwork, cooperation and interchange of information. It is true, however, that the die is not cast until the construction engineer takes over the project, and even though deficiencies exist in the plans and specifications it is often possible for the construction engineer to offset such weaknesses and turn out a good job in spite of everything.

Therefore, no matter how well the preliminary work—such as materials evaluation, design, planning and specification writing—has been done, the problem of turning out a good job still rests with the construction engineer. Consequently, if the construction man often is blamed or criticized for failures which may develop, he also is entitled to a large share of the credit for the many miles of good pavement that have been and are being constructed. In spite of the variety of failures shown in this report, it is encouraging to note that there are more miles of good roads than of poor ones.

Discussion

W.H. CAMPEN, Omaha Testing Laboratories, Omaha, Nebraska—Mr. Hveem has done a fine job of classifying and picturing the types of failures in bituminous pavements. It is not believed, however, that he covered the following types of distress:

1. Pitting, due to soft particles in the coarse aggregate.
2. Rapid wear which resembles raveling but which is due to the action of snow chains on coarse asphaltic concretes.
3. Shoving or rutting of mixtures laid on strong concrete bases, due to excessive asphalt or inherently weak aggregate mixtures.

In regard to item 1, coarse aggregates may meet wear and soundness requirements but may still contain sufficient amounts of soft particles to cause progressive surface disintegration. The allowable percentage of soft particles should be kept very low in asphaltic concretes, not over 2 percent.

As far as item 2 is concerned, it can be said that in recent years the tendency has been to obtain stability at the expense of durability; thus asphaltic concretes are being laid coarse and lean. The stability is thereby increased but the rate of wear is increased. This situation leads to the observation that the designer is now, and probably will always be, confronted with the problem of choosing between stronger short-lived pavements and weaker long-lived ones. Of course, in most instances, he can achieve satisfactory results along both lines.

Item 3 is closely related to item 2; however, the distress can be eliminated or reduced by incorporating angular aggregates, both coarse and fine, and by limiting the asphaltic content.

F.N. HVEEM, Closure—Mr. Campen has mentioned several varieties of distress which were not covered in the examples shown in the paper. Before commenting upon the three types, the author acknowledges that there are other varieties of failures that were not included. One very important type is identified with frost boils. This was omitted not because frost boil failures are unknown in California, but because a photograph was not readily available.

Taking up Mr. Campen's three suggestions:

1. Pitting has been observed in some bituminous surfaces in California, but rarely due to soft stone as some very satisfactory bituminous surfaces have been constructed with aggregates that were far softer than the maximum permitted by any standard abrasion test. The only cases where such pitting has become noticeable was in certain road-mix projects in which lumps of clay or weakly cemented disintegrated granite would dissolve and leave pits in the finished surface. At times these pits were quite numerous, but they appeared to cause little real harm other than to be a little upsetting to the engineer. Only two or three examples have been encountered in an asphaltic concrete pavement that developed some pitting of the coarse aggregate. One particular section in the desert region developed marked disintegration, apparently due to complete softening and disintegration of the coarse stone following infrequent rains. The stone in question met ordinary rattler and hardness requirements, but the road had to be resurfaced because of disintegrated surface. No photographs are available.

Figure 63.

2. Failures or distress caused by rapid wear resembling raveling but due to the action of snow chains on coarse asphaltic mixtures have been noted. Wear from this source has not been a frequent cause of trouble in California, although examples have been known. This type of problem was simply overlooked in the paper. Figure 63 shows surface loss attributed to action of tire chains.

3. The author cannot agree that shoving or rutting of mixtures laid on concrete bases, due to excessive asphalt or inherently weak aggregate mixtures is in any important sense different from distortion of asphalt mixtures on any other type of support. Observations in California have indicated that, other things being equal, unstable mixtures may have less tendency to distort on a rigid concrete base than if resting directly upon a resilient soil. The type of instability shown by Figure 7 or Figure 9 is not essentially different from that which may occur over a concrete base. Shoving or rutting means a mixture having insufficient stability; this is usually attributable to an excessive amount of asphalt, excess moisture content, or both.

In general, there is no disagreement with Mr. Campen's comments, although the necessity for limiting the soft particles to not over 2 percent is questionable. Here it probably is necessary to define more precisely what is meant by "soft" particles. His comments about recent tendencies "to obtain stability at the expense of durability" is a sound observation. Unfortunately, in spite of laboratory test methods and means for accurately estimating the optimum asphalt content, too many construction men will still vary the asphalt content in accordance with the appearance of the fresh mixture. This error is most marked, of course, where the aggregates are more or less porous or absorbent. The total amount of asphalt required for good durability and resistance to abrasion for a period of years always looks excessive before absorption into the aggregate takes place. It is fairly common experience for a laboratory to evaluate absorption and porosity by means of the CKE test only to have the resident engineer or the plant inspector reduce the amount of asphalt because it "just looked too rich" and there is, of course, no doubt that it did "look rich." In these circumstances, as in many others, the engineer on the job must have the courage of his convictions—but, of course, he should first have the right convictions.

Warning Signs of Pavement Distress

H.J. LICHTEFELD, Chief, Technical Branch, Office of Airports,
Civil Aeronautics Administration

Much concern has been evidenced regarding the ability of existing pavements to safely and satisfactorily accommodate present day and proposed aircraft loadings. Although this problem has been given much recent prominence, it is not a new one. In any investigation of pavement performance, it is not only necessary to determine the present condition of the pavement—by such means as condition or performance surveys—but it is also necessary to consider the results of such surveys in light of the basic design principles and construction practices which obtained when the pavement was built. In essence, the evaluation is a reversal of the design procedure. Reported herein is a general method of airport pavement evaluation procedure consistent with the current design principles set forth in Civil Aeronautics Administration publication, "Airport Paving," dated October 1956.

● THE ULTIMATE TEST of any structure is the measure of how well it is performing the job for which it was intended. When the structure can no longer accomplish the function for which it was intended, we may say that it has "failed."

In the case of pavements, the line between an adequate structure and an inadequate one often is exceedingly fine. Pavements do not "fail" instantaneously such as might a column or beam. This leads to the conclusion that pavement distress is progressive, leading up to a condition of "failure." We might say then that there are degrees of distress but not degrees of failure, reserving the use of such term for the superlative.

With respect to pavements, a complicating factor may exist. Although the condition of "failure" might occur it may be local or isolated. To classify the entire structure as "failed" under such a circumstance would be highly misleading and, in fact, incorrect.

Let us then accept the premise that what we are seeking is evidence of distress in a pavement or indications reflecting unsatisfactory conditions for the intended function. What can be done to gather the needed "evidence" and what is the nature of this "evidence" being sought?

We in CAA have a continuing function of studying the performance of airport pavements in relation to our design standards and to construction methods. Our current design criteria, as stated in "Airport Paving," October 1956, contemplate minimum pavement maintenance to assure safe and regular aircraft operations. We believe that from a thickness standpoint our design formulations are adequate for the anticipated wheel loadings of future civil airliners. Our criteria, evolved over a period of many years, are based on (1) theoretical concepts of design, (2) analysis of accelerated traffic tests, and (3) investigations of service behavior of existing pavements. The CAA lays a great deal of stress on this latter item.

Along this line of investigations there was initiated in 1950 a coordinated pavement condition survey. Although limited informal condition surveys had been conducted in the past, the 1950 survey was by far the most comprehensive. This survey had as its broad objective the studying of performance of existing airport pavements in order to check the soundness of the design standards which previously had been established and which were in effect at that time. The survey provided a design performance record as indicated by the pavements physical condition. Airports covered in this survey were so selected as to assure inclusion of a range of pavement surface types, base courses, subbases, subgrades, climatic conditions and types and amounts of aircraft traffic. A total of thirty-four airports was chosen for detailed analysis. For each of the airports included in the survey, a careful study was made of all available records in order to obtain all possible information regarding traffic, pavement thickness, paving design details, maintenance practices, soils, drainage, climate and construction variables. It was necessary to obtain dates of construction and reconstruction, if any, and accurate details of the cross-section design of the surface, base, and subbase. All pertinent information relating to materials, methods, mixes, reinforcing and joint layout was also included. The condition of the pavement was mapped in detail, showing locations and types of obvious failures and any other data or details which might have influenced pavement performance were noted. The data were assembled and analyzed to determine the relationship existing between the type and thickness of pavements, subgrade conditions, and aircraft loadings to which it had been and was being subjected.

Soil data included typical soil profiles, a description of the characteristics of the different layers, results of tests performed on the various soil materials, and the elevation of the ground water table.

Sufficient information was obtained regarding surface and subsurface drainage to permit a determination of the drainage conditions as related to paving design criteria.

Traffic records were studied to determine the number of operations per day for the different types of aircraft using the field, the distribution of the traffic on the various runways, and approximate dates when the heavier types of aircraft started to operate from the airport. This latter item was extremely important in the final analysis.

The condition of the pavement was mapped by walking over the paved areas and sketching the location and extent of distress areas and obvious failures and other details having a bearing on the performance of the pavement. The nature of the distress or failure was described and its cause determined. Emphasis was placed on the conditions caused by the aircraft loadings related to design requirements, rather than defects due to inferior materials or poor workmanship during construction.

In analyzing the data collected in this survey, the pavements were divided into main groups according to whether they were flexible or rigid. Then the performance of runway pavements was distinguished from the behavior of the pavements in the critical areas such as taxiways, aprons, and the runway ends. A further subdivision was made on the basis of the subgrade class. All information relative to pavement details was thoroughly screened and the data reduced to show the relationship between aircraft loadings, pavement thickness, subgrade soil and pavement performance.

Traffic data were the most difficult to obtain and analyze. It was clearly evident that the total number of operations of all types of aircraft was not the significant factor to be considered. A large volume of light aircraft, such as personal and executive types, had negligible effects on pavement performance as compared to limited operations of the heavier commercial types in scheduled service. Also, an occasional landing or takeoff by a plane considerably heavier than those normally operating from a field is not important with respect to pavement performance. Therefore, it was determined that, for the purpose of this study, the activity at a particular airport could best be indicated by the number of scheduled daily operations with DC-3 and heavier types of aircraft.

Most important with respect to this survey were failures resulting from inadequate pavement thickness. A great amount of breakage of both flexible and rigid pavements was encountered where the pavements were underdesigned originally or where there was a great increase in loading over that contemplated in original design. The occurence of other failures or distress resulting from inferior quality of materials and workmanship were also charted and clearly distinguished from structural failures due to overloading. While these deficiencies are of interest, and should be analyzed separately, they did not influence the determination of design requirements relative to pavement thickness and loadings. A typical example disclosed by the survey was the case of a 6-inch portland cement concrete pavement constructed in 1938 which served satisfactorily for DC-3 traffic until 1946. At that time, service was inaugurated with the heavier DC-4 aircraft. Shortly after the inauguration of DC-4 service and over a short period of time, an extensive amount of breakage, faulting, and settlement occurred. It was necessary to reconstruct the pavement.

Another case dealt with progressive deterioration of a relatively thin flexible pavement constructed in 1942. The total thickness of this original pavement was 8 inches. For some five years this airport had been used for small commercial aircraft and light military training planes. Our attention was first directed to difficulties with the inauguration of service by DC-4 aircraft. Subsequently, the service was augmented with DC-6 aircraft. During this period of traffic growth, there occurred progressive surface breakage and rutting which was the direct result of pavement overloading. Because of financial limitations during this time, the owning city was forced to attempt to correct the most severe failures by patching isolated areas. By 1950 the deterioration had reached such a point that reconstruction of the entire pavement was necessary.

The above examples are noted because they are typical cases. When such situations are analyzed and the findings correlated with applicable design criteria and procedures, logical adjustments and modifications in design considerations can be made.

The foregoing approach is similar to the proposal by the Missouri State Highway Department in their 1957 revision of the Flexible Pavement Thickness Design Chart. In the paper describing the Missouri design chart it is stated, "As projects are built with thicknesses based on this chart, and experience records accumulate to help determine the accuracy of the curves, it may once again become necessary to evaluate, review and revise." It is obvious that this approach is geared to the production of roads to give satisfactory performance for the service intended. One other item noted in that paper is the attempt to predict axle loads to which roads will be subjected in 1977. Although all influencing factors may not be definitely validated, this approach appears to have the "forward look." Similarly, the CAA has always attempted to anticipate the pavement requirements which must be fulfilled to satisfy the needs of future civil aircraft. This is particularly true of design procedures followed during the post-World War II period. It has been most fortunate that we made provisions whereby pavements could be designed and constructed which will be adequate for the forthcoming civil turbojet aircraft, even though the exact weight and undercarriage configurations of these aircraft were unknown when current criteria were established. It might be noted that the aircraft which will be immediately forthcoming exceed in weight the largest current reciprocating engine aircraft by nearly 100 percent.

I have emphasized the stress we place on pavement condition surveys and relating the results to current design practices for providing pavements satisfactory for safe and efficient aircraft operations. The federal-aid airport program, inaugurated in 1946, provided an excellent vehicle for accomplishing such surveys. Under this program of assistance in development of civil airports, a project can be undertaken only after establishment of unquestioned need therefor. In the case of a project involving paving, the need must be predicated upon an analysis of the condition of the existing pavement and assurance of the adequacy of corrective measure proposed. In addition, there is currently under way a general program of pavement inspections at all paved airports within one of the Regions of CAA. Based upon experience and success of this inspection program in one Region, procedures will be formulated to extend the program to all CAA Regions. We expect to obtain much valuable data from these inspections.

The foregoing is history—but what was looked for—what were the distress signs which we sought and still seek out in our investigations of pavement behavior?

Generally two classes or series of signs exist. These may be called "direct" evidence and, for lack of a better term, "indirect" evidence. "Direct" evidence consists of the visible signs which appear on the pavement or can be detected by physical tests. "Indirect" evidence may be said to include these operational or similar factors which induced the physical signs.

In our examination of a pavement, it may be noted that there are individual feature failures or other deficiencies that may not be classified as a pavement failure, for essentially a pavement failure must result in a change of the surface characteristics of the pavement. In the case of a rigid pavement, a number of defects may appear and yet the surface will be slightly affected, if at all. For example, many slabs may have intermediate or corner cracks but the surface is essentially unimpaired. Additionally, pumping in itself is not a "failure" of the surface but an indication of impending surface deformation. It is, however, evidence that "failure" of some design feature has occurred.

These two defects, namely random cracks and pumping, thus are excellent indices of impending and potential distress of a rigid pavement. Usually they are followed by progressive defects and deterioration and ultimately result in surface deformities or "failure" of the pavement.

We have observed flexible type pavements which have had "bird baths" and undulations resulting either from construction deficiencies or from the effects of consolidation. Initially these deficiencies may not be of a serious nature; in fact, from a structural standpoint the pavement itself may be of a higher standard. From an operational standpoint, however, it may be necessary to provide a leveling course to permit safe operations.

In addition to the above, the following are some signs or factors that are given consideration in analyzing pavement distress conditions. These may be considered direct evidence: (a) Extrusion of joint material as an indication of the filling of joint space with fine noncompressible material. (b) Displaced joint sealing material permitting the entrance of water to the pavement foundation. (c) Crazing and map cracking. (d) Progressive oxidation of binder material. (e) Excessive binder material as revealed by bleeding. (f) Loss of surface texture and consequent reduction in anti-skid characteristics of the pavement. Texture is an important consideration for operations of high-speed aircraft. (g) Build-up of turf or soil at the pavement edge which results in entrapment of water with possibility of penetration to the pavement foundation.

The signs which constitute indirect evidence are best determined from a review and analysis of the traffic to which the pavement has been subjected and knowledge of the design and construction practices in effect when the pavement was conceived and placed.

A history of operations or a traffic study will disclose when a pavement is being subjected to loads in excess of those for which it was designed. The previously recited examples are again called to your attention. If such overloads become routine it is logical to expect that pavement surface changes will result. Projections of operations related to increased loads may even permit prognostications of rate of pavement distress. It can be seen then that a close check on activity related to traffic can be a guide sign to possible pavement problems.

This feature, that is the traffic growth factor, is particularly acute with respect to airport pavements. Since the advent of commercial aviation, the trend has always been towards larger and heavier aircraft. Planes that were considered large several years ago are dwarfed by those in common use today. Future aircraft will impose total loads on airport pavements greatly in excess of anything experienced to date on civil airports. Although we are reasonably sure that our present pavement design criteria are adequate to accommodate the anticipated load from future large civil airliners as previously mentioned, nevertheless we shall observe closely those pavements where these aircraft are operated for signs of distress and possible failure.

In this regard, not only are the loads themselves important, but the analysis must take into account the nature of the load and the rate of application thereof. At this point it is desired to state that the aircraft manufacturer is becoming more conscious of wheel spacing and arrangements to get the most favorable distribution of the load. This is a healthy sign.

There is one remaining area of investigation where certain warning signs of possible trouble may be read. This area includes the analysis of design practices and actual construction techniques. In some instances due to exigencies of a particular situation, it may be necessary to compromise on the design. Knowledge of such circumstances certainly is ample evidence of possible trouble spots. Use of potentially troublesome or marginal materials also falls into this category.

It has been said, and I believe rightly so, that more failures in pavements result from improper construction practices than from design inadequacies. This condition is exemplified by an actual case of a flexible pavement located on an airport in a northern state. When snow was plowed from the runways it was detected that a group of small, isolated bumps, unnoticed under normal traffic, were scalped by the plow blade. Inspection revealed that the sources of these "bumps" were cobbles, ten or twelve inches in diameter which were being progressively heaved by frost. Failure to conduct conscientious inspections during construction had resulted in depositing of oversize material with the gravel base course. The yearly process of freezing, heaving, and subsequent settlement was sufficient to force the cobbles and surface into the noted "bumps" which "grew" over an extended period of time. It may be argued that this condition never should have been permitted to develop. Such an argument is incontestable. However, cases of inadequate inspections are not isolated and all of us are aware of situations where inspection of construction left something to be desired. The example case points up a "sign" which may be read to forewarn of pavement failure. Knowledge of inspection techniques and capabilities of inspection personnel frequently will be indirect evidence of possible shortcomings in the pavement's performance. In this same vein, knowledge of past maintenance practices and adequacy of the maintenance program may lead to conclusions regarding pavement behavior or potential.

In retrospect then, we may say that the signs of impending distress in pavements are posted along three general avenues. These avenues are named: (a) design and materials, (b) operations and traffic, and (c) people and personalities. These avenues are well marked and posted. In the final analysis, it must be left to the ability of the individual engineer to read and correctly interpret the signs along the way if we are to be forewarned of pavement performance problems.

Evaluation of Rigid Pavement Performance

F.M. MELLINGER, Director, Ohio River Division Laboratories,
Corps of Engineers, U.S. Army

For over fifteen years the U.S. Army Corps of Engineers has been conducting an extensive investigational program in connection with the design, construction and evaluation of concrete airfield pavements. This program has given consideration to paving materials, construction methods, analytical methods of design, traffic on specially constructed test pavements, and the condition of existing concrete airfield pavements. The purpose of this investigational work on rigid pavement is to establish a realistic method of design and evaluation and to insure that the pavements constructed are in accord with the requirements of the design. From time to time these investigations have been reported in the Proceedings of the Highway Research Board and other technical publications (1) (2). This paper summarizes briefly the method for the design and evaluation of rigid pavements based on the Corps of Engineers studies. Although the evaluation of rigid pavement performance involves many factors, the approach taken in this paper is that the load carrying capacity of the pavement with regard to both the magnitude and the frequency of loading, must be of prime consideration before factors other than load can be viewed in their proper perspective.

● MANY TIMES during the life of an airfield it may be necessary, for various reasons, to have an evaluation of different sections of pavement. Pavements may be evaluated to estimate the life remaining in a section, to check and correlate design methods with pavement performance, to provide information for pavement strengthening programs, or to serve as a guide in aircraft operations. The U.S. Army Corps of Engineers, over its years of experience with rigid pavements, has developed a procedure whereby pavement performance can be predicted for a wide range of operating conditions. However, before presenting this evaluation method, some mention should be made of what constitutes pavement failure.

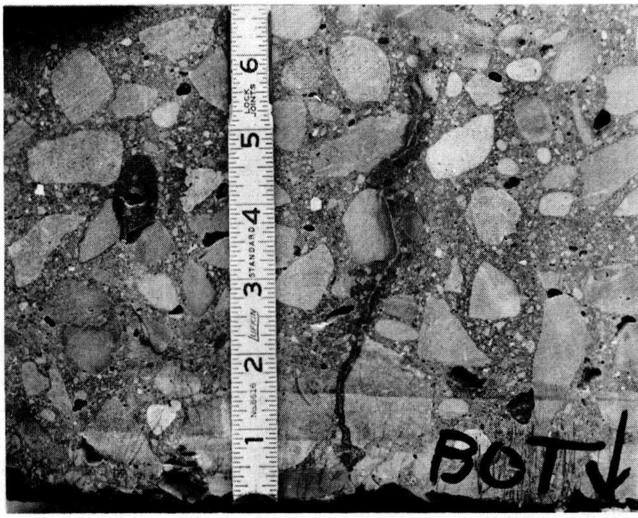
CAUSES OF FAILURE

Depending on the definition of pavement failure, the causes of failure, such as construction defects and over-loading, assume relative degrees of importance. However, with the advances in pavement construction technology, knowledge of concrete materials, and pavement jointing systems developed over the past thirty or more years, the number of failures due to causes other than over-loading by traffic should be small. This has been the trend observed for concrete airfield pavements constructed by the Corps of Engineers over the past fifteen years.

The most difficult as well as the most significant cause of pavement failure to evaluate is over-loading. Over-loading can occur over a period of several years as a function of the fatigue strength of the concrete and supporting media, or the loading may be so excessive that pavement failure results almost immediately. The latter case is not too difficult to evaluate. However, until the former becomes evident by excessive spalling at the joints and structural breaks in the pavement, over-loading is seldom detected; and, even when it is detected, the degree of over-loading still remains a difficult evaluation problem.

In the case of long-time over-loading the degree of over-loading is a problem because of the manner in which failure occurs. The failure is a function of the fatigue strength of the concrete as it fails in flexure at the base of the pavement slab. Minute cracks form which may extend up into the pavement about an inch, leaving the surface of the slab intact. Figures 1(a) and 1(b) show such cracking found in a beam cut from a 14-inch thick plain concrete pavement slab near a joint. This pavement had been subjected to 30,000 cycles of stress repetition by a 100 kip twin-wheel traffic loading. Figure 1(b) shows a close-up view of an unmarked crack extending upward 6 inches from the base of

(a) Cracking in base of 14-in. pavement slab after 30,000 coverages of 100 kip twin wheel load traffic.

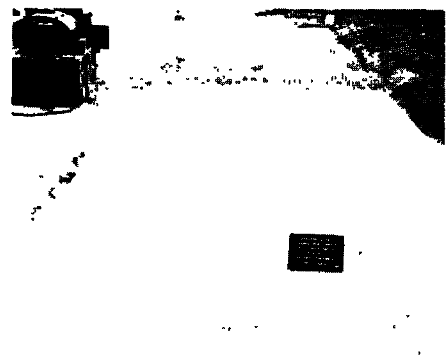


(b) Close up view of unmarked crack in above beam cut from 14-in. pavement.

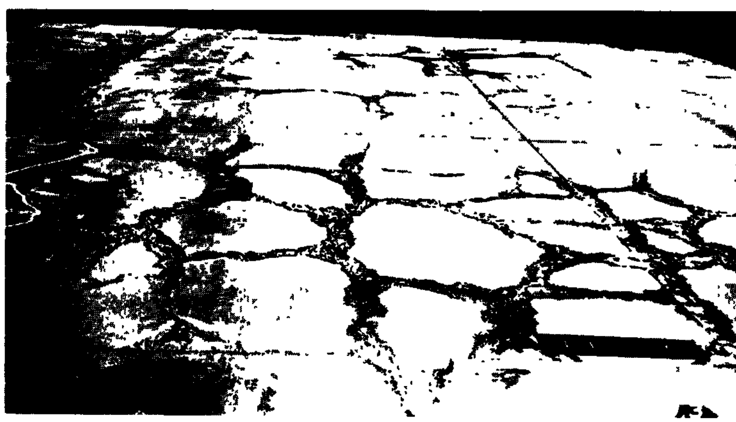
Figure 1. Evaluation of rigid pavement performance.

the pavement. This initial stage of failure is difficult to detect unless instrumentation is located in the precise area. When the crack finally reaches the surface in its development under repeated traffic loading, it generally appears as a hairline crack extending a foot or two inward from the joint. Even at this stage the pavement would not be considered failed. Only after one or two such cracks had developed on the surface for the full length or width of the slab and started to spall, would the slab be considered failed structurally. From the time the first minute crack occurs in the base of the pavement until the final crack pattern has developed, the slab would be considered satisfactory. This process can represent an appreciable part of the design life of the pavement, depending on the rate at which the cracking develops to its final stage. This rate will depend not only on climatic conditions, but also on the modulus of elasticity of the concrete, degree of subgrade support, and frequency of loading.

The detection and evaluation of this type of progressive failure is extremely difficult, even on controlled test pavements. In some cases the failure can be detected with deflection gages when an abrupt increase in deflection takes place. Strain gages also indicate slab failure if the gage located in the base of the slab contains the crack, an abrupt



(a) Failure condition of 16-in. plain concrete pavement after 24,663 coverages of 100 kip twin wheel load traffic.



(b) Complete failure of 12-in. plain concrete slab after 1,359 coverages of 150 kip twin tandem wheel load traffic.

Figure 2. Evaluation of rigid pavement performance.

increase in strain occurs or the gage fails. On the other hand, if the gage is located adjacent and normal to the crack, an abrupt decrease in strain will be observed. Strain gages located on the surface of the slab will give erratic readings as these initial cracks occur, and a general reduction in strain will be observed under continued load application.

The evaluation of the causes of pavement failure may be obvious in some instances but in all cases the question as to whether or not the pavement was over-loaded by the traffic and, if so, to what degree must be answered first. The mechanics of pavement failure and the materials with which pavements are constructed precludes a strictly theoretical approach. Certain empirical relationships must be established to evaluate the load capacity of a pavement. One such approach, as outlined in the following paragraphs, gives a basic design concept, the type of performance observations by which this concept is implemented, and finally the necessary information for translating the design concept into a design procedure for new pavements and an evaluation method for existing pavements.

DESIGN CONCEPT

The evaluation of pavement performance does not evolve from a few observations over a limited time. It must be founded on a basic design concept which takes into account the physical properties of the pavement and its supporting media. Over a period of years this concept will be modified on the basis of actual field performance and, when available, on the results of controlled full-scale traffic tests. The design concept is necessary since a great variety of observations of pavement performance must be correlated for the purpose of obtaining the most economical design applicable for a given set of conditions and a realistic evaluation of a pavement's capabilities while in service. The development of such a concept has been one of the chief objectives of the Corps of Engineers' Rigid Pavement Investigational Program for airfield pavements since early

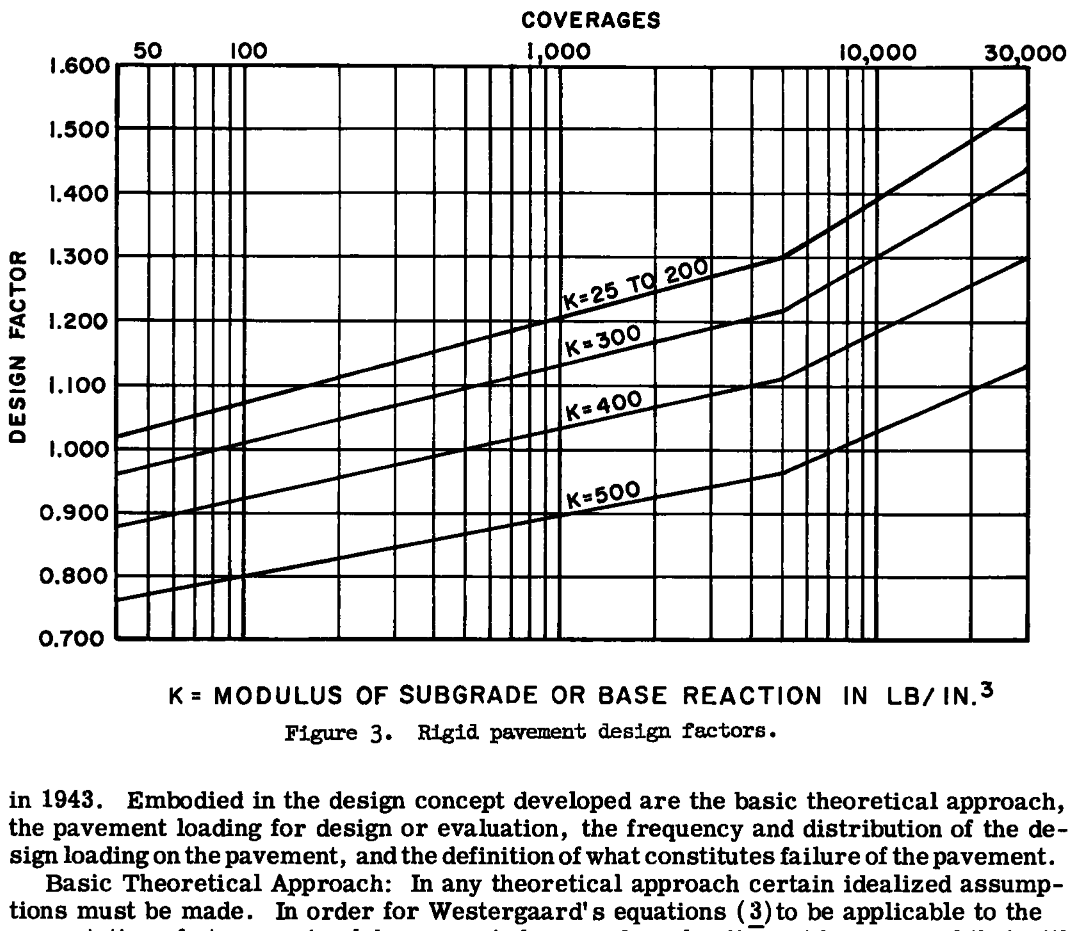


Figure 3. Rigid pavement design factors.

in 1943. Embodied in the design concept developed are the basic theoretical approach, the pavement loading for design or evaluation, the frequency and distribution of the design loading on the pavement, and the definition of what constitutes failure of the pavement.

Basic Theoretical Approach: In any theoretical approach certain idealized assumptions must be made. In order for Westergaard's equations (3) to be applicable to the computation of stresses in slabs supported on a subgrade, it must be assumed that within the range of action, the slab is elastic with single constant values for the modulus of elasticity and Poisson's ratio; that the thickness of the slab is constant; and that the reaction of the subgrade is a vertical pressure, equal, per unit of area, to a constant, "k", (4) times the deflection, the base being uniform in character and everywhere in contact with the slab. No concrete pavement ever constructed meets all these requirements, but the relative performance of concrete pavements agrees surprisingly well with theoretical formulae based on these assumptions. The basic formula used by the

Corps of Engineers is that for an edge or joint of a pavement slab that has no load transfer. The stress computed by this formula is reduced 25 percent for load transfer. Actual measurement of the efficiency of the various types of joint construction used for airfield pavements indicates that this percent is a representative value. This stress is then modified by a design factor, the selection of which is dependent on the number of load or stress repetitions and the modulus "k" of the subgrade reaction. For design the computed stress can be made equal to the flexural strength of the concrete by adjusting the slab thickness or, for evaluation, by adjusting the load.

Pavement Loading: The manner in which a pavement will be loaded is an important determination for any design concept since considerable economy can be effected through this factor. The pavement is generally designed for the heaviest aircraft which it is expected to carry in quantity; that is, the aircraft in continuous operation, not the occasional heavy load. The selection of the design load for pavements which handle military aircraft requires considerable judgment, since the weight of individual aircraft varies with the type of operation, as well as with take-off and landing. In the latter case, the difference in fuel load can be an appreciable percentage of the gross weight of the aircraft. In pavement evaluation work the problem is met where it is necessary to determine whether an existing pavement will support the operation of a specific type of military aircraft.

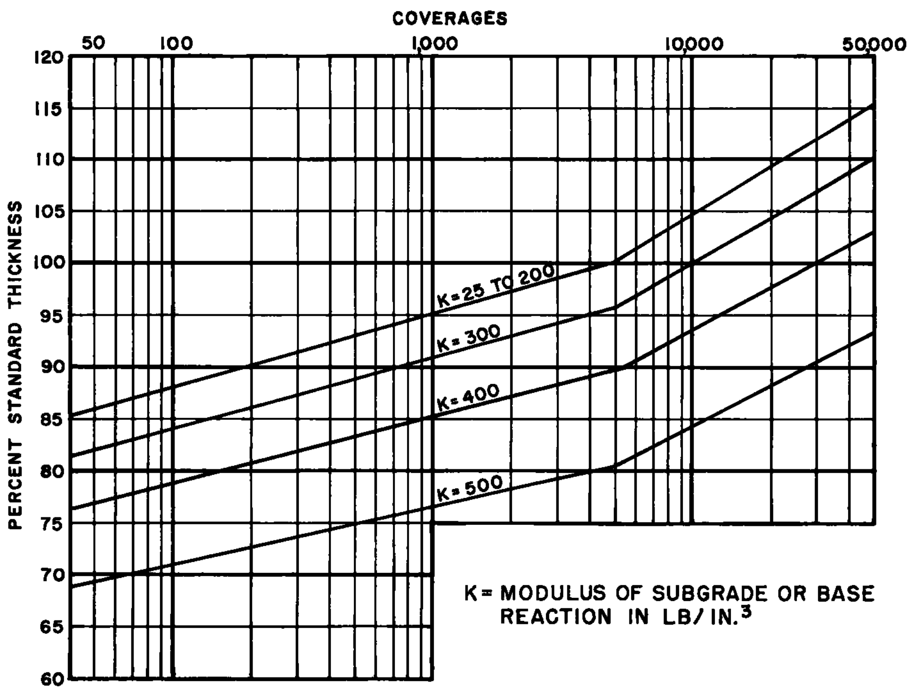


Figure 4. Rigid pavement useful life, 2 to 3 pieces, 1 slab.

Frequency and Distribution of Loading: Regarding the frequency and distribution of loading all possible information on the types of aircraft and their operational characteristics must be studied and considerable judgment exercised in the selection of the appropriate design factor which will determine the pavement life. The term coverage is used to relate the frequency and distribution of the design loading to aircraft operations. One coverage indicates one application of maximum stress at each point in the trafficked area of a pavement and is a function of the number of aircraft operations. In the case of evaluating an existing pavement for a given type of aircraft, the remaining pavement life would be defined by the additional number of coverages which the pavement could reasonably be expected to carry prior to failure.

Definition of Pavement Failure: A pavement facility such as a taxiway apron or runway on an airfield does not fail all at once, the process of failure is gradual. Actually,

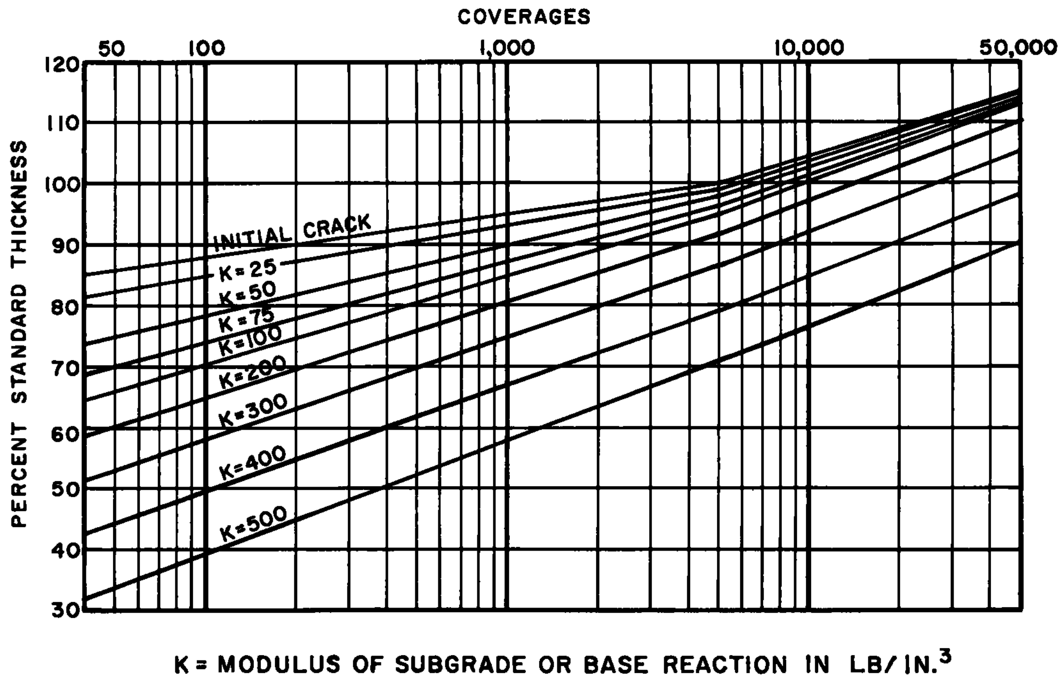


Figure 5. Rigid pavement complete failure, 6 pieces, 1 slab.

an airfield pavement is designed to fail from fatigue after a given number of coverages of the design loading predicted for a 10 to 20 year design life. This design failure is defined as one or two structural breaks or cracks occurring in 30 percent of the slabs in a pavement feature, with the cracks starting to spall. The appearance of a slab in this failed condition is shown in Figure 1(a). For some categories of evaluation, where the pavement is loaded beyond its design capacity, failure is defined as the case where at least 30 percent of the slabs are broken into six pieces and limited maintenance is required to keep the pavement surface suitable for aircraft operation. Figure 2(a) shows an individual pavement slab in this condition.

PERFORMANCE

The observation of pavement performance has one basic objective that is to provide the necessary information for the development of a design procedure. This observation of pavement performance is a continuing process, for once a design procedure is developed, the observation must continue for the purpose of checking and refining the design. Pavement performance is examined under different climatic conditions, and for different types of aircraft loading and operation. In addition, controlled traffic tests are made on specially constructed full-scale test pavements for a variety of loadings and pavement designs. These designs have included overlay pavements on concrete base pavements, reinforced concrete pavements, plain concrete pavements and, more recently, prestressed concrete pavements (5). Since 1943, full-scale traffic tests of pavements have included the loadings, gear configurations and types of pavement shown in Table 1. Not included in Table 1 are tests of rigid, flexible and prestressed overlay pavements (2) (5). The testing of specially constructed test sections under controlled traffic loading provides for a detailed study of the pavement and subgrade materials; also provided is the opportunity to measure strains and deflections at critical areas in the pavement. The information thus developed, in itself, is limited but, when correlated with periodic condition surveys of airfield pavements subjected to actual aircraft operation in areas representative of subgrade soils, construction materials and climate throughout the United States, it provides a good basis for a logically developed design procedure.

TABLE 1

SUMMARY OF TRAFFIC TESTS

Date	Gear Loading		Number of Test Items	Concrete Pavement	
	Weight, kip	Type Wheel		Thickness, in.	Type
1942-43	20, 37 & 60	Single	66	6 to 10	Plain & reinforced
1944-45	150	Single	120	9 to 24	Plain & reinforced
1946-47	150	Twin-Tandem	33	12 to 20	Plain
1955-56	100	Twin	15	11 to 20	Plain & reinforced

EVALUATION

Thus far a design concept with the various factors involved has been presented, with a brief outline of the general means by which information to implement this design concept is obtained. Now remains the method of incorporating this information in an over-all design procedure. However, before proceeding, it is necessary to describe how a rigid pavement can be expected to fail under repeated traffic loading. Failure of a plain concrete pavement generally starts with a crack extending into a slab from a joint. This crack develops with traffic into a longitudinal crack, a transverse crack for the full length or width of the slab, or a corner break. The pavement is not considered as failed until the cracking has developed for the full length or width of the slab. Additional cracking and spalling at the cracks will develop with continued loading. The rate of this failure development will be dependent on the degree of subgrade support. If the subgrade has a high bearing value, the rate of failure will be slow; if the subgrade has a "k" value of less than 200 lb per in.^{3}, the rate of breakup will be relatively fast. This means that a greater degree of cracking or greater number of pavement breaks can be tolerated for a pavement on a high bearing value subgrade before it is considered failed than for a pavement on a weak subgrade. The theoretical formula for edge loading using a fatigue factor for load repetition only will not reflect this difference. Therefore, to correlate the theory with actual pavement performance, it is necessary to vary the fatigue or over-all design factor with the value of the subgrade modulus, as well as with coverages or stress repetitions. Variations in the design factors for different values of subgrade modulus are shown by the curves of Figure 3. This figure gives the design factors used by the Corps of Engineers with Westergaard's formula for stress at a free edge of a slab under load. The stress is reduced 25 percent for load transfer at a joint. This resulting stress multiplied by the appropriate design factor is set equal to the average flexural strength of the concrete to obtain the design thickness of the pavement for a specified loading. For example, if the pavement is to be designed for 5,000 coverages of the 100 kip twin-wheel loading on a subgrade having a "k" value of 200 lb per in.^{3} or less, the design factor would be 1.30. Assuming that the average flexural strength of the concrete will be 700 psi, the design thickness "h" of the pavement should be such that the load

TABLE 2

SUMMARY OF DESIGN FOR 100 KIP TWIN WHEEL GEAR LOADING

Subgrade Modulus "k", lb per in.^{3}	Flexural Strength of Concrete, psi	Design Factor		Pavement Thickness, in.	
		5,000 Coverages	30,000 Coverages	5,000 Coverages	30,000 Coverages
100	700	1.300	1.520	15	18
300	700	1.215	1.435	12	15
400	700	1.110	1.300	11	13
500	700	0.960	1.130	10	12

will produce a stress at a joint equal to the flexural strength of the concrete divided by the design factor (700/1.3 = 538 psi). Table 2 shows the effect on design when applying the design factors from Figure 3 to a 100,000 pound twin-wheel gear loading for different values of subgrade support. Table 2, with the foregoing definitions, indicates how the basic theory is modified by the design factors to obtain agreement with observed pavement performance and a specific definition of failure. The same principles can be applied in the evaluation of an existing pavement for an increase in loading or changes in aircraft operation. In this case it is desired to know the number of coverages of a given loading that a pavement can sustain until failure occurs, and how many coverages it will sustain until complete breakup of the pavement occurs. In the first case, initial failure is defined as "30 percent of the slabs in a trafficked area broken into 2 or 3 pieces by structural breaks," and complete breakup of the slab is defined as "50 percent of the slabs in the trafficked area broken into 6 pieces." Figures 4 and 5 respectively are used to evaluate for these two conditions. In these cases the percent standard thickness is plotted against coverages for different values of subgrade modulus, "k". The percent standard thickness is the thickness of the existing pavement divided by the standard thickness for the evaluation loading times 100. The standard thickness is the thickness required for the loading, using a constant design factor of 1.3 for all values of subgrade modulus. For values of "k" up to 200 lb per in.^{3} this design factor of 1.3 represents the 5,000 coverages level, see Figure 3. For example, assume an existing pavement is 13-inches thick and in good condition, the subgrade modulus, "k", is 100 lb per in.^{3}, and the flexural strength of the concrete is 700 psi. It is required to evaluate this pavement for an aircraft having a maximum twin-wheel gear load of 100 kip. For this particular case, Table 2 gives the standard thickness as 15 inches (first row, column 5). The percent standard thickness would be (13 ÷ 15) x 100 or approximately 87 percent. The evaluation for the number of coverages to produce initial failure is given by Figure 4 as 50 coverages, while for complete failure Figure 5 gives about 1,500 coverages. These coverage numbers are then converted to aircraft operation numbers and the pavement life is predicted for each pavement feature, whether taxiway, runway or apron.

SUMMARY AND CONCLUSION

The evaluation of rigid pavement performance must begin with a design concept which relates the traffic loading and its frequency to the physical properties of the pavement and its supporting media. The significant factors and application of the method of design and evaluation given in this paper are:

1. For either the design or evaluation of a rigid pavement, a definition of the condition of the pavement at failure must be established. In some cases this definition can be more severe for evaluation than for design.
2. Methods of design or evaluation must be based on accurate and detailed observations of pavement performance.
3. Westergaard's theoretical formula for edge loading with an allowance for load transfer at a joint provides an accurate means for appraising the relative capacity of concrete pavements.
4. Where it is necessary to take into account load repetition and to alter the theoretical relationship of values of subgrade modulus, modification of the formula by design factors provides a means of obtaining agreement with actual pavement performance.
5. Although the design and evaluation factors given by Figures 3, 4, and 5 are set up for specific application they provide a scale which translates the results of many pavement tests and observations into usable form for continued evaluation of rigid pavement performance. Where controlled traffic tests are made on specially constructed test pavements these factors will provide a method for predicting failure or analyzing test results.

ACKNOWLEDGMENT

The investigational program on which the design and evaluation procedures given in this paper are based has been carried out by the staff of the Ohio River Division Laboratories, Corps of Engineers, U.S. Army. The program is directed and coordinated by members of the Airfields Branch, Engineering Division for Military Construction, Office, Chief of Engineers. This work was done under and by the authority of the Chief of Engineers, U. S. Army.

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Evaluation of Performance of an Existing Concrete Pavement Under Accelerated Load Application

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● THIS discussion is based exclusively on the experience gained from the load testing, through an accelerated program, of an existing concrete pavement on a section of road which 7 years ago attained national prominence. It is, of course, the research project known as Road Test One-MD. The results of this research were published in 1952 by the Highway Research Board as Special Report 4. It is not intended to present all the results of the test, but to discuss briefly the several methods used to evaluate the performance of the pavement under applied load. The project was conducted under the direction of the Highway Research Board according to a plan of accelerated loading and testing unanimously agreed upon by all the participating states, the Bureau of Public Roads, the Automobile Manufacturers Association, the petroleum industry, the American trucking associations, and the Department of Defense.

The principal purpose of the test was to determine the relative effects on a particular concrete pavement of four different axle loadings—two single axles and two tandem axles. The word "relative" in the objective is stressed because the methods of rating the performance were identical in all test sections under as nearly as possible identical conditions. The only variable was the axle loading. Therefore, any difference in the pavement performance of two parallel test sections was due primarily to the relative effects of the two different axle loadings.

In its operation the test consisted primarily of comparing the relative effects of 18,000- and 22,400-lb single rear axles and 32,000- and 44,800-lb tandem rear axles. The test sections were subjected to the designated load applications at a frequency of one a minute by the single-axle loads and at a frequency of one for each 45 sec by the tandem-axle loads.

The test pavement consisted of two 12-ft lanes each having a 9-7-9 in. cross-section, both reinforced with wire mesh. Expansion joints were spaced at 120-ft intervals with two intermediate contraction joints at 40-ft spacings. All transverse joints had dowel bars ¾ in. in diameter at 15-in. spacing and the adjacent lanes were tied together with ⅝ in. tie bars 4 ft long spaced at 4-ft intervals.

The following methods were used to determine the performance of the existing concrete pavement before, during, and after running of the test traffic: soil survey; physical properties of the concrete; load strains and deflections; temperature warping stresses; surface roughness; and slab settlement—precise leveling. Observations were made daily of the following during the period of test traffic: edge and joint pumping; pavement cracking; and edge and corner spalling.

The principal objectives of the soil survey were the investigation, analysis, and correlation of subgrade information with pavement performance—pumping, cracking, and settlement. Over 1,400 soil samples were analyzed from beneath the 1-mi test section. The results showed (a) that there was a significant difference in the pavement performance on granular and fine-grained subgrade soils for the magnitude and frequency of axle loads used in the test, and (b) that the physical test data could be used to distinguish between satisfactory and unsatisfactory subgrade soils for concrete pavements.

Over 150 cores and 80 beams, obtained from the test pavement, were subjected to various laboratory tests for the determination of the physical properties of the concrete. The results showed that the pavement was of the designed thickness, had an average compressive strength of about 7,000 psi and an average modulus of rupture of over 800 psi. In other words the concrete in the test road was of average quality and its fatigue properties were normal.

During the load-strain and load-deflection tests, 9,000 strain readings, 3,000 deflection readings, and 2,500 readings for the development of the influence line data were obtained. The load strain studies were divided into five cases of loading: interior, free-edge, corner, transverse joint edge, and special. The special case of loading was included primarily to determine the cause of longitudinal cracking. This research developed information of (a) load-stress and load-deflection relations for slabs on granular soil where no pumping existed and for slabs on fine-grained soil prior to and after the development of pumping, (b) comparison of the effects of single- and tandem-axle vehicles, (c) effect of speeds and transverse placement of vehicles, load transfer, faulting, and warping of the slab on the magnitude of stress and deflections caused by loads, and (d) stresses resulting from restrained warping of the slab.

The most important warping stresses in concrete pavements are those caused by the daytime and nighttime temperature differentials. Restrained daytime temperature warping causes tensile stresses in the bottom of the slab, whereas restrained nighttime warping causes tensile stresses in the top of the slab.

Road-surface roughness measurements were obtained at four different periods using the Bureau of Public Roads roughness indicator. Measurements were made in both directions of travel along each normal wheel path at 20 mph. The degree of roughness increased in greater amounts in the sections subjected to the heavier axle loads of each vehicle type.

Slab settlement was determined by using precise levels. The U.S. Coast and Geodetic Survey placed 15 permanent bench marks at 400-ft spacings along the project and determined their elevations. Using these elevations precise level observations were made at four different periods to determine the elevations of 10 spots painted on each slab under test as follows: two at the transverse joint, two 5 ft from the transverse joint, and one at midslab, both at the free edge and at the longitudinal joint. The greatest settlement was found at the free-edge corners of the slabs and the least settlement was noted at the midpoint of the slab along the longitudinal joint.

A pumping survey was made each day during the course of the test. The survey consisted of recording the number of places together with the lineal feet along the free edge, and the number of the transverse joints where pumping was occurring. This method proved very satisfactory for this test. The extent of pumping varied with the magnitude and character of the load applied. For similar types of soil, pumping developed earlier at expansion joints than at contraction joints.

A detailed survey was made of the cracks in each slab prior to the beginning of test traffic. During the test traffic, each slab was checked daily for cracks. The exact position of each crack as it developed was recorded on a card with the date and number of load applications when the crack was first noticed. The structural cracks recorded were those that appeared during the test-load applications for which there could not definitely be assigned a cause other than the probable effects of loads, and which upon examination showed a definite and continuous cleavage plane in the concrete. As new cracks or extensions of old cracks developed, they were painted with lines of contrasting color 1½ in. in width. Early in the study and again after test traffic was terminated, the U.S. Air Force flew a jet plane over the project and obtained a Sonne-strip photograph in color showing the cracks as variously painted in each slab.

In conjunction with the crack survey, observations were made of the number of spalled places and of the number of small corner cracks. Although these areas were greater in number for the heavier axle loads than for the lighter loads, this method of determining pavement performance was not as effective as the other methods used. The number of such such spalled areas and small corner cracks were too few to be significant.

In conclusion it may be stated that for the condition of the Road Test One-MD, the methods used to determine the performance of the concrete pavement were quite satisfactory. The objectives of this particular study were accomplished.

Consideration of Appropriate Elements For Rating a Pavement

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● THE APPROACH to the rating of a pavement is a negative thing. By this is meant that no thought was given to a pavement structure in terms of the original condition which existed in any pavement which was being rated, but always in connection with the amount of destruction which has occurred or the amount of failure which had taken place from the time that the pavement had been constructed. Thinking then about the rating of a pavement in terms of failure, the following is presented.

In approaching the rating of a pavement in a rational manner, it appears to be sound that the pavement, as a structure, can act no differently than would be indicated by the behavior of its constituent parts. Any one of its several parts, for example, wearing course, base or subbase, might behave in a satisfactory manner alone, but might, in combination with other elements of a pavement, behave in a faulty manner.

An excellent wearing course of appropriate design and dimensional characteristics placed on a completely unstable foundation is taken as an example. Certainly, the expectation is that the pavement will fail because of the lack of stability in the foundation. That same wearing course on top of a good foundation would, on the other hand, behave in the desired manner.

ELEMENTS WHICH WILL CONTRIBUTE TO FAILURE

Any one of the elements of a road, starting with the wearing course and proceeding through the base course, subbase course and into the basement soil or foundation, can and does perform in a manner which will cause a pavement failure.

BASIC CAUSES OF A PAVEMENT FAILURE

The knowledge of engineers regarding the design of a wearing course has advanced to the point that pavement technicians can provide formulas of the combinations of aggregates, fillers and binder materials that provide both good stability and good durability. Occasionally, an attempt is made to utilize local materials which are not consistent enough to fall within the limits of good design practice. In these instances, failures in a number of wearing courses have occurred. To the greatest extent, however, the design of wearing courses has been good and their performance has been consistent with our design.

Assuming a wearing course properly designed, with good durability and with resistance to the natural forces of nature such as oxidation, freezing, thawing and moisture changes, then analysis of other basic causes which may result in a pavement failure and which are disassociated from the design of the mixture of the wearing course may proceed.

If a properly designed mixture in the wearing course remains in the exact position of the presumption of its design, there is no evidence of failure. Movement or distortion of the pavement structure can be caused by either the application of loads or by the natural forces of nature which are not associated with loading. The distortions which occur through the application of loads are well known to persons associated with highway construction and maintenance. To summarize briefly, rutting occurs through additional consolidation or displacement; shearing occurs through the application of loads beyond the capabilities of the structure. Not as commonly thought, but just as destructive of the integrity of a pavement, are movements caused by frost or by the change of volume associated with the swelling of some soils that behave badly when in the presence of water.

A project in Colorado was built to a modified AASHO standard of compaction and then covered with a rigid pavement. Within a period of 18 months, there was a differential heaving of the surface that varied from negligible amounts to as much as 12 in. Simply stated, the pavement at certain points was 12 in. higher than when poured. There was no free water source to a depth of 30 ft. This type of differential movement of the basement soil causes disruptive forces which are readily apparent on the surface.

VISIBLE EVIDENCES OF FAILURE

In a wearing course, failures or incipient failures have the visible evidence of distortion from the design cross-section. For instance, where oxidation is present in bituminous materials, a pattern of cracking and surface abrading are common characteristics. In rigid pavements, there is the usual joint faulting, spalling and shearing cracks.

Movement or failure in the foundationing base and subbase courses is often visible in a surface distortion if it is of a magnitude which would not be possible in the wearing course alone. Some of the subsurface indications are rather hard to detect because they are of a type which is not readily detectable at the surface. There is, for instance, the loss in volume due to additional densification of the materials under the vibratory effect of traffic. There are cases where plastic materials have intruded upwards into the granular course and have, with the addition of a proper amount of moisture, caused a plastic flow.

The basement soils can be affected by a number of things, all of which cause them to act in a manner which occasions movement of a magnitude which induces failure of the pavement structure. Most common is a change in volume occasioned by a change in moisture. This increase or decrease in volume can be of an order which will be readily apparent at the surface. An increased volume usually is associated with a decreased bearing value, and this decreased bearing value might be of a magnitude which would put it in an area where the soil no longer would be able to resist the shearing stress.

The generalizations made above regarding wearing courses, supporting courses and the basement soils are certainly not intended to be all inclusive. They have been cited as examples of the types of things which are commonly associated with pavement failures.

OBSERVATIONS AND TOOLS TO MEASURE THE EVIDENCES OF FAILURE

Wearing courses are usually rated by the amount of measurable surface distortion or roughness, the number of linear feet of cracks, the amount of spalling or area of faulting which has occurred. The invisible is, in this case, probably more pertinent than the surface indications.

In recent years, some sonic equipment has been developed which gives a tool for measuring the structure integrity of rigid pavements. In flexible pavements, there are means to extract the binder and determine the amount of hardening of the residual asphalt which has occurred. There are tools to measure increases in density. The pioneering work of Benkleman let to a deflection tool which was associated in the WASHO Test with critical deflections by temperature ranges.

There are no means of evaluating from the surface, the base and subbase courses of the average highway unless the movement has been so severe that the wearing course has been disrupted. Drill tests can determine the thickness of the various layers, their moisture and density and, to some degree, any displacement which has occurred.

The evaluation of basement soils follows the methods that have been discussed for the base and subbase courses.

GROUPING OF ELEMENTS FOR RATING PURPOSES

Having reviewed the elements of the road structure which can have a part in the failure of a pavement, the tools to work with and the extent of the measurements which can be made, those elements which should be given consideration for inclusion in the rating of a pavement should be decided upon.

Table 1 shows the elements, the apparent adequacy of tools of measurement and the interrelationship between the elements which must be rated in order to arrive at a final rating of a pavement.

The assignment of values to any of these elements and their relationships has been omitted because the application of the rating should be known before this is decided. If

TABLE 1
ELEMENTS TO BE RATED, THEIR INTERDEPENDENCY BY RATING ITEMS AND ESTIMATE OF THE AVAILABILITY OF EVALUATION TESTS OR INSTRUMENTS

Elements of Pavement Structure	Items which Contribute to Failure	Dependency on Other Elements of Pavement when Rating	Availability of Tests or Evaluation Instruments for Rating
Wearing course	Design of mixture	No	Yes
	Thickness	Yes	No
	Adequacy of support	Yes	No
	Loading	Yes	Yes
	Environment	Yes	No
Base and subbase course	Basic stability	No	Yes
	Thickness	Yes	No
	Adequacy of support	Yes	No
	Loading	Yes	Yes
	Intrusion of plastic material	No	No
	Change in volume	No	No
Basement soil	Moisture and volume changes	No	Yes
	Overstressing due to inadequate strength in pavement structure	Yes	No

the purpose of the rating is to decide the effectiveness of a design, then the rating is wholly confined to determining the effect of loads of known magnitude on a structure of known characteristic. Opposed to this would be a pavement rating on a highway under normal usage and where the highway geometrics and the placement of the vehicle loads are just as important as the structural elements. The weight that would be given to the various elements in the two cases would have to be substantially different.

CONCLUSION

The preparation of this brief summary has brought to mind the frustration of many years of experience in the rating of highways. Most rating is done at a time when the highway structure has been destroyed as a usable facility, rather than at a time when the rating would provide information of a type which would permit of preventive maintenance. It is hoped that in the not too distant future, tools will become available which will permit prediction of failure in sufficient time to take the necessary steps to stop the destruction that is occurring from either loads or natural forces.

Discussion

W.H. CAMPEN, Manager, Omaha Testing Laboratories, Omaha, Nebraska — The ability to carry loads constitutes the most important function of an existing pavement. This characteristic can be evaluated by making deflection determinations by loaded steel plates or tires.

By either method the maximum load can be determined which will produce practically no permanent deformation and only a limited amount of elastic deformation. As to the latter, there seems to be a difference of opinion in regard to the allowable deflection. However, sufficient information is available to indicate that an elastic deflection of about 0.05 in. will be satisfactory.

R.E. LIVINGSTON, Closure, — The author agrees with Mr. Campen's statement that testing plates do develop good information regarding the load carrying capabilities of existing pavements. The information must be correlated with service behavior. In addition, there is not currently any agreement as to the allowable deflection before a pavement is determined to be distressed.

Failure Criteria For Flexible Airfield Pavements

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● IN THE development of the Corps of Engineers' flexible pavement design procedures, it has been customary to study both failed and unfailed pavements and then to set the design criteria at a level so that the failures would be eliminated.

In the early work of the Corps of Engineers' Flexible Pavement Laboratory, attempts were made to define the word "failure." It became apparent, however, that any reasonable definition of failure would have to consider a stated amount of maintenance, because maintenance is an accepted feature in any type of failure. Since it appeared hopeless to reach agreement on an "acceptable amount of maintenance," attempts to ascribe a specific definition to the term "failure" were abandoned, and now the term is used loosely to refer to an unsatisfactory condition in the pavement of sufficient severity to warrant attention.

The loose definition of failure given in the preceding paragraph is not satisfactory for use in developing design criteria for flexible pavements, which is the principal mission of the FPL, and it has been necessary to develop definitions of conditions which could be accepted as satisfactory and unsatisfactory so that design criteria could be set at the proper level. It has generally been found desirable to avoid the term "failure," except in the loose sense noted above, and to use terms which are descriptive of the behavior or the condition.

The major causes of unsatisfactory conditions in flexible pavements that have been studied by the FPL are (a) inadequate thickness of subbase, base, and pavement, (b) inadequate compaction in the subgrade, subbase, and base, (c) inadequate durability in the bituminous layers, and (d) inadequate stability in the bituminous pavement under traffic during hot weather. It is recognized that unsatisfactory conditions can develop in flexible pavements for reasons other than those listed, but these are not discussed in this paper.

THICKNESS

The FPL considers that the thickness of base and pavement above a given layer is inadequate if detectable shear deformation occurs in the given layer. Shear deformation is defined as change in shape with no change in volume, sometimes referred to as plastic movement or plastic deformation. Shear deformation usually occurs after pore pressures develop. During traffic, materials move out from under the wheel paths, creating a depression in the traffic lane and an upheaval outside the traffic lane. Typically, the bituminous pavement is cracked in the traffic lane. The thicknesses shown on the CBR design curves for a given CBR are intended to prevent all shear deformation in the layer with the given CBR.

Determination of the occurrence of shear deformation in a given layer can be made by a study of deflection measurement, in-place CBR tests, cracking of the pavement, upheaval of the surface, and position of the layers.

Deflection

Deflection is defined as the downward movement under load. Deflections are generally measured at the surface in the accelerated traffic tests conducted by the FPL under standing loads at intervals throughout the period of the traffic tests. Deflections at the level being considered (usually subgrade) are desired, but surface deflections can be used if the overlying layers are of high quality and adequately compacted so that little compression occurs under the load.

Curves of deflections versus coverages can be used to determine if shear deformation is occurring. Figure 1 shows idealized curves. Curves A and B, which show a decreasing or constant deflection with coverages, are typical of conditions where no shear deformation occurs. Curves C and D are believed typical of cases where shear deformation occurs. Case D indicates a severe overload; case C indicates the conditions desired in an accelerated traffic test. This curve shows a small increase in deflections versus coverages during the early stages followed by sharp increase in deflection at a substantial number of coverages. Generally, in the traffic tests conducted by the FPL, which have been made with airplane loads, deflections have been in excess of 0.25 in. when shear deformation developed.

In-place CBR

In-place CBR test, and probably any strength test, can be used to indicate the development of shear deformation in any layer if the tests are made at intervals throughout traffic. Where no shear deformation occurs, the CBR value will remain constant or increase with traffic; where shear deformation occurs, the CBR will show a significant drop.

Cracking

The cracking that develops in a bituminous pavement when shear deformation occurs follows a typical pattern. In the early stages, the cracks are generally parallel to the direction of traffic. As repetitions are continued, transverse cracks occur and a blocky or alligator pattern occurs. Closely spaced cracking indicates shear deformation in a layer near the surface; widely spaced cracking indicates shear deformation in a deep layer.

Upheaval

Upheaval of the surface adjacent to the traffic lane is definite evidence of shear deformation, but the layer in which the shear deformation occurred cannot be determined from the surface. Also, traffic must be continued well beyond the point where shear deformation starts in order to develop sufficient upheaval to be measured.

Position of Layers

A cross-section of the face of a trench cut across the traffic lane can show whether or not a layer has been overstressed to the point where shear deformation occurred (see Fig. 2). A thinning of a layer in the traffic lane accompanied by a thickening of the layer outside the traffic lane is evidence of shear deformation in the layer. Also, upheaval of the subgrade outside the traffic lane is evidence of shear deformation in the subgrade. As noted above in the discussion of upheaval, traffic must be continued well beyond the initial development of shear deformation before it can be detected in a profile.

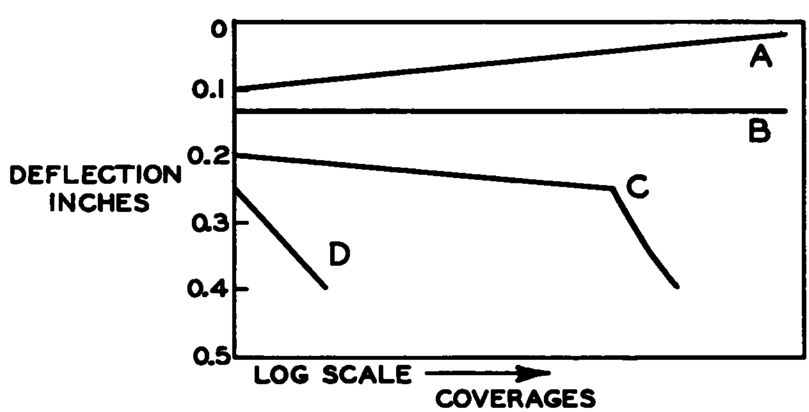

Figure 1. Relationship of deflection to traffic.

COMPACTION

Compaction is defined as a change in shape accompanied by a change in volume as opposed to shear deformation where no change in volume occurs, or simply as a reduction in voids. The compaction due to traffic is generally the only concern as the compaction due to the weight of the flexible pavement structure is generally negligible. Compaction results in a depression beneath the wheel path with no upheaval outside the traffic lane and typically with no cracking of the pavement. The shape of the depression is a clue to the layer that was densified. Compaction in a layer near the surface will produce a sharp depression; compaction at a depth produces a broader depression.

Compaction is not detrimental to a flexible pavement (except where the compaction produces pore pressures and a consequent reduction in strength with probable shear deformation resulting), but the depression which occurs is objectionable to the user if it becomes deep enough. Also, the ponding of water after rains in the depressions tends to shorten the life of the pavement. The acceptable amount of compaction would have to be stated by the user. The procedure used by the Corps of Engineers to design against compaction is to specify a density to be obtained during construction that will not densify any appreciable amount under traffic. Density design criteria were developed by sampling pavements that had been subjected to traffic and measuring the density that had developed. Some of the pavements had settled because of compaction. It is believed that had the compaction that developed under traffic been obtained during construction, densification under traffic would have been negligible.

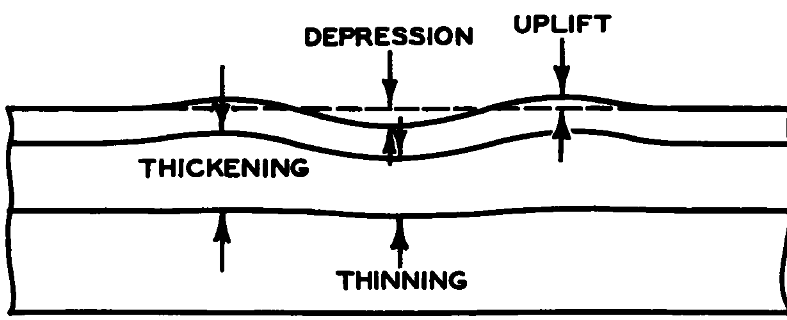

Figure 2. Effect of shear deformation.

DURABILITY OF ASPHALT PAVING MIXTURES

The FPL studies on the problems of durability have been limited primarily to laboratory tests and to exposure tests, and to date no design criteria regarding durability have been developed from these studies. The CE design philosophy to obtain maximum durability is to use as soft an asphalt and as much of it as possible without obtaining a pavement that flushes during hot-weather traffic. This should not be construed, as it might be, to mean that CE-designed pavements involve high percentages of asphalt since the avoidance of flushing in pavements subject to large, high-intensity loads results in designs ordinarily considered quite lean.

STABILITY OF PAVING MIXTURES DURING HOT-WEATHER TRAFFIC

The preceding discussions of shear deformation and compaction were directed toward subgrade, subbase, and base course materials, but these types of behavior also occur in bituminous paving mixtures, although in a bituminous paving mixture shear deformation is generally termed "plastic flow."

Compaction and plastic flow can occur during traffic in other parts of the year than during hot weather, but the effect of temperature is so great that generally only the hot-weather traffic is considered. The FPL has simulated hot-weather traffic by testing only when pavement temperature is above 90 F. Also, the compaction that occurs in

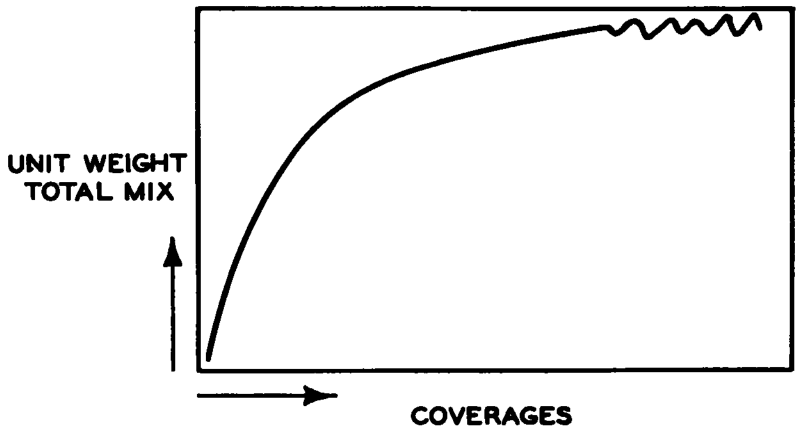

Figure 3. Relationship of density to traffic.

paving mixtures is usually ignored because depressions produced by compaction in paving mixtures are small.

In paving mixtures studied by the FPL, plastic flow does not occur until the mix has flushed; therefore, the most important tool for studying the development of plastic flow in paving mixtures is the measurement of density or voids at increments of traffic. Figure 3 is a typical curve of the relationship of density to traffic. Traffic produces densification to the point where the mix is flushed following which the density shows minor deviations but no further significant densification. If traffic is continued far enough, upheavals develop outside the traffic lane. Where the plastic flow is in the surface course, it can be detected by visual observations of trained observers almost as readily as it can be measured by density sampling. A surface course that is being subjected to plastic flow develops a typical wrinkling that is readily apparent at the edge of the traffic lanes and at any disconformity such as at an old core hole that has been refilled. Where the plastic flow is in the binder course or other underlying layer, sawing trenches with diamond saws becomes necessary so that the individual layers can be traced. A thinning of the layer in the traffic lane and a thickening outside the lane is definite evidence of plastic flow.

SUMMARY

In the preceding discussions, the causes of distress were neatly separated. This is rarely if ever the case in nature. When distress occurs in an actual pavement, both compaction and shear deformation are usually involved and it is necessary to attempt to separate the two. Compaction, though contributing to undesirable surface irregularity, increases the structural strength of a pavement (short of the point at which pore pressure develops) and becomes successively less under a given intensity of traffic. Shear deformation, on the other hand, becomes successively more pronounced in its resultant effects under a given intensity of traffic and has no beneficial effects.

It is important, therefore, to recognize the occurrence of shear deformation as a primary mechanism of failure regardless of the point at which resultant surface irregularities become intolerable for the use for which the pavement was designed. Also, if the behavior is to be used to improve the design criteria, it is necessary to establish the layer or layers which have been overstressed. This deformation requires careful observation and in most cases, sampling and testing.

Pavement Performance Inventory in Michigan

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● MICHIGAN'S EFFORTS to obtain specific data on the subject of pavement performance started in 1924. The study involved actual field mapping of pavement and foundation conditions. The important objective at that time was to obtain information on pavement performance under climatic, soil and traffic conditions as they occur in Michigan. The study served as an excellent training medium for department engineers, and in addition it served as the background for soil engineering practices as developed in the state. The study did not result in extensive publications, probably because of inadequate facilities for handling the mass of data resulting from the large number of variables involved.

The continuous concern regarding pavement condition and pavement performance over the years since that early survey has stimulated much study of methods for making highway evaluations or sufficiency ratings. During the same time there has been a significant change in the average engineer's attitude toward the highway and its function. Instead of being preoccupied mainly with the wearing course, he has learned that pavement performance is a function of the combined effect of wearing course, base course, subbase and foundation soil. The term pavement, therefore, has come to be defined as consisting of the first 3 of 4 elements listed. The second change in attitude concerns the relationship between highway and vehicle. Instead of building the roads and then requiring that the transportation industry fit its operations to the highway provided, there is a trend in thinking which favors designing the highway to fit some optimum vehicle size and axle load which will best serve the transportation industry.

With this modern outlook in mind the next natural step in Michigan was to determine how the existing trunkline system satisfied modern strength requirements. A strength inventory has, therefore, recently been completed of the entire trunkline system. This study involved a review of design and construction histories along with a study of foundation soil conditions. Almost all information needed for the study was obtained from office records. Every mile of the 9,398 mile state trunkline system has been classified into 4 categories, based on adequacy for 32,000-lb tandem axle loading through the spring breakup season. The results of this study have been summarized on a map of the state in order to better picture the present strength status and in order to make the results more readily usable to maintenance, planning and programming engineers.

The four classification categories used for the study may be briefly described as follows:

1. No Seasonal Restriction — Pavement and subgrade adequate for year-around service. These are roads founded on sand and gravel soils which need only to be properly compacted and confined to carry any weight of axle load.
2. No Seasonal Restriction — Pavement designs which compensate for seasonal loss of strength. These roads involve soils which contain significant quantities of silt and clay and which, therefore, seriously lose strength during the spring breakup season. This loss has been adequately considered and compensated for in building the highway.
3. Spring Load Restriction Required — Pavement designs which do not compensate for seasonal loss of strength. This classification may involve portland cement concrete built without means for controlling mud pumping or it may involve bituminous pavement designs without sufficient thickness of surface, base and subbase to support unlimited repetition of legal loads during the spring break-up season.
4. Spring Load Restrictions Required — Pavement design inadequate for legal axle loads at all times. These roads are made to serve present traffic only by expanding extra maintenance effort and by accepting a shortened pavement life span.

This strength evaluation of the trunkline system has been put to immediate practical use. First, it has served as a basis for extending the system of special loading routes on which Michigan law permits one set of tandem axles in a hauling unit to carry 32,000 lb in place of the normal 26,000-lb maximum. Secondly, it is serving as a basis for selecting a system of roads on which special seasonal load restrictions will not be needed. In the third place, it is anticipated that the study will aid in highway programming by more clearly calling attention to weak links in the highway system. For programming purposes the summary map will also serve as a base map for overlays which will summarize alignment, cross-section and wearing course information. Such information, plus strength and traffic data, should form an excellent background of organized facts needed to develop a trunkline system adequate for year-around service without special spring load restrictions.

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