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PAVEMENT FAILURE ANALYSIS WITH GUIDELINES FOR REHABILITATION OF FLEXIBLE PAVEMENTS

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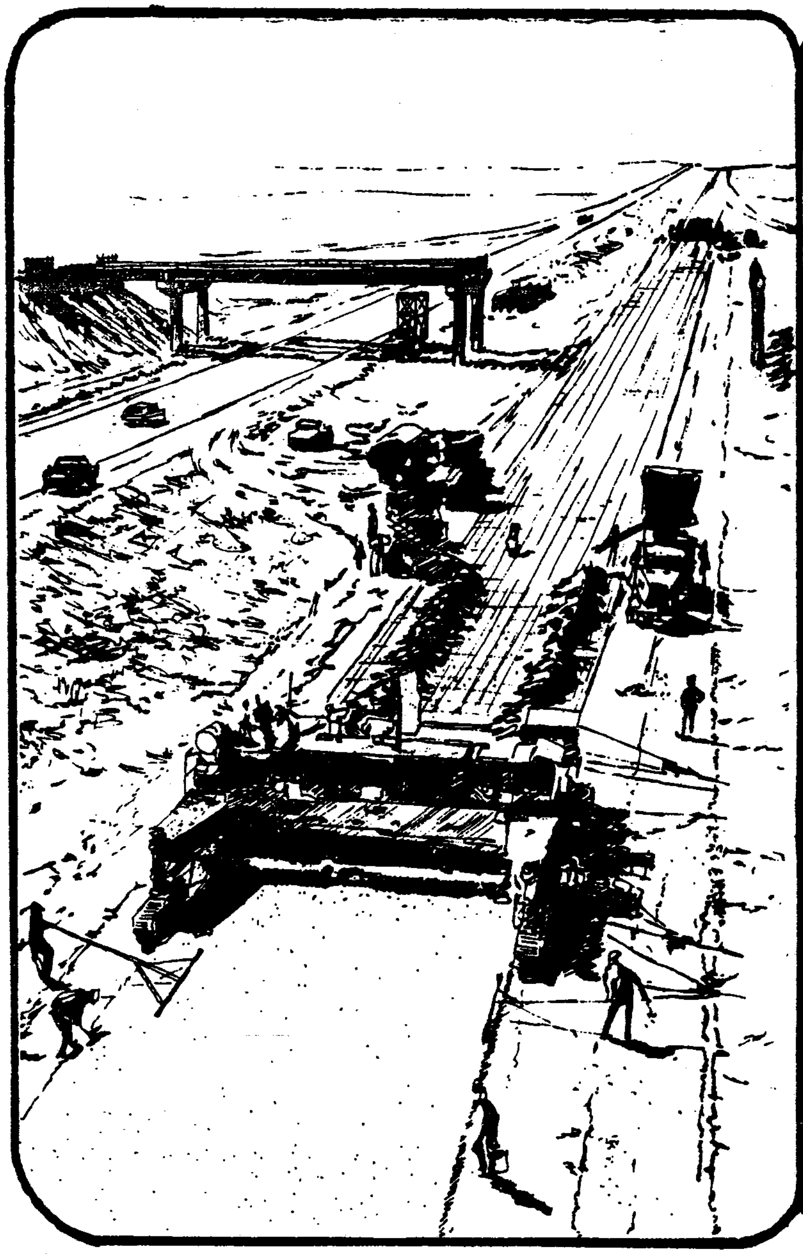

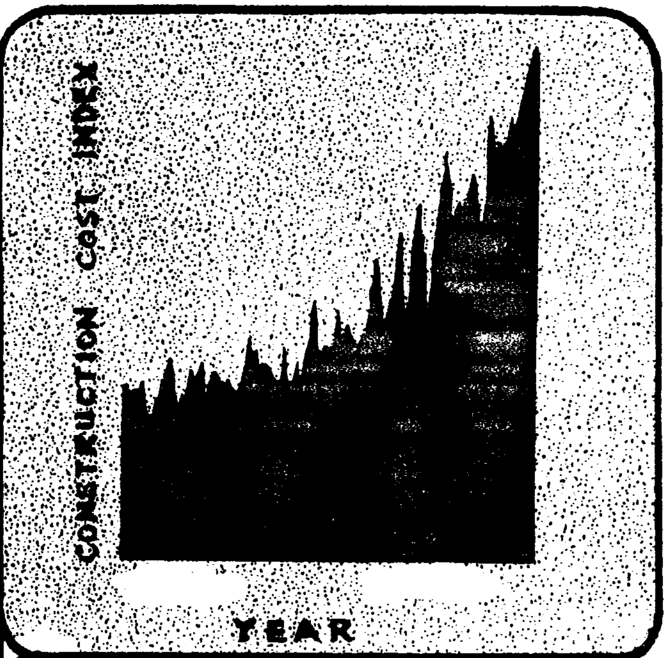

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PAVEMENT FAILURE ANALYSIS WITH GUIDELINES FOR REHABILITATION OF FLEXIBLE PAVEMENTS

BY

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INTRODUCTION

Like death and taxes distress in pavements is inevitable. Some pavements just "wear out" as would be expected for a certain type of construction. Some pavements exhibit distress prematurely while others seem to last "forever". Pavement failure analysis and diagnostic procedures are concerned with distress wherever and whenever it may occur, a major concern is usually indicated in the case of premature distress.

When pavements fail prematurely it is often in the best interest of the department to investigate and identify the probable cause. Based on findings from such investigations it should be possible to initiate corrective procedures to avoid continuing problems of a similar type.

The reliability of a failure analysis will vary depending on the information available. In some cases the cause of failure will be obvious, such as truck loads (number and weight) having increased significantly above expected levels. In many cases the analysis will not be so straightforward and a more in-depth study will be necessary to identify the factors responsible for the undesirable pavement performance. Thus, the investigation can be planned and conducted at two levels: (1) an evaluation of data which requires a minimum of additional testing and depends largely on design and construction records plus comparisons with current observations, and (2) an in-depth evaluation and analysis which would require further field and laboratory testing based on the findings from records and observations.

In some cases the major concern will be rehabilitation of an in-service distressed pavement. Depending on the circumstances, a failure investigation may or may not be appropriate. If there is nothing unusual about the occurrence of distress the main concern will be the selection of appropriate rehabilitation procedures. However, if the occurrence of distress is considered unusual it may be useful to conduct a failure investigation before selecting a rehabilitation procedure. The purpose of such an investigation would be to minimize any adverse effects of the original construction on the performance of the rehabilitated pavement.

Generally, engineers will have several options available for rehabilitation of a specific pavement. These options will depend on the functional class of roadway, traffic, current condition, environment and service requirements. In choosing from among the various rehabilitation alternatives three factors should be evaluated: (1) pavement requirements for rehabilitated pavement, (2) costs, and (3) energy requirements. Inherent in such considerations are reliability, user convenience, and budgetary restraints. Systematic evaluation procedures need to be provided for these factors.

The objectives of this report are to provide information and guidelines for pavement failure analysis and for selection of rehabilitation procedures. The report has been prepared in three parts as follows:

1. Pavement Failure Analysis with Guidelines for Rehabilitation of Flexible Type Pavements.
    a. Identification of Types and Causes of Premature Failure in Flexible Pavements
    b. Guidelines for Detailed Investigation of the Cause of

Premature Failure in Flexible Pavements

   c. Guidelines for Identification of Appropriate Rehabilitation Procedures

2. Economic Evaluation of Alternative Rehabilitation Procedures
3. Energy Evaluation of Alternative Rehabilitation Procedures

Figure 1 is designed to help associate the information contained in the reports with a step-by-step process for failure analysis and selection of rehabilitation procedures.

PART 1a - INITIAL INVESTIGATION TO IDENTIFY CAUSES OF PAVEMENT FAILURE IN FLEXIBLE PAVEMENTS

When a pavement exhibits distress it immediately becomes a concern for the management personnel within the Texas State Department of Highways and Public Transportation (DHPT). A decision is necessary; what should be done to maintain or rehabilitate the pavement? A number of questions need to be resolved; did the pavement fail prematurely or did it perform in accordance with design expectations? If the pavement failed prematurely, what caused it to fail prematurely and what steps are required to avoid a recurrence of the same situation, Is the premature failure an isolated case or have there been other similar occurrences which may indicate more general problems which require changes in design procedures, material requirements, or construction specifications?

The major objective of a failure analysis is to identify the most probable cause of distress on a specific project. By accumulating information over a series of projects it should be possible to determine if there are similarities in causes or if they tend to be random or unassociated. If there are similarities, an appropriate action will be indicated and changes in design, construction or maintenance requirements will be necessary. If the causes are random or different from project to project, no overall changes may be necessary. It should be recognized that the science of pavement design and construction is imperfect, and that some premature failures are inevitable.

Preliminary studies made by the Texas Transportation Institute in three districts within the state indicate that the expected life cycle of most pavements, ranging from seal coats to hot mix asphalt concrete (HMAC) is six years. That is, some type of distress requiring maintenance or rehabilitation can be expected (on the average) within six years of construction, and about 15 percent could require some form of maintenance in four years. With this type of information it might be possible to define premature failure as any condition which would indicate a need for pavement maintenance within six years from date of construction. This definition may not be applicable in all cases. Information on expected life cycles is necessary before setting criteria in a specific district; however, in order to provide some estimate of premature failure the four-year criteria does not appear inappropriate. Longer periods could be considered if the average life cycle is increased and the distribution of life cycle by construction types is known.

Figure 2 illustrates the procedure to be used in identifying the types and causes of premature failure.

FIELD REPORTS OF PAVEMENT CONDITION

In most situations, indications of pavement distress, premature or otherwise, will be reported from a variety of sources; for example, (1) condition surveys, (2) maintenance personnel, (3) resident engineers and in some cases (4) citizen complaints. With the exception of systematic condition surveys it is quite likely that the description of distress will be superficial and not particularly useful in a failure analysis.

Procedures for conducting pavement condition surveys have been developed for the Texas Department of Highways and Public Transportation by the Texas Transportation Institute (1,2). These techniques have been tested by department personnel and modified as is appropriate to the needs of field personnel.

It is recommended that a systematic pavement condition survey be conducted, in accordance with the latest procedures adopted by the department, in order to obtain a reliable and consistent assessment of the type and extent of distress associated with a particular project.

The purpose of the condition survey is to identify the type, extent and severity of observable distress. For the Texas procedures the types of distress identified for flexible pavements are: (1) rutting (2) ravelling, (3) flushing, (4) corrugations, (5) alligator cracking, (6) patching, (7) longitudinal cracking, and (8) pavement failures per mile.

From the condition survey alone it should be possible to (1) judge if the pavement failure warrants further investigation, and (2) associate the type of distress with possible causes.

Special reports or information may be useful to the overall evaluation and should be requested as appropriate. For example, if flushing is reported to be excessive, information on the skid number and number of accidents on the section under investigation should be requested. Skid number information may require some special testing by the Transportation and Planning Division, Research Section. If excessive roughness is reported, information concerning subsurface soil types will be helpful in identifying swelling potential of foundation layers.

IDENTIFICATION OF POSSIBLE CAUSES OF DISTRESS

Initially the identification of possible causes of distress should involve at least three steps as follows:

1. Use of condition survey reports
2. Review of historical records
3. Review of traffic information

Use of Condition Survey Reports

Table 1 summarizes possible causes of the various types of distress. It is pertinent to note that there are several causes identified with each type of distress. There is a good chance that premature distress will be a consequence of two or more of the causes identified.

Review of Historical Records

Information pertinent to design, materials and construction will provide the basis for the failure analysis. However, in assessing what information should be collected, the analyst must first determine the possible association between the type of distress observed and the need for a particular type of background information. For example, if the type of distress is flushing of asphalt, it will not be necessary to obtain information about the strength of the subgrade or thickness of pavement layers. It will be useful to know something about the HMAC mix design: - aggregate type and gradation and asphalt amount and grade. On the other hand, if the type of distress is alligator cracking or longitudinal cracking, a total spectrum of information pertaining to thickness design, material selection and construction requirements will be useful.

Table 1 identifies the possible causes of pavement distress; by association it should be possible to identify the type of background information which would be useful. For example; for rutting, the reference to unstable pavement layers would indicate the need for construction records which document the quality (stability) of the HMAC base and subbase materials.

Table 1 has been made as complete as possible; however, it is recognized that special conditions may exist which can help identify the cause of distress. Three examples would be: (1) high volume change foundation materials, (2) climate at the site during construction and (3) performance of similar construction in the area. Some information appropriate to these special situations may be obtained from historical records; however, it is recommended that personnel involved with the construction under investigation be interviewed as a valuable source of information.

Review of Traffic Information

A major contributor to the occurrence of distress in a pavement is traffic. If the type of premature distress is considered to be traffic related, as most are, a first item of investigation will be to compare the design volume and load characteristics of the traffic with those of actual traffic. In making an evaluation of the traffic it will be necessary to convert the design traffic (estimated for 20 years) into an annual traffic, with some consideration for growth. If preliminary comparisons indicate traffic may actually be more damaging to the pavement than originally estimated, it would be appropriate to obtain ADT and visual truck classification information and to re-estimate the design average ten heaviest wheel load daily (DATHWLD) in accordance with D-10 procedures or equivalent 18,000 lb axle loads.

In this part of the guide for failure analysis, comments have been somewhat general. Even so, if the procedures are carefully implemented three important objectives will have been accomplished as follows: (1) determination of the type of distress associated with a specific project, (2) identification of possible causes and any unusual conditions at the site, and (3) collection of background information in preparation for further evaluations.

The next part of this report will discuss how background information can be used in a failure analysis.

IDENTIFICATION OF PROBABLE CAUSES OF PREMATURE DISTRESS

Table 1 identifies the seven types of distress included in the Texas condition survey procedure for flexible pavements. In addition, items have been added for roughness plus a miscellaneous category. These nine categories will include the types of distress which are most likely to trigger some rehabilitation activity. In the following sections of this report an attempt will be made to relate each type of distress to the background information useful in identifying the probable cause of distress.

It is emphasized that this phase of the investigation is designed to identify the probable causes of premature distress. Experience suggests that premature distress is the result of more than one factor; the investigation should be designed to evaluate each possible cause before identification of the probable cause is made. In this phase of the investigation some sampling and testing may be necessary.

Alligator Cracking (fatigue cracking in HMAC)

In Table 1 seven factors are identified with alligator cracking. Each factor will be discussed briefly; in some cases the factors will require a more detailed evaluation which will be discussed in Part 1b of this report.

Structural Deficiency - A structural deficiency would imply that the load distribution properties of the combined thicknesses of the pavement layers above the subgrade plane are inadequate to prevent distress. The most direct method of evaluation, with a minimum of sampling and testing, is to obtain information necessary for a pavement structural design in accordance with the latest procedures of the Texas State Department of Highways and Public Transportation (Highway Design Division Operations and Procedures Manual, Section 4-400).

Steps to take in a structural analysis are:

- Obtain project information summarizing design inputs such as subgrade strength, traffic, and other factors used in design formula.
- Assess level of risk used in design, specifically, the interpretation of triaxial strength tests for design of the pavement structure (see Section 4-402.3 of Operations and Procedures Manual). The standard procedure would require that the pavement cross section (thickness) should be adequate for two-thirds (67th percentile) of the individual test values. If the design triaxial strength was higher for example, based on one-half (50%) of the triaxial test values, the risk of premature distress would be increased significantly. If the design triaxial strength was based on the 85th percentile the chances of premature distress due to this selection would be reduced.
- Compare design recommendations with construction records - confirm that the as-built pavement meets requirements of design. In order to accomplish this task it will be necessary to do the following: (1) obtain samples of each pavement layer, (2) measure thickness of each layer and (3) obtain samples of subgrade soil to a depth of three feet.

  The total number of samples will depend somewhat on the length of the project and the uniformity of the subgrade. Five sampling locations per mile are recommended for planning purposes. If considerable variation in materials is observed, the sampling frequency should be increased to a maximum of eight locations per mile.

The thickness of each layer should be determined at each sampling location and bag samples of base and subbase should be obtained. It is not intended that all of these materials will be tested. For this phase the materials should be examined carefully to determine if there are obvious problems or, more particularly, if there appears to be variability in the materials. A representative gradation and plasticity index of five samples of base and subbase should be obtained to confirm the visual evaluation of these materials. If the gradation and plasticity characteristics are in compliance with the specifications and visual observations confirm that the materials are of suitable quality, no testing is required. However, if there is any question regarding the quality of the materials, triaxial tests should be scheduled. Some materials with poor durability can disintegrate rapidly under severe environmental conditions, and therefore, careful examination of unbound materials can be important.

During the field sampling procedure outlined above it may be convenient to determine in-place density of the unstabilized material. Texas Test Method 115-E should be used for this determination.

When obtaining samples of the materials (aggregate) placed on the subgrade layer, some effort should be made to isolate the first two inches above the subgrade. If these materials, i.e. base or subbase, have been contaminated by intrusion from the subgrade, a reduction in the effective thickness of this layer must be considered.

Samples of the pavement and subgrade materials will be very important for the following reasons: (1) to determine if the materials are judged to be the class used for design, (2) to determine the amount of variability in material properties with depth and along the length of the project, and (3) to determine if the in-situ water content is greater than that used in testing for the triaxial classification.

With the information obtained above together with traffic data, it will be possible to make an analysis of the structural requirements for a particular pavement section under investigation. In evaluating traffic include only the cumulative amount up to the time pavement failure was observed. Thus, it will be necessary to estimate the traffic factors from the time of construction to failure; the 20 year design estimate will not be a direct consideration in the failure analysis. A full term (20 year) design should also be developed to determine what structural section would have been required using the updated design information.

Excessive Air Voids in the HMAC - High air voids in the asphalt concrete can significantly reduce the fatigue life of the asphalt bound layers.

If a pavement has been in service for 3 to 5 years, the void content should be in the range of 3 to 7 percent. If the air voids are above 10 percent, the fatigue life could theoretically be reduced by 30 percent or more of its expected value; the effective thickness of a 4inch layer of HMAC could be reduced by 1.5 inches. The following tabulation can be used to evaluate the effective thickness of a 4 inch and 6 inch layer of HMAC.

HMAC Air Voids, Percent	Effective Thickness* of HMAC, Inches	
7	4	6
8	3.5	5
9	3.0	4.5
10	2.5	4.0
12	2.0	4.0

*Rounded to Nearest 0.5 Inch

Thus, if the air voids are 7 percent or less, the effective thickness of a 4 inch or 6 inch layer of HMAC would remain 4 inches and 6 inches; i.e., no reduction. However, if the air voids were 12 percent or more, the effective thickness of the 4 and 6 inch layers of HMAC would be 2 and 4 inches respectively.

The estimate of the effect of air voids on effective thickness is based on research findings and lacks complete field documentation. Nevertheless, the analyst is advised that in making a structural analysis some consideration should be given to reducing the effective thickness as a function of air voids in the HMAC; a reasonable approximation is given in the above tabulation. In effect, the HMAC is reduced by a specific amount and the base thickness is increased by a like amount.

The determination of air voids should be made in accordance with ASTM Test Method D3203. Description of the methods used to determine air voids can be found in The Asphalt Institute Manual titled, "Mix Design Methods for Asphalt Concrete and Other Hot-Mix Types", Manual Series No. 2 (MS-2).

It will be necessary to obtain undisturbed samples of the pavement in order to measure air voids. Sampling locations could be identical with those used for other phases of the investigation; e.g. layer thickness measurements or sampling base, subbase and subgrade materials.

Stripping of Hot Mix Asphalt Concrete - Stripping is generally defined as a loss of adhesion between the asphalt and aggregate in the HMAC. The reasons for stripping are extremely complicated and not thoroughly understood by engineers. The net effect is a reduction of tensile strength or cohesion, and a reduced structural capacity. The reduction in the effective thickness of HMAC will be a judgement decision. Stripping may start from the top or bottom of a HMAC and progress through the layer. Visual observations will usually be sufficient to estimate the effective thickness of the pavement. For example, if a four inch layer of HMAC is observed to be stripping in the lower two inches, the analyst should evaluate the structure as though it were composed of two inches of HMAC and an additional two inches of aggregate base. At least five and possibly eight sampling locations per mile should be examined before assigning an effective thickness to the HMAC.

In estimating if stripping has occurred the observer should be careful to verify his conclusions with those of others who have had experience with this condition. Exposed aggregate on the surface of the pavement is not necessarily conclusive evidence that stripping has occurred. It is necessary to break open undisturbed samples and look for bare aggregate. The presence of stripping can best be observed in field samples during or immediately after periods of significant rainfall. Stripping of hot mix asphalt concrete can occur in both the winter and summer.

Aging of Asphalt Cement - Aging of asphalt refers to the change in asphalt consistency with time. The units of consistency are penetration, viscosity and ductility.

It is generally acknowledged that asphalt hardening is detrimental to the structural performance of asphalt pavements. It is rationalized that as the asphalts harden they become brittle and more susceptible to cracking. As yet there are no quantitative criteria for relating asphalt consistency to a reduced life cycle.

In a recent report issued by The California Department of Transportation (3) the following conclusion is indicated; "Penetration values of asphalt used for new AC (usually greater than 40) generally have dropped to less than 15 by the time 10 percent fatigue cracking occurs. No appreciable penetration differences were noted for good and poor performing pavements".

In any investigation of premature distress it will be prudent to investigate possible effects of asphalt hardening. For example, look for other consequences of hardening; e.g. raveling or transverse (low temperature) cracks. Examine construction records to determine if the original asphalt gave any indication of having poor durability properties, specifically, the comparison of original properties to those on residues from thin film oven tests. If the viscosity values approach the maximum allowable, such information should be recorded for future reference.

Recovery and testing of asphalt is difficult and requires considerable experience and knowledge. Scheduling of such testing should be included in the detailed investigation (Part 1b) described herein, if the analyst believes this information to be of significance. The analyst should be aware that research has indicated that for thick (greater than 6 inches) layers of asphalt concrete, the hardening of asphalt may not be damaging to the structural performance. In such cases the so-called flexible pavement will tend to perform much like a rigid pavement.

Properties of Aggregate Used in HMAC - The specific factors associated with aggregate properties are: (1) gradation, (2) shape (rounded, angular, flat), (3) texture (rough, smooth, crushed, uncrushed), (4) cleanliness (sand equivalent), (5) durability, (6) amount of deleterious material, (7) plasticity of portion passing the No. 40 sieve, (8) affinity to asphalt, and (9) absorption. It should be noted that most of the properties are not easily evaluated after the pavement has been in service for several years. Items such as cleanliness, plasticity, and amount of deleterious material can best be evaluated from construction records.

There is little definitive information to indicate the role of aggregate properties on fatigue of asphalt concrete providing the proper amount of asphalt has been used. There is some indication that crushed aggregate will provide better performance than uncrushed, and that rough textured aggregates are superior to smooth aggregates; however, it is not possible to evaluate quantitatively the role of these factors in premature cracking (4). It is recommended that aggregate characteristics be evaluated as part of the routine determination. Aggregate gradation, shape, texture, etc., should be recorded for future reference. The analyst should also summarize specification requirements for the aggregates as described in the Standard Specification under which the project was constructed as well as the most recent version of the Standard Specifications, if any changes have been made.

Absorption properties of the aggregate should be investigated. The mix design records should be checked to determine if corrections have been made for the porosity of the aggregate. Construction Bulletin C-14 indicates that if the aggregates have a water absorption of 2.0 percent or more, evaluation should be made to determine if additional asphalt is required. Also, determine if absorption is a known problem for the aggregates used on the project in question. Visual observation of a cut pavement section may reveal asphalt absorption.

As with most of the other factors, no quantitative information is available to evaluate the effect of absorption. Zube of Caltrans (5) presented the following conclusion based on absorption studies; "There exists a relationship between the percent absorption of the aggregate and the expansion and contraction of the mix. Generally, the higher the absorption, the greater the expansion". No specific criteria have been provided by the Caltrans studies. The most common effect of absorption is ravelling and loss of fatigue properties due to a reduction in the effective asphalt content. The net effect is a reduced effective asphalt content in the mix.

If no information is available concerning asphalt absorption, it is recommended that the amount of water absorption be determined in accordance with Test Method Tex-201-F. If the aggregates have a water absorption of 2 percent or more, a more detailed evaluation of the mix design is indicated.

In general, stripping is most prevalent with siliceous aggregates such as granite or chert. If visual indications suggest that stripping has occurred, the mineralogy of the aggregate should be recorded. Testing for stripping potential (water sensitivity) will be described in subsequent sections of this report related to detailed investigations (Part 1b).

Construction Considerations - Virtually all of the factors associated with premature failure can, in some way, be related to the adequacy of construction. In identifying specific factors for premature cracking the analyst should concentrate on (1) asphalt content and (2) construction variability.

If the asphalt content is consistently low, the life cycle can be expected to be significantly reduced. The air voids analysis previously referred to will provide the major indication of the effect of low asphalt content. The analyst should summarize all construction records to determine if the asphalt content was low even though construction tolerances may have been satisfied.

Large variation in asphalt content during the construction phase is another possible cause of premature cracking and should be summarized as part of the investigation.

Drainage - Both surface and subsurface drainage conditions need to be evaluated. Cracked pavements which are not sealed, will allow water to permeate through a pavement. If precautions are not taken, a water table within 3 feet of the top of the pavement can adversely affect the structural performance of the pavement.

To quantitatively evaluate poor drainage a detailed analysis will be required. The influence of poor drainage of the unbound aggregate will be especially critical if the aggregates are of marginal quality, they tend to disintegrate in the presence of water (poor durability). Studies show that more than 10 percent passing the 200 sieve will produce a relatively impermeable material (6,7) which is undesirable in the base and subbase layers.

Treated materials (asphalt, cement, lime) are less affected by poor surface drainage than untreated materials.

Longitudinal Cracking

Longitudinal cracking in asphalt pavements can be attributed to at least four causes as shown on Table 1.

Structural Deficiency - Longitudinal cracking may be the first indication of a structural deficiency in a pavement. There is no quantitative information from which to predict how fast longitudinal cracking will progress to alligator cracking. It is unlikely that the occurrence of longitudinal cracking would be of sufficient concern to initiate a failure investigation unless there was a rash of premature occurrences in a specific area.

If a failure investigation is considered appropriate, use the same procedure as described for alligator cracking.

Construction Joints - This type of distress is easily recognized by its association with the paving widths used in construction. It is unlikely that the occurrence of excessive wear in construction joints would justify a failure investigation. Such occurrences are normally associated with construction deficiencies; specifically, low density, insufficient crowding of material in the joint or low asphalt content.

If it is considered of sufficient importance the investigation can consist of three activities: (1) density testing in the vicinity of the joint, (2) asphalt content determination, and (3) aggregate gradation of the HMAC.

Preliminary density determinations in the vicinity of the joint can be made with nuclear testing equipment (ASTM D2950). If such equipment is not available, undisturbed samples will be required. Obviously it will not be possible to obtain densities where the material is already raveled away. The objective of the density testing is to detect any trends. It is recommended that three cores be taken on either side of the joint, starting as near to the raveled section as possible and progressing in six-inch intervals transverse to the joint. The initial core could be one foot (approximately) ahead or behind sections of the joint observed to be wearing away prematurely. Five sampling locations, selected at random along the length of the project, should be adequate.

After the density of the cores is measured, they can be used to determine asphalt content and gradation. If the asphalt content is low and the density is low in the vicinity of the joint, there will be a tendency for premature raveling.

In some situations the asphalt concrete at the construction joint may exhibit segregation; i.e. high on the percentage of coarse aggregate. This condition can cause premature raveling in the joint. Segregation can normally be identified by close observation of the pavement surface.

Foundation Settlements - Any permanent movement in the foundation of the pavement will eventually be reflected in the surface of the HMAC. In fills especially, there is often some movement in the vicinity of the unconfined slope. This is not necessarily indicative of a slope stability problem but rather a slow adjustment of the foundation materials to an equilibrium condition. The nature of such movements is such that longitudinal cracks may form in the relatively stiff layer of HMAC.

Rehabilitation of this type of longitudinal crack can be very expensive if the movements continue. Retaining walls or buttressing in some form would be indicated. However, unless there is a compelling reason (e.g. slope instability) the most reasonable procedure is continued routine maintenance and crack sealing.

Volume Change of Subgrade Soils - Soils which are expansive will develop large shrinkage cracks during dry weather. In pavements designed for low traffic volumes, the structural thickness of the pavement may not be sufficient to dampen the shrinkage cracks in the subgrade. In most situations the drying occurs from the shoulder toward the pavement and results in longitudinal shrinkage under the pavement. The cracks are usually concentrated in the outside paved areas; i.e. nearest the shoulder.

Visual observations and local experience are normally all that is necessary to confirm the occurrence of this type of cracking.

Rehabilitation can be accomplished by local replacement or stabilization of materials in the effected zone. To minimize the continued occurrence of this type of distress, aggregate layers or stabilization should be carried beyond the edge of the pavement by two or three feet.

Construction Segregation - Longitudinal cracks are sometimes present at the center of the asphalt concrete mat. This crack is normally associated with segregation resulting from the use of certain types of laydown machines. The newer laydown machines do not produce this segregation and cracking is usually not present.

Shrinkage of Asphalt Concrete or Supporting Layers - Pavements which contain closely spaced (12 feet or less) transverse cracks often contain longitudinal cracks which are most probably caused by low temperature shrinkage of the asphalt concrete or supporting layers (base, subbase, subgrade), presence of stabilized bases and/or subbases, or highly absorptive aggregates in the hot mix. The reader should refer to the section of the report on transverse cracks for more details and an outline of the future investigation actions.

Rutting and Corrugations

Premature rutting or corrugating of the HMAC is usually associated with lack of stability in the asphalt concrete. If corrugations are the major concern the investigation can be limited to those factors related to mix stability; however, if rutting is the major type of distress, the investigation will require a more thorough evaluation.

The potential causes of rutting and corrugating are shown in Table 1.

Structural Deficiency - Research findings suggest that rutting of a pavement can be a function of the amount of deflection at the surface of the subgrade (8). The procedure required to analyze the potential effect of deflection at the subgrade is somewhat beyond the scope of this report. However, if rutting is observed and the cause is not evident, a structural evaluation of the pavement would be appropriate. In general, the procedures would be the same as those used for fatigue cracking. If a structural deficiency is indicated, it should be included in the evaluation as a possible cause of rutting.

Rutting can also occur due to shear failure within the various layers of the pavement structure as well as in the subgrade material. The potential for shear failure in the subgrade is a function of the amount of cover or pavement thickness (surface, base and subbase). Shear failure in the base and subbase will be influenced by the amount of cover over these layers. The analyst should check the pavement layer thicknesses if shear failure in the base or subbase is suspected. If thicknesses are insufficient, rutting can occur even if the base and subbase materials satisfy the required triaxial classification. Shear failure in the pavement layers can usually be identified by field observations. If the pavement surface, outside the wheelpath area, has been pushed up above its normal profile, shear failure in the subgrade, subbase and/or base is highly probable.

It should be noted that rutting can also be a secondary effect of a structural deficiency. For example, if premature alligator (fatigue) cracking occurs, it is possible that "pumping" of unbound aggregates will occur resulting in extensive rutting. Visual observations of the pavement condition can confirm this possibility. Thus, premature cracking may also lead to premature rutting.

To a lesser extent, premature rutting could also lead to premature cracking. Cracking associated with rutting would tend to be longitudinal in the outer zones of the rutted area and may or may not lead to premature alligator cracking. Secondary distress should be reported as part of the failure analysis. Unfortunately, there is no quantitative procedure for making the association between distress types. If such information is systematically accumulated, a pattern should eventually develop which will provide a key to the occurrence of primary and secondary distress types.

<u>HMAC Mix Design</u> - Rutting can be due to deficiencies in HMAC. The analyst should evaluate laboratory stability characteristics of the HMAC. Some mixes can be classified as critical with regard to the effect asphalt content can have on stability. For example, even relatively minor increases in asphalt content of 0.3 to 0.5 percent by weight of aggregate or total mix can significantly reduce the mix stability.

To evaluate the possible effects of asphalt content it is recommended that construction records be used to develop a histogram or bar graph of asphalt content. The plot will indicate the frequency distribution of various amounts of asphalt incorporated in the HMAC. By comparing asphalt content with stability some estimate of the percent of the area susceptible to rutting can be made. For example, if 25 percent of all asphalt contents are associated with mix stability lower than required by specification, it would be reasonable to concluded that 25 percent of the area could exhibit rutting due to plastic deformation.

It should be noted that some pavements with stabilities below specification requirements will not exhibit rutting. There can be compensating considerations such as the consistency of the asphalt, pavement temperatures, and traffic loads which will influence the occurrence of rutting.

If construction records are not available for asphalt content evaluation, it will be necessary to obtain cores or pieces of the asphalt concrete for extraction. Cores or saw-out sections are preferred since these specimens can also be used to determine density and air void content.

It is recommended that a minimum of eight samples of asphalt concrete be obtained in areas with and without rutting (16 total). The samples should be obtained from outside the wheel path areas; care should be taken to avoid any oil drippings on the surface of the pavement.

If it is concluded from field observations that shear failure is causing rutting, it will be useful to measure the stability of the HMAC. The samples obtained for asphalt content can be used for this purpose. Before extracting the asphalt from the HMAC, stability measurements should be made with these materials. The HMAC should be heated, broken into loose mix, and recompacted and tested in accordance with procedures described in Construction Bulletin C-14 (9).

The analyst should be cautious in developing conclusions from the stability tests. First, the asphalt has aged and may cause the test results to be somewhat higher than would be found for an unaged asphalt, the effective asphalt content may be less than was available in the original mix design phase and the air void content of the core samples may be different than that achieved in the laboratory. However, if the stability value is less than 25 it can be concluded that the mix is unstable; if the values are greater than 35 the mix should be considered stable; values in-between will require careful evaluation.

HMAC mix stability will be a major consideration in dealing with corrugations in the surface of the pavement. In all probability, it will not be necessary to conduct a detailed investigation if corrugations are the primary form of premature distress. However, it may be useful to investigate the failure if consideration is to be given to any change in specification or construction requirements.

Asphalt Properties - The consistency of the asphalt can contribute to rutting of the asphalt concrete. If low viscosity asphalts, AC-5 or 10 for example, have been used in order to minimize the occurrence of low temperature cracking, this selection could contribute to rutting. If such materials have been used, the viscosity of the asphalt at 140°F and 275°F should be obtained. This information is normally available from test reports supplied by D-9 and obtained during construction.

More detailed evaluation of the properties of recovered asphalt will be discussed in a subsequent section of the report on detailed investigations.

Unstable Pavement Components - Shear or plastic deformation in the unbound layers can also cause premature rutting. Normally, cement or lime stabilized layers will not contribute to premature rutting.

To evaluate the possibility of shear failure in the sub-surface layers the analyst should carefully examine the configuration of the rut in the field. If the surface is pushed up above its normal profile just outside the wheel path, it is probable that shear or plastic deformation has occurred. In general, the deeper the rut the deeper the depth of the layer which has failed in shear.

If it appears that shear failure has occurred, the analyst should examine construction reports for any clues to possible insufficient strength in the base and subbase materials. If necessary, samples (minimum of five) of these materials should be tested in the laboratory to determine their shear strength. The use of the Texas triaxial test would be desirable; otherwise, a visual classification of the aggregates; i.e. crushed or uncrushed, angular or rounded, rough surface texture or smooth should be made. Aggregate gradation and the plasticity index of the minus 40 sieve material should also be reported.

The overall structural evaluation of the pavement section as previously discussed under alligator (fatigue) cracking should be followed to determine the potential for shear failure in the subgrade materials.

A shear failure analysis may not be necessary if field observations do not indicate that shear failure has occurred. As a minimum any report on rutting should include an assessment of the possibility of shear failure.

Inadequate Compaction of All Layers and Subgrade Materials - A major cause of premature rutting and pavement roughness could be low density and variable density in the various pavement layers, including the upper layers of the subgrade. Any evaluation of this consideration would require extensive laboratory and field testing.

An indication of rutting due to densification can be obtained by careful observations in the field. If the rutting is not associated with shear failure (upward movement of pavement outside of wheel path) it is probable that rutting is associated with low in-place density.

If records are available for densities obtained during construction a histogram (bar graph) of densities will be useful. By comparing the construction densities (frequency and magnitude) with laboratory densities (maximum) some idea of the potential association between density and rutting can be obtained.

Raveling

For purposes of this report raveling is defined as the wearing away of the asphalt concrete surface. The results are a rough textured surface, increased roughness and a general deterioration of the pavement.

Table 1 identifies five likely causes of raveling. It should be emphasized that premature raveling will probably involve more than one of the five potential contributing factors.

Asphalt Content - Low asphalt content can significantly contribute to premature raveling. A review of construction records is a source of information for asphalt content. A histogram showing the distribution of asphalt content during construction will be useful.

If construction records are not available, extraction tests will be necessary. A minimum of ten tests is recommended. Depending on results, additional testing may be required to confirm findings. Since raveling is a surface phenomenon, extraction tests should be made on the surface layer only.

There is no quantitative information to suggest the tolerable deficiency in asphalt content. Construction tolerances of 0.5 percent plus or minus from designated asphalt content are allowed under current (1972) specifications. It can be assumed that when the asphalt content is more than 0.5 percent below the design value, it could contribute to premature raveling. Premature raveling may occur even when the asphalt content is within acceptable construction tolerances. For example, if the HMAC were poorly compacted or if the asphalt had hardened excessively, the mix could ravel regardless of the asphalt content.

Air Void Content - Low density or high air void contents can contribute to accelerated raveling, especially when combined with low asphalt content. While there are no specific construction requirements for density, it is generally believed that HMAC should be compacted to at least 95 percent of the maximum density which can be obtained in the laboratory by standard compaction procedures (9).

Unless samples of the original asphalt and aggregate are available, it will be difficult to reproduce the original laboratory density. Aging of asphalt in the HMAC would make laboratory tests with on-site material of questionable value. However, if no other source of reference information is available, on-site material could be used. These materials should be heated and compacted in accordance with standard mix design procedures as referenced in Construction Bulletin C-14.

Measurements of in-place density or air void content can be made by means of cores (AASHTO T166)(ASTM D3203) or nuclear devices (ASTM D2950). Details of each procedure can be found in The Asphalt Institute's Manual Series No. 8 (MS-8), April 1978. A minimum of ten density tests should be made; if nuclear equipment is available, twenty tests should be taken.

Accelerated Hardening of Asphalt - In order to evaluate the possibility that the asphalt has hardened at an accelerated rate, it will be necessary to recover the in-place asphalt and determine consistency properties, including temperature susceptibility. This activity will be discussed in a subsequent section dealing with more detailed studies.

In regard to the study of asphalt properties it would be useful to obtain information concerning the following items:

- Asphalt supplier
- Name of transport company
- Dates asphalt furnished to project
- Grade of asphalt specified
- Summary of applicable specifications for asphalt

* Summary of asphalt test data from construction and Materials and Tests Division records
* Information concerning asphalt temperature used for mixing and placing
* Additives used, if any; e.g. anti-strip, silicone, etc.
* Any documented performance experience with asphalt obtained from same supplier; specify projects, locations and dates

All of the above information may not be readily available; however, as much information as possible should be reported.

Water Susceptibility - Stripping of asphalt from the aggregate is a very complex subject (10). It can contribute to raveling under specific circumstances. Stripping is a result of poor adhesion of the asphalt to the aggregate, especially in the presence of water or water vapor. Stripping is most commonly associated with the mineralogy of the aggregate. Siliceous aggregates as a class are considered most susceptible to stripping, although no mineralogical criteria are available. Chert, quartzite and rhyolite aggregates will require careful evaluation.

The occurrence of stripping is difficult to identify. Physical testing to identify stripping is still somewhat unreliable. The Texas Transportation Institute is continuing to develop test methods for stripping.

Visual examination of the "fresh" face of HMAC is the best way to evaluate stripping. A cut face will usually not provide an adequate surface for visual examination. However, if core samples can not be obtained from the asphalt concrete because of raveling in the presence of the coring cooling water this may be an indication of water susceptibility. The recommended procedure is to remove a large section; e.g. approximately a 12-inch square, and break it into two pieces. Observations of the "fresh" face will make it possible to make a judgement as to the occurrence of stripping. The appearance of a significant amount of uncoated aggregate is an indication of stripping. The presence of stripping can best be observed in field samples during or immediately after periods of significant rainfall. Stripping of hot mix asphalt concrete can occur in both the winter and summer.

Examination of the surface of the pavement in most cases is not an adequate procedure for estimating the occurrence of stripping. Normal wear will produce a significant amount of bare aggregate on the surface which is not necessarily an indication of stripping.

The results of visual evaluation as well as aggregate type should be included in any report on stripping. Also, the grade of asphalt used and the asphalt content should be indicated; both are secondary contributors to stripping. If anti-stripping additives or hydrated lime are normally used with the project aggregates, this information should be reported. If air void content of the core samples is determined according to ASTM Method D3202, a visual evaluation of the asphalt-aggregate bond during the conduct of ASTM Test Method D2041 may reveal potential water susceptibility problems.

<u>Aggregate Properties</u> - In most situations aggregate properties (except for stripping) will not be crucial to raveling. It is possible that highly absorptive aggregates or soft aggregates with poor durability could contribute to premature raveling. So called "dirty" aggregates; i.e. coated with fines, could also contribute to raveling. The investigator should attempt to obtain as much information about the aggregates as possible. For example, the report should indicate, (1) water absorption by Test Method Tex-201-F, (2) abrasion loss by Test Method Tex-410-A, (3) sand equivalent of combined aggregates by Test

Method Tex-203-F, (4) source of aggregate and (5) any documented information relevant to the past performance of the aggregate.

Surface Flushing (Bleeding) of Asphalt

The major cause of asphalt flushing is too much asphalt. There can be other contributing causes and each should be included in the failure analysis. Table 1 lists four likely causes:

Excessive Amount of Asphalt in HMAC - Compare the amount of asphalt in the mix with mix design information. A histogram (bar graph) showing asphalt content (from construction records) will provide information relating frequency and magnitude of asphalt content. This information should be compared with recommended asphalt content according to mix design procedures as prescribed in Construction Bulletin C-14. If the records indicate the asphalt content was too high; i.e. at least 0.5 percent above design in a significant number of reports (25 percent or more) this information should be emphasized. Also, the density associated with the design asphalt content should be reported. For example, the optimum asphalt content is associated with 97 percent density (3 percent voids). Any increase in the asphalt above the design asphalt content could lead to flushing in portions of the project. Remember that a 0.5 percentage point increase in asphalt content (allowed by specifications) could reduce the air voids by 1 percent and that air voids which average 2 percent will probably exhibit some flushing.

If construction records are not available it will be necessary to determine the asphalt content from extraction tests. A minimum of 10 extraction tests in the vicinity of the asphalt flushing will be sufficient to identify the asphalt content. Samples should be obtained at random intervals along a project but the intervals should never be less than the estimated spacing of a truckload of material. If the type of truck is unknown a conservative estimate should be made.

Excessive Compaction of HMAC - While this is not reported very often there is always a chance that a very dense condition can be produced during construction. One way to evaluate this possibility is to obtain samples from outside the traffic areas. If the densities are in excess of 97 percent, the cause of asphalt flushing could be associated with construction procedures. A maximum density requirement may be necessary if this situation is systematically associated with asphalt flushing.

Temperature Susceptibility of Asphalt - There is a remote chance that some asphalts with unusually low viscosity properties during service could be associated with flushing. There is no direct way to evaluate this possibility except to compare viscosities at 140°F from various projects in the same region which have not exhibited flushing.

At the present time there is a limited amount of quantitative information for evaluating the role of high temperature viscosity; it could be a contributing factor and should be reported as part of a data collecting process.

Loss of Aggregate from Seal Coat - A visual examination will quickly determine if flushing or the presence of excess asphalt on the surface of the pavement is a consequence of a premature loss of aggregate from a seal coat. If this is the case the investigation becomes one of a seal coat failure.

Reasons for loss of aggregate in a seal coat are beyond the scope of this report but would include such items as: (1) amount of asphalt applied, (2) properties of asphalt, (3) aggregate embedment in asphalt, (4) uniformity of distribution of asphalt and aggregate, (5) aggregate gradation, (6) logistics of construction, (7) cleanliness of aggregate, (8) weather, and (9) traffic control during construction.

Water Susceptibility - Stripping of asphalt from the aggregate in black bases or leveling courses may cause flushing. The asphalt which strips from the lower layers is transported (perhaps after emulsification) to the surface of the pavement. Several projects in Texas which exhibit surface flushing have severe water susceptibility problems in the lower asphalt stabilized layers.

Transverse Cracking

Table 1 indicates two likely causes of transverse cracking. In both cases the cracking is associated with low temperature shrinkage of either the asphalt concrete or the supporting layers, e.g. base, subbase or subgrade. In the latter case the shrinkage cracking would be reflected through the HMAC surfacing. It is not unreasonable to suppose that the low temperature shrinkage stresses in the HMAC could be coupled with volumetric shrinkage in the base to cause transverse cracking.

Transverse cracking by itself is not likely to be the cause of a failure investigation. In some situations transverse cracks are a normal occurrence such as with soil cement bases and to a lesser extent lime stabilized soils.

However, in some cases transverse cracking can lead to spalling and general deterioration of the surface due to traffic related fatigue type cracking contiguous to the zone of transverse cracks. Probably the more serious cause for concern is the accelerated rate of increase in roughness associated with water reaching the subgrade; this is particularly true if the subgrade materials possess significant volume change characteristics.

Properties of the Asphalt - Most investigations of transverse cracking in asphalt concrete indicate that the stiffness (hardness) of the asphalt and the temperature susceptibility of the asphalt are the primary causes for such cracking.

In order to evaluate the asphalt properties it is necessary to do testing which is somewhat beyond the routine, such as stiffness and tensile strength of the HMAC at low temperatures and relatively slow rates of loading. Consistency and ductility testing of the recovered asphalt can also be indicators of potential low temperature transverse cracking.

Transverse cracking of HMAC due to low temperature is most commonly associated with temperatures of less than 32°F. When the pavements are young it would be expected that temperatures near 0°F would be required to cause cracking; however, the actual critical temperature will depend on the asphalt properties. As the pavements age the possibility for cracking at higher temperatures increases.

If a preliminary evaluation of asphalt properties is made, the following information should be obtained:

a. Grade of asphalt used in HMAC

b. Asphalt supplier and location of refinery

c. Crude source

d. Asphalt properties from construction records especially penetration at 77°F and viscosity at 275°F. NCHRP Report 195 (11), page 46 and 47 can be used as a reference for evaluating asphalt properties based on these two measurements

e. Dates of placement of HMAC

f. Lowest annual temperatures recorded in the area since date of placement

g. Performance of other pavements in the vicinity placed at the same time as the project being investigated

McLeod (23) has related asphalt properties to low temperature cracking based on properties of the original asphalt. The critical values are summarized in the following tabulation:

Minimum Pavement Temperature, °F	Temperature Susceptibility of Asphalt, P.I.	Penetration at 77°F dmm Minimum	Viscosity at 275°F Centistokes Maximum
-25	0.0	200	250
	-1.5	400	70
-10	0.0	130	370
	-1.5	200	110
0	0.0	100	420
	-1.5	150	120
+10	0.0	85	490
	-1.5	120	160

The following tabulation can be used as a preliminary guide to the assessment of low temperature cracking for asphalts meeting SDHPT specifications.

Asphalt Grade	Pavement Temperature at Which Cracking Could Occur
AC-3	-10°F or less
AC-5	+10°F or less
AC-10	+30°F or less

Asphalt grades of AC-20 and AC-40 could exhibit low temperature cracking at temperatures higher than 30°F. It is emphasized that the above values are furnished only as guidelines. The actual tendency for low temperature cracking would depend on the consistency-temperature relationship (temperature susceptibility), aging, and possibly the number of low temperature cycles to which the pavement has been subjected. Detailed guides for selecting asphalt grade can be found in another project 214 report.

Soil Properties - Research at the Texas Transportation Institute (12) suggests that properties of the unbound aggregate base can contribute to transverse cracking at low temperatures.

According to the studies by TTI (12) some untreated aggregate base courses can undergo volumetric contraction upon freezing that is an order of magnitude larger than that experienced by the asphalt concrete due to temperature changes. This volumetric contraction is related to the surface area and the clay mineralogy of the clay fraction in the aggregate base. An investigation of this possible cause of transverse cracking would require special equipment and expertise which is available through the Materials and Tests Laboratory in Austin.

Roughness

Roughness in pavements can be associated with at least three causes as indicated in Table 1. Premature roughness is most likely to be a consequence of non-uniform construction; i.e. if the roadway is initially constructed rough it will accelerate the rate at which young pavements reach an unacceptable riding quality. Premature roughness can also be a consequence of premature physical distress.

Non-uniform Construction - If for some reason the pavement was relatively rough immediately after construction, the premature roughness may not be a function of the pavement performance but of construction. To evaluate this possibility it would be necessary to obtain roughness measurements immediately after construction and compare with some standard.

If roughness records are not available, inquires of local users of the roadway may be useful in determining if the pavement was or was not rough as a result of construction problems.

If the pavement was not built rough it may develop premature roughness as a consequence of non-uniform compaction of the pavement layers, including the subgrade materials. Examination of construction records would be helpful here. Bar graphs showing construction density variability would be a clue. In order to be meaningful, comparable information from pavements which have not developed premature roughness should be summarized in a like manner.

If field records are not available it would be necessary to obtain field density measurements of each layer and into the subgrade to a depth of approximately three feet. Ten locations should be sampled in order to obtain sufficient information for a modest statistical evaluation.

A field density program as suggested above would require a considerable effort and is not recommended unless the need for finding the cause of premature roughness is very important. In most cases examination of construction records and careful field observations should indicate to the analyst if construction problems are a primary cause of roughness.

Presence of Physical Distress - A linkage may exist between physical distress and roughness. Thus, if premature cracking or rutting has occurred in a pavement it is likely that the pavement will become prematurely rough. The presence of transverse cracks for example may produce a rough ride. Pumping the base course material through these cracks as well as repeated sealing can cause a rough ride.

Soil Properties - Soils with high volume change potential can cause premature roughness if proper precautions have not been taken during design and construction.

A review of design records and particularly the materials survey would be appropriate here.

Usually an experienced observer, familiar with the soils in the area, can tell by riding and walking through a project if roughness is due to expansive soil conditions.

SUMMARY

If the investigation has progressed through this second stage, it should be possible for the analyst to itemize those factors which are considered to be the most probable causes of premature distress. A report summarizing all of the information obtained during the investigation should document the conclusions and make recommendations concerning any action which should be taken to avoid a recurrence of the problems being investigated.

If it is considered of sufficient importance, and further documentation is considered necessary, the final report should recommend a more detailed investigation to verify the conclusions reached through this phase of the study.

Throughout this section very little quantitative information has been provided which can be used to diagnose the cause of distress. The reason for this lack of criteria is due to the fact that investigations of pavement failures have not always been performed in sufficient numbers and detail to allow investigators to establish interpretive criteria. If systematic detailed investigations can be made and the information accumulated into data banks, it is likely that criteria can be developed from which reliable estimates of the cause of failure can be made.

PART 1b - PAVEMENT FAILURE ANALYSIS - DETAILED LABORATORY AND FIELD INVESTIGATIONS

In Part 1a of this report the pavement failure analysis has used information which can be obtained from experience, construction records and a limited amount of what might be considered routine testing. In this phase of the investigation more detailed testing and analysis is outlined which requires specialized equipment and personnel training. The testing can also be relatively expensive and therefore, a well-planned and organized test program is required.

Guidelines for the detailed investigation will be recommended. It is recognized that personnel involved in such studies may wish to modify these guidelines. It is hoped that these guidelines can be useful as a check list of items to be considered depending on the type of pavement failure being investigated.

The analyst should make use of as much background information as possible in planning the testing program and interpreting test data. Specific sources for information include the following:

* Texas Transportation Institute (Texas A&M University)
* Center for Highway Research (University of Texas at Austin)
* Transportation Research Board (Records and Special Reports)
* National Highway Research Program (Reports and Synthesis)
* Association of Asphalt Paving Technologists (Proceedings)
* International Conference on the Structural Design of Asphalt Pavements (Proceedings 1962, 1967, 1972, 1977)
* American Society for Testing and Materials (Test Standards and Reports)

- The Asphalt Institute (Manuals and Research Reports)
- Text Books (Witczak, Cedergren and others)

The emphasis of the detailed analysis discussed herein is in four areas: (1) condition and properties of the HMAC including the asphalt, (2) structural evaluation of the pavement, (3) roughness characteristics and (4) skid number of HMAC surfacing. The actual testing program would depend on the type of distress observed; e.g. skid number would not be included unless there was some indication of the need for such testing.

Figures 3 and 4 illustrate the general program of testing which can be used as a guide for testing specimens of HMAC taken from the pavement.

Figure 3 refers to a program which emphasizes testing of the asphalt and aggregate. Figure 4 outlines a test program for HMAC mix properties.

Figure 5 outlines a series of non-destructive test plans that can be used to evaluate the present condition of an in-service pavement and which can also be used as background information for planning a rehabilitation strategy.

In the following paragraphs a brief explanation will be provided concerning the test programs outlined in Figures 3, 4 and 5. It is emphasized that these are guidelines which are subject to modification. Research currently underway at the Texas Transportation Institute and by NCHRP and FHWA are constantly adding to the engineer's ability to analyze pavement failures.

TEST SCHEDULE FOR CHARACTERIZATION OF MATERIAL PROPERTIES

Figure 3 enumerates seven types of tests or test plans depending on the type of pavement failure being investigated.

Field samples - A minimum of two cores or an equivalent volume of loose material should be obtained from each of ten locations within the project limits. The locations from which the samples are obtained should be randomly selected unless there is some engineering reason for constraining the selection. For example, in order to obtain the best estimate of initial (untrafficked air voids, cores should be obtained at random locations from between the wheel paths and in areas with a minimum of oil drippings. Conversely, for evaluation of asphalt properties, cores or loose samples should be obtained at random locations in the wheel path.

Care should be taken to obtain a sufficient amount of HMAC to accomplish the planned testing program. For example, if asphalt consistency is to be evaluated, sufficient material will be required from each location to perform a penetration, viscosity, ductility and softening point test. The ductility test will require the largest volume of asphalt, approximately 150 grams to make two test specimens. The penetration test will require approximately 50 grams (penetration less than 200); the softening point and viscosity tests will require approximately 30 grams. Asphalt may be used for more than one test but some loss will occur. If the HMAC contains 5 percent asphalt by weight of the mix, a four inch diameter core will yield approximately 20 grams per inch of depth.

Procedures for selecting sampling locations by a random sampling technique are described in Chapter Ten of Manual Series No. 17 (MS-17), First Edition, as issued by The Asphalt Institute.

Bulk Specific Gravity - It is recommended that regardless of the type of distress being investigated, the bulk specific gravity be determined for all core samples. This information can be used as a basis of comparison for each set of specimens obtained in order to estimate the project variability. The information will also be useful if air voids determinations are to be made.

In some situations cores will not be available and bulk specific gravity cannot be measured. However, in most cases cores can and should be obtained, and used for the determination of bulk specific gravity.

Resilient Modulus - The resilient modulus is a measure of the modulus of elasticity of HMAC. It is sensitive to both the time of loading and temperature. As a routine test the resilient modulus can be used as an index property of in-situ characteristics. For indexing purposes the modulus should be performed under standard conditions; e.g. -13, 33, 77 and 104°F at 0.1 second loading time.

The most convenient way to measure the modulus is by means of diametral (indirect tension) testing equipment using procedures appropriate to that equipment (13, 14).

In addition to indexing the characteristics of the HMAC, the resilient modulus can be used to evaluate the structural properties of the pavement (11), water sensitivity (stripping) (10) and low temperature cracking (11, 15) of the HMAC.

In-Situ Air Voids - Air voids above 7 percent in a trafficked HMAC can contribute to accelerated aging of the asphalt and premature fatigue cracking. If the voids are in excess of 7 percent one method of adjustment is to reduce the thickness of the HMAC and to estimate the life cycle of the pavement based on the effective thickness of the HMAC. The following tabulation can be used for pavements built with 4 and 6 inches of HMAC surfacing:

HMAC Air Voids	Effective Thickness* of HMAC, Inches	
7	4**	6**
8	3.5	5
9	3.0	4.5
10	2.5	4.0
12	2.0	4.0

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*Rounded to the nearest 0.5 inches

**No adjustment required

The estimate of the effect of air voids is based on research (13, 16) and lacks detailed field verification. However, in analyzing premature distress this approach provides one method for quantitatively evaluating pavement performance. In making a structural analysis the analyst should reduce the thickness of the HMAC as suggested and increase the thickness of the granular base by an equivalent amount. The traffic would be only the amount and weight (heaviest loads) to which the pavement was subjected when distress was first observed.

The results of the voids analysis should indicate the average voids and the statistical distribution of void content. The actual asphalt content as provided from construction records should be recorded and the effective asphalt content as calculated should also be reported.

Air void determinations should be included in any analysis of asphalt flushing (bleeding). It is probably self-evident that the voids have been overfilled with asphalt; however, it is useful to know the average and standard deviation or distribution of void content. Such information would be helpful in establishing mix design requirements.

It is generally recognized that asphalt content and effective asphalt content are important considerations to the performance of HMAC. Except for stability (see discussion relating to Figure 4) there is very little quantitative information concerning asphalt content and pavement performance. For example, how much will a 0.3 percent reduction in asphalt content affect raveling? What is the effect of such a reduction on fatigue cracking? The answers to these questions are not apparent without a good deal of analysis and interpretation.

Some investigators suggest that the theoretical asphalt film thickness should be in the range of 6 to 8 microns (1 micron equals 10^{-6} meters). For most dense graded HMAC, the minimum required effective asphalt content to meet this film thickness requirement is approximately 4.5 percent, depending on the surface area of the aggregate. The effective asphalt content is the total asphalt content less the amount absorbed into the aggregate.

Asphalt Consistency - Most types of distress in asphalt pavements are thought to be related to the properties of the asphalt. In general it would be desirable to have information concerning the chemical and rheological properties of asphalt.

Any discussion of the chemical properties of asphalt are beyond the scope of this report. However, any detailed analysis involving asphalt should attempt to record information concerning chemical composition. The SDHPT has used the Rostler parameters to identify asphalt components (17). The analyst should obtain any information which may be available which characterizes the properties of the original asphalt. Analysis of recovered asphalt will not be useful unless historical information is available associating the performance of pavements with the chemical composition of these asphalts. In all probability the properties of the original asphalt from a specific crude source and refinery may be available. The analyst should attempt to determine the field performance of asphalts with a similar composition to determine if an association can be made between the failure investigation and the chemical components. If no performance information is available, the data should be recorded for future comparisons.

The pertinent rheological properties of asphalt can be obtained from measurements of consistency. Figure 3 identifies the four tests most frequently used to measure consistency; i.e. penetration, viscosity, ductility, and softening point.

Unfortunately, the relationships between asphalt properties and performance are not always consistent. For example, cracking and raveling are associated with hard, brittle asphalt while rutting and flushing are more commonly related to soft asphalts. The objective of asphalt specifications and mix design is to find the zone in which the asphalt will not contribute excessively to distress and still maintain some degree of flexibility.

Traxler (18) explains some of the complications relative to the factors that can affect asphalt hardening. Quantitative information relating asphalt consistency to pavement performance is not readily available. Most studies of asphalt properties and pavement distress are related to cracking; specifically, alligator (fatigue) cracking and low temperature (transverse) cracking.

Halstead (19) has summarized both field and laboratory studies relating ductility and penetration at 77°F to performance (cracking) of pavements. He indicates that there are combinations of these two properties which tend to identify "critical" relationships. The following tabulation summarizes his conclusions as to this critical relationship.

Value of Penetration* @ 77°F	Minimum Ductility** @ 77°F
25	10
30	20
40	50
50	100

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*0.1 mm with 100 grams for 5 seconds

**Centimeters at rate of 5 centimeters per minute

Halstead's data would suggest that any asphalt concrete containing an asphalt with a penetration less than 20 is highly susceptible to cracking.

It should be noted that many asphalt rheologists have very little faith in ductility measurements. Nevertheless, field correlations have been developed and should not be ignored. Skog et al (3) have found that ductility is related to fatigue cracking in asphalt concrete.

Zube and Skog (20) of Caltrans have indicated a critical asphalt penetration of 30 and viscosity of 30 megapoises both at 77°F. More recent studies by Caltrans (3) indicate the critical asphalt penetration at 77°F is 20 although pavements with asphalts of lower penetration have been observed to perform satisfactorily, i.e. no premature cracking.

Sisko and Brunstrum (21,22) have provided some information concerning the relationship between asphalt consistency and cracking as observed on roads in 12 states including Texas. The data confirms the findings of Halstead; i.e. very high probability of cracking when penetration of the recovered asphalt from the road is 20 or less. There is a 50 percent probability of cracking for pavements with penetration of 40 or less, and zero percent probability of premature cracking, according to their data, when the recovered asphalt penetration is greater than 40.

According to the information by Sisko (22) the critical viscosity for cracking would be 35,000 poises at 140°F; i.e. high probability of cracking above this value. No cracking was observed in pavements with a viscosity of 15,000 poises or less at 140°F. The Texas project in this study reported no cracking with viscosity values ranging from 25,700 to 33,000 poises at 140°F.

The Sisko information also indicates that rutting may be associated with asphalt viscosity of 6,000 poises or less at 140°F, although the data is very limited. Thus, in order to minimize the potential for cracking and rutting, the desirable range for in-situ asphalt viscosity at 140°F would be between 6,000 and 35,000 poises.

Asphalt ductility (recovered) has also been related to low temperature cracking (11). Data from the Washington DOT suggests a critical ductility of 10 cm at 39.2°F (1 cm/min).

McLeod has related asphalt properties to low temperature cracking based on properties of the original or recovered asphalt (23). The critical values of the original asphalt based on the penetration at 77°F and viscosity at 275°F were given in Part 1a of this report.

Haas (24) has summarized information concerning asphalt properties with low temperature cracking.

The asphalt softening point is required for some methods of cracking analysis dealing with the stiffness modulus of asphalt and asphalt concrete (24).

In summary, the literature is full of research dealing with the measurement of asphalt properties. The analyst is urged to review publications of the Association of Asphalt Paving Technologists, National Cooperative Highway Research Program of the Transportation Research Board, Federal Highway Administration, and Texas Transportation Institute for background information. Unfortunately, there is limited quantitative information which can be applied directly to Texas conditions. If detailed investigations are carried out in sufficient numbers, reliable criteria and procedures can be developed.

The previous discussion relative to the determination of material properties is not intended to be complete. It is intended to provide a beginning for a failure investigation. Experience by experts within the Texas Highway Department is available to complement the procedures and criteria described in this report. In some cases additional tests (e.g. brittleness test of SDHPT) will be useful based on experience and equipment. The important consideration should be the development of a plan which will produce useful information based on published criteria or department experience.

Water Sensitivity - The problems associated with water sensitivity and stripping were discussed in Part 1a of this report. Procedures for identifying the potential for stripping are commonly associated with measurements of retained strength after specific exposure to water and/or temperature cycles.

The reliability of this type of testing is still somewhat questionable and should be interpreted carefully. The latest research study pertinent to this subject is summarized in NCHRP Report 192 (10). Both the Texas Transportation Institute at Texas A&M University and the Center for Highway Research at the University of Texas (Austin) are working on this problem.

Aggregate Characteristics - Figure 3 lists the characteristics of aggregate which should be identified in a detailed failure investigation.

a. Aggregate Properties

Type - Figure 6 (25) illustrates how aggregates should be classified by type. If equipment is available, the chemical composition (Figure 7) of questionable aggregates should be measured and reported.

Physical Characteristics - At least three properties should be identified by visual examination or testing; (1) shape, (2) texture, and (3) porosity.

The shape can be characterized in the following terms: (1) rounded, (2) subangular or subrounded, and (3) angular. The characteristics will be a function of judgement but are easily made based on experience. Pictorial references can be used in making classification.

The surface texture can be characterized in the following terms: (1) rough, (2) smooth and (3) polished. Again, this is a judgement evaluation which can be systematized by use of pictorial references. The porosity of aggregate can be measured initially in terms of water absorption by means of Test Method Tex-201-F. If the water absorption is 2 percent or more, a more detailed testing program should be scheduled to evaluate asphalt absorption.

If information is needed as regards asphalt absorption, determinations should be made in accordance with procedures described in The Asphalt Institute publication, "Mix Design Methods for Asphalt Concrete and Other Hot-Mix Types", Manual Series No. 2 (25), Chapter V.

b. Aggregate Durability - The standard tests for durability are the abrasion loss and soundness.

The abrasion loss can be measured in accordance with Test Method Tex-410-A (Los Angeles Abrasion Test). Requirements for abrasion loss as a function of the type of coarse aggregate are given in Item 340 of the SDHPT Standard Specifications.

The soundness test for aggregate is primarily applicable in areas subjected to freeze-thaw cycles. If such conditions are associated with the project under investigation the standard soundness test (AASHTO 104 or ASTM C88) as modified by District 6 should be scheduled.

c. Gradation

Aggregates for HMAC fall into three general categories; (1) dense, (2) open, and (3) gap or skip grading. The requirements for dense and open graded mixes can be found in SDHPT Standard Specifications.

Gap graded mixes are not standard in Texas; however, some mixes may exhibit such characteristics and should be classified accordingly. A gap graded aggregate is one that has a relatively small change in the amount of material passing certain sieve sizes, usually between the No. 8 and No. 30. If there is a relatively small amount of material between the No. 4 and No. 8 sieve it is often referred to as skip grading. Figure 8 illustrates typical gradation curves based on percent (by weight) passing each designated sieve size. These curves can be used to classify aggregate gradation. Typical problems associated with other than dense gradations are shown of Figure 9.

TEST SCHEDULE FOR HOT MIX ASPHALT CONCRETE (HMAC)

Figure 4 summarizes the recommended testing of HMAC as appropriate to the particular type of distress involved. If distress is not related to the characteristics of the HMAC, it will not be necessary to follow through with this schedule; for example, roughness related to swelling clays would not require a detailed evaluation of the HMAC.

In the previous section of this report the test schedule was concerned with the component parts of the HMAC; i.e. asphalt and aggregate. A general discussion was provided for the various tests as background information.

In this section a more comprehensive test schedule is provided which includes testing of the component parts and of the mixture. There is some overlap in testing shown on Figures 3 and 4; for example, the bulk specific gravity, resilient modulus, water susceptibility, air voids, and asphalt properties. The actual choice of tests will be a decision based on the distress being investigated. It should be remembered that one of the major long-term objectives of the detailed investigation is to develop more complete criteria for use in failure investigations. In this regard it will be desirable to systematically schedule as many of the tests as can be reasonably afforded. As data are collected and criteria are developed it will be possible to reduce the testing schedule to just those tests needed for a specific type of investigation.

Some of the tests referred to in Figure 4 are still in a developmental phase; specifically, the water susceptibility tests proposed by Lottman (10), permanent deformation, thermal cracking and fatigue testing.

The tests indicated in Figure 4 are reasonably self descriptive or have been described in the previous section relative to the procedures for Figure 3. No further elaborations will be made.

NON-DESTRUCTIVE TESTING

Figure 5 outlines various non-destructive tests which can be useful in both the failure investigation and for selection of rehabilitation procedures. The following section briefly describes the procedures to be followed in the conduct of non-destructive testing.

Structural Evaluation

Structural evaluation of in-service pavements in Texas is obtained by means of deflection tests using the Dynaflect. The three basic steps are: (1) develop a test plan, (2) implement the plan, and (3) analyze the information.

Non-destructive deflection testing is considered to be associated with alligator (fatigue) cracking. In the analysis of deflection data, the analyst should remember that other forms of distress, with the possible exception of rutting and roughness, are not likely to be related to deflection measurements.

Develop a Test Plan - The primary questions in developing a test plan are (1) frequency of testing, and (2) procedures to be used in identifying homogeneous sections, i.e. sections with similar structural characteristics.

The frequency of deflection testing is usually based on the condition of the pavement. The purpose of the measurement program can be considered a secondary factor.

Deflection measurements can be used in a failure investigation, or for a determination of overlay thickness requirements for a specific project. In general, the frequency of testing (spacing) can be the same for both programs. If some adjustments are considered necessary, it is recommended that the frequency of testing be increased for failure investigations and decreased for overlay design determinations.

General guidelines for spacing of measurements are as follows:

	Purpose of Non-Destructive Testing	
Condition of Pavement	Failure Investigation	Overlay Design
Good		500 feet
Fair	100 feet	200 feet
Poor	50 feet	100 feet

A minimum of 10 measurements should be obtained regardless of the length of the project.

If the measurement program is to be made on a two lane roadway, both lanes should be tested. The spacing in each lane can be doubled; e.g. for pavement in poor condition increase from 100 feet to 200 feet, or from 50 feet to 100 feet, depending on the reason for testing. Measurements should be staggered in order to sample at equal intervals throughout the section to be tested. Test the entire length of the project.

It will be important to identify homogeneous sections for analysis of design. Prior to actually conducting the measurement program the following information should be obtained:

1. Structural section(s) from contract records
2. Historical traffic information
3. Unusual soil, drainage or construction conditions which would influence performance
4. Identify type, extent and limits of distress
5. Select limits for test sections in which (a) structural section, (b) traffic, (c) subsurface conditions, and (d) distress are similar

Based on the evaluation from this information a test plan can be developed.

<u>Implement the Test Plan</u> - In implementing the plan it will be useful to make appropriate notations regarding any field conditions which would influence measurements. For example, the following could be recorded; (a) condition of HMAC at test location, (b) air temperature at least three times per day, (c) pavement temperature at least three times per day, (d) whether pavement is at grade or in cut or fill sections, (e) wheel path being tested, (f) location, and (h) physical features (culverts, bridges, intersections, etc).

In a failure investigation the question to be answered by deflection testing is whether or not the cracking has occurred due to excessive deflection. In this case it is desirable to obtain deflections in uncracked areas which are indicative of the conditions which led to cracking.

In most cases it will be desirable to establish overlay requirements as an objective of deflection testing. In this case deflection testing should be conducted without regard to the presence of cracking, although a notation should be made of its occurrence.

It is usual practice to make all or most deflection measurements in the outer wheel path since this is normally the most critical location. However, adjustments can be made in the field depending on conditions. The majority of deflection measurements should be obtained in the wheel path with the greatest amount of distress.

After the deflection tests have been completed the measurements should be evaluated to assure that homogeneous sections are being analyzed. To achieve this objective the following procedures should be followed:

1. Plot Dynaflect measurements by lanes versus stationing along project.
2. Visually determine if there are systematic variations in deflection measurements along the length of the project.
3. If systematic variations are observed, divide the project into subsections (not less than 1000 feet in length).
4. Subsections should be checked to see if they are significantly different or are from the same population of data. Standard statistical methods for testing of significance between two

sample means should be used for this test. Procedures for such testing can be found in any statistics textbook. Step-by-step procedures can be found on pages 13-17 of Reference (26). A 5 percent level of significance is recommended for testing to determine if the means are from two different populations.

Analysis of Test Data - For each homogeneous section two analyses can be made; (1) determination of structural adequacy and (2) need for structural overlay.

The evaluation of structural adequacy will be a function of the criteria to be used in making such a determination. Two procedures which have gained considerable recognition are those of The Asphalt Institute (27) and the California Department of Transportation (28). Figure 10 illustrates the California procedure. For example, compare the 80th percentile deflection (mean deflection plus 0.84 times standard deviation) to the tolerable deflection shown on Figure 10 for the existing pavement thickness and cumulative equivalent 18 kip single axle loads to date. If the 80th percentile deflection is less than the tolerable deflection, the cause of alligator cracking is not a structural deficiency. In other words if alligator cracking has been observed and deflection measurements are below the tolerable amount, the probable cause is due to the properties of the HMAC; e.g. high voids or brittle asphalt.

If the 80th percentile deflection is greater than the tolerable amount, there is a high probability that the alligator cracking is due to a structural deficiency. In this event the rehabilitation may require an overlay in excess of 1 inch.

The overlay requirements can be established by using the procedures of

The Asphalt Institute (27), Caltrans (28) or FHWA (26). Tentative procedures are under development for specific application by SDHPT. In the meantime any of the methods referenced can be used provided the procedures are carefully followed.

Roughness Evaluation

Pavement roughness is a measure of ride quality or user comfort. A major cause for rehabilitation of roads with high speed traffic is road roughness.

Measurements of pavement roughness are obtained by use of the Mays Ride meter equipment. A complete description of the use of this tool is beyond the scope of this report. For more complete information refer to Reference (29). Extreme care should be taken to assure that the roughness measuring equipment is in proper calibration before and after making field measurements. Standard quality control procedures have been established for use with the Mays Ride meter and must be carefully followed in order to be assured that the measurements are reliable.

The serviceability index (SI) is indicative of riding quality and ranges from 0-5. Road roughness from the Mays Ride meter and serviceability index (SI) have been correlated in Reference (29). Acceptable levels of SI may vary; however, when the values fall below 2.0 on high speed roads, a considerable amount of discomfort will result on long trips, and hazardous driving conditions can be associated with SI values of 1.5 or less.

Overlays to reduce the amount of roughness should be considered with primary, high speed routes having SI values less than 2.5, and when all other routes have SI values less than 2.0.

If structural improvements are required, deficiencies in ride quality will automatically be accommodated. Otherwise, a thin overlay with leveling of some type will be necessary for rehabilitation.

Safety Evaluation

The two major physical indicators to be used in a safety evaluation are: (1) skid number and (2) rut depth. Of course, accident records are also a consideration for an overall safety evaluation; however, this section is primarily concerned with physical, non-destructive measurement programs.

Skid number is the standard procedure for evaluating the coefficient of friction between a tire and pavement. The procedures for measuring and reporting skid number are given in ASTM Test Method E274.

No absolute criteria are available for the interpretation of skid number. Some criteria have been suggested by Kummer and Meyer (30) as follows:

Mean Speed, mph	SN_{40}*
30	31
40	33
50	37
60	41

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*Skid number measured at 40 mph.

Special considerations of skid number are discussed by Farber et al (31). Skid number evaluation for these special cases should be made on an individual basis.

Improvements in skid number can be achieved by grooving, cold milling, surface treatment and special overlays. More complete enumeration of such procedures is contained in Part 1c of this report and in another Project 214 Report.

Hydroplaning is a major safety concern associated with rut depth in flexible pavements. The hydroplaning phenomenon is the result of a buildup of a thin layer of water between the pavement and the tire which results in the tire losing contact with the pavement and a loss in vehicle control (32). The occurrence of hydroplaning is a complex function of water film thickness above the surface, vehicle speed, surface texture, tire thread depth and tire inflation pressure (33, 34).

Extensive research has been conducted by the Texas Transportation Institute relative to friction and hydroplaning characteristics of pavements (34). Specific rut depth criteria as a function of cross slope are as follows:

Cross Slope %	Maximum Desirable Wheel Path Depression, Inches
1	1/8
2	3/16
3	5/16

At these depths virtually no water would be stored in the wheel path areas.

Summary

This portion of the report has concentrated on detailed testing schedules for failure investigations. Wherever possible, criteria for interpretation have been provided. In many situations the criteria are only moderately reliable and need more in the way of field correlations. Detailed investigations systematically conducted as described herein, will help to build the type of information and criteria necessary for use in failure investigations.

The major benefits to be obtained from pavement failure investigations will be the development of a data bank of reliable information which will have application to several important activities of the Texas Department of Highways and Public Transportation. Specifically, for the short term, the information can be used to update pavement design procedures, material requirements, and construction specifications. For the long term, information can be developed which will quantify the effect that material properties and in-situ conditions save on pavement performance. For example, such information could be used for economic analysis related to alternative design considerations with marginal quality material which is relatively inexpensive.

Experience has shown that once a data bank of information, of the type described herein, has been obtained, a wide range of applications will develop.

PART 1c - GUIDELINES FOR REHABILITATION OF FLEXIBLE TYPE PAVEMENTS

In developing guidelines for rehabilitation, three factors have been considered: (1) type of distress observed, (2) extent and severity of the observed distress, and (3) volume and composition of traffic.

The final selection of the preferred rehabilitation procedure should be based primarily on economic comparisons over an extended period of time. Some consideration should be given to the reliability of the rehabilitation procedure as well as energy and user inconvenience associated with each treatment.

Appropriate rehabilitation procedures will often be influenced by the functional classification of a pavement. One convenient way to associate rehabilitation with the functional classification is to classify highways according to traffic volume. For purposes of this report, traffic volume has been defined as the average daily traffic per lane. Table 2 has been prepared to provide traffic classification categories for association with various rehabilitation alternatives.

The recommended rehabilitation alternatives include a variety of local repairs; e.g. seal coat, replacement of distressed areas, crack sealing, and others as noted. The intent of these alternatives is to isolate the repairs to just the locations exhibiting distress. Such repairs may be cost-effective when the extent of distress is relatively small. In general, local repairs are recommended for pavements in Traffic Category 3 and possibly Category 2 depending on the type of distress involved.

The recommended rehabilitation alternatives are subject to some interpretation by those persons responsible for implementation. For example, a slurry seal is one alternative listed for the correction of raveling. However, in selecting this alternative, consideration must be given to the presence of cracking. If cracking is observed it should be repaired or covered with a stress relieving layer before applying the slurry seal, otherwise the existing cracking will reflect through the pavement in a very short period of time.

If a HMAC overlay is contemplated it is recommended that deflection tests be scheduled to determine what thickness of overlay is necessary to satisfy structural requirements.

Footnotes have been provided to indicate special considerations for each alternative; field personnel may want to add to these based on local experience.

Tables 3 through 9 summarize rehabilitation alternatives for the various types of distress indicated on each table. Unless otherwise noted the alternatives are applicable to all three traffic categories.

In a few cases the rehabilitation alternative with cold milling or heater scarification will provide an option as to the need for an overlay or seal coat; for example, cold milling with or without an overlay for asphalt flushing. The selection of the "without overlay" option will depend on funds available and a judgement of the acceptability of the surface texture without a new wearing surface. In all probability any cost estimates should consider the need of a new surfacing in traffic categories 1 and 2 within three to five years.

Recycling is recommended as a rehabilitation alternative for several types of pavement distress. The determination of the need for an overlay or seal coat for the recycled material will depend on the type of recycling and traffic. Table 10 summarizes surfacing recommendations for various recycled materials.

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Table 1

TABULATION OF POSSIBLE CAUSES OF PAVEMENT DISTRESS

Alligator Cracking (fatigue cracking of HMAC)

* Structural deficiency
* Excessive air voids in HMAC
* Change in properties of asphalt with time
* Stripping in HMAC
* Aggregate gradation
* Construction considerations
* Drainage

Longitudinal Cracking

* See alligator cracking - when cracking is in general vicinity of vehicular wheel path, longitudinal cracking is first indication of fatigue cracking of HMAC
* Poor construction joint
* Segregation
* Foundation settlements - usually in fill zones
* Volume change of subgrade soils
* Shrinkage

Rutting

* Structural deficiency
* Mix design (HMAC)
* Asphalt properties

- Unstable pavement layers
- Compaction; all layers

Raveling

- Asphalt content
- Air void content
- Accelerated hardening of asphalt
- Water susceptibility

Flushing

- Excessive amount of asphalt
- Excessive densification
- Temperature susceptibility of asphalt
- Loss of aggregate from seal coat

Transverse Cracking

- Properties of asphalt
- Unusual soil properties

Roughness

- Non-uniform construction
- Combination of effects of physical distress; i.e. rutting, cracking, etc.
- Soil properties

Corrugations

- See rutting (usually associated with areas of deceleration, acceleration or turning movements)

Table 2. Traffic Categories Based on Average Daily Traffic.

Average Daily Traffic	Type of Facility 2-Lane	4-Lane
300	3	NA
300-1000	2	NA
1000-2000	2	3
2000-5000	1	2
5000-7500	1	2
Greater Than 7500	NA	1

NA - Not applicable.

*All other multilane facilities should be classified as traffic category 1.

TABLE 3 - RECOMMENDED REHABILITATION ALTERNATIVES FOR SURFACE RUTTING.

I. Rutting in the moderate category (0.5 to 1.0 inch average) and severe category (greater than 1 inch average) for up to 25 percent of the length.

  - Level up skin patch with HMAC - Traffic category 3.
  - Replacement (particularly for corrugations in local areas)
  - Cold milling and profiling in local areas (with or without thin overlay)
  - Heater-scarification plus HMAC for leveling in local areas.
  - Heater-scarification, shape and surface treatment in local areas only - Traffic categories 2 and 3.
  - Heater-plane plus HMAC for leveling and riding surface in local areas.

II Rutting in the moderate and severe categories in more than 25 percent of the length.

  - Same procedures recommended for rutting in lengths up to 25 percent of project, except activity should be scheduled for full width and length of project.

TABLE 4 - RECOMMENDED REHABILITATION ALTERNATIVES FOR PAVEMENTS EXHIBITING RAVELING.

I. Raveling up to 15 percent of area in moderate category (10 to 50 percent of surface aggregate dislodged) and severe category (greater than 50 percent of surface aggregate dislodged).

- * Dilute emulsion seal (fog seal)
- * Rejuvenate seal
- * Strip seal[*]

II. Raveling greater than 15 percent of the area in moderate and severe categories.

- * Dilute emulsion seal (fog seal)
- * Slurry seal[**]
- * Rejuvenate seal
- * Strip seal (not to exceed 30 percent of area)
- * Full width chip seal
- * Thin HMAC overlay (1 inch)

[*] Recommended if raveling is occurring in isolated areas; e.g. joints

[**] Recommend dig-out and replace all moderate and severe longitudinal and fatigue cracking.

TABLE 5 - RECOMMENDED REHABILITATION ALTERNATIVES FOR FLUSHING OF HOT MIX ASPHALT CONCRETE (HMAC).

I. Flushing in the moderate category (coarse aggregate and asphalt nearly at the same plane but coarse aggregate readily visible) to severe category (black appearing surface, few aggregate particles visible, slick in appearance) for up to 30 percent of the area.

- Chipping, heating and rolling in local areas[*] - Traffic category 3.
- Heater-scarification plus aggregate in local areas[*] - Traffic categories 2 and 3.
- Cold milling without overlay[*] - Traffic categories 2 and 3.
- Heater-scarification plus thin overlay[*] - Traffic categories 2 and 3.
- Strip seal with chips[*] - Traffic categories 2 and 3.
- Thin overlay, open-graded mix.
- Heater-scarification plus thin overlay (open-graded mix).

II. Flushing in the moderate to severe categories for more than 30 percent of area.

- Full-width chip seal - Traffic category 3.
- Overlay (open-graded HMAC).
- Heater-scarification plus thin overlay (open-graded HMAC)[**]
- Cold milling plus thin overlay (open-graded HMAC)[**]

[*] Recommended only for areas with flushing if total area is 15 percent or less; otherwise treatment applied to total area.

[**] Recommended if roughness is a secondary consideration.

TABLE 6 - RECOMMENDED REHABILITATION ALTERNATIVES FOR PAVEMENT EXHIBITING ALLIGATOR (FATIGUE) CRACKING.

I. Cracks in moderate category (limited amounts of spalling and pumping) and severe category (spalling and pumping or cracks greater than 1/4 inch wide) with small amount of cracking (5 percent of less).

* Squeegee seal* - Traffic categories 1, 2, and 3
* Strip seal coat* - Traffic categories 1, 2, and 3
* Dig out and replace with full-depth HMAC* - Traffic categories 1, 2, and 3
* Fabric plus chip seal - Traffic category 3
* Asphalt-rubber and chip seal - Traffic category 3
* Full width seal coat - Traffic categories 2 and 3
* Asphalt rubber plus overlay** - Traffic categories 1 and 2
* Fabric plus overlay** - Traffic categories 2 and 3
* Improve subsurface drainage***

II. Cracks in moderate and severe category with extensive fatigue cracking (greater than 5 percent)

* Dig out and replace with full-depth HMAC* - (applicable in range of 6-25 percent cracking)
* Full width seal coat - Traffic category 1 and 2
* Heater-scarification plus overlay**
* Fabric plus overlay**
* Asphalt rubber plus overlay**
* Crack relieving layer (open graded HMAC) plus overlay****
* Surface recycling with or without overlay**
* Reconstruction - with or without recycling
* Improve subsurface drainage***

* - Recommended only for failed areas

** - Thickness of overlay to be based on structural analysis; if pavement is rough require cold milling with smoothness controls

*** - Usually in combination with other rehabilitation alternative

**** - Procedure recommended by The Asphalt Institute

TABLE 7 - RECOMMENDED REHABILITATION ALTERNATIVES FOR PAVEMENTS EXHIBITING LONGITUDINAL CRACKING.

I. Cracks in moderate category (greater than 1/8 inch or pumping and spalling) and severe category (greater than 1/4 inch with pumping and spalling) and with up to 200 feet of cracking per 100 lineal feet of pavement.

- Crack seal (cracks greater than 1/4 inch wide)
- Squeegee seal*
- Strip seal with chips*
- Fabric plus 1 inch overlay or chip seal**
- Dig out and replace with full-depth HMAC**
- Asphalt-rubber plus chips - Traffic category 3 in less critical areas.

II Cracks in severe category with more than 200 feet of cracking per 100 lineal feet of pavement

- Heater-scarification plus full width overlay***
- Fabric plus full width overlay***
- Asphalt-rubber plus full width overlay***

* - Recommended for all areas exhibiting either moderate or severe cracks.

** - Recommended for wheel path areas.

*** - Thickness of overlay to be based on structural analysis.

TABLE 8 - RECOMMENDED REHABILITATION ALTERNATIVES FOR TRANSVERSE CRACKING.

I. Transverse cracking with 1/4 cracks per station in the moderate category (some spalling or pumping, or greater than 1/8 inch wide).

* Crack sealing

II. Transverse cracking with an average of 5 or more cracks per station in the moderate and severe categories (spalling and pumping).

Rehabilitation of pavements with transverse cracking is dependent on level of roughness which has occurred as a consequence of cracks. Rehabilitation has been divided into corrective (excessive roughness) or preventive (acceptable level of roughness).

Corrective (Coupled with excessive roughness)

- Cold milling to re-establish profile followed by one of the following:
  - Fabric and overlay (open or dense graded)
  - Asphalt-rubber and overlay (open or dense graded)
- Heater-scarification with overlay (dense graded)
- Remove and replace HMAC - only in extreme case where correction to supporting layers is indicated

Preventive

- Crack seal
- Full width chip seal - traffic categories 2 and 3
- Asphalt-rubber and chip seal - traffic category 3

TABLE 9 - RECOMMENDED REHABILITATION ALTERNATIVES FOR EXCESSIVE ROUGHNESS.

I. Recommendations for roughness are dependent on the overall characteristics of the pavement and, except in rare cases, require a leveling procedure throughout the length of the project. Procedures appropriate to the correction of roughness assuming structural adequacy are as follows:

- Overlay with or without leveling*
- Cold milling with or without overlay
- Heater-scarification with overlay
- Heater planing with overlay or seal coat (primarily for local areas with corrugations)
- Recycling HMAC (central plant or in-place)**

* - Need for leveling will depend on ride quality; if in-service serviceability index is less than 2.0, plan on a leveling operation

** - See Table 10 for surfacing recommendations

Table 10. Recommended Recycling Procedure and Type of Surfacing.

Traffic Category	Recycling Method			
	Central Plant		In-Place	
	With HMAC Overlay	With Seal Coat	With HMAC Overlay	With Seal Coat
1		Not Recommended	Not Recommended	
2		Not Recommended		
3	*	*		

*Optional depending on traffic.

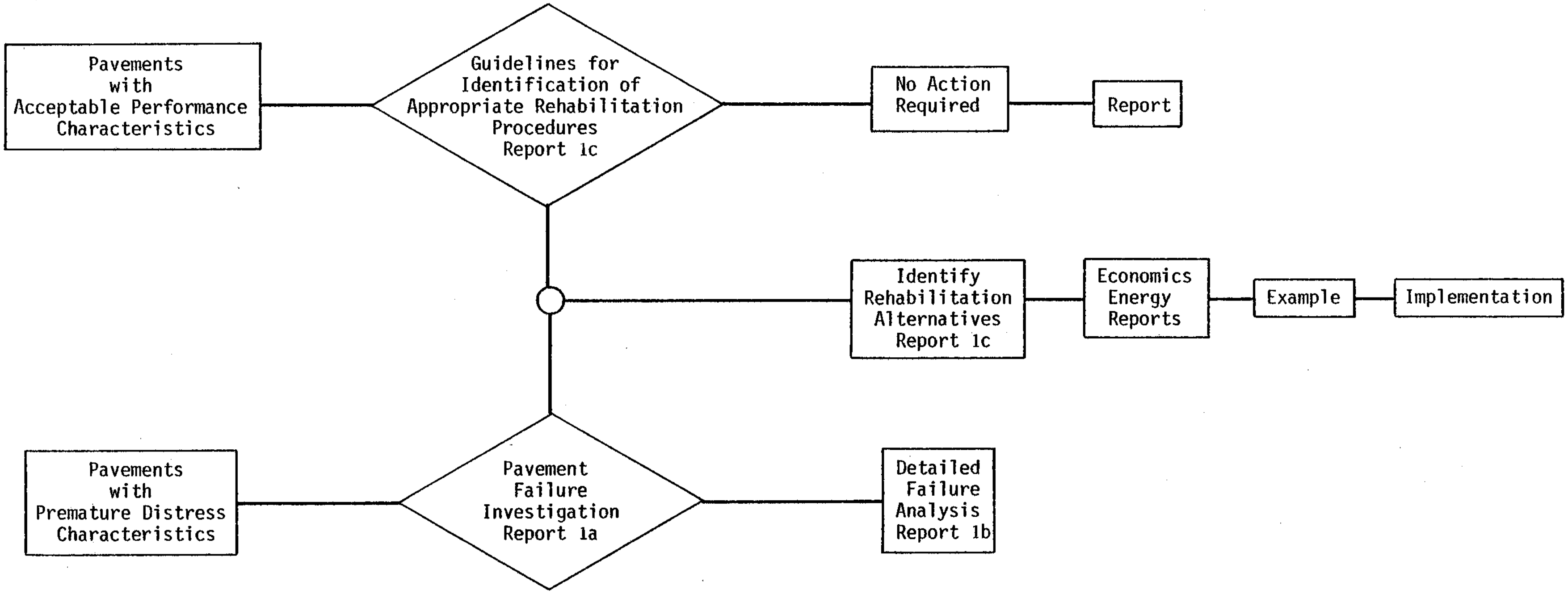

Figure 1. Flow Diagram Illustrating Organization of Reports on Pavement Failure Analysis with Guidelines for Rehabilitation of Flexible Type Pavements

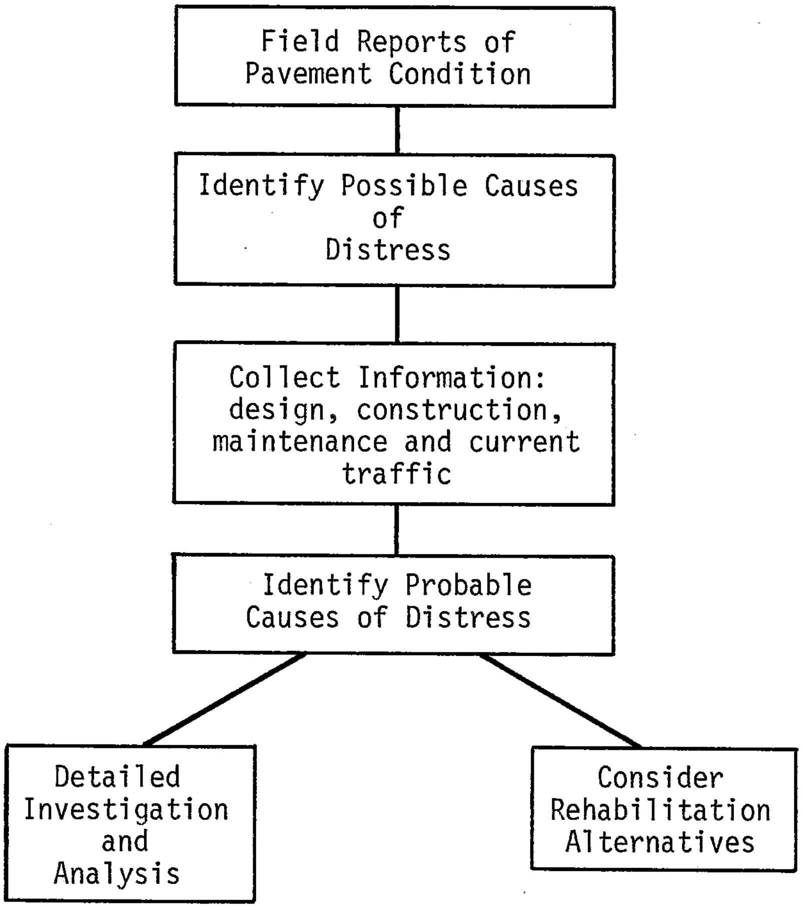

Figure 2. Steps in Identifying Types and Causes of Premature Pavement Failures

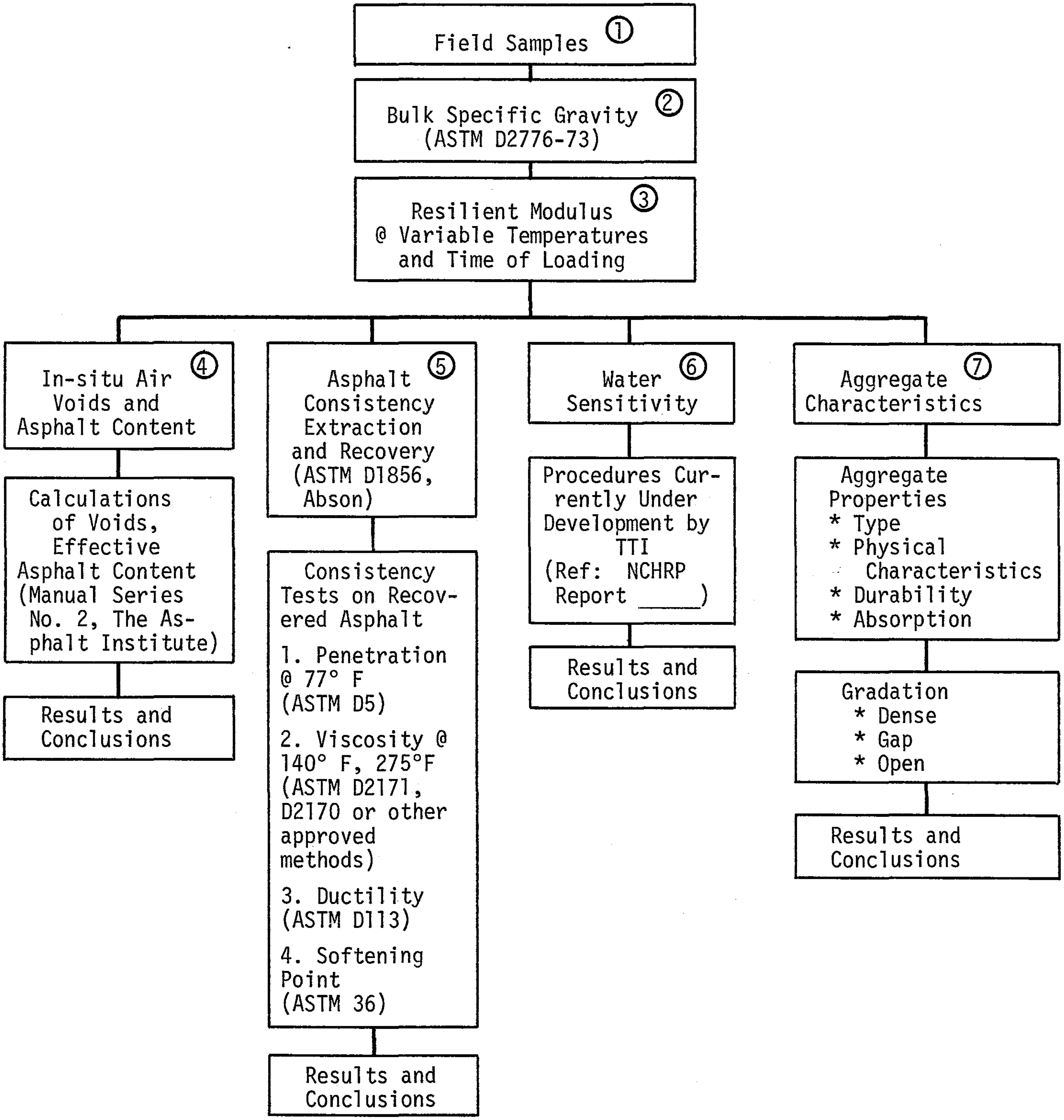

Figure 3. Test Schedule for HMAC Failure Analysis

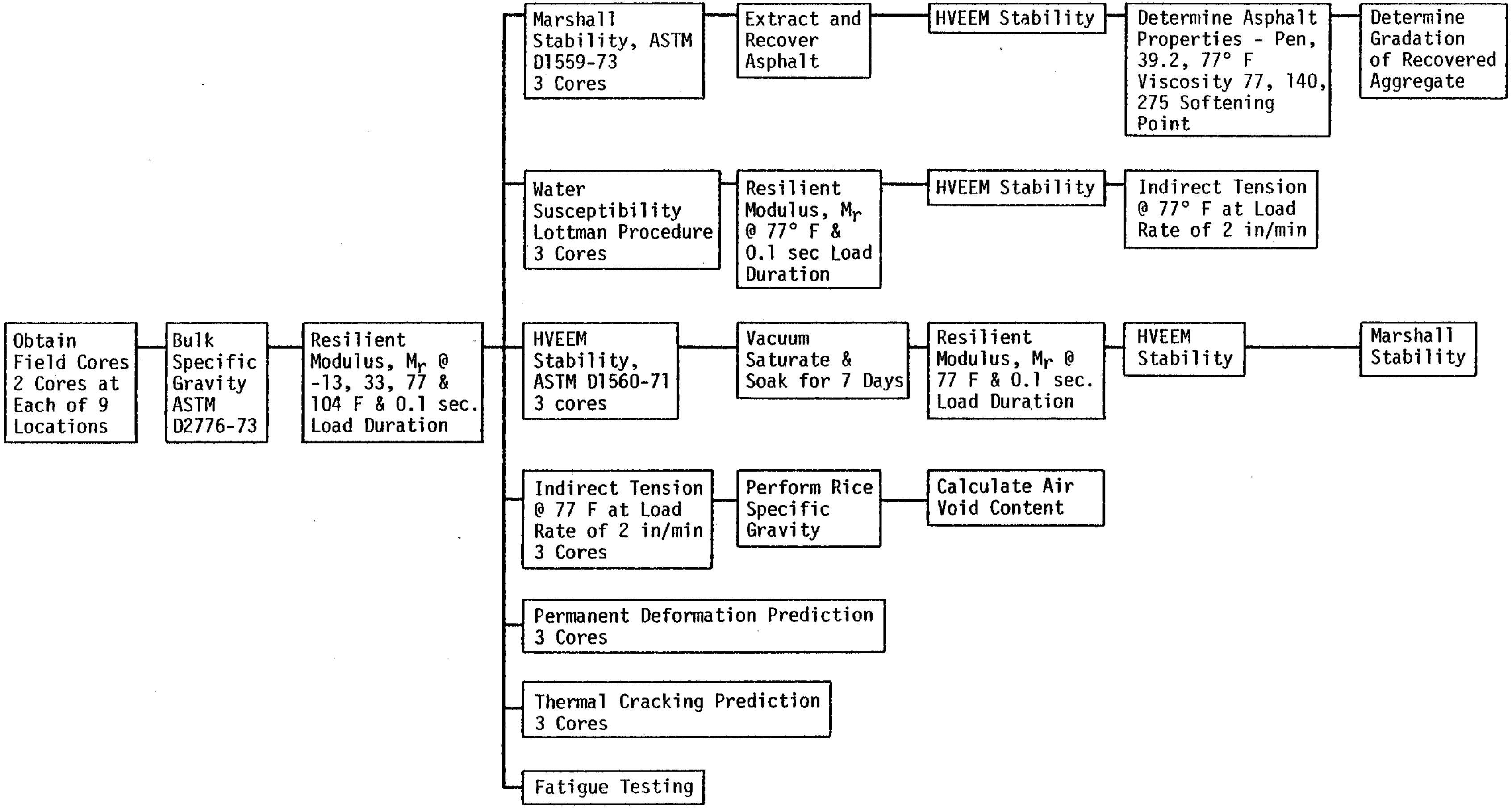

Figure 4. Test Schedule for HMAC Failure Analysis

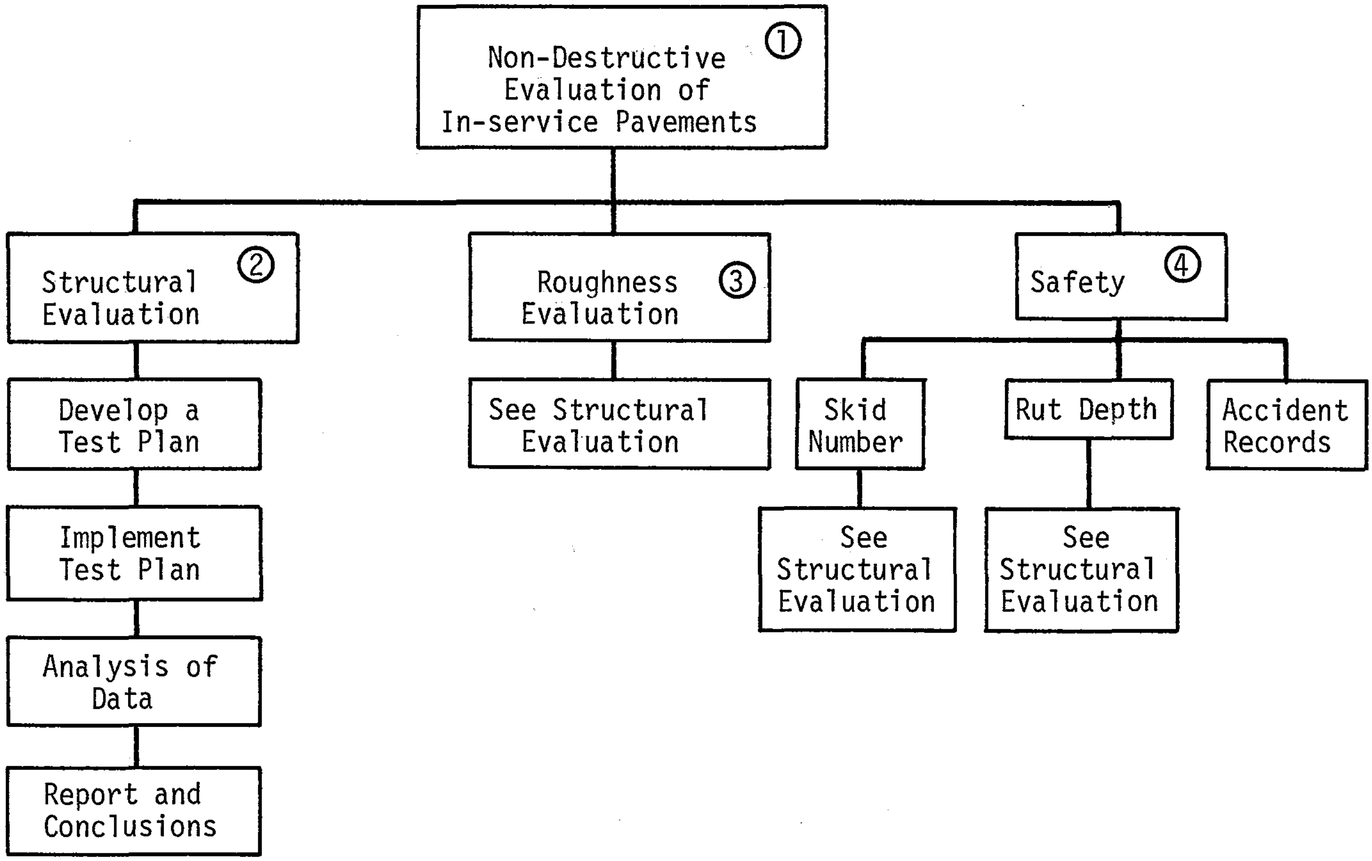

Figure 5. Non-Destructive Testing for Pavement Failure Analysis and Development of Rehabilitation Strategy

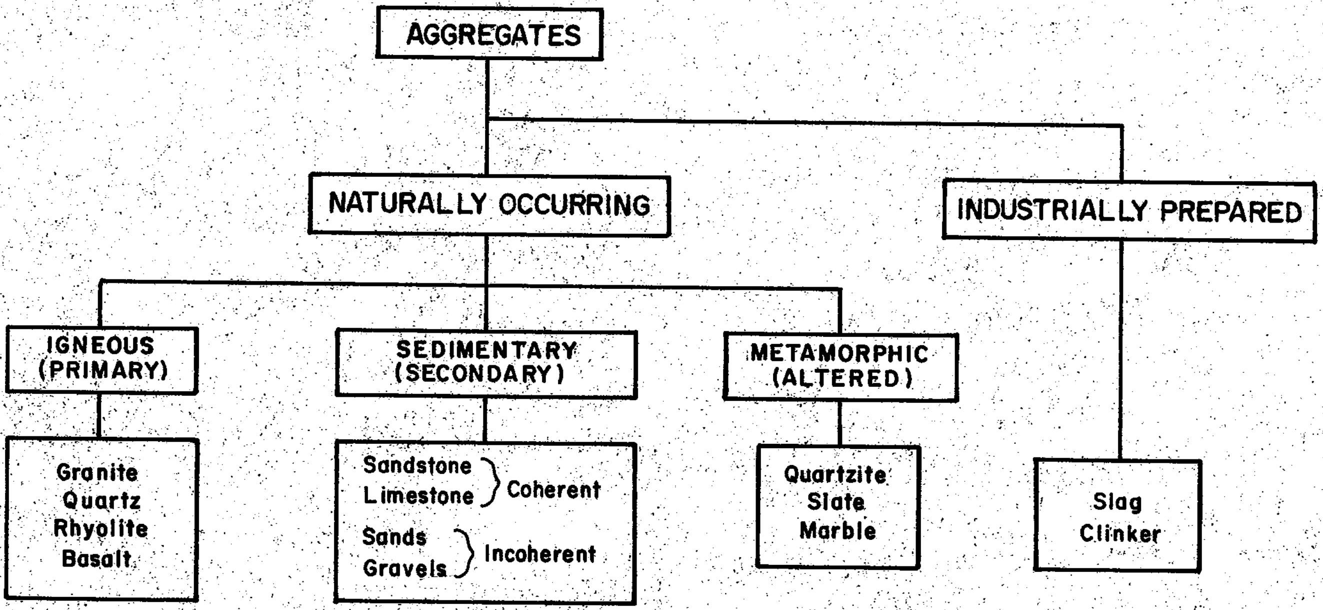

Figure 6. Sources of Aggregates for Asphalt Mixtures.

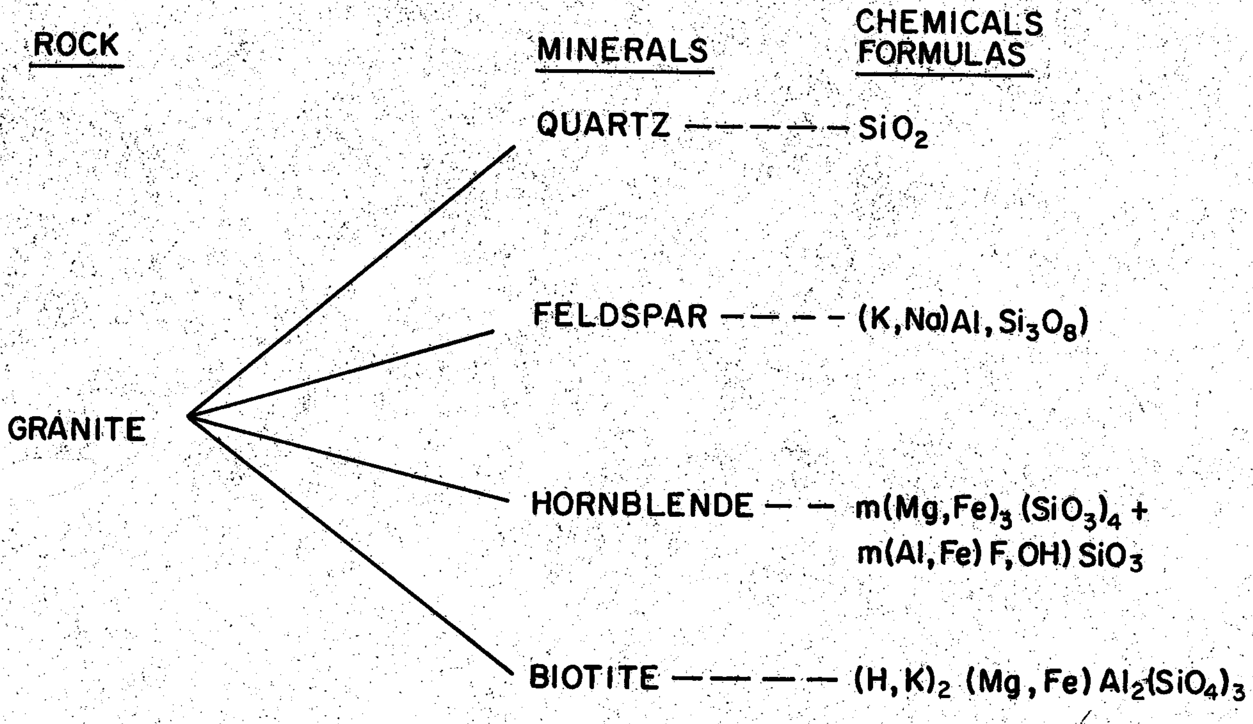

Figure 7. Minerals composing a typical granite.

After Hveem.

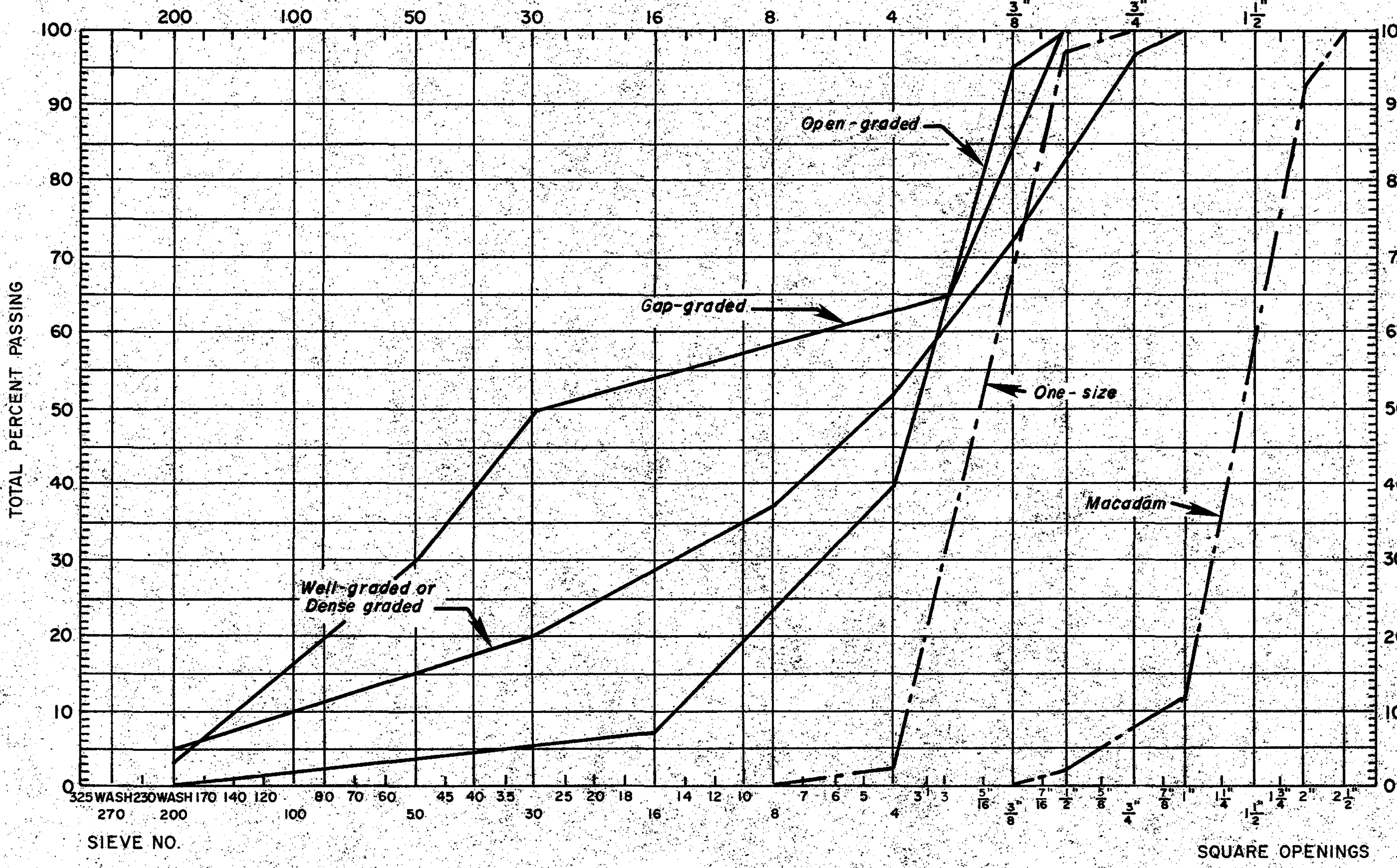

Figure 8. ~~Typical~~ aggregate gradations.

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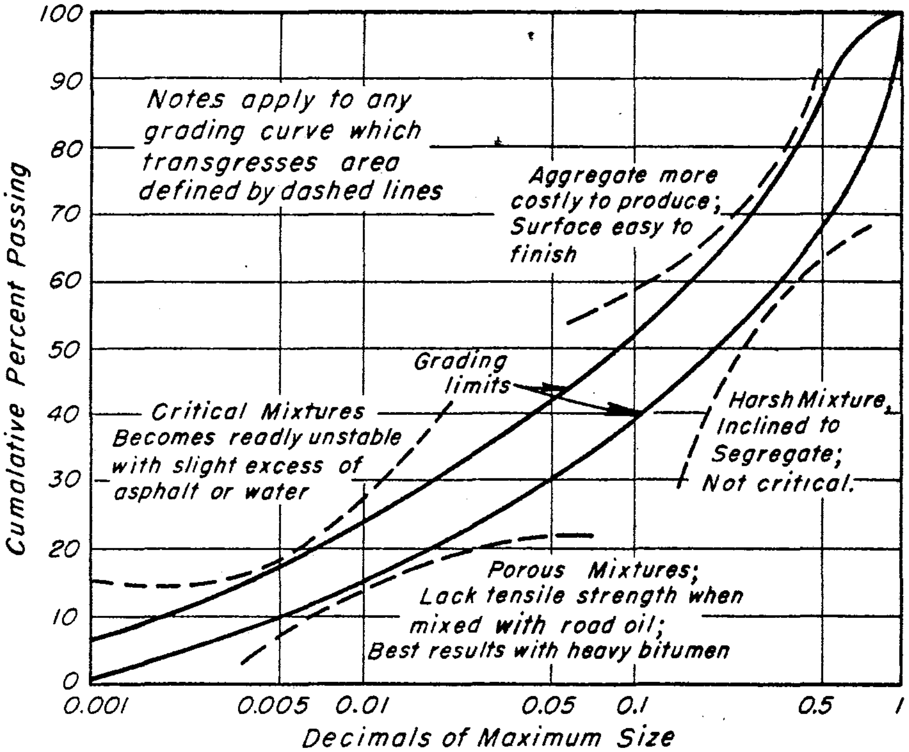
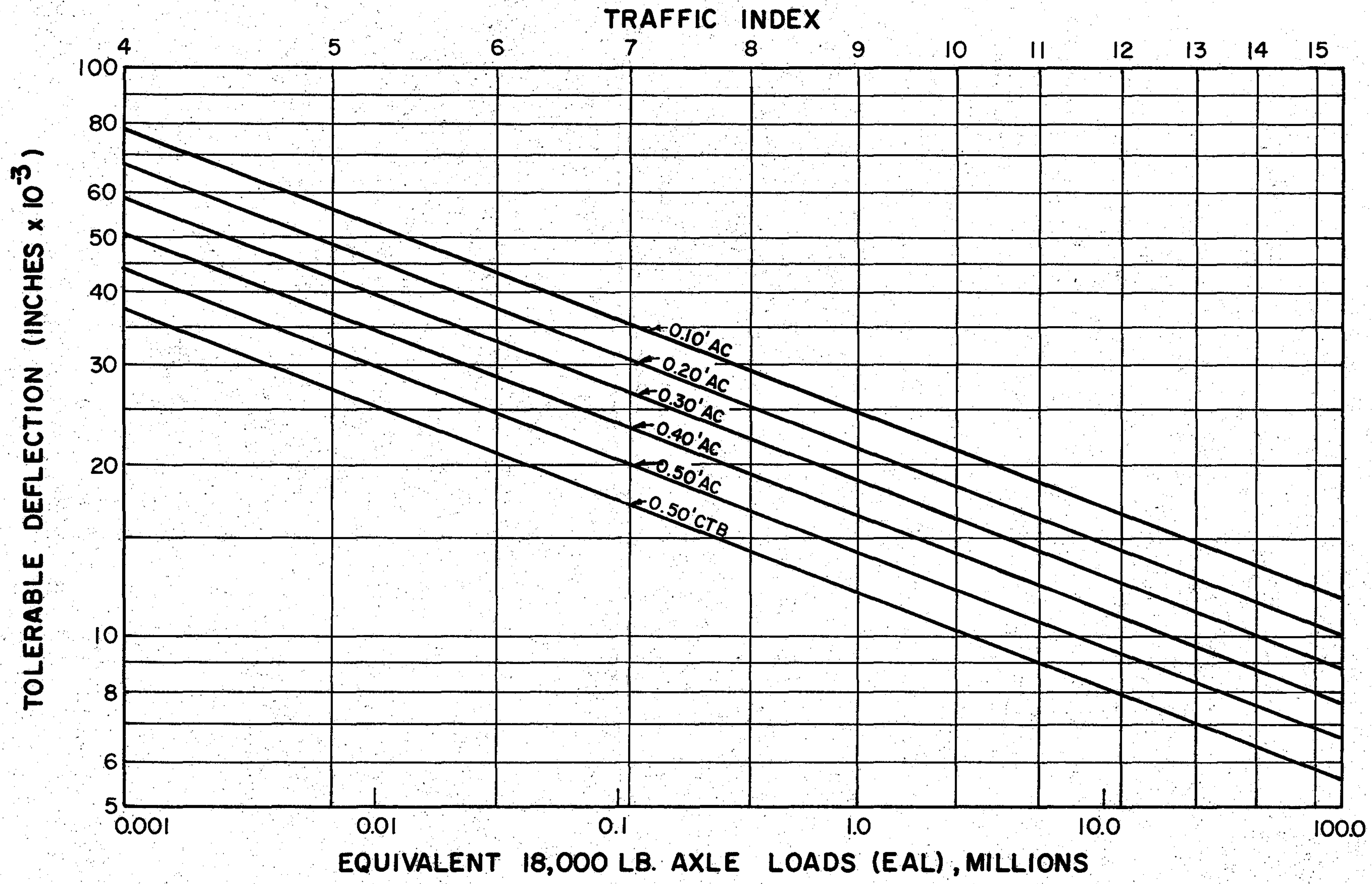


Fig. 9 - Grading chart illustrating grading specifications established to avoid undesirable conditions (After Hveem)



TOLERABLE DEFLECTION CHART

Note 1 in. = 25.4 mm
1 ft. = 0.305 m
1 lb. = 0.454 kg

Figure 10.