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16. Abstract

The Texas Department of Transportation (TxDOT) supported a research project designed to develop formal procedures for conducting forensic investigations on failed pavements. This report describes such a procedure, one based on a scientific method that can ensure that future investigations are completed more efficiently and effectively. The main advantages of a successful forensic investigation include (1) determining the cause of the distress, (2) selecting the appropriate repair strategy, (3) determining how fast the distress is propagating, (4) prioritizing distressed pavement sections, (5) improving design practices, and (6) updating construction techniques. This report discusses the uses and benefits of the resources that are available to TxDOT. These resources include the field diagnostic manual, the detailed diagnostic manual, the electronic version of the diagnostic manual, and the ForenSys database. Finally, regarding the future direction of pavement investigations, the researchers recommend, among other things, the creation of a Knowledge-Based (KB) Engine.

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DEVELOPMENT OF A FORMAL FORENSIC INVESTIGATION PROCEDURE FOR PAVEMENTS

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Project Summary Report Number 0-1731-3F

Research Project 0-1731
Development of a Methodology for Identifying Pavement Design Construction Data Needed to Support a Forensic Investigation and Development of a System to Store and Report this Data

Conducted for the

TEXAS DEPARTMENT OF TRANSPORTATION

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CHAPTER 1 – INTRODUCTION

1.1 BACKGROUND

The main purpose of a forensic investigation is to determine the mechanism related to an observed pavement distress as well as the events that may have led to structural failure. Many times pavement distress mechanisms will be unknown or the distress may be due to a combination of mechanisms. A forensic investigation should find which mechanisms caused the distress and rule out any unrelated mechanisms.

A forensic investigation is most beneficial when it is properly planned and conducted in an efficient manner. The Texas Department of Transportation (TxDOT) conducts forensic investigations on distressed pavement sections but has no formal procedure for such investigations. This report outlines the details of a proposed forensic investigation procedure. The proposed procedure is based on the scientific method for conducting an investigation, which organizes the procedure into problem statement, observations, hypotheses formation, hypotheses testing, data analysis, iteration, and conclusions.

This report also discusses the resources currently available to TxDOT that have been designed specifically for use during forensic investigations of pavement sections. These resources include the ForenSys database, which is used to store pavement section information as well as past forensic reports, and the field diagnostic manual, which was created to help determine the observations that should be made during the first field visit. The field diagnostic manual or the detailed diagnostic manual can then be used to set up a testing program based on the results of the observations. Analysis of the observation results and the testing-program data is done to form conclusions. In addition, an online discussion group has been created in order to aid the formation of conclusions. Finally, the detailed diagnostic manual can be used to provide information about the repair and the degree of urgency of the distress, as well as prevention of distress in the future.

1.2 DEFINITION OF FORENSIC ENGINEERING

Forensic engineering involves investigation of failures, which are defined as instances when a structure does not conform to design expectations [Feld 97]. Forensic engineering is commonly related to structural collapse; however, this type of engineering involves all types of civil engineering structures and all types of failures, not just collapse. Buildings, bridges, dams, domes, and pavements are types of civil engineering structures served by forensic engineering. Likewise, forensic engineering includes failures, besides structural collapse, such as excessive cracking, spalling, and deflections; inadequate strength; pavement roughness; unmet tolerances; punchouts; and any other situation in which differences between the designed structure and the constructed structure are unacceptable.

The purpose of the forensic investigation is to determine the cause of failure during the investigation. Information about the failure and its cause are revealed and engineers can use this information to prevent similar failures from occurring in the future. These preventive measures may consist of changing construction procedures or design methods in order to minimize the chance of failure in the future. However, one of the most common uses of a forensic investigation is the design of an appropriate repair strategy. The repair strategy must address the cause of the failure in order to be effective, so a forensic investigation may be required to determine the failure mechanisms. For example, certain pavement distresses may be due to a material problem or a structural problem. If a given pavement distress were material related, it would do no good to perform a structural repair. The material problem would still exist and the distress would progress. Forensic investigations of pavements are commonly used to ensure that the proper rehabilitation strategy is implemented.

Forensic engineering and pavement rehabilitation strategies are analogous to the treatment of an illness. When a patient becomes ill, a doctor provides routine preventive medicine (maintenance) only after examining the symptoms. Once the symptoms have been examined, the illness can be diagnosed and a treatment administered. The same is true for pavement rehabilitation strategies. If the distress mechanism is unknown, or if there is disagreement concerning the distress mechanism, a forensic investigation must be performed so engineers can make a proper "diagnosis."

1.3 REQUIREMENTS OF A FORENSIC ENGINEER

In order to become a forensic engineer, a person must possess two essential qualities: (1) the person must be an expert in the field of the investigation, and (2) the person must be impartial to cause and responsibility throughout the investigation [ASCE 89]. When an engineer compromises either of these qualities, there is a good chance that the forensic investigation will not be efficient or accurate. Additional time and money may be spent to perform the investigation again with qualified forensic engineers. The need to repair incorrect distress mechanisms may also be a result of an investigation done by an unqualified forensic engineer. Utilizing a qualified forensic engineer should improve the possibility that the investigation will be performed in an efficient and accurate manner.

1.3.1 Expertise

An expert is someone who has a good understanding of the subject being investigated. In this case, the forensic engineer requires expertise in the field of transportation engineering and pavements. "This expertise may be based on a background of experience in design, construction, investigation, education, professional activities, and published works, as well as an extensive term of practice in the area of specialty" [ASCE 89]. The expert should have a strong background of pavements and pavement distress, and each investigation that is conducted will add experiences and knowledge to strengthen the expert's training.

An expert is also constantly striving to obtain additional knowledge in the area of specialization. The expert should attend seminars, or present at them, to extend his or her knowledge of the subject. Experts also research other forensic investigations, read current papers, and do anything else that will help them stay in touch with the latest information regarding their areas of expertise. By continuing to expand their knowledge, experts stay informed about new technologies, developments within their areas of specialties, investigation procedures, and failure mechanisms; in this way they remain experts.

1.3.2 Impartiality

A forensic engineer must also be honest and objective when performing an investigation. An improper investigation does not benefit anyone, insofar as the wrong repair strategy may be implemented, the correct failure mechanism may never be found, the wrong parties may be found to be at fault, and the engineer may damage his or her reputation. In addition, the information regarding the investigation, such as possible hypotheses and test results, should be kept confidential, especially if litigation is involved. An impartial forensic engineer also avoids conflicts of interest.

An impartial engineer should not base his or her conclusions on assumptions. After the observations and the testing program have been completed, the forensic engineer bases his or her conclusions on the facts of the investigation and avoids assumptions when deciding upon failure mechanisms. In other words, the engineer does not assume that particular failure mechanisms are at work based only on a description of the distress.

An impartial forensic engineer also avoids predetermination of failure mechanisms; that is, a forensic engineer should never identify the failure mechanism before the testing program has started. If this predetermination occurs, the testing program will likely include only those tests that support the failure hypotheses. The tests that may contradict the failure hypotheses will probably be avoided to prevent uncertainty. Therefore, the conclusions should be formed only after the testing program and analysis have been completed.

1.4 ADVANTAGES OF A FORENSIC INVESTIGATION

Rehabilitation of existing pavements is often preferred over replacement — a preference based on the high costs of new construction [O'Kon 92]. Most of the time, routine maintenance is performed on pavement sections without a prior forensic investigation. The maintenance may consist of a chip seal, crack or joint sealing, asphalt overlays, or patching. If the distress is a result of the pavement reaching the design life or it is apparent that the distress is not propagating at a high rate, then a forensic investigation does not have to precede routine maintenance. However, if the pavement is deteriorating more rapidly than normal, if the distress has occurred shortly after construction, if the distress mechanism is unknown, or if there is disagreement about the distress mechanism, then engineers should perform the forensic investigation before rehabilitation or maintenance takes place to ensure that the cause of the distress is counteracted by the rehabilitation strategy.

Although a forensic investigation costs money, it can ultimately save much more money. A portion of the budget must provide for forensic investigations, but the advantages of performing an investigation almost always outweigh the costs. The main advantage is that the proper repair strategy is selected so that the distress does not propagate after the pavement section has been repaired. Other advantages of performing a forensic investigation include the engineers' resultant ability to determine how fast the distress is propagating, and prioritize distressed pavement sections; improved design practices; and improved construction techniques.

1.4.1 Selection of Rehabilitation and Maintenance Strategies

One of the primary benefits of a forensic investigation is the selection of the proper rehabilitation strategy. As discussed earlier, the forensic investigation can be thought of as analogous to a doctor's patient. "Similarly, just as 'two aspirins and rest' is hardly a specific treatment for a human disease, two inches of asphalt is equally no cure-all for pavements" [Metcalf 92]. A forensic investigation is used to determine the "symptoms" so that the proper diagnosis, or repair strategy, can be administered.

For example, suppose a concrete pavement is experiencing transverse cracking. Also suppose that the cracks are assumed to be caused by shrinkage of the concrete after construction—a result of the joints being sawed too late. Because the cracks are probably dormant, the concrete pavement section can be repaired with an asphalt overlay. But what if the transverse cracking is actually caused by swelling of the base layers? In this case, the repair strategy will not be effective because the cracks are not dormant. The active cracks undergo movement whenever the base layers swell, and reflection cracking is likely to follow. The proposed repair method will not address the distress mechanism and, consequently, will not stop the progression of the cracking. A forensic investigation would have determined the cause of the cracking. The repair strategy would have then addressed those particular mechanisms so that the distress would not progress into the new repair. The repair strategy should always counteract the distress mechanism.

The investigation must identify the correct distress mechanism in order for the rehabilitation strategy to be effective. At a minimum, the forensic investigation should limit the distress mechanisms considered to only those most likely to be responsible. If the investigation reduces the number of distress mechanisms, the number of repair strategies is also reduced, insofar as the repair strategies counteract the distress mechanisms. In other words, the forensic investigation limits the number of feasible repair strategies for each distress. The investigation may also prevent the use of "cure-all" repair strategies, as explained in the following statement [Haas 94]:

> What is important is that all the available rehabilitation and maintenance alternative strategies are clearly identified by the agency, that provisions exist for adding to or deleting existing strategies, and that a procedure exists for deciding which ones are feasible for given situations.

1.4.2 Prioritization

In addition to helping engineers select an appropriate rehabilitation strategy, forensic investigations can also help with prioritization. After the distress mechanisms are determined from the investigation, the results may show how serious the distress is or whether it should continue to deteriorate at a rapid rate. For the transverse cracking example, the investigation may reveal that the cracking is, in fact, caused by late sawing of the joints. The testing program may discover that the shrinkage cracks are not very deep or wide, so water or debris should not pose a problem. In this case, the cracking mechanism is not as severe as the mechanism of the swelling base layers. The repair strategy may be put on hold so that other pavement sections that have a greater need for repair can be repaired first.

Forensic investigations help to prioritize the pavement sections in the order of the severity of distress, sometimes referred to as the degree of urgency. If it is found that a given pavement distress is not as serious as expected, and that the pavement should not continue to deteriorate, the part of the budget that was going to be spent on repairs can be used on a section that is in greater need of repair. On the other hand, the investigation might determine that repair is urgently needed. In that case, money directed to other pavement sections might then be needed to repair the section that was just investigated.

1.4.3 Determination of a Needs Year

Because forensic investigations may determine how fast the distress should progress, the performance curve for pavement sections can be updated. The investigation may determine whether cracks are dormant or active, whether the base layers experience cycles of shrinkage and swelling, and whether the base layers are susceptible to erosion. These conclusions can be used to estimate the rate of deterioration of the pavement section, which can then be used to improve the accuracy of the performance curve. The pavement section may need to be repaired sooner or later than expected, and the budget can be adjusted according to the new information.

To return to the transverse cracking example, suppose the district did not know that the subgrade was susceptible to shrinkage and swelling when the pavement was constructed. With routine maintenance, the pavement was expected to last 20 years after its original construction. After the transverse cracking was discovered, a forensic investigation was conducted to determine the cause. Only after the investigation did the district discover that the base layers experience several cycles of shrinkage and swelling per year. The shrinkage and swelling cycles cause the pavement to deteriorate faster than the original estimated rate. The pavement section now needs to be replaced sooner than expected, or else the problem with the base layers will have to be mitigated. Either way, a large amount of money will be needed sooner than the expected 20-year predicted life; however, because the forensic investigation revealed this need, proper precautions and budget adjustments can be made and future problems avoided.

The updated deterioration rate may be estimated to be lower or higher than the rate that was originally predicted from the deterioration model. The adjustment in the deterioration results in a new, and more accurate, performance curve. If the performance curve can be predicted more accurately, then the needs year for that pavement may also be determined with greater accuracy, as Haas [94] explains in the following statement:

In order to estimate needs years for the sections in a pavement network, it is necessary to predict the rate of change of those measures for which criteria have been established. As well, it may be desirable to predict the rate of change of some of the components of a measure, such as the cracking component of surface distress, to estimate maintenance requirements.

1.4.4 Improved Design and Construction

Forensic investigations also help to improve design practices and construction techniques. The investigation may reveal that a particular type of distress was caused by improper construction techniques, which can include overfinishing of the concrete surface, construction of the pavement during extremely hot or freezing weather, improper placement of reinforcing steel, or inadequate compaction of the asphalt layer. Likewise, the design techniques, such as mix design, drainage design, calculations of the slope of the shoulder, or thickness calculations, may have resulted in distress.

A slipform-paving example, described in detail in Chapter 7, shows how the investigation can prevent future design and construction errors. In this example, a concrete pavement was being constructed at a military airfield. Shortly after construction, blisters developed on the surface of the pavement. The forensic investigation revealed that the consolidation techniques were inadequate for the concrete mix, which had a high sand content [Rollings 92]. The investigation improved the remaining construction of the pavement by discovering inadequacies in the design and construction techniques. To prevent the blistering from occurring in the future, either the mix design needed to be changed or the slipform paver needed to be adjusted to handle the high-sand-content mix.

Whether forensic investigations discover inadequacies in design, construction, or both, the findings must be published in order to be effective. By publishing a case history of the forensic investigation, different districts and agencies become aware of the problems that can arise in certain situations. Once distress mechanisms for a particular type of distress are recognized, engineers can take action to prevent similar events from occurring in the future. The publication of past failures improves design practices as well as the construction and material technologies so that the failures are less likely to be repeated.

1.5 CURRENT TxDOT FORENSIC INVESTIGATION PRACTICES

The current pavement forensic investigation procedures have been discussed in TxDOT Report 0-1731-1, entitled "Basic Concepts, Current Practices, and Available Resources for Forensic Investigations on Pavements." The report explains that TxDOT conducts forensic investigations on a case-by-case basis and does not have a formal procedure for conducting an investigation. While there is no formal procedure, many of the investigations conducted by TxDOT do resemble the steps of the scientific method. The investigations include preliminary meetings, interviews, on-site investigations, document searches, condition surveys, laboratory testing, data analysis, and the final report. Therefore, the current forensic procedures are similar to the proposed procedure; however, the current procedures have not been formally outlined.

This report outlines the necessary steps for conducting efficient and accurate forensic investigations. The forensic investigations and reports of TxDOT should have the same format so that the information can be easily entered into a database. Each district can then access the database to obtain investigation data from the other districts within TxDOT. The information can be used to research past forensic investigations, to monitor the performance of previously investigated pavement sections, or to provide ideas for current investigations.

This report also describes the resources, such as the ForenSys database and the diagnostic manuals, that are available to TxDOT specifically for forensic investigations. A description of how to utilize each of the resources is also provided in this report. The benefits of the available resources are also discussed.

1.6 SCOPE AND ORGANIZATION OF REPORT

This first chapter explains the background of forensic engineering, including the definition of forensic engineering and the qualities of a forensic engineer. This chapter also describes TxDOT's current forensic engineering procedures and the benefits of an accurate and efficient forensic investigation.

Chapter 2 summarizes a proposed forensic engineering procedure. This procedure is based on the scientific method and utilizes all of the resources that are available through TxDOT.

Chapter 3 discusses the first step of any forensic investigation, obtaining background information. This chapter focuses on identifying the problem, the type of background information needed, and the resources available that might provide this information. Preparation for the forensic investigation is also discussed in this chapter.

Chapter 4 describes the collection of the autopsy data of the distressed pavement section. Observations of the distress, field testing, laboratory testing, and data collection are all detailed in this chapter.

Chapter 5 sets forth methods to analyze the collected autopsy data. This chapter lists the available resources and explains how they can be used for autopsy data analysis. Finally, this chapter discusses hints for forming failure mechanism conclusions based on the hypotheses, the collected data, and the information from the literature search.

Chapter 6 proposes a format for forensic engineering reports. The reports outline the investigation, give the testing program results, and show how the failure mechanism conclusions were formed from the hypotheses.

Case studies are presented in Chapter 7. These examples show the advantages of an accurate forensic investigation, as well as the disadvantages of an improper investigation.

Chapter 8 outlines the conclusions of this report. The future direction of the project is also discussed in this chapter.

CHAPTER 2 – A FRAMEWORK OF THE INVESTIGATION PROCEDURE

2.1 BACKGROUND

"Forensic engineering is the application of engineering principles to the investigation of failures and other performance problems" [Nicastro 97]. This engineering analysis helps to determine the cause of pavement failure as well as establish a set of events that led up to the failure. In many cases, the cause of pavement failure may not be the most common mechanism. In addition, pavement distress is often due to a combination of mechanisms. Forensic investigations are useful because they determine all of the failure mechanisms, not just the most apparent ones.

Once the cause of the distress has been found, the engineers should implement a repair strategy to counteract the distress mechanism. If the repair strategy is implemented to correct the wrong mechanism, the distress is likely to continue to progress. For example, if a flexible pavement section contains alligator cracking, the mechanism may be due to fatigue of the surface layer of the pavement. A seal-coat or a thin overlay would seem to be a reasonable rehabilitation for this type of cracking. However, alligator cracking may also be a result of the pavement being constructed on a resilient subgrade layer or a result of movement of a subgrade layer. If the problem with the subgrade caused the alligator cracking, then a seal-coat or a thin overlay may not cease the progress of the alligator cracking. A properly conducted forensic investigation would have determined all of the possible failure mechanisms. If all the mechanisms were known, the best rehabilitation strategy could be selected and the distress would not progress.

2.2 PROPOSED PROCEDURE STEPS AND RESOURCES

The proposed procedure for forensic investigations requires that judgments be made when it comes to establishing conclusions, but the use of the scientific method helps to organize the procedure of the investigation into a logical series of steps. These steps are defining the problem, conducting field observations and forming possible hypotheses, conducting tests to evaluate the hypotheses, analyzing the test data, and forming conclusions. The last, and most critical, step of the investigation ideally would be to prepare a forensic report to document the details of the investigation. By following each of these steps in order, engineers can perform the most efficient and accurate investigation. The proposed procedure for forensic investigations is outlined in Figure 2.1.

The proposed procedure also uses all of the resources available through TxDOT. Among these resources is the ForenSys database. This database is essential for obtaining background information and should also be used to enter the conclusions from forensic reports for future use. Another tool is the detailed forensic manual, which is useful for determining the correct distress mechanisms, implementing prevention measures, and selecting a strategy for repair. The field forensic manual is an abbreviated form of the detailed manual that summarizes general information about the description and cause of the observed distress as well as outlining suggested investigation and test methods based on field observations. Finally, the Web version of the forensic manual can be used to download and print updated versions of the manual. The Web version also utilizes discussion groups that post pictures and pose questions about that unknown distress mechanisms.

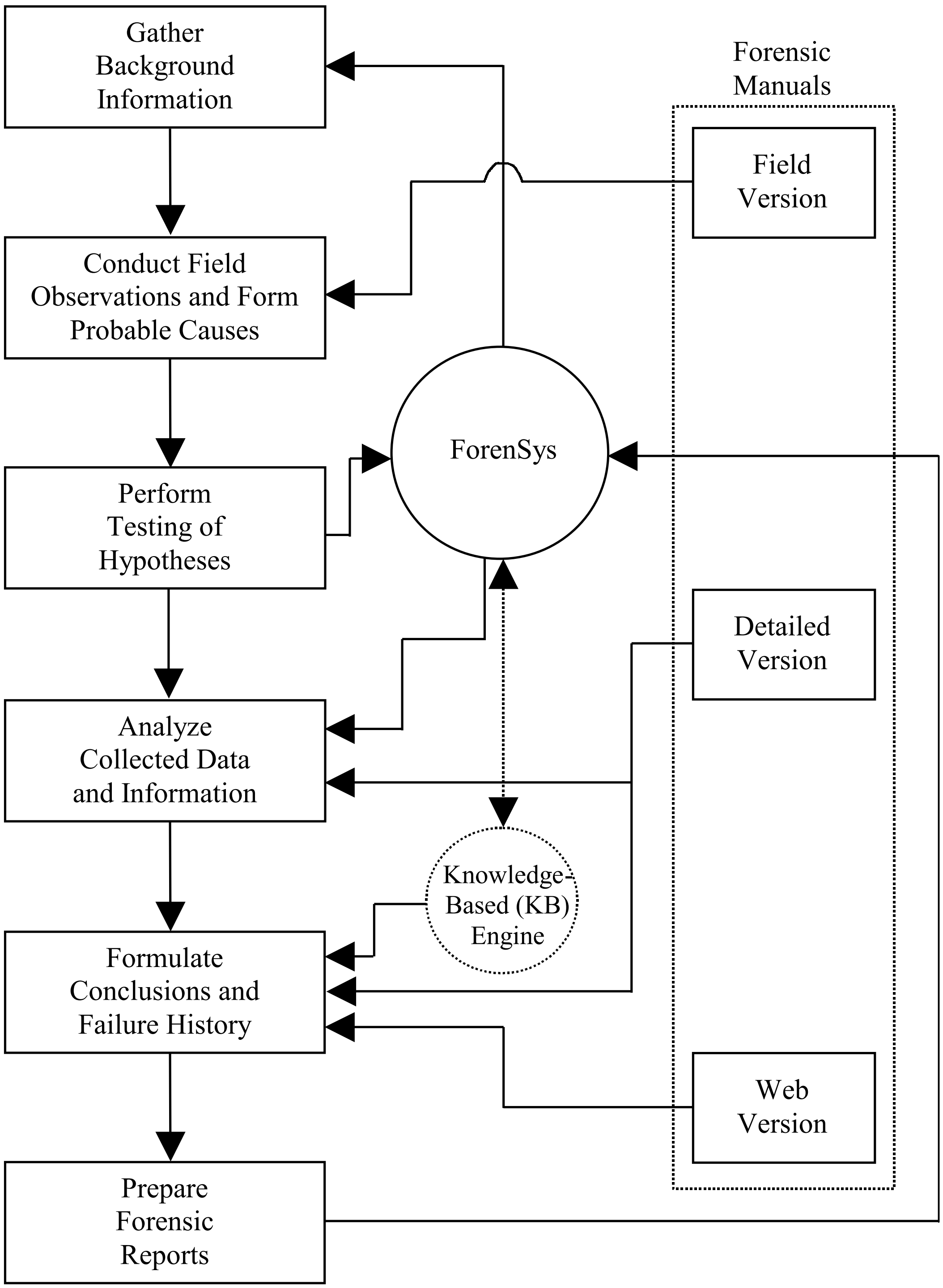


Figure 2.1 – Outline of the proposed procedure for forensic investigations

2.3 PROBLEM STATEMENT

The first step in a forensic investigation, or any problem-solving algorithm, involves problem recognition and definition. For pavements, the problem is the distresses that are occurring on the pavement section. Before an engineer can determine whether a forensic investigation is necessary, the distress needs to be identified and quantified. Distresses are often recognized by pavement condition surveys, which should be conducted at various times throughout the pavement's life. The users of the pavement may also identify distresses.

The problem statement also includes gathering background information for that particular section of pavement. During the document search it is important to obtain as much information about the design and construction of the pavement section as possible. This information can be acquired from construction drawings and specifications, design calculations, contract agreements and changes, project schedules, field reports, shop drawings, test reports, geotechnical reports, inspection reports, project correspondence, consultant reports, and maintenance records. The ForenSys database also contains information about location, age, and the layer structure of the particular pavement section.

The revision of these documents helps to provide background information as well as what one should look for when performing the fieldwork. It may also be helpful to review literature from different projects. These may include past forensic reports from the same agency or from different agencies if possible. A past forensic report may be found with similar pavement design or types of distress. The report may contain information about the mechanisms for the distress and/or the rehabilitation strategies. Even though a past report may show similar distress types and patterns, it should not take the place of a forensic investigation of the current pavement section. Old reports should only provide a head start in the right direction, not an end result.

2.4 FIELD OBSERVATION AND HYPOTHESES FORMATION

Before the mechanism causing the distress can be found, and even before a hypothesis can be formed, detailed observations must be made. These observations begin with the information obtained during the document search and continue in the field. During the initial site visit one should use the field forensic manual to determine what observations should be made. The initial site visit should also be used to plan the testing program. The field forensic manual suggests test methods that depend on the results of the observations. Sometimes the results of the observations do not indicate any particular distress mechanism. To determine the correct mechanism in this case, one should plan the testing to include as many test methods or investigations as the budget allows.

Ideally, multiple site visits should be made, but many times this is not feasible because (1) the site may be so remote that the investigative team cannot visit it more than once or (2) the seriousness of the distress may be such as to require immediate rehabilitation. At a minimum, a team should make a brief initial site visit to visually examine the distress. It is necessary to document the conditions at the site, either by photographing or videotaping the nature of the distress (failure to do so could result in not having a visual record of the distress after the repair takes place). Detailed field notes are also required. These notes should describe the type, size, shape, spacing, and pattern of the distress. Section location, drainage patterns, road geometry, and abnormal site conditions should be recorded on the pavement plans, if possible.

Once all documents have been reviewed and the initial site visit has been made, the hypotheses can be formed. In order to form a distress mechanism hypothesis, one must decide which mechanisms are reasonable candidates by reviewing the project documents, field photographs, and field notes. When a team takes into account all traffic, budget, and time constraints of the pavement section, iteration of hypotheses may or may not be possible. Normally the scientific method requires testing of the most probable hypothesis before another hypothesis is formed. When it comes to pavement forensics, iteration is usually not very efficient. Sometimes the pavement section may be in urgent need of repair, so all hypotheses should be formed before testing proceeds. All hypotheses should then be tested at once in order to minimize the time required to determine the mechanism and begin rehabilitation.

2.5 TESTING PROGRAM

Once the hypotheses are formed, the team should organize another site visit to perform the physical testing, if required. The field forensic manual helps to determine which investigations are necessary based on the observations made. Because the distress may be caused by a combination of mechanisms, as discussed above, separate testing is required for each mechanism. If a distress has an apparent mechanism, a testing program should still be performed to verify the mechanism, if the time schedule and budget allow. A summary of the testing program is described as follows [O'Kon 92]:

> The goals of the testing program include acquisition of data relative to material quality, workmanship, unstable materials, and exposure to deleterious substances or excessive wear. The testing program could include physical and chemical tests on materials of construction as well as other tests including electronic methods.

Field investigations are used to determine the characteristics of the pavement. The in-situ properties of the pavement may differ from the construction or design documents, as field investigations often show. Common field investigations determine the structural adequacy of the pavement and the underlying layers or estimate the layer profile throughout the thickness of the section. Field investigations also include obtaining pavement cores and soil borings for testing in the laboratory.

After the samples are taken back to the laboratory, engineers perform materials tests in controlled conditions to determine the properties of each layer. Strength tests can be performed to enable the researchers to compare the strength and modulus results to the data obtained from the structural investigation. Laboratory investigations can also determine moisture content, shrinking properties, swelling properties, air content, viscosity of the asphalt, density, and grain size distribution. Some distress mechanisms may even be at the molecular level. Therefore, a microscopic inspection of the cores is necessary to reveal these mechanisms. For example, a microscopic evaluation can determine whether the bond between the aggregate and the cement paste or asphalt is adequate, whether ice lenses formed during the curing of a rigid pavement, and whether an alkali-silica reaction has caused the rigid pavement to deteriorate. Laboratory investigations may also include computer analysis or a search of records pertaining to the pavement history. Common records include weather temperature data, precipitation data, traffic history, and information regarding previous maintenance or repairs.

2.6 AUTOPSY DATA ANALYSIS

"Correlation is the strongest tool available to a forensic engineer, so keen observation is necessary to discover links between findings" [Nicastro 97]. Data analysis involves the formation of evidence that validates a hypothesis, conflicts with a hypothesis, or neither supports nor discredits the hypothesis. The detailed forensic manual can be used to help form this evidence because it contains matrices that show which investigations are used to support or conflict certain mechanisms.

Reviewing fieldwork to gain evidence is also part of the data analysis stage. Not all of the evidence comes from test results. Field photographs and observation notes can provide information to support a hypothesis that most field and lab investigations cannot. For example, if joint sealant loss was the mechanism that caused a certain distress, the laboratory investigations would not reveal this.

2.7 FORMING CONCLUSIONS

Conclusions are drawn after all testing and analysis has been completed and there is sufficient proof that a certain mechanism has or has not occurred. The detailed version of the forensic manual gives in-depth descriptions of the distress mechanisms. The evidence obtained from the investigations can be compared to the description of the distress mechanism. The detailed forensic manual also shows, in matrix form, what investigations are required to support certain distress mechanisms. In this stage, the Web version of the forensic manual may also be used. If there is some difficulty in determining the probable distress mechanism, details and pictures of the distress and questions concerning the cause can be posted on the Web. Someone in the discussion group may have had a similar problem and may be quite helpful or may just have some unique suggestions to determine the cause of the distress.

2.8 FINAL REPORT

If it is not required that a formal report be prepared, then, at a minimum, a case history of the project should be created. All factual information about the investigation should be included. A problem statement, the methods of collecting the facts, the ways in which certain hypotheses were determined, the testing procedures, conclusions about the distress mechanisms, and rehabilitation recommendations are all essential parts of the final report. Once the final report is completed, the details should be entered into the ForenSys database. The final report that is produced may aid forensic investigations of a similar kind in the future.

CHAPTER 3 – BACKGROUND INFORMATION GATHERING

3.1 BACKGROUND

Before the forensic investigation or the rehabilitation strategy can begin, it is necessary to identify the problem. The problem consists of one or a combination of distresses occurring in the pavement section. One must measure the quantity and severity of each distress to determine the current condition of the pavement. The pavement condition then helps to indicate the need for rehabilitation. Often the repair strategy can be selected from the condition survey alone; however, the distress mechanism usually needs to be addressed during the repair strategy in order to prevent the distress from progressing. A forensic investigation is necessary in determining the mechanisms of the distress.

Forensic investigations begin by gathering background information. The background information reveals details about the composition, design, and construction of the pavement section. The information may also identify possible mechanisms that may be caused by design errors or improper construction. Finally, the background information is an essential part of forensic investigations if an efficient investigation is required.

3.2 CONDITION SURVEYS

A condition survey is a way of discovering, during routine inspection, the presence of pavement distress. The condition survey can, first, determine the overall condition of the highway system throughout the state and, second, identify those pavement sections having the highest need for rehabilitation. While distresses are customarily discovered through routine inspection, maintenance crews may also find additional distresses that were not found during the inspection. The public may even provide input about the condition of a pavement. For example, the public may notify TxDOT about certain distresses that are causing riding or safety concerns. Although complaints from the public may not be desirable, they are an effective way to determine the current conditions of certain pavement sections.

The condition survey may consist of measurements of ride quality, structural adequacy, or skid resistance; however, the most important part of the condition survey is the visual inspection. The visual inspection identifies and quantifies the distress or deterioration that is occurring in the pavement section. During the visual inspection the crew should utilize TxDOT's Pavement Management Information System Rater's Manual. The Rater's Manual is used as an aid to identify pavement distress. Tables 3.1 and 3.2 display common distresses for rigid and flexible pavements, respectively.

Once the distress is identified, it can then be quantified. The Rater's Manual describes how to quantify, or "rate," the pavement section based on the size and spacing of the identified distress. The rating numbers for distresses such as patching may be entered as a percentage of the lane's total surface area. Ratings for other distresses, such as cracking and punchouts, are entered as whole numbers to represent the spacing or the number of times the distress is observed per mile.

One can find the pavements with the greatest need for rehabilitation by observing the results from the condition survey. The surveys reveal those pavement sections having either the largest quantity of distresses or the most severe distresses. Then, the pavement management system determines the order in which the pavement sections should be repaired.

Table 3.1 – Common rigid pavement distresses

Type of Distress	Description of Distress
Bump	Small, localized upward bulges of the pavement surface of various sizes
Corner Break*	Crack that extends from a transverse joint to a longitudinal slab edge
Crack Spalling*	A crack that has widened and is showing signs of chipping on either side, along some or all of its length
D-Cracking*	Series of closely spaced crescent-shaped hairline cracks that tend to cluster along joints and slab edges
Faulting*	One edge of a joint has a higher elevation than the other side of the joint
Joint Failure	Upward displacement or shattering of the slab edge at the transverse joint
Joint Sealant Extrusion	Removal of the joint sealant from a transverse or longitudinal joint
Joint Separation	Widening of the joint between two traffic lanes or a traffic lane and the shoulder
Joint Spalling*	A joint that has widened and is showing signs of chipping on either side, along some or all of its length
Longitudinal Cracking*	Cracks or breaks that run approximately parallel to the pavement centerline
Loss of Skid Resistance	Polishing of the coarse aggregate in the pavement that results in a slippery surface

*Indicates that the distress is listed in the TxDOT PMIS Rater's Manual

Table 3.1 – Common rigid pavement distresses (continued)

Type of Distress	Description of Distress
Loss of Surface Material	Loss of coarse and/or fine aggregate particles from the pavement surface
Pumping	Ejection of water and fine materials out of joints or cracks under moving loads
Punchout*	Full-depth block of pavement formed when one longitudinal crack crosses two transverse cracks
Reactive Material Distress	Fine, closely spaced map cracking resulting from reactive aggregates
Settlement	Localized area of the pavement that has a lower elevation than the original pavement surface
Shrinkage Cracking	Hairline map cracks that occur on the surface of freshly placed concrete
Slab Shattering*	Slab is severely cracked by cracks that divide the slab into four or more pieces
Transverse Cracking*	Cracks or breaks that travel at right angles to the pavement centerline

*Indicates that the distress is listed in the TxDOT PMIS Rater's Manual

Table 3.2 – Common flexible pavement distresses

Type of Distress	Description of Distress
Alligator Cracking*	Interconnecting cracks that form small, irregularly shaped blocks that resemble an alligator's skin
Block Cracking*	Interconnecting cracks that form rectangular pieces, similar to alligator cracking but much larger
Bump	Small, localized upward bulges of the pavement surface of various sizes
Edge Cracking	Crack or break running parallel to and near the outer edge of the pavement
Flushing/Bleeding*	Presence of asphalt on the pavement surface which creates a sticky and reflective surface
Lane Drop-Off	Difference in elevation between the traffic lane and the shoulder
Longitudinal Cracking*	Cracks or breaks that run approximately parallel to the pavement centerline
Patching*	Repairs made to pavement distress indicating prior maintenance
Polished Aggregates	Loss of skid resistance resulting from the wearing of aggregate particles from angular to smooth
Potholes	Irregularly shaped holes of various sizes in the pavement surface
Raveling/Weathering*	Progressive disintegration of the pavement surface resulting from dislodgement of aggregate particles

*Indicates that the distress is listed in the TxDOT PMIS Rater's Manual

Table 3.2 – Common flexible pavement distresses (continued)

Type of Distress	Description of Distress
Rippling	Closely spaced alternate valleys and crests on the pavement surface
Rutting*	Longitudinal surface depression found in one or both of the wheel paths
Settlement	Localized area of the pavement that has a lower elevation than the original pavement surface
Slippage Cracking	Crescent-shaped cracks on the pavement surface in the direction of traffic
Transverse Cracking*	Cracks or breaks that travel at right angles to the pavement centerline
Water Bleeding	Ejection of water and fine materials out of cracks under moving loads

*Indicates that the distress is listed in the TxDOT PMIS Rater's Manual

3.3 NECESSARY BACKGROUND INFORMATION

The results of the condition survey determine which sections have the greatest need for rehabilitation. Sometimes the rehabilitation strategy can also be determined from the condition survey. This is the case if the distress has only one mechanism. This determination may also be possible if the rehabilitation strategy is the same regardless of what the mechanism is. However, this is not always the case because most pavement distresses result from several different mechanisms. Thus, because it is necessary to determine the mechanism causing the distress before the rehabilitation strategy is selected, a forensic investigation must be performed.

If a forensic investigation is necessary to determine the distress mechanism, a request must be made to perform the investigation. Center for Transportation Research Report 0-1731-1, "Basic Concepts, Current Practices, and Available Resources for Forensic Investigations on Pavements," provides good information about requesting and preparing for a forensic investigation. The director of the Highway Design Division needs to receive the request from the division that requires the investigation. The request is in the form of a memorandum and needs to include various types of background information concerning the pavement section.

3.3.1 Document Search

The requesting division obtains the background information required in the memorandum by conducting a document search. The information obtained in the document search should include, but is not limited to, the pavement history, the pavement structure, materials information, traffic information, description of the distress, construction records concerning the problem, weather records, and soil and geologic information. Because they may reveal a great deal about the origins of the pavement distress, these basic categories of information should be gathered.

3.3.2 Pavement History

Information about the pavement's history is very important for a forensic investigation. Often, pavement history information may reveal something about the distress mechanism. This category of information includes the date of construction of the pavement, as well as its history of overlays, maintenance, and repairs. The history of its performance, such as past distresses and non-destructive test results, is also useful if the information can be obtained.

3.3.3 Pavement Structure

The physical properties of the pavement are also an essential part of the background information. These properties include the thickness of each layer of the pavement and the layer properties. If the pavement is concrete, the sizes and locations of the steel should be obtained. If possible, both the actual properties and the design properties should be identified. Because the location of the pavement is also included in this category, the starting point and ending point of the section should be determined. Finally, any geometric information about the pavement section is included in this category.

3.3.4 Materials Information

The materials information category includes properties of the materials in each pavement layer. The mix design, aggregates, binder, and information about a stabilized base are the types of information included in this category.

3.3.5 Traffic Information

The loading information is an important category that affects pavement distress. The accumulated 18-kip equivalent single-axle loads (ESALs) and the annual average daily truck traffic (AADT) both affect the design life of the pavement. Any information about recent changes in the loading or overloading of the pavement section would also be useful in a forensic investigation.

3.3.6 Description of Distress

The description of the distress is an essential category of the forensic investigation request memorandum. The description is obtained from the condition survey and should include both the quantity and the severity of the distress.

3.3.7 Relevant Construction Records

The construction records often reveal whether the actual pavement structure differs from the design. The construction drawings, specifications, and construction schedules may reveal improper procedures followed during construction. Change orders also indicate if the actual pavement varies from the designed structure.

3.3.8 Weather Records

Weather records are important for weather-related distresses. Distresses are often due to thermal expansion or to freeze-thaw repetitions—patterns that the weather records may reveal. Excessive amounts of rainfall or seasonal moisture patterns may also result in a number of different pavement distresses. Finally, the weather conditions prevailing during the placement of the pavement may affect its performance.

3.3.9 Soil and Geologic Information

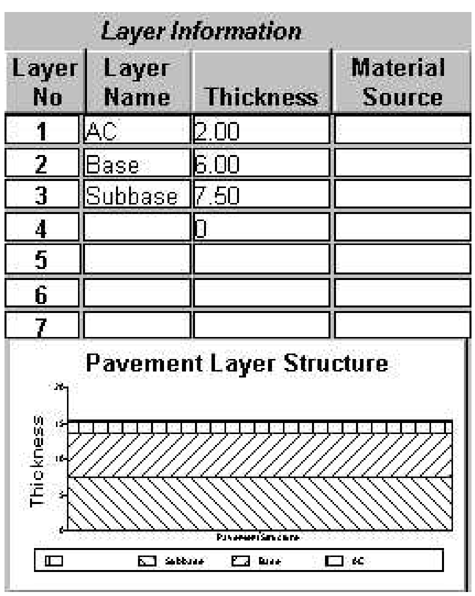
The soil structure below the constructed pavement can affect the pavement's performance. The predominant underlying layers of soil can affect certain distresses, especially distresses involving base movement or water drainage. The soil profile and the location of the water table are important pieces of information in this category. Results from base drainage tests, potential vertical rise tests, or structural tests on the subgrade would also be useful.

3.4 RESOURCES FOR OBTAINING BACKGROUND INFORMATION

Because all of the background information cannot be found in a single source, a bit of additional searching is required. Sources of this information include the ForenSys database, the Pavement Management Information System (PMIS) database, the Maintenance Management Information System (MMIS) database, the Texas Reference Marker System (TRM) database, the Construction Management System (CMS) database, other databases, maps, and paper files. Other sources of information are available, but those listed above are the most readily available. Center for Transportation Research Report 0-1785-2, “Plan for Developing a Materials Performance Database for the Texas DOT,” can be a source of more detailed information about each database.

3.4.1 ForenSys Database

The ForenSys database is one of the most useful resources for forensic investigations. This database provides a great deal of background information, including the county number, highway number, construction year, and beginning and ending road marks of the section. Other types of information are the average daily truck traffic (ADT), ESALs, the percentage of trucks, and the type of distress occurring on the section. Materials information and physical properties are also included in the database. The name and thickness of each layer are shown graphically, as in Figure 3.1. The asphalt mix design is also included in the database.


Layer Information

Layer No	Layer Name	Thickness	Material Source
1	AC	2.00	
2	Base	6.00	
3	Subbase	7.50	
4		0	
5			
6			
7			

Figure 3.1 – Layer structure as shown in the ForenSys database

The downside of using ForenSys is the limited number of pavement sections included in the database. However, the database is a great starting point for forensic investigations of pavement sections that are included.

3.4.2 SiteManager Database

The Construction Management System (CMS) database, more commonly known as SiteManager, may contain critical information for forensic investigations. This database is useful for materials management because it contains many different types of construction records, material test reports, and change orders. The results obtained from field tests conducted during construction can also be entered into the database. The information in the database can be compared with the construction specifications to determine how well they agree (e.g., the distress may have been a result of a disagreement). The SiteManager database is regularly used for new construction projects, and the information is usually kept for 3 years after the project has been completed. However, because this database is still quite new, availability may also be quite limited.

3.4.3 Pavement Management Information Systems (PMIS) Database

The PMIS database is a good tool for researching the condition survey information of pavement sections. This database includes the distresses present, such as visual distress, and any cracking that is present on the pavement section. Deflection test results and roughness measurements are also present in this database. Finally, structural strength data are available for flexible pavements.

3.4.4 Maintenance Management Information Systems (MMIS) Database

Maintenance activities on all highways under TxDOT’s management are tracked in the MMIS database. The amount of maintenance, material used, and cost are types of data recorded in this database. This database can be used to research the maintenance history of the pavement section.

3.4.5 Texas Reference Marker System (TRM) Database

The TRM database is used as an inventory of the current conditions of the roadways throughout Texas. This database primarily provides geographical information about the pavement section, such as a pavement section's starting and ending locations.

3.4.6 Other Databases

Other databases include the Road Life database, the Texas Rigid Pavement database, and the Texas Flexible Pavement database. These databases include useful information but cover only a small number of pavement sections.

3.4.7 Maps

TxDOT has maps for every Texas county. These county maps provide useful geographical information in those instances when the information is not included in a database. (Even when the information *is* included in the database, maps can help determine if the information is accurate.)

3.4.8 Paper Files

Inventory paper files are extremely useful for one seeking to obtain background information; however, they are not easily accessible. The paper files include such basic information as the county name, control number, section number, and highway number. These files also have more detailed information on the date of the pavement's completion and its drain locations. The Log Record of Project Construction and Retirements keeps track of the paper files.

3.5 PREPARING FOR THE INVESTIGATION

After the forensic investigation request has been granted, the team must prepare for the investigation. Preparation leads to organization, which helps forensic investigations to be efficient and economical. Preparation includes investigation planning, identification of the investigative team, operations planning, and an additional literature and document search.

3.5.1 Planning the Investigation

Planning is essential because it helps to create an organized investigation. The planners should identify realistic goals for the project, as well as the path to achieve these goals. Planning also creates the initial scope of the work, preventing unnecessary work from being performed. It should be noted that the scope of the work might change as new facts are discovered. Finally, the planning stage includes creation of the time schedule for the work, identification of budget constraints, and preparation of safety requirements.

3.5.2 Identification of the Investigative Team

The forensic engineer performs a majority of the planning and investigation; however, the help of other professionals may be necessary to determine the correct distress mechanism. Additional engineers, known as experts, may need to be called in to aid the investigation. Experts in pavement design, concrete or asphalt materials, aggregates, petrography, or geotechnical engineering may be required. These engineers also may be from other engineering disciplines and may be called in from other districts. Surveyors, testing laboratories, photographers, and video professionals may be identified to provide assistance for the investigation.

It should be noted that these professionals might not be necessary for every investigation. In addition, it is likely that the forensic engineer will not know which professionals are needed until the initial site visit has been performed. Therefore, a list of professionals and testing laboratories should be created during the planning stage in case these professionals are needed later in the investigation.

3.5.3 Operations Planning

All of the team members must be coordinated to facilitate an efficient investigation. This coordination includes integrating the work so that the investigation causes very little interference with the riding public; the investigation, including the testing, should be arranged so that lane closures and traffic redirections are kept to a minimum. Operations planning also involves arranging future meetings, which are used to discuss the progress of the investigation, the achievement of the project goals, the results of the testing, and the failure hypotheses. Finally, any adjustment of the plan required to account for unforeseen circumstances is included in this stage.

3.5.4 Literature Search

The literature search does not have to take place before the initial site visit, but it should occur before the testing program commences. It entails research about other forensic investigations through investigative reports about pavement sections with similar distress patterns. Past reports are used to provide a starting point for the investigation or ideas for possible mechanisms; they are never used in place of the forensic investigation. Because most types of pavement distresses have many different mechanisms, past reports may provide harmful information if used incorrectly, insofar as the documented repair strategy addresses only a certain distress mechanism. If the repair strategy one adopts addresses the wrong mechanism, the strategy will not perform as expected. In other words, past forensic reports should provide questions to ask, rather than premature answers.

CHAPTER 4 – FIELD OBSERVATION AND AUTOPSY DATA COLLECTION

4.1 BACKGROUND

The data collection stage is the most important stage in any forensic investigation. This stage consists of one or more field visits and a testing program. It is recommended that multiple site visits be made; however, because of time and money constraints, multiple site visits may not be feasible. Sometimes the distress mechanism can be determined by detailed observation, in which case physical or laboratory testing is not required. Thus, the team should make a minimum of one field visit to examine the distress in detail. Then a testing site visit can be arranged if necessary.

The initial site visit is used primarily for observation of the distress and of the site conditions. Researchers can use the field forensic manual to obtain background information about the distress mechanisms. The field forensic manual also helps the team identify what should be observed during the first site visit. These observations are used to form initial hypotheses of the failure mechanisms. Finally, detailed field notes should be taken to document the distress, site conditions, and any possible mechanisms. These notes are used during the data analysis stage to determine the failure mechanism.

After the failure hypotheses have been formed during the initial site visit, the hypotheses must be tested. The tests are conducted to verify, or contradict, the failure hypotheses. In the field forensic manual and the detailed forensic manual, a series of tests are listed for each failure mechanism. The testing conducted during the second site visit is used to determine the in-situ properties of the pavement section. The test results are then used to compare the in-situ properties with the design or constructed properties. The team also uses the second site visit to prepare specimens for laboratory testing. The results of field tests and the laboratory tests may verify the failure hypotheses, contradict the failure hypotheses, or be inconclusive. The hypotheses that are strongly contradicted are eliminated. Likewise, the hypotheses that are supported by the testing program are used to form the conclusions. The final step of the data collection stage is entering the test results and the field observations into the ForenSys database.

4.2 INITIAL SITE VISIT

Raths [79] describes the initial site visit as the "tourist trip" to get the "lay of the land," to see what happened, and to observe the site conditions. The initial site visit is performed so that the team may conduct a visual examination of the distresses occurring on the pavement section. Center for Transportation Research Report 0-1731-1, "Basic Concepts, Current Practices, and Available Resources for Forensic Investigations on Pavements," states that the purpose of the initial visit is to determine the scope and nature of the failure in order to craft an appropriate investigative plan. The initial site visit requires planning, and preparation for it includes reviewing the forensic manuals to determine the background of the distress, the possible mechanisms, and what observations should be made during the site visit. After the observations have been made and documented in detail, the team should form failure hypotheses based on observations. In order to verify or contradict a hypothesis, the team should set up a testing program based on the possible hypotheses and on the results of the field observations. Finally, iteration of the hypotheses may be required if the testing program does not point to any of the tested hypotheses.

4.2.1 Preparation

Preparation involves becoming familiar with each distress included in the forensic investigation and determining what information is required. As an aid in the preparation, the detailed forensic manual describes the distress and shows some typical photographs of each kind. This manual also describes each of the possible distress mechanisms. In addition, the detailed forensic manual lists the observations that should be performed during the first site visit. The field forensic manual lists these observations in flowchart form.

Field sheets, to be used during the initial site visit, should also be prepared during this stage. The field sheets act as reminders that investigators must ensure that all the necessary information is obtained during the initial visit. These sheets may also prevent an unnecessary return trip to the site to gain information that was missed during the initial visit.

Typical field sheets, containing general information categories, are displayed in Figures 4.1 and 4.2. The general information categories include the date of the site visit, the county, the district, the highway number, the location of the pavement section, the pavement type, the direction, the lane that is being investigated, and the CSJ. The names of the forensic team members are also an essential piece of information to be included. A second general field sheet would include the distress observed, recent weather, evidence of previous repairs and their performance, the spacing of the joints, the width of the slab, and a sketch of the distress. Space should also be provided to document any additional general information. This additional information may be the overall dimensions of the section, the number of lanes, the pavement type in each lane, the surrounding terrain, and, if possible, the pavement thickness. The purpose of this field sheet is to verify all of the data obtained during the search for the background information about the pavement section.

The forensic manuals, especially the observation sections, should be used to prepare the distress-specific field sheet. A typical distress-specific sheet, this one for joint spalling of a concrete pavement, is shown in Figure 4.3. On this field sheet, the observations are listed and are followed by the possible results. The distress-specific data sheets also include possible tests to verify each distress mechanism. Some of the tests require preparation, such as marking locations of cores, which can also be performed during the initial visit. Additional blank sheets should be used to document any irregular or unusual observations.

The final step of the preparation is gathering all the necessary tools and equipment before the site visit. Essential tools include a tape measure, a ruler, a crack comparator, a camera, video equipment if appropriate, hard hats, gloves, boots, plastic bags and tags for samples, a flashlight, raingear, a calculator, the field sheets, and writing tools. For engineers regularly involved in forensic investigations, maintaining a "doctor's kit" with the essential tools is recommended. Sometimes the field-testing program includes only tests requiring small or simple equipment. If this is the case, then the tests should be performed during the initial site visit so that a separate testing visit is not required. If the testing equipment is large or requires mobilization, testing during the initial site visit may be more practical (and cost effective) if there are only a few tests to be performed. However, if there are many tests, observations made during the initial site visit should be used to determine which tests are necessary, with the testing then to be performed at a later date.

TxDOT FORENSIC INVESTIGATION

PAVEMENT SECTION GENERAL INFORMATION

DATE:__________________

DISTRICT: ____

COUNTY: ____

HIGHWAY: ____

LOCATION: **From:**________________**To:**________________

DIRECTION: ____

LANE: ____

PAVEMENT TYPE: ____

CSJ: ____

INVESTIGATION TEAM:

____

____

____

____

____

Figure 4.1 – Sample general data sheet for field observation

TxDOT FORENSIC INVESTIGATION
PAVEMENT DISTRESS GENERAL INFORMATION

DISTRESS OBSERVED: ______________________________

RECENT WEATHER: ______________________________

PREVIOUS REPAIRS: ______________________________

PERFORMANCE OF REPAIRS: ______________________

____

TRANSVERSE JOINT SPACING: ______________________

SLAB WIDTH: ____________________________________

SKETCH OF DISTRESS

NOTES:____

____

____

Figure 4.2 – Sample of general distress data sheet for field observation

TxDOT FORENSIC INVESTIGATION

JOINT SPALLING FIELD DATA

OBSERVATION CHECKLIST:

1. Joint sealant is extruded or deteriorated:

   YES NO Comment:____________________

2. Incompressible debris found in the joint:

   YES NO Comment:____________________

3. Evidence of corrosion is found at the spall (e.g., staining):

   YES NO Comment:____________________

4. Spalling is primarily in the wheel path:

   YES NO Comment:____________________

5. Slab is faulted or curling:

   YES NO Comment:____________________

FOLLOW-UP TESTS TO CONSIDER:

1. Pavement cores through the distressed area to determine:
   a. Location and lubrication of dowel bars
   b. Whether dowels or reinforcement has corroded
   c. The compressive strength of the concrete
2. Pavement core through a nearby area that is unaffected by joint spalling so that the compressive strengths can be compared
3. Deflection testing to determine if the load is properly transferred across the joint

Figure 4.3 – Sample of joint spalling data sheet for field observation

4.2.2 Field Observation and Documentation

Once prepared for the initial field visit, the researchers must go to the site to perform the observations. It is not necessary for the entire investigative team to attend the initial field visit unless the testing program is also going to be performed during this visit. At a minimum, the forensic engineer in charge of the project should initially visit the site; however, documentation of the site conditions would be easier with additional people.

The critical part of the initial field visit is the documentation, which involves recording the information requested in the field sheets. All information should be documented rather than simply "remembered," for once information is documented, it will not be lost. The documentation should be neat, organized, clear, and complete, such that it can be referred to at a later date and still be understood. Complete and clear documentation can also be of help if there is subsequent litigation.

Background information, such as the exact location of the distress, should be documented first, followed by a description of the distress. An easy way to document the distress is to start at one end of the pavement section and progress toward the other end, documenting everything along the way. The information to be recorded includes the lane(s) in which the distress is observed, each type of distress that is observed, the location of the distress in the lane, the size of the distress relative to the pavement section, the depth of the distress if possible, and any other distinguishing characteristics of the distress. A sketch is often helpful when one is detailing the distress. All observations should be carefully documented, with the observations displayed for each distress in the field manual. The observation flowchart in the field manual helps organize the progression of the observations. The movement through the flowchart may also suggest possible hypotheses. However, all observations should be documented, even if the observation is passed in the flowchart, so that no possible hypothesis will be overlooked.

Photographs should also be used in the documentation process. Photographs can effectively record the conditions of the site at the time of the investigation, especially before material sampling or repair begins. Because photographs are relatively inexpensive, the photographer should not be concerned with finding the perfect shot. "Shoot when in doubt" is a convenient rule to follow. Photographs can supplement distress sketches, though a reference measure should be used in the photograph so that the size and depth of the distress can be seen. This reference measure may be a tape measure or a ruler. A marking system should also be used when photographs are taken. The marking system is used to document each photograph so the details of each shot are remembered after the photographs are developed. The marking system for each photograph includes the picture number, a description of the photograph, the location, the orientation, and any specific details that the photograph is supposed to show. Including a pavement plan view, with arrows to show the location and direction of each photograph, may be very useful. Sometimes good photography and documentation can make the difference between a successful forensic investigation and an unsuccessful one.

Many times the observed distress is a result of a material problem, in which case material testing is required. If this is the case, the investigators may take a sample of the pavement during the initial site visit. A sample should be taken only if the debris can be removed without special equipment and if there is no compromise of the traveling public's safety. Common distresses resulting in loose debris are spalling, potholes, ravelling, or shattering. However, the sample should not be removed until the distress has been properly documented and photographed. If a piece of debris is removed, it must also be documented. The location of the sample, its orientation, size when removed, and any of its distinguishing characteristics should be recorded. After the sample is marked, it is then stored and protected from the surrounding environment so that it will continue to correctly represent the properties of the pavement section.

4.2.3 Possible Failure Hypotheses

The main purpose of the initial site visit is to eliminate invalid failure hypotheses. By reducing the number of possible hypotheses, the team can also reduce the time and money to be spent on the testing program. Only a fraction of the total hypotheses would then need to be tested. Examining the site visit observations helps to determine whether a hypothesis can be eliminated. For the joint spalling example, the site visit may reveal that the joint sealant is still intact. Consequently, the mechanism of “restrained thermal expansion” may be eliminated because the intact joint sealant prevents incompressible debris from entering the joint.

Information obtained during the document search or the literature search also helps to determine if a hypothesis must be included in the testing program or if it can be eliminated. For example, if the actual strength of the pavement, determined from construction reports, is lower than the design strength, then “inadequate strength” probably needs to be included as a distress mechanism. Alternatively, the mechanism of “inadequate thickness of the asphalt layer” can probably be excluded if the ForenSys database reveals that the layer is actually 2 inches thicker than the design calculations specify.

Some distresses may be a result of yet another distress. For instance, joint sealant extrusion may cause joint spalling, which may progress into joint shattering. The hypotheses-forming stage also involves determining the history of the failure. Knowledge of the distress progression helps to reveal the correct distress mechanisms. The field manual contains, for each distress, a figure that displays the most likely progression of the distress.

4.2.4 Determining the Tests Required

After the possible hypotheses have been selected, a testing program is set up to determine whether the selected mechanism hypotheses are valid. The testing program is based on the possible distress mechanisms, with the results either verifying or contradicting the mechanisms. Sometimes the test results are inconclusive, but it is impossible to tell whether this inconclusiveness would occur unless the test is performed. The field diagnostic manual and the detailed diagnostic manual list the possible tests that can be conducted to test each distress mechanism. At a minimum, the single most probable hypothesis should be tested. However, in order to prevent multiple testing visits (iteration), all of the possible mechanisms should be tested during a site visit.

4.2.5 Iteration

Quite often, a testing program may not reveal any particular failure mechanism. The program may contradict all possible mechanisms or may not provide enough information to verify any mechanism. In this case, it may be necessary to test the omitted hypotheses during an additional site visit. An additional visit results in extra time and money spent on the forensic investigation; thus, to prevent iteration, all mechanisms may be tested during the initial testing site visit. Testing all hypotheses also costs extra money, but it still may be less of an expense than the cost of equipment and mobilization for a second testing visit. The best option is to test all hypotheses and all mechanisms with inexpensive and simple testing procedures. In this way, additional mechanisms can be tested without a significant increase in the time and money spent.

4.3 FIELD-TESTING PROGRAM

The field-testing visit is used to acquire information related to the distress mechanism hypotheses. Each test is used so that conclusions may be drawn from the results. Sometimes the test results may be inconclusive, but it is impossible to tell without actually performing the test. The field tests can be divided into two main categories: non-destructive testing and intrusive testing. Intrusive testing, often referred to as destructive testing, requires that the pavement be repaired after the tests have been performed. The objective of the testing program is to determine the in-situ properties of the pavement layers. The in-situ properties may differ from the properties that were designed, in which case the field tests may find deficiencies that resulted in pavement distress. Typical non-destructive and intrusive field tests are displayed in Tables 4.1 and 4.2, respectively.

4.3.1 Non-Destructive Testing

The most common non-destructive field tests determine the structural adequacy of the pavement and the underlying layers. Deflection testing is the most common test used to determine structural adequacy. From the deflection measurements, the strength and modulus of each layer of the pavement structure can be estimated. The Dynaflect measures pavement deflections under dynamic loading. The falling weight deflectometer also measures pavement deflections, but it uses impulse loading. Another structural analysis device is the dynamic cone pentrometer. This tool measures how far a cone penetrates a pavement layer after it is dropped from a predetermined height. The rate of penetration can be correlated to the strength of the pavement layer.

The physical properties of the pavement layer can be found without using destructive testing techniques. The pavement layer thickness and moisture content can be found using the ground-penetrating radar. By analyzing moisture content changes, the ground-penetrating radar can also determine areas where the drainage of the underlying layers is poor. In addition, ground-penetrating radar can locate voids beneath the surface layer of the pavement.

Other non-destructive test methods include skid resistance measurement tools. This measurement device is useful if the pavement surface is experiencing polishing of the aggregates. A pachometer or similar device is useful for locating and sizing reinforcement in rigid pavements. In extreme situations, X-ray testing can be used to locate reinforcement.

4.3.2 Intrusive/Destructive Testing

Destructive testing involves destruction of all or part of the pavement section to determine different properties. Common types of destructive testing include coring, boring, and trenching. These sampling techniques are performed to determine the thickness, nature, and condition of the pavement layers and materials, their in-situ properties, the water and drainage conditions, and the effects of traffic; they are also used to obtain samples for further laboratory testing [Metcalf 92]. Trenching is a common way to obtain material samples, to access the underlying layers for load testing, to check for a stabilized base, or to locate the water table. While the material sampling must take place in the field, most of the testing of the materials occurs in the laboratory; however, the team can determine many properties from a core while in the field. The thickness of the pavement and any significant deterioration can be observed from a pavement core. In addition, load transfer devices and steel corrosion can be observed from a concrete core that was taken through the steel.

Researchers can use oil borings to measure the layer thickness, observe erosion or weathering, or identify materials, but these samples are most commonly obtained for testing in the laboratory.

An essential part of material sampling is the procurement of representative samples. Samples should be obtained from different areas of the distressed pavement section. The engineers can compare the different samples to determine what is similar and what is different about the samples, recognizing that differences in the properties of the samples may rule out a distress mechanism. The observed distress may be occurring in an area where a material property verifies the mechanism, but the observed distress may also be occurring in an area where the same material property contradicts the mechanism. For instance, assume that two pavement cores are taken from a pavement section experiencing loss of surface material, but only one core exhibits a local clay inclusion. Accordingly, the mechanism of a local inclusion should be carefully examined, since part of the pavement section did not have a local clay inclusion but was nonetheless experiencing loss of surface material.

Sampling of non-distressed areas is also a useful tool of field investigation. If a pavement section is experiencing a certain distress where a pavement core is required, it is useful for the team to take a core from a nearby pavement section that is not experiencing that particular distress. Because the two cores can be assumed to experience the same traffic, the same weather, and possibly the same age, all of these variables can be eliminated. The laboratory tests can determine differences in the material properties, and any difference may verify the distress mechanism. For the loss-of-surface-material example mentioned earlier, if the core from the non-distressed section had a low water-cement ratio at the surface, but the distressed section core did not, it could be concluded that the higher water-cement ratio at the surface resulted in the loss of surface material. Sampling non-distressed areas is also a good technique for pavement distresses requiring soil borings.

4.3.3 Preparation of Laboratory Specimens

The location and size of each sample should be properly documented during the field-testing visit. The location of the material sample, relative to the pavement distress, should also be documented. The researchers may need to observe the sample to obtain certain properties, but most of the material testing is done in the laboratory. Therefore, it is important that the team prepare the material samples during the field-testing visit. The sample should be protected from the environment until the laboratory testing has begun. If the sample is not well protected, the laboratory tests may not reveal the in-situ properties of the material. The sample should be placed in a plastic bag to prevent moisture or foreign material from entering or leaving. If the sample is going to be shipped, it should be packed properly so that it does not crack or break during shipping. The primary purpose of preparing the laboratory specimens is to ensure that the results of the laboratory tests accurately represent the in-situ properties of the material in the field.

Table 4.1 – Typical non-destructive field tests for each pavement type

PAVEMENT TYPE	
Rigid Pavement	**Flexible Pavement**
Deflection Testing (FWD, Dynaflect): Structural evaluation Load transfer Void location	**Deflection Testing (FWD, Dynaflect):** Structural evaluation Void location
Wave Testing (GPR, Impact Echo, Ultrasonic SASW): Thickness determination Void location Poor drainage location	**Wave Testing (GPR, Impact Echo, Ultrasonic SASW):** Thickness determination Void location Poor drainage location
Other measurements: Pachometer: Steel location Steel size determination X-ray testing Skid resistance measurement Roughness profilometer	**Other measurements:** Skid resistance measurement Roughness profilometer

Table 4.2 – Typical destructive/intrusive field tests for each pavement type

PAVEMENT TYPE	
Rigid Pavement	**Flexible Pavement**
Concrete Coring: Thickness determination Steel corrosion observation Load transfer device observation Deterioration observation Lab sample collection	**Asphalt Coring:** Thickness determination Deterioration observation Lab sample collection
Soil Boring/Trenching: Thickness determination Significant erosion observation Material identification Stabilized base check Load testing of the base layers Lab sample collection Water table location	**Soil Boring/Trenching:** Thickness determination Significant erosion observation Material identification Stabilized base check Load testing of the base layers Lab sample collection Water table location

4.4 LABORATORY-TESTING PROGRAM

The laboratory-testing program is performed because much of the testing equipment is too large or expensive to be brought into the field. Shipping the material sample to the laboratory is much less expensive than hauling the bulky testing equipment to the field. The purpose of the laboratory testing is to determine the in-situ properties of the material that still exists in the field. The properties may reveal information that supports or contradicts a distress mechanism hypothesis. Laboratory investigations involve testing that determines the physical, chemical, and material properties of each component of the pavement section. Also included in the laboratory-testing program is computer analysis and/or records search. These types of investigations are included in the laboratory-testing program, because it is performed in an office or on a computer, and is usually not done in the field.

4.4.1 Material Testing

The material testing is performed on the samples that were obtained during the field visit. Part of the material testing involves determining the physical properties of the sample, which include the sample's compressive and tensile strengths, its density, and its modulus. Asphalt cores may also include tests of the stripping, disintegration, viscosity, penetration, and ductility of the asphalt binder. Determination of the sample's material properties is also a part of the laboratory testing. For concrete samples, these properties include the air content, the water-cement ratio, evidence of freeze-thaw damage, evidence of inclusions, and the quality of consolidation. Similarly, the asphalt properties determined during laboratory tests include the degree of compaction, evidence of frost action, and evidence of inclusions. In addition, laboratory testing involves the determination of the materials' chemical properties, which include the chloride content of a concrete sample or the reactivity of aggregate with the cement. Typical laboratory material tests are shown in Table 4.3.

The laboratory testing program also includes the testing of soil samples. Soil tests are commonly used to determine the shrink-swell potential of the soil, its drainage conditions, its degree of permeability, and its resistance to weathering; these tests are also used to determine whether a stabilized base was used. Other common soil tests are used to determine the moisture content; to observe freeze-thaw damage; to measure the Atterberg limits, the thermal coefficient, and the modulus; and to perform a triaxial compression test. Table 4.3 displays common laboratory tests used on soil borings.

4.4.2 Records Search

Because the records search is often carried out in the office, it is included in the laboratory testing. While it is not actually a field test or a laboratory test, it still needs to be conducted sometimes in order to verify certain distress mechanisms. Quite often, the document search includes the necessary records; however, different records commonly need to be obtained if they were omitted from the original document search. A typical record search might involve obtaining weather records if the distress is weather related. Construction, design, traffic, and maintenance records are useful documents for verifying certain distress mechanisms. Table 4.4 shows common uses for the record search.

4.4.3 Computer Analysis

The laboratory-testing program may also include computer analyses of the pavement structure. Physical test results, such as compressive strengths, elastic moduli, or deflections, can be used as material parameters in the computer analysis. The engineers can also use the results of the field tests to analyze the structural adequacy of the pavement section, especially if the distress is structure related. Back calculation to determine layer modulus values may also be useful.

Table 4.3 – Typical laboratory tests for each pavement type

PAVEMENT TYPE	
Rigid Pavement	**Flexible Pavement**
Concrete Core Testing: Density measurement Compressive strength measurement Tensile strength measurement Material modulus measurement Freezing and thawing damage observation Quality of consolidation check Inclusion observation (clay, silt, etc.) Petrographic examination: Air content measurement Water/cement ratio determination Aggregate/paste bond check Inclusion observation (clay, silt, etc.) ASR observation Chloride content measurement **Aggregate Sampling:** Reactivity determination Accelerated polish test	**Asphalt Core Testing:** Density measurement Compressive strength measurement Stripping measurement Disintegration measurement Material modulus measurement Freezing and thawing damage observation Quality of compaction check Inclusion observation (clay, silt, etc.) Asphalt content measurement Aggregate/binder bond check Temperature stability measurement Moisture content determination Asphalt viscosity measurement Penetration of asphalt measurement Ductility of asphalt measurement

Table 4.3 – Typical laboratory tests for each pavement type (continued)

PAVEMENT TYPE	
Rigid Pavement	**Flexible Pavement**
Soil Boring Testing: Moisture content measurement Potential vertical rise measurement Freezing and thawing damage observation Drainage factor measurement Resistance to weathering determination Degree of compaction measurement Triaxial compression test Elastic modulus measurement Plasticity index measurement Liquid limit measurement Sieve analysis Shrink-swell potential measurement Thermal coefficient measurement Degree of permeability measurement Stabilized base use	**Soil Boring Testing:** Moisture content measurement Potential vertical rise measurement Freezing and thawing damage observation Drainage factor measurement Resistance to weathering determination Degree of compaction measurement Triaxial compression test Elastic modulus measurement Plasticity index measurement Liquid limit measurement Sieve analysis Shrink-swell potential measurement Thermal coefficient measurement Degree of permeability measurement Stabilized base use

Table 4.4 – Typical types of record searches for each pavement type

PAVEMENT TYPE	
Rigid Pavement	**Flexible Pavement**
Weather Records: Recent hot/cold weather Winds during placement Recent rainfall **Construction Records:** Layer thickness Stabilized base use Material strengths **Design Records:** Layer thickness Design strengths Joint spacing Mix design **Traffic Records:** Average daily traffic Changes in traffic patterns Studded/chained tire use **Maintenance Records:** Recent repairs Existing overlays	**Weather Records:** Recent hot/cold weather Recent rainfall **Construction Records:** Layer thickness Stabilized base use Material strengths **Design Records:** Layer thickness Design strengths Mix design **Traffic Records:** Average daily traffic Changes in traffic patterns Studded/chained tire use **Maintenance Records:** Recent repairs Existing overlays

4.5 DATA ENTRY INTO FORENSYS DATABASE

Once all the field tests and laboratory tests have been performed, the results should be entered into the ForenSys database. The notes from the initial field visit and the information from the document/literature search should also be entered into the database. After the test results, field notes, and information from the search have been entered into the database, the data can be accessed by anyone who needs to see it without searching for the documents and field notes. Entering the information into the database also prevents incomplete and unclear field notes from being misunderstood or misinterpreted.

CHAPTER 5 – DATA ANALYSIS AND CONCLUSION FORMATION

5.1 BACKGROUND

The purpose of the data analysis and conclusion formation stage is to develop the most probable cause(s) of the pavement distress. This stage allows the information to be analyzed, because not all of the collected information is relevant to the mechanism of the distress. The relevant information allows the correct conclusion to be formed so that the proper repair strategy can be implemented. "The purpose of diagnosis is to determine the cause, or causes, of the pavement distress, preferably sufficiently in advance of failure to indicate a cure" [Metcalf 92].

Data analysis involves organizing and analyzing all of the information that has been collected — information from the document search, the literature search, the ForenSys database, the field observations, the field tests, the photographs, and the laboratory tests. The information is then organized so that any information that does not relate to the failure hypotheses can be eliminated. The relevant information is then analyzed to determine whether it supports or contradicts any of the failure hypotheses. The data analysis stage is often called the "synthesis of the investigation." The team brings all of the collected information together to develop a failure conclusion.

In order to develop the failure conclusion, the collected information should be viewed as part of the whole picture. If all of the information supports one particular failure hypothesis and contradicts all others, the failure conclusion can be clearly identified. However, more often than not, the information both supports and contradicts a given set of multiple failure hypotheses. In this case, the information must be analyzed to determine which failure hypothesis is adequately supported by the collected information. Quite often, multiple failure mechanisms work together to form the pavement distress, so it is common for more than one failure hypothesis to be part of the failure conclusion. The conclusion also develops a failure history for the pavement distress. This history describes the most likely progression of the distress up to the current state.

5.2 DATA ANALYSIS

The first step of data analysis is organizing all of the collected information. The observations, field visits, laboratory tests, literature search, and document search were performed to obtain as much information regarding the distressed pavement section as possible; however, the amount of information that has been collected can be overwhelming. It is therefore necessary to reduce the information down to a manageable form. The reduced data should include information that is relevant to the possible failure mechanism hypotheses. While much of the collected information will not relate to any of the failure hypotheses in any way, it should still be saved until the forensic investigation is complete. A detailed analysis of the failure mechanisms can begin after all of the data have been organized [Raths 79].

Most of the information collected during the literature and document search relates to the design, construction, maintenance, and history of the pavement section. This information is relevant to failure hypotheses relating to the pavement section's design and construction, including inadequate thickness of a pavement layer, improper stabilization of the base layer, or omission of a drainage system during construction. To determine whether a piece of information is relevant, the forensic engineer asks certain investigative questions. Nicastro [97] explains that in order to form evidence, the team must compare the data with the answers to the following four questions:

1. What did the industry standards call for?
2. What did the design documents call for?
3. What was actually constructed?
4. What changed after construction?

The answers of these questions may reveal deficiencies in the design or errors in the construction procedures. It also helps to identify the pertinent information that was obtained during the literature and document searches.

Field observation information was originally used to form possible failure mechanisms, but it can also be used to support a failure hypothesis. Results from field and laboratory testing are always relevant because the tests were conducted to help support or contradict the possible failure hypotheses. Similarly, weather, traffic, or maintenance records are considered relevant if they were obtained to help verify a failure hypothesis. If weather, traffic, or maintenance records were obtained as part of the document and literature search, the information may not pertain to any of the possible distress mechanisms. While it is possible that the data obtained from the field observations, field tests, records check, and laboratory testing may reveal information regarding the design and construction of the pavement, this type of information usually relates to failure mechanisms involving environmental factors, material inadequacies, traffic overloading, or structural deficiencies.

Finally, the field photographs are also helpful when it comes to supporting or contradicting possible hypotheses. The photographs may reveal a certain pattern of the distress that supports a hypothesis. For instance, if the photographs show that transverse cracking occurs about every 10 ft in a concrete pavement, this information may support the hypothesis that the cracks are shrinkage cracks and are due to late sawing of the transverse joints. Photographs may also display unusual environmental factors, signs of abuse, or the conditions surrounding the pavement.

Once the information has been organized into relevant and irrelevant categories, it can be analyzed in detail, or synthesized into possible conclusions. “The synthesizing process is carried out using a systematic appraisal of investigative data combined with technology, deductive reasoning, and practicality” [O’Kon 92]. Each piece of relevant information either supports or contradicts a failure hypothesis; all inconclusive evidence is probably considered irrelevant. In addition, one piece of information may support one hypothesis and contradict another. A possible hypothesis is rarely fully verified. In other words, a possible hypothesis may be supported by one piece of information and contradicted by another piece of information. Every piece of information should be analyzed in detail to determine which hypothesis it supports or contradicts.

Sometimes a piece of relevant information neither supports nor contradicts a possible failure hypothesis. This “gray area” comes into play when the team is dealing with values that are not absolute. For example, inadequate strength of the concrete may be cited as a possible distress hypothesis of joint spalling. Compressive strength tests reveal that the strength is approximately 3,500 psi, when the design required 4,000 psi. The evidence barely supports the possible mechanism of inadequate strength, but a concrete strength of 3,500 psi may be high enough to prevent joint spalling. Is 3,500 psi high enough so that the evidence contradicts the possible joint spalling mechanism? In these situations, the information may be relevant, but it will not firmly support or contradict a possible hypothesis.

5.3 CONCLUSION FORMATION

After all of the pieces of information have been analyzed to determine whether they support or contradict any of the possible hypotheses, the most probable failure hypotheses must be chosen. The most probable hypotheses are those that have the most and strongest evidence supporting them (with the fewest contradictions). Hypotheses with all contradicting evidence and no supporting evidence can be easily eliminated. From the remaining probable hypotheses, a failure conclusion begins to form.

Nicastro [97] describes the matrix method of evaluation as a two-dimensional array used to relate the subjective information to the objective information. The subjective information is the set of possible failure hypotheses that have been tested throughout the forensic investigation. The objective information is all of the facts that have been collected from the field observations, testing program, literature search, document search, photographs, and so on. The placement of certain symbols in intersecting squares of the matrix shows the relationship between the subjective and objective information. An "X" in the intersecting square shows that the objective facts support the subjective hypothesis, and an "O" in the square shows that the facts contradict the hypothesis. If there is no relationship between the facts and the hypothesis, no symbol is placed in the box. Figure 5.1 shows an example of the matrix method of evaluation for joint spalling in a concrete pavement. The hypotheses are placed in the vertical columns and the collected facts are placed in the horizontal rows.

		Subjective Information (hypotheses)					
		Steel corrosion	Restrained slab expansion	Incorrect load transfer	Inadequate concrete strength	Traffic action	Freeze-thaw damage
Objective Information (facts)	Slab is not faulted or curling at the joint					O	
	Joint sealant is deteriorated or extruded	X	X				
	Incompressible debris is not found in the joint		O				
	Spalling is not primarily in the wheel paths					O	
	Evidence of corrosion is not found around the spall (e.g., staining)	O					
	Core reveals dowel bars are properly constructed and lubricated			O			
	Core reveals that reinforcement is slightly corroded	X					
	Compressive strength test reveals the concrete strength is adequate				O		
	Weather records show that hot weather has been common lately		X				
	Weather records show that freezing temperatures are rare for this area						O

X = The fact supports the hypothesis, O = The fact contradicts the hypothesis

Figure 5.1 – Matrix method for concrete pavement joint spalling

The conclusions are then formed from the constructed matrix. In the above example the evidence is probably strong enough to eliminate the hypotheses of incorrect load transfer, inadequate concrete strength, traffic action, and freeze-thaw damage. The remaining evidence shows that the joint sealant has been extruded, hot weather has been occurring lately, and the reinforcement is slightly corroded. These observations suggest that the joint spalling mechanism is a combination of steel corrosion and restrained slab expansion. Even though incompressible debris was not found in the joint, the hot weather suggests that slab expansion was likely. In addition, the debris may have been removed by traffic action. Similarly, even though staining was not present from the corrosion, the concrete core revealed that the reinforcement corrosion probably contributed to the joint spalling mechanism.

In forensic engineering, the critical piece of evidence that proves the proposed failure mechanism is referred to as "the smoking gun." In pavement forensic engineering, rarely will one piece of evidence determine a failure mechanism. Similarly, it is rare that one single mechanism will have contributed to the pavement distress. It is often a combination of mechanisms that result in a given distress. Because a single failure mechanism is uncommon, all of the failure mechanisms must be found. In addition, the interaction between the mechanisms must be determined.

The most important thing to remember when forming the final conclusions is to keep an open mind. The conclusions should not be narrowed to the most apparent mechanisms; instead, the focus should remain on all possible hypotheses [ASCE 89]. Sometimes the least likely hypothesis is the mechanism responsible for the pavement distress. Having an open mind allows the forensic engineer to ask the right investigative questions about the distress mechanisms. Assumptions can be made when asking open-minded investigative questions; however, the assumptions should be made with great care, as Raths [79] explained in the following statement:

> Assumptions have to be made. If there is no way of verifying these, then the assumptions that must be made are those favoring the failure not happening. If the analysis still predicts that the failure will occur, an engineer can be confident he has found the failure mechanism. But, if assumptions are made that favor the failure

developing following site observations, one cannot be sure this is the actual failure mechanism because of the assumptions made. All failure assumptions required for analysis must be in favor of the failure not happening.

After all assumptions have been made, the final conclusions must still fit the facts of the investigation. "The conclusion that is developed must be compatible with the sequence of events, the observed phenomena during failure, and the physical data obtained" [Sowers 86]. To be sure that the conclusions fit the facts of the investigation, the researchers should develop a failure history to describe the progression of the distress in the pavement section. The failure history starts at the point when the section is not distressed, such as just after construction, and follows through the initial formation of the distress up to the current state of the distress. The information in the failure history can be verified using such documents as maintenance records, past condition surveys, or past forensic reports. A failure history that fits the facts is essential because it shows that the distress mechanism is truly understood.

5.4 RESOURCES AVAILABLE FOR DATA ANALYSIS AND CONCLUSION FORMATION

Quite often during the data analysis stage, the forensic engineer has a difficult time keeping track of all of the photographs, field notes, test results, and literature search results. A computer is useful for organizing and reducing the information down to a manageable form; however, once the information is entered into the computer, it still must be analyzed. To ensure that the correct failure mechanisms are found, TxDOT has created a number of resources to aid in the analysis of the data. These resources include the detailed version of the diagnostic manual, the electronic version of the diagnostic manual, and the ForenSys database.

5.4.1 Detailed Version of the Diagnostic Manual

The detailed version of the diagnostic manual was used during the data collection stages to determine the observations and testing procedures to perform on the distressed pavement. This manual can be used again during the data analysis stage to determine how the collected information relates to the possible hypotheses. The observation matrix shows the possible hypotheses that each observation can potentially support. Similarly, the field/laboratory investigation matrix shows what test results are related to each particular hypothesis. Figure 5.2 shows the observation matrix from the detailed diagnostic manual for the previously mentioned joint spalling. Figure 5.3 displays the field/laboratory investigation matrix from the detailed diagnostic manual. Each "X" in Figures 5.2 and 5.3 shows which observations and investigation procedures may be used to support each possible mechanism. If it turns out that the observation is false, or that the investigation results contradict the possible mechanism, the "X" in the box is changed to an "O" in the conclusion matrix to show that the facts contradict the possible mechanism.

	Mechanisms					
Observations	Steel corrosion	Restrained slab expansion	Incorrect load transfer	Inadequate concrete strength	Traffic action	Freeze-thaw damage
Slab is faulted and/or curling					X	
Joint sealant is deteriorated or extruded	X	X				
Incompressible debris found in the joint		X				
Spalling is primarily in the wheel paths					X	
Evidence of corrosion found around the spall (staining)	X					

X = Observation result can potentially support the distress mechanism hypothesis

Figure 5.2 – Joint spalling observation matrix from the detailed diagnostic manual

Investigations	Mechanisms: Steel corrosion	Restrained slab expansion	Incorrect load transfer	Inadequate concrete strength	Traffic action	Freeze-thaw damage
Observe placement and lubrication of dowel bars			X			
Observe degree of corrosion in reinforcement	X					
Deflection testing			X			
Compressive strength test				X		
Check for recent hot weather		X				
Check for recent freezing temperatures						X
Observe the core for freeze-thaw damage						X

X = Investigation result can potentially support the distress mechanism hypothesis

Figure 5.3 – Joint spalling investigation matrix from the detailed diagnostic manual

These two matrices from the detailed diagnostic manual form the basis of the matrix method of evaluation. In other words, the matrices from Figures 5.2 and 5.3 combine to form the conclusion matrix shown in Figure 5.1. The results from the literature search and the document search, as well as those from any other test results, can then be added to complete the matrix and conclusions can then be formed.

The detailed diagnostic manual can also be used to develop the failure history. Once the failure mechanisms have been determined from the investigation, the detailed manual can be used to obtain additional information about these distress mechanisms. The detailed manual describes each distress mechanism and how it works. In addition, if a certain pavement distress is a result of a different distress, the relation between the two distresses is explained. The detailed manual helps to provide an understanding of the distress mechanisms so that the failure history can be created.

5.4.2 Electronic Version of the Diagnostic Manual

The electronic version of the diagnostic manual contains all of the same information that is in the detailed version of the manual; however, it is posted on the World Wide Web so that it can be accessed from anywhere by anyone having Internet access. Therefore, the electronic manual is used when the team is forming conclusions, just as the detailed manual was used.

In addition to the detailed manual's features, the electronic version contains an expert discussion group to discuss any problems that may arise. The password-protected discussion group, which can be accessed by any approved TxDOT employee, helps to ensure that there is adequate feedback for any questions or problems that are posted on the Web site. Questions regarding the current forensic investigation can be posted on the Web site. Photographs, field notes, or a quick summary of test results may also be posted so that the forensic engineer viewing the Web site will have a thorough understanding of the problem. Once the question or problem is posted, anyone with access to the discussion group is able to provide solutions, possible ideas, additional questions, similar problems, or any other type of feedback. The feedback can also be archived so that past discussions may be referenced for current problems.

For instance, suppose bleeding has been occurring on a particular flexible pavement section. The field observations and investigation results were analyzed, but the analysis did not favor any particular distress mechanism. In this case, the mechanism may be unique (e.g., a problem related to the specific type of material used) and, consequently, not included in the diagnostic manuals. A description of the problem, a few photographs, and a summary of the test results are then posted in the discussion group. Forensic engineers, or possibly pavement designers, from TxDOT could then provide feedback to the discussion group. Some of the feedback might relate to common mechanisms of bleeding, while other replies might be from an engineer experiencing the same problem. Yet another engineer may reveal that he or she has had problems with bleeding when trying to properly compact a Type X asphalt binder. When all the replies and feedback are combined, the Web site acts as a type of expert meeting specifically related to the topic of flexible pavement bleeding. While working together, everyone who provides feedback helps to create a solution to the bleeding problem.

5.4.3 ForenSys Database

The ForenSys database acts as an archive to forensic investigation reports completed by TxDOT. Accordingly, the database may aid in the conclusion formation stage when problems arise. Just as problems may be posted in the discussion group so that a solution may be found, the database can be searched to determine if a solution has already been found. The database can be searched according to the type of pavement distress and any forensic reports corresponding to that particular distress can be viewed.

In the bleeding example mentioned previously, the ForenSys database could conduct a search to identify the available forensic investigation reports relating to bleeding of flexible pavements. The reports could then be viewed to help the engineers find ideas, possible testing methods, or additional hypotheses; however, the results should never be directly used as a solution to the problem. If the database search helps to form hypotheses that differ from those tested during the investigation, the new hypotheses should always be tested before the conclusions are developed.

5.5 DATA ANALYSIS AND CONCLUSION FORMATION IMPROVEMENTS

Although the detailed diagnostic manual, the electronic diagnostic manual, and the ForenSys database provide useful information when performing data reduction, analysis, and conclusion formation, the tasks can still be quite tedious. Significant amounts of data and information can be collected during complicated forensic investigations. It may take the engineers an enormous amount of time to reduce and analyze these data to form conclusions, even with the help of the available resources. In addition, keeping track of the data is difficult enough without the researchers having to worry about determining what is relevant or how strongly the evidence supports a particular failure hypothesis. Additional tools may be necessary to help the team analyze the data and form conclusions. One helpful tool would be a Knowledge-Based Expert System (KBES). Linking the expert system with pavement management system software should be a goal of future development [Metcalf 92].

In a future scenario, after the initial field visit had narrowed the possible hypotheses and the hypotheses had been tested, an expert system, or Knowledge-Based (KB) engine, would be used for the data analysis and conclusion formation stage. The data and information from the literature search, the document search, the testing program results, and the records search would be entered into the engine. Photographs cannot be input directly, but such information as crack spacing, spall dimensions, and pothole depths could be entered into the engine for analysis.

The Knowledge-Based engine does the tedious work, such as reducing the data to only the information that is relevant. The engine also determines whether the information supports or contradicts any of the possible hypotheses. In addition, the information can be weighted to differentiate between evidence that strongly supports/contradicts and evidence that somewhat supports/contradicts a hypotheses. For example, suppose that a concrete pavement is experiencing transverse cracking. The investigations reveal that the joints were constructed too far apart and that the base is susceptible to swelling. The engine can weight these findings so that the overlong joint spacing slightly supports the "improper joint construction" mechanism and the potential vertical rise of the base materials strongly supports the "swelling of base materials" mechanism. Therefore, the end result of the Knowledge-Based engine activity will be a conclusion that best fits all of the available facts.

Finally, the Knowledge-Based engine can be linked to the ForenSys database to aid the data input stage. After the forensic investigation report is completed, it must be entered into the ForenSys database. If most of the information has been entered into the Knowledge-Based engine during the data analysis stage, the information can be linked to the ForenSys database. Thus, once the report is completed, the conclusions and the failure history information would be the only data entry requirements for the ForenSys database.

CHAPTER 6 – FORENSIC REPORT PREPARATION

6.1 BACKGROUND

"The culmination of forensic pavement analysis should be the preparation of a comprehensive written report which details the fact-finding mission that resulted in the cause of the distress and recommendations for repair" [O'Kon 92]. The forensic investigation report is used to inform other divisions and districts within TxDOT. Each report explains the mechanisms associated with the particular distress under investigation. By making the forensic reports available, we may present similar problems in the future. These problems include design-related problems, material selection problems, and construction-related problems. "Only through the dissemination of failure information can similar incidents be prevented" [Nicastro 97].

A forensic report should be created after every investigation and should include all of the important aspects of the investigation; consequently, previous reports should be used only for that previous investigation [Sowers 86]. A previous report should never be used for a current investigation, even if there are only slight differences in the testing program, hypotheses, or conclusions. With the creation of a new report for each investigation, the amount of information available for future investigations is always increasing. The more information made available for future investigations, the more likely it is that the future investigation will be successful.

An investigator should take the time necessary to write a quality forensic report, insofar as the report is a reflection on the author. The easiest way to write a quality report is to have a thorough understanding of the investigation procedures and the reasons certain conclusions were formed. Most importantly, the report must be written so that the reader cannot misinterpret any of the report statements. The report must also be clear and concise and should use simple language to explain ideas. A quality report does not require additional interpretation; in other words, the report should speak for itself [Suprenant 88]. If detailed technical information is to be included in the report, it should be separate from the main report, perhaps in an appendix.

After a TxDOT pavement investigation has been completed, two reports should be created. The first report is a distributable report, one that contains the basic facts and conclusions of the investigation. The second report is a more detailed report that includes additional supporting information that was used to form hypotheses and conclusions. TxDOT currently has no formal procedure for producing forensic investigation reports. The following sections propose a format for future reports.

6.2 THE DISTRIBUTABLE REPORT

Besides being useful as a future reference, the report on the forensic investigation can be used to prevent similar occurrences in the future and to organize the major details of the investigation into one document. Therefore, each step of the investigation and the details of each step should be included in the report, as discussed below [ASCE 89]:

> The various reports that chronicle a forensic investigation should encompass the complete history of the fact-finding mission. They should begin with the failure incident, traverse the complete investigation, and provide accounts of critical events.

The search through previous TxDOT forensic reports revealed that there is currently no standard format for these reports. Many of the forensic reports were neatly organized into the different steps of the investigation; however, many of the reports were made up of a series of memoranda that were originally used as updates to the investigation's progress. In order for the forensic investigation resources to be the most effective, and in order for future investigations to be efficient and effective, a standard report format needs to be created. The American Society of Civil Engineers' document, entitled "Guidelines for Failure Investigation" [ASCE 89], recommends that forensic investigation reports be composed of the following eight sections:

1. Purpose
2. History
3. Description of Project
4. Observations
5. Testing

6. Analysis
7. Conclusions
8. Recommendations

"Distributable report" is a term used to describe the basic report that is created after each investigation. This report may be distributed to different TxDOT districts, entered into the ForenSys database, and given to other agencies if necessary. The distributable report also serves as the basis for the detailed report. The detailed report includes more in-depth information, such as the collected data before it is reduced. The proposed format for future TxDOT forensic reports follows the above outline and is displayed in Figure 6.1.

6.2.1 Purpose

The first section of the report briefly describes the pavement section's location information, including the district, county, highway, mile marker numbers, traffic direction, lane designation, and pavement type. This section is also used to explain why a forensic investigation was being conducted on that particular pavement section. Finally, the names of everyone involved in the investigation, such as team members, district managers, or outside contractors, are listed.

TxDOT FORENSIC INVESTIGATION
FORENSIC REPORT OUTLINE

Section One: Purpose
- Location information
- Why investigation was performed
- Parties involved

Section Two: History
- Past pavement section history/documents
- Document/literature search information

Section Three: Description of Project
- Description of distresses occurring
- Quantity and severity of each distress

Section Four: Observations
- Initial field observations
- Important field notes and photographs
- Basis for each hypothesis

Section Five: Testing
- Field-testing program and results
- Laboratory-testing program and results
- Computer analysis and/or records search

Section Six: Analysis
- Methodology for review
- Evaluation procedures
- Important computations

Section Seven: Conclusions
- Most probable distress mechanisms
- Failure history

Section Eight: Recommendations
- Repair options
- Prevention measures
- Degree of urgency

Appendix: (Detailed Report Only)
- Additional photographs and field notes
- Unreduced testing program data
- Confidential data

Figure 6.1 – General format for forensic investigation reports [ASCE 89]

6.2.2 History

Section 2 details the history of the pavement section. This information is obtained in the document and literature search and is summarized in this section. Beginning with the date of construction, this section also reveals information about the performed maintenance, past forensic investigations, and previous condition surveys of the pavement section. The details of the pavement structure, the materials information, the traffic history, the critical construction documents, the design details, and the related soil reports are also included in this section.

6.2.3 Description of Project

Section 3 of the report is mainly used to describe the distress that is occurring on the pavement section. All of the distresses that exist on the pavement section should be listed. A summary of the quantity and severity of each distress is also given; photographs may be used to aid the description.

6.2.4 Observations

Section 4 is used to outline the details of the initial site visit. Each observation is discussed and is supported by field notes or photographs. Any initial assumptions, and the basis for these assumptions, would also be discussed here. Finally, the initial hypotheses are introduced.

6.2.5 Testing

Section 5 should present an overview of the testing program used in the investigation. First, the field tests that were performed are described, along with the purpose of each test. Test results should be shown only if the data have been reduced, such as to graphical form. Second, each laboratory test, its purpose, and the results are explained. Finally, any hypotheses-related information about structural capacity, environmental conditions, traffic conditions, or other conditions determined from the computer analysis and record search is presented.

6.2.6 Analysis

Section 6 is used to describe the analysis of the collected information. The results of the synthesis of the investigation, an analysis of the failure, the methodology, the computations, and the hypothesis evaluation are all described in this section [ASCE 89]. The matrix from the matrix method of evaluation may be included to provide clarity.

6.2.7 Conclusions

Section 7 discusses the conclusions of the investigation. The facts of the investigation must fit the conclusions, and the report must support each conclusion with the collected facts. When discussing each conclusion, it is important that the author prevent misinterpretation of the conclusion. By supporting each conclusion with facts, misinterpretation can be avoided. There must also be a discussion of the reliability of each conclusion. If the conclusion is strongly supported by the collected facts, then the conclusion of the most probable distress mechanism is quite reliable. However, if the conclusions are partly based on assumptions, the reliability of the conclusions must be addressed. Finally, the failure history is presented in this section. The history describes the progression of the distress from initiation to the current state.

In this section it is important not to confuse conclusions with assumptions or opinions. "The report must be careful to distinguish which are facts and which are conclusions derived from the facts" [Sowers 86]. It should be noted that sections 1 through 6 include only the facts of the forensic investigation. The conclusions and recommendations sections are mostly opinions based on the facts of the previous report sections.

6.2.8 Recommendations

Section 8 of the report discusses the possible repair strategies or changes in design and/or construction. Because the repair strategy is based on the distress mechanism, the number of possible repair strategies may be limited. This section lists the feasible repair strategies and suggests the repair strategies that should be avoided.

"The treatment, of course, must focus on the cause of the illness, not simply the symptoms, and any recurrence should be the signal for a more extensive investigation" [Metcalf 92]. This statement explains that the investigation may not be completely accurate if the selected repair strategy does not perform well. Just as the reliability of the conclusions was discussed in the previous section, the reliability of the repair strategy should also be discussed. The possibility that the repair strategy will not work, even if the strategy addresses the mechanism, should always be considered.

The detailed diagnostic manual would be helpful when writing the recommendations section of the forensic report. First of all, the detailed diagnostic manual lists the recommended repair strategies for each distress mechanism. The recommendation section of the forensic report can include measures for prevention so that similar problems may be avoided in the future. The detailed diagnostic manual describes the prevention measures for each distress mechanism. Finally, the detailed diagnostic manual gives an estimate of the degree of urgency so that the need for repair can be discussed in the forensic report.

6.2.9 Use of the ForenSys Database

The report should not be considered complete until the details of the investigation have been entered into the ForenSys database. In order to increase the resources available for future investigations, researchers should enter every report into the database upon the report's completion. Figure 6.2 shows the format for data entry into the database. The section definition portion allows the location of the pavement section to be entered. It is also important that the observed distress be entered because this data category is commonly used to search for forensic reports. The traffic information from the document/literature search, such as ADT, ESALs, and percentage trucks, should be entered and updated when necessary. There are also multiple data categories in which one should enter material property results from the field-testing and laboratory-testing programs. Finally, the "View/Modify Report" button enables the engineer to enter additional information from the forensic report that is not included in the pre-designated data categories.

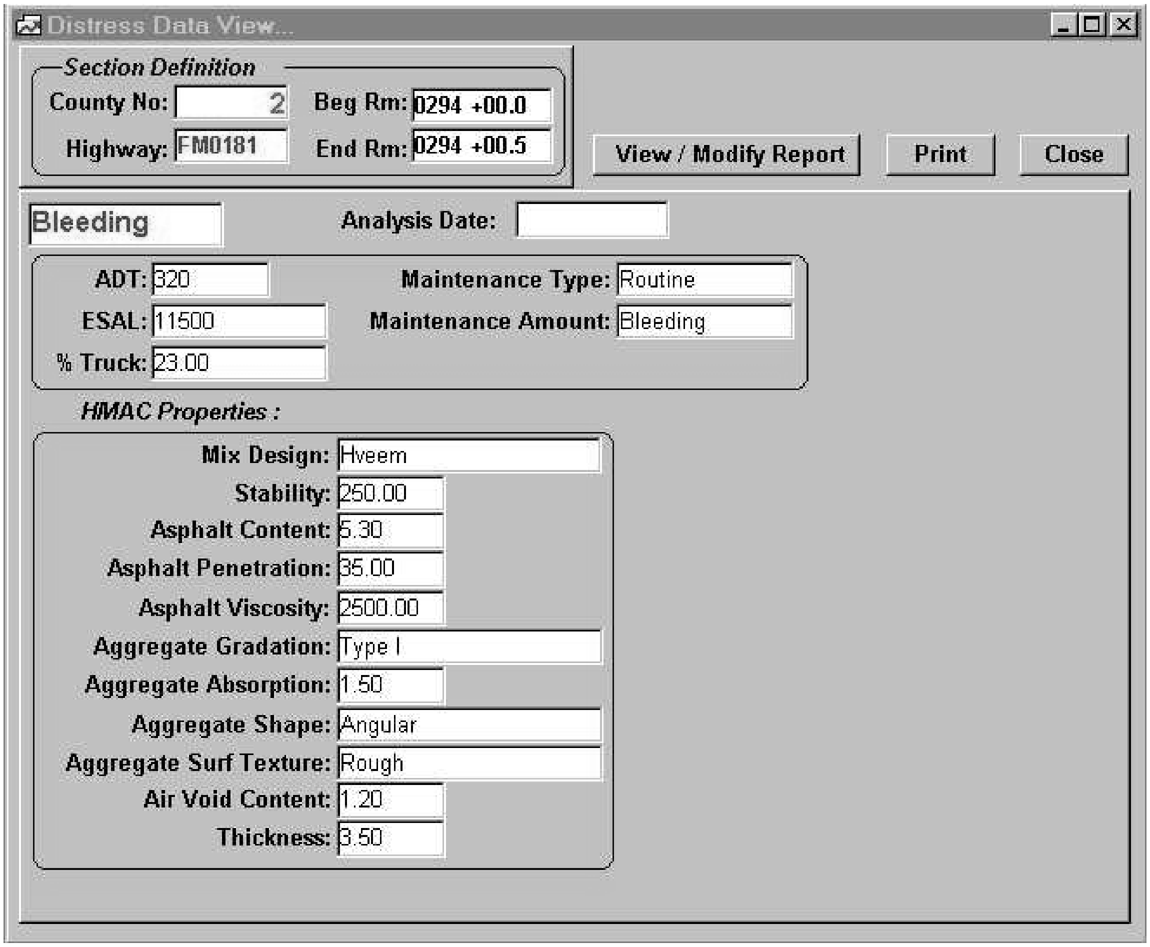


Figure 6.2 – Data entry format for the ForenSys database

6.3 THE DETAILED REPORT

The primary difference between the distributable report and the detailed report is the inclusion of an appendix in the latter. The detailed report is based on the distributable report—additional technical information is simply added in an appendix. The outline shown in Figure 6.1 displays the proposed format for TxDOT forensic investigation reports. The field notes, sketches, and photographs that were taken but that were not included in the distributable report are included in the detailed report. Information from the document/literature searches that was not critical to the hypotheses formation may also be included. While graphical data are included in the distributable report, raw data from the testing program would be included in the detailed report. In general, the raw data and information (prior to separation, organization, or reduction) would be too technical and confusing to include in the distributable report. Thus, the detailed report includes the unreduced data as well as all types of information not essential to the conclusion formation.

CHAPTER 7 – CASE STUDIES AND DISCUSSION

7.1 BACKGROUND

The advantages of a forensic investigation are best illustrated by a presentation of case studies. Specific examples of the benefits of a successful investigation, or problems with unsuccessful ones, underscore the importance of an effective investigation. This chapter presents three different case studies and discusses the advantages and disadvantages of each.

7.2 CASE STUDY #1 – ODESSA DISTRICT, STATE HIGHWAY 158

In December 1988, a portion of State Highway 158 in Midland County underwent total reconstruction, including widening. The project consisted of 1.75 inches of asphalt concrete pavement (ACP) surface placed over 10 inches of crushed limestone flexible base [Jones 91]. During the construction, ravelling, or flaking of the pavement surface, occurred. The sections that displayed signs of ravelling were replaced before they were opened to traffic. After the highway was opened, severe block cracking began to form on the surface. The areas of cracking ranged from 1 ft to 2 ft widths. Alligator cracking began to form from the block cracking; no other signs of distress, such as rutting, were apparent. Because the cracking continued even after some of the sections were patched, the mechanism seemed to be a base failure. Before the base reconstruction was performed to control the cracking, a forensic investigation was performed.

The forensic investigation began with the formation and testing of the initial hypotheses. The observation of continued cracking after patching resulted in an initial hypothesis that a weak base caused the cracking. Next, the researchers conducted tests to see whether the initial hypothesis was valid. In April 1991, they performed tests to evaluate the structural capacity of the pavement. These tests included Dynaflect, falling weight deflectometer, and the dynamic cone penetration tests. The thickness of each layer was measured using ground-penetrating radar. Penetration, viscosity, and ductility tests were performed on the asphalt extracted from some of the road samples. The final series of tests involved material sampling of the asphalt from the surface layer.

Next, the data were evaluated in a number of ways. The team used computer programs to calculate the material strength and modulus of each layer with the data from the falling weight deflectometer and the Dynaflect tests. While the test data revealed that the base and the subgrade had a considerable amount of strength, there were some reservations about the data. First, some rain had fallen the night before, and some of the water had traveled through the surface cracks and soaked into the base layer. In addition, the presence of the cracks on the surface may have had an effect on the geophone readings from the falling weight deflectometer test. The combination of these two factors may have distorted the deflection data; thus, the results from the other tests could be evaluated before any conclusions made. The dynamic cone penetration tests also revealed that the base was adequate and was classified as a Triaxial Class 1 type material. The ground-penetrating radar data could not distinguish between the base and the subgrade because the two had similar moisture contents. The moisture content of the base was around 7 percent, which seems reasonable considering the rain from the night before. The thickness of the surface layer was found to be about 1.75 inches, just as the design specified. So far, none of the tests had revealed any problems in the material, design, or construction of any of the three layers. However, the material tests on the surface layer found that, although the asphalt content and gradation of the asphalt surface were correct, the viscosity was extremely high. The measured viscosity was more than double the normal viscosity of asphalt of that type.

After the testing was completed and the data were analyzed, the conclusions were formed. Because the Dynaflect, falling weight deflectometer, and dynamic cone penetration tests did not indicate a problem with the base, the initial hypothesis of a weak underlying layer was considered incorrect. The mechanism of the cracking was then considered to be low ductility of the asphalt in the surface layer. An adequate rehabilitation strategy was chosen based on the final conclusion. The repair method involved replacing the surface layer with a higher quality asphalt concrete pavement. The repair strategy also called for a portion of the base layer to be recompacted before the asphalt surface was placed. The base recompaction was a precautionary measure to ensure that water did not ruin the base by entering through the cracks in the surface.

7.2.1 Case Study #1 – Discussion

The cost of a forensic investigation is clearly much smaller than the potential costs of incorrect repair strategies, design errors, or improper construction; however, a forensic investigation has many other advantages besides reducing total costs. This example clearly shows the benefits to be gained from performing a forensic investigation. These benefits include the selection of an effective repair strategy and the adjustment of current design procedures.

If the original hypothesis, a weak base layer, had been assumed to cause the cracking of the pavement surface, the repair strategy would have been completely incorrect. The asphalt surface would have been removed and the base would have been strengthened. Once the base had been considered sufficient, the asphalt surface would have been replaced. The original surface would probably have been recycled and used as part of the new pavement surface. If this had been the case, the asphalt in the new surface would still have had a high viscosity. The ductility of the asphalt in the new surface might have been lower than before, but it still might not have been low enough to control the block cracking. Therefore, even after TxDOT had incurred large expenses by strengthening the base material, the cracking might still have continued to occur. A forensic investigation conducted before a rehabilitation strategy was chosen probably saved money on the cost of repair. More importantly, the investigation determined the correct mechanism so that the optimal repair method could be selected.

Performing the forensic investigation also provided the researchers with insight into the current design procedures. After realizing that high-viscosity asphalt was the mechanism that caused the cracking, they were able to take steps to ensure that a similar occurrence would not happen in the future. If the problem had been a construction or a quality control problem, it is evident that the materials should have been tested at the site to determine whether the properties were consistent with the specifications. If high-viscosity asphalt had been a common problem in many of the pavement sections in the Odessa District, the forensic investigation might have led to a viscosity test during construction instead of higher rehabilitation and maintenance expenses in the future.

7.3 CASE STUDY #2 – HOUSTON, STATE HIGHWAY 36

State Highway 36 through Houston, in Fort Bend County, was reconstructed in 1990 and experienced rapid deterioration shortly thereafter. The reconstruction recycled the original pavement and added a 150 mm layer stabilized with cement. An additional 150 mm cement-stabilized layer was also placed using limestone and sand. These placements resulted in a 300 mm cement-treated base (CTB); a 75 mm hot-mix surfacing was placed as the top layer. After about 3 years in service, the pavement experienced distress in the form of multiple transverse depressions. These depressions were first observed in the wheel paths but were later noticed on the shoulder. In addition, the depressions were centered about transverse cracks and reflection cracks. A forensic investigation was performed to determine the cause of the distress and to recommend a feasible repair strategy.

The original hypothesis suggested that the depressions were load-related durability problems, though durability tests on pavement samples revealed otherwise. During material sampling, the engineers observed that the top layer of the cement-treated base was experiencing disintegration, while the bottom layer was intact. The fine material appeared to be pumped out from the top base layer, indicating that the depressions were due to this disintegration. Additionally, cores taken through transverse cracks revealed that the cracks extended through the top layer of the CTB, but not the bottom layer. This observation suggested that the top CTB layer was debonded from the bottom layer. Therefore, the subsequent hypotheses and testing concentrated on the deterioration of the cement-treated base layer. A testing program was established to determine whether the CTB was adequate. The testing program included ground-penetrating radar (GPR) analysis, laboratory analysis of the base material with X-ray diffraction, thermal properties testing, and a soak test.

The testing program revealed many facts relating to the cement-treated base layer. The GPR testing revealed that the upper CTB was attracting and trapping moisture [Bredenkamp 95]. The laboratory analysis of the base materials showed that some samples contained up to 15 percent clay. Even with all of the clay particles, the plasticity index (PI) of the samples was approximately 9, meeting the TxDOT specification limit of PI<10. The inclusions of the clay caused the material to retain moisture, which agreed with the GPR results. The X-ray diffraction results concluded that this type of clay was naturally expansive. The thermal properties tests showed that the thermal coefficient of the bottom layer of the CTB was 2 times the coefficient of the top layer. The use of different materials for each layer of the CTB also supported the discovery of different thermal coefficients. The assumption that the layers had debonded was also supported because temperature cycling probably would have caused separation of the base layers. Finally, the soak tests revealed that the absorption was much higher for material samples containing clay particles. Leaching of calcium hydroxide was also evident from the soak tests.

The distress mechanism conclusions were created following the analysis of the investigation results. First of all, the leaching of the calcium hydroxide was the primary cause of the depression formation. The loss of the calcium hydroxide resulted in a loss of layer strength. Because the depression formed on the shoulder, the mechanism was concluded to be chemical related and not structure related. Adding to the distress propagation was the presence of clay in the cement-treated base layer, as well as debonding of the CTB layers. The clay allowed water to enter the top layer of the CTB. Because the debonding prevented cracks from continuing to the bottom layer of the CTB, water could not escape through these cracks.

7.3.1 Case Study #2 – Discussion

Many times a forensic investigation alters design practices because problems can arise even if a pavement has been designed according to specifications. The results of the investigation often show that the design requirements may not be stringent enough to prevent failure. This case study discovered two areas in which TxDOT specifications may need to be revised.

First, the plasticity index of the cement-treated base layer was acceptable, but the material was questionable. The specifications at the time this project was conducted required that the plasticity index be less than 10. The plasticity index was 9 for this project, even though the CTB contained up to 15 percent clay particles. This finding shows that the specifications may need to be revised to prevent problematic materials from being used on pavement projects. The forensic investigation report for this project suggested that the maximum PI be lowered to 8 to prevent future problems.

The forensic investigation report also suggested that the practice of placing stabilized layers one on top of another should be reviewed [Bredenkamp 95]. Because different layers had been placed on top of one another, debonding occurred as a result of the different thermal coefficients. Because the cracks did not propagate to the bottom layer, the debonding prevented water from escaping the top layer. Eventually, the moisture in the top layer caused leaching, strength loss, and deterioration of the CTB layer. As a minimum requirement, the report proposed that the practice of layering stabilized-base layers should be limited to the use of similar materials.

This case study also shows how distresses often have multiple mechanisms. The surface depressions were not due to a single mechanism, but to several. The leaching of the calcium chloride, the debonding of the two base layers, and the presence of the clay particles all contributed to the disintegration of the top layer of the CTB. Quite often pavement distress is a result of a combination of mechanisms. One mechanism may initiate the distress while another propagates the distress. Forensic investigations are used to determine all of the probable distress mechanisms.

7.4 CASE STUDY #3 – CONCRETE PAVEMENT AT A MILITARY AIRFIELD

"During the slipform construction of a portland cement concrete taxiway at a military airfield, blisters periodically developed on the surface of the concrete behind the slipform paver" [Rollings 92]. Blisters are air or water voids trapped just below the surface of the concrete. The surface mortar is dense, so the trapped water and the air cannot escape before the concrete sets. On the military taxiway, these blisters ranged in size from almost invisible to more than 2 inches in diameter. The number of blisters within each pavement section also varied. Some sections had no blisters, while others had hundreds. After the construction crew realized that blisters were being formed, they made various adjustments, such as equipment adjustments, changes in the concrete mixture, and changes in the finishing of the surface. Because the blisters would break under airplane loadings, it was necessary that they be repaired. (Chips of broken concrete could be sucked into the aircraft engines, causing serious damage.) To repair the blisters the contractor injected the voids with epoxy. A forensic investigation was conducted long after the problem was recognized.

The forensic investigation took place in two phases. The first phase consisted in reviewing construction records, reviewing literature, and taking samples of materials from the construction site. The literature search revealed that the blistering may have been caused by premature troweling of the surface, placement of the concrete on a cool subgrade, sticky concrete mixes, thick slabs, excessive slump, or poor consolidation [Rollings 92]. A review of the construction documents showed that, because of a problem with the local coarse aggregates, a high-sand-content concrete mix had been used to reduce construction costs. Eighteen cores from the blistered pavement were taken during the first phase of the investigation. These cores were used in laboratory tests that included freezing and thawing resistance tests, deicing chemical resistance tests, air content of hardened concrete tests, a petrography examination, and shear and compressive strength tests.

Phase 2 of the project involved taking ten more cores from the original project and eight cores from four different projects. The eight cores were taken from projects in which a high-percent-sand mixture, similar to that used in this project, was used. The second set of eighteen cores was subjected to freezing and thawing resistance tests as well as to a petrography examination.

The laboratory tests confirmed that the aggregate mixture was composed of a high percentage of sand (approximately 70 percent sand and 30 percent coarse aggregate). The petrography examinations revealed that there was no apparent difference between the cores that experienced blistering and the cores that did not. Freezing and thawing tests found that the durability of the concrete was significantly reduced if blisters were present, but that the epoxy repair greatly improved the freezing and thawing resistance. However, the cores with high sand mixtures still had lower durability than regular concrete mixes.

The laboratory tests, together with evidence from the fieldwork, strongly suggested that many of the blistering and the durability problems encountered in this project were directly due to the selection of a high-sand-content concrete mixture [Rollings 92]. The blistering may have been amplified by a problem with the consolidation techniques of the slipform paver, as no blisters formed when another paver was used during construction of some sections. A combination of other factors, such as the sticky concrete mix, thick slab, poor consolidation, and a cool subgrade, may have also influenced the blistering.

7.4.1 Case Study #3 – Discussion

While forensic investigations are useful in determining the causes of structural failures, they are also helpful in correcting construction problems before construction continues. This example demonstrates how a considerable amount of time and money could be saved if a forensic investigation is performed as soon as the distress is noticed.

The performance of a forensic investigation on this project probably changed the design practices of the military base, insofar as the use of a high sand mix proved to cause blistering and low freezing and thawing durability. If the investigation had been performed when the blistering had been noticed, the mixture proportions could have been changed and the blistering and durability problems could have been solved. “It appears, in retrospect, that the blistering problem could have been solved without ever having to undertake thousands of epoxy repairs and legal wrangling if the concrete mixture proportioning had been changed” [Rollings 92]. Thus, this case study again shows that the cost of a forensic investigation is much smaller than the costs of continuing improper construction.

Continuing improper construction did not just raise costs; it also caused problems for everyone involved in the project. The epoxy repairs were expensive, time consuming, and probably avoidable. The pavement blistering most likely caused delays in construction as well as delays in the pavement use. However, construction still continued even after the distress was noticed. Rollings [92] summarizes this project very well when he states: “Neither the contractor who had to repair the blisters at his expense, the construction agency which had to bear the cost of extensive testing to discover the cause of problems and to deal with the contractors claim, or the owner who was left with a patched pavement of questionable durability has been well served by this project.” Most of these problems were avoidable, and could indeed have been avoided if an investigation had been performed when the blistering was first discovered.

CHAPTER 8 – CONCLUSIONS AND RECOMMENDATIONS

8.1 CONCLUSIONS

The primary purpose of forensic investigations is to determine the mechanism, or mechanisms, of the observed pavement distresses. There are many advantages to an accurate investigation. Most importantly, the repair strategy is more likely to perform as expected. If the repair addresses the distress mechanism(s), then the repair is not likely to experience the same distress as the original pavement section. In addition, future design and construction practices may be improved by forensic investigations. If the distress mechanism is directly related to the procedures used in design or the techniques of construction, current practices can be changed to prevent similar distresses from occurring in the future. Forensic investigations can also improve prioritization and the determination of a needs year by estimating the distress propagation rate.

TxDOT presently has no formal procedure for conducting forensic investigations. The goal of this research project was to develop a forensic investigation procedure to help make investigations more efficient and effective. The effectiveness of the investigation actually refers to the performance of the rehabilitation strategy; however, the repair performance is greatly influenced by the accuracy of the determined failure mechanism(s). In order for an investigation to be performed accurately, it must be performed thoroughly; there is no such thing as an easy answer. The formalization of the investigation procedure developed in this report was used to improve the thoroughness of forensic investigations, as well as the effectiveness of the rehabilitation strategy. The efficiency of the investigation is improved with the use of the resources that are available to TxDOT. These resources include the field diagnostic manual, the detailed diagnostic manual, the electronic version of the diagnostic manual, and the ForenSys database.

8.1.1 Formalization of the Forensic Investigation Procedure

Before the forensic investigation can begin, the problem must be defined. The problem statement deals with identification of the distress, or distresses, of the pavement section. Condition surveys or routine inspections determine the quantity and severity of the distresses occurring in the section. A forensic investigation may be required if the distress is widespread or severe, if the mechanism is in question, or if the distress occurred shortly after construction. If an investigation is necessary, it should adhere to the following six steps.

1. **Gather Background Information** – Often a pavement distress mechanism may be determined from background information about the pavement section. The document search involves collecting facts related to the design procedures, construction techniques, materials specifications, traffic records, weather records, soil and geologic information, pavement history, layer structure, and any other documents related to the pavement section. A literature search reveals information concerning past forensic investigations of similar distresses or similar pavement conditions, with the intention of providing ideas for the current investigation.

2. **Conduct Field Observations and Form Probable Causes** – The initial field visit is used to make observations regarding the pavement distress and the surrounding conditions. Distress mechanism hypotheses are based on these observations as well as on any reasonable assumptions that are produced. Observations are also used to eliminate other possible mechanisms—a practice that reduces the amount of testing required. The final failure hypotheses are used to establish a testing program to verify these hypotheses.

3. **Perform Testing of Hypotheses** – The testing program is divided into two main categories: the field investigations and the laboratory investigations. In addition, the field investigations may be non-destructive or intrusive. Overall, the testing program is used to collect information related to the proposed failure hypotheses. This information includes material properties, structural evaluation data, physical properties, environmental conditions, and soil and geologic conditions. Records searching, especially if the records are related to the distress mechanism hypotheses,

are included in the laboratory-testing category. Traffic records, weather records, design records, construction records, and maintenance records may be included in this search.

4. **Analyze Collected Data and Information** – The synthesis of the investigation is performed when all of the data and information are combined, reduced, and analyzed. This synthesis includes information from the document search, the literature search, the field notes and photographs, the testing program, and any other information collected during the course of the investigation. The engineers analyze all of this information to determine whether it relates to any of the possible failure hypotheses. The analysis of the information also establishes how evidence relates to the possible failure hypotheses, such as supporting or contradicting a particular hypothesis.

5. **Formulate Conclusions and Failure History** – Each hypothesis, as well as its supporting information, is studied to determine which is the most likely to be true. The hypotheses with an overwhelming amount of supporting information are probably the most likely distress mechanisms. Hypotheses with mostly contradicting information can probably be eliminated. The conclusions are then based on the most likely distress mechanisms; more importantly, the conclusions must fit the facts of the investigation. In addition, because pavement distresses often have multiple mechanisms, all of the probable mechanisms must be included in the conclusions. Finally, the researchers create a failure history that discusses how the chosen mechanisms relate and how the distress progressed from initial formation to the current state.

6. **Prepare Forensic Reports** – The forensic report represents the culmination of the investigation. By preparing a report after every investigation, the researchers can ensure that the information that was discovered is made available to other engineers. This information can be used to prevent future design errors and to modify ineffective

construction techniques. The forensic report resembles the investigation procedure and contains the following sections: purpose, pavement history, description of the project, observations, testing, analysis, conclusions, and recommendations.

8.1.2 Use of the Resources Available to TxDOT

While the proposed investigation procedure helps investigations become more effective, the use of the available resources helps create efficiency. The resources are used to aid certain steps of forensic investigations and to provide additional ideas for these investigations. These resources are the ForenSys database, the field diagnostic manual, the detailed diagnostic manual, and the electronic version of the diagnostic manual.

The ForenSys database can be considered the central point of all of the forensic investigation resources. It is used to obtain information for an investigation, and information is entered into it after the investigation has been completed. The ForenSys database is first used during the literature search. It can be searched to find past investigations involving similar distresses or distress manifestations. These investigations can be used to obtain ideas on observations, testing procedures, or possible hypotheses, but they must never be used in place of the current investigation. If the ForenSys database is not used during the literature search, it can be used during the data analysis stage to research past investigations. Finally, the testing program data, as well as the final report information, are entered into the database after the investigation is complete. This information is required so that past investigations can assist future ones.

The field diagnostic manual is primarily used during the initial site visit. The manual can help prepare the research team for the initial visit by providing background information about the observed distress. A summary of the mechanisms, the distress progression, and a distress description are included in the field manual. Most importantly, this manual discusses what to look for during the initial field visit. The manual also discusses suggested tests and investigations to verify any possible hypotheses, based on the engineers' observations.

The detailed diagnostic manual is a more in-depth version of the field manual. Just like the field manual, the detailed manual can also be used to determine what observations should be made and what tests may verify the hypotheses; however, the detailed manual features a deeper discussion of the distress mechanisms. The detailed manual helps in the data analysis stage because it shows what tests potentially support each mechanism. The detailed manual is also used when the researcher is writing the final forensic report. The measures for distress prevention, possible repair strategies, and the degree of urgency for each distress are outlined in the detailed manual and should be included in the recommendations section of the final report.

The electronic version of the manual is used to assist the research team in the data analysis stage. The electronic manual is an Internet version of the manual that includes a discussion group that allows other TxDOT employees to answer posted questions. These questions often relate to the investigation in progress. Questions or a description of the problem can be posted on the Web site and supported with test data or photographs. Everyone with access to the site may reply with solutions to the problem, answers to the questions, suggestions to help find the solution, or any other type of help on the problem. In addition, past discussion group topics are saved so that they can be referenced at any time. Finally, because the electronic version of the manual also includes the information in the detailed manual and field manual, this information can be referenced when the engineer does not have a hard copy of the manuals on hand.

8.2 RECOMMENDATIONS

We recommend that TxDOT adopt a formal forensic investigation procedure to better use the resources available to it. This project developed a methodology to improve the efficiency and accuracy of current pavement investigations. Additional improvements can be made to assist future investigations and to further update the proposed procedure. The data analysis stage of the proposed investigation procedure is probably the most tedious stage of the investigation. The investigation produces large amounts of data and information that may be too time consuming to manage by hand. The use of computer storage to handle the information would be a tremendous aid, but the analysis of all the data would still be quite time consuming. Therefore, the future creation of a Knowledge-Based (KB) engine is proposed.

The KB engine would be used during data reduction and analysis of the large amounts of investigative data. It would evaluate each piece of data, test result, and observation to determine whether it was relevant to any of the proposed distress mechanisms. The relevant information would then be observed to determine whether it supports or contradicts each mechanism. A weighted system can be used to differentiate between somewhat supportive and extremely supportive information, and between somewhat contradicting and extremely contradicting information. The supporting and contradicting information could then be used to eliminate possible hypotheses and to evaluate the remaining hypotheses so that conclusions concerning the distress mechanisms can be created. In addition, the KB engine would be linked to the ForenSys database so that the investigation data will not have to be entered multiple times. The use of the KB engine could reduce the amount of time spent during the data analysis stage and could provide probable conclusions to pavement forensic investigations.

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