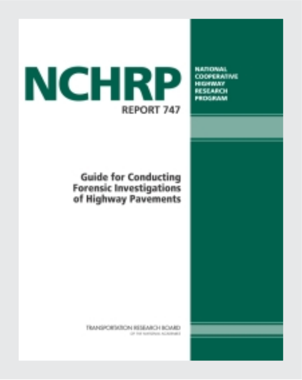

Guide for Conducting Forensic Investigations of Highway Pavements

DETAILS

151 pages | 8.5 x 11 | PAPERBACK
ISBN 978-0-309-28345-8 | DOI 10.17226/22507

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NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

NCHRP REPORT 747

Guide for Conducting Forensic Investigations of Highway Pavements

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Subscriber Categories
Pavements • Materials

Research sponsored by the American Association of State Highway and Transportation Officials
in cooperation with the Federal Highway Administration

TRANSPORTATION RESEARCH BOARD

WASHINGTON, D.C.
2013
www.TRB.org

NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

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NCHRP REPORT 747

Project 01-49
ISSN 0077-5614
ISBN 978-0-309-28345-8
Library of Congress Control Number 2013944805

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NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

are available from:

Transportation Research Board
Business Office
500 Fifth Street, NW
Washington, DC 20001

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http://www.national-academies.org/trb/bookstore

Printed in the United States of America

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The preparation of this guide was performed under NCHRP Project 01-49 by Fugro Consultants, Inc. Dr. Gonzalo R. Rada of AMEC Environment and Infrastructure, Inc., formerly of Fugro, served as the Principal Investigator. The other authors of this guide included Dr. David J. Jones and Dr. John T. Harvey with the University of California, Davis; Mr. Kevin A. Senn of Nichols Consulting Engineers, Chtd.; and Mr. Mark Thomas of Fugro.

FOREWORD

By Amir N. Hanna
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This report presents a recommended *Guide for Conducting Forensic Investigations of Highway Pavements.* The guide includes a practical and logical process for conducting forensic investigations of pavements to help understand the reasons behind premature failures or exceptionally good performance, and to collect data for use in developing or calibrating performance-prediction models. The information obtained from these investigations will provide a basis for improving pavement design and construction practices. The material contained in the report will be of immediate interest to state materials, pavement, and construction engineers, design consultants, paving contractors, and others involved in the different aspects of pavement design and construction.

Forensic investigations of highway pavements are generally conducted to (1) investigate underlying causes of premature pavement failures; (2) understand the factors contributing to exceptional pavement performance and longevity; and (3) collect data to support development and/or calibration of performance prediction models. Although forensic investigations have frequently been conducted by highway agencies, these investigations have often been conducted following different practices and have focused on a specific issue, and their processes and findings have not been adequately documented, making it difficult to use the generated data in other studies. In addition, there are no widely accepted guidelines for conducting these investigations that consider relevant factors, such as functional and structural performance, material-related distress, pavement type, sampling and testing requirements, and sequence of activities. Research was needed to identify and evaluate current practices for conducting forensic investigations and develop a rational process that consider all relevant factors and provide a realistic means for conducting these investigations. Also, there was a need to incorporate this process into a *Guide for Conducting Forensic Investigations of Highway Pavements* to help highway agencies conduct cost-effective investigations that will enhance understanding of pavement performance and provide the necessary data for improving pavement design and analysis procedures and construction practices.

Under NCHRP Project 1-49, “Guidelines for Conducting Forensic Investigation of Highway Pavements,” Fugro Consultants, Inc. of Austin, Texas worked with the objective of developing a *Guide for Conducting Forensic Investigations of Highway Pavements*. In pursuing this objective, the research recognized that forensic investigations are generally concerned with acquiring and evaluating data to identify the causes of premature pavement failure; understand the factors contributing to longevity of pavements; and document/understand observed performance and support development and/or calibration of performance prediction models (e.g., for use in local calibration of the models contained in the AASHTO Pavement ME—the Mechanistic-Empirical Pavement Design Guide [MEPDG]). The data acquired from these investigations can then be used to enhance pavement design and construction practices. To accomplish this objective, the research identified and evaluated traditional and innovative processes for conducting forensic investigations of pavements and incorporated the best practices into a rational *Guide for Conducting Forensic Investigations of Highway Pavements*. The process contained in the guide is structured in three phases to allow review after each phase and identify the most appropriate actions for subsequent phases. In this manner, actions that optimize use of resources and enhance the potential for achieving the investigation's objective will be identified and implemented. The process is supplemented by examples of pavement investigations to illustrate the application of the guide and a set of forms to facilitate recording and use of the acquired data. A summary of the research performed to develop the guide is presented as an attachment to the guide.

CONTENTS

Note: Many of the photographs, figures, and tables in this report have been converted from color to grayscale for printing. The electronic version of the report (posted on the Web at www.trb.org) retains the color versions.

CHAPTER 1

Introduction

1.1 Background

The concept of pavement forensic investigations has been around for a long time. Hundreds of such investigations have been performed in the United States in past decades, mostly to investigate the underlying causes of premature pavement failures. Other reasons for conducting forensic investigations include one or a combination of the following:

- Determining reasons for poor pavement performance/premature failures,
- Understanding exceptional pavement performance and/or longevity,
- Validating pavement performance prediction (actual versus predicted),
- Closing-out/conducting final investigations of experimental test sections,
- Collecting project specific data for:
  - Rehabilitation design,
  - Litigation purposes (e.g., settling disputes or defending/supporting claims and lawsuits),
- Collecting general data to:
  - Support development and/or calibration of pavement performance prediction models,
  - Understand/quantify long-term effects of traffic and environment on material properties,
  - Evaluate specific design and/or construction practices,
- Certifying pavement-related warranties, and
- Evaluating new pavement-related products or techniques.

The word forensic comes from the Latin adjective forensis, meaning “of or before the forum.” In Roman times, a criminal charge meant presenting the case before a group of public individuals in the forum. Both the person accused of the crime and the accuser would give speeches based on their side of the story. The individual with the best argument and delivery would determine the outcome of the case.

In modern use, the term “forensics” in place of “forensic science” can be considered incorrect, as the term “forensic” is effectively a synonym for legal or related to courts. However, the term is now so closely associated with the scientific field that many dictionaries include the meaning that equates the word “forensics” with “forensic science.” Within that context, the term forensics now encompasses the accepted scientific methodology and norms under which the facts regarding an event, or an artifact, or some other physical item are ascertained as being the case. In that regard the concept is related to the notion of authentication, whereby an interest outside of a legal form exists in determining whether an object is what it purports to be, or is alleged as being.

A literature review and survey questionnaire responses from state highway agencies identified poor performance or pavement failures as a primary reason for conducting a forensic investigation.

A forensic investigation may be conducted to achieve one or more of these objectives. This guide addresses the planning and conduct of investigations for any of these applications.

1.2 Objectives

The objective of this guide is to provide a systematic process for conducting forensic investigations of highway pavements. It includes guidance on organization and planning of the investigation, sampling and testing requirements, interpretation of results, and decision-making processes. Several case studies are presented to illustrate each of these activities.

An important element in a forensic investigation is achieving a balance between requirements, priorities, and available resources. Implementation of the guide will help focus the investigation on the factors relevant to the issues being raised and lead to benefits, such as:

- Enhanced utilization of the collected information,
- More cost-effective investigations,
- Improved understanding of pavement behavior/performance and insight into extending pavement life and eliminating premature failures, and
- Improved collection of data to support development of models for pavement evaluation and design.

A standard format is suggested for reporting and storing the findings from these investigations to facilitate future use and reference.

1.3 Scope

There are many reasons for performing forensic investigations. Certain key elements must be addressed for each reason to ensure a successful outcome of the investigation. It is important to understand the reasons why the investigation is needed, and how the results from the investigation will be used. However, it is also necessary to adopt an agency-wide protocol or standard for forensic investigations that addresses generic agency and project specific issues.

The generic agency issues relate to the establishment of the agency's forensic investigation protocol and should be in place prior to initiating an investigation. These issues only need to be addressed once, with periodic monitoring and revision to ensure they are still appropriate. While not part of the investigation, these issues are vital to the success of an agency's forensic investigation program. Generic agency issues are discussed in Appendix A. Project specific issues, on the other hand, focus on the procedures necessary for carrying out a forensic investigation, from planning of the investigation to the close-out activities. These issues are discussed in Chapters 3 through 9 and illustrated through case studies in Appendix B.

Although pavement forensic investigations are conducted for different purposes, they all seek an understanding of pavement performance. Accordingly, the success of a forensic investigation can be measured by its contribution to the understanding of the performance of the investigated pavement.

Four sets of factors, separately or in combination, influence the performance of pavements: (1) pavement structure (including pavement type, pavement layers, and construction); (2) subgrade soil; (3) traffic; and (4) drainage and environmental conditions. For example, good pavement performance or premature pavement failures are typically the result of a combination of these factors and the investigation must ensure that all relevant factors have been adequately and properly considered and addressed.

Gathering information on every possible pavement performance measure and every factor potentially affecting pavement performance is unnecessary and often beyond the available resources of most agencies. Forensic investigations will contain common elements (e.g., environment), but specific investigation elements will ultimately depend on the issues being investigated and the associated relevant pavement factors. Falling Weight Deflectometer (FWD) testing, distress surveys, Ground Penetrating Radar (GPR) surveys, and coring, for example, may be common to many investigations of poor pavement performance or premature pavement failures, but are not required for investigating pavement friction and/or noise-related issues. Therefore, achieving an appropriate balance between requirements, priorities, and available resources is a requisite for each investigation. Clearly establishing and understanding the investigation objectives and using them as the basis for collecting and analyzing the appropriate data will help eliminate the collection of unnecessary data and ensure a successful outcome.

Ideally, a series of flowcharts or a decision support system that guides the forensic investigator to the most likely reason for the observed pavement performance would be developed. However, because pavement performance is dependent on many factors and their interactions, both poor and exceptional performance is usually attributed to a combination of factors, and often to some unique and/or unexpected factors. Attempting to cover all of these factors in a single flow chart or decision support system is impractical and would often lead to misleading or incorrect conclusions, which could have serious implications. A phased approach that encourages the investigator to consider a range of factors is therefore followed in this guide. The reasons for adopting this approach are discussed in Chapter 2.

1.4 Investigation Approach

A phased approach, starting with a formal request for a forensic investigation and ending with a formal investigation close-out, is necessary to ensure that the appropriate combinations of contributing factors are investigated and that no unnecessary work, especially destructive testing, is under-

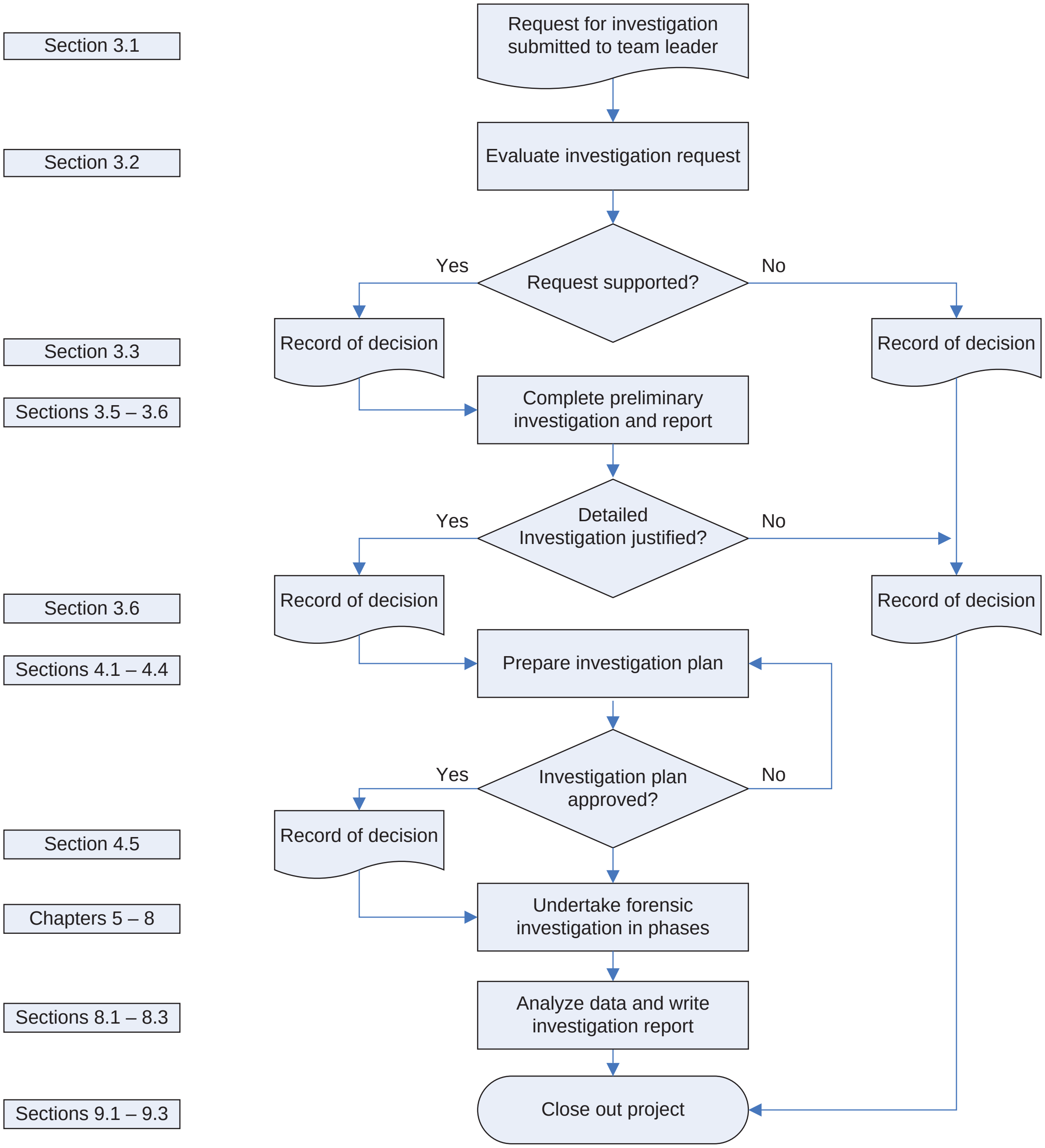


Figure 1.1. Recommended general approach to forensic investigations.

taken. This approach, which is used in this guide, encourages the use of formalized (but quick and easy to complete) documentation procedures at all stages to record the investigation. A flowchart summarizing this approach (with relevant section numbers in this guide) is shown in Figure 1.1.

1.5 Organization of the Guide

This guide is organized into nine chapters. This introductory chapter provides background information and the objectives, scope, approach, and organization of the guide. Chapter 2 summarizes the philosophy behind forensic investigations and the approach followed in this guide. Chapter 3 addresses requests for and initiation of a forensic investigation, including conduct of a preliminary investigation or background study. Chapter 4 covers the planning of the investigation, including selection of the investigation team, pre-investigation site visit, and non-destructive testing requirements. Chapter 5 discusses non-destructive testing, analysis of the data collected, the preparation of an interim report, and making a decision on the adequacy of the collected information to address the issues being investigated. Chapter 6 covers updating the investigation plan based on the non-destructive testing analysis. Chapter 7 discusses destructive field testing and laboratory testing of samples and specimens removed from the pavement. Data analysis and hypothesis testing and preparation of the final report are covered in Chapter 8. Chapter 9 includes review of the investigation, actions resulting from the investigation, and close-out of the investigation. Chapters 3 through 9 offer a suggested approach and are written in a procedural style to improve readability. This approach can be modified to suit agency procedures and expertise.

References cited in the guide are listed after Chapter 9. Appendix A addresses generic issues associated with the establishment of an agency's forensic investigation protocol; these issues are not part of the investigation, but are critical to the success of an agency's forensic investigation program. Appendix B includes a series of case studies that illustrate the use of the process described in this guide. Appendix C and Appendix D include example forms and checklists, respectively, for use during the conduct of the investigation. These forms can be modified to suit the particular requirements and procedures for the agency. The example forms are provided on a CD-ROM (CRP-CD-135), attached to the guide in a format that permits entering data and thus facilitates use of the guide.

CHAPTER 2

General Investigation Philosophy

Developing a framework or flowchart that provides a step-by-step process to guide the investigator in identifying the most likely reasons for the observed performance (be it poor or exceptional) would be highly desirable. However, such an approach can realistically be developed only for investigations in which one issue only contributed to the observed performance (e.g., poor compaction leading to early rutting). The combination of potential investigation objectives and the numerous factors associated with each investigation make it difficult if not impossible (and in some cases, counterproductive) to develop a practical framework that covers all possibilities. Instead, a general philosophy is provided in this chapter to better use the information obtained from the investigation. The philosophy entails the following three fundamental aspects:

- Understanding pavement performance and the factors that affect it,
- Recognizing pavement performance data and information needs, and
- Avoiding premature or unsupported conclusions about pavement performance.

2.1 Understanding Pavement Performance

The success of a forensic investigation requires a clear understanding of how pavements perform and why they perform/behave as they do. Four factors, separately or in combination, define the performance of a pavement:

- Pavement structure — includes pavement type (e.g., new or rehabilitated asphalt or concrete pavement) and pavement layers (thicknesses, material types and properties, drainage, shoulders, joints and steel reinforcement in concrete pavements, construction procedures, quality of construction and related issues, ambient conditions at time of construction, and others).
- Subgrade soil — includes material types, material properties, stabilization, embankment, cut/fill, depth to bedrock, drainage, and others.
- Traffic — includes traffic volumes, traffic loads/load spectra, traffic growth, seasonal trends, load restrictions, and others.
- Environmental conditions — includes air and surface temperatures, precipitation, wind, solar radiation, subsurface moisture, subsurface temperature, construction ambient conditions, unusual and/or catastrophic events, freeze/thaw cycles, freezing days, and others.

Environmental conditions, for example, may affect the pavement material layer properties. High moisture contents in unbound pavement and subgrade materials will generally lead to weaker layers, especially when they approach saturation conditions (e.g., during spring-thaw conditions). Similarly, high or low air temperatures result in low or high stiffness in asphalt concrete layers, respectively, which could make the asphalt concrete layer more susceptible to rutting or to cracking, respectively. The extent of the damage caused by traffic depends on the applied traffic loadings and volumes and pavement and subgrade material properties at that time.

To fully understand the performance of a given pavement, whether good, poor, or as anticipated, it is essential that each of the four pavement performance-related factors and their interactions be understood. This understanding is often difficult given the number of possible considerations in each of the four factors. Table 2.1 provides example considerations for three of the four factors, which are based on two pavement failure case studies presented in Appendix B. This example is intended to illustrate the potential complexities of forensic investigations. Additional considerations, which look at pavement performance scenarios including distress types and their causes, are presented in Section 2.4.

Table 2.1. Pavement performance-related factors and considerations.

Primary Factor		Considerations
Pavement Structure	Asphalt concrete surface layer	Poor surface preparation, inadequate mix strength/stability, inadequate mix gradation, low binder content, incorrect binder grade/viscosity, incorrect fines content, incorrect mix tenderness, mix segregation, low mix temperature during paving/compaction, loose material on surface of base prior to paving, poor prime coat application, incorrect rolling pattern leading to isolated area of high air-void content, temporary change in construction process, moisture/freeze-thaw damage related to isolated poor compaction, paver malfunction, removal of chunks with insufficient material replacement, temporary change in construction process, incorrect thickness design, incorrect/variable as-built thickness, crack reflected from base problem, excess moisture in mix, rapid aging binder
	Treated base layer	Differential compaction caused by recycler tires, incorrect compaction procedure to correct differential compaction, incorrect roller choice, poor/inconsistent compaction/rolling pattern, compaction after stabilizer set up, incorrect overlap procedure on second recycler pass, poor distribution of cement/double cement content in overlap/cement windrow caused by recycler apron, poor distribution of asphalt emulsion/foamed asphalt/double application of binder in overlap, incorrect compaction water application, poor material mixing, poor mix design, incorrect fines content, asphalt emulsion incompatible with aggregate, incorrect asphalt binder content, incorrect cement content, incorrect compaction moisture content/uneven distribution of water (e.g., damaged spray bar), incorrect stabilizer selection, incorrect base thickness design, incorrect/variable as-built base thickness, material change due to historical lane addition with different materials, incorrect reclaiming width (deleterious materials incorporated into base), excessive recycling depth, excessive fines/plasticity in recycled material
Environment		Surface drainage problem, subsurface drainage problem, drought causing clay shrinkage on side of road, seasonal roadside activity, abnormal rainfall event/season, seismic activity
Traffic		Inappropriate trafficking on stabilized base prior to surfacing, higher than design traffic, overloading

2.2 Recognizing Data and Information Needs

Understanding the performance of a given pavement requires that data and information about each of the factors affecting performance (discussed in Section 2.1) be collected and analyzed. Three potential sets of data should be pursued in addition to the performance measures (e.g., surface distress or roughness) of interest:

- As-designed data and information,
- As-constructed data and information, and
- Comparison data and information.

Because performance expectations are generally established during the pavement design process, gathering information on the as-designed conditions is vitally important to any given forensic investigation as it helps establish the basis for performance expectations or, in essence, the forensic investigation datum. The data and information needs apply to the four pavement performance factors discussed in Section 2.1 (i.e., pavement structure, subgrade soil, traffic, and environmental conditions).

Recognizing that the as-designed conditions are often not replicated during the construction process, it is also important that data and information on the four pavement performance factors for the as-constructed conditions are collected and compared to the as-designed conditions. Heavier or more voluminous traffic, worse than anticipated climatic conditions, weaker and/or thinner pavement layers than designed, for example, in combination or alone, could help explain why a pavement performed worse than expected.

Comparing as-designed data and information to the as-constructed data can help establish the reasons for the observed performance. To the extent feasible, the use of comparison data in the investigation is highly encouraged. For example, comparing the construction procedures, as-constructed data, and related information to those from another similar nearby project can help identify the reasons for the differing performance of similar pavement structures. If the issues being pursued pertain to the surface layer, for example, then a comparison project having similar subgrade soil, environmental conditions and base/subbase layers would allow for the direct comparison of the surface layer. Comparisons are also useful for investigating situations in which unexpected factors contribute to the observed performance. For example, poor spreading of cement in the construction of cement treated bases can lead to isolated areas of high cement contents that result in isolated areas of reflected shrinkage cracks.

Table 2.2. Forensic investigation data and information needs.

Performance Factors		As-Designed	As-Constructed	Comparison
Pavement Structures	Asphalt concrete surface thickness			
	Asphalt concrete surface modulus			
	Cement treated base thickness			
	Cement treated base modulus			
	Granular subbase thickness			
	Granular subbase modulus			
Subgrade Soil	Subgrade soil type			
	Subgrade soil modulus			
Traffic	Load spectra			
	Volumes			
Environmental Conditions	Precipitation data			
	Ambient temperature data			
	Subsurface moisture conditions			
	Subsurface temperature conditions			

Historical data on older projects is often difficult to recover, which can complicate the design, as-constructed, and comparative reviews. This is a problem when attempting to understand why a particular pavement has performed better than expected.

The tracking and completion of a data and information matrix is also encouraged. An example for a new asphalt concrete pavement is provided in Table 2.2.

These matrices enable forensic investigators to identify available data and information and those unavailable at any point during the investigation. They require regular updates throughout the investigation process.

Depending on the application, pavement performance may be characterized by a form of distress, deflection, roughness, friction, or noise, individually or in combinations, such as:

- Pavement distress data (using manual or automated distress surveys).
  - Asphalt concrete surface.
    - Cracking: fatigue cracking, block cracking, edge cracking, longitudinal cracking, reflection cracking, and transverse cracking.
    - Surface deformation: rutting and shoving.
    - Patching and potholes: patch deterioration and potholes.
    - Surface defects: bleeding, polished aggregate, and raveling.
    - Other distresses: lane-to-shoulder drop-off, water bleeding and pumping.
  - Jointed plain concrete (JPC) surface.
    - Cracking: transverse cracking, longitudinal cracking, corner breaks, and durability cracking (“D” cracking).
    - Faulting of transverse joints and cracks.
    - Joint deficiencies: transverse joint seal damage, longitudinal joint seal damage, spalling of longitudinal joints, and spalling of transverse joints.
    - Surface defects: map cracking, scaling, polished aggregate, and popouts.
    - Other distresses: blowups, lane-to-shoulder drop-off, lane-to-shoulder separation, patch deterioration, and pumping.
  - Continuously reinforced concrete (CRC) surface.
    - Cracking: transverse cracking, longitudinal cracking, and durability cracking (“D” cracking).
    - Punchouts.
    - Surface defects: map cracking, scaling, polished aggregate, and popouts.
    - Other distresses: blowups, transverse construction joint deterioration, lane-to-shoulder drop-off, lane-to-shoulder separation, patch deterioration, spalling of longitudinal joints, pumping, and longitudinal joint seal damage.
- Pavement deflection data (using FWD or other devices): maximum deflection, deflection basin, deflection indices, layer moduli, overall structural capacity, load transfer and voids, longitudinal and transverse variability, other deflection parameters, etc.
- Pavement roughness/elevation data (longitudinal and/or transverse): pavement roughness, International Roughness Index (IRI), rutting, elevation versus station, other roughness parameters, longitudinal and transverse roughness variability, etc.
- Pavement surface friction data: surface macro-texture, surface micro-texture, skid resistance, other friction parameters, longitudinal and transverse friction variability, and other considerations.
- Pavement surface noise: surface macro-texture, surface micro-texture, faulting in PCC, surface tining and grooving, clogging and/or raveling of open-graded friction courses, longitudinal and transverse noise variability, and other noise parameters and considerations.

Similarly, the factors that, separately or combined, influence pavement performance may be obtained from the following sources:

- Pavement structure and subgrade soil information available or obtained through one or more of the following methods: trenching; test pits and coring/boring; GPR; Dynamic Cone Penetrometer (DCP); drainage surveys (video or other means); field materials sampling and testing activities (e.g., tube suction and retained strength tests); laboratory materials testing; specialized testing (digital and scanning electron microscope analysis, and chemical tests); pachometer surveys of jointed and continuously reinforced concrete pavement (CRCP); magnetic tomography technology (MTT) scan of PCC; and other destructive and non-destructive testing techniques.
- Construction records from the resident engineer's and other staff logs.
- Traffic information available or obtained through one or more of the following methods: automatic traffic recorder (ATR) or automatic vehicle classifier (AVC) counts, weigh-in-motion (WIM) measurements, average daily traffic (ADT) and estimated single-axle load (ESAL) estimates (if monitoring data is not available).
- Environmental information available or obtained from one or more weather stations (e.g., National Climatic Data Center) or through the use of surface and/or subsurface instrumentation.

In addition to performance measures, the collection of as-designed and as-constructed data and information may help identify possible reasons for the observed pavement performance or its variation from that anticipated. Comparing data from good and poor performing sections within a project (or good and poor performing pavements of the same design in the same area) helps to isolate factors that led to the differences in performance.

2.3 Avoiding Premature Conclusions

Gathering data and information on every possible pavement performance measure and every factor potentially affecting pavement performance is unnecessary and often beyond the available resources of most agencies. Forensic investigations will contain common elements, but specific investigation elements will ultimately depend on the issues being investigated and the associated relevant pavement factors. Achieving a balance between requirements, priorities, and available resources is part of each investigation. Establishing and understanding the investigation objectives and using them as the basis for collecting and analyzing the appropriate data and information will help eliminate the collection of unnecessary data and ensure a successful outcome.

The first task in a forensic investigation is to understand the issues underlying the request for the investigation and then setting objectives to address these issues. Establishing these issues and objectives will help guide the investigation process and ensure that appropriate data and information are gathered and analyzed before any conclusions are drawn. Investigators are cautioned against focusing on a single factor contributing to the performance in question, as several factors (some of which may be unexpected and/or unanticipated) may have contributed to the observed performance. In those cases where a single factor can be clearly identified, it is likely that a comprehensive forensic investigation would not be necessary. The case studies (Appendix B) have shown many instances in which the apparent cause of a premature failure was not the sole or even the correct cause of poor performance.

2.4 Pavement Performance Investigation Scenarios

Most forensic investigations are carried out to understand poor pavement performance, early distress, or premature failures. To a certain extent, these investigations are probably easier to conduct because considerable information on such issues is readily available. Table 2.3, for example, shows typical asphalt concrete pavement distress types and their possible (common or occasional) causes *(1)*. Table 2.4 lists possible data and information requirements to identify the most likely causes of these distresses *(1)*. Table 2.5 provides similar information for investigations of portland cement concrete pavements *(2)*, and Table 2.6 summarizes key material related distresses (MRD) *(3)*.

The information contained in Table 2.3 through Table 2.6 addresses to a large extent the aspects of the investigation discussed in this chapter, namely understanding pavement performance and the factors that affect it, recognizing data and information needs, and avoiding premature or unsupported conclusions. However, it is important to recognize that these tables do not address all types of pavement failures (e.g., pavement roughness and loss of friction) or the full range of possible investigation objectives.

The conduct of forensic investigations into exceptionally well performing pavements is generally a more complex process, because there is no clear "starting point" as is the case with poor performing or failed pavements, and because these investigations usually take place later in the life of the pavement when obtaining design and construction data is more difficult. For example, it is possible that a pavement is considered performing exceptionally simply because the pavement surface was constructed thicker than designed. On

Table 2.3. Example Hot-mix Asphalt (HMA) distress types and possible causes *(1).*

Overall Problem		Possible Causes of Distress																																								
				Construction																		Materials								Climate					Traffic			Structural Design			Geometric Design		
		Mix Design																																								
Distress Category	Distress Type	Low Strength or Low Stability Mix	Poor Mix Gradation	Low Asphalt Content	High Asphalt Content	Low Air Void Content	High Air Void Content	Improper Fines Content	Tender Mix	Segregated Mix	Poor Surface Preparation	Excess/Insufficient Prime/Tack	Improper Crack Sealing Techniques	Improper Compaction Techniques	Excess Moisture in Mix	Low HMA Thickness	Low Base/Subbase Thickness	Poor Subgrade Compaction	Poor Base/Subase Compaction	Poor Base/Subase Gradation	High Asphalt Binder Viscosity	Low Asphalt Binder Viscosity	Temp. Susceptible Asphalt Binder	Rapid Aging Asphalt Binder	Moisture Sensitive Mix	Poor Aggregate Durability	Poor Aggregate Soundness	Poor Aggregate Cleanness	High Exposure to Moisture	Cool/Cold Prevailing Temperatures	Hot Prevailing Temperatures	Freeze-Thaw Cycling	Large Daily Temperature Cycles	High Traffic Volume	High ESAL Truck Volume	Exposure to Studded Tires/Chains	Inadequate Pavement Structure	Poor Material Selection	Poor Drainage	Narrow or Non-Existent Shoulders	Narrow Lane Width	Excessive Horizontal Geometry
Cracking	Longitudinal	●	○	●			●	○	○	○			○	○	○	●	○	●	●	○	●		○	●	○			○	●	○		○			●		●	○	●	○	○	
	Fatigue	●	○	●			●	○	○	○			○	○	○	●	○	●	●	○	●		○	●	○			○	●	○		○			●		●	○	●	○	○	○
	Transverse	○	○				○	○	○	○				○	○						●		○	●	○			○		○		●	●					○				
	Reflective	○	○				○	○	○	○			●	○	○	●					●		○	●	○			○		○		●	●		●		○	○				
	Block	○	○				○	○	○	○				○	○						●		○	●	○			○		○		●	●					○				
	Edge	○	○	○				○	○	○				○	○	●		○	○	○	●		○	●	○			○	●	○		●	○		○		●	○	●	●	●	●
Deformation	Rutting	●	●		●	●	●	○	○	○				○	○	●	○	●	○	○		●	●		○			○	●		●				●	●	●	○	●	○	○	
	Corrugation	○	○		●	●	○	○	○	○				○	○							○	●					○			●			●	●			○				
	Shoving	●	●		●	●	○	○	○	○		○		○	○							●	●					○			●				●			○				○
	Depression	●	○		○	○	○	○	○	○				○		○	○	○	○	○		○						○	○		○				○		●		●	○		
	Overlay Bumps												●																		●		●									
Deterioration	Delamination										●	●		○	○	●									○			○	○			●			○			○	○			
	Potholes	●	○	○			○	○	○	○			○	○	○	●	○	●	●	○	○			○	○				●	●		●		●	●	○	●	○	●	○	○	○
	Patching	●	○	○	○	○	○	○	○	●	○	○	○	○	○	●	○	●	●	○	○	○	○	○	○	○	○	○	●	●	○	●			●	○	●	○	●	○	○	○
	Raveling		●	●			●	●	●	●				●	○						○			●	●			●	●		○			○	●	●		○	○			
	Stripping		○	●		○	●	○		●			○	●	●						○			○	●	○	●	●	●		○	●			○			●	●			
	Polished Aggr																									○	●							○	●	●		○				
	Pumping	○	○				○			○			○			●	○	●	●	●									●			○			●		●	○	●	○		○
Mat Problems	Segregation		●					●		●																												○				
	Checking	○	●	○	●			○	●		○			●	●	○	○	●	●	○	○	○	○	○				○		○								○				
	Bleeding		○		●	●		○		○		○		○	○							○	○								●			○	●			○			○	

Legend ● Common cause of distress

○ Occasional cause of distress

the other hand, the observed performance may be due to one or more less-easily identifiable reasons such as adjustments made at the asphalt or concrete plant on a particular paving day, use of different sources of aggregates, substitution of construction equipment, or use of different curing procedures of stabilized materials.

While the reasons for undertaking the investigation may differ, the aspects discussed in this chapter are applicable to all types of forensic investigation including those undertaken to collect data for the calibration of mechanistic-empirical performance models. These aspects include understanding the factors affecting performance, collecting the necessary data and information, avoiding reaching premature or unsupported conclusions, and recognizing that a combination of factors contribute to the observed performance.

2.5 Investigation Phases

The investigation approach presented in this guide consists of three phases:

1. Preliminary investigation,
2. Non-destructive testing, and
3. Destructive and/or laboratory testing.

This phased approach is intended to eliminate the need for collecting data and information beyond what is required to address the objectives and issues in question. It is possible, for example, that the investigation be successfully completed (issues addressed and questions answered) by completing the preliminary phase if sufficient data and information are available at this stage to draw valid conclusions.

Table 2.4. Example data requirements to identify cause of HMA pavement distress *(1)*.

	Possible Causes of Distress	Records Review										Distress Survey		Structural Evaluation				Field Sampling & Testing Methods					Laboratory Testing (General Material Characteristics)																	
																							Unbound Mat's				Bound Materials										(Strength Related)			
		Design Reports	Plans and Specifications	QC/QA Records	As Built Drawings	Lab Material Test Results	Past Surveys/NDT/Sampling	Maintenance/Repair Histories	Traffic Data	Environmental/Climate Records	PMS Reports	Windshield Survey	Detailed Distress Survey	Nondestrudive Testing	Evaluation of NDT Uniformity	Struct.. Capacity Eval. (Caltrans)	Struct Capacity Eval. (Backcalc.)	Coring	Auger Base, Subbase and/or Subgrade	Shelby (Push) Tube	Test Pit (Trench)	Dynamic Cone/Standard Penetrometer	Soil Classification	Gradation	Moisture Content	Density	Density	Asphalt Content	Air Void Content	Asphalt Binder Viscosity	Asphalt Temperature Susceptibility	Aggregate Gradation	Coarse Aggregate Abrasion	Aggregate Durability	Aggregate Soundness	Moisture Sensitivity	R-Value (Unbound Materials	Indirect Tensile (Bound Materials)	Resilient Modulus (Fine/Coarse Mat'ls)	Modulus (Asphalt Mixtures)
Mix Design	Low Strength or Low Stability Mix	○	○	●		●	●	○					●	○	○			●									○									○		●		●
	Poor Mix Gradation	○	○	●		●	●	○					○					●									○					●								
	Low or High Asphalt Content	○	○	●		●	●	○					○					●									○	●				○								
	Low or High Air Void Content	○	○	●		●	●	○					○					●									○		●	○		○								
	Improper Fines Content	○	○	●		●	●	○					○					●														●								
Construction	Tender Mix			●				○				○						●									○					●						●		●
	Segregated Mix			●		●	●	○					●					●									○		○			●								
	Surface Prep/Excess/Lack Prime/Tack		●	●	○			○				○						●																						
	Improper Crack Sealing Techniques			○				○				●	○																											
	Improper Compaction Techniques			●		●	○	●				○	●	○	○			●									●		●											●
	Excess Moisture in Mix			●		●	○	○				○	●																											
	Low HMA Thickness	○	●	●	○	○	○	○					●	●	●	○	●	●																						
	Low Base/Subbase Thickness	○	●	●	○	○	●	○					○	●	●	○	●	○	●		○	○																		
	Poor Subgrade Compaction	○	○	●		●	●	○					○	●	●	○	●	○	○	○	○	●	○	○	○	●											○			
	Poor Base/Subase Compaction	○	○	●		●	●	○					○	●	●	○	●	○	○	○	○	●	○	○	○	●											○			
	Poor Base/Subase Gradation	○	○	●		●	●	○					○	●	●			○	●				●	●	○	○														
Materials	Low or High Binder Viscosity	○	○	●	○	●	●	○										●												●	○									○
	Temp. Susceptible Asphalt Binder			○		●	●	○				○						●												○	●									○
	Rapid Aging Asphalt Binder					○	○	○				○		○	○			●												○	○					●		○		○
	Moisture Sensitive Mix		●			○	○	○					○	●	●	○	○	●									○			○	○	○			●	●				
	Poor Aggregate Durability		●			○	○	○										●									○					○	○	●	○					
	Poor Aggregate Soundness		●			○	○	○											●								●								●					●
	Poor Aggregate Cleanness		●	●		○	○	○										●									○	○	○	○		○	●			●				
Climate	High Exposure to Moisture							○		●	○	○	●	●	●	●	○	○	●	○	○	●	○	○	●	○										○	○	○	○	○
	Cool/Cold Prevailing Temperatures							○		●	○	○															○											○		○
	Hot Prevailing Temperatures							○		●	○	○		○	○		○	○									○													
	Freeze-Thaw Cycling							○		●	○	○		○	○	○	○					●		●		●												●		
	Large Daily Temperature Cycles							○		●	○	○						●												●	●									
Traffic	High Traffic Volume	●						○	●		○	○																												
	High ESAL Truck Volume	●					○	○	●		○		●	●	●	○	●																					●		
	Exposure to Studded Tires/Chains	○				○	○	○	●		○	○						●													●			●	●					
Structural Design	Inadequate Pavement Structure	○	●	●	●	○	○	○			○		●	●	●	○	●	●	●	○	○	●	○	○	○	○	○										○	○	○	○
	Poor Material Selection	○	●	●	●	●	●	○			○		●	●	●	○	●	●	●	○	○	●	○	○	○	○	○	○	○	○	○		○	○	○	○	○	○	○	○
	Poor Drainage	○	●	○	●	○	●	○			○		●	●	●	○	●	●	●	○		●	○	○	○	○	○		○			○				●	○	○	○	○
Geometric Design	Narrow or Non-Existent Shoulders	●	●	●	●		○	○	○			○		○	○	○	○																							
	Narrow Lane With	●	●	●	●		○	○	○			○		○	○	○	○																							
	Excessive Horizontal Geometry	●	●	●	●		○	○	○			○		○	○	○	○																							

Legend
● Typical test or data requirement
○ Occasional test or data requirement

Table 2.5. Example PCC distress types and possible causes *(2)*.

Structural Distress	Contributing Factors[1]					
	Pavement Design	**Load**	**Water**	**Temp.**	**Pavement Materials**	**Construct.**
Structural Distress						
Cracking[2]						
Transverse	P	P	N	C	C	P
Longitudinal	P	P	N	C	C	P
Corner	C	P	C	C	N	N
Intersecting	C	P	C	N	C	N
Possible causes of cracking: Fatigue, joint spacing too long, shallow or late joint sawing, base or edge restraint, loss of support, freeze-thaw and moisture-related settlement/heave, dowel bar lock-up, curling, and warping.						
Joint/Crack Deterioration						
Spalling	C	C	N	C	P	C
Pumping[2]	C	P	P	N	C	N
Blowups	C	N	N	P	C	N
Joint Seal Damage[2]	C	C	C	C	P	C
Possible causes of joint/crack deterioration: Incompressibles in joint/crack, material durability problems, subbase pumping, dowel socketing or corrosion, keyway failure, metal or plastic inserts, rupture and corrosion of steel in JRCP, high reinforcing steel.						
Punchouts[2]	P	P	C	N	C	N
Possible causes of punchouts: Loss of support, low steel content, inadequate concrete slab thickness, poor construction procedures.						
Durability						
D-cracking	N	N	P	C	P	N
Alkali-Silica Reactivity (ASR)	N	N	P	C	P	N
Freeze-thaw damage	N	N	P	P	P	C
Possible causes of durability distresses: Poor aggregate quality, poor concentrate mixture quality, water in the pavement structure.						
Functional Distress						
Roughness						
Faulting[2]	P	P	P	C	C	N
Heave/swell[2]	C	N	P	P	C	N
Settlement[2]	C	C	C	N	N	C
Patch deterioration	C	C	C	C	C	C
Possible causes of roughness: Poor load transfer, loss of support, subbase pumping, backfill settlement, freeze-thaw, and moisture-related settlement/heave, curling and warping, and poor construction practices.						
Surface Polishing	N	C	N	N	P	N
Possible causes of surface polishing: High volumes of traffic, poor surface texture, wide uniform tine spacing, wide joint reservoirs, and wheel path abrasion because of studded tires or chains.						
Noise	P	C	N	N	C	P
Possible causes of noise: High volumes of traffic, poor surface texture, wide uniform tine spacing, wide joint reservoirs, and wheel path abrasion because of studded tires or chains.						
Surface Defects						
Scaling	N	N	C	C	P	P
Popouts	N	N	C	C	P	C
Crazing	N	N	N	C	C	P
Plastic shrinkage cracks	N	N	N	C	C	P
Possible causes of surface defects: Over-finishing the surface, poor concrete mixture, reactive aggregates, and poor curing practices.						

[1] P= Primary Factor C= Contributing Factor N= Negligible Factor

[2] Loss of support is an intermediary phase between the contributing factors and these distresses. Loss of support is affected by load, water, and design factors.

Table 2.6. Summary of key Materials Related Distresses (MRD) in PCC pavements *(3).*

Type of MRD	Surface Distress Manifestations and Locations	Causes/ Mechanisms
Materials Related Distress Due to Physical Mechanisms		
Freeze-Thaw Deterioration of Hardened Cement Paste	Scaling, spalling, or map cracking, generally initiating near joints or cracks; possible internal disruption of concrete matrix.	Deterioration of saturated cement paste due to repeated freeze-thaw cycles.
Deicer Scaling/ Deterioration	Scaling or crazing of the slab surface with possible alteration of the concrete pore system and/or the hydrated cement paste leading to staining at joints/cracks.	Deicing chemicals can amplify freeze-thaw deterioration and may interact chemically with cement hydration products.
Freeze-Thaw Deterioration of Aggregate	Cracking parallel to joints and cracks and later spalling; may be accompanied by surface staining.	Freezing and thawing of susceptible coarse aggregates results in fracturing and/or excessive dilation of aggregate.
Materials Related Distress Due to Chemical Mechanisms		
Alkali-Silica Reactivity (ASR)	Map cracking over entire slab area and accompanying expansion-related distresses (joint closure, spalling, and blowups).	Reactions involving hydroxyl and alkali ions in pore solution and reactive silica in aggregate resulting in the build-up of expansive pressures within aggregate, until tensile strength of surrounding paste matrix is exceeded, resulting in cracks.
Alkali-Carbonate Reactivity (ACR)	Map cracking over entire slab area and accompanying pressure-related distresses (spalling, blowups).	Expansive reaction involving hydroxyl and alkali ions in pore solution and certain dolomitic aggregates resulting in dedolomitization and brucite formation.
External Sulfate Attack	Fine cracking near joints and slab edges or map cracking over entire slab area, ultimately resulting in joint or surface deterioration.	Expansive formation of ettringite that occurs when external sources of sulfate (e.g., groundwater, deicing chemicals) react with the calcium sulfoaluminates.
Internal Sulfate Attack	Fine cracking near joints and slab edges or map cracking over entire slab area.	Formation of ettringite from internal sources of sulfate that results in expansive disruption in the paste phase or fills available air voids, reducing freeze-thaw resistance.
Corrosion of Embedded Steel	Spalling, cracking, and deterioration at areas above or surrounding embedded steel.	Chloride ions penetrate concrete, resulting in corrosion of embedded steel, and formation of high-volume oxidation products and resultant expansion.

CHAPTER 3

Investigation Request and Preliminary Investigation

This chapter follows the suggested agency forensic investigation protocol and staffing discussed in Appendix A. It covers preparing and evaluating investigation requests, deciding to proceed or not to proceed with an investigation based on the request, initiating a forensic investigation, undertaking a background study, identifying issues of interest and preparing objectives to address them, collecting relevant information, determining whether a forensic evaluation is justified, preparing a preliminary investigation report, and recording the decision to proceed or not to proceed with a forensic investigation.

3.1 Preparing a Forensic Investigation Request

A forensic investigation begins with a formal request (example Form #1 in Appendix C) from an agency employee or from an organization undertaking research or other work on behalf of the agency (e.g., a university research center or an appointed consultant) to the forensic investigation coordinator (discussed in Appendix A). The requestor:

1. Completes the formal request that includes contact details, location of the issues to be investigated, the reasons for the investigation (why the investigation needs to be carried out and how the results will be used), a summary of work already undertaken that prompted the request for the investigation, details about the project that the issue is part of, and a justification for urgency. Preliminary details about the project may include, but are not limited to:
   - Pavement structure and surface type.
   - Date opened to traffic.
   - Suspected source of problem.
   - Length of the project or proportion of job affected.
2. Submits the request to the agency forensic investigation coordinator.

3.2 Evaluating a Forensic Investigation Request

On receipt of the request, the forensic investigation coordinator:

1. Acknowledges receipt of the request form.
2. Opens a project file and starts a budgeting/cost-tracking spreadsheet and/or assigns a charge number for team members to book time to during the investigation.
3. Issues an investigation number. This number should include the year plus a consecutive number as a minimum (e.g., 2011/01), but can include other agency specific data that will facilitate later retrieval (e.g., district, route number and post-mile, pavement type, investigation type code, etc.).
4. Evaluates the request and determines whether the request should be supported. This may require discussion with the requestor to fully understand the request intent and issues to be investigated. Reasons to consider a request inappropriate include:
   - The problem is identical to one that has already been investigated or is currently being investigated.
   - The problem is clearly linked to a known construction deficiency (e.g., compaction requirements were not met and were not corrected at time of construction).
   - The issues can be clearly linked to normal pavement behavior/deterioration.
   - The issues can be linked directly to a known event (e.g., severe rutting linked to the issuance of an abnormal load permit).
5. Records whether the investigation should be supported or not on the request form and signs the form.

3.3 Record of Decision to Proceed or Not to Proceed with Investigation

The record of decision is completed by signing the request form. The investigation coordinator notifies the investigation requestor of the decision. If the decision does not support proceeding with the investigation, the project file is closed.

3.4 Initiating a Forensic Investigation

The investigation coordinator initiates a forensic investigation after the decision to proceed has been recorded. The investigation coordinator should then identify the investigation director (discussed in Appendix A) and request permission (and if necessary, funding) to proceed with a preliminary investigation.

3.5 Undertaking the Preliminary Investigation

A preliminary investigation is undertaken to formulate the objectives, determine whether a forensic investigation is necessary to meet these objectives, and, if it is, the level of required investigation. The preliminary investigation is typically undertaken by the forensic investigation coordinator and, if appropriate, the individual requesting the investigation, and includes the following tasks:

1. Identify the issues that need to be considered/addressed.
2. Prepare objectives to address the identified issues.
3. Collect and review relevant information.
4. Determine whether a forensic investigation is justified.
5. Prepare a record of decision.
6. Identify an appropriate level of investigation.
7. Prepare a preliminary investigation report.

3.5.1 Identifying Relevant Issues and Objectives

The first task in a forensic investigation is to understand the issues underlying the request for the investigation and then setting the objectives to address these issues. Examples of typical issues and related objectives include:

- Issue: Premature pavement failure.
  - Example objectives:
    - Determine the causes of premature failure at site location.
    - Identify if the failure is likely to occur in other areas where it has not yet been observed.
    - Determine how the failure will be repaired.
    - Determine whether design and/or specifications should be changed to avoid recurrence.
- Issue: Pavement performed much better than expected.
  - Example objectives:
    - Determine the reasons for exceptional performance at site location.
    - Determine whether design and/or specifications should be changed.
- Issue: One pavement section performed differently than another.
  - Example objectives:
    - Determine the reasons for different pavement performance at site location.
    - Determine actions needed to obtain uniform performance.
- Issue: Repair of the pavement failure under warranty.
  - Example objectives:
    - Determine the causes of pavement distress.
    - Determine how the distress should be repaired.
    - Determine compliance with warranty provisions.
- Issue: Poor surface characteristics of the pavement.
  - Example objectives:
    - Determine whether the pavement functionality is influenced by material, construction, and/or maintenance-related factors.
    - Determine what corrective action needs to be taken, if any.
    - Determine whether specifications need to be changed.
- Issue: Performance of experimental pavement sections.
  - Example objectives:
    - Compare the distresses between the control and experimental sections.
    - Determine whether or not the technology/method experimented with warrants implementation.
    - Determine whether or not design procedures and specifications need to be changed.
    - Collect data for developing/calibrating/refining performance models.

The forensic investigation coordinator documents the issues to be addressed and the study objectives on an appropriate form (example Form #2 in Appendix C.)

3.5.2 Collecting Relevant Information

Relevant information needs to be collected to determine whether or not a forensic investigation is justified, and, if it is, to determine the level of investigation required and prepare a budget and plan for successful completion. This information typically includes the following:

- An interview with the individuals requesting the investigation to clarify reasons for the request and the issues to be investigated.
- Interviews with agency and industry personnel (e.g., inspectors and contractors) familiar with the project/experiment to obtain their views regarding the issue under investigation.
- Project information (e.g., location, extent) to identify the location and extent of the road section requiring investigation.
- Structural design and as-built/constructed information to check if the issues being investigated can be explained by any apparent deviations from normal procedures. This includes a review of Quality Control/Quality Assurance (QC/QA) information for construction variables such as thickness and material type.
- Materials design and as-built/constructed material properties information to determine whether the issues being investigated can be explained by deviations from expected procedures (e.g., review of daily progress and QC/QA reports for information on equipment changes, weather impacts, construction variables such as compaction, opening times, opening temperatures, mix design formulae, admixtures, and strength, etc.).
- Pavement management system data to examine past performance of the section, determine whether the issues is new, and/or determine whether past performance is a factor in the issues being investigated.

Note that while network-level data is useful for screening purposes, it often lacks the resolution required for detailed forensic investigations.

- Maintenance records to obtain surface treatment and drainage maintenance histories.
- Climate records to identify climatic events that may have contributed to the issues being investigated. The Road Weather Information System (RWIS) is a useful source for this.
- Soil and geology maps to identify any subgrade soils or geologic anomalies.
- Traffic data to identify changes in traffic patterns that may have contributed to the issues being investigated, including data on overload permits issued. Traffic data may be available from the agency weigh-in-motion database, or may be collected specifically for the investigation. Seasonal traffic variation (e.g., related to agriculture or to the use of studded tires/chains in winter) will need to be taken into consideration. Note that if traffic data is collected specifically for a forensic investigation, it may not be representative of the traffic that led to/caused the issues being investigated (e.g., a short period of overloaded trucks moving equipment to an industrial development).
- Results of non-destructive or destructive testing already undertaken (e.g., GPR, FWD, profile, cores, etc.). All state highway agencies (SHAs) are required to collect longitudinal profile data on their network as part of the required Highway Performance Monitoring System (HPMS) reporting of federal aid projects, and to submit the computed roughness in terms of the IRI. Most SHAs include longitudinal profile in their pavement management systems and have network-level IRI data readily available.
- Other relevant information (e.g., information on accidents/incidents, permits issued, etc.).
- Information on underground services (e.g., gas lines, cables, pipelines, etc.) to determine whether they contributed to the issues being investigated, and whether they will influence the forensic investigation in any way.

Warning

Information on underground utilities may not be covered in design and as-built documentation.

- Past forensic investigations to determine if similar issues have been investigated previously.
- Existing soil information, which may be of value when identifying any failure mechanisms from well below the surface of a pavement. National soils databases, provided by entities such as the National Resources Conservation Service, can provide relevant insight into existing conditions.
- An internet search using selected keywords to determine whether similar experiences have been documented elsewhere. These searches can be particularly useful in identifying unexpected or unusual issues related to the observed performance.

By scanning the collected data, the forensic investigation coordinator can determine whether any factors can be identified that satisfactorily explain the issues being investigated. The forensic investigation coordinator also summarizes the findings on the Preliminary Investigation form (example Form #2 in Appendix C).

3.5.3 Determining Whether or Not a Forensic Evaluation is Justified

The information collected in the previous task is used to determine whether a forensic investigation is justified by considering the typical reasons for undertaking an investigation, such as:

- Poor performance, premature distress, and/or premature failure that can be linked to:
  - Inappropriate design (i.e., under design);
  - Deviations from accepted construction practice that do not directly affect standard QC/QA test results (e.g., stabilizer spreading and mixing procedures or pre-pulverization techniques on full-depth recycling projects that result in a different to expected grading);
  - Quality control/quality assurance issues (e.g., materials and construction deviations from specifications);
  - Significantly higher than expected traffic;
  - Overloading;
  - A specific event (e.g., rutting associated with an overload permit, rutting or cracking related to extreme temperatures, deformation associated with flooding, etc.);
  - Changes in drainage (blocked, installed) or other hydraulic conditions (change in irrigation practice nearby, change in shoulder condition); and/or
  - Maintenance actions that may have affected materials or structure (e.g., joint sealing or repair, slab jacking, sprayed asphalt treatments that may soften or darken the asphalt near the surface, sanding, etc.).
- Exceptionally good performance attributed to:
  - Inappropriate design (i.e., over-design);
  - Quality control/quality assurance issues (e.g., exceptional materials and construction quality in comparison to those specified); and/or
  - Significantly lower than expected traffic.
- Consensus among agency practitioners on the causes of observed pavement performance.
- Agreement between the agency and the contractor in a warranty claim.
- Ability to collect the data required for performance modeling through routine methods.

A forensic investigation is probably justified unless the issues can be readily explained. The forensic investigation coordinator should make a recommendation on whether or not to proceed with a forensic investigation. Where appropriate, the recommendation should include the benefits of undertaking the investigation or the consequences of not undertaking the investigation.

The forensic investigation coordinator documents the recommendation on an appropriate form (example Form #3 in Appendix C).

3.6 Preparing a Preliminary Investigation Report and Record of Decision

The investigation coordinator prepares a preliminary investigation report for record purposes consisting of a cover sheet (example Form #4 in Appendix C), the investigation request (example Form #1 in Appendix C), the preliminary investigation summary (example Form #2 in Appendix C), and the suggested record of decision (example Form #3 in Appendix C).

The forensic investigation coordinator then:

1. Obtains approval from the investigation director for the decision to proceed/not to proceed with a more detailed forensic investigation.
2. Records the decision and reasons for it in the project file (example Form #3 in Appendix C).
3. Notifies the requestor of the decision.

CHAPTER 4

Initial Forensic Investigation Plan

Forensic investigations are often undertaken because of the unclear reasons for specific pavement performance. Given this uncertainty, deciding on the most appropriate level of investigation is often difficult. Therefore, a systematic phased approach in which the results of early phases define the actions required in subsequent phases is desired (Figure 4.1, with relevant section numbers in the guide). This approach may take a little longer if all phases are ultimately required and, in some instances, may require more than one site visit and more than one closure, but it will limit unnecessary work, which is especially important if destructive testing is being considered. The phases typically include visual assessments, NDT, and if necessary, destructive testing and laboratory testing.

> Opening a pit or trench is often the first consideration in many forensic investigations, and although desirable for data collection and project completeness, a number of factors should be considered before carrying out such an extensive study.

A phased approach will also require a phased investigation plan. The initial investigation plan typically includes details on establishing the team, a pre-investigation site visit and deciding on NDT requirements. The findings from this first phase of the study are then used to determine whether sufficient data has been collected to address the issues being considered, or if additional information from a more intensive study, usually with non-destructive and possibly also destructive testing, will be required.

4.1 Selecting a Project Investigation Team

The forensic investigation coordinator selects a project investigation team with the expertise (and team size) needed to address the issues being investigated. The team, selected from the virtual team (discussed in Appendix A), depends on the specific issues being investigated and location of the project, but will typically include one or more of the following individuals:

- The forensic investigation coordinator:
  - Manages the investigation.
  - Compiles the documentation (e.g., investigation plan, reports, approvals, records of decision, etc.).
  - Makes all logistical arrangements (e.g., notifies other departments, arranges for traffic closures, arranges NDT, etc.).
  - Obtains all necessary approvals.
- The individual requesting the investigation, if appropriate:
  - Provides local input and project-related data.
  - Implements (or supports/directs the implementation of) the actions identified on completion of the investigation.
- The design engineer:
  - Participates in discussions about differences between the design and as-built records.
- The area maintenance superintendent (or similar position):
  - Provides information on maintenance and highway performance/behavior trends in the area.
  - Provides input on maintenance activities undertaken on the project being investigated.
  - Provides information regarding existence and condition of drainage features such as edge drains, permeable layers, and daylighting of drainage layers.
  - Makes all arrangements for the local work crew and equipment.

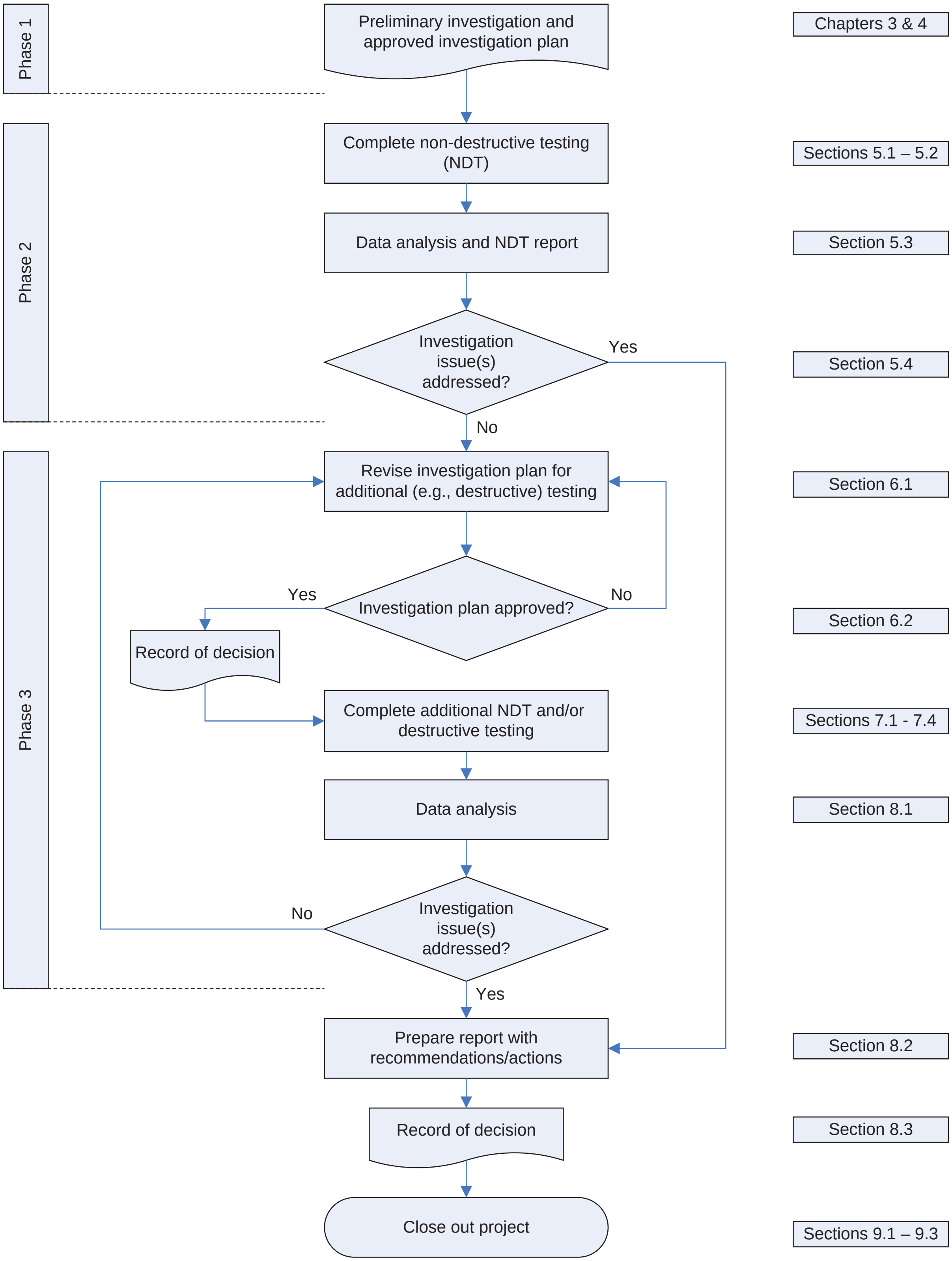


Figure 4.1. Phased approach to forensic investigations.

- The district materials engineer (or similar position):
  - Relates the issues being investigated to performance/behavior of other roads in the area.
  - Coordinates collection of specimens (e.g., cores), raw materials, etc.
- An agency or university/research center "expert" on the particular issues being investigated (if appropriate):
  - Provides specialist expertise and testing services and assists with data analysis, interpretation, and preparation of the report.
- If appropriate, the contractor and/or material supplier (if the investigation will not lead to a claim or legal action):
  - Identifies deviations from standard practice.
  - Identifies any deviations in material sourcing or properties.

Detailed forensic investigations will usually also require the following:

- NDT equipment managers.
- Laboratory to perform required routine and specialized testing.
- A work crew.

The investigation coordinator documents the team names, contact details, and responsibilities on an appropriate form and distributes it to the team (example Form #5 in Appendix C).

4.2 Pre-Investigation Site Visit

A pre-investigation site visit is undertaken by all or by selected team members to:

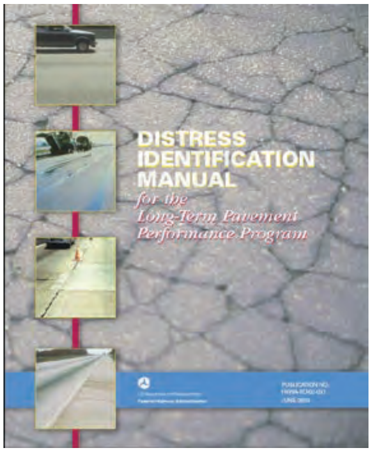
- Conduct an initial visual assessment.
- Determine the initial limits of the forensic investigation.
- Conduct a safety assessment.
- Identify the need for NDT, and if required, types and potential test locations.

The pre-investigation site visit is undertaken from a vehicle with observations and photographs from the shoulder and usually does not require a road closure. Photographs of the issues being investigated together with possible contributing factors are used to prepare test plans and inform members of the team who did not participate in the site visit.

The forensic investigation coordinator documents the pre-investigation site visit on an appropriate form (example Form #6 and Form #7 in Appendix C).

4.2.1 Initial Visual Assessment

An initial visual assessment allows the team to review the issues under investigation; observe any distress (or absence of distress) associated with the issues; identify any other distresses and/or performance, environmental, and traffic-related issues that may influence the investigation; determine the limits of the investigation; identify the tests that need to be considered; and identify potential safety and logistical problems associated with later assessments and testing. The assessment involves first driving the project in both directions for general familiarization with the site and identification of locations requiring closer observation, and then returning to those locations for a more detailed evaluation from the shoulder. State visual assessment guidelines (if available) and/or the *Distress Identification Manual for the Long-term Pavement Performance Program (4)* should be followed and observations documented on the appropriate forms (example Forms #8 and #9 in Appendix C). Consider the following:



DISTRESS IDENTIFICATION MANUAL

for the Long-Term Pavement Performance Program

- Observe the distress under traffic and record any specific issues (e.g., pumping, increased noise levels, or driver reaction to the conditions). Consider the effect of different weather conditions on performance and look for evidence of this performance (e.g., discoloration of pavement from pumped fines or temporary flooding, rutting caused by higher than normal temperatures, rutting caused by studded tires/chains, damage caused by snow removal equipment).
- Look for causes of problems that are restricted to a short section of the pavement (e.g., end-of-load segregation of materials, an accident that has caused mechanical damage, a spill that has affected the surfacing, a blocked drain, influence from road side activities, transition from cut to fill, utility cut reinstatements, etc.).
- Look for evidence of construction activities that lead to cyclical types of distress (e.g., end-of-load segregation that can cause raveling, daily start or end of construction problems).
- Check for widened sections of road that may have different structural sections or that place the wheelpath on the joint.
- Take photographs of all observations.
- Identify and record potential locations for destructive testing that may be required later in the study. This may include comparative sections (e.g., good and poor performance).

Figure 4.2. Blocked side drain and culvert.

- Include an assessment of roadside conditions and activities that may contribute to the issues being investigated. Investigators are encouraged to observe, investigate, and document all possible contributing factors, recognizing that poor performance is often attributed to a number of reasons. Examples include:
  - Side drains and culverts have been blocked by agricultural activity or new access roads (example of filled-in drains to facilitate equipment movements in Figure 4.2).
  - Side drains are used for moving irrigation water (example in Figure 4.3). FWD measurements will often differentiate areas where side drains are flooded for prolonged periods.
  - Plow furrows run perpendicular or at an angle to the road (example in Figure 4.4).
  - Irrigation water contacts the road (example in Figure 4.5 also common with vegetated medians in urban areas).
  - Water flows into the roadway from access roads and driveways (example in Figure 4.6).
  - Unstable slopes.
  - Dysfunctional slope drainage systems.

Figure 4.3. Side drain used for irrigation water.

Figure 4.4. Plow furrows perpendicular to road.

Figure 4.5. Irrigation water sprays on the road.

Figure 4.6. Access road drainage problems (note digout).

- Work on underground services and utilities (i.e., distress may be associated with utility failure/work).
- Vegetation (especially large trees) in close proximity to the road.
- Isolated areas receiving prolonged shade when the remainder of the road is in constant sunlight.
- Transitions between cut and fill.
- New developments that may have resulted in temporary large increases in construction traffic.

4.2.2 Initial Limits of the Forensic Investigation

The initial limits of the forensic investigation (i.e., begin and end points) will depend on the investigation and the issues being considered. The extent of the sections being investigated may be limited to an isolated location, a single lane, or all lanes for the entire length of a construction project. The area within the limits should include the issues being investigated and to the extent possible, and, if applicable, a "control" section, where the issues being investigated are not apparent, to allow for comparisons. Examples of control sections include (but are not limited to) the following:

- The area between the wheelpaths if the issue being investigated appears to be limited to the wheelpaths.
- A different day's production if the issue being investigated appears to be limited to a specific day or batch of materials.
- Conventional construction or materials if alternatives were experimented with over a short section (e.g., experimental sections, comparing HMA to warm-mix asphalt).
- A section with no distress on a different part of the project or similar project.
- A smooth section adjacent to one with poor ride quality.

Depending on the issues being investigated, initial limits are typically set based on project information and/or the visual assessment and then refined using non-destructive tests.

Generally, construction issues account for a majority of premature pavement failures. Hence, it is important to identify the extent of existing and potential failures. NDT on distressed and control sections (i.e., sections with no distress) is useful for identifying those areas that have not yet shown such distress but may exhibit similar performance at a later time.

4.2.3 Safety Assessment

A safety assessment should be undertaken to identify potential safety hazards for the crew and road users in later investigations. This assessment will help determine the most appropriate time to undertake the investigation and identify locations that should be avoided if possible, such as ramps, curves, intersections, and rises.

> This guide does not cover safety management for forensic investigations. Agency guidelines for road closures, NDT, and other related activities should be followed.

4.2.4 Initial NDT Requirements

Although the issues being investigated are likely manifested on the surface of the road, the factors contributing to the issues will invariably be a result of something occurring within the pavement structure, and consequently "out of sight." An appropriate form of NDT is often the most effective means of identifying and quantifying these factors and determining the extent of their impact. The need for destructive testing and the precise location where it takes place will usually be decided based on the findings of these assessments. NDT is also used to identify additional problem areas that have not yet exhibited signs of distress, to delineate uniform sections, and to quantify variation along the project being investigated.

> Many agencies conduct routine NDT as part of their pavement management system activities. Pavement Management System (PMS) data for the section of road being investigated should be checked during the background study to determine whether additional testing is required.

4.2.4.1. Introduction to Commonly Used NDT Equipment

Ground Penetrating Radar (GPR), Falling Weight Deflectometer (FWD), friction testers, and profilometers are the most common types of NDT equipment used in forensic investigations. GPR equipment is typically used to provide a rapid assessment of layer thickness and to delineate certain problem areas such as debonding, presence of moisture, voids under concrete slabs, and other issues that are normally assessed through coring. FWD equipment is typically used to measure deflections to quantify structural issues. Friction testing and profile measuring equipment are used to assess frictional (skid) resistance and ride quality issues, respectively. On-board Sound Intensity (OBSI) equipment

for measuring noise is less common, but of growing interest. Other more labor intensive types of non-destructive testing equipment such as nuclear and non-nuclear density gauges (for measuring compaction), seismic pavement analyzers (SPA, for measuring site-specific stiffness), laser texture meters (for measuring texture), permeameters (for measuring permeability), and magnetic tomography technology (for determining dowel presence, location, and alignment) are typically used within a traffic closure in later stages of the investigation.

Information on non-destructive testing equipment and on the specifics of set up and operation is available in the literature and not covered in this guide. Most agencies routinely perform deflection, friction, and profile measurements and further discussion is not warranted. However, some key issues are highlighted. GPR is a relatively new technology used in forensic investigations; some information is provided for guidance. The forensic investigation coordinator must ensure that the investigation team has adequate expertise with the operation of the equipment and associated data analysis.

Ground Penetrating Radar (GPR) GPR is an electromagnetic sounding method in which a transducer (transmitter/receiver) is passed over the surface of a pavement. Short-duration pulses of radio energy are transmitted into the pavement and reflections from within are detected by the receiver. Changes in the dielectric properties are used (in conjunction with positional [GPS] information) to assess layer thickness, presence of moisture, voids, and other anomalies. The technology is maturing, but developments in the apparatus and the way in which the data is interpreted continue. Equipment configuration (i.e., antenna choice and frequency) and data interpretation is dependent on the nature of the investigation and requires specific expertise.

Air-coupled antennas (Figure 4.7) are typically used to identify and delineate wearing course problems such as overlay thickness variation, stripping, and possibly debonding. They can be operated at highway speeds; however, data quality decreases with increasing speed and a closure may be required to obtain more accurate results. They can be adversely affected by other transmitters such as cellular telephone towers. Ground-coupled antennas (Figure 4.8) generally have better lateral resolution than air-coupled antennas and are either used in contact with the road or slightly above it (~0.75 in. [20 mm]). They are suited for assessing the entire structure (except for about 1.0 in. [25 mm] near the surface), including most surface issues discussed earlier, assessing the thickness of pavement layers and identifying voids under slabs. Ground-coupled antennas are more suited for slow speeds, which allow the collection of higher resolution data but typically require a road closure. They are less influenced by outside interference and can be used at highway speeds.

Figure 4.7. GPR with rear mounted air-coupled transducer.

Figure 4.8. GPR pod containing MHz ground-coupled transducers.

Figure 4.9. Cart-based GPR with low frequency ground-coupled transducer.

Low frequency transducers (200 to 600 MHz [Figure 4.9]) have good depth penetration, but relatively poor lateral/vertical resolution and are used for assessing subgrade and base layers. Higher frequency transducers (>600 MHz) have relatively poor depth penetration, but good lateral/vertical resolution and are used with air-coupled antennas for assessing wearing course layers. Combinations of antennas type and frequency are possible and should be used where information on the full depth of the pavement and its foundation layers is required.

The output from any GPR configuration is unlikely to be conclusive when used alone in forensic investigations. However, when used in combination with other equipment such as FWD, GPR can be useful for identifying areas of the project that require additional investigation. Limited coring is generally required to calibrate GPR data.

Example reference materials for GPR testing include:

- *NCHRP Synthesis of Highway Practice 255: Ground Penetrating Radar for Evaluating Subsurface Conditions for Transportation Facilities (5).*
- FCC 02-48, Revision of Part 15 of the Commission's Rules Regarding Ultra-Wideband Transmission Systems *(6).*
- ASTM D4748, Determining the Thickness of Bound Pavement Layers Using Short Pulse Radar.

Falling Weight Deflectometer (FWD) FWD testing (Figure 4.10) generally requires a full closure, but rolling closures can be used on lower traffic volume roads with good sight distance. A small number of cores will be required to confirm layer thickness. FWD measurements are highly influenced by the test location and temperature; these factors must be considered when correlating test measurements to performance.

Figure 4.10. Falling Weight Deflectometer.

Key issues to consider include:

- Ensure that the equipment has a valid calibration certificate.
- On rutted asphalt pavements, test in between the wheelpaths to ensure that the plate seats firmly on the surface. On cracked asphalt pavements, test in the area of least cracking (also typically between wheelpaths). Test any asphalt pavements when the surface temperature is above 60°F (15°C), especially for thick asphalt layers, otherwise the deflections will be very small and difficult to distinguish from general noise. Always use a non-recorded "seating" drop prior to recorded drops to ensure all geophones are in stable contact with the highway surface.
- On concrete pavements, test location on the slab will depend on the issues being investigated. Load transfer efficiency is measured across the joints in the wheelpaths, stiffness is measured in the center of the slab, and curling is measured across the joint at the slab corners. Example test locations for jointed concrete pavements are shown in Figure 4.11.
- Load transfer efficiency can only be evaluated when testing temperatures are low, preferably below 77°F (25°C). At higher temperatures, the slabs will often have expanded sufficiently for aggregate interlock to produce uniformly high load transfer measurements.
- For stiffness testing on concrete, take measurements at cooler temperatures (i.e., at night or early in the morning) to ensure contact between the slab and underlying layers at the center of the slab. Testing at high temperatures (i.e., afternoon) can result in misleading backcalculated stiffnesses as the center of the slab may not be in contact with the underlying layers.

Example reference materials for FWD testing include:

- Long-Term Pavement Performance Program Manual for Falling Weight Deflectometer Measurements, Version 4.1, December 2006 *(7).*

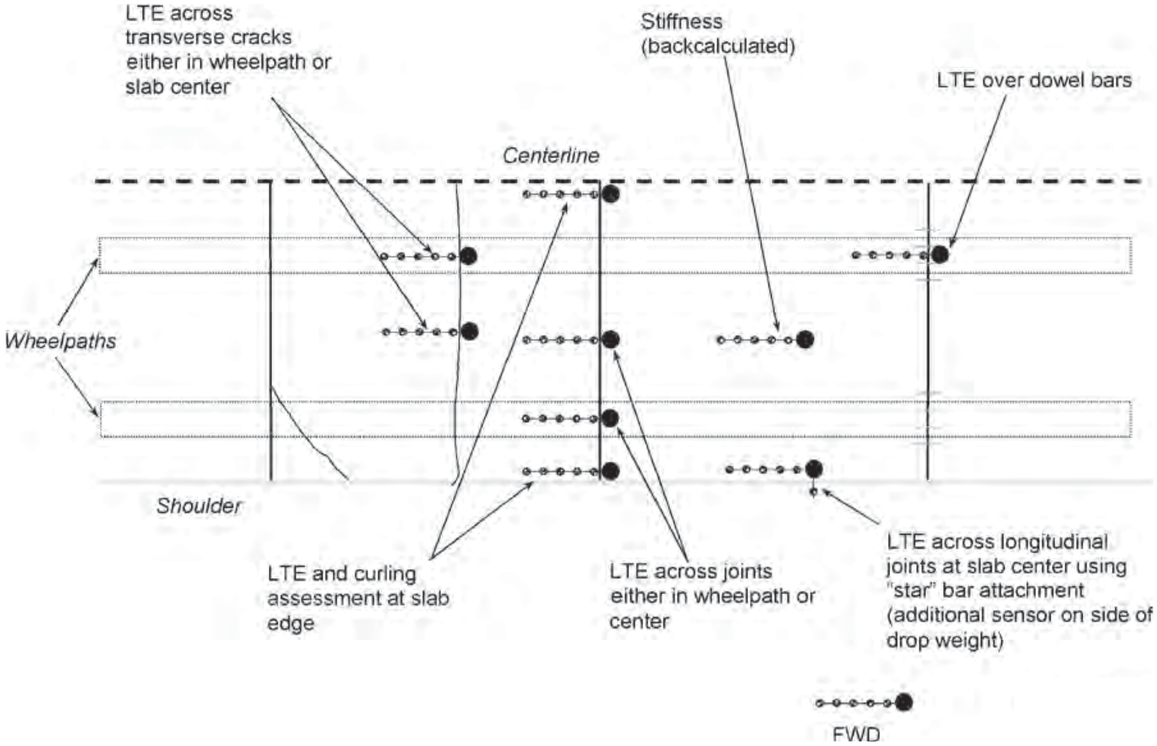


Figure 4.11. Example FWD test locations on jointed plain concrete pavements.

- ASTM D4694, Standard Test Method for Deflections with a Falling-Weight-Type Impulse Load Device.
- ASTM D4695, Guide for General Pavement Deflection Measurements.

Profilometer Profile is usually measured with lasers in customized vehicles (Figure 4.12) that collect a range of data for use in pavement management systems including longitudinal and transverse profile, micro- and macro-texture, crack pattern, photologs, and GPS coordinates. Stand-alone units that can be attached to any vehicle are also available. Profile can be measured at highway speeds without the need for a road closure, and therefore the entire project under investigation is typically measured. Data quality is usually sufficient to quantify smoothness/ride quality issues that would typically be studied in a forensic investigation. However, detailed investigations of small areas may be required and can be undertaken with walking profilometers, if necessary, within a road closure. Equipment should be appropriately calibrated.

Figure 4.12. Profilometer van.

Example reference materials for profiling include:

- AASHTO PP 37, Standard Practice for Determination of International Roughness Index for Quantifying Roughness of Pavements.
- AASHTO R36, Standard Practice for Evaluating Faulting of Concrete Pavements.
- ASTM E867, Terminology Relating to Vehicle-Pavement Systems.
- ASTM E950, Standard Test Method for Measuring the Longitudinal Profile of Traveled Surfaces with an Accelerometer Established Inertial Profiling Reference.
- ASTM E1166, Guide for Network Level Pavement Management.

Friction Testers Frictional (or skid) resistance is measured with a variety of equipment such as locked wheel friction testers (Figure 4.13), dynamic friction testers, and pendulum testers. Locked wheel friction testers do not require a

Figure 4.13. Locked wheel friction tester.

traffic closure and are more likely to be used in initial investigations over a length of road to determine whether friction values are above or below agency norms and to identify specific areas requiring additional investigation. Dynamic friction testers and pendulum testers are typically used for more detailed examination of micro-texture and require a traffic closure. Skid resistance standards are set by state highway agencies and will depend on a number of factors including aggregate characteristics, climate, and traffic.

Example reference materials for friction testers include:

- ASTM E274, Standard test method for skid resistance of paved surfaces using a full-scale tire.
- ASTM E2340, Standard test method for measuring the skid resistance of pavements and other trafficked surfaces using a continuous reading, fixed-slip technique.

Noise Testers The most common method for measuring tire-pavement noise is the OBSI method (Figure 4.14), in which measurements are taken at highway speed. Data quality is sufficient to quantify pavement surface issues contributing to noise such as raveling, large aggregates, or clogging/overcompaction of open-graded friction courses that would typically be studied in a forensic investigation. Results are usually used in conjunction with visual assessment data (e.g., areas of raveling, large stone size, crack sealing, or joint spalling), and/or permeability measurements to assess clogging on open-graded mixes, and with texture measurements (such as mean profile depth [MPD] on asphalt concrete surfaced pavement or mean texture depth [MTD] on PCC surfaced pavement).

Example reference materials for noise measurements include:

- *NCHRP Report 630: Measuring Tire-Pavement Noise at the Source (8)*.
- AASHTO TP76, Standard Method of Test for Measurement of Tire/Pavement Noise Using the On-Board Sound Intensity (OBSI) Method.

Figure 4.14. On-board Sound Intensity Meter (OBSI).

4.2.4.2. Examples of the Use of NDT in Forensic Investigations

Examples of how NDT is used in forensic investigations are provided in Table 4.1 for asphalt surfaced pavements and in Table 4.2 for concrete surfaced pavements. Additional examples cited in the literature are summarized in Appendix F. Concrete surfaced pavement includes jointed plain concrete pavement (JPCP), continuously reinforced concrete pavement (CRCP), and jointed reinforced concrete pavement (JRCP). If the pavement being investigated consists of an asphalt surface over concrete pavement, then information for both asphalt surfaced and concrete surfaced pavement should be considered depending on the distresses appearing on the pavement surface.

Targeted coring is always required for determining actual pavement thickness for FWD tests and for calibrating GPR results for thickness estimation and layer type identification. Some cores are also needed to determine the theoretical maximum density (TMD) of HMA, which can be used with nuclear or non-nuclear bulk density measurements to calculate air-void content. These cores can also be used to check for factors contributing to the issues being investigated (e.g., stripping, debonding, ASR, and aggregate degradation). Coring can often be done during the road closure for FWD testing to eliminate the need for additional road closures if no further field investigation is required.

4.2.4.3. Testing Frequency

The amount of testing required depends on the issues being investigated; however, consideration should be given

Table 4.1. Examples of NDT on asphalt surfaced pavements.

Issue	Possible Contributing Factors	Type of Non-Destructive Testing	Typical Testing Frequency
Exceptional performance	Design Construction Materials	GPR, FWD GPR, FWD, nuclear gauge GPR, FWD	- GPR: continuous (2 scans/yd [m]) - FWD: 75 ft (25 m) intervals, 3 to 15 ft (1 to 5 m) in defined problem areas, offset in adjacent lanes
Rutting	Asphalt densification Asphalt shearing Base, subbase or subgrade failure Stabilization failure Insufficient layer thickness Moisture damage Poor compaction Incorrect binder Inappropriate or not followed mix design	Nuclear gauge[1] Transverse profilometer/ straightedge FWD, drain inspection FWD GPR, FWD, nuclear gauge[1] GPR, FWD, nuclear gauge[1] GPR, nuclear gauge[1] Not appropriate Not appropriate	- GPR: continuous (2 scans/m) - FWD: 75 ft (25 m) intervals, 3 to 15 ft (1 to 5 m) in defined problem areas - Nuclear gauge: per state test method - Transverse profilometer/straightedge in defined problem areas
Alligator cracking	Base, subbase or subgrade failure Moisture damage Layer debonding Thickness, compaction Incorrect binder Excessive binder aging Inappropriate or not followed mix design	FWD, drain inspection GPR, FWD GPR, FWD GPR, nuclear gauge[1] Not appropriate Not appropriate Not appropriate	- GPR: continuous (20 scans/yd [m]) - FWD: 75 ft (25 m) intervals, 3 to 15 ft (1 to 5 m) in defined problem areas - Nuclear gauge: per state test method
Transverse cracking	Compaction Incorrect binder Reflection cracking Shrinkage in stabilized base Frost/moisture damage in unbound layer	Nuclear gauge[1] Not appropriate Not appropriate (GPR in some situations)[2] Not appropriate (GPR in some situations) Drain inspection	- Nuclear gauge: per state test method
Longitudinal cracking	Base, subbase or subgrade failure Moisture damage Construction joint compaction Shoulder design and construction Excessive stabilizer in recycling overlaps Stabilization failure	GPR, FWD, drain inspection GPR, FWD Nuclear gauge[1] GPR, FWD GPR Not appropriate	- GPR: continuous (2 scans/yd [m]) - FWD: 75 ft (25 m) intervals, 3 to 15 ft (1 to 5 m) in defined problem areas - Nuclear gauge: per state test method
Block cracking	Shrinkage in stabilized base Binder properties (burning or rapid aging)	Not appropriate (GPR in some situations) Not appropriate	
Ride quality/roughness	Constructed ride quality Cracks Potholes Large aggregates Raveling	Profilometer[3] Profilometer[3] Profilometer[3] Profilometer[3] Not appropriate	- Profilometer continuous (use measurement from between wheelpaths to determine initial IRI)
Surface failure/potholes	Moisture damage Delamination Shoulder design and construction Poor cross slope	GPR, FWD GPR, FWD GPR, FWD, drain inspection Survey or measure with level	- GPR: continuous (20 scans/yd [m], multiple scans) - FWD: 75 ft (25 m) intervals, 3 to 15 ft (1 to 5 m) in defined problem areas - 15 ft (5 m) intervals in affected area
Excessive noise	Mix design Raveling Cracking Clogging of porous surface	OBSI OBSI, longitudinal profilometer[3], laser texture meter[4] OBSI Permeameter	- OBSI: continuous - Profilometer: continuous - Laser texture meter: affected area - Permeameter: In and between wheelpaths
Frictional characteristics	Polished aggregate Flushing/bleeding	Friction tester, texture meter Friction tester	- Friction tester: continuous - Texture meter: affected area

[1] Take at least three cores of each material to determine TMD per ASTM D2041 or AASHTO equivalent. Take nuclear gauge measurements between the wheelpaths and in the wheelpath to determine construction compaction and extent of densification, minimum 10 in problem areas.

[2] GPR may be used to identify the source of reflective or shrinkage cracks deep within a pavement structure.

[3] Profilometer can potentially be run between the wheelpaths to estimate as-constructed ride quality.

[4] Mean profile depth can be measured using a high-speed longitudinal profilometer on a test vehicle requiring no closure or by a stationary laser texture meter in a traffic closure

to assessing as much of a construction project as is feasible to:

- Identify other areas where the issues being investigated have not yet manifested on the surface but may occur.
- Check variability to determine if it is consistent with the issues being investigated.
- Identify trends in performance/behavior that may correlate with factors identified in the preliminary investigation (e.g., weather events, changes in materials suppliers, breaks in production, equipment breakdowns, etc.).

Profile, friction, noise and some GPR testing can be done at highway speeds and consequently these tests do not require traffic closures. FWD testing is a stop-and-start activity, while project level GPR is undertaken at walking speeds, with both requiring a full or rolling closure, which needs to be taken into consideration when setting investigation limits.

Table 4.2. Examples of NDT on concrete surfaced pavements.

Issue	Possible Contributing Factors	Type of Non-Destructive Testing	Typical Testing Frequency
Exceptional performance	Design Construction Materials	GPR[1], FWD[1] Profilometer, OBSI GPR, FWD	- GPR: continuous (2 scans/yd [m]) - FWD: corners, mid-slab, mid-joint - Profilometer: continuous
Corner cracking	Voids Load transfer Temperature and shrinkage curl Concrete stiffness Dowel failure or absence of dowels	GPR[1] FWD[3] Profilometer[2] FWD[4], SPA MTT scan	- GPR: continuous (slow speed, 20 scans/m) - FWD: corners - FWD,SPA: slab center - Profilometer: continuous - MTT scan: affected area
D-cracking	Materials or moisture/frost damage	Not appropriate	
Longitudinal cracking	Base or subgrade failure/stabilization cracks Temperature and shrinkage curl Concrete stiffness	FWD FWD[3,4] FWD[4], SPA	- FWD: either side of crack - FWD: corners - FWD: slab center - SPA: slab center
Transverse cracking	Edge support Load transfer on tied shoulders Swelling soils/frost heave	GPR[1] FWD Not appropriate	- GPR: continuous (20 scans/yd [m]) - FWD: both sides of joint
Early age cracks	Improper curing, late sawing	Not appropriate	
Faulting	Erosion/pumping Load transfer	GPR[1] FWD	- GPR: continuous - FWD: corners and joints
Spalling	Construction/maintenance deficiencies Frost	Not appropriate Not appropriate	
Joint failure/separation	Design/construction/maintenance deficiencies Dowel bar failure/seizure from misalignment	Not appropriate MTT scan	- MTT scan: affected area
Pumping	Load transfer Base erosion	FWD[3] FWD	- FWD: joints and corners - FWD: corners
Punchouts	Base failure and/or subbase erosion	GPR[1]	- GPR: continuous (20 scans/yd [m])
Ride quality/roughness/ Settlement	Construction deficiencies Faulting Moisture/frost Support (voids)	Profilometer[2] Profilometer[2] GPR, FWD GPR	- Profilometer: continuous - GPR: continuous (slow speed, 20 scans/yd [m], multiple profiles) - FWD: joints and corners
Excessive noise	Surface texture from construction, grinding, grooving, fines loss	OBSI Texture meter	- OBSI: continuous - Texture meter: affected area
Poor skid resistance	Polished aggregate Poor surface texture from construction, grinding, grooving	Friction tester Friction tester, texture meter	- Friction tester: continuous - Texture meter: affected area

[1] GPR and FWD may not be appropriate on CRCP as steel reinforcement attenuates the signal.

[2] A wide spot or bar laser is needed for effective road roughness measurements on tined or grooved concrete. Texture measurements with a standard laser profilometer are not effective, and a texture meter should be used if these lasers are not available.

[3] FWD for estimating load transfer.

[4] FWD for backcalculation of stiffness.

Typical NDT intervals in forensic investigations are listed in Table 4.3.

4.2.4.4. Initial NDT Plan

The investigation coordinator prepares an initial NDT plan based on the initial investigation observations and team member discussions. The plan should include the following (example Form #10 in Appendix C):

- Type of NDT required and why it is required.
- Start and end points of each test.
- Lanes to be tested.
- Sampling frequency.
- Date that the testing is required.
- Expected duration of testing.
- Data requirements/format.
- Specific requirements.
- Closure requirements.
- Core requirements (for GPR and FWD calibration and initial investigation).
- Data analysis/interpretation requirements.
- Arrangements for the testing (e.g., contacting the testers, arranging for closures and crew, arranging for data interpretation expertise, etc.).

4.3 Preparing a Cost Estimate

After collecting all relevant data for the plan, the investigation coordinator prepares a cost estimate using a spreadsheet template that includes agency costs of the various components.

4.4 Writing an Initial Investigation Plan

The forensic investigation coordinator prepares an initial investigation plan at this point in the investigation to document the formation of the investigation team, the findings of the

Table 4.3. Example NDT intervals.

Test	Interval	Test Duration/ Lane-mile[1]	Road Closure Required?
GPR – General layer thickness/layer definition	Continuous (2 scans/m)	2 minutes	No[2]
GPR – Asphalt densification	Continuous	2 minutes	No
GPR – Problem identification/delineation on AC	Continuous (20 scans/m)	90 minutes	Yes
GPR – Problem identification on PCC	Joint/joint area/crack	-	Yes
GPR – Void location	Suspected area	-	Yes
FWD – Problem delineation on AC pavement	80 ft (25 m)[3]	90 minutes	Yes
FWD – Specific problem investigation on AC	30 ft (10 m)	225 minutes	Yes
FWD – Problem delineation on PCC pavement	Not appropriate	-	-
FWD – Specific problem investigation on PCC	Joint/crack/slab center	50 drops/hour	Yes
Profilometer – Overall smoothness	Continuous	2 minutes	No
Friction tester – Skid resistance	Continuous	2 minutes	No
OBSI – Noise levels	Continuous	2 minutes	No

[1] Test duration does not include closure set up and take down.

[2] A limited number of cores are required for calibration. A road closure is required for coring.

[3] Longer test intervals can be adopted if there are constraints such as traffic or limited closure schedules; however, this increases the risk of missing weaker sections. A second round of testing with closer intervals (e.g. 30 ft [10 m]) may be required to test specific problem areas.

pre-investigation site visit, and to provide details of the NDT, the results of which will be used to finalize the investigation plan. The initial plan should include the following (example Form #11 in Appendix C):

- Preliminary Investigation Report (example Form #4 in Appendix C).
- Team members and each team members' contact details and responsibilities (example Form #5 in Appendix C).
- Initial visual assessment forms (example Forms #6 through #9 in Appendix C) with:
  - Summary of observations.
  - Investigation start and end points.
  - Safety assessment.
- The initial NDT plan (example Form #10 in Appendix C).
- Data analysis/interpretation requirements.
- Reporting formats and due dates.
- Logistical arrangements (e.g., road closures, notifications, team and equipment availability, etc.).
- Schedule, including dates and times for each resource and activity.

If the agency does not have access to GPR equipment and the issues being investigated are related to layer thickness, moisture damage, and/or layer debonding, destructive testing will be required and the guide for preparing the final investigation plan discussed in Chapter 6 should be followed.

4.5 Approval of Initial Investigation Plan and Record of Decision

The forensic investigation coordinator obtains approval (and if necessary, funding) for the initial investigation plan from the investigation director and adds a record of decision to proceed with NDT to the project file.

CHAPTER 5

Non-Destructive Testing

This chapter discusses the implementation of the investigation plan described in Chapter 4 as well as analysis of the non-destructive testing data, the preparation of an interim report, and the decision to continue or terminate the study based on the findings at this stage of the investigation.

5.1 Implementing the Initial Investigation Plan

Conducting the NDT identified in the initial investigation plan should begin as soon as possible after the pre-investigation site visit. The testing procedures (i.e., setup and operating the equipment) recommended by the equipment manufacturer should be followed at all times.

5.2 Non-Destructive Testing Analysis

Interpretation of NDT results will depend on the issues being investigated. Although analysis and interpretation of the results of some non-destructive tests are relatively straightforward (e.g., profile), others (e.g., GPR and FWD) require considerable experience with analysis methods and data interpretation, which may necessitate additions to the investigation team at this stage. The following sections discuss the key issues to consider when analyzing results from the various types of equipment and when considering the need for additional destructive testing to address the issues being investigated.

During analysis, there is a need not only to focus on the issues being investigated, but also to recognize the possible influence of other factors. Consider the following during analysis and interpretation:

- If the results provide a well supported explanation of the issues being investigated, no additional testing will be required.
- If the results are inconclusive, determine what additional non-destructive or destructive testing is required to explain the issues, and use available results to identify/delineate areas where this additional investigation needs to be carried out (e.g., locations for coring, Dynamic Cone Penetrometer [DCP], or test pits).

5.2.1 Ground Penetrating Radar

The interpretation of GPR data is complex and requires considerable expertise, training, and experience. The forensic investigation coordinator/team leader will need to identify an individual within the agency or engage the services of a specialist to assist with this interpretation. The following key issues should, however, be considered:

- Use the radargram (example in Figure 5.1) or other GPR output to assess layer thickness and changes in construction as a means for identifying specific locations where cores need to be taken to validate observations. Thickness/depth values may not be accurate without calibration (from cores), but the visual presentation is useful for assessing variation in thickness. Highlight any problem/anomalous areas.
- Use the amplitude analysis to identify and delineate problem areas such as delamination, debonding, stripping, or voids. Figure 5.2 shows an example of a void under concrete slabs in a jointed plain concrete pavement. Conclusive evidence is unlikely, but sufficient resolution should be available to select points where cores can be taken to validate the observation.
- Use the frequency analysis to identify and delineate changes in moisture content and moisture-related problems such as stripping. Figure 5.3 shows an example of an area within the pavement that has higher moisture content than that of the surrounding materials. This area could be investigated

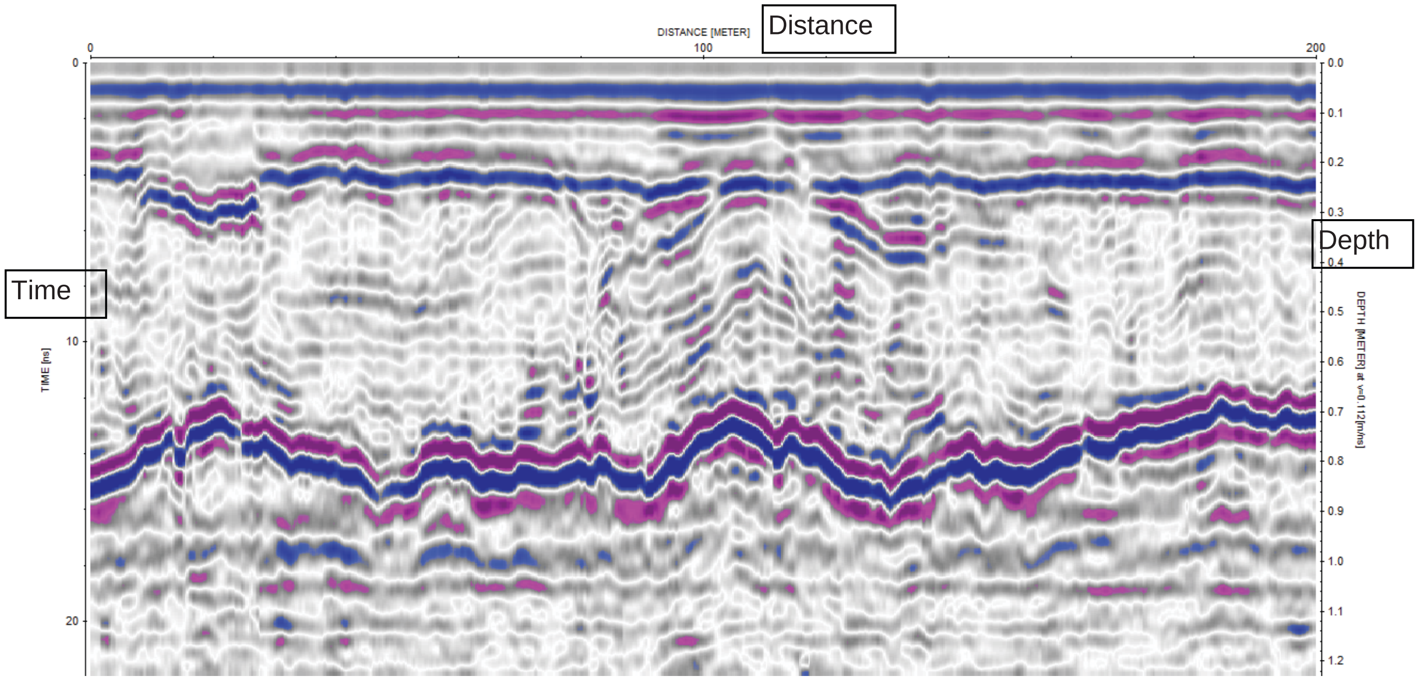


Figure 5.1. Example GPR radargram showing layer depth.

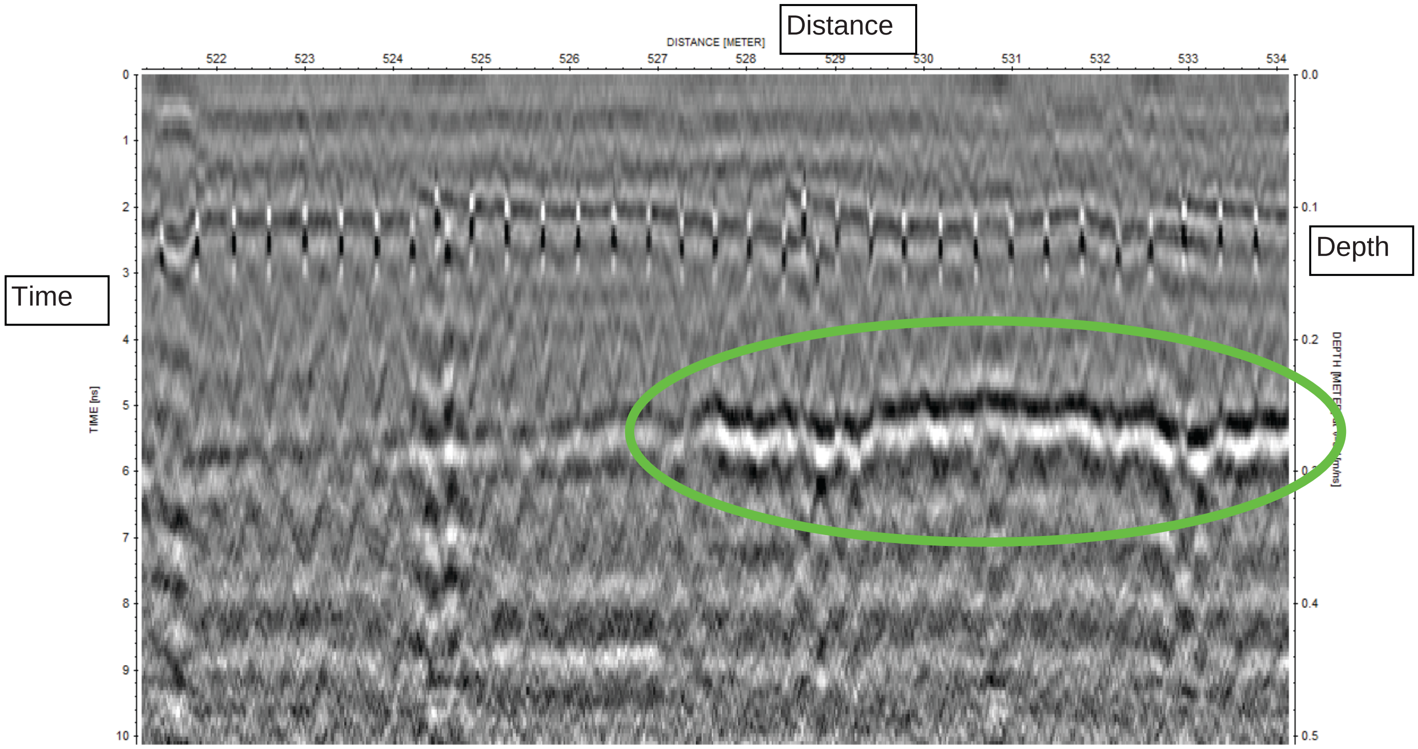


Figure 5.2. Example amplitude analysis showing a void under JPCP.

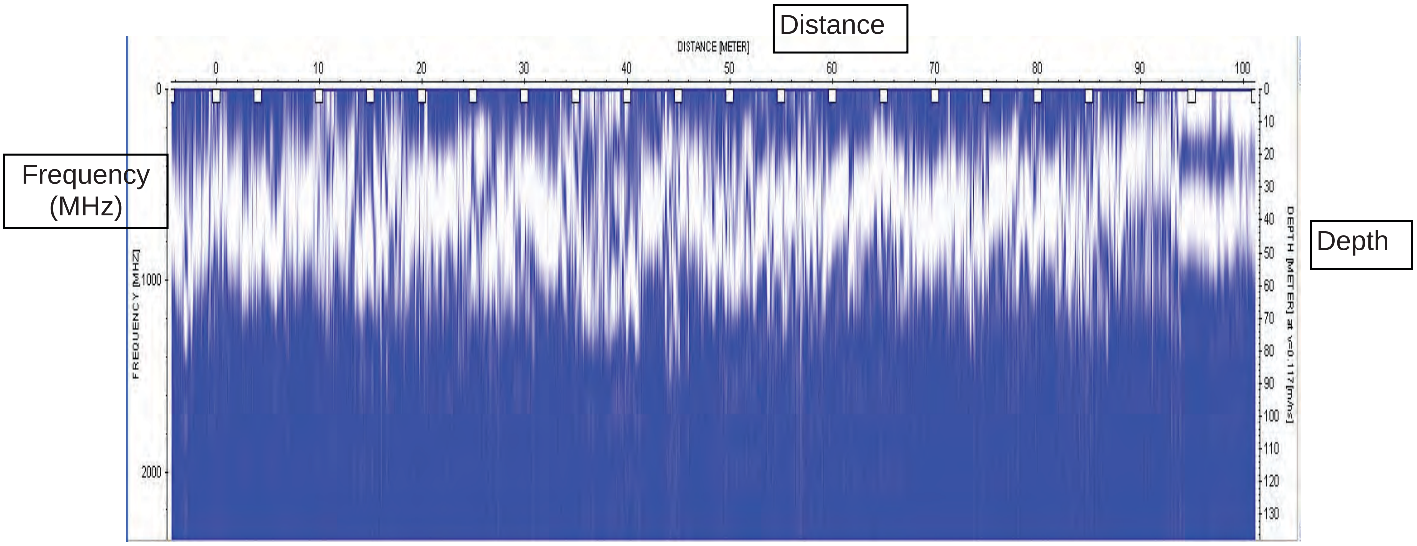


Figure 5.3. Example frequency analysis showing areas of high moisture content. (Dark areas indicate higher moisture content.)

in more detail for stripping. While conclusive evidence is unlikely, sufficient resolution should be available to select locations where cores can be taken or a DCP can be driven to validate the observation.

- Link the GPR observations to the results from other NDT (e.g., FWD), and to the observations from the initial visual assessment to determine if the issues being investigated can be explained.

5.2.2 Falling Weight Deflectometer (FWD)

A number of commercial software programs have been developed for FWD interpretation. No recommendations are provided in this guide on the suitability of any software package for specific issue analysis. Use the following procedure for analyzing pavement structure issues recognizing that accurate surfacing and base layer thicknesses are required to obtain reasonable backcalculated values:

- Study the as-built data and layer thicknesses determined from GPR or core measurements to provide a baseline for interpreting the FWD data (deflections and backcalculated stiffnesses depend on the stiffness and thickness of the pavement layers and subgrade). Deflection moduli and backcalculated stiffnesses (and in some cases the raw deflections or indices based on raw deflections) can be used to identify weak or damaged layers by comparing expected values with measured values, or by comparing values in areas with good performance to those in areas with poor performance.
- Select the sensor or sensors that will be used in the analysis.
  - Deflections from the geophone directly under the load provide an indication of overall pavement structure including the subgrade. The furthest sensors from the load provide an indication of subgrade response with little influence from the pavement structure. The middle sensors provide deflection data on the layers between the surface and the subgrade.
  - The sensor used for assessing a specific layer's response will depend on the total thickness of the pavement structure, thickness of individual layers, and the layer type (e.g., cement stabilized or aggregate base). In general, a sensor is affected by pavement layers at depths greater than the distance of that sensor from the load. For example, a sensor located 2 ft (600 mm) from the center of the load will be affected by pavement layers that are 2 ft (600 mm) or more below the pavement surface.
- Plot the measured deflections or calculated parameter (e.g., stiffness, modulus, deflection modulus, etc.) against distance for the length of the project (example in Figure 5.4). Contour plots and cumulative-sum plots (1986 AASHTO *Guide for Design of Pavement Structures* [9]) are also useful for analyzing deflection data.
- Use the plots to:
  - Assess the spatial variability of the deflection data in both the longitudinal and transverse directions and determine the uniformity of the pavement structure and subgrade stiffness.
  - Identify unique sections, weak/problem areas, or anomalous areas.

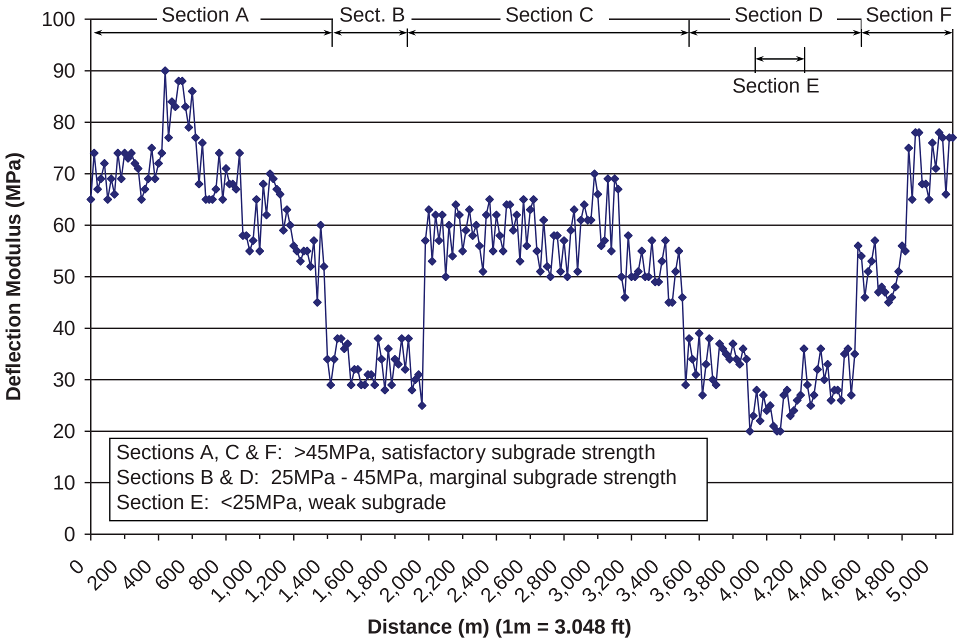


Figure 5.4. Example plot of subgrade deflection modulus against distance.

  - Link weak/problem areas to the issues being investigated (or confirm exceptional performance). For example, areas with debonded asphalt concrete layers will typically have higher deflections than areas with no debonding because the layers act individually and not as a monolithic single layer.
  - Determine whether sufficient information has been collected to address the issue being investigated and, if not, identify areas requiring additional investigation. For example, the deflection modulus calculated (from FWD Sensor 6) in an investigation of suspected subgrade failures shown in Figure 5.4 reveals variability in subgrade stiffness in the area under investigation. Sections A, C, and F have a stiffer subgrade, Sections B and D are less stiff and Section E (within Section D) is soft. Sections B, D, and E coincided with areas of pavement failure (alligator cracking).
- Determine the stiffness (layer moduli) of the pavement and subgrade layers using an appropriate backcalculation method (e.g., layered elastic solutions; non-linear, finite element analysis; or dynamic solutions). Remember to take temperature and moisture conditions into consideration.
- Determine the overall structural capacity of the pavement using an appropriate backcalculation method (e.g., Burmister two-layer solutions [equivalent pavement thickness having standard modulus and subgrade modulus]).
- On asphalt pavements, compare the backcalculated stiffness results against expected values for different material types. Expected values will vary depending on the pavement design, pavement structure, age of the asphalt, performance grade of the asphalt, compaction, etc. Modulus ranges for different layer types, based on the authors' experience, are listed in Table 5.1.
  - Identify problem areas or problem layers (i.e., lower than typical values) that could be contributing to the issues being investigated. For example, early rutting and fatigue cracking could be attributed to stripped asphalt layers, debonding of asphalt layers, weak stabilized layers, or saturated subgrade layers that can be identified from the deflection and backcalculated data.
  - Alternatively, use the data to explain observed good performance if the stiffnesses are higher than typically experienced and justify new approaches to design or construction (e.g., stricter compaction requirements, better drainage, different stabilization methods, etc.).
- On jointed concrete pavements, calculate the load transfer efficiency (LTE) at mid-slab or wheelpath joints, working cracks and mid-slab edges for tied shoulders.
  - The load transfer efficiency can use either the simple definition of LTE ($\delta_{unloaded}/\delta_{loaded}$ where δ is deflection on the loaded slab and the unloaded slab on the other side of the joint) or Westergaard's equation. It is important to note the method used because these methods give different values.
  - Lower than typical load transfer would explain faulting and corner cracks, especially if the pavement has an erodible (unstabilized) base and is in an area of high rainfall.
  - For a set of joints (or transverse cracks if measured), LTE will likely increase as the temperature of the slabs increases. Check the results by plotting LTE versus

Table 5.1. Example modulus ranges for different layer types.

Layer Type	Modulus Range[1]			
	Lower Bound		Upper Bound	
	psi	MPa	psi	MPa
Portland cement concrete	2,200,000	15,000	7,000,000	50,000
Asphalt concrete	100,000	700	1,000,000	7,000
FDR[2] + cement	80,000	550	800,000	5,500
FDR + foamed asphalt	50,000	350	600,000	4,100
FDR + asphalt emulsion	50,000	350	600,000	4,100
FDR/no stabilizer	40,000	275	150,000	1,035
PDR[3] + emulsion	80,000	550	800,000	5,500
Asphalt-treated base	100,000	700	900,000	6,750
Asphalt emulsion base	50,000	350	500,000	3,500
Cement treated base[4]	-	-	-	-
Lean concrete base	1,500,000	10,000	5,500,000	40,000
Aggregate base	15,000	105	50,000	350
Granular subgrade	10,000	70	50,000	350
Fine-grained subgrade	5,000	35	50,000	350

[1] Ranges are highly dependent on test temperatures.
[2] Full-depth reclaimed.
[3] Partial-depth reclaimed/cold in-place.
[4] Modulus range depends on the level of cracking.

surface temperature to determine if temperature is controlling the results. If it is, comparing the surface temperatures at the time of testing against surface temperatures across the year will help determine if the LTE results are representative of high or average temperatures. General ranges for LTE are:

- Excellent — 90 to 100 percent (by the simple definition)
- Good — 80 to 90 percent
- LTE contributing to faulting/pumping — 50 to 80 percent
- LTE likely resulting in faulting/pumping — less than 50 percent

– If LTE is low, identify potential causes and, if necessary, identify core or DCP locations to confirm these reasons and suggest corrective measures. Low LTE values could result from absence of dowels, or corroded, missing, or misplaced dowels.
  - LTE less than 50 percent usually occurs only when there are no dowels, dowels have become corroded or have become loosened due to high bearing stresses between the dowel and surrounding concrete under loading.
  - Loss of aggregate interlock (because of shrinkage or traffic damage) or voids under the corners can also reduce LTE.
  - Coring will confirm the presence and condition of dowels and voids, and the condition of the base (e.g., degradation of a cement-treated base).
  - The presence of chlorides may contribute to dowel corrosion, which can be determined by measuring the chloride content in cores.

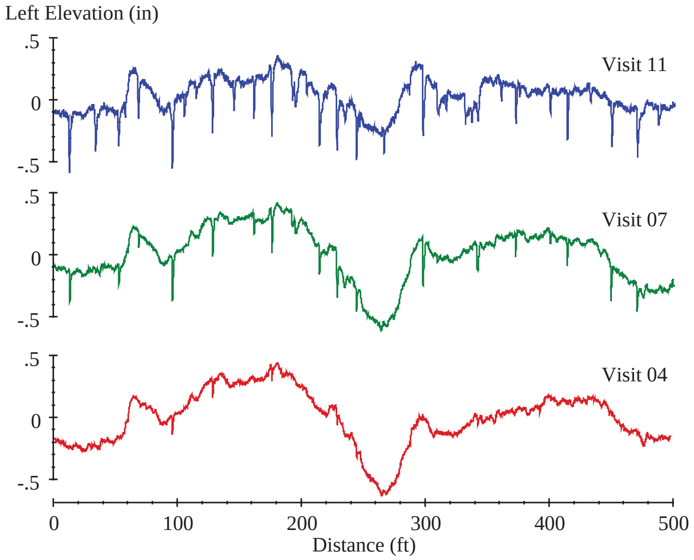
- If investigating corner, mid-slab or wheelpath cracks, or mid-slab edge deflections on JPCP, the software should report vertical deflections at these locations.
  - These deflections will typically be larger when the temperature difference between the pavement surface and the bottom of the slab is greatest, usually in the early morning. They will be smallest in the late afternoon and early evening when the surface is much hotter than the bottom of the slab. Under these conditions, the highest deflections may be an indication of voids beneath the corners or mid-slab edge. Interpret the results relative to temperatures over the rest of the year.
  - The effects of temperature gradient will be less pronounced for joints tested away from the corners and mid-slab edges than for corners.
  - A high joint deflection difference (the absolute value of the difference in deflections across a loaded joint) can provide an indication of potential for faulting.
  - Reasons for high deflection differences associated with faulting and corner breaks can sometimes be determined from cores (e.g., visual observation to check for evidence of disintegrated or eroded base, thinner than design thickness, etc.).
- If investigating cracking on concrete pavements, use backcalculation software that provides accurate k-values for a mechanistic-empirical evaluation (note that good layer thickness information is necessary for estimating stiffness values from backcalculation).
  - Premature cracking, if not related to overloading or overtrafficking, can be due to poor support of the slab as manifested by a low k-value, or low concrete strength.

  - The software should estimate the elastic modulus of the slab and the k-value of the combined underlying layers, as a minimum. Backcalculate as a two-layer system consisting of the concrete and the underlying layers. Consider an alternative two-layer system where there is a cement- or asphalt-treated base because thin cemented layers are difficult to separate from the concrete slabs in backcalculation. Combine the concrete slab and base and keep the remaining underlying layers as the second layer.
  - Check modulus values for reasonableness. Lower than expected values for the concrete layer (e.g., <2,200 ksi [15 GPa]) may be an indication of voids beneath the concrete or internal problems in the concrete.
  - If the backcalculated concrete modulus is low, plan to take cores to test for compressive strength. Modulus and compressive strength are usually correlated. Typical modulus values generally range between 2,200 and 7,000 ksi (15 and 50 GPa).
  - The k-values of the underlying layers are an important indicator of the support being provided to the concrete by the base/subbase layers and subgrade. Use the same set of layers in the forward M-E analysis software to determine if the support to the slab would have a significant effect on expected performance.
  - Bonding in the vertical direction between the concrete and base layers can play an important role in cracking performance. If stiffness and k-value are as expected, then coring to determine bonding between slab and base can be performed to identify whether this is contributing to the issue being investigated. Good bonding contributes to long-term fatigue performance, although high friction in the horizontal direction can contribute to cracking shortly after construction.
- If FWD testing was carried out in conjunction with GPR testing, compare data sets to refine the analysis discussed above. Bonding issues, voids, problem layers, etc., can be better identified through the combined use of the two techniques.
- If the issues being investigated cannot be satisfactorily explained from the FWD data, use the plots to identify areas/locations for additional observation and testing (e.g., a more intensive visual assessment, coring, and/or a test pit or trench).

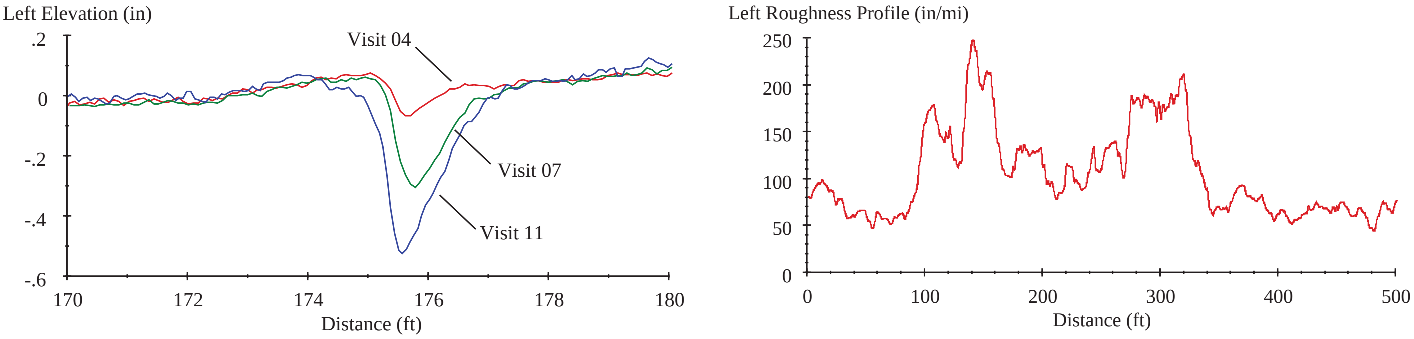
5.2.3 Profilometer

Use the following procedure for analyzing roughness issues:

- Compare the IRI values for the pavement sections investigated against the limits in use by the agency. IRI provides a single value that reflects the overall roughness of the segment and is useful in comparing relative roughness as well as in tracking changes in roughness over time.
- Apply a high pass filter with a base length between 25 and 100 ft (8.0 and 30 m) to remove noise and obtain more detailed information regarding the nature of the roughness for each segment (example in Figure 5.5a and b). The FHWA *ProVAL* software *(10)* can be used for this and other data analyses.
- Determine if high IRI values occur consistently over the entire project (e.g., due to poor asphalt paving, poor joints on concrete pavements, raveling), or at localized areas (e.g., pothole, example in Figure 5.5c).
- Compare results with pavement management system data to determine if performance is typical of other roads with similar characteristics.
- If the data shows consistently rough and worse than expected pavement when compared to the network, review the as-built records to better understand construction-related problems (e.g., subgrade issues) and the visual assessment notes to determine if raveling is a contributing factor. In the latter case, review the mix design and as-built records for deviations from the norm (e.g., binder content, choice of binder, temperature issues on asphalt, tining and grinding issues on concrete, evidence of subgrade heave, etc.).
  - On asphalt pavements, review the visual assessment notes to determine if the roughness appears to be surfacing related (e.g., end-of-load segregation) or subgrade (e.g., clay or frost heaving) related. If subgrade issues are the likely cause, compare results with FWD test data to identify weak or wet subgrade areas. Review design documentation for subgrade plasticity, frost design, local knowledge of sulfate-related problems, etc.
  - If high roughness occurs in isolated areas, compare results to the as-built records and visual assessment notes to determine the cause (e.g., potholes, transverse cracks, construction joints, slab joint faulting, asphalt pick-up of spills, raveling associated with an equipment breakdown, supply trucks standing for long periods, etc.).
  - On jointed concrete pavements, measure fault heights at transverse joints and cracks using *ProVAL* or analysis software provided by the profilometer equipment supplier following the AASHTO R36 specification (Standard Practice for Evaluating Faulting of Concrete Pavements). The data should not be filtered, and the data collection interval must be between 0.75 and 1.5 in. (19 and 38 mm).
  - If no satisfactory explanation is found, consider a more detailed visual assessment to check problem areas and laboratory tests to check material properties in the affected areas. Subgrade problems may require Shelby tube samples or a test pit investigation if no satisfactory explanation can be found.



a) Unfiltered Profile Data



b) Filtered Profile Data

c) Section Roughness Profile

Figure 5.5. Example profile data.

5.2.4 Skid Resistance/Friction

Use the following procedure for analyzing skid resistance/ friction issues:

- Compare the friction values for the investigated pavement sections to the friction index in use by the agency. Data plots of friction against distance are useful for identifying problem areas or areas of better-than-expected performance (Figure 5.6, for example, shows difference in friction values for two adjacent lanes).
- Delineate sections on the project that fall within acceptable, investigatory, or intervention range.
- Compare results with pavement management system data to determine if performance is typical of other roads with similar characteristics.

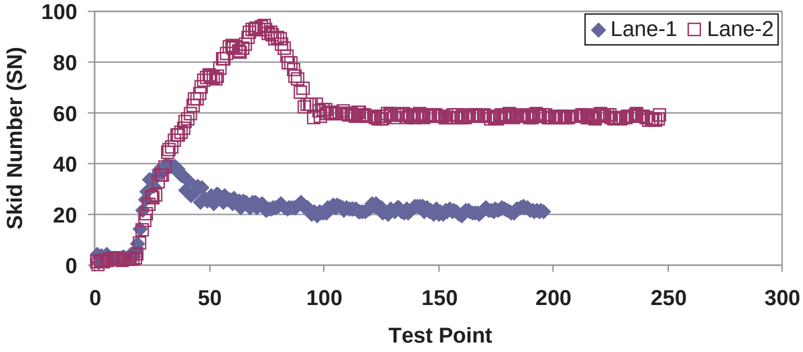


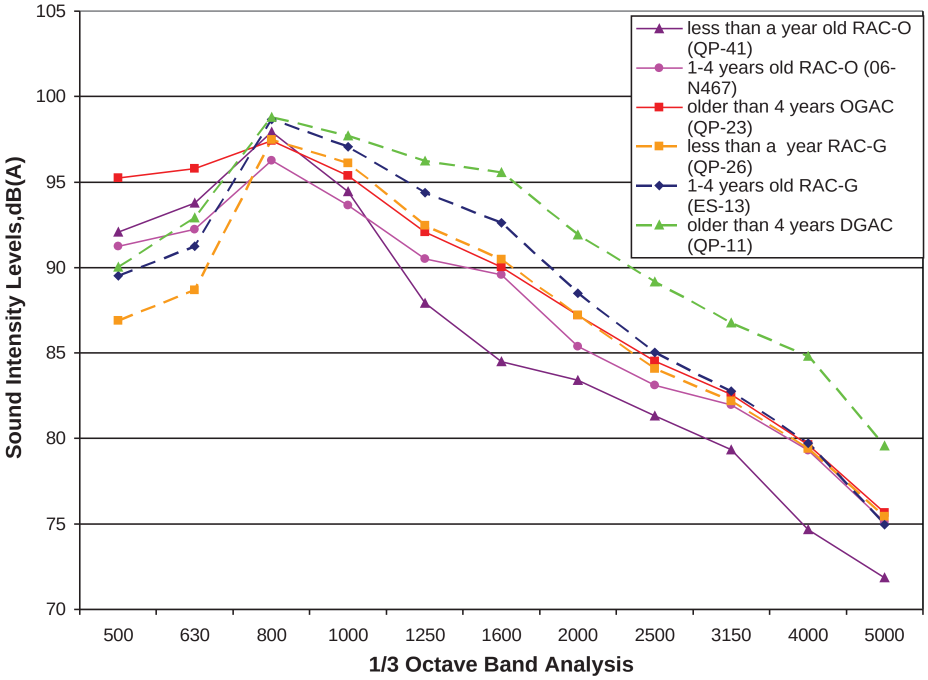
Figure 5.6. Example plots of skid resistance against distance.

- If the comparison indicates underperformance or better-than-expected performance, review the mix design and as-built records to determine whether aggregate selection (asphalt, surface treatment, and concrete), surface texturing (concrete), or other problems (e.g., slow break on a fog spray or other surface treatment) were noted.
- If no satisfactory explanation is found, consider a more detailed visual assessment to check surface texture and laboratory tests to check polished stone values.

5.2.5 Tire-Pavement Noise at the Source

Use the following procedure for analyzing noise-related issues:

- Plot the OBSI measurements against distance. Several sections can be placed within the area of interest for the investigation to serve as controls, comparisons, or replicates.
- Check that all measurements were taken at the same speed. OBSI is dependent on the vehicle speed with most testing done at 60 mph (97 km/h) on highways or 35 mph (55 km/h) on lower speed routes.
- Apply corrections identified in the test method. Apply a tire correction if different tires have been used, with the correction based on OBSI testing at the same time on the same sections with the different tires. Note that each individual tire will have different sound intensity response on a given pavement section, even if they are the same type (e.g., the Standard Reference Test Tire [SRTT]).
- Analyze tire/pavement noise in terms of overall OBSI, or by frequency in terms of 1/3 octave band frequencies (example in Figure 5.7 shows OBSI for several mixes of different ages plotted by frequency).
- Evaluate tire/pavement noise. Humans can typically only identify changes in noise of 2 to 3 dBA or greater. Most pavements surfaces have overall OBSI between 95 and 115 dBA with an SRTT tire at 60 mph (97 km/h). The tire/pavement noise level is highly dependent on the tire, with more aggressive tread patterns, such as snow tires, causing more noise.
- If tire/pavement noise is higher or lower than anticipated, then identify potential sources, in conjunction with visual assessment notes, contributing to the noise.
  - On dry asphalt and chip-sealed pavements, the major contributor to tire/pavement noise at low frequencies is raveling, accentuated by increasing maximum aggregate size, which can be evaluated using a macro-texture measurement (see Section 5.2.6) or visual condition survey (see Section 4.2.1). Distresses such as cracking and high roughness can also increase tire/pavement noise. At high frequencies the major contributor to tire/pavement noise is low air permeability. Open-graded asphalt mixes that are noisy may have been over-compacted or become



RAC-O – Open-graded rubberized asphalt concrete
RAC-G – Gap-graded asphalt concrete
OGAC – Open-graded asphalt concrete
DGAC – Dense-graded asphalt concrete

Figure 5.7. Example plot of OBSI against one-third octave frequencies.

  clogged and should be checked for permeability in the wheelpath (see Section 5.2.7). Bleeding and water on the road may also contribute to noise through the sound of the tire sticking to the asphalt on the surface or the water being squeezed out from under the tire.
  - Good performance on asphalt pavements is typically attributed to the aggregate grading and the use of rubber or other modified binders.
  - On dry concrete surfaced pavement, the major contributors to tire/pavement noise are the original texture applied to the concrete surface and subsequent surface abrasion that may leave stones protruding from the surface. In general, transverse tined concrete is the noisiest of the different types of concrete pavement surface texture. Measurements should be made on other concrete pavement sections with the same nominal texture to determine if the pavement section under investigation is noisier than normal. Concrete pavement textures can be measured using a scanning texture meter (see Section 5.2.6) to determine if the section under investigation has the same texture as other sections in the investigation or other pavements.
  - Determine if chains and studded tires are contributors, as these can significantly increase the tire/pavement noise in a very short period of time on both asphalt and concrete surfaces.

5.2.6 Texture Meter

Use the following procedure for analyzing texture-related issues. Example reference standards include ASTM E1845, Standard Practice for Calculating Pavement Macrotexture Mean Profile Depth.

- Mean profile depth (MPD) can be calculated from vehicle-mounted laser profilometer data measurements, from laser scanning instrument data obtained from a scan of the pavement surface in the field, or on a core brought to the laboratory.
- If data is not analyzed and downloaded by the testing equipment, use software provided by the equipment supplier to produce an MPD statistic. For laser profilometer data, calculate MPD for the pavement length of interest. For laser scanning instrument data, the calculation is for the scan area (usually on the order of 4.0 by 2.5 in. [100 by 60 mm]).
- Plot the data over distance or area.
- MPD for pavement surfaces typically ranges from 400 to 2,500 microns for asphalt surfaces or non-directionally textured concrete surfaces. MPD does not have meaning for directionally textured pavement surfaces, such as tined or grooved pavement. High MPD generally indicates greater raveling or more stones protruding from the pavement surface.

5.2.7 Permeameter

Use the following procedure for analyzing permeability issues:

- Compare the permeability values for the pavement sections being investigated against better performing areas on the pavement, or against agency standards. A permeability of 0.08 to 0.4 in./s (0.2 to 1.0 cm/s) is typical of new open-graded asphalt friction coarse surfacings, while a permeability of less than 0.04 in./s (0.1 cm/s) is typical of older, clogged surfacings (based on use of the NCAT falling head permeameter, commonly used for testing permeability on asphalt concrete surfaces). Note that very different permeability results can be obtained if a different type of permeameter is used, such as a constant head device (e.g., ASTM C1701), and that differences within each type of device (falling head, constant head) depend on the characteristics of the device and on the test method.
- If the permeability is unacceptable, examine the pavement closely to determine the causes for the lower permeability. Problems could include clogging (e.g., fines washed from the side of the road, windblown fines, material spillages, organic matter from roadside activities, mud from agricultural vehicles, incorrect maintenance activities, etc.), bleeding (incorrect binder content), or poorly connected voids.
- If the cause is not clear, consider removing cores from affected and unaffected areas to determine whether the problem can be attributed to the mix design (i.e., incorrect binder content and/or aggregate grading). Dry cores (air cooled) are preferable to prevent contamination, but if wet cores are taken, ensure that coring slurry and debris are flushed from the cores to prevent clogging.

5.2.8 Magnetic Tomography Technology

Use the following procedure for analyzing dowel bar placement and alignment issues:

- Check conformity of the number, size, and location of all dowel bars with the design requirements.
- Check that the dowel bars are at the correct depth, correct spacing (distance between dowels), and have equal length on both sides of the joint.
- Check that the dowels are correctly aligned (parallel to direction of traffic and parallel to the surface).
- Note that scans are usually sufficient to identify any problems, but some core examination may be required to verify the observations.

5.3 Interim Report

Interim reports are often not completed by state highway agencies, but are encouraged in this guide to ensure that studies are adequately documented, that appropriate actions are taken, and to prevent recurrences of the problem. In the event that a study is terminated, the interim report becomes the final report.

An interim report is prepared at this point to document the findings and support the decision to either (1) end the study (i.e., sufficient information has been collected from this phase of the investigation to address the issues being investigated), or (2) continue the study with more detailed investigations. Include the following in the report:

- Introduction
  - Lists the reasons for doing the investigation.
- Objectives and hypothesis
  - Lists the issues being investigated and the potential reasons (hypothesis) for the issues.
- Investigation plan
- Observations and measurements
  - Provides tables of key observations and measurements from the initial site visit and non-destructive testing that support the findings.
- Analysis and interpretation
  - Summarizes non-destructive testing (and limited coring) data interpretation in terms of answering the investigation questions.
- Findings/conclusion
  - Determines whether or not the issues have been adequately addressed.
- Decision
  - Documents decision to (1) terminate the study or (2) continue with additional (e.g., destructive) testing.

If continuation of the study is proposed, provide a justification for the additional testing.

An example cover sheet for the interim report is provided in Appendix C (example Form #12).

5.4 Decision to Continue or Terminate the Study

A decision to continue with or end the study is made at this point. If the team concludes that the investigation issues have been satisfactorily addressed, the interim report becomes the final report (discussed in Section 8.2) and recommended actions based on the findings are prepared (discussed in Section 9). A record of decision (Section 8.3) is prepared and the project closed (Section 9.3).

If the information collected does not satisfactorily address the issues being investigated, refine the investigation plan to include the work required to collect additional information and proceed as described in Chapter 6.

CHAPTER 6

Final Investigation Plan

This chapter covers finalizing the investigation plan if a decision was made to continue with the study to gather more information to address the issues being investigated.

6.1 Finalizing the Investigation Plan

If a decision to continue the study was made, the investigation coordinator prepares a final investigation plan based on the findings of the earlier work. This plan includes:

- The initial investigation plan.
- Additional visual assessment requirements including:
  - Specific areas on road and adjacent to road (e.g., drainage, slope stability, etc.) to examine.
- Additional non-destructive testing details if required, including (example Form #13 in Appendix C):
  - Types of test (e.g., GPR, FWD, profilometer, skid tester, noise measurements, dowel bar locater, permeability, density, stiffness, load transfer, etc.).
  - A revised non-destructive testing plan (see Section 4.4).
- Destructive testing details including (example Form #14 in Appendix C):
  - Types of test. The need for and type of testing will depend on the issues being investigated and the results of initial non-destructive testing, but will usually include cores; sampling of materials from individual layers for laboratory testing (from drilling, Shelby tube or test pit); DCP tests; and/or a test pit/trench if a visual assessment of layers is required. The plan should specify if dry cores or dry test pit/trench saw cuts (i.e., air cooled for moisture-related investigations) are required.
  - Test plans. Numbers of tests, test locations (including a drawing with precise locations), and protocols that should be followed. It is extremely important to sample from multiple locations of varying performance (i.e., distressed and non-distressed [control] areas).
    - ▪ Core requirements: laboratory testing typically requires 4 in. (100 mm) or 6 in. (150 mm) diameter cores. Visual inspections typically require a larger core (6 in. [150 mm] or 12 in. [300 mm] in diameter) to obtain the largest surface area to identify potential problems. Cores removed only for observation purposes can be replaced in the road after evaluation. Suggested numbers of cores required for various laboratory tests associated with forensic investigations are summarized in Table 6.1.
    - ▪ Test pit/trench requirements (e.g., location [including a drawing with precise locations], dimensions, inpit testing requirements, a checklist of expected and potentially unexpected factors to look out for, etc.).
- Sampling requirements, including location of samples, conditions under which samples should be taken, quantity of samples, packaging and storing of samples, and location where samples should be delivered.
- Laboratory testing requirements, including test methods and number of tests. Examples of laboratory tests associated with forensic investigations are provided in Table 6.2, Table 6.3, and Table 6.4 for asphalt, concrete, and unbound materials, respectively.
  - Routine laboratory tests to check conformance with material specifications or that materials have rapidly degraded/weathered to the point that deleterious minerals are present (e.g., Atterberg limits, gradations, aggregate durability, asphalt content/voids/specific gravity, concrete strength [compressive or split tensile]).
  - Specialized laboratory tests to assess performance (e.g., resilient/complex modulus, asphalt and soils repeated load permanent deformation tests, asphalt fatigue tests [flexural beam, direct tension, reflective cracking], asphalt wheel-tracking tests, concrete coefficient of thermal expansion, chemical analyses, microscope analyses, CT scans, etc.).
- Logistical arrangements (e.g., road closures, notifications, team and equipment availability, etc.).

Table 6.1. Example number of cores required for various laboratory tests.

Test	Thickness of Material of Interest		Number of Cores Per Test	
			Core Type	
	in.	mm	4 in. (100 mm)	6 in. (150 mm)
Standard tests	As per test method			
Grading (ignition oven)	2	50	3	2
	4	100	2	1
Asphalt binder grade (binder extracted from cores)[1]	2	50	1	1
	4	100	1	1
Theoretical Maximum Density	2	50	3	2
	4	100	2	1
Permeability/clogging	2	50	2	2
	4	100	2	2
Surface texture	2	50	2	2
	4	100	2	2
Other specialty tests (e.g., CT scan, impedance, x-ray diffraction)	Dependent on test method			

[1] Number of cores depends on binder content; shown are suggested number of cores for 5% binder by mass of mix and bulk density of the asphalt of 18.4 lb/gal. (2.2 kg/liter).

Table 6.2. Examples of laboratory testing requirements for asphalt pavement investigations.

Issue	Possible Contributing Factors	Example Types of Laboratory Testing[1]	
Exceptional performance	Design, construction, and/or materials	- Any combination of tests below depending on the specific issue being investigated	
Rutting	Poor compaction Asphalt densification Asphalt shearing Moisture damage Incorrect binder grade Incorrect gradation Incorrect binder content Inappropriate or not followed mix design Base, subbase or subgrade failure	- Surface layer	Air-void content, wheel track test, binder content, binder type (modifier presence, PG-grading, classification tests, contaminants), aggregate grading and properties, tensile strength retained, stability, repeated load triaxial (flow number) repeated load shear, triaxial or shear frequency sweep, resilient modulus, extracted binder frequency sweep, Hamburg Wheel Track Test (moisture sensitivity)
		- Unbound/bound layer	California Bearing Ratio, resilient modulus, R-Value, unconfined compressive strength, indirect tensile strength, gradation, Atterberg limits
Alligator cracking	Poor compaction Moisture damage Excessive aging Layer debonding Incorrect binder grade Incorrect binder content Incorrect gradation Inappropriate or not followed mix design Base, subbase or subgrade failure	- Surface layer	Air-void content, flexural fatigue, direct tension fatigue, binder content, binder type (modifier presence, PG-grading, classification tests, contaminants), aggregate grading and properties, triaxial, direct tension or flexural frequency sweep, resilient modulus, tensile strength retained, Hamburg wheel tracking test (moisture sensitivity), Texas Overlay test
		- Unbound/bound layer	California Bearing Ratio, resilient modulus, R-Value, unconfined compressive strength, indirect tensile strength, gradation, Atterberg limits
Transverse cracking	Incorrect binder grade Excessive aging Reflection cracking Poor compaction Frost/moisture damage in unbound layer Shrinkage in stabilized base	- Surface layer	Air-void content, binder content, binder type (modifier presence, PG-grading, classification tests, contaminants), aggregate grading and properties, triaxial, direct tension or flexural frequency sweep, Texas Overlay test
		- Unbound/bound layer	Stabilizer content, California Bearing Ratio, resilient modulus, R-Value, unconfined compressive strength, indirect tensile strength, gradation, Atterberg limits
Longitudinal cracking	Poor compaction at joints Excessive stabilizer in recycling overlaps Desiccated subgrade	- Surface layer	Air-void content at longitudinal joints
		- Unbound/bound layer	Stabilizer content, unconfined compressive strength, indirect tensile strength, Atterberg limits
Block cracking	Excessive aging of binder Shrinkage in stabilized base	- Surface layer	Air-void content, binder content, binder type (modifier presence, PG-grading, classification tests, contaminants)
		- Unbound/bound layer	Shrinkage, stabilizer content, unconfined compressive strength, indirect tensile strength, expansion/contraction tests under soaking/drying

Table 6.2. (Continued).

Issue	Possible Contributing Factors	Example Types of Laboratory Testing[1]	
Ride quality/ roughness	Raveling (durability) Incorrect binder content Incorrect gradation Inappropriate or not followed mix design	- Surface layer	Durability (Cantabro test), aggregate gradation and properties, air-void content, binder content, binder type (modifier presence, PG-grading, classification tests, contaminants), bond strength
		- Unbound/bound layer	Stabilizer content, Atterberg limits
Failure/potholes	Base, subbase or subgrade failure Moisture damage Delamination	- Surface layer	Air-void content, Hamburg Wheel Track, tensile strength retained, bond strength
		- Unbound/bound layer	California Bearing Ratio, Atterberg limits
Excessive noise	Mix design Raveling Cracking Clogging of porous surface Chain or studded tire damage	- Surface layer	Durability (Cantabro test), permeability
Skid resistance	Polished aggregate Flushing/bleeding	- Surface layer	Polished stone value, binder content

[1] Tests may be performed on samples taken from the pavement in the field, and on field or plant samples saved from construction, or on both for comparison.

Table 6.3. Examples of laboratory testing requirements for concrete pavement investigations.

Issue	Possible Contributing Factors	Example Types of Laboratory Testing
Exceptional performance[1]	Design, construction, and/or materials	- Any combination of tests below depending on specific issue being investigated
Corner cracking (JPCP, JRCP)	Low PCC strength Load transfer (joint or edge)	- PCC: Compressive strength, splitting tensile strength, chloride content of concrete near dowel/tie bar - Dowel: Dowel/tie bar coating type
D-cracking[1]	Susceptible aggregate Poor drainage	- PCC: Aggregate analysis (sedimentary with high fine pore content), freeze-thaw
Longitudinal cracking[1]	Low PCC strength High coefficient of thermal expansion (CTE) Warping or curling stresses (high CTE) Poor load transfer to tied shoulder	- PCC: Compressive strength, splitting tensile strength, CTE, chloride content of concrete near dowel/tie bar
Transverse cracking (JPCP)	Low PCC strength High CTE Tied shoulder load transfer	- PCC: Compressive strength, splitting tensile strength, CTE, chloride content of concrete near dowel/tie bar - Dowel: Dowel/tie bar coating type
Map cracking[1]	Alkali-silica reaction (ASR)	- ASR tests
Faulting (JPCP, JRCP)	Load transfer (dowel corrosion, looseness, misplacement, incorrect size) Erosion/pumping	- Dowel bar coating type
Dowel bar retrofit failure (JPCP)	Low grout strength Poor bonding of grout to slab Dowel bar corrosion	- PCC: Chloride content of concrete near dowel/tie bar - Grout: Grout strength, compressive strength, splitting tensile strength, Grout/PCC bond strength - Dowel: Dowel/tie bar coating type
Spalling[1]	Poor finishing Weak aggregate Frost	- PCC: Aggregate petrography
Joint failure/separation (JPCP, JRCP)	Dowel bar failure/seizure	- PCC: Chloride content of concrete near dowel
Punchouts (CRCP) (See longitudinal cracking for preceding mechanism)	Low PCC strength Steel reinforcement corrosion	- PCC: Compressive strength, splitting tensile strength, CTE, chloride content of concrete near rebar
Excessive noise[1]	Poor texture from construction or grinding/grooving. Faulting, wide joint openings, spalled joints Chain or studded tire damage	- PCC: Laboratory texture tests
Skid resistance[1]	Poor surface texture from construction, grinding, grooving Polished aggregate, loss of texture	- PCC: Laboratory texture tests, aggregate classification, polishing tests

[1] All types of PCC pavement.

Table 6.4. Examples of laboratory testing requirements for base and subgrade materials investigations.

Issue	Possible Contributing Factors	Example Types of Laboratory Testing
Exceptional performance	Design Construction Materials	- Any combination of tests below depending on specific issue
Rutting	Base, subbase or subgrade failure Moisture damage Carbonation of stabilized layers Incorrect stabilizer contents Construction deficiencies	- Bound: Stabilizer content, density, unconfined compressive strength, wet/dry durability, triaxial shear, resilient modulus - Unbound: California Bearing Ratio (CBR), triaxial shear, resilient modulus, classification tests (gradation, Atterberg limits)
Alligator Cracking	Base, subbase or subgrade failure	- Unbound: Resilient modulus, CBR, classification (gradation, Atterberg limits)
Transverse, longitudinal, block, and/or random cracks in asphalt surfaced pavement	High stabilizer contents in base Soil/stabilizer expansive reaction Excessive stabilizer in recycling overlaps Expansive soils	- Bound: Cement content - Unbound: Classification (gradation and Atterberg limit tests), CBR, swelling tests
Early age transverse, longitudinal, block, and/or random in JPCP; Longitudinal cracks in CRCP and JRCP	High stabilizer contents in base	- Bound: Cement content
Ride quality/roughness	Soil/stabilizer expansive reaction Expansive soils	- Bound: Cement content - Unbound: Classification (gradation and Atterberg limit tests), CBR, swelling tests, sulfate content
Failure/potholes	Base, subbase or subgrade failure	- Unbound: Classification (gradation and Atterberg limit tests), CBR
Salt damage to surfacing	High salt contents in compaction water or base materials	Conductivity and pH, soluble salt content

- Schedule, including dates and times for each resource and activity.
- General data requirements (e.g., traffic, weather, other environmental, etc.).
- Checklists and forms.
- Data analysis, including protocols.
- Report requirements, including how the results will be interpreted and used to address the reasons why the investigation was undertaken.
- Report review procedures (e.g., who will review the report).
- Updated cost estimate.

An example final investigation test plan is provided in Appendix C (example Form #15).

6.2 Approval of the Final Investigation Plan and Record of Decision

The forensic investigation coordinator obtains approval (and if necessary, funding) for the final investigation plan from the investigation director and adds a record of decision to proceed in the project file.

CHAPTER 7

Destructive and Laboratory Testing

This chapter covers destructive field testing and laboratory testing of samples and specimens removed from the pavement being investigated. Investigation arrangements, detailed visual assessments, coring, test pits, and laboratory tests are discussed.

7.1 Investigation Arrangements

Detailed investigations (e.g., detailed visual assessments, coring, test pits/trenches, collection of samples for laboratory testing) will typically require a road closure. Logistical arrangements for forensic investigations are usually adequately covered in existing agency procedures. Key issues that need to be considered include, but are not limited to:

- Special notifications to other agency departments and highway law enforcement.
- Closure protocols (e.g., FHWA *Manual on Uniform Traffic Devices, Part 6: Temporary Traffic Control* [*11*], or agency equivalent) and arrangements with law enforcement. Note that traffic volumes might dictate that the closure is at night and/or for a limited time period, which may influence the volume and level of testing.
- Crew and equipment arrangements.
- Coordination with utility service providers to mark locations within the section where destructive testing will take place.
- Repair of destructive test locations and reinstatement of core holes and test pits.

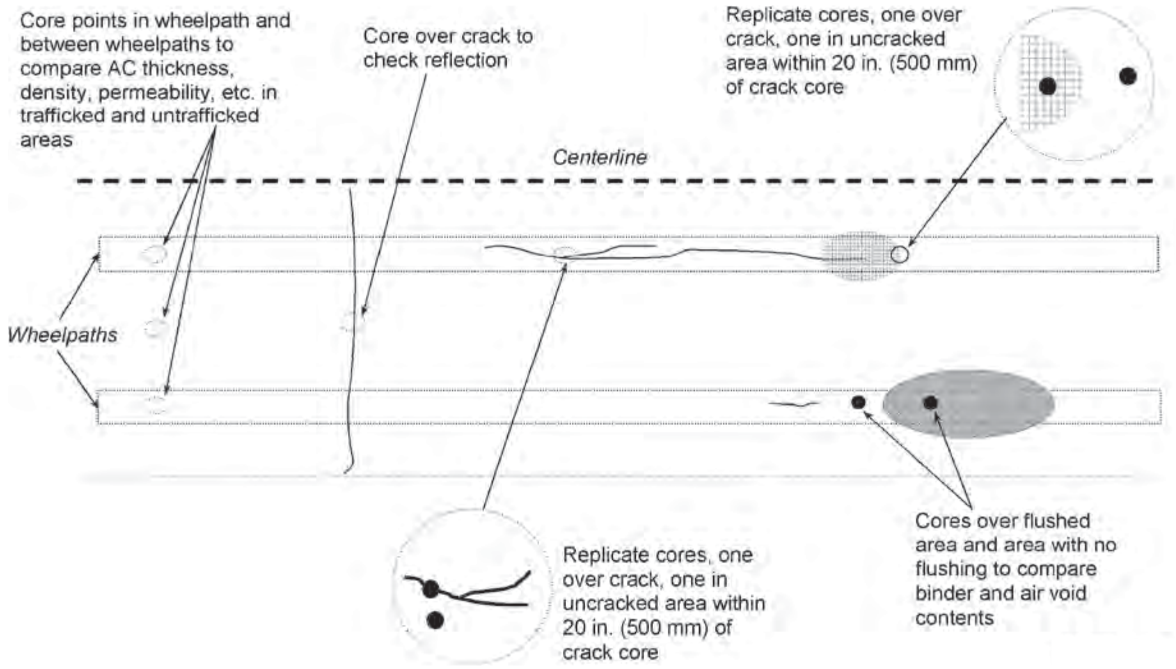
7.2 Visual Assessments

Visual assessments are usually made in a road closure, which allows closer assessment of distresses than the initial assessment discussed in Section 4.2. Although the investigation may focus on only one specific issue, a comprehensive visual assessment is usually undertaken to identify all possible contributing factors. Reassess roadside conditions and activity in light of the initial findings, especially if moisture or other environmental factors are being considered. Always look for abnormalities and be constantly aware of unexpected phenomena.

7.2.1 Activity Location

The precise location of destructive and additional nondestructive testing (if required) within the investigation is usually determined during the visual assessment. Consider the following:

- Destructive testing is usually carried out in both distressed areas and those areas with no distress to allow a comparison and to aid in identifying the key contributing factors. Examples of core locations on asphalt concrete/asphalt surface treatment, JPC, and CRC pavements for various types of distress are provided in Figure 7.1, Figure 7.2, and Figure 7.3 respectively.
- DCP tests are typically taken in the same locations through a core hole or drill hole (a dry drill hole is preferred since the DCP test results are influenced by soil moisture content, which will increase through use of water to cool the core barrel).
- Test pit/trench locations and associated tests (e.g., Shelby tube) are best identified from FWD and/or GPR measurements and, where feasible, include both “good” and “poor” performing areas for comparison. An example of a test pit layout with associated tests is provided in Figure 7.4.
- Allocate a unique number to each activity location.
- Mark precise core and drill locations and test pit boundaries each with their identifying number on the pavement with spray paint.
  - Record these locations on the Investigation Site Report (example Form #16 in Appendix C).



For the safety of work crews and road users, always keep sufficient space between the core rig and the centerline when coring in the wheelpath closest to traffic. Do not take cores between the centerline/lane delineator and the wheelpath unless both lanes are in the closure.

Figure 7.1. Examples of core locations for asphalt and surface treatment sections.

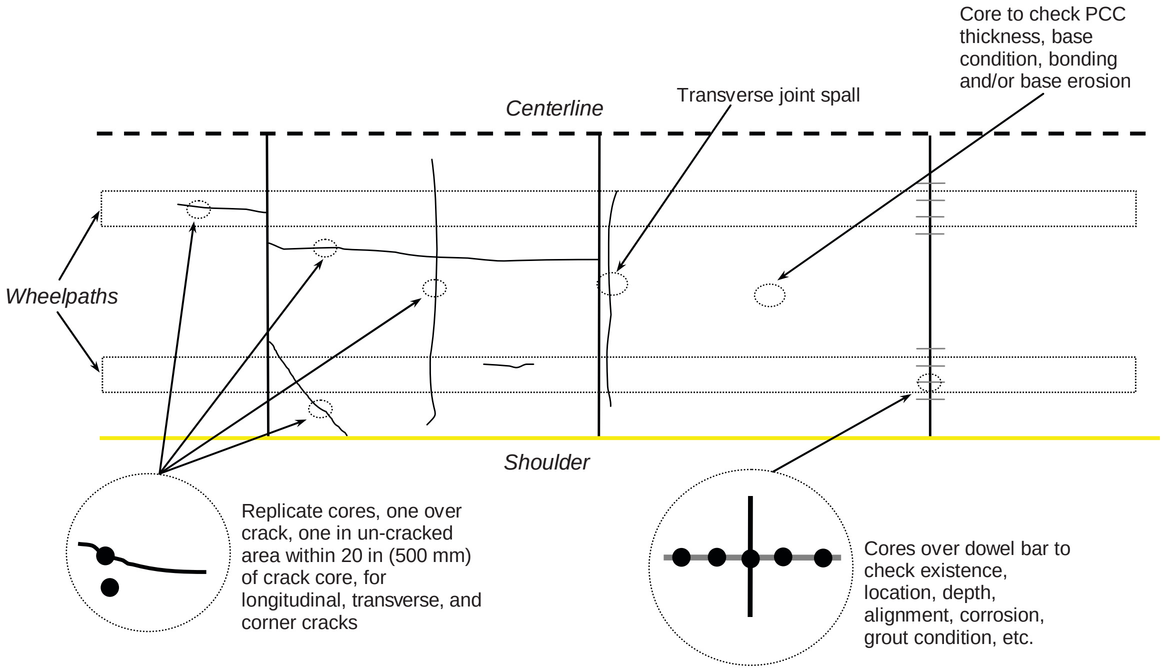


Figure 7.2. Examples of core locations for jointed plain concrete sections.

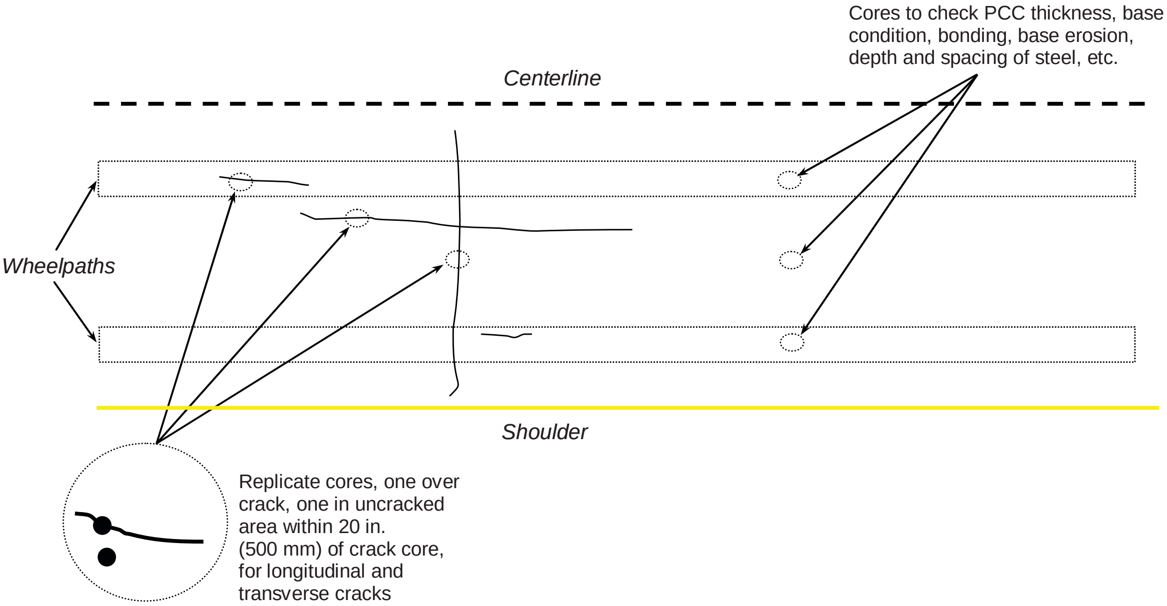


Figure 7.3. Examples of core locations for continuously reinforced concrete sections.

- Follow agency practice and standards for location references in a linear reference system (chainage, post-mile, station).
- In many locations, relatively inexpensive GPS devices can use multiple satellites to provide precise latitude and longitude coordinates for core locations and other data, which allow the use of mapping software to plot all data together.
- The FWD, profilometer, and other field testing equipment often has an integrated GPS capability, but distance measurements from fixed objects (landmarks, bridges) are useful as an independent cross-check on the linear reference and GPS location data.

7.3 Key Issues Concerning Destructive Testing

7.3.1 Coring

7.3.1.1 Reference Material

The following reference standards are applicable to coring activities conducted in forensic investigations:

- AASHTO R 13, Conducting geotechnical subsurface investigations
- AASHTO T 24, Obtaining and testing drilled and sawed beams of concrete

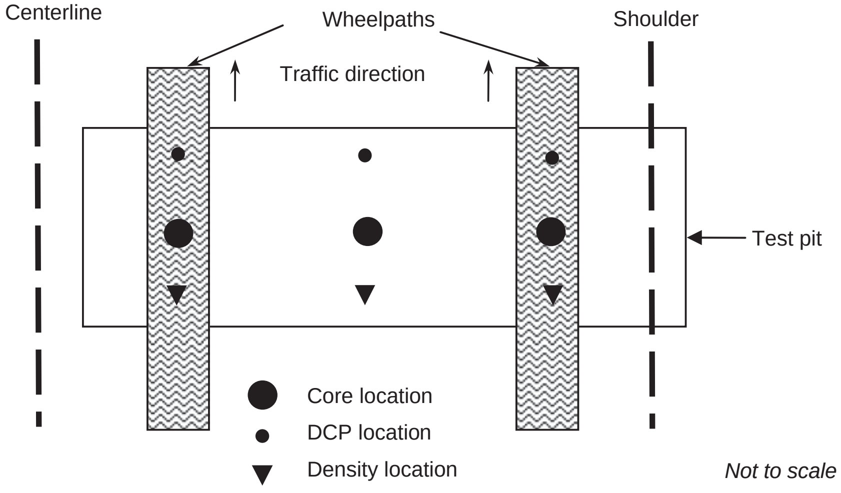


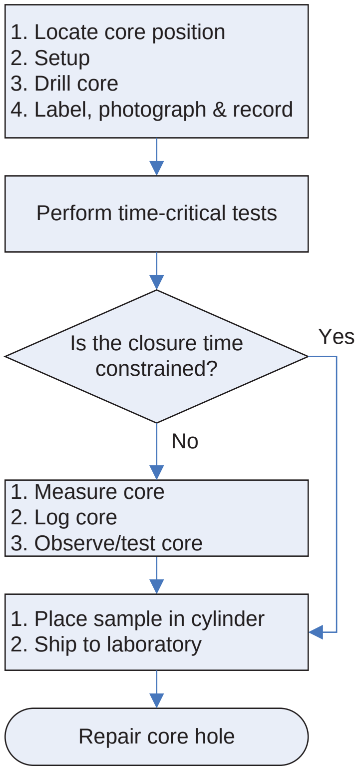
Figure 7.4. Example test pit layout.

- AASHTO T 225, Diamond core drilling for site investigation
- ASTM D2488, Description and identification of soils (visual-manual procedure)
- ASTM D4083, Description of frozen soils (visual-manual procedure)
- ASTM D4220, Preserving and transporting soil samples

7.3.1.2 Coring Procedures

General information on coring procedures is not provided in this guide. However, the following key issues should be considered when coring in forensic investigations:

- Keep a log of each core and core hole. The level of detail recorded will depend on the extent of the information needed. Core log forms typically include procedural details (e.g., cooling medium, difficulties encountered in coring); core measurements; and core and core hole observations (discussed under core logging). Example forms are provided in Appendix C (example Forms #17a and #17b).
- Use a diamond bit coring drill to remove cores. Mist-cooled equipment is typically used; however, if moisture damage is a potential cause of the failure being investigated, air-cooled coring equipment should be used to limit the influence of the coring activity on the assessment.
- Take cores at an angle of 90° to the surface in a manner that ensures the recovery of straight, intact smooth-surfaced samples suitable for layer analysis and laboratory testing.
- Observe the core hole (a flashlight may be required) to identify problems that may be contributing to the issues being investigated (e.g., areas of stripping, debonding, segregation, etc.). If available, use a borescope (Figure 7.5) to photograph problem areas. Borescopes are also useful for identifying and observing voids under concrete slabs (examples in Figure 7.6).
- If cores do not come out intact, take a measurement down the core hole as a cross-check to the core measurement to account for any discrepancies in core height/layer thickness caused by stripped layers, broken pieces, debonding, etc.



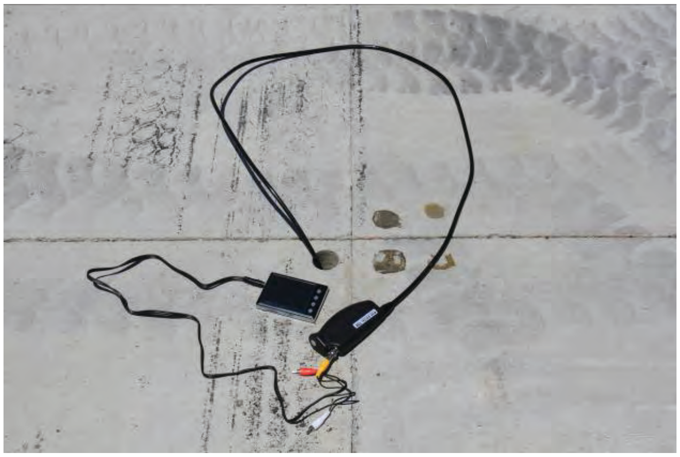


Figure 7.5. Example use of flexible video borescope in core hole.

7.3.1.3 Types of Core Log

Core logging requirements depend on the issues being investigated; however, cores serve one or more of three general purposes in forensic investigations (i.e., for thickness, for cause of distress, and for laboratory testing). One core can serve all three purposes if required, but care will need to be taken to obtain all required measurements and photographs before testing.

7.3.1.4 Core Logging Procedure

Cores are a key component of most forensic investigations on all pavement types and they need to be logged in a systematic manner with all observations carefully noted to facilitate use of data in subsequent interpretation and analysis. Traffic closure time constraints may dictate that only critical measurements, observations, and tests are taken on-site with non-critical activities performed after the closure.

Figure 7.6. Borescope views of void under concrete pavement.

If there is a time constraint on the closure, consider the following:

- Immediately number all cores and mark them in terms of orientation to traffic direction (typically an arrow marked on the surface of the core with a waterproof marker). Record the core numbers and precise position where it was taken on the core log form (example Forms #17a and #17b in Appendix C).
- Photograph the core and record the photograph number on the core log. Photographs of the cores against a measure (Figure 7.7) may be required if the investigation is part of a contractual dispute. The core photo/measurement platform (Figure 7.7) can also be used to assemble broken cores for photos and provides an approximate measurement for later reference when taking precise measurements in the laboratory. These photographs provide a record of the order of the layers and their condition for later assessment, which is particularly useful when pavement layers come out in pieces or have layers that are not intact due to stripping or other causes.
- Immediately make observations, tests, or measurements that are time-critical, such as:
  - Checking for carbonation of cementitiously stabilized layers. For cement or lime stabilized layers, spray the layer with a phenolphthalein solution to determine whether any carbonation of the layer has occurred (Figure 7.8). Spray those areas of stabilized materials that do not react with the phenolphthalein solution (i.e., do not turn a dark red color) with a dilute hydrochloric acid solution and record the degree of any reaction (fizzing). If available, check similar material that has not been stabilized for the acid reaction and whether the reaction is weaker or the same as the stabilized layer. This will indicate whether calcium carbonate occurs naturally in the material. Carbonated material is generally unbound and is unlikely to come out of a core hole intact.
  - Measurements and inspection of cores that are likely to disintegrate with handling or exposure to the elements. If there is any concern that the properties of a core may change in between the time that it is taken and the time that it is studied (e.g., cracks widen with removal of confinement [Figure 7.9]), a photograph can be taken on-site to allow for later off-site comparisons.

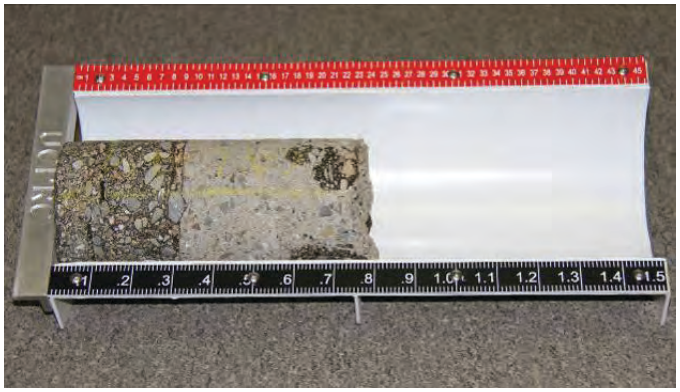
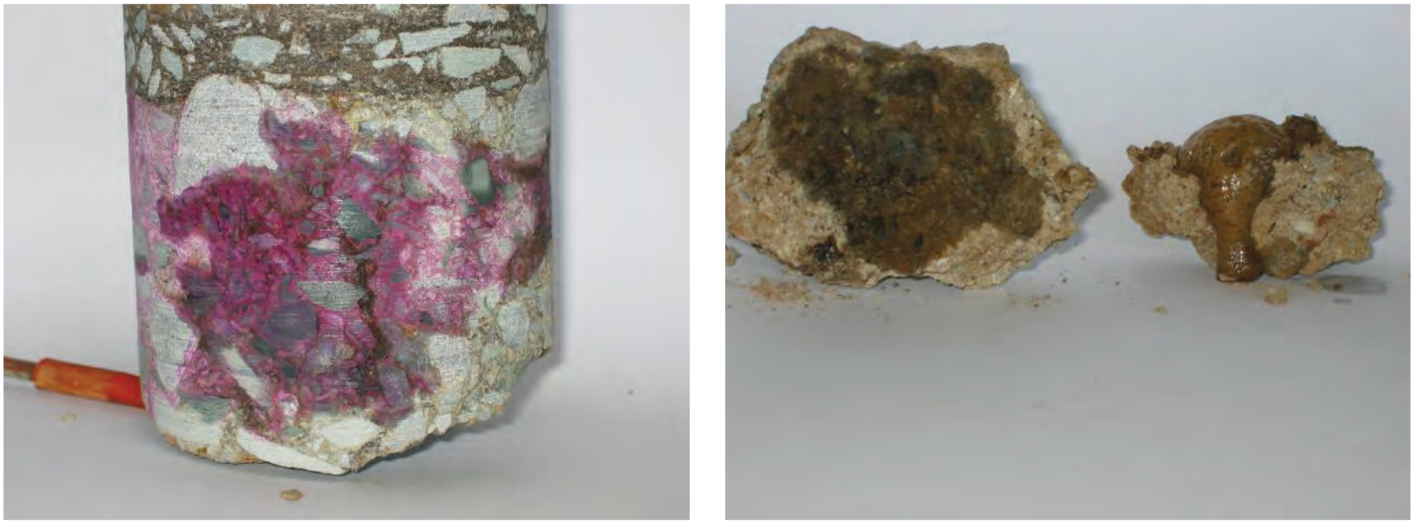


Figure 7.7. Core measurement platform.

Special precautions for handling phenolphthalein and hydrochloric acid should be taken and suitable protective clothing and equipment should be worn when handling the chemicals



Phenolphthalein reaction on core

Hydrochloric acid reaction on disintegrated core

Figure 7.8. Phenolphthalein and hydrochloric acid reactions on core.

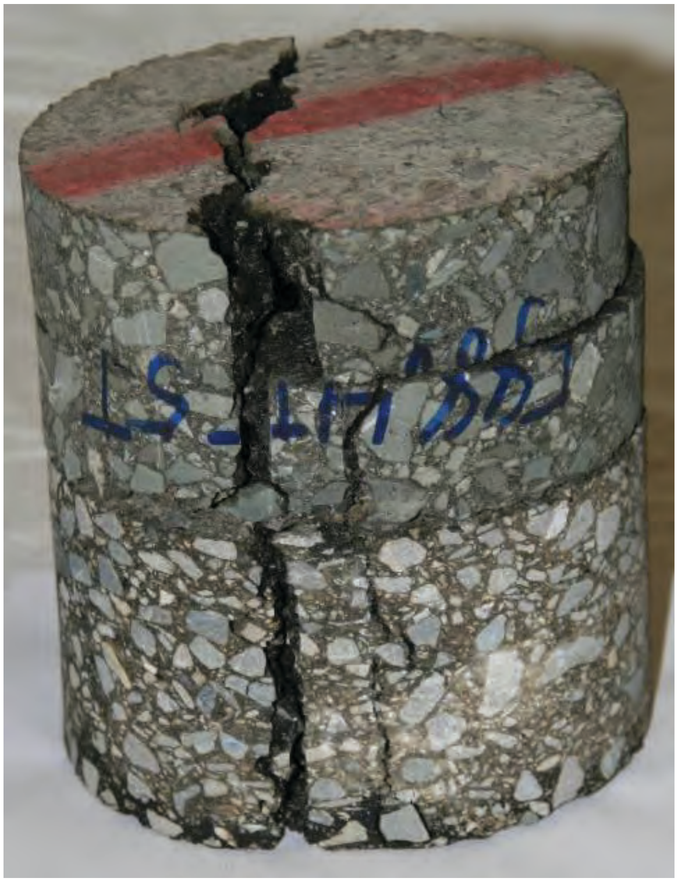


Figure 7.9. Example of crack widening with loss of confinement.

 - Document key observations on the form for later reference when logging the cores off-site.
 - Pack the cores in an air tight plastic canister and place the canisters in a crate to prevent damage during transport.

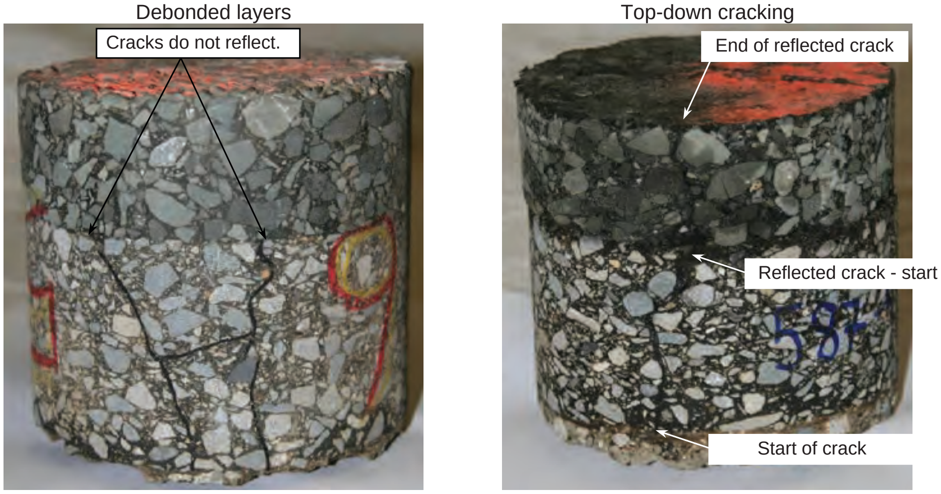
If there is no time constraint on roadway closure, or if the core logging is conducted after the closure, consider the following:

- Start core logging as soon as possible after extraction. On-site, this should be within 15 minutes after removal from the pavement before the moisture content of the surface changes substantially.
- Number and mark the core and record number and location on the core log.
- Lightly brush the core with a stiff brush to remove dust and sludge accumulated during drilling. Complete the cleaning by wiping the core with a damp cloth.
- Do a quick visual assessment of the core to identify any distinct distresses or abnormalities. Log any observations on the form.
- Photograph the core, if required, with an appropriate scale (Figure 7.7).
- When the core includes intermediate layers that are no longer bound together by asphalt or cement, or it is badly cracked, use a ruler to measure the depth from the surface to the bottom of the core. This will provide a reference measurement for the overall core height when assembling the pieces in the laboratory for detailed measurements.

- If required in the test plan, measure and record the total thickness of the core as well as the thickness of each layer on the core to the nearest ± 1⁄10 in. (or 1.0 mm) at four even intervals around the core using a core measuring jig, calipers, or a tape measure. Highlight the thickest and thinnest measurements.
- If required in the test plan, describe any observed distress in each layer in accordance with the layer designations provided on the preliminary data sheets. Examples of core observations are shown in Figure 7.10 and Figure 7.11. Summaries of pertinent parameters for asphalt and portland cement concrete wearing courses, and stabilized (bound) and unbound layers are provided in Checklists #1 through #4 in Appendix D (note that unbound layers are unlikely to be extracted intact with the core). These parameters are assessed in terms of the following

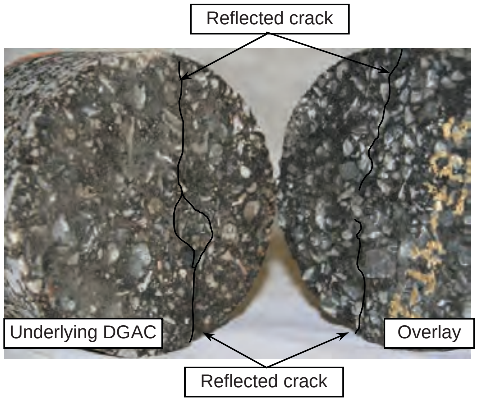
Debonded layers

Top-down cracking



Cracks did not reflect through overlay

Cracks reflected through overlay

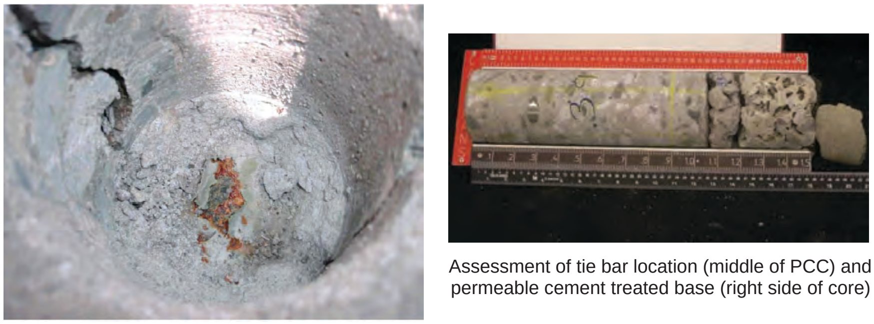


Reflected cracks in debonded layers

Figure 7.10. Examples of observations on asphalt cores.

Failure around dowel bar on pre-cast slab

Failure around dowel bar on dowel bar retrofit



Assessment of tie bar location (middle of PCC) and permeable cement treated base (right side of core)

Dowel bar failure/corrosion seen in core hole

Figure 7.11. Examples of observations on concrete cores.

suggested criteria (additional/other criteria may be appropriate depending on the issue being investigated).

- *Severity:* where applicable, rated on a scale of 1 (low), 2 (moderate), or 3 (high). Severity descriptors are provided in Checklists #5 through #8 in Appendix D.
- *Extent:* describes the percentage area, number of and/or length of the parameter being assessed. Extent descriptors are also listed in Checklists #5 through #8 in Appendix D.
- *Start:* where applicable, the start point of the distress (e.g., top or bottom of the surface layer).
- *End:* where applicable, the terminal point of the distress.
- *Layers affected:* indicates which layers are influenced by the parameter being assessed, listed in order from start to its terminal point.
- *Description:* describes the pertinent aspects of the parameter being assessed.
- *Implications:* where applicable, lists the implications and consequences of the parameter (e.g., vertical crack provides a path for the ingress of water and the egress of pumped fines) and links to other distresses/attributes.

- Compare cores taken in the wheelpaths with those taken between the wheelpaths to establish traffic effects such as densification and surface rutting (note that it is unlikely that unbound material from the base, subbase, and subgrade will be extruded in a core and, consequently, determining precisely where rutting has occurred in the lower layers is not possible using cores alone). Examine the condition and shapes of the layer interfaces to determine if rutting is confined to the surface layers and where any other distresses originate.
- Note and describe any evidence of debonding between layers (e.g., AC to AC, AC to base, AC to PCC, and PCC to base) and any other distress related to the debonding (e.g., crack origin).

- Note and describe evidence of leveling or correction courses in asphalt concrete pavements and interlayers in concrete pavements and between concrete and the base.
- Note and describe other distresses and/or observations and the potential implications such as material degradation or segregation, pumping of fines from lower layers, erosion of the surface of stabilized base layers due to pumping, and drainage deficiencies. Degradation of the material as a result of frost action can be observed in areas where ground freezing occurs beneath the pavement. If the core was sampled to a depth that is deeper than the normal frost depth, visual observations of the material above and below the frost line will reveal the depth of degradation. Other distress phenomena that should be sought and noted in the cut face of the surface layer include tensile crack formation at the bottom of asphalt concrete layers and D-cracking in concrete layers.
- Take close-up pictures of specific distresses and associated consequences (e.g., mottling around cracks indicating water saturation).

7.3.2 Test Pits and Trenches

7.3.2.1 Reference Material

The following reference standards are applicable to test pit excavation activities conducted in forensic investigations:

- AASHTO R 13, Conducting geotechnical subsurface investigations
- AASHTO R 19, Operational guidelines on test pits for evaluating pavement performance
- AASHTO T 24, Obtaining and testing drilled and sawed beams of concrete
- AASHTO T 310, In-place density and moisture content of soil and aggregate by nuclear methods (shallow depth)
- ASTM D2488, Description and identification of soils (visual-manual procedure)
- ASTM D4083, Description of frozen soils (visual-manual procedure)
- ASTM D4220, Preserving and transporting soil samples
- ASTM D5195, Test method for density of soil and rock in-place at depths below the surface by nuclear methods

7.3.2.2 Test Pit Excavation: Removing the Surface Layers

The following key issues pertaining to test pit/trench excavation procedures should be considered:

- Document all observations and measurements on an appropriate set of forms (example Forms #18 through #23 in Appendix C).

> Motorist and worker safety during test pit excavation, sampling, and testing are of major concern and appropriate measures need to be taken.

- Saw the pavement to the full depth of the wearing course and bound layers to the specified overall dimensions and into smaller pieces as necessary for removal.
  - Minimize the use of cooling water during sawing to reduce water contamination of layers. Vacuum water from the sawcut and sampling area during sawing.
  - Use air-cooled equipment if a moisture-related failure is being investigated.
  - If saws of sufficient blade diameter to cut through to the base of the treated layers are not available, use pneumatic spades and chisels, but with care to minimize damage to underlying untreated layers.
  - If material samples from the test pit are required, cut slabs of the wearing course to the appropriate dimensions to satisfy the testing requirements.
- When taking slabs to investigate potential dowel problems of jointed plain concrete pavements, identify the length of the dowels (including any longitudinal misalignment) and cut the slab on both sides of joint behind the dowels. Drill


Saw cutting for test pit


Test pit slab removal

four holes on the slab, place eyebolts in them and epoxy the bolts into place. Once the epoxy has set, use a small hydraulic lift arm or other available equipment to lift the joint out of the pavement and onto a truck for transport to the laboratory. Similar procedures can be used for extracting sections from CRCP.

- Mark wearing course samples on the top with an arrow to show the direction of traffic prior to removal from the pavement and a sample number. Log the number on the test pit evaluation form. The marking material should be waterproof to remain clearly visible.
- Place the selected samples top down on a sheet of plywood and remove any excess water and loose material from the underlying layer. Do not put any excess pressure on the slab as this may cause it to crack.
- Check the underside of the slab (Figure 7.12 and Figure 7.13). On asphalt surfaces, a clean surface with no base material attached indicates the surface may have debonded (Figure 7.12c). The presence of salt crystals may indicate salt damage in the upper regions of the base or lower region of the surfacing.
- Check all around the slab for any distress not related to the sawcut, specifically evidence linked to the issues being investigated, such as moisture damage in asphalt (stripping).
- If the surface material is required for laboratory testing, place it in a cloth or plastic bag and label the bag with the sample number. Log the sample on the sample inventory form.

7.3.2.3 Observation of Underlying Layers

Before disturbing the surface of the underlying layers, check for any unusual conditions that may have had an influence on the issues being investigated, such as:

- A layer of fine material, which could be an indication of over-rolling/crushing during construction, disintegration under traffic, or pumping of fines from lower layers.

a) Investigation of slab underside

b) Layer assessment of slab

c) Debonded layers

Figure 7.12. Checking AC slabs after removing from the test pit.

Figure 7.13. Removing and checking PCC slabs.

- Mottling, which usually indicates fluctuating moisture contents.
- A layer of loose material on top of a stabilized layer, which could indicate that carbonation of cemented layers has occurred, or inappropriate curing, re-mixing and/or final compaction techniques were followed on cementitious or asphalt stabilized layers.
- A thin layer of inconsistent material on top of the base, which could indicate that a leveling course of potentially substandard material was used to bring the layer to grade.
- The presence of salt crystals and other chemical substances, which may be encountered when using certain mine dump rock as base materials, or if the compaction water or ground water contain certain minerals.

Log all observations on the assessment form (example Form #18 in Appendix C). Photographs should be taken and logged to record any key observations.

7.3.2.4 In-Pit Testing

Once the visual assessment is complete, destructive in-pit testing can continue. The need for and type of in-pit testing on the layers underlying the surfacing layers will depend on the issues being investigated. Potential tests include:

- Density and moisture content measured with a nuclear density gauge or similar device to determine whether base and subbase compaction influenced performance (note that moisture contents can be influenced by water from the sawing operation).
- Layer thickness and shear strength determined with a DCP (note that DCP measurements can be influenced by water from the sawing operation, coarser aggregate, and the presence of stabilized layers).
- Permeability measured with a permeameter to determine the rate of ingress of water into the base for investigating moisture-related problems and permeable base performance.

Follow standard test procedures and log all results on an appropriate form (example Forms #22 and #23 in Appendix C for density/moisture content and DCP tests, respectively).

7.3.2.5 Test Pit Excavation: Base and Subgrade Layers

Excavation of the test pit can continue once the surface visual assessment and in-pit testing are complete. The following considerations are relevant to the excavation of the base and subgrade layers:

- Carefully remove the remaining base course layer to expose the subbase and/or subgrade layers, which may also be sampled if required. Continue excavation to a depth of at least 6 in. (150 mm) below the top of the subgrade or fill material. Separate the materials from each layer (Figure 7.14).

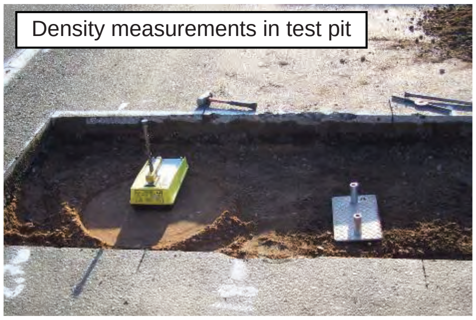


Figure 7.14. Separated layer samples from test pit excavation.

  - Take a 10 lb (5.0 kg) sample for laboratory moisture determination from each layer stockpile.
  - If a backhoe bucket with teeth is used to excavate untreated layers, care must be exercised during the last 1 in. (2~3 cm) to avoid disturbing the underlying layer if specific testing is required on the layer. Hand excavation of the last part of each untreated layer is preferred.
- Select the test pit face that will be assessed.
- Scrape the face with a spade to get as smooth a surface as possible. Brush to remove dust, sludge and any excess water from sawing (Figure 7.15). Wipe the wearing course layers with a damp cloth to highlight any distresses (e.g., cracks are clearer when the test pit face is damp).
- Demarcate each layer with string lines. This entails hammering nails at each side of the test pit face and at high and low points across the layer and connecting the nails with a string line, keeping it tight and level (i.e., no sag).
  - Use the string lines to provide a reference line for measurements, layer observation and description, and photographs (Figure 7.16).
  - Be careful when identifying the different layers, especially if the saw cut has gone into unbound materials. The smooth cut left by the saw blade can often be mistaken for a bound layer.
- Collect samples from the stockpiles of uncontaminated material of those layers identified as needing additional testing. Care must be exercised to avoid contamination of material from one layer with material from another layer. The sample size will depend on the identified testing. Log the sample on the material inventory sheet (example Form #21 in Appendix C).

7.3.2.6 Test Pit Logging

Test pit logging involves a series of measurements and observations on the test pit face. Every assessment will be different and will depend on the purpose of the investigation, the distress that has developed (or would typically develop, but has not) over time, its causes and related consequences. Therefore, each pit will have to be closely examined, measured, logged, and photographed in a systematic

Hand-finished test pit face

Close-up of brushed pit face

Figure 7.15. Test pit after excavation and finishing.

> *It must be remembered at all times that the purpose of a forensic investigation is not only to establish the cause of distress and/or failure (i.e., a post mortem investigation), but also to understand how the pavement behaved and to enable comparison with other similar pavements. Test pit assessors should look for and expect the unexpected, and try to relate what they see to material properties and construction practices, as well as traffic, and/or environmental influences.*

Figure 7.16. Test pit layer definition.

manner and all observations carefully noted to ensure that data is useful for subsequent interpretation and analysis. Capture all relevant and potentially relevant information on a form, or series of forms (example Forms #20 through #23 in Appendix C).

The following procedure is recommended for logging test pits:

- Start logging the test pit within 15 minutes after completion of excavation, before the moisture content of the face of the test pit changes significantly. For consistency, logging should be carried out on the "front" face of the test pit relative to traffic direction (Figure 7.17), but this can be changed to suit specific investigation requirements (e.g., location of distress) or because of the position of the sun. If appropriate to the investigation, simplify the assessment by dividing the test pit face into zones (Figure 7.18), such as:
  - Zone 1: Edge of test pit (shoulder) to outside edge of outer wheelpath
  - Zone 2: Outer wheelpath
  - Zone 3: Outside edge of outer wheelpath to inside edge of inner wheelpath
  - Zone 4: Inner wheelpath
  - Zone 5: Outside edge of inner wheelpath to edge of test pit (inside lane edge)

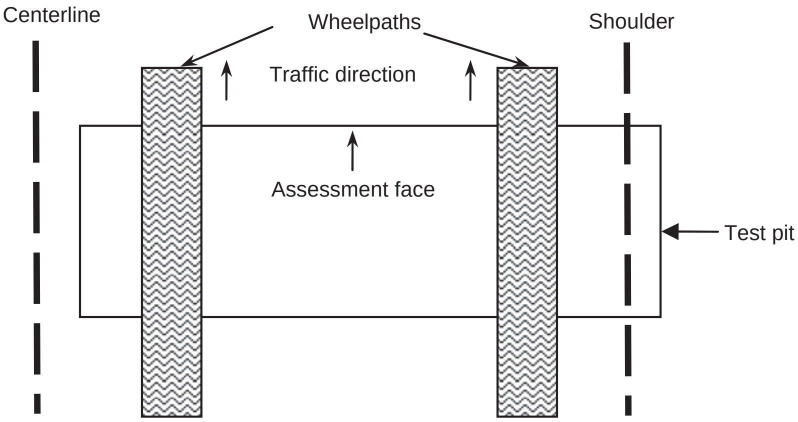


Figure 7.17. Plan view of test pit face to be logged.

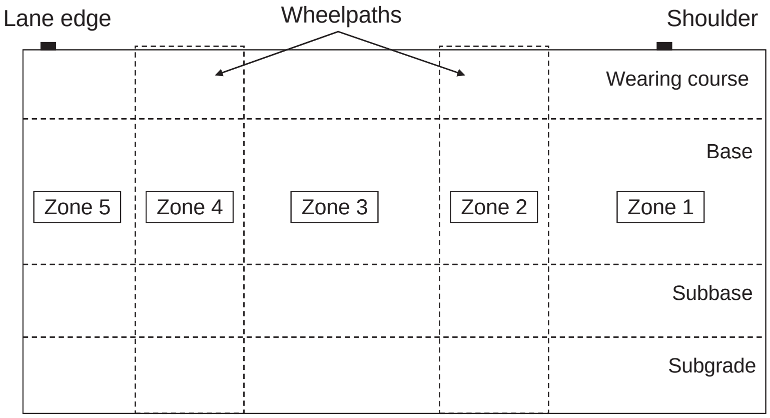


Figure 7.18. Zoning of the test pit face.

or combine Zones 2, 3, and 4 into one zone and divide the test pit face into three zones as follows:

- Zone 1: Edge of test pit (shoulder) to outside edge of outer wheelpath
- Zone 2: Area under and between the wheelpaths
- Zone 3: Outside edge of inner wheelpath to edge of test pit (inside lane edge)

- If layer thickness is an issue to be investigated, accurate measurements will be required. Take measurements as follows:
  - Place a straight edge with marked 2.0 in. (50 mm) intervals on the top edge of the test pit.
  - Raise the low end of the straight edge until level so that crossfall can be measured.
  - Mark the edges of the wheelpaths on the straight edge.
  - Starting at the shoulder/outside edge of the lane and working towards the inside, take a series of measurements to the nearest 0.1 in. (or 1.0 mm) that will be used to record the thickness of each layer and the degree of rutting in each layer. Measure from the top of the straight edge to the:
    - Top of the surface
    - Top of each layer in the surface
    - Top of the base
    - Top of each subsequent layer below the base
    - Top of the subgrade
- Record the layer profiles and measurements on the test pit profile form (example Form #18 in Appendix C). Also note the edges of the wheelpaths. Actual layer thicknesses can be determined later using a spreadsheet (Figure 7.19). Note deviations from the expected measurements together with the possible influence of this deviation on the overall performance of the pavement. Give special attention to:
  - Rutting in underlying layers but not in the surface (Figure 7.20a).

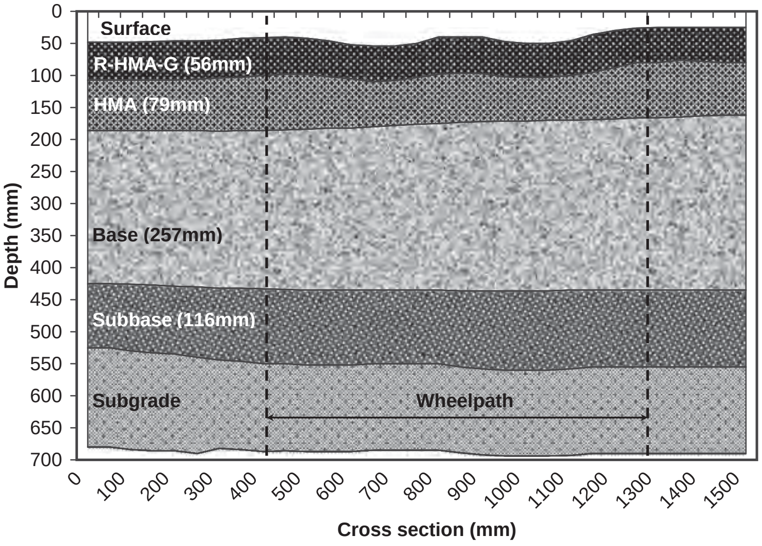


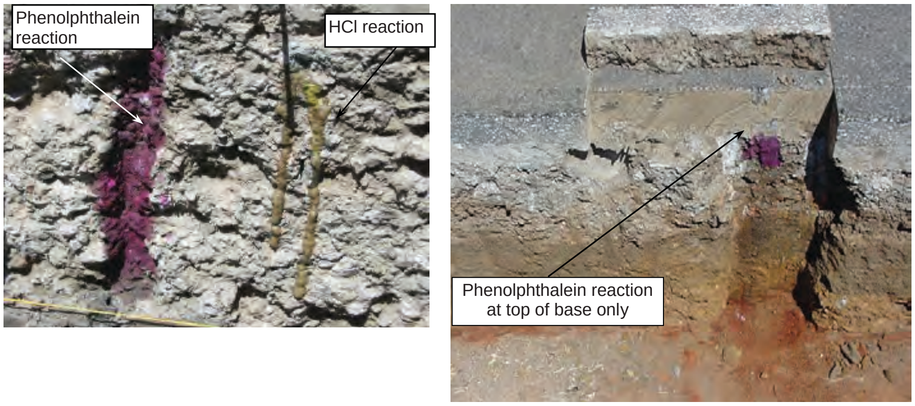
Figure 7.19. Example spreadsheet plot of layer thickness measurements.

a) Note rutting in underlying AC layer.

b) Note variable thickness of all layers.

Figure 7.20. Example observations from test pits.

  - Obvious differences between the pavement design and as-built records (e.g., thicker or thinner layers [Figure 7.20b]).
  - Thin layers that may have been added as a leveling course and become delaminated.
  - Describe each layer in accordance with the layer designations provided on the preliminary data sheets using the parameters provided in Checklists #1 through #4 in Appendix D. These parameters are assessed in terms of the following suggested criteria (additional/other criteria may be appropriate depending on the issue being investigated):
    - *Severity:* where applicable, rated on a scale of 1 (low), 2 (moderate), or 3 (high). Severity descriptors are provided in Checklists #5 through #8 in Appendix D.
    - *Extent:* describes the percentage area, number of and/or length of the parameter being assessed. Extent descriptors are also listed in Checklists #5 through #8 in Appendix D.
    - *Start:* where applicable, the start point of the defect (e.g., surface or 1.0 in. [25 mm] below subbase/base interface in Zone 1).
    - *End:* where applicable, the terminal point of the defect.
    - *Layers and zones affected:* indicates which layers and zones are influenced by the parameter being assessed, listed in order from start to its terminal point.
    - *Description:* describes the pertinent aspects of the parameter being assessed.
    - *Implications:* where applicable, lists the implications and consequences of the parameter (e.g., vertical crack provides a path for the ingress of water and the egress of fines) and links to other distress/attributes.
- Spray bound layers that have been stabilized with cement or lime with a phenolphthalein solution to determine if carbonation of the layer has occurred (Figure 7.21) or if the entire layer was correctly stabilized.
  - Well cemented layers will turn a dark red color, while carbonated areas will have little or no reaction, with severity usually increasing from top to bottom. The upper regions of carbonated layers are often also weak and relatively loosely bound and carbonated layers typically have lower than expected strengths and stiffnesses when tested with FWD and DCP.



Strong cementation throughout layer

Cement stabilization at top of layer only

Figure 7.21. Phenolphthalein and hydrochloric acid reactions in test pits.

Special precautions for handling phenolphthalein and hydrochloric acid should be taken and suitable protective clothing and equipment should be worn when handling the chemicals.

  - Spray areas of suspected carbonation with a dilute hydrochloric acid (HCl) solution to check for the presence of cement and the degree of reaction (fizzing). Note that calcareous materials in the layer aggregate such as dolomite and limestone will react with the hydrochloric acid and this should be factored into the interpretation. If possible, check the acid reaction with similar material that has not been stabilized and determine whether the reaction is weaker or the same as the stabilized layer. This will indicate if calcium carbonate occurs naturally in the material.
- Look for signs of reworking of cemented layers, typically indicated by weak cementation.
- Examine the condition and shapes of the layer interfaces to determine where rutting and other distress originates.
  - Deep ruts at the surface not reflected at the base/subbase interface indicate that the rutting has taken place in the base course or asphalt concrete surfacing. Surface ruts that are mirrored at the base/subbase interface or the subbase/subgrade interface are generally a consequence of compaction or shear at a depth below the interface.
  - Shearing/movement within layers in the form of shiny shear planes (slickenslides) that is sometimes observed in specific layers may indicate problems within that layer.
- Note and describe any other distress/behavior and its implications such as material degradation or segregation, stripping, cracking (e.g., tensile crack formation at the bottom of asphalt concrete layers, thermal cracks starting at the surface of asphalt layers, D-cracking in portland cement concrete layers, and shrinkage cracking or heaving of swelling subgrade soils), debonding, intrusion of subgrade fines into the subbase and/or base, erosion of the surface of the base layer due to pumping, and drainage deficiencies. Trace cracks from start point to end point and determine cause of the crack (e.g., shrinkage, settlement, differential compaction, fatigue, reflection, thermal, etc.).
  - Degradation of the material due to frost action can be observed in areas where ground freezing occurs beneath the pavement. If the test pit is deeper than the normal frost depth, visual observations of the material above and below the frost line will reveal to what depth degradation has progressed.
- Take good quality digital photographs of the test pit profile and key observations during the evaluation. The photographs should be taken at and keyed to the locations described on the test pit log, and provide a total view of the test pit as well as close-up views of the pavement profiles (Figure 7.22). All photographs should be taken with the sun behind the photographer whenever possible to avoid shadows. Close-up pictures should be taken of distress and associated consequences (e.g., mottling around cracks indicating water saturation) within the pavement structure and cross-referenced to the assessment form.
- Collect any additional samples from specific layers or specific points in the layer for additional testing and/or observation. Number each sample and record the sampling position and reason why it was taken (e.g., type of testing required) on the material inventory form.
- On completion of all test pit activities, ensure that the pit is correctly backfilled and all excess materials are removed from the site before the road is reopened to traffic.

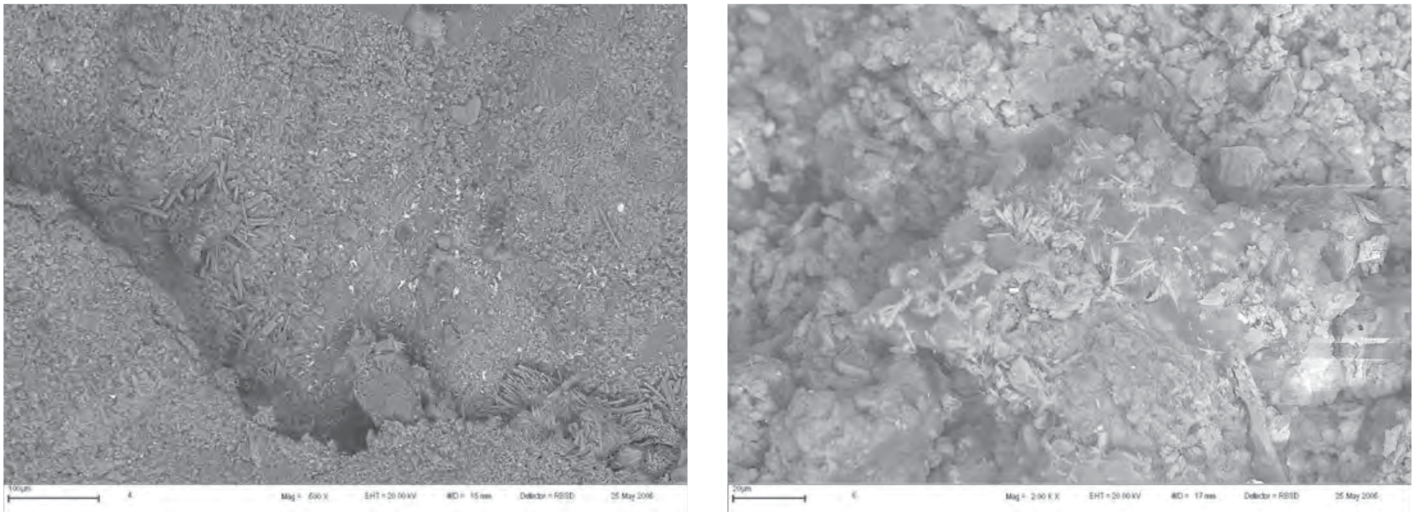
7.4 Key Issues Concerning Laboratory Testing

The need for laboratory testing and the type and number of tests required will depend on the issues being investigated. Laboratory test methods and procedures are not discussed in this guide.

Total view of test pit

Close-up view of distress (rut in underlying AC)

Figure 7.22. Example general test pit photographs.



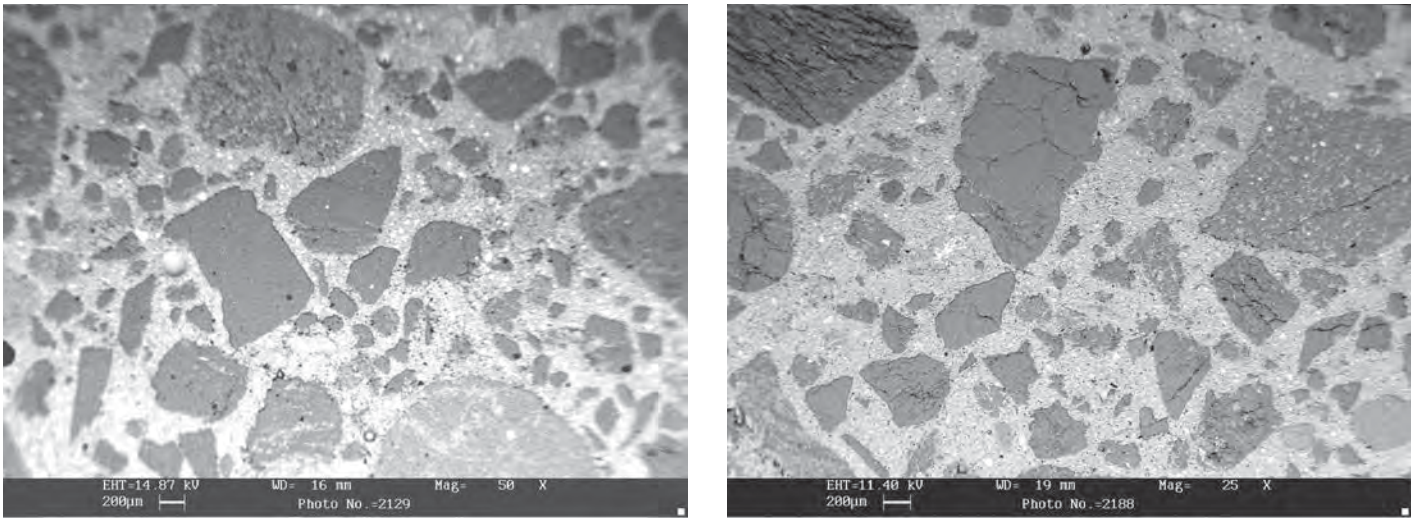
Development of calcite crystals associated with cracking during carbonation (x270)

New calcite crystals developing on previously well cemented aggregation of particles (x1,100)

Figure 7.23. Example scanning electron microscope images used in carbonation study.

In addition to standard tests, specialists on the investigation team may request/undertake specialized testing to fully understand the issues being investigated. Examples include:

- X-ray diffraction and surface energy measurements to assess aggregate chemistry and its effects on bonding of asphalt and cement and hydration products of portland and other hydraulic cements.
- Microscope and scanning electron microscope analyses (example in Figure 7.23) to observe bonding mechanisms, micro-cracking, and new cement crystal growth.
- CT scans to assess void connectivity and aggregate orientation.
- Petrographic analysis of aggregates (example in Figure 7.24), for ASR and other aggregate-related problems.
- Chloride contents of concrete to determine corrosion potential around reinforcing steel and dowels.
- Phase analysis of reinforcing steel and other metallic materials to compare with specifications.
- Chemical analysis of epoxy coatings and other anti-corrosion coatings.
- Chemical analysis for the presence of solvents, softening agents, fuel spills, and other materials that may be in the asphalt from contamination during manufacturing, transportation or other construction processes, or have been spilled on the pavement during use.



1 day

7 days

Figure 7.24. Example petrographic analysis of ASR in PCC pavement.

CHAPTER 8

Data Analysis, Hypothesis Testing, and Final Report

Data analysis and hypothesis testing are carried out once all the relevant observations and test results have been documented and assessed. This part of the study relates these observations and results to the issues being investigated and needs to provide sufficient data to address them, as well as to support/justify any conclusions and recommendations that are made.

8.1 Data Analysis and Hypothesis Testing

The method and approach followed will depend on the issues being investigated. Specific details on approaches to and methodologies for data analysis are not discussed in this guide, but the following items should be considered:

- Check the data and observations for reasonableness and correctness, and if necessary, compare to agency norms. If satisfied with the reasonableness, continue with the analysis.
  - Reasonableness checks are especially important for calculated data such as backcalculated stiffnesses from FWD deflection measurements, IRI from profile data, layer thickness from GPR, etc. For example, an effective modulus backcalculated from deflection data of 2,000 ksi (14 GPa) is reasonable for a cracked concrete layer but a much higher value (double or more) would be expected for a sound concrete layer.
- Focus on the issues being investigated and analyze the data with consideration to the objectives of the investigation (see Sections 0 and 3.5.1). All observations and test results should be considered because both good and poor performance are often the result of a number of factors (e.g., the presence of punchouts in a CRCP pavement may be attributed to poor subgrade resulting from inadequate drainage during higher than average rainy conditions, but other factors such as heavier than anticipated traffic loadings and/or poor construction quality may also have contributed to the problem).
- Consider the fundamentals of pavement performance, namely pavement structure (including pavement type, pavement layers and construction); subgrade soil; traffic; drainage (including subsurface); and environmental conditions; and how each of these influences the result.
- If applicable, compare as-designed/as-specified with as-built pavement structure information.
  - Determine whether any differences have influenced pavement performance. Deviations in construction requirements (e.g., compaction), layer thickness, substitution of layers with others, the addition of leveling courses, actual strengths and stiffnesses, etc., could explain both exceptional and poor performance.
  - Compare pavement performance (e.g., stiffness, profile, noise, permeability, etc.) against agency norms. If there are deviations, account for them from the observations and results and link them to the issues being investigated.
- If applicable, link any key climate, environmental, and/or traffic events to the issues being investigated. Determine whether the pavement design considered the effects of the events and/or whether the as-constructed pavement was adequate to accommodate these events. Examples of such events include flooding; freezing; abnormal traffic loads; higher or lower than design traffic; actual traffic mix (volumes, loadings, or both); and periods of excessive heat, etc.
- If applicable, assess any variability in construction or structure (e.g., layer thickness) across the entire project and its relationship to the issues being investigated. Localized problem areas may be explained from these observations and QC/QA documentation.
- Assistance or an outside opinion with interpretation of specialized test results may be necessary if that expertise is not on the team. Newly developed tests may not have a proven track record in pavement forensic investigations and their use may need to be justified. Specialized tests are useful for confirming other observations.

8.2 Forensic Investigation Report

A final report is prepared at this point to document the findings of the study and to make recommendations based on these findings. The report will be a continuation of the initial investigation report discussed in Section 5.3 and should include the following:

- Executive summary.
  - Summarizes reasons for undertaking the forensic investigation, the key findings, implications of the findings, and recommendations on actions that need to be taken.
- Introduction.
  - Lists the reasons for continuing with the investigation.
- Objectives and hypothesis.
  - Refines the issues being considered and potential hypothesis investigated.
- Final investigation plan.
- Observations and measurements.
  - Includes tables of key observations, measurement location, and measurement results that support the findings.
- Analysis and interpretation.
  - Summarizes test data interpretation in terms of addressing the investigation issues/questions.
  - Justifies that the investigation has satisfactorily addressed the investigation issues/questions.
- Findings/Conclusion.
- Recommendations.
  - Provides recommendations on using the findings from the investigation, for example:
    - Changes to design manuals, construction and quality control procedures, specifications, test methods, and/or contractual documentation.
    - Dealing with contractual claims.
    - Corrective actions on premature failures.
    - Calibration factors for mechanistic models.
- Lessons learned.
- Dissemination of findings.
  - Details of the findings that need to be disseminated and recipients.
- Costs of the investigation and if applicable, cost-benefit analysis comparing the costs of undertaking the investigation against the benefits of implementing the findings.
- Location of data files (e.g., website address for forensic investigation database).

An example final report cover sheet is provided in Appendix C (example Form #24 in Appendix C).

8.3 Record of Decision

The forensic investigation coordinator obtains approval of the final report and recommendations from the investigation director and adds a record of decision to proceed with implementation of the recommendations and dissemination of findings in the project file.

CHAPTER 9

Investigation Close-Out

The investigation close-out is the final stage of any pavement forensic investigation and includes a review of the investigation, identifying actions that need to be implemented based on the investigation findings, and finalizing project management tasks.

9.1 Investigation Review

An investigation review (or post mortem) by the team (and if appropriate, the project director, division program manager, or other relevant manager) is recommended for all forensic investigations to:

- Check that the objectives have been met and whether or not the investigation was successful (e.g., an investigation scorecard).
- Revisit the initial investigation and reasons for conducting (or not) various investigation phases and determine whether these were valid.
- Establish with hindsight whether the approach followed in the investigation was appropriate or whether a different one would have provided the same result more quickly or with less effort.
- Compare approach and results to previous forensic investigations to determine if there are any trends that need to be considered when implementing the recommendations and disseminating the findings, or that could be used to support the recommendations.
- Discuss approaches for best disseminating and implementing the findings.
- Discuss changes in the process for planning and conducting future forensic investigations.

The investigation coordinator should document the discussions and revise agency forensic investigation protocols accordingly. The results of the investigation review may influence how the recommendations are implemented and findings are disseminated.

9.2 Actions Resulting from the Forensic Investigation

The distribution of the forensic investigation report to appropriate agency personnel and use of its findings, conclusions, recommendations, and lessons learned is an important step in enhancing agency practices for pavement design, construction, rehabilitation, and maintenance.

Depending on the reasons for the investigation and the nature of the information contained in the investigation report and agency processes adopted, actions from the forensic investigation could include one or more of the following:

- Recommendations for changes to design guides, specifications, test methods, and/or contractual documentation.
- Preparation of technical bulletins or briefs to disseminate information resulting from the investigation such as:
  - Lessons learned (i.e., how to carry out better investigations).
  - Improved design, construction, or quality control practices.
  - Means for dealing with contractual claims and corrective actions on premature failures, and calibration factors for local mechanistic models.
- Preparation of papers and/or presentations for dissemination of the investigation findings at conferences, workshops, webinars, etc.

The forensic investigation coordinator is responsible for initiating these actions and should ensure that:

- An estimate of the resources required for completion of the action items is prepared and, if necessary, approved by the project director.
- If required, an individual is identified and assigned responsibility for the implementation of the action items.
- A due date is assigned for the actions.
- Progress on the action items is monitored.

9.3 Investigation Close-Out

The investigation close-out is the final task for the forensic investigation coordinator. This includes:

- Acknowledgments to all individuals involved in the study.
- Notifications to all parties affected by the outcome of the investigation.
- Initiating any actions listed in the final report.
- Completing the documentation process.
- Completing the investigation cost spreadsheet.
- Updating the forensic investigation database.
- Completing and closing the project file.

An example checklist for investigation close-out is provided in Appendix D (example Checklist #9).

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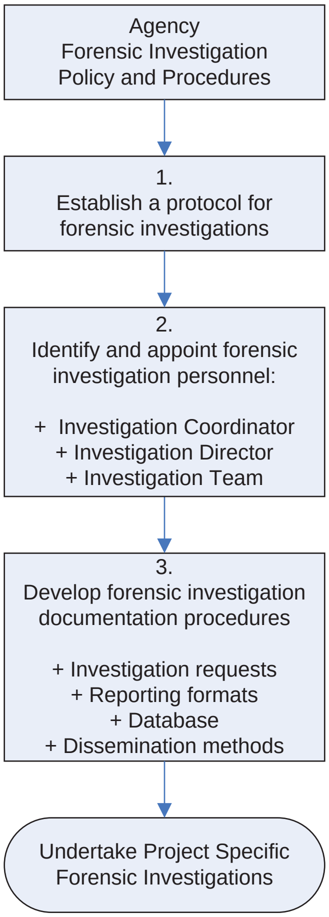
APPENDIX A

Generic Issues

This Appendix addresses issues associated with the establishment of an agency's forensic investigation protocol. The issues covered are required to ensure that forensic investigations are performed appropriately and systematically and results are reported in a consistent manner throughout an agency to support appropriate changes to guidelines, manuals, specifications, current practices, and to eliminate the recurrence of problems.



There are three general topics that an agency needs to address and/or have in place to conduct project specific forensic investigations both efficiently and effectively:

- Establishing a protocol for forensic investigations,
- Identifying and appointing forensic investigation personnel:
  - Appointing a forensic investigation coordinator,
  - Identifying individuals within the agency to approve investigations and facilitate implementation of findings (i.e., investigation directors), and
  - Establishing forensic investigation teams.
- Developing forensic investigation documentation procedures:
  - Forensic investigation requests,
  - Uniform reporting formats,
  - Forensic investigation database, and
  - Dissemination of forensic investigation results.

These topics usually only need to be addressed once, but should be monitored and re-visited periodically to ensure they are still appropriate.

A.1 Establishing a Protocol for Forensic Investigations

This step deals with establishing an agency protocol for forensic investigations. Adoption, implementation, and acceptance of this protocol will help formalize forensic investigations and support using the results to improve existing agency policies, procedures, manuals, guidelines, specifications, and test methods. This protocol should be communicated to individuals in the agency and they should be encouraged to follow it. The protocol should include:

- Reasons for having the protocol,
- Agency approach to:
  - Assembling forensic investigation teams.

  - Requesting a forensic investigation.
  - Undertaking forensic investigations.
- Procedures for documentation and dissemination of findings, and
- Procedures for implementing findings and/or adopting recommendations.

A.2 Identifying and Appointing Forensic Investigation Personnel

A.2.1 Appointing a Forensic Investigation Coordinator

This step deals with identifying and selecting an individual who will lead the program and defining the responsibilities of that individual. This person, designated the agency's forensic investigation coordinator, is expected to be involved in all facets of the agency's forensic investigations (and possibly in establishing the protocol for the agency). This activity may or may not be a full-time position.

Key responsibilities of the forensic investigation coordinator, who should have an appropriate level of decision-making authority, include, but are not limited to:

- Being a central point of contact for all forensic investigations within the agency to:
  - Receive forensic investigation request forms.
  - Ensure that each forensic investigation request is acted upon including:
    - Initiating the forensic investigation.
    - Conducting the background study.
    - Deciding on whether to proceed or not to proceed with the forensic investigation.
- Establishing forensic investigation teams in accordance with the agency's protocol.
- Leading activities associated with the storage and dissemination of results from forensic investigations within the agency in accordance with agency protocol.
- Coordinating the adoption of changes to practice based on forensic investigation findings.

To ensure consistency, the forensic investigation coordinator should, where possible and practical, also serve as the team leader (i.e., project manager) on all forensic investigations performed within the agency (it is assumed that this is the case in this guide) with the following responsibilities:

- Manages the project in accordance with the guide.
- Forms a project specific team, documents the team (names and contact details) on an appropriate form, and assigns responsibilities to each team member.
- Compiles the investigation documentation (e.g., investigation plan, reports, approvals, records of decision).
- Makes all logistical arrangements for the investigation (e.g., notifies other departments, arranges for traffic closures, arranges non-destructive testing).
- Obtains all necessary project-related approvals.
- Serves as the quality control officer for the project to ensure the quality of the work throughout the investigation.

The agency's forensic investigation coordinator is expected to have the following qualifications to effectively perform these responsibilities:

- Possess sufficient stature within the agency to make decisions on undertaking forensic investigations and delegate activities and responsibilities to others.
- Have sound understanding, background, and experience in pavement design and performance-related issues.
- Possess good project management skills, including sufficient leadership and communications skills to organize the various activities associated with forensic investigations within the agency.

The agency's forensic investigation coordinator should be given the responsibility of recommending changes to practice and protocol based on the findings of forensic investigations, and be provided with the necessary technical and administrative support to properly and efficiently address forensic investigation issues within the agency.

A.2.2 Identifying Forensic Investigation Directors

This step covers identification of individuals within the agency who will be responsible for approving the various stages of the investigation, and supporting implementation of the findings and/or recommendations arising from the investigation. The choice of investigation directors will depend on the agency structure, complexity and profile of the investigation, and the issues being investigated. Examples of such individuals are the state materials engineer, state pavement engineer, or head of construction. In some instances, the investigation director may also be the investigation requestor (e.g., the state pavement engineer requests investigation of a pavement failure, the head of construction requests an investigation into a contractual dispute, or the state materials engineer requests an evaluation of experimental test sections that were constructed to evaluate a new technology).

A.2.3 Establishing a Forensic Investigation Team

This step deals with establishing a forensic investigation team. This can be accomplished through a variety of approaches depending on the agency's resources and capabilities, such as:

- A permanent team for all pavement forensic investigations within the agency.
- Ad hoc teams that are set up each time an investigation is required.
- A "virtual" team made up of key individuals from across the agency and organizations supporting the agency, from which project specific investigation teams are selected based on the issues being investigated and the location of the investigation.

There are advantages and disadvantages to each of these three approaches. The establishment of a permanent team provides continuity, consistency, and uniformity to forensic investigations within the agency. This approach also provides for an easy-to-contact group of individuals to manage investigation requests, make go/no-go decisions, and rapidly undertake investigations with minimal logistical planning and arrangement. However, establishing a permanent team to undertake all investigations is often not feasible because of the wide range of expertise required to handle all potential issues and the expense of maintaining such a dedicated team. On the other hand, ad hoc teams do not require a long-term commitment and allow tailoring for specific investigations. However, this approach does not provide for continuity, consistency, and uniformity of forensic investigations within the agency.

The formation of a virtual team within the agency makes the best use of available resources by providing a permanent focus group of individuals within the agency and the research organizations that the agency supports (e.g., university research centers). Specific investigation teams are selected from the virtual team depending on the location and issues being investigated. In this guide, it is assumed that agencies will adopt some form of virtual team approach.

Virtual teams will typically include the following members:

- Agency design engineers.
  - Support formation of the project specific team.
  - Participate in discussions about differences between the design and as-built records.
  - Participate in discussions related to the anticipated and actual pavement performance.
  - Support the project team leader in all phases of the forensic investigation, including the decision to proceed or not, planning and execution of the investigation, analysis and interpretation of the results, and dissemination of the investigation findings.
- State/district/region materials engineers.
  - Relate the issues being investigated to performance/behavior of other roads in the area.
- State/district/region maintenance engineers.
  - Relate the issues being investigated to performance/behavior of other roads in the area.
- State/district/region construction/resident engineers.
  - Provide input on construction-related issues.
- Area maintenance superintendents.
  - Provide information on maintenance, highway performance/behavior trends, traffic, and climate in the area.
  - Provide input on all maintenance undertaken on the project being investigated.
  - Make all arrangements for closures, local work crews, and equipment.
- Non-destructive testing equipment managers.
  - Plan, and coordinate non-destructive testing requirements.
  - Interpret non-destructive test results.
- Laboratory supervisor.
  - Plan and coordinate laboratory testing.
- Agency data managers.
  - Provide traffic and traffic-related information and data.
  - Provide pavement management system data.
  - Provide project contractual data.
- University/research center specialists and/or consultants.
  - Provide specialist non-destructive, destructive and/or laboratory testing services.
  - Assist with data analysis, interpretation, and report preparation.
  - Relate the issues being investigated to research undertaken.
  - Provide input for research quality data requirements (e.g., for performance models).

Expertise matrices can be used to identify investigation team members with relevant expertise to support the different parts of the forensic investigations. An example of a simplified virtual team expertise matrix is presented in Table A.1. Actual agency matrices would have additional columns identifying specific expertise in each knowledge area.

It is anticipated that a project specific team will consist of four to six members depending on the issues being investigated; the actual number of team members will depend on the extent of the different parts of the investigation. For example, the objectives of the investigation could be met during the background study phase, and hence require little involvement from some team members.

A.3 Developing Forensic Investigation Documentation Procedures

This step deals with the establishment of documentation procedures, which includes a document management process, budgeting, cost-tracking, and cost-benefit analyses, and an auditable documentation trail of each investigation. These procedures are used to facilitate build-up of knowledge

Table A.1. Simplified virtual team expertise matrix.

Pavement Type	Knowledge Area			
	Pavement Conditions	Pavement Performance	Field and Lab Testing	Specialist Expertise
	Familiarity with project and local conditions*	Design, construction, maintenance, and rehabilitation*	Non-destructive, field and lab testing*	Special knowledge, testing, analysis and/or modeling*
AC/Surface treatment				
PCC, PCC over PCC, PCC over AC				
AC Over PCC				
Bound and unbound layers				
Other				

*Names and contact details are added to each cell or cross-referenced from a separate list of names

(lessons learned), dissemination of results throughout the agency, and agency-wide adoption of findings (e.g., changes to policies, procedures, practices, guidelines, manuals, specifications, and test methods). Important considerations for this element include the establishment of:

- A protocol and procedures for requesting an investigation.
- Communication channels to ensure that investigation request forms are directed to the agency's forensic investigation coordinator.
- Standard reporting formats, including checklists, forms, records of decision, investigation reports, and implementation of recommendations.
- Spreadsheet templates for preparing cost estimates. These templates should include agency costs for typical forensic investigation activities.
- Formal procedures for report acceptance and implementation of the findings and/or recommendations.
- Options for dissemination of investigation results, which could include a forensic investigation website, paper and web-enabled reports, a forensic investigation database, workshops and webinars, and an annual forensic investigation DVD.

A.3.1 Forensic Investigation Requests

Requests for forensic investigations will come from a range of sources within or associated with the agency, triggered by a variety of reasons. To properly manage such requests, it is necessary that the agency have a clear protocol in place that addresses the submittal of an investigation request, and handling of the request (i.e., responsible individual). This will expedite processing the request within the agency and limit problems such as repeat pavement failures and lost opportunities to improve pavement practices. The protocol must be readily accessible to all individuals within or associated with the agency who could potentially submit a request for a forensic investigation. Agency staff should be informed of this protocol, either through the agency's website or by a staff bulletin.

> The costs of doing a forensic investigation (either for exceptionally good or bad performance) are usually negligible in terms of the cost of the project being investigated and the potential consequences of not understanding the issue, or not changing documentation and procedures to incorporate the findings

The recommended elements of this protocol include the following:

- A procedure for individuals to submit a request for a forensic investigation. Requests should go to the agency's forensic investigation coordinator, preferably via email to facilitate document management and distribution to other agency personnel who will be part of the investigation. The procedure must also provide the name and contact details of the coordinator.
- A form for requesting a forensic investigation. The form must include basic information and explain why the investigation is necessary.
- A procedure for logging the request with the agency, assigning it an investigation number, and opening a project investigation file. The investigation numbering systems will almost certainly vary between agencies.

- A procedure for acknowledging receipt of request and listing a date by which a decision to proceed or not with the investigation will be made, and listing a date by which the individuals requesting the investigation will be notified of the decision.

A.3.2 Uniform Reporting Formats

Uniform reporting formats facilitate dissemination of information gained and adoption of recommendations. Forensic investigation reports should follow a specific table of contents, which should include the following chapters:

- Executive summary.
- Introduction.
- Objectives and hypothesis.
- Final investigation plan.
- Observations and measurements.
- Analysis and interpretation.
- Findings/conclusions.
- Recommendations.
- Lessons learned.
- Dissemination of findings.
- Appendices with completed investigation forms and test results.

Agencies should develop a template for reports, which include the above chapters and accommodate agency specific formats and styles, and report numbering systems.

A.3.3 Forensic Investigations Database

With advances in computer hardware and software technology, those agencies with an active forensic investigation program should establish a forensic investigations database within available resources. Ideally, this database would help track the status of forensic investigations from receipt of request to dissemination of results and store forensic investigation information (e.g., checklists, forms, and reports). Where appropriate, this database should link to other agency databases (e.g., pavement management system) to make best use of available data. More importantly, a functional database will facilitate dissemination and use of the results from forensic investigations within the agency and between agencies.

A suggested framework for establishing a forensic investigations database is illustrated in Table A.2. It assumes a relational database structure consisting of modules, tables and data fields. This framework is consistent with the general investigation philosophy presented in Chapter 2 in that pavement performance measures and data on the factors affecting performance (pavement structure, subgrade soil, traffic, drainage and environmental conditions) are contained in the database. Data on the as-designed and as-constructed or actual conditions are also reflected for each of the factors affecting performance.

In addition to the investigation data, the database framework incorporates other important information about the investigation, including:

- General project information — route name, route type/function, project location information (limits, post-miles), pavement surface type, and shoulder type.
- General investigation information — investigation request details, investigation issues and investigation team.
- Investigation results — findings, conclusions, recommendations, implementation/adoption of recommendations and lessons learned.
- Ancillary investigation information — investigation photographs, completed investigation forms and investigation reports.

The suggested database framework is primarily intended for storage of forensic investigation data and information, but if desired, the framework can be expanded for use of the database in other applications such as tracking and monitoring the progress of investigations. For example, a tracking module can be incorporated into the database that would include tables and data summarizing the major investigation activities to be performed (i.e., submittal of request form, decision to proceed or not with the investigation, completion of final report, etc.), the date when those activities were scheduled for completion, the dates when the activities were actually completed, and issues of significance impacting the outcome of the respective activities. As with the schedule, the database could also be used for tracking planned versus anticipated investigation resources.

If an agency decides to pursue the establishment of a forensic investigations database, it is important to recognize that:

- The suggested database framework is geared to agencies with an active or planned active forensic investigations program, and as such it could lead to a fairly sophisticated and comprehensive database.
- More than two decades and a vast amount of resources have been spent on the development and implementation of the FHWA's Long-term Pavement Performance (LTPP) database. This database, and more specifically the schema associated with it, provides an excellent foundation for the creation of a forensic investigations database — many of the data and information needs are the same.

For those agencies with a less active forensic investigations program, but which are still interested in the development and implementation of a database to track their investigations, less sophisticated and comprehensive options are available. For example, the forms contained in Appendix C of this

Table A.2. Forensic investigations database framework.

Module	Tables	Data / Information		
General Project Information	Route Information	Route Name (e.g., I-81)		
		Route Type/Function (e.g., 4-lane divided highway)		
		Project Location Information (limits, mileposts)		
		Surface Type (e.g., HMA, PCC)		
		Shoulder Type (e.g., HMA, PCC)		
General Investigation Information	Investigation Request	Date of Request		
		Name of Requestor(s)		
		Reason(s) for Reeqest		
	Investigation Team	Date of Team Formation		
		Number of Team Members (for each member)	Name of Team Member	
			Role and Responsibility of Team Member	
	Investigation Issues	Number of Issues (for each issue)	Description of Issue	
Investigation Data	Pavement Performance Measures (e.g., distress)	Number of Performance Measures Considered		
		Performance Measures Considered		
		Performance Measures (for each measure considered)	Current Pavement Condition	
			Current Pavement Condition Date	
			Current Pavement Condition Determination Method(s)	
			Historical Pavement Condition/Performance	
			Historical Pavement Condition/Performance Determination Method(s)	
			Historical Pavement Condition/Performance Dates	
	Pavement Performance Factors	Pavement Structure and Subgrade Soil	Pavement Type (e.g., HMA, PCC, HMA over HMA, or HMA over PCC)	
			Pavement Layers (for each layer from subgrade to surface)	Layer Numer (subgrade = 1)
				Material Type (e.g., PCC, HMA, CTB, DGA, or silty soil)
			As-Designed Layer Information (from subgrade to surface)	Layer Thickness
				Material Properties (e.g., modulus, CBR or mix properties)
				Drainage Information
				Reinforcement Information (PCC layers)
			As-Constructed Layer Information	Layer Thickness
				Layer Thickness Determination Method(s)
				Date of Construction
				Material Properties (e.g., modulus, CBR, mix properties or compaction)
				Material Property Determination Method(s)
				Material Property Determination Date(s)
				Drainage Information
				Reinforcement Information (PCC layers)
				QC/QA Information
				Other Construction Information (e.g., ambient conditions during consteruction, maintenance history)
		Traffic	As-Designed Traffic	Traffic Volumes
				Traffic Loadings
				Traffic Growth
			Actual Traffic	Traffic Volumes
				Traffic Loadings
				Traffic Growth
				Traffic Determination Method(s)
		Environmental Conditions	As-Designed Conditions	Air, Surface and Subsurface Temperatures
				Precipitation and Subsurface Moisture
				Freese/Thaw Cycles/Freeze Days
			Actual Conditions	Air, Surface and Subsurface Temperatures
				Precipitation and Subsurface Moisture
				Freese/Thaw Cycles/Freeze Days
				Unusual Events (e.g., hurricanes or flloding)
				Environmental Conditions Determination Method(s)
Investigation Results	Findings	Number of Findings	Description of Findings	
	Conclusions	Number of Conclusions	Description of Conclusions	
	Recommendations	Number of Recommendations	Description of Recommendations	
			Description of Recommendations Implementation/Adoption	
	Lessons Learned	Number of Lessons Learned	Description of Lessons Learned	
Ancillary Investigation Information	Photographs	Number of Photographs	Description of Photograph	
			Photograph Date	
			Name of Photographer	
	Forms	Number of Forms	Copy of Forms (PDF format)	
	Reports	Copy of Report (PDF format)		

guide and their associated data and information requirements can serve as the basis for development and implementation of such a database. The resulting database could be further augmented by the incorporation of the investigation reports (in PDF format).

Regardless of the level of sophistication, the ultimate objective of a functional forensic investigations database, as stated earlier, is to facilitate dissemination and use of the results from forensic investigations within the agency.

A.3.4 Dissemination of Forensic Investigation Results

It is expected that the findings, conclusions, and recommendations resulting from the investigations will be disseminated throughout the agency to effect improvements to policies, procedures, practices, guidelines, manuals, specifications, and test methods.

The following are dissemination options that an agency may consider:

- Forensic investigation websites. Most agencies maintain a website with links to various types of information relevant to the agency, including information about the pavements program. The addition of a forensic investigation link within the agency's pavement information area is a simple means for making the information available to a large group of potential users both within and outside the agency. The final reports resulting from forensic investigations could be posted on the link, either as web-enabled reports or in PDF format. The agency forensic investigator coordinator should be responsible for maintaining and updating the website content.
- Paper reports. In addition to the website, the agency may distribute the investigation report (in paper format) to those individuals/offices most affected by the outcome.
- Annual Forensic Investigation DVD. The agency may produce a forensic investigation DVD for distribution to a targeted group of individuals associated with the investigation or effected by the findings of an investigation.
- Forensic investigation database. Maintaining a forensic investigation database is beneficial for those agencies that either already have or will be pursuing an active forensic investigation program.
- Workshops, webinars, and conferences. Presentations by one or more members of an investigation team at agency in-house or national pavement-related workshops, webinars and conferences are also an effective method of disseminating results, especially if a change in current practice is being recommended. Periodic webinars are an appropriate and cost-effective means of disseminating forensic investigation findings to key individuals within agencies.

A.4 Forensic Investigation Project Management

Quality control and project management tools are important to the success of both the agency's overall forensic investigation program and project specific investigations. General forensic investigation project management procedures are not covered in this guide.

A.4.1 Quality Control

Quality control procedures within the agency specifically tailored to the forensic investigation program should address not only quality control throughout the forensic investigation process (e.g., equipment calibrations, personnel training), but also other issues such as:

- Clear definition of roles and responsibilities of involved individuals within the forensic investigation program and the individual investigations, including sign-off procedures and lines of communication.
- Paper and/or electronic project filing system/structure.
- Numbering and file naming conventions:
  - Investigation numbering (i.e., number assigned to each investigation).
  - Project pavement section numbering (i.e., number assigned to each pavement project being investigated).
  - Non-destructive testing file naming.
  - Core numbering and tracking system.
  - Test pit numbering and tracking system.
  - Sample numbering and tracking system.
- Feedback from the individual requesting the investigation to determine whether his/her concerns were adequately addressed.
- Feedback process that enables improvement in the conduct of forensic investigations within the agency, whether in terms of this guide (generic and project specific issues), management and execution of the investigations, etc.
- Periodic (annual or more frequent) internal and/or external audits to ensure compliance with the agency's quality control procedures. Although the forensic investigation coordinator will have overall responsibility for quality control of forensic investigations within the agency, a quality control officer should be appointed for each investigation.

A.4.2 Project Management Tools

Project management tools (preferably electronic) will enable the project team leader to track the utilization of resources (personnel, equipment and budget) as well as the progress of the investigation and its schedule. In addition, such tools facilitate resource and schedule changes to accommodate the actual progress and expenditures.

APPENDIX B

Case Studies

The following eight case studies are examples of forensic investigations conducted for different purposes. Case studies 4 through 8 were investigated during the trial implementation of this guide. These studies illustrate the use of the process described in this guide.

1. Exceptionally Good Performance of a Thin Asphalt Concrete Pavement Structure.
2. Longitudinal Crack on a Recently Rehabilitated Pavement.
3. Premature Failure on a Recently Rehabilitated Pavement.
4. Exceptionally Good Performance of a Mill and Asphalt Concrete Overlay.
5. Premature Rutting of an Asphalt Concrete Inlay.
6. Exceptionally Good Performance of PCC Overlay over Existing PCC Pavement.
7. Exceptionally Good Performance of New PCC Pavement.
8. Structural Failure on a Recently Completed Widening Project.

B.1 Case Study 1: Exceptionally Good Performance of a Thin Asphalt Concrete Pavement Structure

B.1.1 Background

A 30-year old section of asphalt concrete road carrying relatively heavy traffic was performing exceptionally better than other sections of the road. The road agency was interested in determining the factors contributing to this exceptional performance.

B.1.2 Preliminary Investigation

A preliminary investigation indicated that the original design for this section of the road had included an 8.0 in. (200 mm)-thick lean concrete base with a relatively thin (2.0 in. [50 mm]) asphalt concrete surfacing. The road exhibited severe block cracking within three years after construction. The section in question was ripped with a bulldozer to break down the cemented material and mix it with the cracked asphalt. This material was then sprayed with a dilute asphalt emulsion (1.0 percent residual bitumen) and recompacted. Excess material was removed to bring the surface level to the desired grade. A new 2.5 in. (60 mm) asphalt concrete layer was placed on the reworked base followed by a 0.5 in. (13 mm) rubber modified chip seal to slow the rate of oxidation of the asphalt. The road received no further overlay or surface treatments.

B.1.3 Investigation Plan

The investigation plan called for FWD testing to determine the structural integrity of the pavement, cores to determine layer thickness, and a test pit to assess the condition of the reworked concrete material.

B.1.4 Non-Destructive Testing

A visual assessment revealed no evidence of distress and rated the surface condition as very good (Figure B.1a). FWD measurements indicated a consistently strong structure that was not representative of an asphalt pavement with typical unstabilized aggregate base.

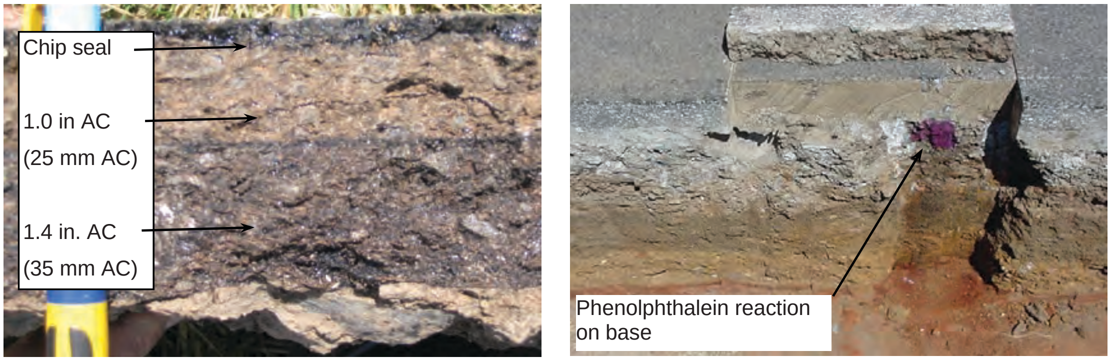
B.1.5 Destructive Testing

B.1.5.1 Coring

Core measurements indicated that the surfacing layer thickness was consistent with the design and as-built documentation. Unexpectedly, the base material was intact when the core was extracted and was strongly adhered to the bottom of the asphalt layer (Figure B.1b). A strong phenolphthalein reaction was observed, which was unexpected since no additional cement was added during reconstruction and there was no evidence of surface shrinkage/block cracking.

a) Surface condition (no distress)

b) Intact core



c) Surface layer evaluation

d) Phenolphthalein reaction

Figure B.1. Investigation photographs for Case Study 1.

B.1.5.2 Test Pit

The asphalt layer showed remarkably little oxidation and brittleness (Figure B.1c). The DCP did not penetrate the base layer, indicating a strongly cemented material. Excavation of the base layer revealed large lumps (4.0 in. [100 mm]) of the original base strongly bound to the rest of the material. A strong phenolphthalein reaction was observed over the entire depth of the reworked layer (Figure B.1d). A scanning electron microscope study showed new calcite crystal growth on freshly exposed surfaces indicating that re-cementation of the previously cemented material was still occurring.

B.1.6 Conclusion

The exceptionally good performance was attributed to a combination of:

- Re-cementation of the reworked material,
- The use of diluted asphalt emulsion as a compaction aid,
- The presence of large aggregate (i.e., previously cemented) base materials, and
- The application of a surface treatment (rubber modified chip seal), which slowed the rate of oxidation of the asphalt concrete.

B.2 Case Study 2: Longitudinal Crack on a Recently Rehabilitated Pavement

B.2.1 Background

A single straight longitudinal crack developed within one year after rehabilitation of a distressed asphalt concrete pavement using full-depth reclamation with foamed asphalt and portland cement (Figure B.2a). Apart from the crack, the road was performing well. The road agency, which had not built many full-depth reclamation projects with foamed asphalt/cement, was interested in determining the cause of the crack and whether this type of rehabilitation was appropriate for future projects.

B.2.2 Preliminary Investigation

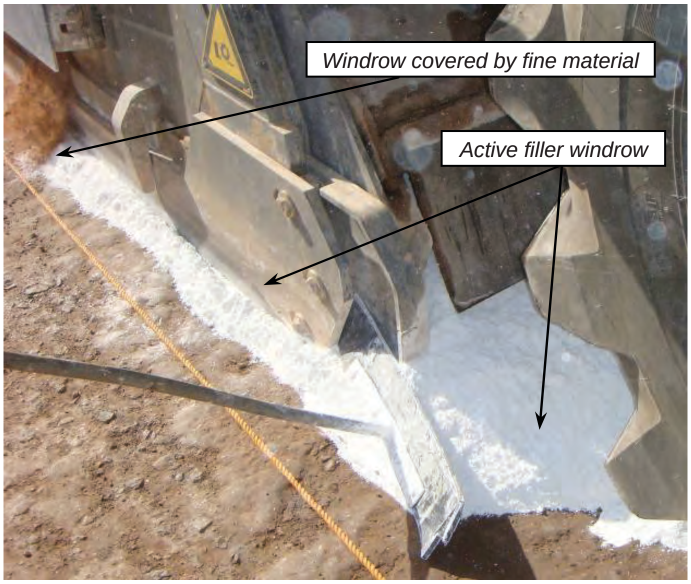
A preliminary investigation indicated no apparent reason for the crack. The portland cement content was 1.0 percent, which was unlikely to result in shrinkage cracks. Construction quality control was carried out according to the specifications.

B.2.3 Investigation Plan

An initial investigation plan called for a visual assessment and FWD testing on either side of the crack to identify any differences in structural integrity.

a) Longitudinal crack on surface

b) Vertical crack to mid point in reclaimed base



c) Active filler windrow on edge of reclaimer path

Figure B.2. Investigation photographs for Case Study 2.

B.2.4 Non-Destructive Testing

The visual assessment and FWD testing identified no apparent cause for the crack. However, the crack was aligned with the approximate edge of the first pass of the recycler. One member of the team, who had observed construction, recalled that recycler passes had sufficient overlap and that the compaction sequence was correctly followed. The investigation team then recommended a test pit to observe the underlying materials.

B.2.5 Destructive Testing

B.2.5.1 Test Pit

A test pit across the crack revealed that the crack initiated approximately at mid-depth in the reclaimed layer (Figure B.2b) suggesting no problems with the asphalt concrete. The crack was vertical suggesting some association with the recycler overlap. An expert opinion regarding the cause of the crack was sought and after discussion and observations of a nearby full-depth reclamation project, it was concluded that the crack was caused by shrinkage due to an excess of cement that accumulated under the skirt of the recycler (Figure B.2c), resulting in a narrow band of excessively stiff material.

B.2.6 Conclusion

The longitudinal crack was attributed to the inadequate spreading of excess cement on the edge of the recycler pass. Recommendations from the investigation included requiring the contractor to control cement spreading and to rake any excess cement windrows prior to overlap passes with the recycler.

B.3 Case Study 3: Premature Failure on a Recently Rehabilitated Pavement

B.3.1 Background

A recent full-depth reclamation project using asphalt emulsion showed signs of severe distress along certain sections of the road within 12 months of construction (Figure B.3a). The road agency, which had not undertaken many full-depth reclamation projects with emulsion, was interested in determining the cause of the cracking and appropriateness of this type of rehabilitation for future projects.

B.3.2 Preliminary Investigation

A preliminary investigation indicated that the mix design approach followed did not pay sufficient attention to testing under soaked conditions and that the active filler content may have been too low.

B.3.3 Investigation Plan

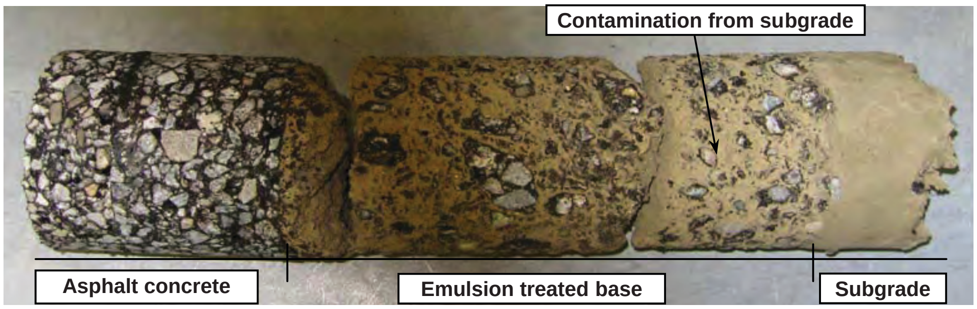
An initial investigation plan called for a visual assessment and FWD testing along the project to identify problems areas requiring additional investigation.

B.3.4 Non-Destructive Testing

The visual assessment identified blocked drains and roadside agricultural activities that may have influenced moisture in the pavement (Figure B.3b). FWD testing identified a series of weak areas that corresponded with the drainage problems and distressed areas. It also identified some areas which did not show distress, but observations from the road suggested

a) Distress 12 months after construction

b) Drainage issues



c) core

d) Test pit showing wet base material

Figure B.3. Investigation photographs for Case Study 3.

possible distress in the future. Locations for coring and test pits were identified to assess the condition of the recycled layer.

B.3.5 Destructive Testing

B.3.5.1 Coring

Dry cores at selected locations in the distressed areas indicated that the recycled base layer was very wet, with indications of pumping of subgrade fines into the layer (Figure B.3c). DCP tests through the core holes indicated lower than expected strengths in the recycled layer.

B.3.5.2 Test Pit

A test pit in the distressed area revealed a very wet base with evidence that the recycled layer had not cured (i.e., the emulsion did not fully break after construction) (Figure B.3d). The test pit also revealed variability in thickness across the width of the lane, although this was not considered a contributor to the distress.

B.3.6 Conclusion

Early distress was attributed to a combination of poor drainage and inappropriate mix design. Recommendations from the investigation included:

- Modifications of the mix design approach to incorporate soaked testing.
- Basing minimum strength values for pavement design on soaked test results only.
- Modifications to full-depth reclamation project investigation guidelines to give closer attention to roadside activities.
- Educating farmers on the consequences of their current plowing and irrigation activities.

B.4 Case Study 4: Exceptionally Good Performance of a Mill and Asphalt Concrete Overlay

B.4.1 Background

The pavement project investigated was located on I-81 in Frederick County, Virginia. The Virginia DOT (VDOT) was interested in determining the factors contributing to the exceptionally good performance.

B.4.2 Preliminary Investigation

A desktop study indicated that the original project design included 9.3 in. (235 mm) of asphalt concrete on 6.0 in. (150 mm) of crushed aggregate base and 12 in. (300 mm) of select material, over a highly plastic clay subgrade with bedrock near the surface. The pavement surface was milled and a thin asphalt concrete overlay placed in 1991. A micro-surfacing was applied in 2011. Since the 1991 rehabilitation, the International Roughness Index (IRI) of the pavement has remained consistently below 50 in./mile (80 cm/km). Similarly, the structural and overall condition indices have consistently remained high, indicating an excellent pavement in condition. The preliminary investigation also included a review of soils and geology, traffic, utilities, and climatic data.

It was initially hypothesized that the installation of prefabricated under-drains on each side of the project in 1991 was the major reason for the observed performance. However, as a result of the preliminary investigation, it was concluded that although the under-drains may have contributed to the good performance, the most important factor was the pavement over-design due to an over-estimation of the anticipated traffic.

B.4.3 Investigation Plan

The investigation plan consisted of a video camera inspection of the existing under-drains, GPR to confirm the pavement layer thicknesses, and FWD testing to confirm the high structural capacity of the pavement. A control section with a similar pavement structure and subjected to similar traffic and climatic conditions on Interstate 81 near the project was included in the investigation for comparison purposes.

B.4.4 Non-Destructive Testing

The video camera inspection results showed that under-drains were only present within a 2-mile section of the project (not the entire length as originally assumed) on the median side only, with no outlets or other sign of edge drainage on the shoulder side of the pavement.

Analysis of the GPR data revealed that the asphalt concrete on the travel lane was 2.0 in. (50 mm) thicker than on the passing lane. The results of the FWD test data confirmed the high structural capacity of this lane. Both GPR and FWD test results showed the travel lane to be uniform, with a relatively low coefficient of variation (COV)(Table B.1).

B.4.5 Destructive Testing

Because of the NDT findings, VDOT decided to proceed with the excavation of a test pit on the shoulder immediately adjacent to the travel lane (Figure B.4). The purpose of the test pit was to (1) confirm the GPR-derived layer thicknesses, especially the asphalt concrete layer, which was found to be 2.0 in (50 mm) thicker than the design and (2) establish the presence or absence of edge drains.

No drains of any kind were detected during the test pit excavation. The localized installation of under-drains only

Table B.1. FWD test results for travel lane on I-81.

Location		From MP	To MP	Average SN	COV
Right Wheelpath	Control Section	311.9	318.4	10.3	7.9%
	Test Section	318.4	324.9	10.5	5.8%
Center of Lane	Control Section	311.9	318.4	10.2	8.1%
	Test Section	318.4	324.9	10.1	11.7%

on the lower side of a super-elevated section (MP 319.4 to MP 321.0) appeared to validate the later hypothesis that the exceptionally good performance could not be solely attributed to the retrofitted drains. While these certainly improved performance in the areas that they were installed, the over-design due to conservative initial traffic estimates provided a perpetual pavement type structure.

B.4.6 Conclusion

The exceptionally good performance was attributed to a combination of:

- Over-design of pavement as a result of an over-estimation of traffic loadings.
- Thicker (2.0 in. [50 mm]) asphalt concrete layer than the design thickness on the travel lane. A separate VDOT study determined that trucks tend to stay in this lane.

B.5 Case Study 5: Premature Rutting of an Asphalt Concrete Inlay

B.5.1 Background

The purpose of this investigation was to determine the cause of premature rutting at three intersections along state route OR-62 in Oregon that were rehabilitated with hot-mix asphalt. Oregon DOT (OrDOT) considered it an urgent investigation because of an interest in making mix adjustments prior to the next paving season.

(Photo courtesy of Virginia Department of Transportation)

Figure B.4. Case Study 4 test pit photograph.

B.5.2 Preliminary Investigation

The paving project was completed in the summer of 2009 using an asphalt concrete (PG70-22ER binder) inlay. Within three days of paving, rutting occurred at three different intersections. The project was shut down and the decision made to remove and replace the affected areas with HMA with a stiffer binder (PG76-22). The areas in question were repaved with the new mix, but started rutting again, albeit at a slower rate. It was initially hypothesized that the premature rutting was due to the use of a softer binder; however, the binder change did not eliminate the rutting. It was then hypothesized that rutting was caused by a combination of material properties and construction practices.

Mix design, quality control, and inspector's data were reviewed to identify suspect mix properties. Laboratory testing results were also reviewed for both the mix and the binder. Mix properties reviewed included asphalt content, laboratory air voids, maximum and bulk specific gravity of the mix, voids in the mineral aggregate (VMA), voids filled with asphalt (VFA), gradation and field compaction. The data review effort did not provide a definitive explanation to the rutting problem, but several potential indicators were identified: low air voids, high field compaction, high asphalt content, high VFA, and aggregate gradation not meeting specifications. Observations of the roller pattern and equipment also suggested a possibly unstable mix.

B.5.3 Investigation Plan

The preliminary investigation focused on QC/QA data from the original mix with PG70-22ER along with construction information. The data showed potential but inconclusive issues with the mix volumetric parameters and compaction effort. Accordingly, the OrDOT decided to: (1) conduct laboratory tests on backup samples from the PG70-22ER mix, (2) take cores at the three intersections (within and outside of rutted areas) to test for mix volumetric parameters, and (3) review the QC/QA data for the PG76-22 mix. Aggregate gradation, air voids, and asphalt content were the primary mix properties to be investigated. Non-destructive testing was not considered in formulating the plan, as mix properties and construction practices were believed to be the cause of the rutting.

B.5.4 Destructive and Laboratory Testing

Results from the laboratory tests performed on eight backup samples from the PG70-22ER mix showed that key mix properties (asphalt content, air voids, VFA and VMA) were skewed towards a rut susceptible mix. Two cores were taken at each of the three intersections in question; one in the rutted area and another one outside. Results from the laboratory tests performed on the six cores also showed signs of rut susceptibility because of the high asphalt content, low air-void content, and VFA and aggregate gradation (one or more sieves) not meeting specifications. Review of the QC/QA data (from 14 samples and two verification samples) for the PG76-22 mix revealed that VFA for 11 of the 16 samples exceeded specification limits, while the other mix properties were within specifications, which suggested VFA was the primary cause of rutting for this mix, although at a slower rate when compared to the PG70-22ER mix.

B.5.5 Conclusion

Premature rutting of the initial mix was caused by a combination of factors. The primary contributing factor was the high VFA of the mix. Initial QC testing did not show the extent of the problem, but QA and backup samples tested after rutting was observed confirmed the VFA issue. High asphalt content and low air voids were also contributing factors. Use of a stiffer binder did not eliminate the rutting, and the cause was attributed to the high VFA. The asphalt content of the mix was also high on many of the QA and backup samples. This information was not available during construction to allow making appropriate adjustments. An early sign of the mix problems was apparent when compaction was achieved too easily and the roller order was changed to keep lighter machines on the mat during compaction. Both materials and construction practices were found to be responsible for the premature rutting. This finding suggested the need to adopt a more effective QC/QA system to identify material and construction problems.

B.6 Case Study 6: Exceptionally Good Performance of PCC Overlay over Existing PCC Pavement

B.6.1 Background

A 9.2 mile (14.7 km) portion of I-90 in Freeborn and Mower Counties, Minnesota has been performing exceptionally well since the concrete pavement was overlaid with jointed unbonded concrete in 1998 (Figure B.5). The Minnesota DOT (MnDOT) was interested in determining the factors contributing to this exceptional performance.

(Photo courtesy of Minnesota Department of Transportation)

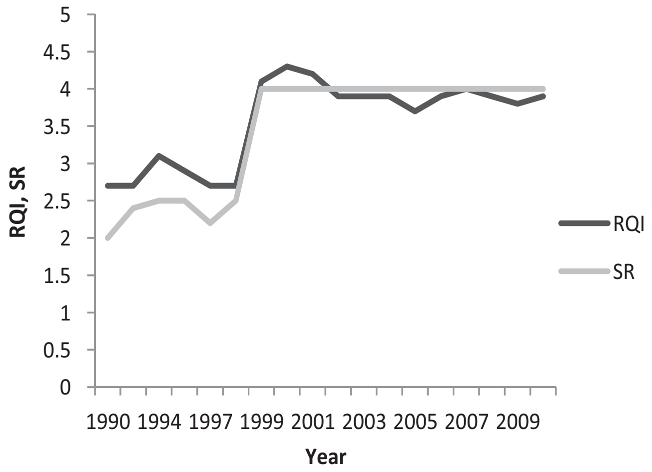
Figure B.5. I-90 pavement project.

B.6.2 Preliminary Investigation

A preliminary investigation indicated that the original project design included 9.0 in. (225 mm) of jointed reinforced concrete pavement (JRCP) on 2.25 in. (55 mm) of gravel base and 3.0 in. (75 mm) of sand and gravel subbase. The 1998 overlay consisted of 8.5 in. (215 mm) of non-reinforced jointed plain concrete over a 1.0 in. to 3.0 in. (25 mm to 75 mm) permeable asphalt stabilized stress relief course (PASSRC). The existing concrete pavement, which exhibited poor ride quality, joint faulting, joint spalling, faulting, and cracked panels, was repaired prior to overlay placement. In addition, interceptor drains were constructed at contraction joints or mid-panel cracks to enhance the drainage of the new concrete overlay.

Other information gathered as part of the preliminary investigation included performance and traffic data. Figure B.6, for example, illustrates the change in the ride quality index (RQI) and surface rating (SR) of the project since 1990. A field visit confirmed the excellent condition of the pavement, which exhibited little to no cracking, no faulting, very limited spalling, and only a few corner breaks over the entire project length. The adjacent ditches were relatively steep and provided good drainage. The ride quality was excellent, and the transverse joints could hardly be felt inside a passenger vehicle traveling at 70 mph (110 km/h).

On completion of the preliminary investigation, MnDOT concluded that sufficient information was available to explain the observed performance of the pavement. However, MnDOT recognized that additional information would help to confirm the findings, provide a more thorough comparison of the



(Plot courtesy of Minnesota Department of Transportation)

Figure B.6. Change in ride quality between 1990 and 2009 for Case Study 6 (WB I-90 from R.P. 174 to R.P. 175).

as-designed versus as-constructed conditions, and recommended conducting a comparison of the project with another concrete overlay project to further confirm the findings.

B.6.3 Conclusion

Based on the findings of a preliminary investigation only, the exceptional pavement performance was attributed to the following factors:

- Repairing the existing concrete prior to placement of the overlay.
- Implementing drainage condition improvements as part of the overlay rehabilitation.
- Relatively light traffic loading on the pavement.
- Structural capacity provided by the combination of existing concrete and concrete overlay over quality subbase materials.

B.7 Case Study 7: Exceptionally Good Performance of New PCC Pavement

B.7.1 Background

Construction of the Ohio/SHRP test road on US 23 in Delaware County was completed in August, 1996 (Figure B.7). The northbound direction was made up of several new jointed plain PCC sections that utilized various pavement designs. The Ohio DOT (OhDOT) was interested in determining the factors that contributed to the exceptionally good performance of some of the sections (Figure B.8).

(Photo courtesy of Ohio Department of Transportation)

Figure B.7. Ohio/SHRP test road on US 23.

B.7.2 Preliminary Investigation

The preliminary investigation compared available data relevant to performance of the PCC sections after subjectively sorting the sections by how they performed. The sections were grouped by age at time of reconstruction, cracking level, and design life comparisons. The majority of the sections with exceptionally good performance were on the north end of the project. The design strength of the mix, the locations of the sections within the project, and the placement temperatures were all obvious contributing factors to the observed performance. The pavement was placed from south to north, with a higher strength mix used at the southern end. These mixes had higher cement contents and thus higher placement temperatures. It was hypothesized that these factors, together with the placement when ambient air temperatures were high, resulted in slabs that had more built-in curl, leading to mid-panel cracking.

B.7.3 Investigation Plan

The investigated pavements are part of the LTPP program, which has a database that contains extensive information on performance, including distress, roughness, and FWD surveys, as well as pavement structure, materials tests, maintenance and rehabilitation, traffic, and climatic data. This information provided the basis for the preliminary investigation and associated findings; collecting additional data and information to support the investigation was not considered necessary.

B.7.4 Non-Destructive Testing

The only non-destructive testing activity that was not available from the LTPP database and could support the

a) Good performance on slab

b) Mid-slab crack

Figure B.8. Investigation photographs for Case Study 7.

investigation was FWD testing prior to the development of mid-panel cracking to check for voids at the joints. However, such testing was no longer possible. Edge drain inspections were also considered but not undertaken.

B.7.5 Destructive Testing

No additional destructive or laboratory testing data beyond that contained in the LTPP database was considered necessary to support the investigation.

B.7.6 Conclusion

The exceptionally good pavement performance at the north end of the experiment was attributed to less built-in curl due to a combination of:

- Concrete mixes with lower cement contents.
- Lower concrete placement temperatures.
- Lower ambient air temperatures at the time of construction.

B.8 Case Study 8: Structural Failure on a Recently Completed Widening Project

B.8.1 Background

A recently completed project in California exhibited alligator cracking and potholes in the outer wheel path and shoulder. Migration of fines from the base was also obvious in the cracks. In one location, surface rutting up to 0.75 in. (19 mm) was measured. An area with severe potholing was patched with cold mix.

B.8.2 Preliminary Investigation

A preliminary investigation documented the project as a 5.0-ft (1.5-m) widening in the eastbound and westbound lanes. This included constructing 11 in. (275 mm) of asphalt concrete over 24 in. (600 mm) of aggregate base and adding a 6.0-ft (1.8-m) wide shoulder with the same thickness of HMA, but over only 5 in. (125 mm) of aggregate base. The existing pavement was milled to a depth of 3 in. (75 mm) and filled with 3 in. (75 mm) of new asphalt concrete. The design plan required that the pavement widening start at 11 ft (3.35 m) from the center line including a 2.0-ft (0.6-m) median buffer.

Discussion with the district construction staff revealed that the widened section may have been shifted a few feet away from the center line because of a safety concern (narrow roadway) during the first stage of construction in the eastbound direction. As a result of this deviation from the design, 1.0 to 3.0 ft (0.3 m to 0.9 m) of the existing pavement and shoulder was not replaced with the new structural section. It was also mentioned that in some locations the base material along the vertical plane of the existing pavement became loose after the excavation. With the addition of the 2.0-ft (600 mm) median buffer and re-stripe of the travel lane, the remaining pavement with only about 0.6-ft (180 mm) of existing asphalt concrete, became the outer wheel path where the distresses were observed.

An initial field visit supported the earlier discussion and suggested that the problem appeared to be primarily related to a lack of structural adequacy, particularly in the outer wheel path, and/or possible base failure as evidenced by the existence of fines in the cracks. This preliminary finding was based on the exhibited distresses and examination of core samples obtained during the initial field visit (Figure B.9).

Alligator cracking

Rutting in the problem area

View of distressed area

Patched pothole

6; 0.91

4; 0.51

2; 0.59

0; 0.65

Distance from pavement edge (white strip line) and HMA thickness, in ft

(Photos courtesy of California Department of Transportation)

Figure B.9. Initial investigation photographs for Case Study 8.

(Photos courtesy of California Department of Transportation)

Figure B.10. Core photographs for Case Study 8.

B.8.3 Investigation Plan

An investigation plan was developed based on the initial field visit. The plan called for deflection testing using a Falling Weight Deflectometer (FWD) and additional coring to verify the preliminary findings.

B.8.4 Non-Destructive Testing

The FWD testing was performed on the inner wheelpaths, between the wheel paths, outer wheelpaths, and shoulder (the newly widened section).

B.8.5 Destructive Testing

Additional cores were obtained near the pavement stripe on a longitudinal crack. Inspection of the cores revealed that the crack reflected through the full thickness of asphalt concrete. The crack interface in the bottom portion of the cores showed a clear separation of the existing pavement from the newly widened section, indicating a loss of structural integrity at this location. It also confirmed the earlier suggested shifting of the widened section of up to 3.0 ft (0.9 m) away from that shown on the contract plans. Figure B.10 shows the separation of the existing asphalt concrete material from the widened section along the vertical face of the longitudinal crack.

B.8.6 Conclusion

Based on the pavement failure modes, core results, and deflection measurements, it was concluded that a weakened base due to the excavation of the widened section, and structural deficiency due to inadequate asphalt concrete and aggregate base thickness, in the outer wheel path of the eastbound lane, were the primary causes of the pavement failure.

APPENDIX C

Example Forms

This Appendix contains examples of 24 forms that may be useful in documenting the various stages of forensic investigations. Use of the forms and the level of detail captured will depend on the specific investigation, the level of detail required, and the level of information needed for implementing the findings. These forms can be modified to suit specific agency requirements (Microsoft Word® fillable forms and instructions on how to modify them are included in the attached CD at the end of the report).

The forms and the section in the guide in which they are referred to are:

Form #1: Forensic Investigation Request (Section 3.1)
Form #2: Preliminary Investigation (Sections 3.5.1 and 3.5.2)
Form #3: Decision to Proceed (Section 3.5.3)
Form #4: Preliminary Investigation Report (Section 3.6)
Form #5: Forensic Investigation Team (Section 4.1)
Form #6: Pre-Investigation Site Visit (Section 4.2)
Form #7: Photograph Record (Section 4.2)
Form #8: Visual Assessment Form (Asphalt/Surface Treatment) (Section 4.2.1)
Form #9: Visual Assessment Form (Portland Cement Concrete) (Section 4.2.1)
Form #10: Initial Non-Destructive Testing Plan (Section 4.2.4.4)
Form #11: Initial Forensic Investigation Plan (Section 4.4)
Form #12: Interim Report Cover Sheet (Section 5.3)
Form #13: Final Non-Destructive Testing Plan (Section 6.1)
Form #14: Destructive Testing Plan (Section 6.1)
Form #15: Final Forensic Investigation Plan (Section 6.1)
Form #16: Forensic Investigation Site Report (Section 7.2.1)
Form #17a: Core Log (Single Core) (Section 7.3.1.2)
Form #17b: Core Log (Multi Core) (Section 7.3.1.2)
Form #18: Test Pit Profile (Sections 7.3.2.2 and 7.3.2.3)
Form #19a: Asphalt Concrete/Asphalt Surface Treatment Layer Log (Section 7.3.2.2)
Form #19b: Portland Cement Concrete Layer Log (Section 7.3.2.2)
Form #20: Gravel and Stabilized Layer Log (Section 7.3.2.2)
Form #21: Sample Log (Section 7.3.2.4)
Form #22: Density and Moisture Content (Section 7.3.2.4)
Form #23: Dynamic Cone Penetrometer (Section 7.3.2.6)
Form #24: Final Report Cover Sheet (Section 8.2)

Examples of selected forms are provided for Case #2 in Appendix B.

PAVEMENT FORENSIC INVESTIGATION	**FORENSIC INVESTIGATION REQUEST**					**Form #1**
Requester name					**Date**	
Phone number			**Email**			
Investigation location						
Post-mile			**GPS Coordinates**			
Reasons for Investigation **(Check all that apply)**		Determine reason for premature pavement failure				
		Determine reason for poor pavement performance				
		Understand exceptional pavement performance/ longevity				
		Collect specific data for rehabilitation design				
		Validate pavement performance (actual vs. predicted)				
		Closeout investigation of experimental test sections				
		Collect data to support development/calibration of models				
		Collect data to understand/quantify effects of traffic and environment				
		Collect data to implement improved design and/or construction practices				
		Collect data in support of pavement-related legal matters				
		Certify warranties				
		Evaluate new products or techniques				
		Other (specify)				
Description of Issues Requiring Investigation						
Description of Work Already Undertaken to Understand Issues						
Urgency / Due Date	High		Medium		Low	
Justification for Urgency / Due Date						
Project Information						
Investigation Number			**Investigation Name**			
Investigation Valid?	Yes	No	**Proceed with Investigation**		Yes	No
Investigation Coordinator					**Date**	

PAVEMENT FORENSIC INVESTIGATION	**FORENSIC INVESTIGATION REQUEST**	**Form #1**

Requester name		**Date**	
Phone number		**Email**	
Investigation location	COUNTY ROAD NAME		
Post-mile	PM 21.0 TO 30	**GPS Coordinates**	N/A

Reasons for Investigation **(Check all that apply)**	X	Determine reason for premature pavement failure	
		Determine reason for poor pavement performance	
		Understand exceptional pavement performance/ longevity	
		Collect specific data for rehabilitation design	
		Validate pavement performance (actual vs. predicted)	
		Closeout investigation of experimental test sections	
		Collect data to support development/calibration of models	
		Collect data to understand/quantify effects of traffic and environment	
		Collect data to implement improved design and/or construction practices	
		Collect data in support of pavement-related legal matters	
		Certify warranties	
		Evaluate new products or techniques	
	X	Other (specify)	DETERMINE CAUSE OF LONGITUDINAL CRACK

Description of Issues Requiring Investigation	CONSISTENT LONGITUDINAL CRACK RUNS ALONG NORTH BOUND LANE. DOES NOT APPEAR TO BE LINKED TO ASPHALT PAVING JOINT POSSIBLY COMPACTION JOINT? SEE ATTACHED PHOTO
Description of Work Already Undertaken to Understand Issues	CHECKED CONSTRUCTION RECORDS. SPOKE TO RE AND STAFF ON-SITE OR ASSOCIATED WITH PROJECT. NO VALID CONCLUSIONS DRAWN

Urgency / Due Date	High		Medium	X	Low	

Justification for Urgency / Due Date	NEED TO UNDERSTAND PROBLEM BEFORE FURTHER FDR-FA PROJECTS ARE CONSIDERED
Project Information	REHABILITATION WITH FDR-FA (12") WITH 4" HMA IN TWO LIFTS WELL KNOWN CONTRACTORS. NO MAJOR ISSUES/CLIMATE/TRAFFIC FROM NORMAL

Investigation Number	2011/06		**Investigation Name**		
Investigation Valid?	[✓ Yes]	No	**Proceed with Investigation**	[✓ Yes]	No
Investigation Coordinator			**Date**		

PAVEMENT FORENSIC INVESTIGATION	**PRELIMINARY INVESTIGATION**		**Form #2**
Investigation Name		**Investigation #**	
Requested by			

Questions to be answered	

Category	Premature failure		Poor performance		Exceptional performance	
	Warranty		Research		Other	

Objectives of investigation	**1.**
	2.
	3.
	4.
	5.

Objectives are:	Specific		Measurable		Achievable		Realistic		Time-based	

Tasks required to meet objectives	**1.**
	2.
	3.
	4.
	5.

Preliminary Investigation Checklist

Interviews	Requestor		Maint. Super	
	DME		Contractor	
	Lab Super			
Documents	Design		As-built	
	Contractual		Warranty	
	Daily records			
Records	PMS		Maintenance	
	Traffic		Climate	
Testing Completed	Non-destr.		Destructive	
	Lab			

	Notes

Investigation Coordinator		**Date**	

PAVEMENT FORENSIC INVESTIGATION	**PRELIMINARY INVESTIGATION**	**Form #2**

Investigation Name		**Investigation #**	2011/06
Requested by			

Questions to be answered	WHAT CAUSED LONGITUDINAL CRACK ON ROAD XXX

Category	Premature failure	X	Poor performance		Exceptional performance	
	Warranty		Research		Other	

Objectives of investigation	**1.** DETERMINE CAUSE OF CRACK
	2. MAKE RECOMMENDATIONS TO PREVENT RECURRENCE
	3. ALTER SPECS IF NECESSARY
	4.
	5.

Objectives are:	Specific	X	Measurable	X	Achievable	X	Realistic	X	Time-based	X

Tasks required to meet objectives	**1.** PRELIMINARY INVESTIGATION
	2. POSSIBLE GPR, FWD, CORES
	3. TEST PIT IF NO CONCLUSIONS DRAWN FROM EARLIER PHASES
	4.
	5.

Preliminary Investigation Checklist

Interviews	Requestor	YES	Maint. Super	YES
	DME	YES	Contractor	YES
	Lab Super	YES (CEMENT CONTENT)		
Documents	Design	YES	As-built	YES
	Contractual	NO	Warranty	NO
	Daily records	YES		
Records	PMS	NO	Maintenance	NO
	Traffic	YES	Climate	NO
Testing Completed	Non-destr.	YES	Destructive	YES
	Lab	NO		

	Notes
1	CHECK RECORDS FOR ANY NOTES ON CEMENT SPREADING/MIXING, ROLLING PATTERN, ROLLER TYPE.
2	CHECK WITH MAINT. SUPERVISOR IF SIMILAR PROBLEMS BEFORE REHAB
3	TEST PIT ONLY AS LAST RESORT

Investigation Coordinator		**Date**	

PAVEMENT FORENSIC INVESTIGATION	**DECISION TO PROCEED**		**Form #3**
Investigation Name		**Investigation #**	
Requested by			
Requestor details			
Question to be answered			

Category	Premature failure		Poor performance		Exceptional performance		
	Warranty		Research		Other		

Findings of Preliminary Investigation	

Question Satisfactorily Answered in Preliminary Investigation?	Yes		No	

Justification to Continue with Forensic Investigation	

Proceed with Forensic Investigation?	Yes		No	

Investigation Approved By:		Date	

	Notes

Investigation Coordinator		**Date**	

PAVEMENT FORENSIC INVESTIGATION	**DECISION TO PROCEED**	**Form #3**

Investigation Name		**Investigation #**	2011/06
Requested by			
Requestor details			

Question to be answered	WHAT CAUSED LONGITUDINAL CRACK ON ROAD XXX

Category	Premature failure	X	Poor performance		Exceptional performance	
	Warranty		Research		Other	

Findings of Preliminary Investigation	NO REASON FOR CRACK FOUND. UNLIKELY TO BE SHRINKAGE CRACKING RELATED TO CEMENT BECAUSE OF NATURE OF CRACK. POSSIBLE REASONS REQUIRING FURTHER INVESTIGATION INSUFFICIENT OVERLAP ON RECYCLE PASS INSUFFICIENT OVERLAP ON ROLLER PASS – NOTE THAT CRACK IS APPROXIMATE WIDTH OF ROLLER FROM EDGE OR ROAD ISOLATED CEMENT STABILIZATION ISSUE RELATED TO EDGE OF RECYCLER PATH – NOTE THAT CRACK IS IN APPROXIMATE POSITION OF OVERLAP

Question Satisfactorily Answered in Preliminary Investigation?	Yes		No	X

Justification to Continue with Forensic Investigation	POSSIBLE ISSUE ASSOCIATED WITH FDR-FA PROCESS THAT NEEDS TO BE UNDERSTOOD BEFORE FURTHER FDR-FA PROJECTS ARE COMPLETED

Proceed with Forensic Investigation?	Yes	X	No	

Investigation Approved By:		Date	

Notes

Investigation Coordinator		**Date**	

PAVEMENT FORENSIC INVESTIGATION	PRELIMINARY INVESTIGATION REPORT	Form #4

Investigation Name		**Investigation #**	
Requested by			
Requestor details			
Questions to be answered			

Category	Premature failure		Poor performance		Exceptional performance	
	Warranty		Research		Other	

Attached Documents

Forensic Investigation Request	Yes		No	
Preliminary Investigation	Yes		No	
Decision to Proceed	Yes		No	

Notes

Investigation Coordinator	
Date	

PAVEMENT FORENSIC INVESTIGATION	**PRELIMINARY INVESTIGATION REPORT**		**Form #4**
Investigation Name		**Investigation #**	2011/06
Requested by			
Requestor details			
Questions to be answered	WHAT CAUSED LONGITUDINAL CRACK ON ROAD XXX		

Category	Premature failure	X	Poor performance		Exceptional performance		
	Warranty		Research		Other		

Attached Documents

Forensic Investigation Request	Yes	X	No	
Preliminary Investigation	Yes	X	No	
Decision to Proceed	Yes	X	No	

Notes

SEE NOTES ON FORMS

Investigation Coordinator		**Date**	

PAVEMENT FORENSIC INVESTIGATION	**FORENSIC INVESTIGATION TEAM**			**Form #5**
Investigation Name			**Investigation #**	
Investigation Coordinator	Name			
	Role			
	Phone		Email	
Investigation Requestor	Name			
	Role			
	Phone		Email	
Area Maintenance Superintendent	Name			
	Role			
	Phone		Email	
	Name			
	Role			
	Phone		Email	
	Name			
	Role			
	Phone		Email	
	Name			
	Role			
	Phone		Email	
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	Role			
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	Role			
	Phone		Email	
	Name			
	Role			
	Phone		Email	
	Name			
	Role			
	Phone		Email	
	Name			
	Role			
	Phone		Email	
Investigation Coordinator			**Date**	

PAVEMENT FORENSIC INVESTIGATION	**FORENSIC INVESTIGATION TEAM**			**Form #5**
Investigation Name			**Investigation #**	2011/06
Investigation Coordinator	Name			
	Role	MANAGE/DO FORENSIC INVESTIGATION		
	Phone		Email	
Investigation Requestor	Name			
	Role	ASSIST WITH INVESTIGATION/SOURCE LOCAL DOCUMENTS		
	Phone		Email	
Area Maintenance Superintendent	Name			
	Role	DETAILS ON ROAD BEFORE REHAB. ORGANIZE CLOSURE		
	Phone		Email	
DISTRICT MATERIALS ENGINEER	Name			
	Role	ASSIST WITH INVESTIGATION. KNOWLEDGE FROM OTHER PROJECTS		
	Phone		Email	
UNIVERSITY RESEARCH CENTER	Name			
	Role	ASSISTANCE WITH FDR-FA EXPERTISE (EARLIER RESEARCH)		
	Phone		Email	
	Name			
	Role			
	Phone		Email	
	Name			
	Role			
	Phone		Email	
	Name			
	Role			
	Phone		Email	
	Name			
	Role			
	Phone		Email	
	Name			
	Role			
	Phone		Email	
	Name			
	Role			
	Phone		Email	
Investigation Coordinator			**Date**	

PAVEMENT FORENSIC INVESTIGATION	**PRE-INVESTIGATION SITE VISIT**	**Form #6**

Investigation Name		**Investigation #**	

Visual Assessment

Description of Distress Associated with Issues being Investigated	
Description of Other Distresses and Observations	

Checklist	**Structural**		**Surface**		**Material**		**Construction**	
	Traffic		**Environment**		**Ride/Safety**		**Other**	

Initial Investigation Limits

Investigation Start Point		Investigation End Point	
Focus #1 Start Point		Focus #1 End Point	
Focus #2 Start Point		Focus #2 End Point	
Focus #3 Start Point		Focus #3 End Point	
Control Start Point		Control End Point	

Refine points with NDT?	Yes		No		Type of NDT	
NDT Test Plan	Yes		No			

Safety Assessment

Description of Safety Issues and Actions	

Investigation Coordinator		**Date**	

PAVEMENT FORENSIC INVESTIGATION	**PRE-INVESTIGATION SITE VISIT**	**Form #6**

Investigation Name		**Investigation #**	2011/06

Visual Assessment

Description of Distress Associated with Issues being Investigated	LONGITUDINAL CRACK APPROX 8.5 FT FROM EDGE OF ASPHALT VERY STRAIGHT/CONSISTENT, CRACK IS NOT IN WHEELPATH APPEARED APPROX 12 MONTHS AFTER CONSTRUCTION APPROX 1/8 IN. WIDE. DOES NOT APPEAR TO BE GETTING WORSE NO EVIDENCE OF PUMPING CONSTRUCTION QUALITY APPEARS TO BE VERY GOOD
Description of Other Distresses and Observations	NO OTHER DISTRESS OBSERVED

Checklist	**Structural**	X	**Surface**	X	**Material**	X	**Construction**		X
	Traffic	X	**Environment**	X	**Ride/Safety**	X	**Other**		X

Initial Investigation Limits

Investigation Start Point	FULL PROJECT		Investigation End Point		FULL PROJECT
Focus #1 Start Point	LENGTH OF CRACK		Focus #1 End Point		
Focus #2 Start Point			Focus #2 End Point		
Focus #3 Start Point			Focus #3 End Point		
Control Start Point	NO CONTROL		Control End Point		
Refine points with NDT?	Yes		No		Type of NDT: FWD
NDT Test Plan	Yes	X	No		

Safety Assessment

Description of Safety Issues and Actions	TWO PASSES OF FWD, 30 FT INTERVALS, ONE CLOSE TO CRACK, OTHER ON OTHER SIDE OF LANE WHERE NO CRACK IS PRESENT. AVOID LIKELY OVERLAP AREAS IN CONTROL SECTION ROLLING CLOSURE

Investigation Coordinator		**Date**	

PAVEMENT FORENSIC INVESTIGATION

PHOTOGRAPH RECORD

Form #7

Investigation Name

Investigation #

Investigation Phase

Photo #	Description	Photo #	Description

Storage location

Investigation Coordinator

Date

PAVEMENT FORENSIC INVESTIGATION	**PHOTOGRAPH RECORD**		**Form #7**
Investigation Name		**Investigation #**	2011/06
Investigation Phase			

Photo #	Description	Photo #	Description
1	GENERAL VIEW OF CRACK		
2	CLOSE-UP VIEW OF CRACK		
3	CLOSE-UP VIEW OF CRACK		
4	GENERAL VIEW OF LANE		
5	CORE 1		
6	CORE 2		
7	TEST PIT FACE		
8	TEST PIT FACE		
9	TEST PIT FACE		

Storage location	INVESTIGATION COORDINATOR COMPUTER		
Investigation Coordinator		**Date**	

PAVEMENT FORENSIC INVESTIGATION	**VISUAL ASSESSMENT - AC**	**Form #8**	
Investigation Name		**Investigation #**	

Surfacing assessment							**Sketch**
Surfacing type							
Texture	Varying	Fine	F - M	Medium	M - C	Course	
Voids	Varying	None	N - F	Few	F - M	Many	

	Degree						Extent					Length	Width	Number	Location
	Slight				Severe		<5				>80				
Mechanical distress	0	1	2	3	4	5	1	2	3	4	5				
Other distress	0	1	2	3	4	5	1	2	3	4	5				
Bleeding/flushing	0	1	2	3	4	5	1	2	3	4	5	Narrow	Wide	Position	
Surface cracks	0	1	2	3	4	5	1	2	3	4	5				
Binder condition	0	1	2	3	4	5	1	2	3	4	5	Active	Stable	Position	
Aggregate loss	0	1	2	3	4	5	1	2	3	4	5				

Structural assessment

	Degree						Extent					Narrow (% area)	Wide (% area)	Position	Location
	Slight				Severe		<5				>80				
Cracks - block	0	1	2	3	4	5	1	2	3	4	5				
Cracks - longitudinal	0	1	2	3	4	5	1	2	3	4	5				
Cracks - transverse	0	1	2	3	4	5	1	2	3	4	5				
Cracks - fatigue	0	1	2	3	4	5	1	2	3	4	5				
Pumping	0	1	2	3	4	5	1	2	3	4	5				
Rutting	0	1	2	3	4	5	1	2	3	4	5				
Undulation/settlement	0	1	2	3	4	5	1	2	3	4	5				
Edge cracking/break	0	1	2	3	4	5	1	2	3	4	5	Number	Diameter		
Potholes	0	1	2	3	4	5	1	2	3	4	5				
Delamination	0	1	2	3	4	5	1	2	3	4	5				
												Small	Medium	Large	Location
Patching/digouts	0	1	2	3	4	5	1	2	3	4	5				

Functional assessment

	Degree					Influencing factors									
	Good				Poor										
Riding quality	1	2	3	4	5	Potholes		Patching		Undulation		Corrugation		Fatigue	
Skid resistance	1	2	3	4	5	Bleeding		Polishing							
Surface drainage	1	2	3	4	5										
Side drainage	✓	✗													

Notes	**Photos**

PAVEMENT FORENSIC INVESTIGATION	**VISUAL ASSESSMENT - AC**	**Form #8**

Investigation Name		**Investigation #**	2011/06

Surfacing assessment

Sketch

Surfacing type	¾HMA					
Texture	Varying	Fine	F - M	[✓ Medium]	M - C	Course
Voids	Varying	None	[✓ N - F]	Few	F - M	Many

	Degree						Extent					Length	Width	Number	Location
	Slight					Severe	<5				>80				
Mechanical distress	[✓ 0]	1	2	3	4	5	1	2	3	4	5				
Other distress	[✓ 0]	1	2	3	4	5	1	2	3	4	5				
Bleeding/flushing	[✓ 0]	1	2	3	4	5	1	2	3	4	5	Narrow	Wide	Position	
Surface cracks	[✓ 0]	1	2	3	4	5	1	2	3	4	5				
Binder condition	[✓ 0]	1	2	3	4	5	1	2	3	4	5	Active	Stable	Position	
Aggregate loss	[✓ 0]	1	2	3	4	5	1	2	3	4	5				

Structural assessment

	Degree						Extent					Narrow (% area)	Wide (% area)	Position	Location
	Slight					Severe	<5				>80				
Cracks - block	[✓ 0]	1	2	3	4	5	1	2	3	4	5				
Cracks - longitudinal	[✓ 0]	1	2	3	4	5	1	2	3	4	5				
Cracks - transverse	0	1	2	[✓ 3]	4	5	[✓ 1]	2	3	4	5			8.5FT IN	NB LANE
Cracks - fatigue	[✓ 0]	1	2	3	4	5	1	2	3	4	5				
Pumping	[✓ 0]	1	2	3	4	5	1	2	3	4	5				
Rutting	[✓ 0]	1	2	3	4	5	1	2	3	4	5				
Undulation/settlement	[✓ 0]	1	2	3	4	5	1	2	3	4	5				
Edge cracking/break	[✓ 0]	1	2	3	4	5	1	2	3	4	5	Number	Diameter		
Potholes	[✓ 0]	1	2	3	4	5	1	2	3	4	5				
Delamination	[✓ 0]	1	2	3	4	5	1	2	3	4	5				
												Small	Medium	Large	Location
Patching/digouts	[✓ 0]	1	2	3	4	5	1	2	3	4	5				

Functional assessment

	Degree					Influencing factors									
	Good				Poor										
Riding quality	[✓ 1]	2	3	4	5	Potholes		Patching		Undulation		Corrugation		Fatigue	
Skid resistance	[✓ 1]	2	3	4	5	Bleeding		Polishing							
Surface drainage	[✓ 1]	2	3	4	5										
Side drainage	[✓ ✓]	×													

Notes	**Photos**
ROAD IS IN EXCELLENT CONDITION APART FROM SINGLE CRACK	SEE PHOTO RECORD

PAVEMENT FORENSIC INVESTIGATION	**VISUAL ASSESSMENT - PCC**	**Form #9**	
Investigation Name		**Investigation #**	

Surfacing assessment

Pavement type	JPCP	JPCP + dowel	CRCP	JRCP		
Surface finish						
Texture	Varying	Fine	F - M	Medium	M - C	Course
Voids	Varying	None	N - F	Few	F - M	Many

Sketch

	Degree						Extent					Length	Width	Number	Location
	Slight				Severe		<5				>80				
Mechanical distress	0	1	2	3	4	5	1	2	3	4	5				
Other distress	0	1	2	3	4	5	1	2	3	4	5	Narrow	Wide	Position	
Surface cracks	0	1	2	3	4	5	1	2	3	4	5				
Aggregate loss	0	1	2	3	4	5	1	2	3	4	5				

Structural assessment

	Degree						Extent					Narrow (% area)	Wide (% area)	Position	Location
	Slight				Severe		<5				>80				
Cracks - corner	0	1	2	3	4	5	1	2	3	4	5				
Cracks - longitudinal	0	1	2	3	4	5	1	2	3	4	5				
Cracks - transverse	0	1	2	3	4	5	1	2	3	4	5				
Cracks - D	0	1	2	3	4	5	1	2	3	4	5				
Cracks - other	0	1	2	3	4	5	1	2	3	4	5				
Pumping	0	1	2	3	4	5	1	2	3	4	5				
Rutting (chain/snotire)	0	1	2	3	4	5	1	2	3	4	5				
Faulting	0	1	2	3	4	5	1	2	3	4	5				
Spalling	0	1	2	3	4	5	1	2	3	4	5	Number	Diameter		
Punchouts	0	1	2	3	4	5	1	2	3	4	5				
Joint damage	0	1	2	3	4	5	1	2	3	4	5				
												Small	Medium	Large	Location
Patching/digouts	0	1	2	3	4	5	1	2	3	4	5				

Functional assessment

	Degree					Influencing factors									
	Good				Poor										
Riding quality	1	2	3	4	5	Joints	☐	Cracks	☐	Spalling	☐	Punchouts	☐		☐
Skid resistance	1	2	3	4	5	Tining	☐	Polishing	☐						
Surface drainage	1	2	3	4	5										
Side drainage	✓	×													

Notes

Photos

PAVEMENT FORENSIC INVESTIGATION	INITIAL NON-DESTRUCTIVE TESTING PLAN		Form #10
Investigation Name		**Investigation #**	

Test Requirements					**Description/purpose of test**
GPR	Yes		No		
FWD	Yes		No		
Profile	Yes		No		
Skid/friction	Yes		No		
Noise	Yes		No		
	Yes		No		
	Yes		No		
	Yes		No		

Parameter	**Test**	**Detail**	**Test**	**Detail**
Start point				
End point				
Lanes to be tested				
Sampling frequency				
Date of testing				
Expected duration				
Data requirements				
Specific requirements				
Core requirements (for calibration of GPR and FWD)		Size/location		Size/location
		Size/location		Size/location

Checklist	
Arrange with tester	
Traffic control	
Data analysis arrangements	
Crew arrangements	

Investigation Coordinator		**Date**	

PAVEMENT FORENSIC INVESTIGATION	**INITIAL NON-DESTRUCTIVE TESTING PLAN**		**Form #10**
Investigation Name		**Investigation #**	2011/06

Test Requirements					**Description/purpose of test**
GPR	Yes		No	☒	
FWD	Yes	☒	No		CHECK IF THERE IS DIFFERENCE IN STIFFNESS ACROSS LANE
Profile	Yes		No	☒	
Skid/friction	Yes		No	☒	
Noise	Yes		No	☒	
	Yes		No	☒	
	Yes		No	☒	
	Yes		No	☒	

Parameter	**Test**	**Detail**	**Test**	**Detail**
Start point		START OF CONTRACT		
End point		END OF CONTRACT		
Lanes to be tested		NORTHBOUND		
Sampling frequency		30FT		
Date of testing		2011/06/18		
Expected duration		6 HOURS		
Data requirements		DEFLECTION		
Specific requirements				
Core requirements (for calibration of GPR and FWD)		Size/location 4'' EVERY 1,500FT		Size/location
		Size/location		Size/location

Checklist			
Arrange with tester	YES		
Traffic control	ARRANGED BY MAINT. SUPERINTENDENT		
Data analysis arrangements	INVESTIGATION COORDINATOR		
Crew arrangements	ARRANGED BY MAINT. SUPERINTENDENT		
Investigation Coordinator		**Date**	

PAVEMENT FORENSIC INVESTIGATION	**INITIAL FORENSIC INVESTIGATION PLAN**	**Form #11**

Investigation Name		**Investigation #**	

Attached Documents

Preliminary Investigation Report	Yes		No	
Team Members	Yes		No	
Initial Visual Assessment	Yes		No	
Non-Destructive Testing Plan	Yes		No	
Cost Estimate	Yes		No	

Testing Schedule

#	**Type of Test/Sampling**	**Test Date**	**Start Time**	**End Time**
1				
2				
3				
4				
5				
6				
7				
8				
9				
10				

Notifications	Crews		Equipment		Closures		Highway Patrol	

Analysis and Reporting

#	**By Team Member**	**Due Date**	**Reporting Format**
1			
2			
3			
4			
5			
6			
7			
8			
9			
10			

Plan Approved By		**Date**	
Investigation Coordinator		**Date**	

PAVEMENT FORENSIC INVESTIGATION	**INITIAL FORENSIC INVESTIGATION PLAN**		**Form #11**
Investigation Name		**Investigation #**	2011/06

Attached Documents

Preliminary Investigation Report	Yes	X	No	
Team Members	Yes	X	No	
Initial Visual Assessment	Yes	X	No	
Non-Destructive Testing Plan	Yes	X	No	
Cost Estimate	Yes	X	No	

Testing Schedule

#	Type of Test/Sampling	Test Date	Start Time	End Time
1	FWD	2011/06/18	09:00	15:00
2	CORES	2011/06/18	09:00	15:00
3				
4				
5				
6				
7				
8				
9				
10				

Notifications	Crews	X	Equipment	X	Closures	X	Highway Patrol	X
	DME	X	HQ LAB	X				

Analysis and Reporting

#	By Team Member	Due Date	Reporting Format
1	INVESTIGATION COORDINATOR	2011/06/30	MEMO (WORD)
2	INVESTIGATION COORDINATOR	2011/06/30	SPREADSHEET
3			
4			
5			
6			
7			
8			
9			
10			

Plan Approved By		**Date**	
Investigation Coordinator		**Date**	

PAVEMENT FORENSIC INVESTIGATION	**INTERIM REPORT COVER SHEET**	**Form #12**

Investigation Name		**Investigation #**	

Checklist for Report Content

Introduction	Yes		No	
Objectives and hypothesis	Yes		No	
Investigation Plan	Yes		No	
Analysis and Interpretation	Yes		No	
Findings/Conclusion	Yes		No	
Investigation Costs	Yes		No	
Questions Satisfactorily Answered in Initial Investigation?	Yes		No	

Justification to Continue with Forensic Investigation	
If Continuing, Testing Requirements for Next Phase of Study	1. 2. 3. 4. 5. 6. 7. 8. 9. 10.

Checklist	Non-destructive		Destructive		Laboratory		Other		

Proceed with Forensic Investigation?	Yes		No	

Notes

Investigation Approved By:		**Date**	
Investigation Coordinator		**Date**	

PAVEMENT FORENSIC INVESTIGATION	**INTERIM REPORT COVER SHEET**		**Form #12**
Investigation Name		**Investigation #**	2011/06

Checklist for Report Content

Introduction	Yes	X	No	
Objectives and hypothesis	Yes	X	No	
Investigation Plan	Yes	X	No	
Analysis and Interpretation	Yes	X	No	
Findings/Conclusion	Yes	X	No	
Investigation Costs	Yes	X	No	

Questions Satisfactorily Answered in Initial Investigation?	Yes		No	X

Justification to Continue with Forensic Investigation

FWD AND CORES PROVIDED NO REASON FOR CAUSE OF CRACK

If Continuing, Testing Requirements for Next Phase of Study

1. TEST PIT OVER LANE WIDTH TO IDENTIFY ORIGIN OF CRACK
2. OBSERVE OTHER FDR-FA PROJECT TO IDENTIFY ANY PARTS OF PROCESS THAT
3. MAY LEAD TO SIMILAR DISTRESS
4.
5.
6.
7.
8.
9.
10.

Checklist	Non-destructive		Destructive	X	Laboratory	X	Other	

Proceed with Forensic Investigation?	Yes	X	No	

Notes

Investigation Approved By:		**Date**	
Investigation Coordinator		**Date**	

PAVEMENT FORENSIC INVESTIGATION	**FINAL NON-DESTRUCTIVE TESTING PLAN**		**Form #13**
Investigation Name		**Investigation #**	

Test Requirements					**Description/purpose of test**
GPR	Yes		No		
FWD	Yes		No		
Profile	Yes		No		
Skid/friction	Yes		No		
Noise	Yes		No		
	Yes		No		
	Yes		No		
	Yes		No		

Parameter	**Test**	**Detail**	**Test**	**Detail**
Start point				
End point				
Lanes to be tested				
Sampling frequency				
Date of testing				
Expected duration				
Data requirements				
Specific requirements				
Core requirements (for calibration of GPR and FWD)		Size/location		Size/location
		Size/location		Size/location

Checklist	
Arrange with tester	
Traffic control	
Data analysis arrangements	
Crew arrangements	

Investigation Coordinator		**Date**	

PAVEMENT FORENSIC INVESTIGATION	**DESTRUCTIVE TESTING PLAN**		**Form #14**
Investigation Name		**Investigation #**	

Test Requirements					**Description/purpose of test**
Core	Yes		No		
Test pit	Yes		No		
	Yes		No		
	Yes		No		
	Yes		No		

	Label	**Size**	**Quantity**	**Location**	**Date**	**Plan**	
Cores						Y	N
						Y	N
						Y	N
Test Pit/ Trench						Y	N
						Y	N
						Y	N
						Y	N
						Y	N
						Y	N
						Y	N

In-Pit Testing Requirements	1.
	2.
	3.
	4.

	Quantity	**Location**	**Tests Required**	**Plan**	
Sample Requirements				Y	N
				Y	N
				Y	N
				Y	N
				Y	N
				Y	N

Checklist			
Arrange with testers			
Traffic control			
Data analysis arrangements			
Crew arrangements			
Utility Provider notification			
Investigation Coordinator		**Date**	

PAVEMENT FORENSIC INVESTIGATION	**DESTRUCTIVE TESTING PLAN**		**Form #14**
Investigation Name		**Investigation #**	2011/06

Test Requirements					**Description/purpose of test**
Core	Yes		No	X	
Test pit	Yes	X	No		
	Yes		No		
	Yes		No		
	Yes		No		

	Label	**Size**	**Quantity**	**Location**	**Date**	**Plan**	
Cores						Y	N
						Y	N
						Y	N
Test Pit/ Trench	2011/06/TP1	6 X 3 FT	1	PM26.0	2011/07/15	[✓ Y]	N
						Y	N
						Y	N
						Y	N
						Y	N
						Y	N
						Y	N

In-Pit Testing Requirements

1. SAMPLE FOR CEMENT CONTENT
2. PHENOLPHTHALEIN
3.
4.

	Quantity	**Location**	**Tests Required**	**Plan**	
Sample Requirements	1	BASE, AREA AROUND CRACK	CEMENT CONTENT	[✓ Y]	N
	1	BASE, AWAY FROM CRACK	CEMENT CONTENT	[✓ Y]	N
				Y	N
				Y	N
				Y	N
				Y	N

Checklist			
Arrange with testers	YES		
Traffic control	ARRANGED BY MAINT. SUPERINTENDENT		
Data analysis arrangements	INVESTIGATION COORDINATOR		
Crew arrangements	ARRANGED BY MAINT. SUPERINTENDENT		
Utility Provider notification	N/A		
Investigation Coordinator		**Date**	

PAVEMENT FORENSIC INVESTIGATION	**FINAL FORENSIC INVESTIGATION PLAN**			**Form #15**
Investigation Name			**Investigation #**	

Attached Documents

Interim Report	Yes		No			
Non-Destructive Testing Plan	Yes		No		N/A	
Destructive Testing Plan	Yes		No		N/A	
Cost Estimate	Yes		No			

Testing Schedule

#	Type of Test/Sampling	Test Date	Start Time	End Time
1				
2				
3				
4				
5				
6				
7				
8				
9				
10				

Notifications	Crews		Equipment		Closures		Highway Patrol	

Analysis and Reporting

#	By Team Member	Due Date	Reporting Format
1			
2			
3			
4			
5			
6			
7			
8			
9			
10			

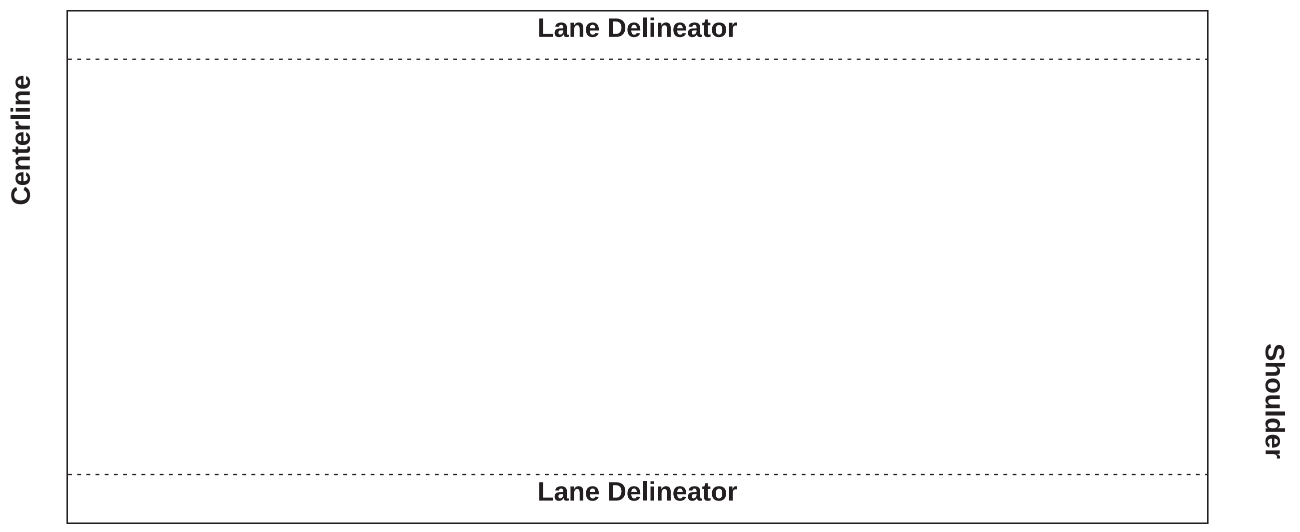
Notes

Plan Approved By		**Date**	
Investigation Coordinator		**Date**	

PAVEMENT FORENSIC INVESTIGATION	**FORENSIC INVESTIGATION SITE REPORT**	**Form #16**

Investigation Name				**Investigation #**	
Date		**Start Time**		**End Time**	
Crew chief			**Traffic Control**		
Weather					
Description of Work Done and Comments					

Investigation Section Plan and with Test Pits, Core Points, Sampling and Testing Locations



Core Coolant	Air	Water		**Saw Coolant**	Air	Water

Site Notes	

Forms Completed

Density/Moisture	☐	DCP	☐	Profile	☐	Test Pit Log	☐
Core Log	☐	List of Photographs	☐	Sample Log	☐		☐
	☐		☐		☐		☐

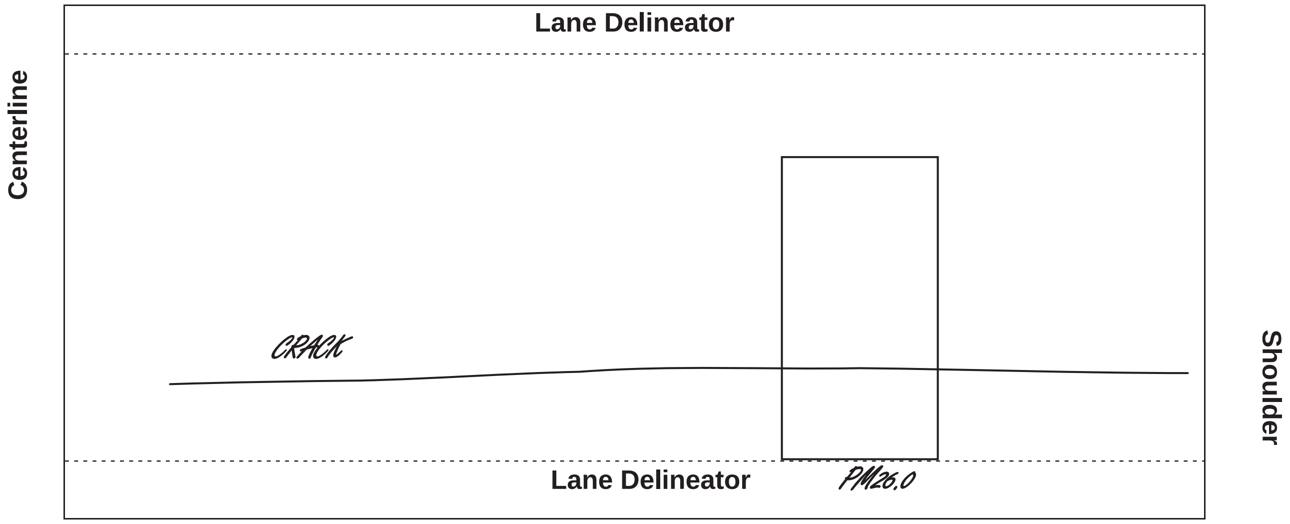
Core Hole and Test Pit Reinstatement

Core Holes	☐	Test Pits	☐	Site Cleaned	☐		☐

Investigation Coordinator		**Date**	

PAVEMENT FORENSIC INVESTIGATION	**FORENSIC INVESTIGATION SITE REPORT**				**Form #16**
Investigation Name				**Investigation #**	2011/16
Date		**Start Time**	09:00	**End Time**	15:00
Crew chief				**Traffic Control**	
Weather	HOT, DRY, LIGHT WIND. NO CLOUDS				
Description of Work Done and Comments	OPEN TEST PIT, SAMPLE MATERIALS, LOG TEST PIT, CLOSE TEST PIT				

Investigation Section Plan and with Test Pits, Core Points, Sampling and Testing Locations



Core Coolant	Air	Water		**Saw Coolant**	Air	[✓ Water]
Site Notes	NO ISSUES ASSOCIATED WITH AC THICKNESS AND BASE REMOVAL					

Forms Completed

Density/Moisture		DCP		Profile	X	Test Pit Log	X
Core Log		List of Photographs		Sample Log	X		

Core Hole and Test Pit Reinstatement

Core Holes		Test Pits	X	Site Cleaned	X		
Investigation Coordinator					**Date**		

PAVEMENT FORENSIC INVESTIGATION		**CORE LOG (Single Core)**				**Form #17a**	
Investigation Name					**Investigation #**		
Plan Reference					**Date Sampled**		
Core No			**Location Desc.**				
Reasons for Core							
Drill Notes							
					Coolant	A	W
Log Location							
Core Diameter		**Core length**	**Plan**		**Actual**		

Depth	**Layer Thickness and Distress Description**	**Photo No.**	**Sample No.**	**Material Code**

	Notes

Evaluator		**Date**	

PAVEMENT FORENSIC INVESTIGATION	**CORE LOG (Multi Core)**		**Form #17b**	
Investigation Name		**Investigation #**		
Plan Reference		**Date Sampled**		
Drill Notes		**Core Size**		
		Coolant	A	W

Core#	**Location**	**Layer Thickness**			**Observations and Distress Description**	**Photo**
1						
2						
3						
4						
5						
6						
7						
8						
9						
10						
11						
12						
13						
14						
15						
16						
17						
18						
19						
20						
21						
22						
23						
24						
25						

	Notes

Evaluator		**Date**	

PAVEMENT FORENSIC INVESTIGATION | **CORE LOG (Multi Core)** | **Form #17b**

Investigation Name

Investigation # 2011/06

Plan Reference

Date Sampled 2011/06/18

Drill Notes

Core Size 4

Coolant A [✓ W]

Core#	**Location**	**Layer Thickness**			**Observations and Distress Description**	**Photo**
1	21.25	4	12		NO DISTRESS	Y
2	21.50	4	12		“	N
3	21.75	4	12		“	N
4	22.00	4	12		“	N
5	22.25	4	12		“	N
6	22.50	4	12		“	N
7	22.75	4	12		“	N
8	23.00	4	12		“	N
9	23.25	4	12		“	N
10	23.50	4	12		“	N
11	23.75	4	12		“	N
12	24.00	4	12		“	N
13	24.25	4	12		“	N
14	24.50	4	12		“	N
15	24.75	4	12		“	N
16	25.00	4	12		“	N
17	25.25	4	12		“	N
18	25.50	4	12		“	N
19	25.75	4	12		“	N
20	26.00	4	12		“	N
21	26.25	4	12		“	N
22	26.50	4	12		“	N
23	26.75	4	12		“	N
24	27.00	4	12		“	Y
25	27.25	4	12		“	N

Notes

Evaluator

Date

PAVEMENT FORENSIC INVESTIGATION	**TEST PIT PROFILE**	**Form #18**

Investigation Name		**Investigation #**		**Evaluator**		**Date**	

Slab Observations	
Pit Surface Observations	

Zone 3 (Untrafficked to Centerline)	Zone 2 (Wheelpaths)	Zone 1 (Untrafficked to Shoulder)

Profile

Layer	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24

PAVEMENT FORENSIC INVESTIGATION

TEST PIT PROFILE

Form #18

Investigation Name

Investigation # 2011/06

Evaluator

Date

Slab Observations CRACK VISIBLE RIGHT THROUGH SLAB. SLAB BROKE ALONG CRACK. GOOD BOND ON PRIME COAT. NO DEBOND BETWEEN LIFTS

Pit Surface Observations CRACK VISIBLE ON SURFACE. NOT OTHER DISTRESS OBSERVED

Zone 3 (Untrafficked to Centerline)	Zone 2 (Wheelpaths)	Zone 1 (Untrafficked to Shoulder)
4" HMA		
4" HMA		
	CONSISTENT THICKNESS NO DEBONDING CONSTRUCTION APPEARS GOOD	CRACK

Profile

Layer	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
SURF	72	71	70	69	68	67	66	65	64	63	62	61	60	59	58	57	56	55	54	53	52	51	50	50	50
LIFT 1	122	121	120	119	118	117	116	115	114	113	112	111	110	109	108	107	106	105	104	103	102	101	100	100	100
LIFT 2	172	171	170	169	168	167	166	165	164	163	162	161	160	159	158	157	156	155	154	153	152	151	150	150	150
BASE	475	475	475	475	475	475	475	475	475	475	475	475	475	475	475	475	475	475	475	475	475	475	475	475	475

PAVEMENT FORENSIC INVESTIGATION	**ASPHALT CONCRETE / ASPHALT SURFACE TREATMENT LAYER LOG**	**Form #19a**

Investigation Name		**Investigation #**		**Evaluator**		**Date**	

Depth	**Layer**	**Zone 3 (Untrafficked to Centerline)**	**Zone 2 (Wheelpaths)**	**Zone 1 (Untrafficked to Shoulder)**	**Sample**
To					

Checklist	Cracks									
	Rutting		Heaving		Bleeding		Raveling		Segregation	
	Interface bond		Moisture at interface		Layer definition		Pumping		Stripping	

To					

Checklist	Cracks									
	Rutting		Heaving		Bleeding		Raveling		Segregation	
	Interface bond		Moisture at interface		Layer definition		Pumping		Stripping	

To					

Checklist	Cracks		Description							
	Rutting		Heaving		Bleeding		Raveling		Segregation	
	Interface bond		Moisture at interface		Layer definition		Pumping		Stripping	

Notes	

PAVEMENT FORENSIC INVESTIGATION	**ASPHALT CONCRETE / ASPHALT SURFACE TREATMENT LAYER LOG**	**Form #19a**

Investigation Name		**Investigation #**	2011/06	**Evaluator**		**Date**	

Depth	**Layer**	**Zone 3 (Untrafficked to Centerline)**	**Zone 2 (Wheelpaths)**	**Zone 1 (Untrafficked to Shoulder)**	**Sample**
0	19mm	NO PROBLEM	NO PROBLEM	NO PROBLEM OTHER THAN CRACK	NO
To	HMA				
50					

Checklist	Cracks	Y	VERTICAL BOTTOM UP CRACK FROM BASE							
	Rutting	N	Heaving	N	Bleeding	N	Raveling	N	Segregation	N
	Interface bond	G	Moisture at interface	N	Layer definition	G	Pumping	N	Stripping	N

50	19mm	NO PROBLEM	NO PROBLEM	NO PROBLEM OTHER THAN CRACK	NO
To	HMA				
100					

Checklist	Cracks									
	Rutting		Heaving		Bleeding		Raveling		Segregation	
	Interface bond		Moisture at interface		Layer definition		Pumping		Stripping	

To					

Checklist	Cracks		Description							
	Rutting		Heaving		Bleeding		Raveling		Segregation	
	Interface bond		Moisture at interface		Layer definition		Pumping		Stripping	

Notes	

PAVEMENT FORENSIC INVESTIGATION	PORTLAND CEMENT CONCRETE LAYER LOG	Form #19b

Investigation Name		Investigation #		Evaluator		Date	

Depth	Layer	Zone 3 (Untrafficked to Centerline)	Zone 2 (Wheelpaths)	Zone 1 (Untrafficked to Shoulder)	Sample
To					

Checklist	Cracks									
	Rutting						Raveling		Spalling	
	Interface bond		Moisture at interface		Layer definition		Pumping			

To					

Checklist	Cracks									
	Rutting						Raveling		Spalling	
	Interface bond		Moisture at interface		Layer definition		Pumping			

To					

Checklist	Cracks		Description							
	Rutting						Raveling		Spalling	
	Interface bond		Moisture at interface		Layer definition		Pumping			

Notes	

PAVEMENT FORENSIC INVESTIGATION	**GRAVEL AND STABILIZED LAYER LOG**	**Form #20**

Investigation Name		**Investigation #**		**Evaluator**		**Date**	

Depth	**Color**	**Moisture**			**Cementing**			**Consistency**					**Structure**							**Size**		**Plasticity**				**Other**	**Sample**
Layer																											
		D	M	W	W	M	S	VL	L	MD	D	VD	IN	St	F	Sl	B	L	V	F	C	N	L	M	H		
To																											

Cracks									
Rutting		Pumping		Interface bond		Moisture in join		Layer def	
Carbonation		Phenolphthalein		HCl		Re-cement		Organic matter	

Depth	**Color**	**Moisture**			**Cementing**			**Consistency**					**Structure**							**Size**		**Plasticity**				**Other**	**Sample**
Layer																											
		D	M	W	W	M	S	VL	L	MD	D	VD	IN	St	F	Sl	B	L	V	F	C	N	L	M	H		
To																											

Cracks									
Rutting		Pumping		Interface bond		Moisture in join		Layer def	
Carbonation		Phenolphthalein		HCl		Re-cement		Organic matter	

Moisture

D	Dry
M	Moist
W	Wet

Cementing

W	Weak
M	Medium
S	Strong

Consistency

VL	Very Loose
L	Loose
MD	Medium Dense
D	Dense
VD	Very Dense

Structure

IN	Intact
St	Stratified
F	Fissures
Sl	Slickenslides
B	Boulders
L	Laminations
V	Voids

Size

F	Fine
C	Coarse

Plasticity

N	Non-Plastic
L	Low Plasticity
M	Medium Plasticity
H	High Plasticity

PAVEMENT FORENSIC INVESTIGATION

GRAVEL AND STABILIZED LAYER LOG

Form #20

Investigation Name		**Investigation #**	2011/06	**Evaluator**		**Date**	

Depth	**Color**	**Moisture**	**Cementing**	**Consistency**	**Structure**	**Size**	**Plasticity**	**Other**	**Sample**
Layer	BASE								
100	GREY	D [✓ M] W	W [✓ M] S	VL L MD D [✓ VD]	[✓ IN] St F Sl B L V	F [✓ C]	[✓ N] L M H		
To	GOOD QUALITY RECYCLED LAYER. GOOD DISTRIBUTION OF ASPHALT AND CEMENT. GOOD MATERIAL GRADING								YES
400	PHENOLPHTHALEIN CONSISTENT ACROSS BASE EXCEPT AROUND CRACK WHERE COLOR IS MUCH DARKER								
	INDICATING HIGHER CEMENT CONTENT. NO INDICATION OF COMPACTION SHEAR FAILURE								
Cracks	VERTICAL STARTING ABOUT 1/3 FROM BOTTOM OF LAYER. VERY STRAIGHT								
Rutting	N	Pumping	N	Interface bond	GOOD	Moisture in join	N	Layer def	GOOD
Carbonation	N	Phenolphthalein	Y	HCl	Y	Re-cement	N	Organic matter	N
Layer	SUBGRADE								
400	BROWN	D [✓ M] W	[✓ W] M S	VL L MD [✓ D] VD	[✓ IN] St F Sl B L V	[✓ F] C	N [✓ L] M H		
To	TYPICAL SUBGRADE. NO UNUSUAL OBSERVATIONS								
INF									
Cracks									
Rutting	N	Pumping	N	Interface bond	G	Moisture in join	N	Layer def	G
Carbonation	N	Phenolphthalein	N	HCl	N	Re-cement	N	Organic matter	SOME

Moisture

D	Dry
M	Moist
W	Wet

Cementing

W	Weak
M	Medium
S	Strong

Consistency

VL	Very Loose
L	Loose
MD	Medium Dense
D	Dense
VD	Very Dense

Structure

IN	Intact
St	Stratified
F	Fissures
Sl	Slickenslides
B	Boulders
L	Laminations
V	Voids

Size

F	Fine
C	Coarse

Plasticity

N	Non-Plastic
L	Low Plasticity
M	Medium Plasticity
H	High Plasticity

PAVEMENT FORENSIC INVESTIGATION

SAMPLE LOG

Form #21

Investigation Name

Investigation #

Evaluator

Date

Sample Number	Sample Location	Sample Size	Sample Type	Material Type and Code	Sample Condition	Program of Work

PAVEMENT FORENSIC INVESTIGATION	**SAMPLE LOG**	**Form #21**

Investigation Name		**Investigation #**	2011/06	**Evaluator**		**Date**	

Sample Number	Sample Location	Sample Size	Sample Type	Material Type and Code	Sample Condition	Program of Work
2011/06/01	AROUND CRACK	10KG	BASE	BASE	GOOD	CEMENT CONTENT
	MID-BASE					(SEALED IMMEDIATELY)
2011/06/02	AWAY FROM CRACK	10KG	BASE	BASE	GOOD	CEMENT CONTENT
	MID-BASE					(SEALED IMMEDIATELY)

PAVEMENT FORENSIC INVESTIGATION	**DENSITY AND MOISTURE CONTENT**					**Form #22**	
Investigation Name					**Investigation #**		
Calibration	**Std**	**Std**	**Std**	**Calibration Reference**			
Std Count				**Std Density**			

	Position	Depth	Wet	Dry	MC	Notes
Test A		8 (200)				
	↔	6 (150)				
		4 (100)				
		2 (50)				
	↕	8 (200)				
		6 (150)				
		4 (100)				
		2 (50)				
Test B		8 (200)				
	↔	6 (150)				
		4 (100)				
		2 (50)				
	↕	8 (200)				
		6 (150)				
		4 (100)				
		2 (50)				
Test C		8 (200)				
	↔	6 (150)				
		4 (100)				
		2 (50)				
	↕	8 (200)				
		6 (150)				
		4 (100)				
		2 (50)				

Gravimetric Moisture Content

	Depth	Tin	MC	Actual DD	Notes
A					
B					
C					

Evaluator		**Date**	

PAVEMENT FORENSIC INVESTIGATION	**DYNAMIC CONE PENETROMETER**	**Form #23**
Investigation Name		**Investigation #**

Position A			**Position B**			**Position C**		
0			0			0		
5	205	405	5	205	405	5	205	405
10	210	410	10	210	410	10	210	410
15	215	415	15	215	415	15	215	415
20	220	420	20	220	420	20	220	420
25	225	425	25	225	425	25	225	425
30	230	430	30	230	430	30	230	430
35	235	435	35	235	435	35	235	435
40	240	440	40	240	440	40	240	440
45	245	445	45	245	445	45	245	445
50	250	450	50	250	450	50	250	450
55	255	455	55	255	455	55	255	455
60	260	460	60	260	460	60	260	460
65	265	465	65	265	465	65	265	465
70	270	470	70	270	470	70	270	470
75	275	475	75	275	475	75	275	475
80	280	480	80	280	480	80	280	480
85	285	485	85	285	485	85	285	485
90	290	490	90	290	490	90	290	490
95	295	495	95	295	495	95	295	495
100	300	500	100	300	500	100	300	500
105	305	505	105	305	505	105	305	505
110	310	510	110	310	510	110	310	510
115	315	515	115	315	515	115	315	515
120	320	520	120	320	520	120	320	520
125	325	525	125	325	525	125	325	525
130	330	530	130	330	530	130	330	530
135	335	535	135	335	535	135	335	535
140	340	540	140	340	540	140	340	540
145	345	545	145	345	545	145	345	545
150	350	550	150	350	550	150	350	550
155	355	555	155	355	555	155	355	555
160	360	560	160	360	560	160	360	560
165	365	565	165	365	565	165	365	565
170	370	570	170	370	570	170	370	570
175	375	575	175	375	575	175	375	575
180	380	580	180	380	580	180	380	580
185	385	585	185	385	585	185	385	585
190	390	590	190	390	590	190	390	590
195	395	595	195	395	595	195	395	595
200	400	600	200	400	600	200	400	600

Evaluator		**Date**	

PAVEMENT FORENSIC INVESTIGATION	**FINAL REPORT COVER SHEET**	**Form #24**

Investigation Name		**Investigation #**	

Checklist for Report Content

Introduction	Yes		No	
Objectives and Hypothesis	Yes		No	
Investigation Plan	Yes		No	
Observations & Measurements	Yes		No	
Analysis and Interpretation	Yes		No	
Findings/Conclusion	Yes		No	
Recommendations	Yes		No	
Dissemination	Yes		No	
Cost Summary	Yes		No	

Question Satisfactorily Answered?	Yes		No	

Checklist	Notifications		Dissemination		Backups		Project File	

Notes

Report Approved By:		**Date**	
Investigation Coordinator		**Date**	

PAVEMENT FORENSIC INVESTIGATION	**FINAL REPORT COVER SHEET**	**Form #24**

Investigation Name		**Investigation #**	2011/06

Checklist for Report Content

Introduction	Yes	X	No	
Objectives and Hypothesis	Yes	X	No	
Investigation Plan	Yes	X	No	
Observations & Measurements	Yes	X	No	
Analysis and Interpretation	Yes	X	No	
Findings/Conclusion	Yes	X	No	
Recommendations	Yes	X	No	
Dissemination	Yes	X	No	
Cost Summary	Yes	X	No	

Question Satisfactorily Answered?	Yes	X	No	

Checklist	Notifications	X	Dissemination	X	Backups	X	Project File	X

Notes

BASED ON TEST PIT OBSERVATIONS, CEMENT CONTENT TESTS AND OBSERVATIONS OF OTHER FDR-FA PROJECTS, CAUSE OF CRACK ATTRIBUTED TO WINDROW OF CEMENT ON EDGE OF MACHINE CAUSED BY DRUM ACTION AND MACHINE SKIRT. WINDROW IS COVERED BY DUST DURING MILLING PROCESS. RECOMMEND INCLUDE ISSUE AND HOW TO DEAL WITH IT IN JUST-IN-TIME TRAINING

Report Approved By:		**Date**	
Investigation Coordinator		**Date**	

APPENDIX D

Example Checklists

This Appendix contains examples of checklists recommended for use in forensic investigations. These checklists can be modified to suit specific agency requirements. The checklists and the section in the guide in which they are referred to are:

Checklist #1: Logging of AC Wearing Course Layers (Sections 7.3.4 and 7.4.6)
Checklist #2: Logging of PCC Wearing Course Layers (Sections 7.3.4 and 7.4.6)
Checklist #3: Logging of Bound Layers (Sections 7.3.4 and 7.4.6)
Checklist #4: Logging of Unbound Layers (Sections 7.3.4 and 7.4.6)
Checklist #5: Severity and Extent Descriptors for AC Wearing Course Layer Assessment (Sections 7.3.4 and 7.4.6)
Checklist #6: Severity and Extent Descriptors for PCC Wearing Course Layer Assessment (Sections 7.3.4 and 7.4.6)
Checklist #7: Severity and Extent Descriptors for Bound/Stabilized Layer Assessment (Sections 7.3.4 and 7.4.6)
Checklist #8: Severity and Extent Descriptors for Unbound Layer Assessment (Sections 7.3.4 and 7.4.6)
Checklist #9: Investigation Closure (Section 9.3)

CHECKLIST – LOGGING OF AC WEARING COURSE LAYERS

Checklist #1

Parameter	Evaluation					
	Severity	Extent	Start	End	Layer	Description and implications
Cracking						
• Transverse	✓	✓	✓	✓	✓	✓
• Longitudinal	✓	✓	✓	✓	✓	✓
• Fatigue	✓	✓	✓	✓	✓	✓
• Reflective	✓	✓	✓	✓	✓	✓
Rutting	-	✓	✓	✓	✓	✓
Shoving	-	✓	✓	✓	✓	✓
Raveling	-	✓	-	-	-	✓
Bleeding	-	✓	✓	✓	✓	✓
Pumping	-	✓	✓	✓	✓	✓
Polished aggregate	-	✓	-	-	-	✓
Aggregate condition	-	-	-	-	-	✓
Moisture condition	-	-	-	-	-	✓
Pothole repair	-	✓	✓	✓	✓	✓
Crack repair	-	✓	✓	✓	✓	✓

CHECKLIST – LOGGING OF PCC WEARING COURSE LAYERS

Checklist #2

Parameter	Evaluation					
	Severity	Extent	Start	End	Layer	Description and implications
Cracking						
• Transverse	✓	✓	✓	✓	✓	✓
• Longitudinal	✓	✓	✓	✓	✓	✓
• Block	✓	✓	✓	✓	✓	✓
• Edge	✓	✓	✓	✓	✓	✓
• Corner	✓	✓	✓	✓	✓	✓
• Durability	✓	✓	✓	✓	✓	✓
• Map	-	✓	✓	✓	✓	✓
Rutting (chain wear)	-	✓	✓	✓	✓	✓
Scaling	-	✓	-	-	-	✓
Spalling	✓	✓	-	-	-	✓
Faulting	-	✓	-	-	-	✓
Joint seal damage	✓	✓	-	-	-	✓
Pumping	-	✓	✓	✓	✓	✓
Polished aggregate	-	✓	-	-	-	✓
Aggregate condition	-	-	-	-	-	✓
Moisture condition	-	-	-	-	-	✓
Alkali-silica reaction	-	✓	✓	✓	-	✓
Corrosion	-	✓	-	-	-	✓
Pothole repair	-	✓	✓	✓	✓	✓
Crack repair	-	✓	✓	✓	✓	✓

CHECKLIST – LOGGING OF BOUND LAYERS

Checklist #3

Parameter	**Evaluation**					
	Severity	**Extent**	**Start**	**End**	**Layer**	**Description and Implications**
Cracking						
• Horizontal	✓	✓	✓	✓	✓	✓
• Vertical	✓	✓	✓	✓	✓	✓
• Other	✓	✓	✓	✓	✓	✓
Rutting	-	✓	✓	✓	✓	✓
Pumping	-	✓	✓	✓	✓	✓
Erosion	-	✓	✓	✓	✓	✓
Fines intrusion	-	✓	✓	✓	✓	✓
Degradation	-	✓	✓	✓	✓	✓
Aggregate condition	-	-	-	-	-	✓
Moisture condition	-	-	-	-	-	✓
Mottling	-	✓	✓	✓	✓	✓
Frost action	-	✓	✓	✓	✓	✓
Layer definition	-	-	-	-	-	✓
Interlayer bond	-	-	-	-	-	✓
Moisture at interface	-	-	-	-	-	✓
Pothole repair	-	✓	✓	✓	✓	✓
Crack repair	-	✓	✓	✓	✓	✓
Bleeding[1]	-	✓	✓	✓	✓	✓
Carbonation[2]	-	✓	✓	✓	✓	✓
Aggregate description • Angularity • Shape • Color • Odor • HCl Reaction • Consistency • Cementation • Structure • Size range • Max particle size • Hardness • Condition	Described as per ASTM D 2488 - Description and identification of soils (visual-manual procedure)					

[1] Asphalt-treated base only

[2] Cement treated base only

CHECKLIST – LOGGING OF UNBOUND LAYERS

Checklist #4

Parameter	Evaluation					
	Severity	Extent	Start	End	Layer	Description and Implications
Cracking						
• Horizontal	✓	✓	✓	✓	✓	✓
• Vertical	✓	✓	✓	✓	✓	✓
• Other	✓	✓	✓	✓	✓	✓
Rutting	-	✓	✓	✓	✓	✓
Pumping	-	✓	✓	✓	✓	✓
Erosion	-	✓	✓	✓	✓	✓
Fines intrusion	-	✓	✓	✓	✓	✓
Degradation	-	✓	✓	✓	✓	✓
Aggregate condition	-	-	-	-	-	✓
Moisture condition	-	-	-	-	-	✓
Mottling	-	✓	✓	✓	✓	✓
Frost action	-	✓	✓	✓	✓	✓
Layer definition	-	-	-	-	-	✓
Interlayer bond	-	-	-	-	-	✓
Moisture at interface	-	-	-	-	-	✓
Pothole repair	-	✓	✓	✓	✓	✓
Crack repair	-	✓	✓	✓	✓	✓
Aggregate description • Angularity • Shape • Color • Odor • HCl Reaction • Consistency • Cementation • Structure • Size range • Max particle size • Hardness • Condition	Described as per ASTM D 2488 - Description and identification of soils (visual-manual procedure)					

CHECKLIST – SEVERITY AND EXTENT DESCRIPTORS FOR AC WEARING COURSE LAYER ASSESSMENT

Checklist #5

Parameter	Severity rating	Rating description	Extent description
Transverse cracks	1 - Low 2 - Moderate 3 - High	Distress Identification Manual	Number, length
Longitudinal cracks	1 - Low 2 - Moderate 3 - High	Distress Identification Manual	Number, length
Fatigue cracks	1 - Low 2 - Moderate 3 - High	Distress Identification Manual	% area, depth
Reflective cracks	1 - Low 2 - Moderate 3 - High	Distress Identification Manual	Number, length
Rutting	Severity not rated	-	Width, depth
Shoving	Severity not rated	-	% area, depth
Raveling	Severity not rated	-	% area, depth
Bleeding	Severity not rated	-	% area
Pumping	Severity not rated	-	Number, depth
Polished aggregate	Severity not rated	-	% area
Aggregate condition	Severity not rated	-	Description only
Moisture condition	Severity not rated	-	Description only
Pothole repair	Severity not rated	-	Description only
Crack repair	Severity not rated	-	Description only

CHECKLIST – SEVERITY AND EXTENT DESCRIPTORS FOR PCC WEARING COURSE LAYER ASSESSMENT

Checklist #6

Parameter	Severity rating	Rating description	Extent description
Transverse cracks	1 - Low 2 - Moderate 3 - High	Distress Identification Manual	Number, length
Longitudinal cracks	1 - Low 2 - Moderate 3 - High	Distress Identification Manual	Number, length
Block cracks	1 - Low 2 - Moderate 3 - High	Distress Identification Manual	% area, depth
Edge cracks	1 - Low 2 - Moderate 3 - High	Distress Identification Manual	Number, length
Corner breaks	1 - Low 2 - Moderate 3 - High	Distress Identification Manual	Number, depth
Durability cracks	1 - Low 2 - Moderate 3 - High	Distress Identification Manual	% area, depth
Map cracks	Severity not rated	-	% area, depth
Rutting	Severity not rated	-	Width, depth
Scaling	Severity not rated	-	% area, depth
Spalling	1 - Low 2 - Moderate 3 - High	Distress Identification manual	Number, depth
Faulting	Severity not rated	-	Depth
Joint seal damage	1 - Low 2 - Moderate 3 - High	Distress identification Manual	Depth
Pumping	Severity not rated	-	Number, depth
Polished aggregate	Severity not rated	-	% area
Aggregate condition	Severity not rated	-	Description only
Moisture condition	Severity not rated	-	Description only
Alkali-silica reaction	Severity not rated	-	% area
Corrosion	Severity not rated	-	Length
Pothole repair	Severity not rated	-	Description only
Crack repair	Severity not rated	-	Description only

CHECKLIST – SEVERITY AND EXTENT DESCRIPTORS FOR BOUND/STABILIZED LAYER ASSESSMENT			Checklist #7
Parameter	**Severity rating**	**Rating description**	**Extent description**
Horizontal cracks	1 - Low 2 - Moderate 3 – High	≤ 0.25 in. (5 mm) 0.25 – 0.75 in. (5 - 20 mm) > 0.75 in. (20 mm)	Number, length
Vertical cracks	1 - Low 2 - Moderate 3 – High	≤ 0.25 in. (5 mm) 0.25 – 0.75 in. (5 - 20 mm) > 0.75 in. (20 mm)	Number, length
Other cracks	1 - Low 2 - Moderate 3 – High	≤ 0.25 in. (5 mm) 0.25 – 0.75 in. (5 - 20 mm) > 0.75 in. (20 mm)	Number, length
Rutting	Severity not rated	-	Width, depth
Pumping	Severity not rated	-	Number, depth
Erosion	Severity not rated	-	% area
Fines intrusion	Severity not rated	-	% area, depth
Degradation	Severity not rated	-	% area
Aggregate condition	Severity not rated	-	Description only
Moisture condition	Severity not rated	-	Description only
Mottling	Severity not rated	-	% area
Frost action	Severity not rated	-	Depth
Layer definition	Severity not rated	-	Description only
Interlayer bond	Severity not rated	-	Description only
Moisture at interface	Severity not rated	-	Description only
Pothole repair	Severity not rated	-	Description only
Crack repair	Severity not rated	-	Description only
Bleeding	Severity not rated	-	% area
Carbonation	Severity not rated	-	% area, depth

CHECKLIST – SEVERITY AND EXTENT DESCRIPTORS FOR UNBOUND LAYER ASSESSMENT			Checklist #8
Parameter	**Severity rating**	**Rating description**	**Extent description**
Horizontal cracks	1 - Low 2 - Moderate 3 - High	≤ 0.25 in. (5 mm) 0.25 – 0.75 in. (5 - 20 mm) > 0.75 in. (20 mm)	Number, length
Vertical cracks	1 - Low 2 - Moderate 3 - High	≤ 0.25 in. (5 mm) 0.25 – 0.75 in. (5 - 20 mm) > 0.75 in. (20 mm)	Number, length
Other cracks	1 - Low 2 - Moderate 3 - High	≤ 0.25 in. (5 mm) 0.25 – 0.75 in. (5 - 20 mm) > 0.75 in. (20 mm)	Number, length
Rutting	Severity not rated	-	Width, depth
Pumping	Severity not rated	-	Number, depth
Erosion	Severity not rated	-	% area
Fines intrusion	Severity not rated	-	% area, depth
Degradation	Severity not rated	-	% area
Aggregate condition	Severity not rated	-	Description only
Moisture condition	Severity not rated	-	Description only
Mottling	Severity not rated	-	% area
Frost action	Severity not rated	-	Depth
Layer definition	Severity not rated	-	Description only
Interlayer bond	Severity not rated	-	Description only
Moisture at interface	Severity not rated	-	Description only
Pothole repair	Severity not rated	-	Description only
Crack repair	Severity not rated	-	Description only
Bleeding	Severity not rated	-	% area

CHECKLIST – INVESTIGATION CLOSURE

Checklist #9

General Issues		**Yes**	**No**	**Comments**
1	Has the investigation been completed in terms of the requirements of the experiment work plan?			
2	Have the objectives of the investigation been met?			
3	Is termination of the investigation justified?			
4	Have all reports as required in the investigation work plan been written?			
5	Have all reports had an independent technical review?			
6	Have all reports been logged and numbered in the central register?			
7	Have the required steps been taken to have the findings implemented?			
8	Have the findings been presented to relevant departments and if applicable, published?			
9	Has all data been captured in the database and backed up?			
10	Have the cost spreadsheet and project file been closed and archived?			
11	Have materials samples been disposed of?			
12	Have signs, markings, and instrumentation been removed from site?			
13	Have all team members and other interested and affected parties been notified?			
14				
15				

Recommendation

Was the investigation successfully completed?	Yes	No

If no, state why and what needs to be done to complete it

Name:		**Signature:**		**Date:**	

ATTACHMENT

Guide for Conducting Forensic Investigations of Highway Pavements: Background Research

CONTENTS

1. Introduction

Hundreds of pavement forensic investigations have been performed in this country over the decades to address a number of objectives. However, rarely are any two forensic investigations carried out in the same manner primarily because:

- Objectives of and the reasons for doing a forensic investigation vary from one project to another.
- Budget, time, and manpower constraints limit the variety of available investigation techniques and procedures.
- Recording and documentation of observations often vary.
- Standard or widely accepted guidelines to promote consistency on a national scale do not exist.

In essence, each pavement forensic investigation undertaken in the past has typically been a case study that provided limited useful information for subsequent studies, and hence there was a need for developing a standardized guide for nation-wide use in conducting forensic investigations of highway pavements. NCHRP Project 01-49 was initiated to address this need.

The objective of this study was to develop a Guide for Conducting Forensic Investigations of Highway Pavements that considers relevant factors, such as functional and structural performance, construction- and/or material-related distress, long-term effects of traffic and environment, pavement type, sampling and testing requirements, and sequence of activities. Moreover, the guide needed to address the full spectrum of possible objectives to allow use throughout the pavements community. Achieving this objective will lead to other benefits, such as:

- Maximizing the information collected from an investigation,
- Conducting more cost-effective investigations,
- Improving understanding of how and why pavements behave as they do, and
- Providing valuable data in support of model development for use in pavement evaluation and design procedures and/or improved technologies.

These benefits will be manifested as forensic investigations are performed in a more systematic fashion throughout the United States. In addition, it is important to use a standard format for storing and disseminating the findings and outcomes from completed investigations.

Pavement forensic investigations are carried out for wide-ranging reasons, including:

- Investigating why pavements fail, and more specifically, the underlying causes of premature pavement failures.
- Understanding the factors contributing to exceptional pavement performance and longevity.
- Collecting data to support development and/or calibration of performance prediction models.
- Collecting data to support investigations into the long-term effects of traffic and environment on material properties.
- Checking the functionality and calibration of pavement instrumentation.

Because pavement forensic investigations can serve many objectives and they may be performed under widely varying conditions (pavement type, distresses, traffic, ambient conditions, etc.), the guide should address the numerous possible combinations of objectives and conditions. Moreover, when conducting forensic investigations, it is important to “expect the unexpected,” and allow flexibility in adapting to field conditions. In addition, multiple levels of assessment should be considered when performing such investigations, ranging from simple visual observations, to coring and trenching operations, to routine pavement performance and materials testing, and to the more sophisticated techniques such as chemical analyses and digital and scanning electron microscope studies.

Accordingly, the guide developed under this project effort helps establish clear and concise objectives for carrying out a forensic investigation on a particular project (i.e., determine the purpose of the forensic investigation and identify how the investigation results will be used). In addition, the guide explains the level of investigation and activities at each level that are required to meet the objectives.

Because there is not a single set of activities that applies to all possible objectives and project specific conditions (pavement type, environment, traffic, etc.), the implementation of the guide developed in this project will provide:

- A step-by-step procedure that will guide highway agency personnel and other interested parties in tailoring forensic investigation plans to meet the desired objectives and project specific conditions.
- Detailed information (the “what” and the “how”) and guidance to allow highway agency personnel and other interested parties to develop and implement a well thought out and planned forensic investigation.
- Suggestions for database architecture for storing the findings of forensic investigations to facilitate use by others.
- Guidance on how best to use the forensic investigation results, including changes in practice to prevent recurrence of premature failures, means for disseminating results, and lessons learned.

Ultimately, the approach to any given forensic investigation will depend on the objective of the investigation, how the findings from the investigation will be used, and the available resources.

The approach for developing the guide consisted of the following activities:

1. Review the literature on forensic investigations.
2. Identify and evaluate forensic investigation elements.
3. Prepare a forensic investigation guide outline and development process.
4. Develop preliminary forensic investigation guide.
5. Prepare and execute a plan for assessing the preliminary guide in the field.
6. Revise the guide.

This report documents the results and findings of this work, which were intended to establish the foundation (i.e., outline and process) for and actual development, assessment, and finalization of the pavement forensic investigation guide. The information presented in this report is organized in five chapters. Chapter 1 provides an introduction that covers background, project objective, and major research issues. Chapter 2 presents a review of existing practices, including general trends and major findings from the available information and from the survey of state highway agencies. Chapter 3 describes the forensic investigation elements, including the identification and evaluation of the applications and elements involved in conducting investigations of different pavement types and conditions. Chapter 4 discusses the process for guide development, and Chapter 5 provides a summary, conclusions, and recommendations for research.

2. Review of Existing Practices

The objective of this review was to collect and assess information relevant to pavement forensic investigations to establish a reasonable body of knowledge for use in the development of the guide. To accomplish this objective, the following two activities were pursued: (a) review of literature available from various sources and (b) a web-based survey questionnaire of state highway agencies.

2.1 Literature Review

The purpose of the literature review was to identify, review, and synthesize information for use in the preparation of the guide. A large number of documents from various sources were identified and reviewed. Key information was extracted from the relevant documents, which are listed in the Bibliography.

With regards to the types of pavements studied and the reasons for conducting the investigation, the majority of the investigations involved asphalt pavements or layers, the majority of which were concerned with poor performance or pavement failures. Investigations of concrete and composite pavement failures were also documented, as well as investigations into exceptionally good performance and other reasons such as calibration of performance models and evaluating instrumentation and forensic equipment.

The specific objectives of reported investigations, in descending order of frequency, were:

- Evaluation of poor pavement performance.
- Comparative evaluation of pavement performance.
- Application of pavement testing equipment or method.
- Forensic investigation approach.
- Evaluation of good pavement performance.

Regarding forensic investigation techniques, the most common field activity was coring followed by distress surveys, deflection (e.g., falling weight deflectometer [FWD]) testing, dynamic cone penetrometer (DCP) testing, sampling, trenching, roughness surveys, and ground penetrating radar (GPR) measurements.

The literature review provided valuable insight into the practice of forensic investigations that was used in preparing an outline for forensic investigation guide. The most common forensic investigation elements in these references were analysis/interpretation and forensic techniques followed by planning/implementation, use in broader pavement applications, recording/documenting/dissemination, and lessons learned. Most of the documents involved studies of new HMA pavements, but numerous investigations also involved new PCC pavements, overlays, and other pavement structures. Most investigations dealt with the cause of poor pavement performance or failure. Coring was the most common forensic investigation technique discussed, followed by routine laboratory testing, distress surveys, and deflection testing.

2.2 State Highway Agency Survey Questionnaire

To gather additional information for development of the guide, a survey questionnaire was distributed to the state highway agencies. The survey questionnaire was also intended to identify agencies interested in conducting field assessments and provide input to finalize the guide.

Of the 52 highway agencies (50 states, the District of Columbia, and Puerto Rico) contacted, 37 completed the questionnaire. Table 1 summarizes the reasons reported by these agencies for conducting (or not conducting) forensic investigations. Other reported reasons include:

- To support studies conducted as part of an accelerated pavement test facility.
- To assist development of repair techniques (e.g., a forensic investigation was done during development of an experimental process to use precast concrete repair slabs).

Table 1. Purpose for conducting forensic investigations.

Purpose of Investigation	Response Percent
1. To investigate underlying causes of pavement failures	81%
2. To collect data to support development and/or calibration of performance models	43%
3. To collect data to support investigation into the long-term effects of traffic and the environment on layer and material (HMA, PCC, etc.) properties	35%
4. To understand factors contributing to exceptional pavement performance/longevity	24%
5. Agency does not perform forensic investigations	16%
6. Other	16%

- To evaluate new products.
- To evaluate existing pavement conditions and properties for use in determining rehabilitation strategies.

Among the reasons reported for not performing forensic investigations were the lack of an established investigation program, the unavailability of specialized manpower, or the fact that such investigations are performed by a state university or the FHWA when needed.

The reasons for conducting forensic investigations stated in Table 1 are consistent with those identified from the literature review, with pavement failures being the most common purpose of these investigations. Data collection to support development or calibration of performance models and investigation into the long-term effects of traffic and the environment on layer and material properties, exceptional pavement performance or longevity, and all other objectives were less common. Calibration of models and long-term effects are usually undertaken by universities or other research organizations on behalf of state highway agencies, therefore these options may have been underrepresented by the agency when completing the survey questionnaire.

In summary, the results of the questionnaire revealed that forensic investigations are being conducted primarily to investigate the underlying causes of pavement failures. Investigations to understand pavement longevity, to collect data to support development or calibration of performance models, and/or investigate long-term effects of traffic and environment are conducted less frequently. The survey identified agencies interested in supporting a field assessment of the guide and expanding upon the purpose of forensic investigations.

3. Forensic Investigation Elements

This chapter provides a framework for development of the guide using the applications and critical elements identified in Chapter 2. These elements are divided into generic agency issues and project specific issues.

3.1 Applications

A critical element to a successful pavement forensic investigation is having a clear understanding of the purpose of the investigation and how the results from that investigation will be used. Potential pavement applications include the following:

- Determining reasons for poor pavement performance/premature pavement failures
- Understanding exceptional pavement performance/longevity
- Collecting specific data for rehabilitation design
- Validating pavement performance (actual vs. predicted)
- Close-out investigations of experimental test sections
- Collecting data to support development/calibration of pavement performance prediction models
- Collecting data to understand/quantify long-term effects of traffic and environment on material properties
- Collecting data to implement improved design and/or construction practices
- Collecting data for support of pavement-related legal matters
- Certifying warranties
- Evaluating new products or techniques
- A combination of two or more of the above

Each of the above applications is generic in nature and can and should be made more specific (e.g., to investigate premature rutting of HMA pavements on Interstate XYZ between mileposts X and Y).

Although there may be many reasons for carrying out forensic investigations, they all address pavement performance. Therefore, successful achievement of any given forensic investigation requires a clear understanding of how pavements perform/behave and why they perform/behave as they do.

There are four factors whose separate and combined effects define the performance of pavements. These are:

- Pavement structure
  - Pavement type: new asphalt (with or without a cement treated base or CTB layer); new PCC (jointed plain, jointed reinforced, continuously reinforced, precast, etc.); asphalt overlay over existing asphalt; asphalt overlay over existing concrete; concrete overlay over existing concrete (bonded and unbonded); concrete overlay over existing asphalt; and others (integrated concrete pavers, whitetopping overlay, etc.).
  - Pavement layers: thicknesses, material types, material properties, drainage, shoulders, joints and steel reinforcement in concrete pavements, quality of construction and related issues, ambient conditions at time of construction, and others.
- Subgrade soil: material types, material properties, stabilization, embankment, cut/fill, depth to bedrock, drainage, and others.
- Traffic: traffic volumes (design versus actual), traffic loads/load spectra (design versus actual), traffic growth (design versus actual), seasonal trends, load restrictions, and others.
- Environmental conditions: air and surface temperatures, precipitation, wind, solar radiation, subsurface moisture, subsurface temperature, construction ambient conditions, unusual and/or catastrophic events, freeze/thaw cycles, freezing days, and others.

Successful forensic investigations require the collection of information pertaining to pavement performance and the factors affecting that performance. Depending on the application, pavement performance measures may include one or more of the following elements:

- Pavement distress data (using manual or automated distress surveys): for asphalt surfaces this includes cracking, patching and potholes, surface deformation, surface defects, and miscellaneous distresses; for jointed plain concrete surfaces this includes cracking, joint deficiencies, surface defects, and miscellaneous distresses; for continuously reinforced concrete surfaces this includes cracking, surface defects, and miscellaneous distresses.
- Pavement deflection data (using FWD or other devices): maximum deflection, deflection basin, deflection indices, layer moduli, overall structural capacity, load transfer and voids, other deflection parameters, longitudinal and transverse variability, etc.
- Pavement roughness/elevation data (longitudinal and/or transverse): pavement roughness, International Roughness Index (IRI), rutting, elevation versus station, other roughness parameters, longitudinal and transverse roughness variability, etc.
- Pavement surface friction data: surface macro-texture, surface micro-texture, skid resistance, other friction parameters, other considerations, and longitudinal and transverse friction variability.
- Tire pavement noise: surface macro-texture, surface micro-texture, faulting in PCC, pavement surface tining and grooving, clogging and/or raveling of open-graded friction courses, longitudinal and transverse noise variability, and other considerations.

Similarly, information regarding the factors that influence pavement performance may include one or more of the following elements:

- Pavement structure and subgrade soil information available or obtained through one or more of the following methods: trenching, test pits and coring/boring, ground penetrating radar (GPR), dynamic cone penetrometer (DCP), drainage surveys (video or other means), field materials sampling and testing activities (e.g., tube suction and retain strength tests), laboratory materials testing, specialized testing (digital and scanning electron microscope analysis, and chemical tests), pachometer surveys of JPC and CRC, MIT scan (magnetic tomography technology) of portland cement concrete (PCC), and other destructive and non-destructive testing techniques.
- Traffic information available or obtained through one or more of the following methods: automatic traffic recorder (ATR) or automatic vehicle classifier (AVC) counts, weigh-in-motion (WIM) measurements, average daily traffic (ADT) and estimated single-axle load (ESAL) estimates (if monitoring data is not available).
- Environmental information available or obtained from one or more weather stations (e.g., National Climatic Data Center), from a road weather information system (RWIS), or through the use of surface and/or subsurface instrumentation.

Unless it is already available, gathering the information on all of the pavement performance measures and all of the factors affecting pavement performance is unnecessary and generally beyond the available resources of most state highway agencies. Forensic investigations may contain common elements amongst them, but the actual elements will ultimately depend on the forensic investigation application and relevant pavement factors. FWD testing, distress surveys, GPR surveys, and coring, for example, may be common to pavement failure/poor performance investigations but these techniques may not be necessary for pavement friction and/or noise-related issues. Accordingly, another critical element in an investigation is achieving the best balance between requirements, priorities, and available resources. Clearly setting and understanding the objectives of the investigation should aid in determining the appropriate data that should be collected.

3.2 Generic Issues

A clear understanding of the reasons for conducting a forensic investigation and how the results will be used is important. However, there are three other elements that need to be addressed in advance of consideration of any forensic investigation. They are:

- Establishing a protocol for forensic investigations,
- Identifying and appointing forensic investigation personnel, and
- Developing forensic investigation documentation procedures.

The activities associated with these elements are shown in Figure 1.

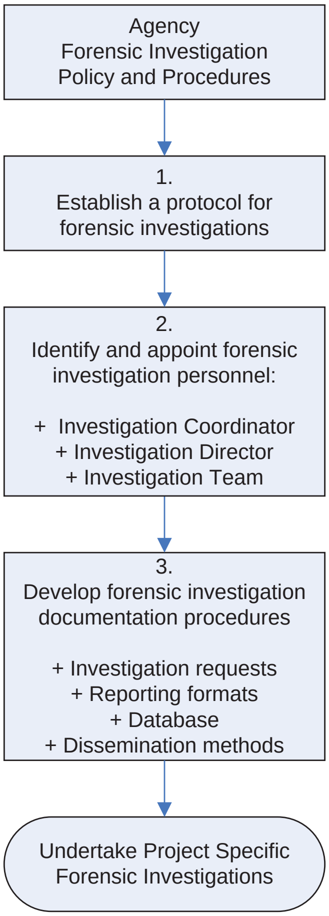


Figure 1. Generic issues.

To ensure that forensic investigations are performed in a consistent and systematic matter, it is important that an agency establish a forensic investigation protocol. This practice will increase the chances of success and ensure consistent reporting of results throughout an agency; help justify changes to guidelines, manuals, specifications, and current practices; and eliminate the recurrence of problems. This protocol should be communicated to individuals in the agency, and they should be encouraged to follow it. The protocol should include:

- Reasons for having the protocol,
- Agency approach to:
  - Assembling forensic investigation teams.
  - Requesting a forensic investigation.
  - Undertaking forensic investigations.
- Procedures for documentation and dissemination of findings, and
- Procedures for implementing findings and/or adopting recommendations.

Three alternate approaches to the formation of the forensic investigation team were reported in the literature: (1) the team is established on a project-by-project basis and it typically consists of both contractors and highway agency personnel; (2) a project specific team approach, where the team is established based on the magnitude of the investigation and the controlling jurisdiction; and (3) a permanent team to handle all forensic investigations.

There are advantages and disadvantages to each of these approaches. The establishment of a permanent team, for example, provides continuity, consistency and uniformity to forensic investigations within the state. This approach also provides for a group of individuals who are easy to identify and to contact to handle investigation requests, make go/no-go decisions, etc. However, establishing a permanent team that undertakes all investigations is often not feasible because of the range of expertise required to handle all potential applications.

The formation of a virtual team of one or two key, permanent individuals from within the highway agency who select other team members depending on the issue being investigated has desirable features. This approach makes good use of the available resources by providing a permanent focus group (consistency and document management), but allows tailoring of the team (specific expertise) to address project specific conditions (e.g., asphalt vs. concrete), objectives, and level of investigation.

Also of importance is the establishment of forensic investigation documentation procedures within the highway agency. Specifically, a document management process and an auditable documentation trail of each investigation will help move away from the case study approach that has been historically used by highway agencies towards the build-up of knowledge (lessons learned) and the consistent dissemination of results throughout the agency. In this manner, the information provided by the document management process will enable highway agencies to justify changes to construction practices and specifications, address problem issues to avoid recurrence, or improve performance.

A key element of the documentation procedures is the establishment of an agency protocol for requesting an investigation, including a form for requesting an investigation and a communication channel to ensure that forms are directed to the forensic investigation team leader. Another key element is the establishment of a standard reporting format, including checklists, forms, records of decision, investigation reports, implementation of recommendations, etc. Yet another key element is the establishment of a means of dissemination such as a website, paper and web-enabled reports, a database, workshops and webinars, or an annual DVD.

Because information on forensic investigation documentation procedures is not readily available, the establishment of such procedures was a critical element of the guide. Recommendations for establishing the database architecture and critical elements are provided.

3.3 Project Specific Issues

Once the generic agency issues have been addressed, project specific issues must be considered as part of a forensic investigation. These project specific issues are shown in Figure 2 and listed in chronological order from the planning of the investigation to the close-out activities, as follows:

- Preparing a forensic investigation request: a forensic investigation begins with one or more individuals within or associated with the highway agency requesting an investigation. Establishing the need for such an investigation should then be addressed; i.e., why should the investigation be undertaken, what are the associated expectations, and how will the results be used. Therefore, the use of a standard "forensic investigation request form" is considered an appropriate tool and hence was included in the guide. This form will provide basic information necessary for understanding why the investigation is necessary.
- Initiating the forensic investigation: within the documentation procedures, it is necessary to acknowledge receipt of the forensic investigation request and to open a forensic investigation file for the project in question. To ensure consistency among investigations and to maximize the benefits from these investigations, the contents of the file should be specified.
- Undertaking a background study: the purpose of this study is to determine whether or not the requested investigation is indeed necessary, the required level of investigation, and the objectives that need to be met. Activities under this element of the investigation typically include:
  - – Determining whether the request is valid and the objective is appropriate, and if so, establishing a preliminary hypothesis as to the probable reasons for the noted pavement observation/performance.
  - – Collecting relevant information, including:
    - ▪ An interview with individuals requesting the investigation,
    - ▪ Interviews with agency and industry personnel familiar with the road/project, and
    - ▪ Gathering relevant information (e.g., design and as-built/constructed information; pavement management system data; maintenance records; and climate, traffic, and other relevant information such as accidents and incidents).

  The outcome of this effort is a brief report that contains information about the request for the investigation, the summary of available information, justification for and expected benefits from undertaking the investigation, priorities and suggested level of investigation, preliminary estimate of resources, and record of decision (i.e., go or no-go decision).
- Completing a standard "record of decision form," "available and missing data/information form," "site visit form," and "summary report" is important to the successful completion of the activities to be carried out under this element of the forensic investigation. These forms as well as a suggested summary report template are included in the guide.
- Preparing a detailed investigation plan: if the decision is made to proceed with the investigation, the next step is to prepare a detailed investigation plan. This plan will typically include:
  - – Selecting the forensic investigation team. Guidance must be provided as to the composition and expertise of the team as well as the roles and responsibilities of the individual team members based on the issues being investigated. Ultimately, this team will develop the detailed investigation plan.
  - – Preparing clear and concise objectives, including an understanding of how the results will be used.
  - – Establishing the nature of the investigation: general investigation (e.g., premature failure on a highway) or investigation of a research test section.
  - – Selecting an appropriate level of investigation to meet the objectives and to balance requirements and resources, and understanding the consequences of not undertaking the appropriate level of investigation. The level of investigation can range from simple visual assessments, to non-destructive testing, to coring, and/or to test pits and trenches. Selecting a higher than necessary

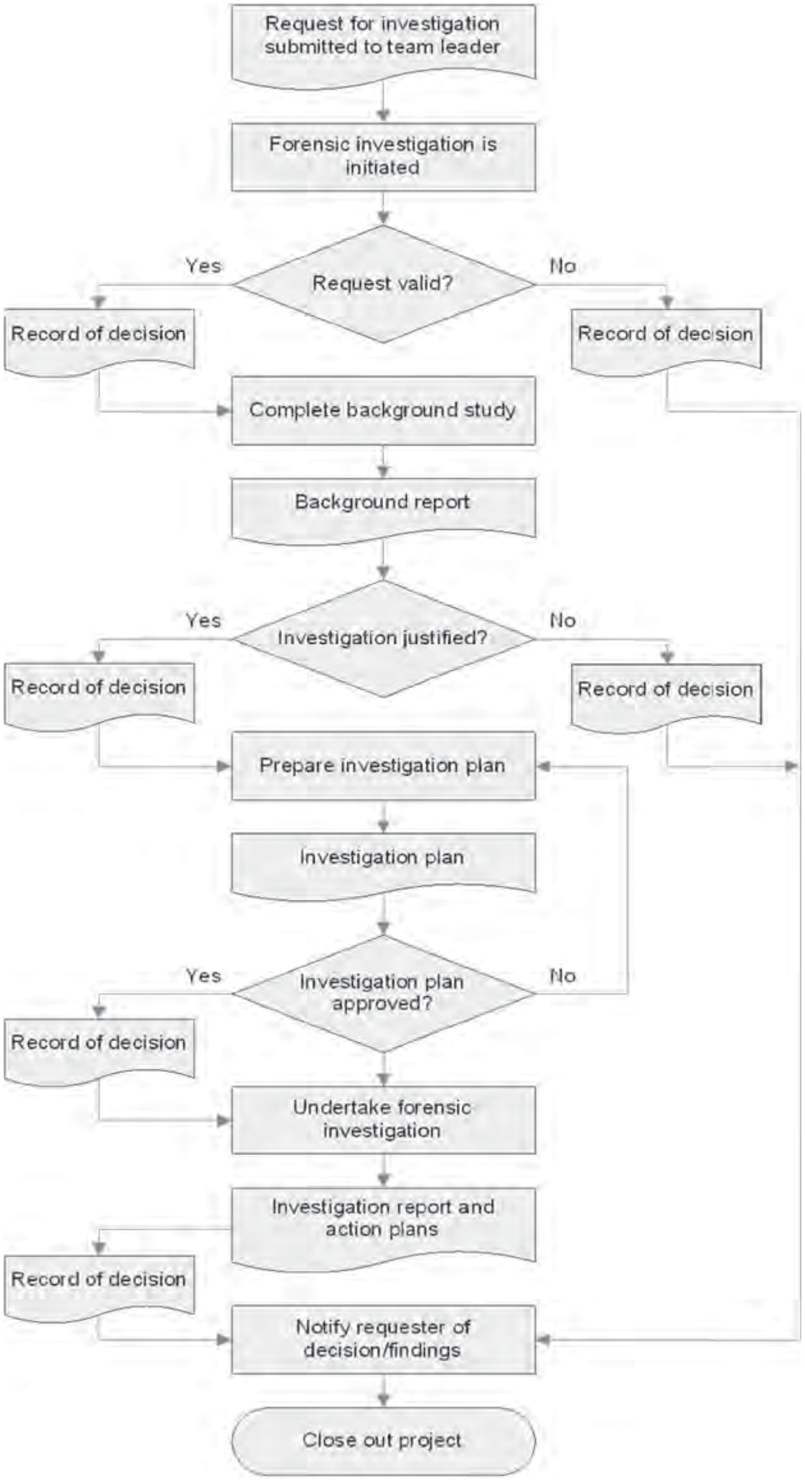


Figure 2. Project specific issues.

level of investigation will result in a waste of time and resources. Conversely, selecting a less than necessary level of investigation will lead to an inadequate evaluation and possibly inadequately address the issue and require follow-up actions.

– Performing a pre-investigation site visit to: (1) establish longitudinal and transverse limits of the forensic investigation project either visually or with non-destructive testing; (2) visually assess the delineated forensic investigation project section; (3) establish the surface condition, longitudinal and transverse variability, and identify "good" and "bad" comparison sections; (4) identify locations for destructive testing if required; (5) assess safety, traffic control, logistical, and time requirements;

and (6) document the project site using photographs and/or videos.

  - Writing an investigation plan that addresses the activities that need to be performed in order to meet the objectives. This plan must address the following:
    - Use of data available,
    - Logistical arrangements (e.g., road closures, notifications, team and equipment availability, etc),
    - Schedule (including dates and times for each resource and activity),
    - General data requirements (e.g., traffic, weather, other environmental, etc.),
    - Visual assessment requirements (including on-road and adjacent to road such as drainage and slope stability),
    - Non-destructive testing requirements (including types of test, numbers of tests, test locations, and protocols that should be followed such as FWD, GPR, profilometer, skid tester, and noise measurements),
    - Destructive testing requirements (types of test, numbers of tests, test locations, test methods and test protocols, and repairs after testing — e.g., coring [dry or wet], boring, trenches, test pits [dry saw cut or wet saw cut], DCP, etc.),
    - Sampling requirements (including location of samples, conditions under which samples should be taken, quantity of samples, packaging and storing of samples, and location where samples should be delivered),
    - Routine and/or specialized laboratory testing requirements (e.g., Atterberg limits, gradations, mix asphalt content/voids/specific gravity, SuperPave tests, PCC compressive strength, resilient/complex modulus, thermal coefficient of expansion, as well as chemical analyses, microscope analyses, and CT scans), including test methods and number of tests,
    - Data analysis requirements (including protocols),
    - Reporting requirements (including how the results should be interpreted and used to address the investigation objective),
    - Investigation plan review and approval, and
    - Record of approval of plan.

  To ensure consistency and uniformity among investigations, the use of flowcharts, checklists, templates, examples and forms is necessary; such forms have been included in the guide. Similarly, the use of matrices detailing typical activities associated with the different forensic investigation applications and pavement types is important; such matrices have also been included in the guide.

- Implementing the forensic investigation plan: this element of the investigation entails undertaking the actual investigation and recognizes that a number of issues may not have been addressed as part of the detailed investigation plan. Issues that could potentially need to be addressed at this stage include:
  - Specific details concerning the investigation arrangements, which may not have been considered,
  - Specific details concerning visual assessments (e.g., "expecting the unexpected," roadside activities such as the use of side drains for irrigation channels, blocked drains, filled-in drains and plough furrows perpendicular to the road, construction and/or road use irregularities, etc.),
  - Specific details concerning destructive testing (e.g., special coring procedures such as taking dry cores if moisture damage is being investigated, additional information on logging of cores and interpretation of observations, as well as timing of specific observations in relation to removal of the core),
  - Specific information on the excavation of test pits/trenches and preparing the test pit faces, specific information on the logging of test pits/trenches as well as timing of specific observations in relation to opening of the test pit, or adjusting the sampling and laboratory testing plan based on observations,
  - Specific information on in-pit testing including density, DCP, and chemical tests (e.g., to assess carbonation of cemented layers, presence of deleterious materials, etc.).

  The guide covers specific issues not typically addressed in manuals and procedures, but does not cover the basics of coring procedures, excavation of test pits/trenches, etc.

  In addition, this phase of the investigation must also address the following items:

- Analyzing the collected data and testing the preliminary hypothesis proposed at the beginning of the investigation.
- Preparation of the forensic investigation report using a standard format that covers, as a minimum, the following items:
  - Executive Summary,
  - Introduction,
  - Objectives and hypothesis,
  - Final investigation plan,
  - Observations and measurements,
  - Analysis and interpretation,
  - Findings and conclusions,
  - Recommendations,
  - Lessons learned,
  - Dissemination of findings,
  - Investigation costs and cost/benefit analysis (if applicable), and
  - Location of data files.
- Turning the investigation results into actions and disseminating the lessons learned.
- Closing-out of the investigation, including sending notifications, initiating actions, completing the documentation

process, closing the project file, and updating the forensic investigations database as appropriate.

As was the case with the preparation of the detailed investigation plan, the use of flowcharts, checklists, examples, matrices, and forms is necessary for implementation of the plan and ensuring consistency and uniformity among investigations; they are also included in the guide. Recommendations for developing a forensic investigations database have been provided in the guide.

4. Guide Development

The process of developing and assessing the forensic investigation guide is described in this chapter.

4.1 Preliminary Guide

The preliminary guide was developed through the following means:

- Use of information gathered during the literature review and from the state highway agency survey questionnaire responses. This information was particularly useful in addressing the project specific issues.
- Communications with state highway agencies such as the California, Colorado, Illinois, and Texas DOTs, which already have forensic investigation guidelines in place and also with other agencies such as the Minnesota and Virginia DOTs, which have performed numerous forensic investigations. These communications helped address the generic issues because limited information was found in the literature.
- Relevant forensic investigation experience of the project team.

The initial version of the guide consisted of the following five parts:

- Introduction: described what forensic investigations are, detailed the objectives and scope of the guide, provided an overview of the key forensic investigation elements, and summarized the organization of the guide.
- Generic Agency Issues: provided a procedure to help the state highway agency establish a forensic investigation team and forensic investigation documentation procedures. Although these issues are applicable to all forensic investigations, they must be periodically reviewed and updated to account for organization changes and technological advances. The formation of a virtual team in which one or two key individuals select other team members depending on the issue being investigated was recommended. This approach provides a permanent focus group, but allows tailoring of each team to address project specific conditions, objectives, and level of investigation. Key elements of the documentation procedures include the establishment of (1) a policy for requesting an investigation, (2) a standard reporting format, and (3) dissemination options for use by the agency.
- Project Specific Issues: provided a step-by-step procedure to help state highway agencies logically and sequentially conduct forensic investigations on a project-by-project basis. These steps included:
  - Preparing forensic investigation requests;
  - Initiating forensic investigations;
  - Undertaking background studies (determine if the request is valid and the objective appropriate, establish an initial hypothesis as to the probable cause of the pavement condition, collect relevant information, and make go or no-go decisions);
  - Preparing detailed investigation plans (select a forensic investigation team, prepare clear and concise objectives, establish the nature of the investigation, select an appropriate level of investigation to meet the objectives and to balance requirements and resources, pre-investigation site visit to plan the investigation, and write an investigation plan that addresses activities that need to be performed); and
  - Implementing forensic investigation plans (address specific details concerning the investigation, such as how to analyze the data collected, prepare the forensic investigation report using a standard format, turn the results into actions, disseminate the lessons learned, and close-out the investigation).
- References: provided lists of relevant reference material used in the development of the guide.
- Appendices: provided sample checklists, forms, matrices, and example completed checklists and forms in support of the generic and project specific issues described in the guide.

To develop a practical guide and to ensure consistency and uniformity among investigations, it was necessary to include flowcharts, checklists, examples, and forms, as well as matrices detailing typical activities associated with the different forensic investigation applications and pavement types. In progressing to finalizing the guide, it was concluded that the most rational approach for conducting a forensic investigation would involve three phases:

- Background Study — collecting available project information and determining if it is sufficient to answer the questions posed in establishing the investigation.

- Preliminary Investigation — performing non-destructive data collection (e.g., FWD, longitudinal profile) and analysis, and once again determining if it is sufficient to answer the questions posed in establishing the investigation.
- Final Investigation — following the plan developed based on all information collected to date, and performing destructive data collection (i.e., coring, test pit) and analysis. As with the first two parts, this also concludes with determining if it is sufficient to answer the questions posed in establishing the investigation.

  By performing investigations in these three phases, agency resources will be optimized. For example, if the background study clearly answers the questions associated with the investigation, then the costs associated with non-destructive and destructive sampling, testing, and analysis would be saved for those investigations where a background study is insufficient.
- Forensic investigation case studies are included as an appendix to the guide. These case studies were selected to cover representative examples and to demonstrate how the guide applies in each instance.

The preliminary guide was used in conducting the field assessments detailed in the next section.

4.2 Assessment of Preliminary Guide

4.2.1 Field Assessment Plan

The purpose of this effort was to prepare a plan for assessing the preliminary guide using in-service pavements. The plan provided specific information on the proposed sites, data collection effort, anticipated level of participation by the highway agency, and other relevant information.

Thirteen state highway agencies expressed interest in supporting the field assessments, but only six state DOTs participated in the field assessments: California, Kentucky, Minnesota, Ohio, Oregon, and Virginia. These states cover three AASHTO Regions; attempts to include an agency within Region 1 were unsuccessful. Based on these responses, assessment of the preliminary guide was planned for six in-service pavements. These pavements address different pavement types and were strategically selected across the United States to provide representative geographical/climatic/geologic coverage. It was expected that multiple objectives could be assessed at each of the six sites, some of which are listed below:

- Investigating the underlying causes of premature pavement failures.
- Understanding the factors contributing to exceptional pavement performance and longevity.
- Collecting data to support development and/or calibration of performance prediction models, including materials and pavement performance information.
- Collecting data to support investigation into the long-term effects of traffic and the environment on layer and material (HMA, PCC, etc.) properties.

The field assessment plan presented in Table 2 details geographical location (state), pavement type, and purposes of the forensic investigations for the six field assessment sites. One site each was proposed for California, Kentucky, Minnesota, Ohio, Oregon, and Virginia. Four of the sites were asphalt surfaced pavements and the other two sites were concrete surfaced pavements. Two investigation objectives were planned for each site with the exception of California, where three were planned, resulting in a total of 13 investigations.

Table 2. Field assessment plan by highway agency.

Pavement Type	Investigate Poor Performance/ Pavement Failure	Understand Exceptional Performance	Development/ Calibration of Performance Models	Quantify Long-Term Traffic and Environment Effects
New AC		California (CA-1-1)	California (CA-1-2)	California (CA-1-3)
New PCC		Ohio (OH-1-1)		Ohio (OH-1-2)
AC Overlay on AC	Oregon (OR-1-1)	Virginia (VA-1-1)	Oregon (OR-1-2)	Virginia (VA-1-2)
AC Overlay on PCC	Kentucky (KY-1-1)		Kentucky (KY-1-2)	
PCC Overlay on PCC		Minnesota (MN-1-1)		Minnesota (MN-1-2)

Notes: First two letters in parentheses denote the state abbreviation, first number denotes the field assessment site within the state, and second number denotes the investigation within the agency.

To maximize the benefits to the state highway agencies as well as to the project, participating agencies were asked to assist with activities such as traffic control, coring/trenching, and pavement repairs.

Each of the agencies was provided with a copy of the preliminary guide at least 1 month in advance of the actual field assessments. The preliminary guide described the activities associated with the field assessments, including the following:

- Conducting an initial meeting with each agency to review and discuss generic agency issues and to plan the preliminary investigation according to the guide.
- Supporting agencies with completion of the preliminary investigation. If the preliminary investigation fully answered the questions of the investigation, then the project team would support the agencies with completion of the investigation as detailed in the guide; no further work would be required.
- Conducting a second meeting with each agency to review, discuss, and plan the non-destructive testing investigation detailed in the guide.
- Supporting agencies with the actual conduct of the non-destructive testing investigation, which could include activities such as distress surveys, GPR surveys, FWD testing, DCP testing, and roughness surveys. If the non-destructive testing investigation fully answered the questions of the investigation, then the project team would support the agencies with completion of the investigation as detailed in the guide; no further work would be required.
- Conducting a third meeting with the agencies to review, discuss, and plan the destructive/laboratory testing investigation detailed in the guide.
- Supporting agencies with the actual conduct of the destructive/laboratory testing investigation, which could include activities such as coring, trenching, routine laboratory testing, and specialized laboratory testing. On completion of the destructive/laboratory testing investigation, the project team would support the agencies with completion of the investigation as detailed in the guide.

In addition to the project team's experiences and lessons learned from the field assessments, the agencies provided valuable input towards finalizing the guide, by means of comments on the preliminary guide and the field assessments. It was also anticipated that summaries of the field assessments would be included in the case studies appendix (Appendix B) of the guide.

4.2.2 Field Assessments

The assessment process was led by agency personnel and not by team members to provide more relevant feedback. Field assessment activities began in the summer of 2011 and were completed in the spring of 2012. The conduct of the assessments varied from agency to agency, as described in the following sections. Details of these investigations are provided in Appendix B of the guide.

4.2.2.1 Virginia

The project selected by the Virginia DOT (VDOT) for the field assessment was an AC section on Interstate 81 that was exhibiting exceptionally good performance. A previous internal investigation had concluded that the observed performance was due to subsurface drainage improvements performed in a previous rehabilitation.

During the initial assessment meeting, roles and responsibilities of the various participants were reviewed. VDOT chose to have the investigation effort be led by a district materials engineer, with support from others in VDOT and the Virginia Center for Transportation Innovation and Research (VCTIR). Also, a site visit was performed and the potential contributing factors to the pavement performance were discussed.

As part of the preliminary investigation phase, VDOT prepared a report containing information on the construction history, soils, geology, traffic, climate, and performance data. The report concluded that another contributing factor to the observed performance was an over-estimation of traffic during the design. To confirm various report elements, VDOT decided to proceed with the non-destructive testing (NDT) phase. The three techniques selected were edge drain videos, GPR, and FWD. The edge drain videos indicated that the drainage had clogged in a few locations and that the underdrains were not in place for the full length of the test section, while the GPR results indicated the travel lane was about 2 in. thicker than the passing lane. The FWD data showed a uniform, high structural capacity throughout the section.

Based on the findings from the first two phases, VDOT concluded that the original hypothesis was incorrect and that the primary reason for the exceptional performance was the thicker than designed pavement together with actual traffic loading below the design loads. To confirm these conclusions, VDOT proceeded with a destructive phase. A test pit was excavated on the shoulder, immediately adjacent to the pavement travel lane to confirm the GPR-derived layer thicknesses, especially the asphalt concrete layer, and to conclusively establish the presence or not of edge drains. The test pit confirmed the absence of edge drains and the accuracy of the GPR-derived layer thicknesses.

4.2.2.2 Ohio

The Ohio DOT (OhDOT) field assessment focused on the exceptionally good performance of a number of PCC pavement sections that are part of the Specific Pavement Studies (SPS 2) experiment of the Long-Term Pavement Performance (LTPP) program. These sections, located on the north end of the project, were outperforming those on the south end of the project. It was hypothesized that the water table level and construction timing was the reason for the better performance on the northern end.

During the initial assessment meeting, roles and responsibilities of the various participants were reviewed. An OhDOT headquarters pavement engineer was charged with leading the investigation with assistance from Ohio University, as needed. A site visit, also carried out as part of the initial meeting, confirmed that the PCC sections were in excellent condition with little cracking and no faulting. Some sections had received dowel bar retrofitting of transverse cracks.

Because the pavement sections in question were part of the LTPP program, a significant amount of data were available (including on-site WIM). As a result, the OhDOT field assessment was concluded during the preliminary investigation phase without the need for NDT or destructive testing. The exceptionally good performance of the pavement sections in question was attributed to less built-in curl resulting from lower air temperatures, lower placement temperatures, and use of concrete mixtures with low cement contents.

4.2.2.3 Minnesota

The selected project was approximately 10 miles long and consisted of an 8.5 in. PCC overlay over a 9 in. PCC pavement (with a 1.5 to 3 in. bond breaker). The overlay was placed in 1998 and was performing exceptionally well. A significant amount of information had been compiled in advance of the initial assessment meeting, but no hypothesis had been established. A Minnesota DOT (MnDOT) intern was assigned to lead the assessment activities with support from MnRoad personnel (including a MnRoad forensic engineer).

The preliminary report, which contained relevant information regarding the pavement structure, soils, traffic, climate, and pavement performance, was provided along with a set of completed forms from the guide. The report attributed the exceptional performance to relatively low traffic volumes, good drainage, good materials in the base and subbase, and good pavement base structure.

While the preliminary report concluded that there was no need to proceed to the NDT evaluation phase, selected NDT activities were recommended to strengthen the conclusions. These included the collection and analysis of GPR data, FWD testing, and drainage videos. However, these NDT activities were not carried out due to weather and staff availability constraints.

4.2.2.4 Kentucky

An engineer in training from the maintenance section of the Kentucky Transportation Cabinet (KYTC) Pavement Management Division was charged with conducting the assessment. The engineer reviewed a number of potential projects related to premature failure of AC overlays on PCC pavements and initially proposed a project that had received an overlay in 2009 that was exhibiting reflection cracking.

As part of the preliminary report, the purpose of the investigation was modified to comparing the performance of thick and thin AC overlays on PCC pavements. The report concluded that thin AC overlays do not perform as well as thick ones and that adequate overlay thickness must be provided to control reflective cracking.

While considerable useful information was compiled as part of the preliminary investigation phase, FWD testing was recommended as part of the NDT phase to strengthen the conclusions, but such testing was not performed because of resource constraints.

4.2.2.5 Oregon

The Oregon DOT (OrDOT) field assessment was led by a pavement specialist from the construction section. The purpose of the investigation was to determine the cause of premature rutting at three intersections that were rehabilitated with mill-and-asphalt inlay. The binder grade originally used was changed after significant rutting within days of beginning paving. Within 1 year, the re-blended mix exhibited substantial rutting and shoving. However, projects paved the following construction season with the same binder grade did not have this issue.

Following the initial assessment meeting, the preliminary data review included studying available materials data such as asphalt binder content, laboratory determined air voids, maximum specific gravity, bulk specific gravity, voids in the mineral aggregate (VMA), voids filled with asphalt (VFA), gradation, and field compaction. Mix design, quality control, and inspector's data were also reviewed. The hypothesis was that a combination of material properties and construction practices caused the premature failure.

Due to the rapid onset of the rutting, a decision was made not to pursue the NDT phase, but to move directly to developing a plan for destructive and laboratory testing. Cores were taken from areas of rutting and from areas where no rutting was observed. Eight control samples from the original mix were also obtained. Tests for asphalt content, air voids, VMA, and VFA all showed indications of a rut-susceptible mix. In addition to the high asphalt content and low air void content, the VFA and aggregate gradation on one or more sieves did not meet OrDOT specifications. Review of the QC/QA data for the replacement mix, which also exhibited rutting, albeit at a slower rate than the original mix, showed VFA above the specification for most specimens tested.

Upon analyzing the information gathered, the cause for the premature rutting was attributed to a combination of factors. Primary among these was the high VFA, with the high asphalt binder content, low air voids, and a change made during construction to use lighter rollers during compaction also contributing to the failure.

4.2.2.6 California

The California Department of Transportation (Caltrans) project involved a premature failure (alligator cracking and potholes in the outer wheel path and shoulder) on a recent mill-and-overlay and widening project. The assessment was led by an engineer from the Office of Flexible Pavements in the Division of Pavement Management. The team included others from the same office and district staff involved in the project.

The project started with a review of the original project investigation, the project design, and the construction records. This was followed by a preliminary site visit to gather additional information, identify the limits of the investigation, and identify areas of good and poor performance within the project, with an attempt to isolate the cause of the poor performance. A lack of structural adequacy and/or possible base failure was observed.

Because no conclusive evidence identifying the cause of the problem was found during the preliminary phase, the investigation proceeded to the NDT phase (GPR and FWD) in an attempt to identify additional potential causes of the problem, including variation in the structure, differences in overlay thickness, and the presence of moisture. Based on the information collected, it was determined that for safety reasons, an undocumented lateral shift was made during rehabilitation that resulted in a portion of the overlay being loaded on a significantly reduced pavement structure.

4.3 Revised Guide

The experience gained from the field assessments and the comments provided by the participating agencies were used to revise the guide. The guide contains nine chapters. Chapter 1 provides background information and the objectives, scope, approach, and organization of the guide. Chapter 2 summarizes the philosophy behind forensic investigations and the approach followed in this guide. Chapter 3 addresses requests for and initiation of a forensic investigation, including conduct of a preliminary investigation or background study. Chapter 4 covers the planning of the investigation, including selection of the investigation team, pre-investigation site visit, and NDT requirements. Chapter 5 discusses NDT, analysis of the data collected, the preparation of an interim report, and making a decision on the adequacy of the collected information to address the issues being investigated. Chapter 6 covers updating the investigation plan based on the NDT analysis. Chapter 7 discusses destructive field testing and laboratory testing of samples and specimens removed from the pavement. Data analysis and hypothesis testing, and preparation of the final report are covered in Chapter 8. Chapter 9 includes review of the investigation, actions resulting from the investigation, and close-out of the investigation. Chapters 3 through 9 offer a suggested approach and are written in a procedural style to improve readability. This approach can be modified to suit agency procedures and expertise.

5. Summary, Conclusions, and Recommendations

NCHRP Project 01-49 developed a guide for conducting forensic investigations of highway pavements. The following sections provide an overview of the process, as well as major conclusions and recommendations resulting from the project effort.

5.1 Summary

Following a thorough review of existing practices and input from state highway agencies, a comprehensive guide regarding the conduct of pavement forensic investigations was developed. This guide was designed to support a wide range of purposes and a varying degree of experience by the individuals performing the investigation.

Responses received from 37 state highway agencies indicated that six of the 37 did not perform forensic investigations, while the other 31 agencies performed investigations for the following reasons:

- Investigate underlying causes of pavement failure (30 of 31)
- Collect data to support development and/or calibration of performance models (16 of 31)
- Collect data to support investigation into the long-term effects of traffic and the environment on layer and materials properties (13 of 31)
- Understand factors contributing to exceptional pavement performance (9 of 31)
- Other (6 of 31)

A preliminary guide was developed and assessed through field investigations in six states. The guide was then revised based on the field investigation results. Key elements of the revised guide include:

- A general investigation philosophy to help users better understand forensic investigations and, in turn, to ensure the successful implementation of the guide. The philosophy entails the following three fundamental aspects:
  - Understanding pavement performance and factors that affect it,
  - Recognizing pavement performance data and information needs, and

  - Avoiding premature conclusions about pavement performance.
- A phased approach to forensic investigations to optimize agency resources. The phases include:
  - A desktop study of available project information,
  - NDT and analysis, and
  - Destructive testing and analysis.
- Consideration of generic agency issues not tied to a specific investigation, but critical to the success of an agency's forensic investigation program. Those issues include:
  - Establishing a protocol for forensic investigations,
  - Identifying and appointing forensic investigation personnel, and
  - Developing forensic investigation documentation procedures.
- Case studies selected to cover representative examples of forensic investigations and to demonstrate how the guide applies in each instance.
- Examples of forms and checklists recommended for use in forensic investigations.

5.2 Conclusions

Through the performance of this project, a number of relevant conclusions were drawn, including the following:

- There is a need for a formal forensic investigation process in many state highway agencies. In some instances, this is due to staff turnover and in others it will be a mechanism for ensuring that problems are not repeated and specifications, test methods, manuals, and guidance documentation are changed to reflect the learning that occurs in a forensic investigation. The guide will be particularly helpful to those with no or limited pavement forensic investigation experience.
- When selecting the forensic investigation coordinator, it is important to have this individual sufficiently high in the organizational structure to facilitate any requisite data collection, testing, and analysis activities.
- Following a phased approach will be beneficial to state highway agencies so that time, money, and resources can be saved, and because the need for destructive testing may be eliminated where it is not necessary.
- Keeping an open mind is an important element for a successful investigation; focusing on a single factor as the sole basis for the performance of a given pavement should be avoided.
- A decision tree approach does not lend itself well to forensic investigations—there are too many variables to consider and a prescriptive process might miss key contributing factors and interactions.
- Understanding exceptional performance can be more challenging than determining the causes of poor performance.
- There are significant issues related to documentation of forensic investigations and implementation of the findings. An investigation is not successful if the findings are only available to those who participated in the investigation.
- Implementation of investigation findings is a necessary step to accrue the benefits of the investigation.

Considering that many of the assessment investigations did not require the destructive testing phase, the phased approach appears to be most effective in using the least resources to address the issues being investigated, recognizing that more expensive sampling and testing activities should be performed only when absolutely necessary. These savings can be used for performing additional investigations or updating guidance documents, manuals, test methods, codes of practice, and specifications to incorporate what has been learned from the investigations.

5.3 Recommendations

Highway agencies are expected to benefit from the guide prepared in this project to varying degrees, depending on the agency's experience with forensic investigations, and particularly with the effort spent on the generic issues overriding the entire forensic investigation process. However, to enhance these benefits, two elements in particular need to be considered:

- Establishing a consistent process for staffing forensic investigations. A virtual team for the conduct of investigations, from which specific members would be involved with any particular investigation based on the elements of the investigation, is highly desirable. This approach allows for maximum flexibility within available resources. Alternate approaches include establishing a permanent forensic team (likely an option only for large agencies) or a different investigation team for every project.
- Developing documentation procedures that ensure an auditable documentation trail, facilitate the build-up of knowledge throughout the agency, and aid the implementation of investigation findings.

Creating a national repository for forensic investigations would also be extremely beneficial to the pavements community. A National Highway Pavements Forensics Clearinghouse would be a valuable online resource that could allow the sharing of information between agencies, and support consistent documentation of completed investigations.

Abbreviations and acronyms used without definitions in TRB publications:

A4A	Airlines for America
AAAE	American Association of Airport Executives
AASHO	American Association of State Highway Officials
AASHTO	American Association of State Highway and Transportation Officials
ACI–NA	Airports Council International–North America
ACRP	Airport Cooperative Research Program
ADA	Americans with Disabilities Act
APTA	American Public Transportation Association
ASCE	American Society of Civil Engineers
ASME	American Society of Mechanical Engineers
ASTM	American Society for Testing and Materials
ATA	American Trucking Associations
CTAA	Community Transportation Association of America
CTBSSP	Commercial Truck and Bus Safety Synthesis Program
DHS	Department of Homeland Security
DOE	Department of Energy
EPA	Environmental Protection Agency
FAA	Federal Aviation Administration
FHWA	Federal Highway Administration
FMCSA	Federal Motor Carrier Safety Administration
FRA	Federal Railroad Administration
FTA	Federal Transit Administration
HMCRP	Hazardous Materials Cooperative Research Program
IEEE	Institute of Electrical and Electronics Engineers
ISTEA	Intermodal Surface Transportation Efficiency Act of 1991
ITE	Institute of Transportation Engineers
MAP-21	Moving Ahead for Progress in the 21st Century Act (2012)
NASA	National Aeronautics and Space Administration
NASAO	National Association of State Aviation Officials
NCFRP	National Cooperative Freight Research Program
NCHRP	National Cooperative Highway Research Program
NHTSA	National Highway Traffic Safety Administration
NTSB	National Transportation Safety Board
PHMSA	Pipeline and Hazardous Materials Safety Administration
RITA	Research and Innovative Technology Administration
SAE	Society of Automotive Engineers
SAFETEA-LU	Safe, Accountable, Flexible, Efficient Transportation Equity Act: A Legacy for Users (2005)
TCRP	Transit Cooperative Research Program
TEA-21	Transportation Equity Act for the 21st Century (1998)
TRB	Transportation Research Board
TSA	Transportation Security Administration
U.S.DOT	United States Department of Transportation