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Subsurface Condition Evaluation for Asphalt Pavement Preservation Treatments

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16. Abstract

This report presents a case study on the SR-70 section with microsurface for understanding its performance; a development of a methodology for evaluating the asphalt pavement subsurface condition for applying pavement preservation treatments; and a development of a tool for identifying and quantifying the subsurface distresses.

From the case study, it was found that the main distresses on SR-70 were longitudinal cracks, fatigue cracks, and potholes. The longitudinal cracking was the most widely distributed distress with 22% of lane length in the 2-mile test section among the three distress types. Based on the water stripping test results and the core visual observations, it was confirmed that the test section on SR-70 had the water stripping problem.

In order to have a representative condition indicator for the test section, the conditions were converted into the scores scaled from 0 to 100. Layers with closer to a score of 100 have the better subsurface condition. Therefore, the 28% of the test section length with the surface distress was detected as the fair subsurface condition with a score of 56. The rest 72% of the length was estimated as the good subsurface condition with a score of 78. Similarly, 20.5% of the test section length with the problem locations determined by GPR had the fair subsurface condition with a score of 56 and the rest 79.5 % of the length had the good subsurface condition with a score of 76.

The lab test results showed poor correlations among the water stripping severities, air voids, and tensile strengths. Thus, the air voids or tensile strength cannot properly estimate the water stripping severity or vice versa. When the laboratory test results with the surface distresses or in the GPR-based problem locations were compared to that without the surface distresses or in the GPR-based non-problem locations, in general, average air voids and water stripping severities decrease and average tensile strengths increase. The observation confirms that the evaluation processes are applicable for evaluating the subsurface condition. Furthermore, the probability that a location determined to be problematic by GPR to be on one of poor conditions based on lab tests was 1.0. The same probability was obtained for a GPS-based problem location. Accordingly, it was concluded that the laboratory tests with the surface distresses survey or the GPR measurement were reliable method to evaluate the subsurface condition. The FWD results had a weak correlation with the laboratory test results possibly due to fairly long testing interval (i.e., 328 ft). The current FWD test protocol should be improved for evaluating the subsurface condition in pavement preservation application.

Guidelines of subsurface condition evaluation for pavement preservation treatment application was developed utilizing the findings from the case study. A concept of hierarchy was used in the guideline by taking project importance and available resources into consideration. A tool including guidelines, computer software (e.g., iSub and iMoisture), and its manual was also developed based on the methodology as a research product. Based on the guideline, it was concluded that the subsurface condition of the case study section on SR-70 was inadequate for the application of the pavement preservation treatments.

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EXECUTIVE SUMMARY

SUBSURFACE CONDITION EVALUATION FOR ASPHALT PAVEMENT PRESERVATION TREATMENTS

Introduction

Most pavement preservation treatments involve some sort of surface coating to the existing pavement. Surface sealing is one of the purposes of such a treatment, and 99% of the time, results in extended life of the pavement. However, in some cases where the existing pavement is not structurally sound due to high air voids (low density) and water stripping of the existing underlying pavement, the surface treatments fail with delamination, potholes, cracks, etc. In addition, the treatment can accelerate the water stripping process of the underlying pavement layer. For example, the SR-70 section with microsurfacing in the Vincennes district had several small areas of localized failures due to water stripping underneath the pavement.

According to the INDOT Design Manual, water stripping consists of the debonding of the binder film from the aggregate. Visible signs of water stripping include surface delamination, raveling, potholing, or surface discoloration. Water stripping is an aggregate-dependent distress caused by a combination of heat, pressure, and water. The recommended treatment for water stripping is to remove the stripped material by asphalt milling and then to overlay the milled surface.

INDOT currently does not have any guideline for evaluating or identifying the potential for high air voids and water stripping on existing asphalt pavements. Currently, there is a need to develop methods for making a quick diagnosis of pavement subsurface condition to identify severity and extent of the physical and mechanical distresses. The method can be used for selecting the right pavement for treatment application.

The primary objectives of this research project were: (1) to develop a tool for identifying and quantifying the subsurface distresses; and (2) to develop a methodology for evaluating the asphalt pavement subsurface condition in selecting optimum pavement preservation treatments, including microsurface, ultra-thin bonded wearing course, and 4.75 mm HMA overlay.

Findings

The subsurface condition test methods selected for the study were evaluated and correlated.

The lab test results showed poor correlations among the water stripping severities, air voids, and tensile strengths. Thus, the air voids or tensile strength cannot properly estimate the water stripping severity or vice versa.

When the laboratory test results with the surface distresses or in the GPR-based problem locations were compared to that without the surface distresses or in the GPR-based non-problem locations, in general, average air voids and water stripping severities decrease and average tensile strengths increase. The observation confirms that the evaluation processes are applicable for evaluating the subsurface condition. However, t-test revealed that the laboratory test results, which were conducted with and without the surface distresses, were not significantly different. In contrast, the laboratory results in the GPR-based problem and non-problem locations were significantly different.

The probability that a location determined to be problematic by GPR to be on one of poor conditions based on lab tests was 1.0. The same probability was obtained for a GPS-based problem location. Accordingly, it was concluded that the laboratory tests with the surface distresses survey or the GPR measurement can be reliable method to evaluate the subsurface condition.

The FWD results had a weak correlation with the laboratory test results possibly due to fairly long testing interval (i.e., 328 ft). The current FWD test protocol should be improved for evaluating the subsurface condition in pavement preservation application.

A guideline of subsurface condition of pavement for pavement surface treatment application was developed utilizing the findings from the study on SR-70. A concept of hierarchy was used in the guideline by taking project importance and available resources into consideration. Tools including the guideline, computer software (e.g., iSub and iMoisture), and its manual were also developed based on the methodology as a research product. iSub provides user-friendly system which helps to follow the hierarchy of evaluation steps. Furthermore, iSub automatically calculates the overall condition of the pavement subsurface as severity rating for each laboratory test result was implemented into the software. iMoisture detects uncoated aggregates and quantifies the area in a sample by employing the digital image analysis technology.

Two different evaluation methods, GPR based (Level 1) and surface distress based (Level 2), were applied on SR-70 test section and the subsurface condition was evaluated. It was found that the main distresses on SR-70 were longitudinal cracks, fatigue cracks, and potholes. The longitudinal crack was the most widely distributed distress among the three distress types with 22% of lane length in the 2-mile test section. Based on the water stripping test results and the core visual observations, it was confirmed that the test section on SR-70 had the water stripping problem. In addition, overall, there was no subsurface condition difference between left wheel and right wheel paths. In general, based on the laboratory test results, a layer consisted of the micro-surfacing and the asphalt surface course was the poorest condition among asphalt layers in the test section.

The level 1 evaluation with GPR on the SR-70 test section determined that 20.5% of the test section length contained the problem locations with the fair subsurface condition and the rest 79.5% of the length had the good subsurface condition. Similarly, 28% of the test section length with was determined to have the fair subsurface condition by the level 2 evaluation with surface distress. The rest 72% of the test section without surface distresses was estimated to have the good subsurface condition. In addition, the PPT applicability on SR-70 test section was determined. Considering the subsurface distress distribution analysis using distress coverage of unit analysis length (DUCAL), the test section was determined to be inadequate for the PPT application. The case study confirms that the evaluation processes are applicable and can help a consistent and rational decision making process for project level or district level pavement preservation programs.

Implementation

The evaluation tool developed in this study can help achieving a consistent and rational decision making process for project level or district level pavement preservation program. The findings, guidelines, iSub, and iMoisture will be introduced to the INDOT pavement engineers in order to assist them with district level preservation treatment practices. The details in the report and software are intended for reference only, not as specifications or design guidance. In the event that any information presented herein conflicts with the Indiana Design Manual, INDOT's Standard Specifications or other INDOT policy, said policy will take precedence and the software will be managed by the Asset Preservation Engineer so that conflicts do not arise.

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1. INTRODUCTION

1.1 Research Background

The Indiana Department of Transportation (INDOT) has been implementing a Pavement Preservation Initiative (PPI) since 2009. PPI treatments for asphalt surface pavements include crack seal/fill, seal coat, microsurface, ultrathin bonded wearing course (UBWC), and 4.75 mm hot mix asphalt (HMA) overlay. The plan for FY 2011 covered 1,726 lane miles of 103 road projects using \$ 30.7 million. The basic and best practice of PPI is the application of the right pavement preservation treatments for the right pavement at the right time.

Most pavement preservation treatments involve some sort of surface coating to the existing pavement. Pavement surface sealing is one of the main purposes of such a treatment, and results in extended life of the pavement in most of cases. However, in rare cases where the existing pavement is not structurally sound due to high air voids (low density) and stripping of the existing underlying pavement, the surface treatments fail with delamination, potholes, cracks, etc. In addition, the surface treatment can accelerate the stripping process of the underlying pavement layer. For example, the SR-70 section with microsurface in the Vincennes district had several small areas of localized failures due to water stripping underneath the pavement, as of 2011.

Typical HMA in-place air voids (as constructed) are approximately 8%. Improper constructions (e.g., temperature control failure, improper compaction, etc.) and materials can generate high air voids that provide easy access for infiltration of water, resulting in eventual stripping and raveling. Generally, high voids tend to appear in joint areas due to improper compaction, which leads to structure-related distress (e.g., fatigue crack due to HMA dynamic modulus reduction) that cannot be fixed by pavement preservation treatments.

According to the INDOT Design Manual, water stripping consists of the debonding of the binder film from the aggregate. Visible signs of water stripping include surface delamination, raveling, pothole, or surface discoloration. Water stripping is an aggregate-dependent distress caused by a combination of heat, pressure, and water. The recommended treatment for stripping is to remove the stripped material by asphalt milling and then overlay the milled surface.

INDOT currently does not have any guideline for evaluating or identifying the potential for high air voids and water stripping on existing asphalt pavements. There is currently a need to develop methods for evaluating subsurface condition of the existing asphalt pavement to assess severity and extent of the physical and mechanical distresses. The method can be used for selecting the right pavement for PPI application.

1.2 Research Objectives

The primary objectives of the proposed research project are as follows:

- To develop tools for identifying and quantifying the subsurface distresses;
- To conduct a case study of the SR-70 section with microsurface treatment for understanding its subsurface condition and performance;
- To develop a methodology for evaluating the asphalt pavement subsurface condition to determine the applicability of pavement preservation treatments, including seal coat, microsurface, ultrathin bonded wearing course, and 4.75 mm asphalt overlay.

1.3 Report Organization

This report is composed of five chapters plus appendices. Chapter 1 introduces the research and presents the research needs and objectives. Chapter 2 summarizes the literature review of state practices of Midwest region on limitations of the pavement preservation regarding the existing pavement conditions as well as available evaluation methods for water stripping in asphalt pavement. Chapter 3 describes the experimental study conducted for the evaluation of subsurface condition test methods along with the analysis. Chapter 4 discusses the guidelines of subsurface condition evaluation for pavement preservation treatments. In addition, two software programs developed in part of guidelines are introduced. Chapter 5 presents the example application of the developed guideline on SR-70 test section. The Conclusions from this research and future research recommendations are given in Chapter 6.

2. LITERATURE REVIEW

2.1 State Practice

Specifications and manuals of state departments of transportation (DOT) in the Midwest region have been reviewed in order to find limitations (e.g., water stripping in existing pavement) in application of asphalt pavement treatment to the existing pavements. The reviewed states included Illinois, Indiana, Iowa, Kentucky, Michigan, Minnesota, Missouri, and Ohio. Specifically, limitations from pavement having structural or/and material damages (e.g., water stripping, low density, etc.) were searched.

Overall, the states have similar types of treatments for asphalt pavement; yet, their requirements regarding the application vary by the pavement condition, traffic volume, and construction. While weather limitation for their construction is most commonly specified, pavement condition is the least specified criteria. The requirements are summarized in Table 2.1 and Table 2.2, and findings indicate the following:

- Illinois DOT provides treatment selection guidelines for each type of pavement condition/distress. The guideline provides what specific type of treatment is recommended, feasible or not applicable.
- Minnesota DOT has developed its own decision tree which helps to determine the proper maintenance based

TABLE 2.1
Existing pavement condition limitations for each type of surface treatments (Indiana, Illinois, Iowa, and Kentucky)

	Indiana	Illinois	Iowa	Kentucky
Crack Seal/Fill	No existing pavement condition limitations	Structural failures exist Extensive pavement deterioration Appropriate for cracks 0.25 in. to 0.75 in. (6 mm to 19 mm) wide	**Not available**	**Not available**
Fog Seal	Structural deficiencies	Structural failures exist Flushing/bleeding, friction loss, or thermal crack	No existing pavement condition limitations	**Not available**
Scrub Seal (Sand Seal)	**Not available**	Structural failures exist Flushing/bleeding, friction loss, or thermal crack	**Not available**	**Not available**
Seal Coat (Chip Seal)	Structural deficiencies	**Not available**	No existing pavement condition limitations	No existing pavement condition limitations
Flush Seal	Stripping of underlying mixtures	**Not available**	**Not available**	**Not available**
Microsurface	Large cracks or excessive surface irregularities such as shoving Stripping condition	Structural failures High-severity thermal crack Extensive pavement deterioration	**Not available**	**Not available**
Ultrathin Bonded Wearing Course (UBWC)	Ruts greater than 0.25 in Severe distresses	Structural failures exist (e.g., significant fatigue cracking, deep rutting) High severity thermal cracking Extensive pavement deterioration	**Not available**	**Not available**
Profile Milling (Diamond Grinding)	Major distresses	Significant faulting or other signs of structural failure Materials-related distresses	**Not available**	**Not available**
Thin HMA Mill and Fill (Thin HMA Inlay)	Significant potholes Major distresses	**Not available**	**Not available**	**Not available**
Thin HMA Overlay with Milling	Significant potholes Major distresses	**Not available**	**Not available**	**Not available**

on distress type, distress severity and pavement condition index system.

- Most state DOT specification/manual determines the suitability of each treatment by the presence of type of distress and its severity. It is typically assumed that pavements with high severity fatigue crack and rutting are the indication of structural problems.
- Iowa DOT shows that limitations for different type of treatment methods are provided in Standard Specification Division 23; however, limitations regarding existing pavement conditions are not presented.
- It is interesting to note that crack sealing application limitation of Ohio DOT is the expected amount of sealing material. A pavement, which requires the use of material in excess of 5000 lb per lane-mile, is determined not to be suitable for such treatment.
- Most states specified that a pavement with a structural problem is not suitable for any type of treatment and surface distresses are used as an indicator for the pavement structural condition. There are no specifications for the application limitation with any subsurface condition evaluation (e.g., Falling Weight Deflectometer (FWD), Ground Penetration Radar (GPR), etc.).
- INDOT specification and manual states existing pavement condition limitations for all treatments except the scrub seal; yet, it does not contain details regarding measurement of the structural deficiencies or detection of the water stripping.

In summary, the review shows that the existing pavement condition is a major factor in determining the applicability of treatment for asphalt pavement. However, the specifications/manuals do not contain information about the application limitation with the pavement subsurface condition.

2.2 Evaluation Methods for Water Stripping

Guideline or detailed procedures for evaluation of pavement structures in project-level are generally available from most DOT (e.g., Ch. 52 Pavement Preservation, Illinois DOT) and is also described with detail in Ch. 5 Evaluation of Existing Pavement s for Rehabilitation of Guide for Mechanistic–Empirical Design (*1,2*).

TABLE 2.2
Existing pavement condition limitations for each type of surface treatments (Michigan, Minnesota, Missouri, Ohio)

	Michigan	Minnesota	Missouri	Ohio
Crack Seal/Fill	Transverse cracks with excessive secondary crack around the main crack	No existing pavement condition limitations	Cracks less than 0.1 in. wide or greater than 1 in. in width	Pavements with significant raveling Pavements that requires the use of sealing material in excess of 5000 lb per lane mile
Fog Seal	**Not available**	No existing pavement condition limitations	Surface not porous enough to absorb the emulsion	**Not available**
Scrub Seal (Sand Seal)	**Not available**	No existing pavement condition limitations	Pavements with AADT more than 7,500 Unstable pavements	**Not available**
Seal Coat (Chip Seal)	No existing pavement condition limitations	No existing pavement condition limitations	Rough or uneven pavement	Pavements that are not structurally sound
Flush Seal	**Not available**	No existing pavement condition limitations	**Not available**	Pavements that are not structurally sound
Microsurface	Moderate to heavy surface cracks	No existing pavement condition limitations	No existing pavement condition limitations	Pavements that are not structurally sound
Ultrathin Bonded Wearing Course (UBWC)	Milled surface Rutted pavements or pavement exhibiting distortion	No existing pavement condition limitations	Any cracks greater than 1/4 in., which are not cleaned and sealed Patches and potholes exceed moderate severity levels Rutting exceeds 0.5 in.	**Not available**
Profile Milling (Diamond Grinding)	No existing pavement condition limitations	**Not available**	**Not available**	**Not available**
Thin HMA Mill and Fill (Thin HMA Inlay)	Severely distressed pavement Debonding Pavement with excessive amounts of crack sealing	No existing pavement condition limitations	**Not available**	**Not available**
Thin HMA Overlay with Milling	Pavement with a weak base	No existing pavement condition limitations	Consolidation rutting exceeding 3/8 in. Pavements with a weak base	**Not available**

While stripping is also considered to be major factors affecting the applicability of treatment by many state agencies, its identification/evaluation methods are not available. Initial literature review revealed that only recently an attempt had been made to develop a procedure to detect stripping in existing pavement was conducted by Georgia Department of Transportation (DOT). The limitations concerning identification of stripping were also noted during a national seminar (Moisture Sensitivity of Asphalt Pavements, Topic 7, 2003). In addition, a survey conducted by Colorado DOT which included 50 states DOT revealed that moisture sensitivity in asphalt pavement was not only a local problem but a national issue.

An emphasis was put on the available identification/ evaluation methods for stripping in the following literature review. The list of test methods are based on Georgia DOT's stripping identification manual as they employed wide range of non-destructive test (NDT) methods available. Finally, previous case studies related to moisture damage were reviewed.

2.2.1 Field Sampling

Despite the introduction of advanced pavement testing methods in recent years, asphalt core sample provides more direct and reliable information about pavement condition. The process of obtaining core data consists of three main steps: (1) core sampling location selection, (2) core extraction, and (3) core sample testing. Core sample testing is further categorized into laboratory experiments and visual inspections.

Various core sampling methods have been developed and adopted by state DOTs, as coring is required in part of pavement evaluation. The most widely used type of core sampling method is to randomly select pavement location for the core sampling.

2.2.2 Laboratory Test

Volumetric properties. The volumetric properties are considered to be the most important factors affecting the performance of asphalt pavement. Consequently, the volumetric properties serve as both the most widely used mix design parameter and specified pavement acceptance criteria by state agencies. Furthermore, the volumetric properties are imperative in pavement investigation and the selection of treatment accordingly (*3*).

Indirect tensile test. The tensile strength property of an asphalt mixture gives an indication on the overall strength of the mix and its resistance to crack. In addition, the tensile strength ratio is a commonly used indicator on the moisture damage potential of asphalt mixtures (*4*). According to Aschenbrener in 1995, AASHTO T283 was able to predict the stripping potential of Colorado aggregates with reasonable accuracy (*5,6*).

Kandhal, Lynn and Parker also reported that of all the test methods available for evaluating moisture susceptibility, AASHTO T283 (modified Lottman test) is more widely used and considered to have relatively better reliability than numerous other test methods (*7*).

Recent field studies by Lu and Harvey focused on evaluating the long-term effectiveness of antistripping additives under prolonged moisture conditioning situations. Two test methods were used: indirect tensile strength ratio (TSR) test and flexural beam fatigue test. The TSR test examines the strength loss of asphalt mixes due to moisture, whereas the flexural beam fatigue test examines the effect of moisture on the fatigue response of asphalt mixes (*8*).

Water stripping test. Two standardized methods from Montana DOT and Virginia DOT used for identifying and quantifying water stripping using in-situ samples were reviewed and summarized in Table 2.3 and Figure 2.1. The methods require core samples to be split diametrically for visual examination of the broken faces; Montana DOT and Saskatchewan Highway and Transportation procedures specify the use of the tensile loading for splitting core samples.

2.2.3 Non-Destructive Test (NDT)

Ground penetration radar. Ground penetration radar (GPR) is a high resolution geophysical technique that utilizes electromagnetic radar waves to locate and map subsurface targets, including pavement layer contacts. GPR operates by transmitting short pulses of electromagnetic energy into the pavement. These pulses are reflected back to the radar antenna. The amplitude and arrival time correspond to the thickness and material properties of the pavement layers (*9*).

In a study by Minnesota DOT, it was found that the effectiveness of GPR is highly affected by the equipment used and experience of interpreters. Yet, the study suggested that the GPR performed successfully on detecting layer thicknesses, void locations, and stripping locations (*10*).

Montana DOT (MDOT) also evaluated the feasibility of GPR to a broader range of pavement evaluation as the GPR is currently used in conjunction with Falling Weight Deflectometer (FWD) only to collect the layer thickness data. Based on an evaluation of MDOT's rehabilitation and reconstruction practices, it was concluded that the GPR program can provide useful information for the following applications: (a) calculation of structural number for pavement reconstruction and rehabilitation design; (b) insuring proper depth control for mill and fill rehabilitation, and cold in-place recycling; (c) improved structural capacity calculation for network level evaluation; and (d) quality assurance of new pavement thickness and density (Montana DOT, GPR Analysis).

Furthermore, Leng in 2011 introduced a correlation model which can predict the bulk specific gravity of asphalt mixture from measurement by GPR. The model was validated using data from a construction site and showed that its accuracy was better than that of a traditional nuclear gauge measurement (*11*).

The GPR equipment currently used by Indiana Department of Transportation consists of one data collection system (GSSI SIR 20), 2 ground-coupled antennas (1.6 GHz and 2.6 GHz) and 1 air-coupled

TABLE 2.3
Core sample visual inspection guideline

Rating	Montana DOT	Virginia DOT
4 (Severe)	Most aggregates are not coated	Course Aggregate: >50% Fine Aggregate: >40%
3 (Moderate)	Moisture damage Some coarse aggregates are not coated	Course Aggregate: 30–49% Fine Aggregate: 25–39%
2 (Slight)	Some fine aggregates are not coated	Course Aggregate: 15–29% Fine Aggregate: 10–24%
1 (Good)	All aggregates are coated Surface is black	Course Aggregate: 0–14% Fine Aggregate: 0–9%

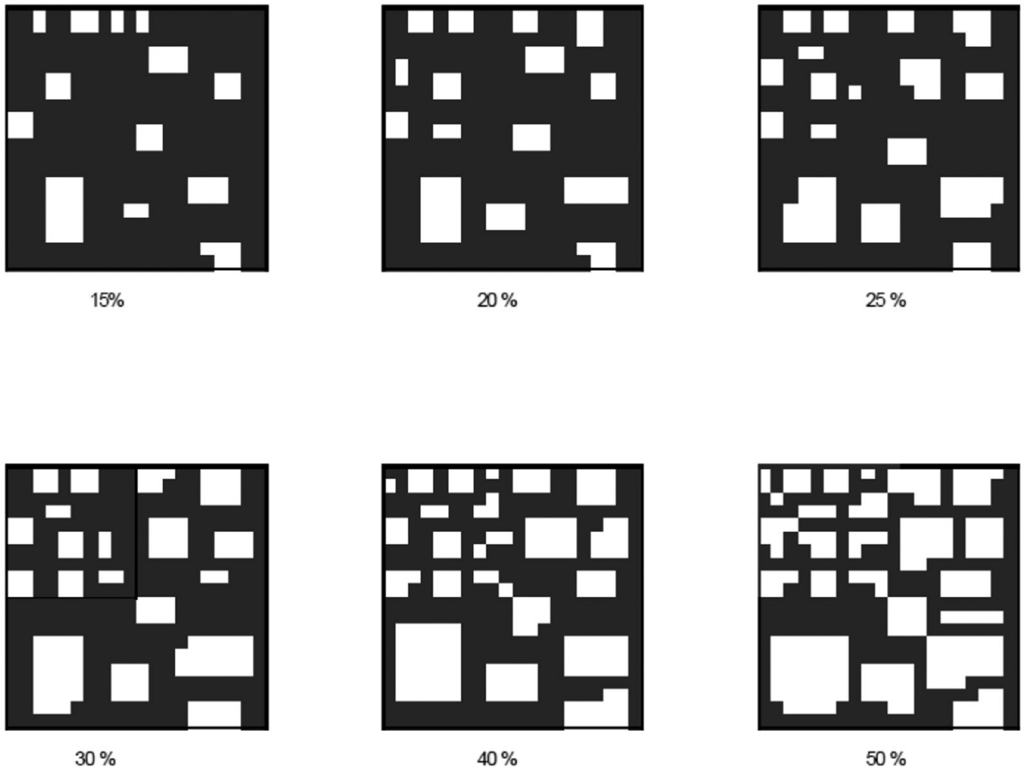


Figure 2.1 Core sample visual inspection guideline (Saskatchewan Highway and Transportation).

antenna (1.0 GHz). The approximate depths of penetration for each of these antennas are 6 in. 1 foot and 1.5 feet for 2.6 GHz, 1.6 GHz and 1.0 GHz, respectively. In general, the depth of penetration is inversely proportional to the frequency of an antenna. In addition, INDOT maintains a vehicle reserved only for GPR data collection that includes an independent power source and electronic distance measuring instrument (DMI) device.

Falling weight deflectometer (FWD). The Falling Weight Deflectometer (FWD) is a rapid, nondestructive means of determining a deflection basin response to a measured dynamic load with amplitudes similar to those imposed by trucks. The FWD consists of a mass mounted on a vertical shaft and housed in a trailer that can be towed by automobile or light truck. The FWD generates an impulse load by dropping a mass from different heights. By varying the drop height and mass, a different force can be applied to existing pavements. The drop weight falls directly onto rubber buffers that control the load pulse time. The resulting impulsive load on the pavement approximates a half sine wave. The loading plate is equipped with a strain-gage type load cell to measure applied force. The pavement surface deflection is measured by electronic integration of the signals from seven velocity transducers (geophones). Typically, one geophone is located at the center of the load plate while the remaining six are located along an array emanating from the center of the loading plate. The FWD equipment currently used by Indiana Department of Transportation is Dynatest Model 8000. The typical loadings used for the testing are 7,000 lb., 9,000 lb., and 11,000 lb.

Since pavement layers with stripping damage have lower stiffness than sound asphalt pavement layers, Georgia DOT selected FWD as one of their test methods for stripping detection. When the FWD results for locations exhibiting stripping in core samples was compared to that for locations without any stripping, some differences were observed. However, it was concluded that the difference in layer stiffness was not statistically significant (*12*).

Seismic test. Asphalt stripping will cause a decrease in the modulus of the asphalt pavement. Seismic methods measure travel time required for waves to propagate to other points on the surface of the pavement (*12*). Earlier studies conducted on suitability of the test method on detection of stripping in asphalt pavement demonstrated positive result (*13*).

A recent study, which was also conducted by Nazarian and Celaya, also demonstrated its effectiveness in identifying areas with less stiffness due to stripping. Another advantage shown by the study was that the method was able to detect both poorly constructed layers and stripped layers. It was noted, however, that the stripping located deeper than 10 in. could not be detected.

Nuclear density gauge. Pavement density is used as an indicator of abnormality in pavement (e.g., segregation and stripping). A nuclear gauge is used for density measurements as a construction quality control tool (*14*).

Georgia DOT evaluated the nuclear gauge in identifying the segregation in asphalt pavements. The evaluation result showed that significant differences exist among density measurements for eight of nine locations of segregation (*15*).

Thermal imaging. Infrared thermograph (IR) technique has been evaluated as a tool for identifying debonding of layers on bridge decks. The IR technique requires environmental conditions with a high rate of warming or cooling and assumes that stripped area has higher specific heat, which means that more energy is required to raise the temperature, or it will have more energy to give up during a cooling cycle (*12*).

Thermal imaging equipment was field-tested on an existing pavement to determine its overall effectiveness in detecting distress. However, the thermal-imaging equipment was found to be ineffective. The equipment also did not detect any distress occurring below the pavement surface. Furthermore, thermal images do not yield quantitative results, making the inspection process subjective (*14*).

A research by Sebesta and Scullion in 2002, along with several studies performed by other agencies, provided strong support to the capabilities of infrared imaging in inspecting paving operations for uniformity. However, previous study indicated that temperature differentials in excess of 25 °F would be considered as potential distress in the pavement (*16*).

2.2.4 Surface Distress Identification

Asphalt pavement with water stripping problems are likely to affect the durability and often show other signs, such as localized areas with surface distress, including severe fatigue crack, potholing, raveling or a greater frequency of transverse and block crack. Kandhal and Rickards (*17*) observed that stripping in overlays also resulted in "flushing" of stripped asphalt binder to the surface and white staining of the surface where fines in the asphalt concrete have been pumped to the surface. The presence of stripping can also result in more variability that might increase the potential for rutting and/or localized longitudinal profile distortions and/or increased rutting in localized areas.

National Center for Asphalt Technology (NCAT) report, titled "Premature Failure of Asphalt Overlays from Stripping", presents details of visual observation of pavement distress from four case histories from Pennsylvania, Oklahoma, and New South Wales in Australia. Summary of findings from each site are the following (*17*):

- Pennsylvania:
  - All typical symptoms of stripping were presented as white or gray spots, flushing, and potholes.
  - The stripped asphalt binder started to migrate upwards causing the flushing of the pavement surface. A pothole then developed in the flushed area which has almost bare aggregates underneath.
  - For a certain section, no significant distress was observed even though core sample displayed the signs of stripping which had taken place.
- Oklahoma:
  - Most of the potholes occurred in the wheel track of the slow lanes and they were usually the result of stripping of underlying layer.
  - Big stains appeared initially when the stripping was initiated in the underlying layer.
  - Rutting and/or potholes were likely to be developed due to stripping.
- South Wales, Australia:
  - White stains on the surface indicated possible upward migration of fines after stripping occurrence.
  - Alligator type fatigue crack was likely the result of stripping, which would lead to the development of potholes.

2.2.5 Previous Case Studies

In order to effectively identify the cause of stripping in pavement, forensic investigations were carried out by applying a combination of existing technologies. This chapter reviews three forensic investigations related to moisture damage.

Forensic investigations of roadway pavement failures, Texas (2007). Texas DOT had a formalized forensic team approach, which consisted of nondestructive testing, including, Ground Penetrating Radar (GPR) and Falling Weight Deflectometer (FWD), Dynamic Cone Penetration (DCP), coring, and laboratory testing. The findings of the study were the following:

- A combination of GPR and FWD was extremely successful at identifying stripping in the HMA pavement.
- The extent of stripping and high porosity that caused delamination were detected by GPR and verified by core samples.
- FWD data demonstrates that a pavement structure were inadequate.
- GPR, laboratory density, and permeability tests indicated the existence of moisture damage in the layer.
- Results of repetitive tri-axial test in laboratory revealed that the stiffness and load carrying capability became inadequate when base materials were exposed to moisture.

Case study of an innovative forensic investigation of a dramatic pavement failure, Canada (2007). Calgary, Canada investigated surface and subsurface distresses on one kilometer pavement section, which was heavily damaged by an extreme rainfall. The investigation employed Road Radar™, GPR, and FWD. Additional information was also gathered by detailed visual surveys and interviews. Results of the field investigation are the following:

- GPR was generally able to reveal all significant subsurface layers and anomalies; yet, GPR was determined to be best used as an overview tool.
- Road Radar correctly measured layer thicknesses although a classification of an individual layer material type may cause some errors using this characteristic material dielectric approach.
- FWD was used to confirm the analysis result of Road Radar and coincided with the fact that no structural deficiency existed.

Forensic investigation of pavement failures due to moisture on interstate highways, Oregon (2002). Oregon DOT investigated premature failures on five interstate highway projects to determine conditions and mechanisms. Field investigations as well as laboratory testing of cores were used and the findings are the following:

- Visual examination of cores obtained from the projects provided valuable information regarding layer depths and conditions. However, the presence of moisture damage was not always identified from these observations.
- Results of air void analyses of the pavement layers correlated reasonably well with visual observations made from the site. Based on these results, the threshold for relatively high or low air void appeared to be about 7% when measured by following ASTM D 6752.

2.3 Comparison of Non Destructive Testing Method for Water Stripping Evaluation

Four factors, including applicability to the pavement subsurface, data measurement type, reliability/accuracy of measurement, and positive review were considered in comparing NDT methods reviewed in this study.

- Subsurface evaluation: For the application of water stripping evaluation as well as subsurface condition evaluation, the proposed test method should be able to applicable to the pavement subsurface.
- Measurement type: There are two types of measurement methods; stationary and continuous. FWD uses a stationary data collection method as it needs to be stationed at one specific location and typical data collection interval is about 100 m (328 ft). Continuous data collection method collects data with high frequency or minimal interval between collections and GPR can perform 6 scans per each foot at low speed (less than 10 mph).
- Reliability: The reliability factor determines how collected data accurately represent the actual condition of the pavement.
- Positive review: The positive review factor reflects overall user satisfaction based on the past case studies.

For test method evaluation, all test methods introduced in the literature review were evaluated and scored based on four different factors. If a test method meets the characteristics of each factor, one point was given. For example, GPR is applicable to the pavement subsurface evaluation then one point was given. The results are summarized in Table 2.4. Finally, a sum of all the points were taken for each type of test method and compared. GPR and FWD had four and three points, respectively, factors out of four, thus it was concluded that they were most appropriate NDT methods applicable for the surface condition evaluation in asphalt pavements.

3. EVALAUTION OF SUBSURFACE CONDITION TEST METHODS

A study was conducted on SR-70 to explore applicable evaluation methods to the subsurface condition investigation. SR-70 contained multiple potholes and fatigue cracks started occurring after the construction of a microsurface treatment on full-depth asphalt pavement. Cores were sampled from locations selected using the Ground Penetration Radar (GPR), Falling Weight Deflectometer (FWD), surface distress evaluation. Finally, the validity of the results of surface distresses and NDT test were evaluated by comparing them to the core laboratory test results. In addition, correlations among test results were also analyzed.

3.1 Evaluation Process

An overall experimental plan, as illustrated in Figure 3.1, is described below:

- Collect general site information: This step involves the collection of information regarding location, pavement history, design values, and any existing data.
- Site survey &investigation: This step includes the site visit to obtain most current information of the pavement, including surface condition, drainage system, and notable feature in surroundings.
- Non-destructive testing: This step involves non-destructive testing (i.e., GPR and/or FWD) performed on a

TABLE 2.4
Characteristics of available non-destructive methods

Name	SubsurfaceEvaluation	Continuous Measurement	Reliability	Positive Review	Overall Score
GPR	1	1	1	1	4
FWD	1	0	1	1	3
Seismic	1	0	1	0	2
Nuclear Density Gauge	1	0	0	0	1
Thermal Imaging	0	1	0	0	1

specific section of the test road, where core samples are obtained. In addition, surface distresses are individually examined to assess severity and extent (coverage).

- Core location determination and core sample collection: This step involves analyzing data collected in the previous steps, and determining the required number of core samples and sampling location. This step is critical as feasible number of cores to be sampled and tested is limited while various factors, including surface distress location and NDT data, should be considered. Finally, core samples are collected.
- Laboratory test: This step involves conducting laboratory experiments on collected core samples, namely volumetric property test (Bulk specific gravity (Gmb) and theoretical maximum specific gravity (Gmm)) and indirect tensile test. Core samples are also examined for the severity of water stripping.
- Correlation analysis: This is a validation process using the results of surface distresses, NDT test and core laboratory test. In detail, the factors to be examined are the following:

  – Air voids, indirect tensile strength, or water stripping severity of core specimens vs. GPR or FWD analysis data.
  – Air voids, indirect tensile strength, or water stripping severity of core specimens vs. surface distress analysis data.
  – Surface distress analysis data vs. GPR or FWD analysis data.

- Correlation analysis: This is a subsurface condition evaluation process using the results of laboratory test results.

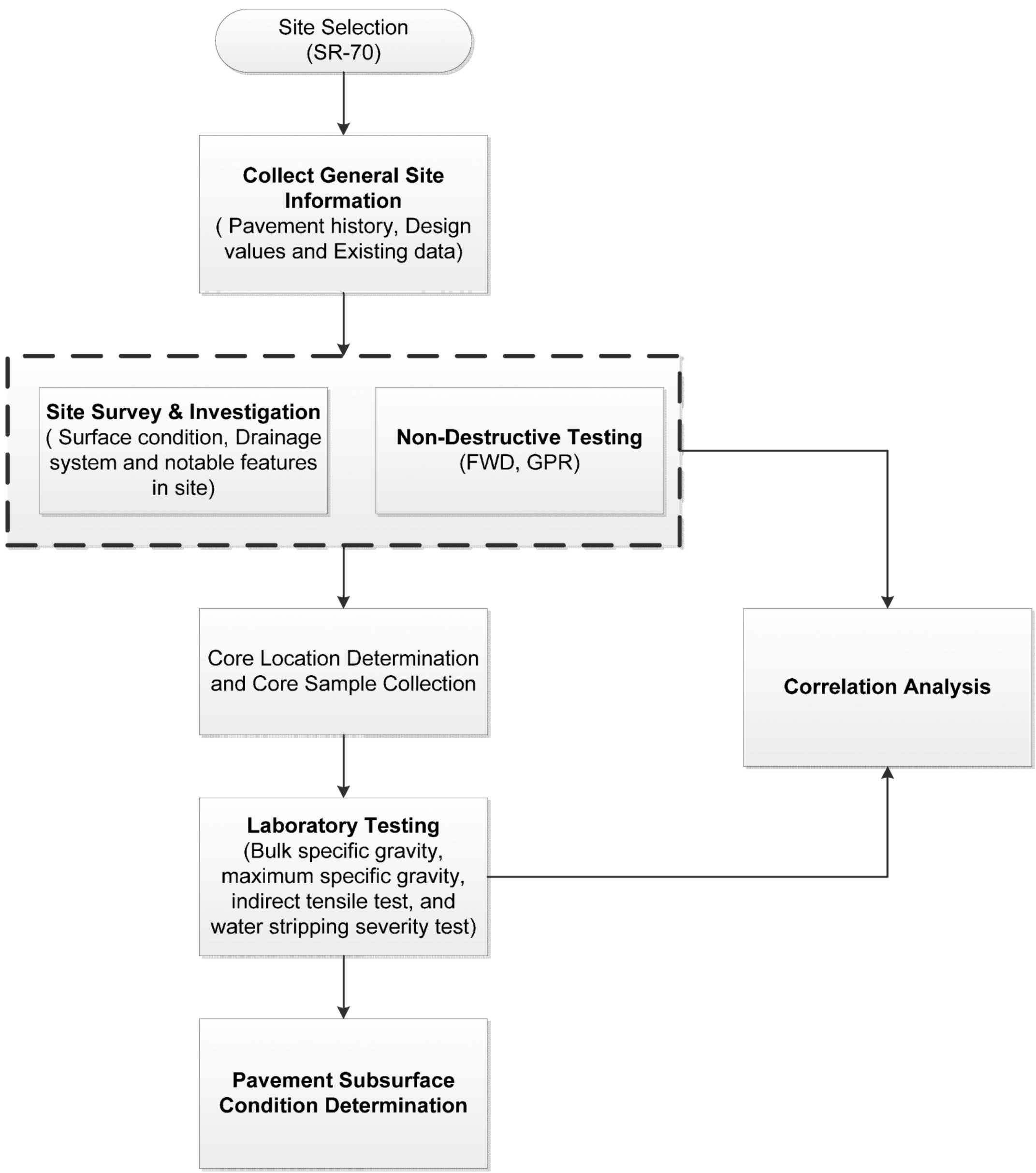


Figure 3.1 Diagram for experimental plan.

Figure 3.2 Location of the case study road.

3.2 Site Information

The case study road is located on SR-70 in the INDOT Tell City Sub-district near Tell City, Indiana. The SR-70 is a two-lane highway with a 10-in. full-depth asphalt. The approximate extent of the project is shown in Figure 3.2 and the project section is set to be 0.25 mile east of junction with US-231 to SR-66, reference points (R. P.) 0.5 to 9.75, respectively. Weigh in motion (WIM) data from INDOT shows that the traffic volume through the test sections in 2006 was approximately 1,743 vehicles per day with trucks counting about 8%.

The climate of the region could be considered as a warm, semi-humid and continental type. Although it has four distinct seasons, mild winters and hot and dry summers are often observed (Some characteristics of southern Indiana climate (*18*)). The climatic data, including average daily temperature and precipitation from August 1, 2008, through August 1, 2012, is presented in Figure 3.3.

Rehabilitation history shows two occasions of activities since the original construction of SR-70, which are the resurfacing and the microsurfacing. The test section was milled and resurfaced in 1992, accompanied by the expansion of the pavement width from 20 ft to 24 ft. According to the contract document, the 1 in. of the existing surface was milled and intermediate and surface course were laid at 220 lb/SYD and 110 lb/SYD, respectively. AADT for 1987 was recorded as 2022 and projected AADT for 2007 was 3120. The truck traffic data was not available.

The construction of microsurfacing on SR-70 was started on August 7, 2008, and concluded on August 11, 2008. The contractor applied the microsurfacing with the application rate ranging from 22 lb/SYD to 33 lb/SYD after patching and crack sealing were completed on the existing pavement.

3.3 Test Methods

3.3.1 Site Survey and Surface Distress Investigation

To evaluate pavement surface distresses, digital images of pavement surface were collected and analyzed.

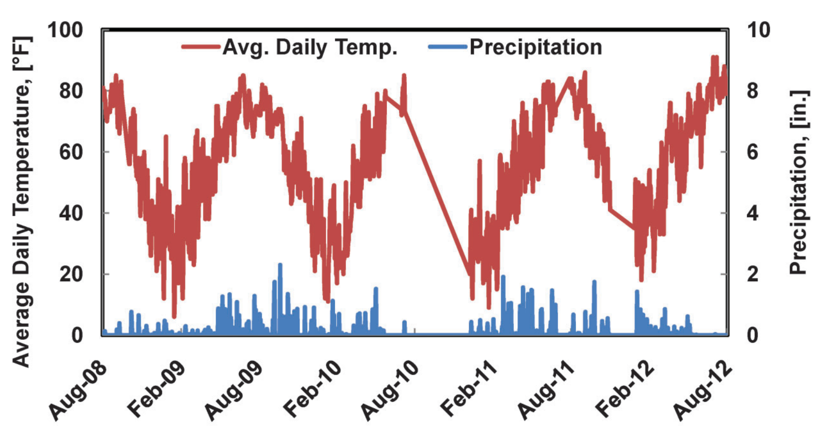


Figure 3.3 Climate condition of Tell City Sub-district (National Climatic Data Center).

Figure 3.4 Surface distress survey vehicle.

A digital image acquisition system was developed using a digital camera mounted on a vehicle with a distance measuring instrument (DMI) unit connected to the digital camera, as shown in Figure 3.4. The digital camera, Nikon D300 providing 4,288 by 2,848 pixels color images, was mounted at 15 ft high from the ground. This setup covered an area of 12 ft by 9 ft. The digital camera periodically took digital images of the pavement surface ahead of the vehicle as the vehicle travels along the lane. A digital image acquisition system, which is integrated with a DMI unit, provides uniform coverage of pavement surface regardless of the vehicle traveling speed.

Types and extents of surface distresses were visually analyzed using the digital images of the pavement surface and the FHWA distress identification manual (*19*). The extents of distress should be measured by either linear distance (ft) or area (ft^2) depending on the types of surface distresses. The extents of distresses were measureable since all images had the uniform coverage area of 12 ft by 9 ft.

3.3.2 Non-Destructive Test

Ground penetration radar (GPR). The GPR test was conducted using air-coupled antenna (1.0 GHz) in August 2011 on right and left wheel paths. The measurement interval was 6 in.

Falling weight deflectometer (FWD). FWD tests were conducted in 2008, 2009, and 2010 in order to evaluate structural adequacy of the test section. Tests were conducted in the driving lanes in both directions at 328 ft intervals. Based on previous INDOT experiences, a minimum of 16 testing locations per mile is required to provide statistically sound analysis. The 11-kip load level was used for the testing. For the calculation of stiffness and deflections, ELMOD6, a software system developed by Dynatest, were used.

3.3.3 Laboratory Test on Cores

Cores sampling. CA test section in the test road was first determined before determining the core sampling locations. The changes of surface condition over time were observed from the analysis of pavement surface digital images, as shown in Figure 3.5. Numbers on the top in the plot shows R. P. and lines at each side of pavement represent roads connected to the test road (SR-70). Top lane and bottom lane separated by thick yellow line in the middle represents west bound and east bound, respectively. Green dots indicate surface distresses (i.e., potholes and patches) identified in October 2010 field survey, while red dots indicate newly formed distresses in between October 2010 and August 2011 field survey. As a result, the 2 mile section between R.P. 3 and R.P. 5 was subjected for the core sampling location as the test section includes both the most and least surface distresses occurrence locations. In addition, constraints on traffic control and time required for traveling between core sampling locations were also considered in the process.

The 2 mile test section was evaluated and categorized into two areas representing “good” and “poor” conditions based on GPR and FWD measurements. Core sampling locations were then determined based on the subsurface (i.e., GPR and FWD measurements) and surface distress condition (e.g., crack, potholes and patch).as subsurface condition indicators which are to be introduced in a following chapter in detail. Total of 28 cores were sampled from the test section (14 cores from the right or left wheel path and 14 cores from between wheel paths). The final locations of core samples are summarized in Table 3.1. Each core sample was given identification number which is a combination of number and letter (R for right, C for center, and L for left) for wheel path on which core was obtained.

Laboratory sample preparation. The core samples were prepared for the laboratory testing once arrived in the laboratory. Each core sample was washed to remove excess aggregate or any other materials introduced during coring or handling, and dried in the environmental chamber at room temperature of 77 °F. Once the core sample was sufficiently dry, each one was visually examined for interfaces, thickness of each layer, and visible distress.

Each core sample was then cut using a circular saw based on the layers identified from the visual inspection. The physical dimensions of each core layer samples were measured to the nearest 0.1 in. Once all the measurements were completed, the core layer samples were again placed in the environmental

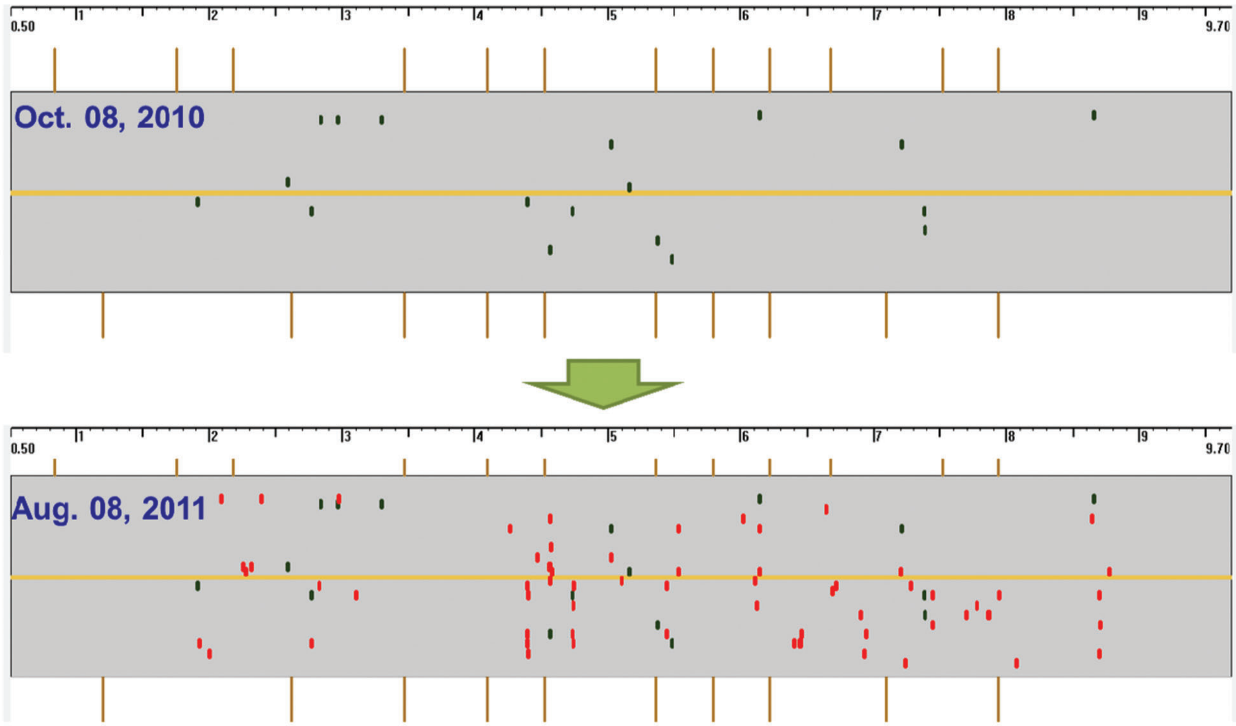


Figure 3.5 Visual analysis results from 2010 and 2011 on potholes and patches.

chamber for the final drying process before the laboratory testing.

Bulk specific gravity (G_{mb}). The measurement of bulk specific gravity (G_{mb}) is the basis for the volumetric calculation, namely air voids, voids in mineral aggregates, voids filled with asphalt and percent maximum density. Thus, it is imperative to have accurate measurement of bulk specific gravity. The measurement of bulk specific gravity has been based on the concept of water displacement, using samples which are assumed to be in saturated-surface dry condition. However, a core sample with larger air voids (e.g., coarse-graded mix or sample with water stripping damage) can negatively affect the measurement process as water can quickly drain from the core sample once removed from the water bath (*19*).

TABLE 3.1
Locations of core samples with labels

R. P.	Left Wheel Path	Center of Lane	Right Wheel Path
3.227	3L	3C	
3.317	11L	11C	
4.275	35L		35R
4.282		23C	23R
4.55		38C	38R
4.65		40C	40R
4.926		26C	26R
3.004		24C	24R
3.198		7C	7R
3.387		21C	21R
3.515		25C	25R
3.543		29C	29R
3.551	12L	12C	
3.697	13L	13C	
5.108	1L	1C	

Unlike core samples from newly constructed pavements, samples obtained from the existing pavement may show signs of various types of distresses, and water stripping is one of them. Asphalt mixes with stripping damage are generally recognized to have high air voids through water retention. Previous evaluations from NCAT and Florida DOT indicated that the Corelok procedure is a better measure of bulk specific gravity, especially for mixes prone to high levels of water absorption. Accordingly, this study utilized the Corelok with AASHTO T331 for the measurement of bulk specific gravity for each core layer sample (*20*).

Theoretical maximum specific gravity (G_{mm}). The theoretical maximum specific gravity (G_{mm}) was determined by AASHTO T209. The standard test is to be performed with particles of the sample with complete coating, which is essential for accurate measurement as aggregate particle should not absorb any water during the test (*22*). However, the aggregate particle samples to be tested in the study were obtained from field core samples. The sample contained cut aggregates on the surface of the core, which was prone to the water absorption.

The specimen for the maximum specific gravity test was prepared by first having core samples heated in the oven by 158 °F. Once the specimen became sufficiently workable, outer portion of the core sample containing

(a) (b)

Figure 3.6 Sample preparation process for Gmm measurement: (a) Sample heating in the oven at 158 °F; (b) Separation of uncoated aggregates from coated aggregates.

aggregates with cut surfaces were removed, as shown in Figure 3.6. Then, the rest were separated without fracturing any aggregates until there were no aggregate particles larger than 0.25 in.

Indirect tensile test (IDT). The indirect tensile test is performed by loading a cylindrical specimen with a single or repeated compressive load which acts parallel to and along the vertical diametral plane. This loading configuration develops a relatively uniform tensile stress perpendicular to the direction of the applied load and along the vertical diametral plane which ultimately causes the specimen to fail by splitting along the vertical diameter, as shown in Figure 3.7. A curved loading strip is used to provide a uniform loading width which produces a nearly uniform stress distribution.

The calculation of the TSR in accordance to AASHTO T283 is the standard method under the Superpave mix design system to evaluate a mixture's moisture sensitivity (*6*). The standard test method uses a sample set, which is conditioned by saturation and immersion to simulate the moisture damage of a mixture in field. The indirect tensile strengths of the unconditioned and conditioned sets are then compared to evaluate the moisture damage induced by conditioning. However, this study was not to examine the moisture sensitivity of a mixture and there was no fresh mixture sample (e.g., as-constructed sample) which needs to be compared to. Thus, only the indirect tensile test was used for the assessment of each core layer specimen's condition.

Specimens completed with the bulk specific gravity measurement were tested by IDT and the specimen placed in the IDT equipment is shown in Figure 3.7. A load was applied to the specimen at a constant rate of 2 in. (50 mm) per min. The maximum load was recorded, and the load continued until the failure of the specimen. The tensile strength of the specimen was determined

(a) (b)

Figure 3.7 IDT setup: (a) IDT chamber; (b) specimen after IDT test.

using Equation 3.1:

$$S = \frac{2 \times p}{\pi \times D \times T} \tag{3.1}$$

Where: S = Tensile strength of the specimen (psi)
p = Peak load (lb)
D = Specimen diameter (in.)
T = Specimen thickness (in.)

Water stripping measurement. The severity of water stripping was quantified by Digital Image Analysis (DIA). Asphalt mix is primarily composed of asphalt and aggregate. The aggregate should be fully coated with asphalt in the good condition mix. Literatures revealed that typically, the water stripping severity was evaluated by calculating the stripped area over the total area. However, this evaluation method does not consider the change of aggregate or asphalt volume fractions by different mixture types. Thus, the same size of uncoated area in a sample with higher aggregate volume fraction or lower asphalt volume fraction should result in lower severity than that with lower aggregate volume fraction or higher asphalt volume fraction. A mixture with the more asphalt volume fraction has the less aggregate volume fraction. In addition, generally, the larger nominal maximum aggregate size (NMAS) shows the less asphalt fraction. For example, the typical effective binder content by volume in asphalt mixtures used in Vincennes district from 2005 to 2007 are 8.69%, 9.53%, 10.66%, and 11.61% for 25.0 mm, 19.0 mm, 12.5 mm, and 9.5 mm NMASs, respectively (*23*). Accordingly, since the stripping can only occur to the coated aggregate, the severity of water stripping was defined as percent uncoated aggregate volume over total aggregate volume in a sample in this study.

Accordingly, the DIA for the water stripping measurement requires two images including cut-face and split-face in a sample. The cut face and the split-face are used for quantifying the aggregate fraction and the uncoated aggregate fraction, respectively.

A uniform image quality is a critical factor in the DIA. However, controlling conditions for image acquisitions in different projects is not simple in practice, which results in image by image quality variation. Nevertheless, a uniform image quality for a pair of the digital images (i.e., cut-face and split-face) in a sample for a project is easily obtainable. The DIA with the pair images can minimize quality variation-related factors from project by project or laboratory by laboratory on the stripping measurement since the measurement is relative quantification in a sample.

Primary process for DIA for the calculating the percentage area covered with uncoated aggregate and covered with aggregate are identical except the type of image used:

1. Digital Image Collection: Digital image of the cut-face of core specimen before IDT and the split-face after IDT are required for the DIA. The image should contain only the specimen surface without any back ground, as shown in Figure 3.8 and Figure 3.9.
2. For the analysis with the split specimen surface image, any one face of the split surfaces can be used since they are symmetrical. Minimum resolution required for the image is 320 by 240. A pixel of digital image for 6 in. by 2 in. sample size With a resolution of 320 by 240 (i.e., the minimal resolution which any digital camera) represents less than 0.02 in. of width in a specimen. Considering aggregate No. 35 sieve size is 0.0197 in., the area represented by each pixel in minimal resolution is deemed to be sufficient for the measurement.
3. Digital Image Analysis (DIA): Color information on each pixel is transformed into HSV (i.e., *hue, saturation, and value*) in an RGB (i.e., red, green, and blue) color model. To be specific, *value* in HSV model represents "brightness". Thus, *value* indicates an extent of light reflection on the specimen surface. The specimen image contains only two material types, namely asphalt and aggregate. Generally, the light reflection of asphalt material has much lower *value* than that of aggregate and the light reflection of asphalt material is more uniform. Accordingly, the percentage of area represented by either aggregate or uncoated aggregate can be measured by identifying and quantifying pixels representing asphalt area or aggregate area in the surface.
4. Quantification: The severity of water stripping is presented as a percentage for amount of pixels identified as uncoated aggregate (A_{wsa}) in total amount of pixels identified as aggregate (A_{ag}). The water stripping severities (WS) were calculated using Equation 3.2. Figure 3.8 and Figure 3.9 show examples of DIA images from this study. It should be noted that the DIA cannot differentiate uncoated aggregate surface from crushed aggregate surface by the result of indirect tensile test.

$$WS = \frac{A_{wsa}}{A_{ag}} \times 100 \tag{3.2}$$

3.4 Test Result

3.4.1 Surface Distress Survey

Surface distresses on the test section were examined and categorized in terms of distress type: longitudinal crack, transverse crack, fatigue crack, and pothole/patch, as shown in Figure 3.10. The longitudinal crack was quantified with respect to locations in transverse direction (i.e., left wheel path, center of lane, and right wheel path) and the crack distribution is summarized in Figure 3.11. If a longitudinal crack is formed diagonally over the entire lane width, then the crack length was separately measured at each location. In total, 807 ft, 130 ft and 1,383 ft of longitudinal crack on left wheel path, center of lane, and right wheel path, respectively, were identified over the test section. The longitudinal cracks in most cases occurred along both wheel paths. Almost all longitudinal cracks located in left wheel path and center of lane were observed in the first 1 mile of the test section.

Pothole/patch, transverse crack, and fatigue crack were also measured summarized in Figure 3.12. Generally, pothole distribution overlaps the patch

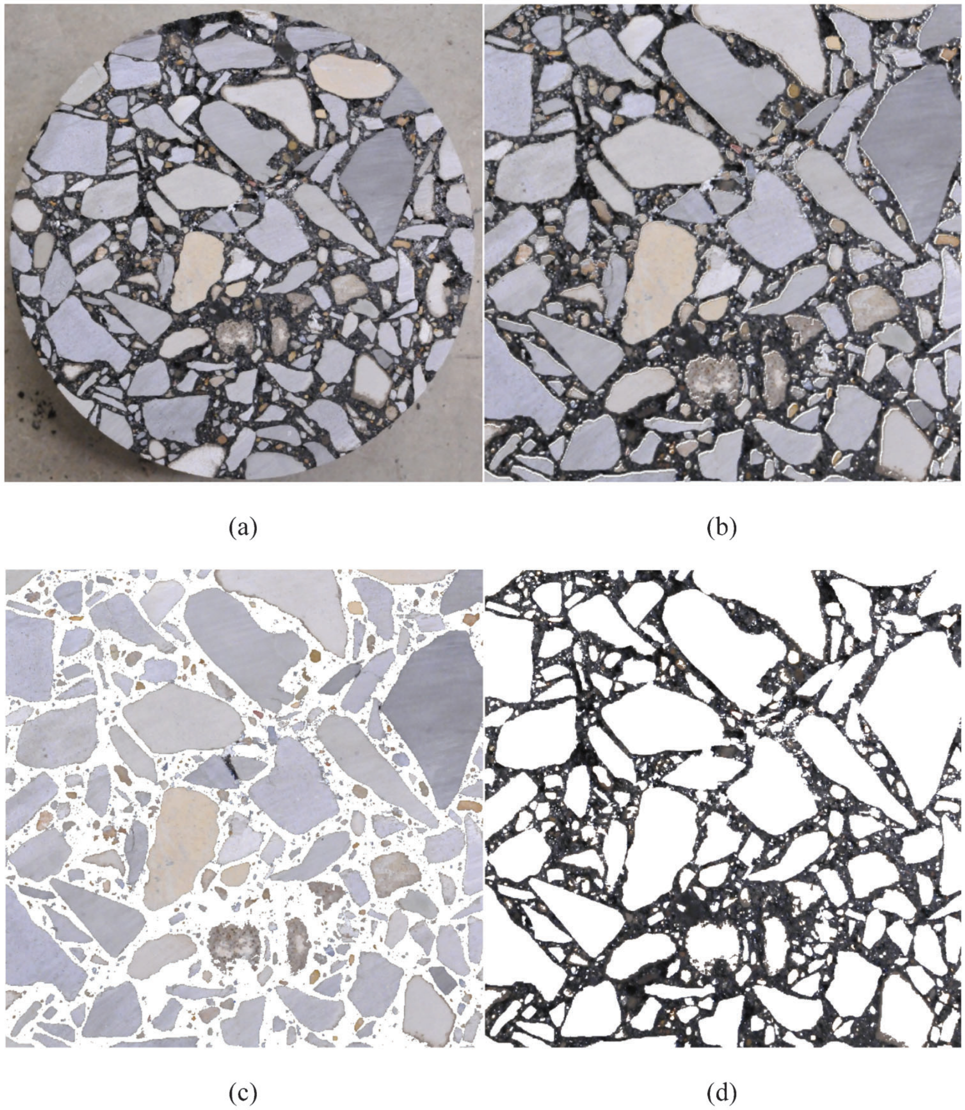
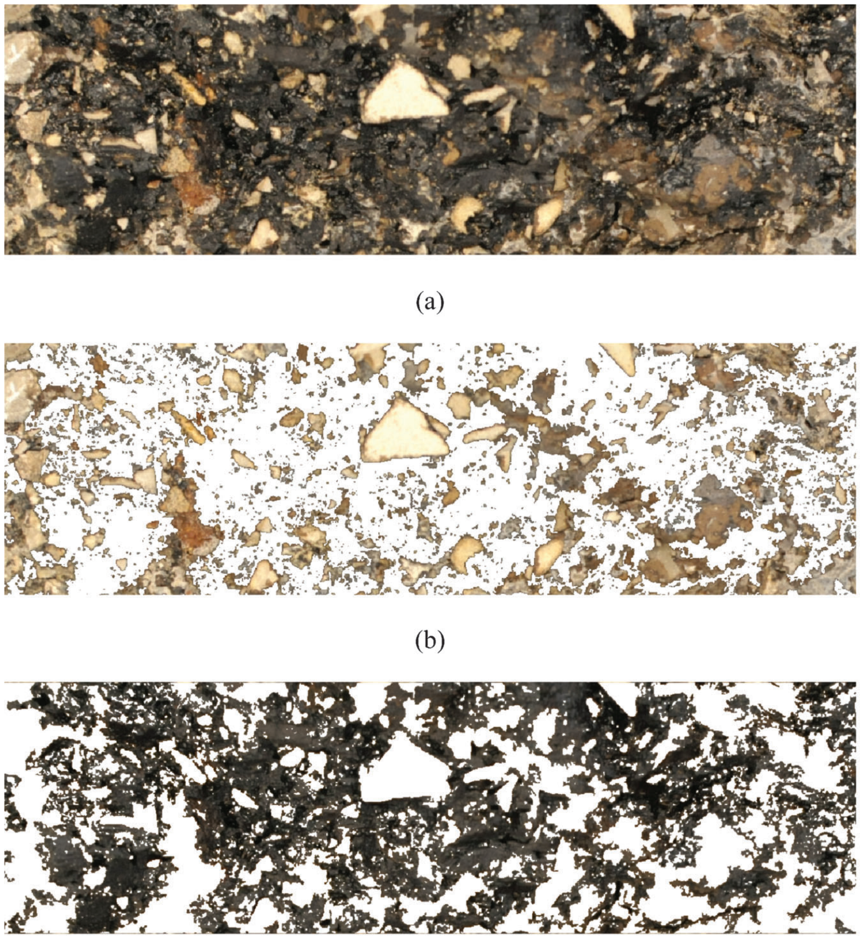


Figure 3.8 Images from DIA process for aggregate area calculation: (a) original image; (b) original image processed for DIA; (c) identified aggregates; (c) identified asphalt and air voids.

distribution in the test section. All potholes/patches were found between R.P. 4 and R.P. 5. The extent of transverse crack was the number of transverse crack in each 100 ft unit interval section. Transverse crack, which were shorter than a half of lane width (< 6 ft) was disregarded. Although transverse cracks were presented over the entire test section, slightly larger number of them occurred in the first 1-mile section (R.P. 3-R.P. 4). In addition, the distribution of the fatigue crack also showed similar trend as most of fatigue cracks occurred in the first 1-mile section. It should be noted that the distribution of pothole and patches was very different from that of transverse and fatigue cracks.

Distress coverage on pavement can be a good indicator to understand the extent of distress. Typically, the coverage can be defined as the length or area covered by distress in a given test section or the crack space. The total extent of longitudinal crack was divided by 10,560 ft (i.e., the total length of 2-mile test section), and the total extents of fatigue crack, pothole, and patch were divided by 126,720 ft^2 (i.e., the total surface area of 2-mile test section) to obtain their coverages. The coverage of transverse crack could be expressed as its crack space assuming the cracks are evenly distributed along the 2-mile test section. The coverage of each type of distress was calculated and is summarized in Table 3.2.

In this study, the length-based coverage was uniformly used in order to add up all the extents of distress types and to use a single coverage value representing a pavement condition. Specifically, the length-based coverage can be defined as the longitudinal length covered with distress in a given test section and add effective length for the length-based calculation of transverse crack and pothole. Consequently, the



(a)

(b)

(c)

Figure 3.9 Images from DIA process for uncoated aggregate surface area calculation: (a) original image; (b) identified uncoated aggregate image; (c) identified asphalt image.

length-based coverage calculation of longitudinal crack remained same. In case of fatigue crack and patch, only the longitudinal length of each distress area was included and divided by the total length instead of the area. For the length-based coverage calculation of transverse crack and pothole, it was assumed that each distress has an effective length of 20 ft. For example, 83 transverse cracks were converted into 1,660 ft (83 × 20 ft) and the length-based coverage was then calculated to be 15.7% (1,660 ft divided by 10,560 ft). Finally, the total length-based coverage of surface distress in percentage was 28%. In other words, 72% of the test section did not display any signs of surface distress. In case of multiple surface distresses presented in the same section, it is included in the calculation once thus prohibiting the same section from being included multiple times.

3.4.2 Non-Destructive Test

Ground penetration radar. GPR recorded reflected signals (i.e., amplitude over travel time) from the pavement surface and subsurface along the test section. The layer interface locations were identified with GPR pulse wave velocities at relatively high amplitudes along the GPR measurements.

Figure 3.13 shows relatively high amplitudes depths with respect to measurement points presented as trace. The measurement interval was 6 in. The average interface depths were 7 in. and 10 in. The layer thicknesses were 7 in. and 3 in. for layer 1 and layer 2, respectively. It should be noted that there was a slight difference between the GPR determined layer thickness and visual observed thicknesses from core samples because of variations from pavement construction and from a GPR result interpretation. It should be noted that L1 and L2 correspond to a combination of Layer 1 and Layer 2 and to Layer 3 in the core visual observation, respectively.

Physical conditions of layers were evaluated by investigating the dielectric constant distribution in each layer. In general, a sound-condition layer has a relatively uniform dielectric constant because of its material homogeneity along the measurements. However,

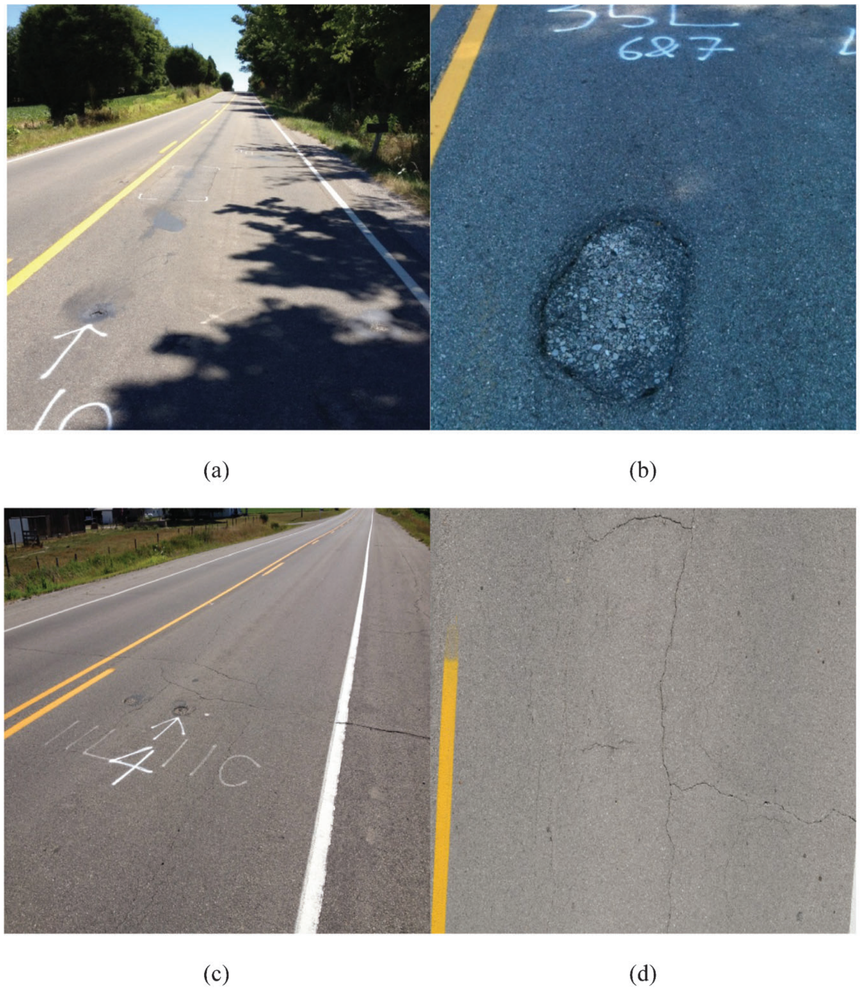


Figure 3.10 Surface distresses on the test section: (a) patch and core holes; (b) pothole; (c) fatigue cracks with core holes; (d) fatigue cracks.

dielectric constants with presence of voids or water have high variations.

Generally, the distribution of dielectric constant is not normally distributed. This abnormal distribution limits the most outlier methods for inhomogeneity detection. Therefore, In consideration of the limitation, a detection method with skewed distributions developed by Huber and Van der Veeken (*24*) was employed to identify problem locations in the test section.

Table 3.3 shows the coverage of problem locations for L1 and L2 by wheel path. In order to have a combined coverage for both wheel paths and for L1 and L2, the coverage was combined by adding the coverage of wheel paths and L1 and L2 together considering the overlapped locations. The overlapped locations were a certain sections where both wheel path were determined to be problematic. Consequently, the combined coverage should be counted only once and was less than the sum of the coverage of both wheel paths. The combined coverage for left and right wheel path at L1 and L2 were 13.6% and 9.6%, respectively. In a similar manner, the coverages of L1 and L2 were combined. The total coverage for the test section combining both wheel paths and L1 and L2 was 20.5%. Thus, the non-problem location had 79.5% coverage.

Falling weight deflectometer. FWD results including surface deflection, subsurface deflection, and stiffness on the test section are presented in Figure 3.14. The average stiffness over the test section was 297 ksi with a standard deviation of 181 ksi. The average deflections of surface and subsurface were 12.8 mils and 2.5 mils with standard deviation of 3.22 mils and 0.64 mils, respectively.

In order to validate FWD results using the subsurface condition, FWD test spots located in less than 30 ft away from the core locations were identified. Then, the core samples were divided into two groups: intact and damaged sample groups as explained in the Visual Observation chapter. The significance of difference between the groups was tested and its results are shown in Table 3.4. If the significance level of 5% is assumed, it can be concluded that FWD results on locations of

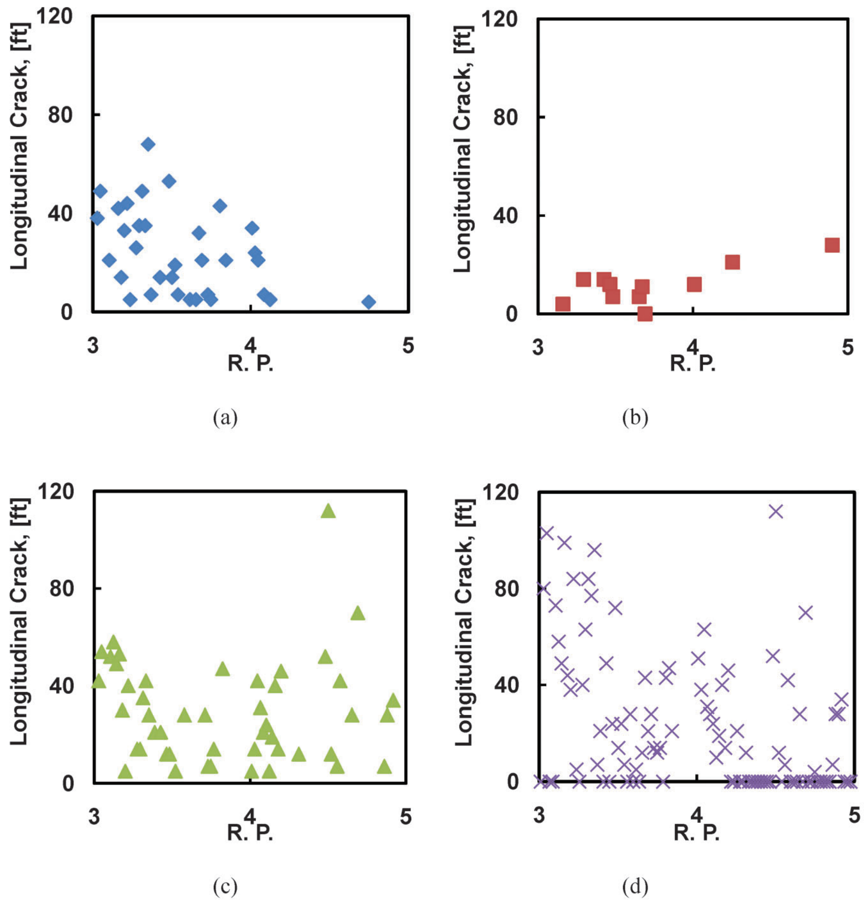


Figure 3.11 Extent of longitudinal crack by location: (a) left wheel path; (b) center of lane; (c) right wheel path; (d) total extent of longitudinal crack.

the intact samples are not significantly different from that of the damaged samples.

Another validation for FWD results was conducted using surface distresses on the test section. The surface distress survey in Chapter 3.3.1 resulted in that the pavement section between R.P. 4 to 5 contained more potholes and patched areas while the pavement section between R. P. 3 to 4 had higher number of longitudinal and fatigue cracks. The average FWD stiffness and surface deflection were 247.9 ksi and 12.86 mils and 283.8 ksi and 12.06 mils for the first and the second 1 mile sections, respectively. Differences in the stiffness and the deflection between the sections were determined to be statistically insignificant. Consequently, the FWD results have a lack of correlation with the surface distresses.

3.4.3 Laboratory Test

Visual observation. Visual observation was made on core samples to identify layer thicknesses and to investigate any damage on them. As shown in Figure 3.15, the thickness of full depth asphalt was approximately 12 in. Three interfaces were identified in most core samples by visual inspection. The layer interface depths from their surface were approximately 1.5 in., 6 in., and 9 in. These layers were labeled with Layer 1, Layer 2, and Layer 3 from the surface. Layer 1 included a microsurfacing layer and a HMA surface course placed in 1992.

The visual observation found 14 out of 28 core samples were damaged. There were two typical layers with damage, which are near surface and approximately 4 in. to 6 in. deep as shown in Figure 3.15. The probable causes of damage were structural defect, material problem, or over-stress from the coring process. This study assumed the influence of coring process is minimal.

Figure 3.16 presents the typical cut-faces of layers. Aggregate sizes of layers were determined to be 9.5 mm, 19.0 mm, and 25.0 mm NMASs for Layer 1, Layer 2, and Layer 3, respectively. There was an unidentified layer beneath Layer 3 with gasoline-like smell. This layer was excluded in this study because of its severe disturbance from the core drilling process.

Air voids. Amount of air voids in asphalt mix is important information for interpreting its mix condition. Percent air voids were calculated using G_{mm} and G_{mb} of cores. G_{mm} for each layer was obtained as 2.45, 2.49, and 2.44 for Layer 1, Layer 2, and Layer 3, respectively. It should be noted that the

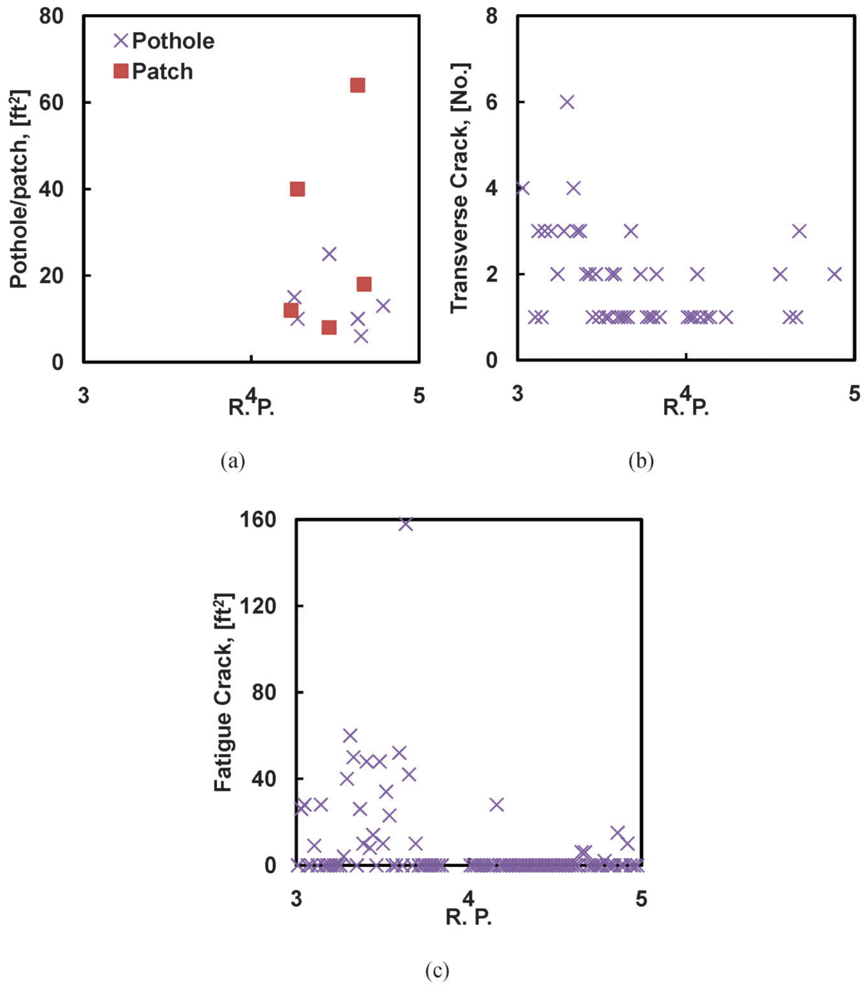


Figure 3.12 Extent of surface distress by location: (a) pothole/patch; (b) transverse crack; (c) fatigue crack.

measured 2.44 G_{mm} for Layer 3 (25.0 mm NMAS) was remarkably lower than 2.514 G_{mm} that for the typical Indiana 25.0 mm NMAS mix from 166 Indiana Job Mix Formulas used between 2005 and 2007.

Figure 3.17 (a) shows air void distribution in terms of depth over the 2-mile test section. Air voids in percentage points are displayed in different colors. The blue and red color corresponds to 0% and 14% air voids, respectively. It should be noted that all plots in Figure 3.17 are not to scale; x-axis is in mile and y-axis is in inch. The surface layer has higher air voids then other subsequent layers and air voids generally decrease as layer depth increases. Throughout the entire section, higher air voids were only observed in Layer 1, and there are three locations with higher air voids, which are located around R.P. 3, 3.5 and 4.75.

Table 3.5 presents average air voids in terms of depth at wheel paths. The core samples from right wheel path showed higher air voids then that from left wheel path in all layers. However, a t-test with a 95% confidence interval showed that air voids difference between wheel paths were not statistically different except Layer 1.

Indirect tensile test. A distribution of IDT tensile strengths in the test section is presented in Figure 3.17 (b), which is not drawn to scale. The color blue and red

TABLE 3.2
Summary of distress extent and coverage over the test section

Distress Type	Total Extent	Coverage	Coverage (length-based)
Longitudinal Crack	2,320 ft	22.0%	22.0%
Fatigue Crack	795 ft^2	0.6%	2.5%
Transverse Crack	83	127 ft (crack to crack space)	15.7%
Pothole	11N, 79 ft^2	0.1%	1.51%
Patch	3, 142 ft^2	0.1%	0.4%

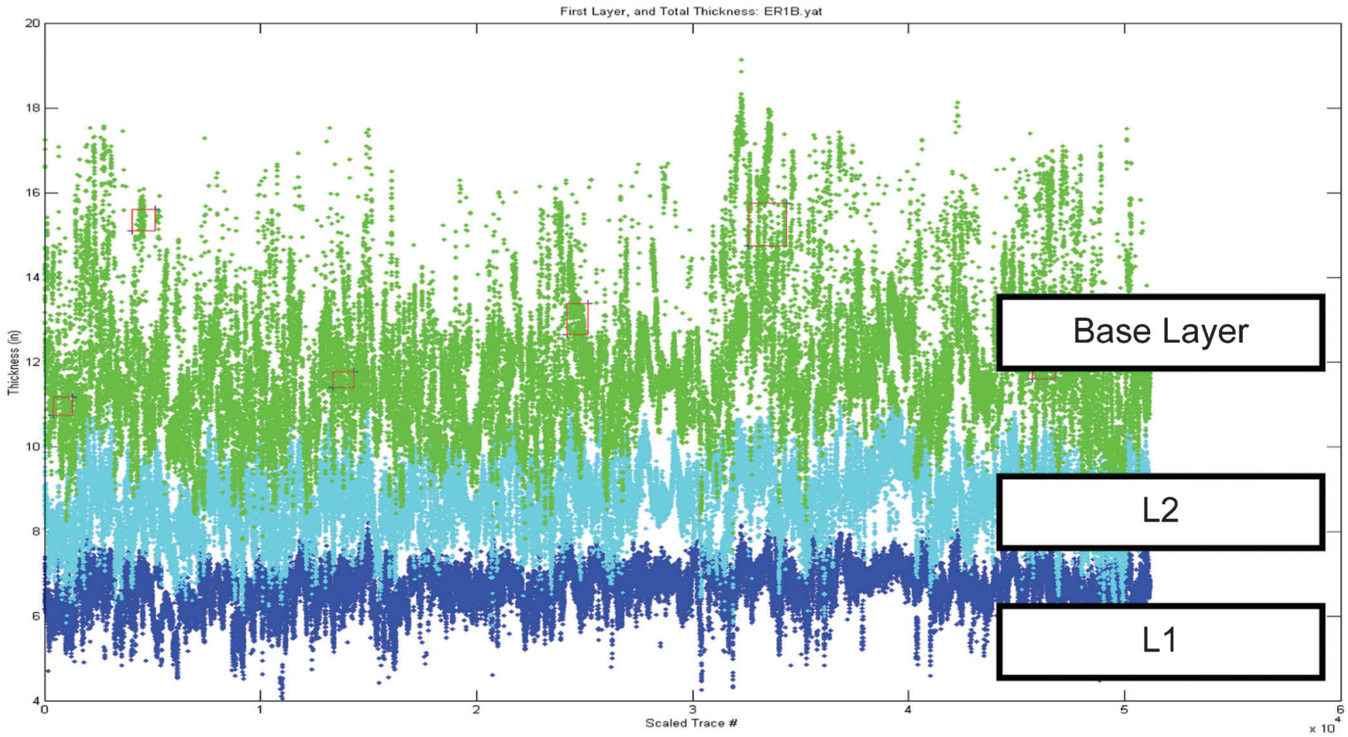


Figure 3.13 GPR layer interface detection result.

corresponds to 0 psi and 239 psi strength, respectively. A core layer sample with tensile strength of 0 psi denotes one with damages within the layer. Overall, Layer 1 showed higher tensile strength than that of Layer 2 and 3; however, tensile strengths in Layer 2 and 3 were more uniform throughout test section. Additional observation made was that Layer 1 around R. P. 3.5 and 4.8 shows relatively high air voids and low tensile strength.

Table 3.6 presents average tensile strengths in terms of depth at wheel paths. The deeper layers had the lower tensile strength at both wheel paths. A t-test result showed that tensile strengths between the wheel paths were not statistically different in all layers.

Figure 3.18 shows correlation between air voids and tensile strength of core specimen for each layer. Layer 1 and Layer 2 showed the higher air voids showed the lower tensile strength except for Layer 2. Overall correlation showed that the tensile strength was inversely proportional to the air voids with poor correlation coefficient ($R^2 = 0.155$). This concludes that the air voids as a physical property are not a main factor affecting the tensile strength as a mechanical property.

TABLE 3.3
Summary of problem location coverage over the test section

	Coverage		
	Left Wheel Path	**Right Wheel Path**	**Total**
L1 (Layer 1 + Layer 2)	7.25%	4.99%	11.81%
L2 (Layer 3)	9.35%	8.15%	16.96%
Total	13.6%	9.95%	20.5%

Water stripping. The water stripping test using DIA (details in Ch. 3.3.2) was applied to the core samples, which were damaged and broken from the coring process explained in the Visual Observation Chapter. It was found that all damaged faces of the samples showed the signs of water stripping and the water stripping test resulted in the severity range from 18% to 53%, as shown in Figure 3.19 and Table 3.7. The results confirm that the test section of SR-70 has the water stripping problem. It should be noted that “X” and “O” represent sample locations with and without water stripping, respectively in Table 3.7.

Additional water stripping test were carried out on split faces of IDT specimens and resulted in that the average severities were 14.5%, 37.2%, and 32.2% for Layer 1, Layer 2, and Layer 3, respectively, as shown in Table 3.8. The severity ranged from 3.5% to 64%. The water stripping damage was found to be more severe in Layer 2 and 3, as shown in Figure 3.17 (c). It also shows that high severities of water stripping are only shown in certain depths throughout the test section, which are 2 in., 4 in. and 7 in. deep. When compared the location of high severities of water stripping to that of higher air voids and low strength; however, it did not show good correlations.

The observation showed that the samples from right wheel path showed the higher severity in all three

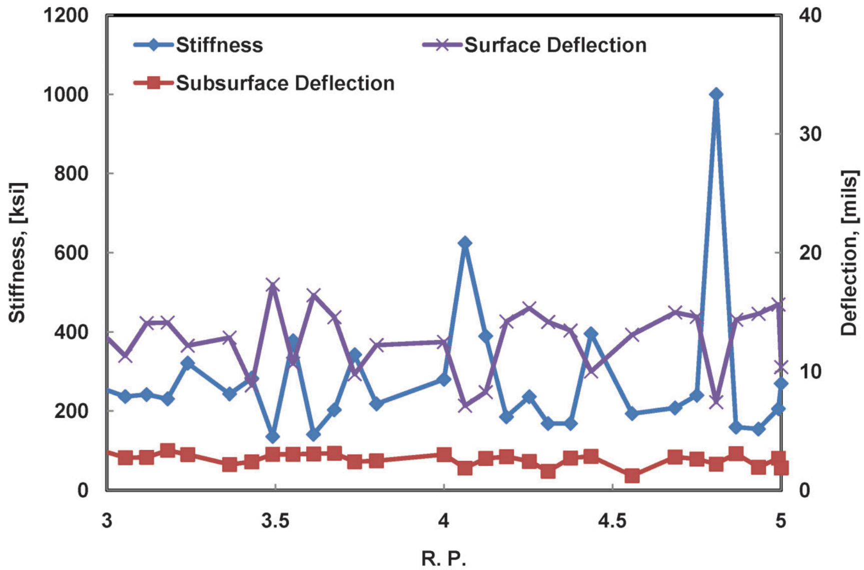


Figure 3.14 FWD test results from June, 2010.

TABLE 3.4
Statistical comparison of stiffness and deflections

		Stiffness, ksi	Surface D, mils	Subsurface D, mils
Avg. (Std.)	**Sound**	306 (229)	12.7 (2.52)	2.5 (0.62)
	Fail	251 (73.8)	13.1 (1.62)	2.5 (0.85)
Overall Avg. (Std.)		297 (212)	12.8 (3.22)	2.5 (0.64)
t-Test (p-value)		0.53 (0.6)	0.25 (0.8)	≈0 (1.0)
Results		Not different	Not different	Not different

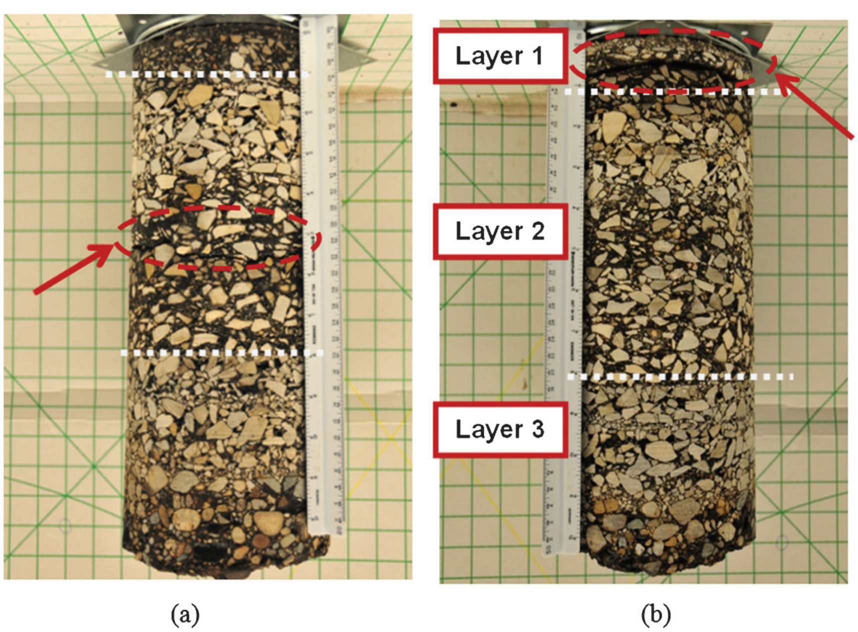
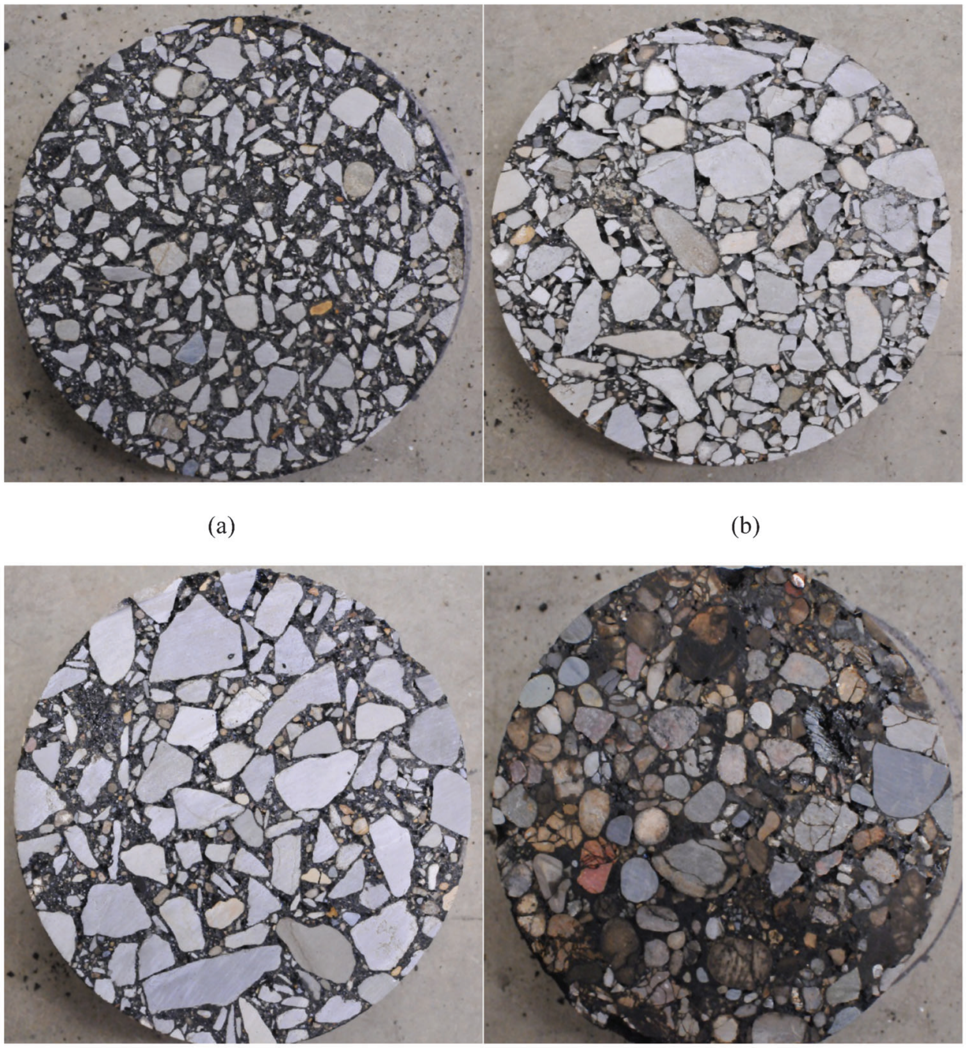


Figure 3.15 Core samples with damage: (a) mid-depth damage; (b) near surface damage.



(a) (b)

(c) (d)

Figure 3.16 Cut-faces of layers: (a) Layer 1 (9.5 mm); (b) Layer 2 (19.0 mm); (c) Layer 3 (25.0 mm); (d) Unidentified layer.

layers. However, t-test showed that they were not statistically different in all three layers, as shown in Table 3.8. Based on the definitions of water stripping severity levels of Virginia DOT, a percentage of stripping higher than 50% is considered to be most severe level. This case study had four samples with the severity over 50%. Figure 3.20 shows two core layer specimens as examples with the water stripping severity of 3.5% and 64%, which were the lowest and highest severities observed from core layer samples, which were damaged and broken.

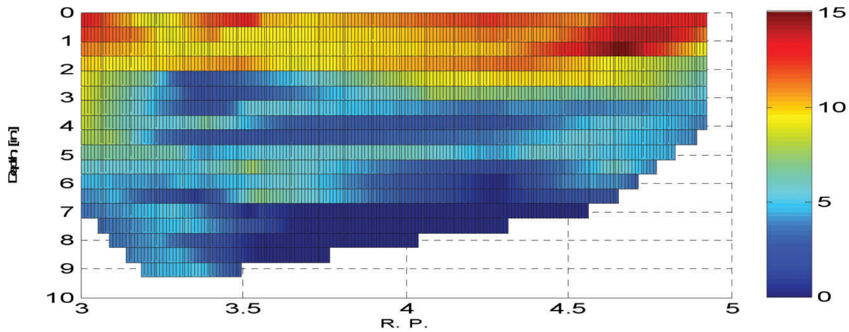
Correlations among water stripping severity, air voids, and tensile strength were examined as shown in Figure 3.21 and Figure 3.22. When the water stripping severities are compared to tensile strengths, Layer 1, Layer 2, and overall layers showed inverse proportion except Layer 3. However, R^2 values for all three layers were too small to be significant. In the same manner, the water stripping was also compared to air voids and only Layer 1 showed good correlation. Moreover, overall layers showed very poor correlation between them. Therefore, it can be concluded that there were insignificant correlations among the water stripping severities, air voids, and tensile strengths in the condition used in this study.

3.5 Evaluation of NDT Test Methods

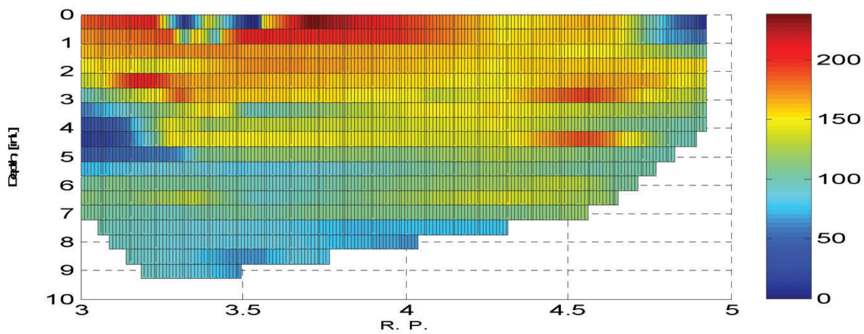
This chapter mainly presents multiple comparisons among laboratory test results (i.e., air voids, tensile strength, and the water stripping severity) on core samples, surface distresses, and NDT results.

3.5.1 Problem Location Determination Based on Laboratory Results

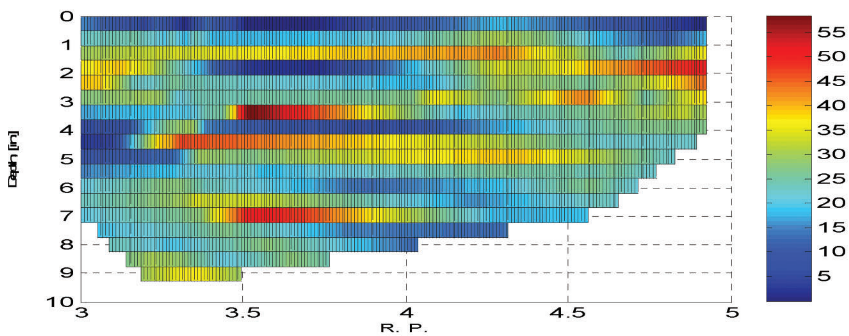
A single GPR measurement at a certain location does not provide interpretable information. Therefore, a relative comparison with a binary logistic approach in a series of GPR measurements was used for detecting



(a)



(b)



(c)

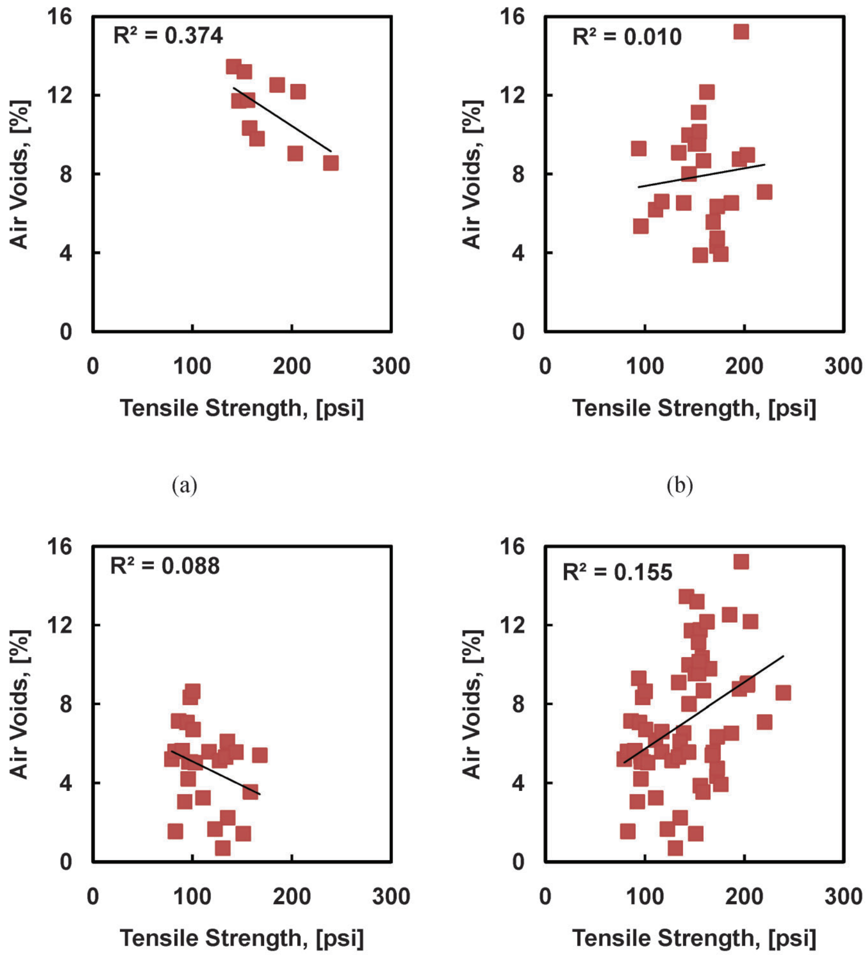
Figure 3.17 Core layers laboratory test results over test section: (a) air voids; (b) tensile strength; (c) water stripping severity.

TABLE 3.5
Average air voids in terms of depth at wheel paths and statistical comparison between wheel paths

Layer	Overall	Left Wheel Path	Right Wheel Path	P-value
1	11.42%	9.75%	12.08%	0.007
2	7.91%	6.99%	8.34%	0.26
3	4.76%	4.00%	5.02%	0.27

TABLE 3.6
Average tensile strengths in terms of depth at wheel paths and statistical comparison between wheel paths

Layer	Overall	Left Wheel Path	Right Wheel Path	P-value
1	125 psi	146 psi	117 psi	0.59
2	157 psi	143 psi	164 psi	0.14
3	109 psi	103 psi	124 psi	0.14



(a) (b)

(c) (d)

Figure 3.18 Air voids vs. tensile strength: (a) Layer 1; (b) Layer 2; (c) Layer 3, (d) overall layers.

(a) (b)

Figure 3.19 Damaged faces in core samples: (a) 18% severity; (b) 53% severity.

TABLE 3.7
Overview of core conditions and water stripping severity results

R. P.	Left W. P.	Depth/Water Stripping Severity	Center of Lane	Depth/Water Stripping Severity	Right W. P.	Depth/Water Stripping Severity
3.004			O		X	5.5 in./34%
3.198			X	4 in./29%	O	
3.227	O		O			
3.317	X	1.25 in./24%	O			
3.387			X	4.75 in./31%	O	
3.515			O		X	1.5 in./32%
3.543			X	5.5 in./43%	X	1.5 in./37%
3.551	O		X	1.25 in./37%		
3.697	O		O			
4.275	X	1.25 in./18%				
4.282			O		O	
4.55			X	7.5 in./28%	O	
4.65			X	4 in./26%	O	
4.926			O		X	1.5 in./53%

TABLE 3.8
Average water stripping severity in terms of layer at wheel paths and statistical comparison between wheel paths

Layer	Overall	Left Wheel Path	Right Wheel Path	P-value
1	14.5%	3.5%	18.9%	0.86
2	37.2%	20.6%	45.4%	0.79
3	32.2%	28.7%	33.5%	0.12

pavement locations having subsurface problems as explained in Ch. 3.4.2. Accordingly, to make fair comparisons and to verify each test used in this study, the binary logic was used for categorizing the laboratory test results into two groups for defining sound and problem core samples (e.g., high air voids content, low tensile strength, high water stripping severity).

High air voids. The air void distribution varies in terms of layers due to difference in types of asphalt mix and subsurface stress distribution from traffic loadings, as shown in Figure 3.23. Thus, the air voids within each layer were evaluated to find its abnormality and to define a significance level that may potentially have problems in pavement performance. Even though 5% is a widely accepted significance level in statistics, this study selected 10% because of lack of data from a limited number of samples at 5%. In other words, a sample having air voids above 90th percentile of its distribution represents a poor performance sample.

Table 3.9 shows core sample locations having high air voids in the test section for L1 (Layer1 and 2) and L2 (Layer 3). It was assumed that locations with high air voids in any layer have high potential for poor performance. "O" represents the presence of high air voids. The first 1 mile section had more problem locations than the second 2 mile section. In addition, there were less core locations with higher air voids in L2 (Layer 3).

Low tensile strength. The tensile strengths in the layers were evaluated to define problem locations. The

(a) (b)

Figure 3.20 Example of water stripping severity: (a) 3.5% severity; (b) 64% severity.

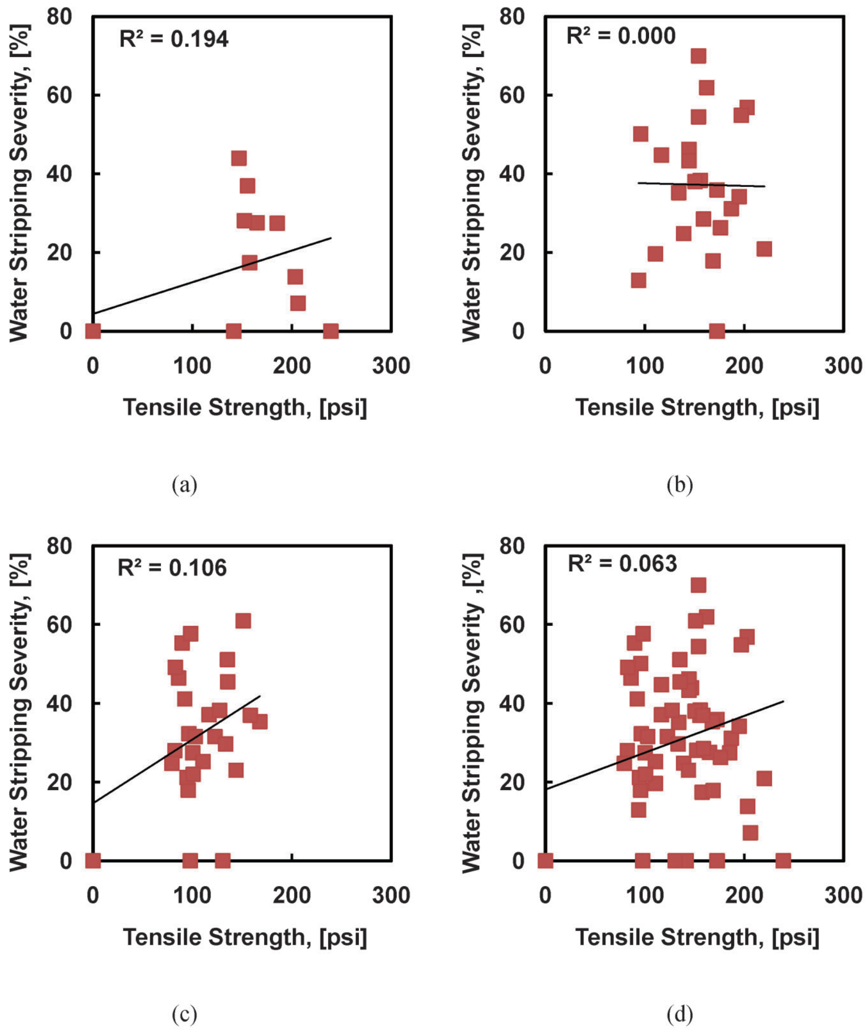


Figure 3.21 Correlation between water stripping severity and tensile strength by layer: (a) Layer 1; (b) Layer 2; (c) Layer 3; (d) Overall layers.

overall average tensile strength was 130 psi with a standard deviation of 53 psi. Based on the tensile strength rating, tensile strength of 80 psi or higher are considered to be good. The problem locations were then defined to be ones with tensile strength of lower than 80 psi, and the 80 psi approximately corresponds to the low 10th percentile. Table 3.10 shows core sample locations having low tensile strengths in the test section for L1 (Layer1 and 2) and L2 (Layer 3). It was interesting to note that all core samples with low tensile were found to be located in L2.

High severity of water stripping. Problem locations based on water stripping severity in the layers were determined. The rating for water stripping severity defines the poor to be 40% or higher. Overall, the average of severity was 25% and 10% of core layer samples fall in the poor rating based on its normal distribution. The problem locations indicated by "O" with high severity of water stripping are shown in Table 3.11.

3.5.2 Comparison of Test Results

Surface distresses and laboratory test results. Locations of samples with higher air voids, low tensile strength and high severity of water stripping were compared to locations with pothole, patch, and fatigue crack, as shown in Table 3.12. Longitudinal crack was excluded in the comparison analysis because 12 out of 14 core locations have the longitudinal crack. Thus, the results are not comparable in this analysis. A number of problem locations in the test section were 11, 5, and 7 for high air voids, low strength, and high severity of water stripping, respectively. In addition, the number of locations with distress was seven. The probabilities that a surface distress matches a location with poor condition determined by high air voids, low strength, and high severity of water stripping were 1.0 (7 out of 7), 0.29 (2 out of 7) and 0.57 (4 out of 7), respectively. Thus, the probabilities of a surface distress on one of poor conditions and on all poor conditions determined by the laboratory tests were 1.0 and 0.17, respectively.

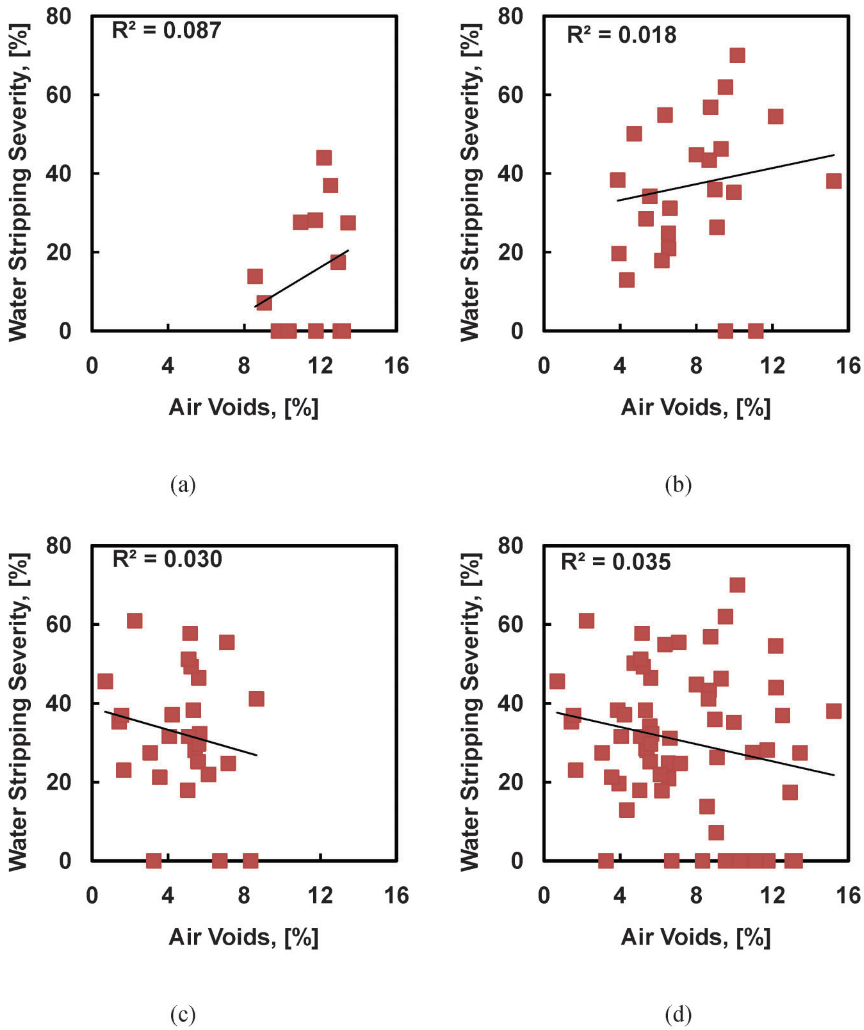


Figure 3.22 Correlation between water stripping severity and air voids by layer: (a) Layer 1; (b) Layer 2; (c) Layer 3; (d) Overall layers.

GPR and laboratory test results. The problem locations based on the laboratory results and the GPR analysis were compared by the layer, as shown in Table 3.13 and Table 3.14. The probabilities that a problem location determined by GPR matches a location with poor condition determined by high air voids, low strength, and high severity of water stripping were 1.0 (6 out of 6), 0.0 (0 out of 6), and 0.67 (4 out of 6) for L1, respectively. In case of L2, the matching rates were 0.29 (2 out of 7), 0.29 (2 out of 7), and 0.43 (3 out of 7), respectively. The high air voids and the low tensile strength showed the highest and the lowest matching rates, respectively. Overall, the probability that a location determined to be problematic by GPR to be on one of the poor conditions based on lab tests was 1.0.

FWD and laboratory test results. A FWD deflection at each location represents a structural integrity of all layers in pavement. In order to make the laboratory results comparable to the FWD, one representative laboratory value at each core location was required.

Weight factors in terms of depth were developed for calculating the representative laboratory values for locations. A multilayer elastic solution (i.e., Kenpave) was used to calculate vertical stress changes in terms of depth in pavement. The stress is used for determining the weight factor used for each layer. The pavement structure was simulated under a standard 18-kip single axle load with 88 psi tire pressure; layer thickness measured form the core specimens; and Poisson's ration of 0.35. Figure 3.24 (a) shows calculated vertical stress reduction over a range of depth from 0 in. (surface) to 100 in. Below the depth of 72 in., vertical stress was determined to be less than 1 and vertical stress below that depth were assumed to be negligible. In order to determine how much stress was applied over different depth, weight factor was calculated using Equation 3.3, as shown in Figure 3.24 (b)

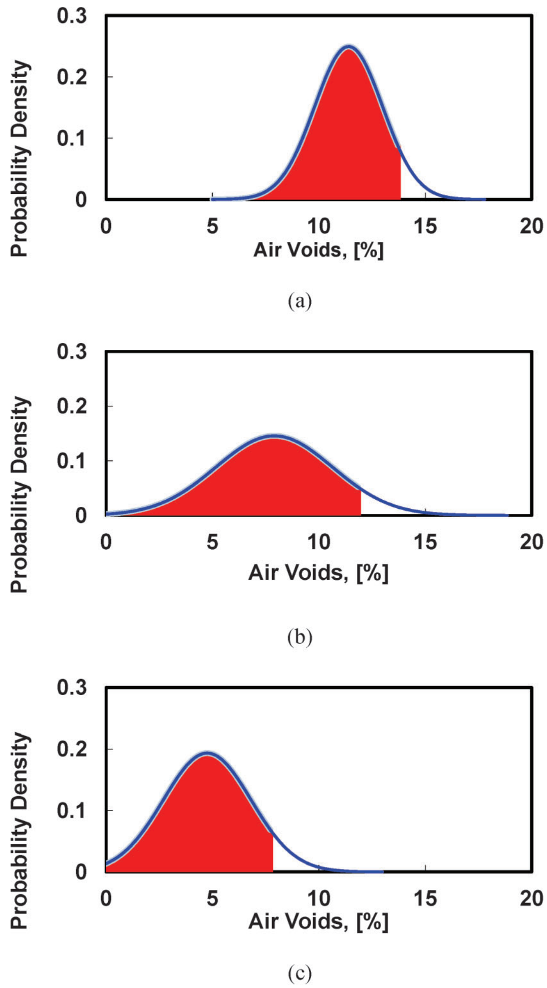


Figure 3.23 Air voids distributions and 90th percentiles by layer: (a) Layer 1; (b) Layer 2; (c) Layer 3.

$$\text{Weight factor}_d = \frac{\text{Vertical stress}_d}{\sum_{d=0\text{ in.}}^{72\text{ in.}} \text{Vertical stress}_d} \times 100 \qquad (3.3)$$

The representative value for each core location was calculated by summing laboratory test values multiplied by the weight factors for corresponding layer depth. Weighted air voids, weighted tensile strength, and weighted water stripping severity for each location were compared to the FWD surface deflection, as shown in Figure 3.25. It should be noted that there were 7 out of 14 core locations which coincided with the FWD test locations, thus, there were less data points plotted for each plot. The R^2 values for the correlations of the FWD results with air voids, tensile strength, and water stripping severity were 0.175, 0.021, and 0.205, respectively. In other words, they had a very weak correlation.

Surface distress and NDT results. Fatigue cracks, potholes, or patches were compared to the GPR analysis results. The GPR analysis identified problem locations with total length of 2,203 ft long in the test section. Comparing the problem locations determined by GPR to the locations of surface distresses, they are overlapped by approximately 19%. It is noteworthy that no comparison analysis could be made between the surface distresses and the FWD results since only one location showed fatigue crack among the FWD locations.

3.5.3 Test Method Evaluation Summary

- Laboratory test result correlation: The study showed poor correlations among the water stripping severities, air voids, and tensile strengths. Thus, the air voids or tensile strength cannot properly estimate the water stripping severity or vice versa.
- Surface distress and GPR results vs. laboratory test results: The probabilities of a surface distress and a GPR based location on one of the poor conditions determined by the laboratory tests was 1.0. Accordingly, it was concluded that the surface distresses and the GPR were reliable indicators to evaluate the subsurface condition.
- FWD vs. laboratory test results: The R^2 values for the correlations of the FWD results with air voids, tensile strength, and water stripping severity were 0.175, 0.021, and 0.205, respectively. Consequently, since they had a weak correlation, which is possibly due to fairly long testing interval (i.e., 328 ft), the FWD test protocol is not recommended for evaluating the subsurface condition

TABLE 3.9
Core locations with higher air voids

	High Air voids			High Air voids	
	L1	L2		L1	L2
R. P.	(Layer 1 and 2)	(Layer 3)	R. P.	(Layer 1 and 2)	(Layer 3)
3.004	O	O	4.275	O	O
3.198			4.282	O	
3.227			4.55		
3.317	O		4.65	O	
3.387	O	O	4.926	O	
3.515	O	O			
3.543	O	O			
3.551	O	O			
3.697	O				

TABLE 3.10
Core locations with low tensile strengths (less than 80 psi)

	Low Tensile Strength			Low Tensile Strength	
	L1	L2		L1	L2
R. P.	(Layer 1 and 2)	(Layer 3)	R. P.	(Layer 1 and 2)	(Layer 3)
3.004		O	4.275		O
3.198			4.282		
3.227			4.55		
3.317			4.65		
3.387		O	4.926		
3.515					
3.543					
3.551		O			
3.697		O			

TABLE 3.11
Core locations with high severity of water stripping

	High Severity of Water Stripping			High Severity of Water Stripping	
	L1	L2		L1	L2
R. P.	(Layer 1 and 2)	(Layer 3)	R. P.	(Layer 1 and 2)	(Layer 3)
3.004	O		4.275	O	O
3.198			4.282		
3.227			4.55	O	
3.317		O	4.65		
3.387		O	4.926	O	
3.515	O	O			
3.543					
3.551					
3.697					

TABLE 3.12
Comparison of laboratory test results to surface distresses and GPR results

R. P.	High Air Voids	Low Strength	High Severity of Water Stripping	Pothole/Patch/Fatigue Cracks
3.004	O	O	O	
3.198				
3.227				
3.317	O		O	O
3.387	O	O	O	O
3.515	O		O	O
3.543	O			O
3.551	O	O		
3.697	O	O		
4.275	O	O	O	O
4.282	O			O
4.55			O	
4.65	O			O
4.926	O		O	

TABLE 3.13
Comparison of laboratory test results to GPR results for L1

R. P.	High Air Voids	Low Strength	High Severity of Water Stripping	GPR Analysis
3.004	O		O	O
3.198				
3.227				
3.317	O			O
3.387	O			
3.515	O		O	O
3.543	O			O
3.551	O			
3.697	O			
4.275	O		O	O
4.282	O			
4.55			O	
4.65	O			
4.926	O		O	O

TABLE 3.14
Comparison of laboratory test results to GPR results for L2

R. P.	High Air Voids	Low Strength	High Severity of Water Stripping	GPR Analysis
3.004	O	O		
3.198				O
3.227				O
3.317			O	O
3.387	O	O	O	
3.515	O		O	O
3.543	O			
3.551	O	O		
3.697		O		O
4.275	O	O	O	O
4.282				
4.55				
4.65				O
4.926				

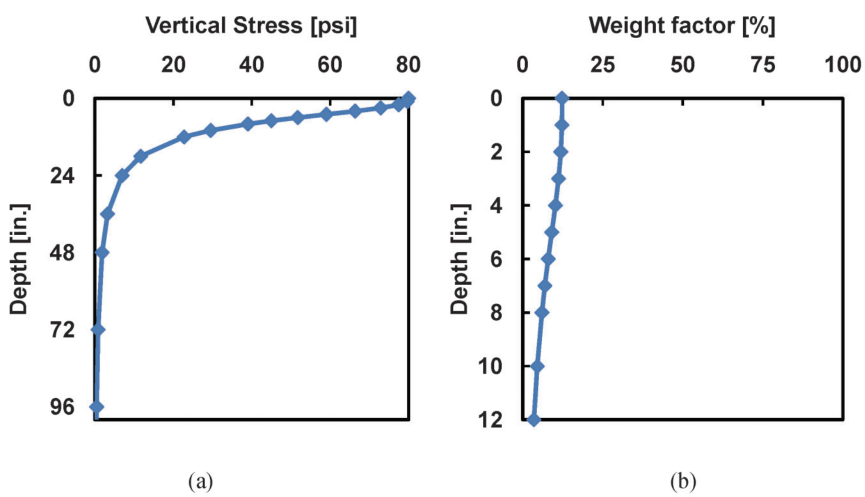


Figure 3.24 Kenpave analysis result on vertical stress over depth: (a) vertical stress change over depth; (b) percent vertical stress change over depth.

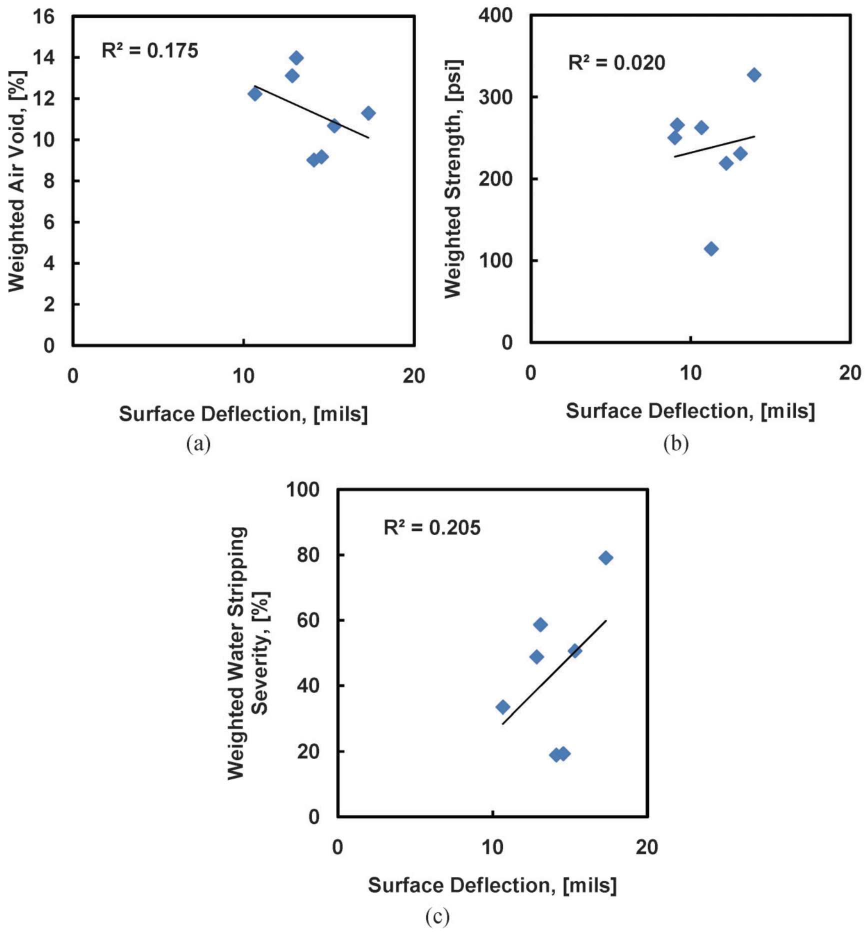


Figure 3.25 Plot of weighted laboratory test results and surface deflection: (a) weighted air voids, (b) weighted tensile strength; (c) weighted water stripping severity.

determined by high air voids, low strength, or high severity of water stripping.

- GPR vs. surface distress: The GPR analysis identified problem locations with a total of 2,203 ft long in the test section. Comparing the problem locations determined by GPR to the locations of surface distresses, they are overlapped by approximately 19%. This low correlation indicates that the GPR and the surface distress should be interpreted with the laboratory test results to improve the accuracy level of their estimations.

4. GUIDELINES OF SUBSURFACE CONDITION EVALUATION FOR PAVEMENT PRESERVATION TREATMENTS

4.1 Guideline Overview

This guideline provides a project level tool for subsurface evaluation of asphalt pavements for the applicability of pavement preservation treatments (PPTs), including seal coat, microsurface, ultrathin bonded wearing course (UBWC), and 4.75 mm HMA overlay, etc. The evaluation defines severity of subsurface distresses, quantifies their coverage (extent) and distribution in a project using ground penetration radar (GPR) test or surface distress, and laboratory tests. An evaluation process developed through JTRP/SPR-3507 consists of five major steps, including preliminary assessment (checklist); analysis level selection and core location determination; layer determination, laboratory tests; and test result analysis, as shown in Figure 4.1. Details of each step are in the following sections.

4.2 Evaluation Procedure

4.2.1 Site Selection

This step involves the collection of information regarding location, pavement history, design values, and any existing data upon the selection of test site. The specific portion or lane should be selected if the entire test section is not subject to subsurface condition evaluation. The length of a test section can be up to five miles long. A section longer than five miles should be divided by multiple subsections, where the length of each subsection should not be longer than five miles.

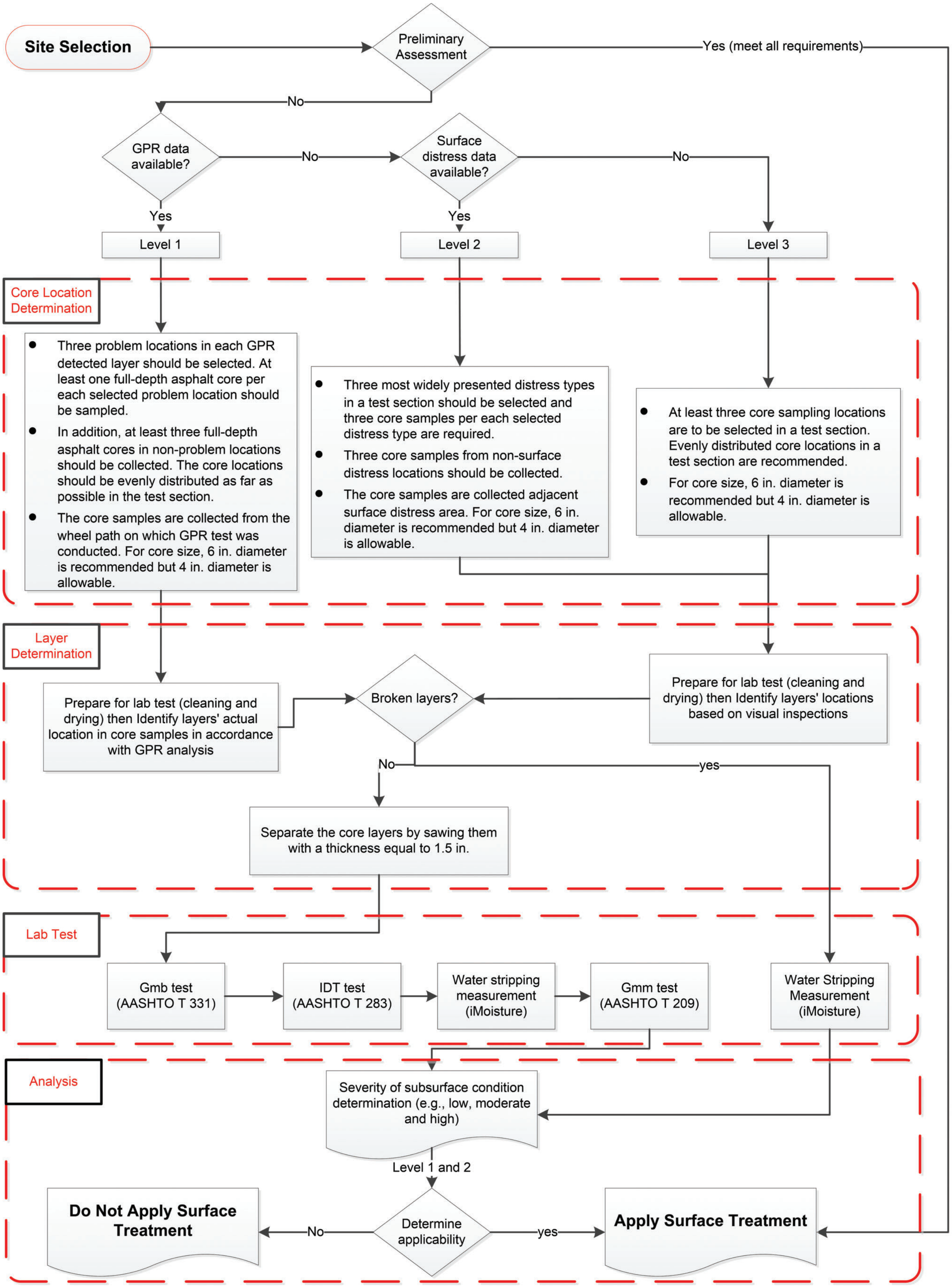


Figure 4.1 Schematic of evaluation process.

Date		**Engineer**	
District		**Subdistrict**	
Road Name			
From Location		**From R. P.**	
To Location		**To R. P.**	
Lane Direction	**North, South, East, West**	**Lane Location**	**Passing Lane, Driving Lane**

No or little patching and other repairs (less than 10 % of area)	☐
No alligator crack in wheel path	☐
No or little longitudinal crack in wheel path (less than 265 ft / mile or 5 %)	☐
Transverse crack spacing more than 120 ft	☐
No or little shoving in wheel path (less than 10 % of area)	☐
No sign of water stripping	☐
No water bleeding or pumping	☐

Figure 4.2 Preliminary assessment of pavement subsurface condition evaluation for pavement preservation treatment (checklist).

4.2.2 Preliminary Assessment (Checklist)

This preliminary assessment aids for assessing adequacy of pavement condition for the application of PPTs based on the information obtained from a visual inspection of surface distress on the test section. The pavement is considered to be a good candidate if it meets all categories as shown in Figure 4.2. Otherwise, a further examination of the pavement is required to assess the adequacy.

4.2.3 Analysis Level Determination

The general approach for selecting or determining evaluation inputs for the evaluation is a hierarchical level system. The system is based on the philosophy that the level of engineering effort exerted in the pavement subsurface evaluation process should be consistent with the relative importance, size, and cost of the project. Level 1 is the most comprehensive procedure, involving laboratory and GPR tests. In case of Level 2, pavement distress surveys with the laboratory tests are conducted. In contrast, Level 3 requires only the laboratory tests to be conducted on randomly sampled cores and provides the most simplified results among 3 analysis levels. It should be noted that Level 1 analysis should be performed if both Level 1 and Level 2 are applicable for the project.

Level 1

- GPR data identifies problem locations in terms of layers in a test section by selecting areas with relatively high discrepancies in their dielectric values measured between layers. It should be noted that the GPR data should be collected from the right wheel path. Three problem locations in each GPR detected layer should be selected. At least one full-depth asphalt core per each selected problem location should be sampled. In addition, at least three full-depth asphalt cores from non-problem locations should be collected. The core locations should be evenly distributed as far as possible in a test section. All core samples are collected from the right wheel path on which GPR test was conducted. For core size, 6 in. diameter is recommended but 4 in. diameter is allowed.

Level 2

- Mapping surface distress by visual inspection or 3D laser scanner (available at the INDOT Research and Development) is required for Level 2 analysis. Types of distresses considered in the analysis are crack, pumping, potholes, and patch. Distress measurements should be presented as length (linear feet) in longitudinal direction. Up to three most widely presented distress types in a test section should be selected and three core samples per each selected distress type are required for the test. Three core samples from non-surface distress locations should be collected. The core samples are collected from the area, which is adjacent to the surface distress area.

Level 3

- At least three core sampling locations are to be selected in a test section. Evenly distributed core locations in a test section are recommended.
- For core size, 6 in. diameter is recommended but 4 in. diameter is allowed.

4.2.4 Layer Determination

Once the collected core samples are cleaned and dried, visual inspection is conducted to identify layers and exam any broken layer existence in core samples.

Level 1

- Based on GPR analysis and visual inspection, identified layers are located and marked on the surface of each core sample.
- Each core sample is then inspected for broken layers. If found, record the core sample and layer number. Only water stripping severity test is conducted for core layer specimen containing broken layer.
- Test specimen, 6 in. or 4 in. of diameter with1.5 in. of thickness, should be obtained from middle of each layer. A specimen thickness range from 1.0 in and 1.5 in. is acceptable in case of a layer thickness shorter than 1.5 in. and thicker than 1 in. For a layer thickness shorter than 1in., a specimen should be prepared with combining an adjacent layer (e.g., a combination of microsurface layer with surface course) to meet the thickness requirement.

Level 2 and Level 3

- By visual inspection of each core sample, interface(s) should be located first. Available construction documents can be a good reference in identifying different layers.
- Thickness of each layer should be recorded.
- Each core sample is then inspected for broken layers. If found, record the core sample and layer number. Only water stripping severity test is conducted for core layer specimen containing broken layer.
- Test specimen, 6 in. or 4 in. of diameter with1.5 in. of thickness, should be obtained from middle of each layer. A specimen thickness range from 1.0 in and 1.5 in. is acceptable in case of a layer thickness shorter than 1.5 in. and thicker than 1 in. For a layer thickness shorter than 1in., a specimen should be prepared with combining an adjacent layer (e.g., a combination of microsurface layer with surface course) to meet the thickness requirement.

4.2.5 Laboratory Test

Asphalt Mix Bulk Specific Gravity Test (AASHTO T 331). The bulk specific gravity test should be conducted for each core layer specimen according to AASHTO T 331. AASHTO T 209 can also be used for the measurement of bulk specific gravity only if CoreLok® is not available (*1,2*).

Indirect Tension Test (AASHTO T 283). The tensile strength of each core layer specimen is tested according to AASHTO T 283 without conditioning (*3*). The loading rate is 2 in. per min. Upon completion of IDT test, digital image of split surface should be taken.

Water Stripping Severity Measurement (iMoisture). The water stripping severity is measured on core layer specimen using iMoisture. For additional information regarding the usage of software, refer to the iMoisture user's manual (Appendix G).

Asphalt Mix Theoretical Maximum Specific Gravity Test (AASHTO T 209). The maximum specific gravity should be determined from the materials of at least two replicates from the same core sampling location.

Laboratory Test Data Record (iSub). Laboratory test results as well as general information of the test section for each specimen should be recorded for analysis. Figure 4.3 represents the form which may be used in recording data. The test data can be recorded using iSub explained in later chapter.

4.2.6 Analysis

Condition Rating. In order to determine the subsurface condition, the laboratory test results should be properly interpreted, core sample with higher air voids, lower tensile strength, high water stripping can have higher probability of poor performance. Accordingly, the results of laboratory tests were converted into three conditions; good, fair, and poor conditions.

Air voids. Prior to the adoption of Percent Within Limit (PWL), 8% air voids corresponded to a pay factor of 1 for a dense-graded mixture in the INDOT asphalt QC/QA. Furthermore, generally, air voids less than approximately 8% in an asphalt mix are known as good condition. Therefore, the condition ratings for air voids to dense-graded type of mixture are the following:

- Good condition $\leq$ 8%
- 8% $<$ Fair condition $\leq$ 10%
- Poor condition $>$ 10%

Tensile strength. The rating for the tensile strength was constructed based on the Illinois DOT's guideline as the same test method (modified AASHTO T 283) was utilized by their guideline (*25,26*). Illinois guideline defines tensile strength of 80 psi or higher to be good and 30 psi or lower to be poor. Those values were selected and the final rating guideline was determined as follows:

- Good condition $>$ 80 psi
- 50 psi $<$ Fair condition $\leq$ 80 psi
- Poor condition $\leq$50 psi

Water stripping severity. The rating for the water stripping severity was determined based on the laboratory test results. As the rating consists of three levels, two threshold values were selected. By the

Date		Engineer		From Location		From R. P.	
District		Subdistrict		To Location		To R. P.	
Road Name				Lane Direction		Lane Location	

□ Level 1		□ Level 2		□ Layer 3
□ Problem Location		□ Problem Location		
□ Non-problem Location		□ Non-problem Location		
		Distress Type		

		1						2						3					
		R. P.						R. P.						R. P.					
Layer No.		TS[1] [psi]	WS[2] [%]	AV[3] [%]	G_{mb}	G_{mm}	B[4] [y/n]	TS[1] [psi]	WS[2] [%]	AV[3] [%]	G_{mb}	G_{mm}	B[4] [y/n]	TS[1] [psi]	WS[2] [%]	AV[3] [%]	G_{mb}	G_{mm}	B[4] [y/n]
1	Mid Layer Depth (in.)																		
2	Mid Layer Depth (in.)																		
3	Mid Layer Depth (in.)																		
4	Mid Layer Depth (in.)																		
5	Mid Layer Depth (in.)																		

TS[1]: Tensile Strength, WS[2]: Water Stripping Severity, AV[3]: Air Voids, B[4]: Broken Sample

Figure 4.3 Laboratory testing results form.

inspection of core samples, as shown in Table 3.7, the minimum severity which damaged core surface showed was 18%. The good rating was then defined to be the one with the water stripping severity less than 18%. On the other hand, the severity above 90th percentile was 40.4% in its normal distribution, as shown in Figure 4.4. The severity of 40% was selected to be the other threshold value. The final rating guideline is shown below:

- Good condition $\leq$ 18%
- 18% $<$ Fair condition $\leq$ 40%
- Poor condition $>$ 40%

Scoring System for Subsurface Distress Severity. In order to understand the subsurface condition in a test section, lab test results are converted to scales using poor, fair, and good based on their distress severities as shown in Table 4.1. It should be noted that the poorest severity rating should be assigned for a broken sample from the core sampling process.

The converted severities from lab data are utilized in determination of the overall subsurface condition using a condition scoring system: 2 for good condition; 1 for fair condition; and 0 for poor condition. Among the scores from air voids, tensile strength, and water stripping severity, the lowest score (**s**) is selected for each cut core sample. Then, the overall score (**S**) for each location can be calculated using Equation 4.1. It should be noted that subsurface condition for "problem locations" in Level 1 and surface distress locations in Level 2 are separately processed from non-problem locations and non-surface distress locations. **S** can be interpreted as shown in Table 4.2. **S** accepting for PPTs should be higher than 40.

$$S = \frac{\sum_{l=1}^{m} \sum_{r=1}^{n} s_{rl}}{\mathrm{m} \times \mathrm{n} \times \mathrm{S_{max}}} \times 100 \tag{4.1}$$

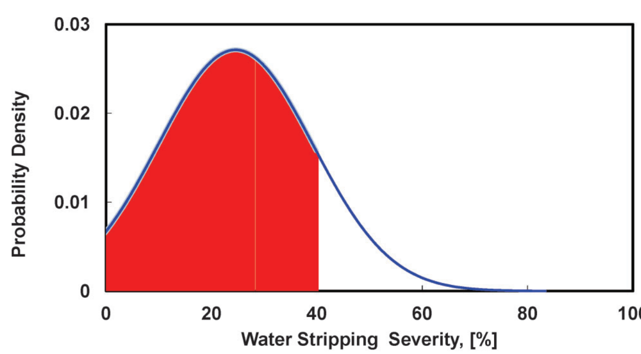


Figure 4.4 Water stripping severity distributions and 90th percentiles.

TABLE 4.1
Lab test result conversion to severity

Air Voids(AV)	Tensile Strength(TS)	Water Stripping Severity (WS)	Condition	Score(s)
≤ 8 %	> 80 psi	≤ 18 %	Good	2 (S_{max})
$8 < AV \leq 10$ %	$50 < TS \leq 80$ psi	$18 < WS \leq 40$ %	Fair	1
> 10 %	≤ 50 psi	> 40 %	Poor	0

Where,

S: overall score ($\mathbf{S_p}$ for "problem locations" and surface distress locations; $\mathbf{S_n}$ for "non-problem locations and non-surface distress; $\mathbf{S_a}$ for all locations in case of Level 3 analysis)

m: total number of layers

n: total number of replicates

$\mathbf{S_{max}}$: the maximum value of converted severities

$\mathbf{s_{rl}}$: the lowest **s** for each cut sample ($\mathbf{s_{prl}}$ for "problem locations" and surface distress locations; $\mathbf{s_{nrl}}$ for "non-problem locations and non-surface distress; $\mathbf{s_{arl}}$ for all locations in case of Level 3 analysis)

$_\mathbf{r}$: denotes the replicate number

$_\mathbf{l}$: denotes the layer number

Applicability of Pavement Preservation Treatments (PPT). The GPR analysis result or surface distresses are strongly related to the material properties measured in lab. However, in reality, some of GPR detections and surface distresses cannot be explained by the limited lab test results only. Therefore, if a difference between the lab test results from non-problem locations and from non-surface distress locations is insignificant, those locations are treated as problem and surface distress locations. Thus, the test section has uniformly distributed subsurface condition. Subsequently, the acceptable Sn and $\mathbf{S_p}$ in Level 1 and Level 2 are used for determining the PPT applicability as shown Table 4.3. The non-uniform condition (i.e., $\mathbf{S_p} \leq 60$ and $\mathbf{S_n} > 60$) requires a further analysis and is explained following chapters. Since an assumption in Level 3 analysis is the uniform distribution of subsurface distress, the allowable $\mathbf{S_a}$ is only a factor for the PPT determination as shown in Table 4.4.

Analysis for Non-Uniform Distribution. Evaluating the subsurface condition coverage (%) and the distribution along a test section is an important process for determining PPT applicable lane length, For example, a 5-mile long pavement section with uniformly distributed 20% coverage of problem locations may not be a good candidate for the PPT. However, if all problem locations are located within 1-mile, the PPT can be applicable for the rest of 4-mile section.

Coverage (Extent) of Problem Location. The coverage (extent) of subsurface condition can only be determined when either Level 1 or Level 2 was selected for the evaluation. In case of Level 3, only the severity rating of the test section is reported. The guideline for the extent level of subsurface distresses is the following:

Level 1. The GPR analysis results should provide the coverage of problem locations for each identified layer. In case multiple layers are determined to have problematic subsurface condition, the total coverage is determined by adding the coverage of all layers while excluding the overlapped area. The overlapped locations are a certain section which was determined to be problematic in more than one layer. Consequently, overlapped locations should only be counted once in the calculation of total coverage of problem locations.

Level 2. The coverage of surface distresses types selected for determining core sampling locations are only used in the analysis. The length-based coverage can be defined as the longitudinal length covered with distress in a given test section and add effective length for the length-based calculation of transverse crack and pothole. The length-based coverage is uniformly used in order to add up the extents of all distress types and a single coverage value representing a pavement condition can be used. Consequently, the length-based coverage calculation of longitudinal crack remains the same. In case of fatigue crack, pumping, potholes, and patch, only the effective longitudinal length of each distress area is included and divided by the total length instead of the area. It is assumed that each distress has an effective length of 20 ft. For example, 10 potholes are converted into 200 ft (10 × 20 ft). In case more

TABLE 4.2
Score interpretation for subsurface condition

S (S_p, S_n, or S_a)	Condition
≥ 81	Excellent
$61 \leq S \leq 80$	Good
$41 \leq S \leq 60$	Fair
$21 \leq S \leq 40$	Poor
$S \leq 20$	Very poor

TABLE 4.3
PPT applicability for subsurface conditions (Level 1 and Level 2)

S_p	S_n	PPT Applicability	Distribution
> 60	> 60	Yes	Uniform
≤ 60	≤ 60	No	Uniform
≤ 60	> 60	No or partial yes	Non-uniform

TABLE 4.4
PPT applicability for subsurface conditions (Level 3)

S_a	PPT Applicability	Distribution
> 60	Yes	Uniform
≤ 60	No	Uniform

TABLE 4.5
Allowable DCUAL for road type

DCUAL	PPT Applicability
≤ 5 %	Interstate
≤ 10 %	US Highway
≤ 20 %	State road/Others

than one pavement sections with surface distresses are included in the analysis, the total coverage should be determined by adding the coverage from all types of distresses excluding the overlapped area. The overlapped locations are in a certain section which was determined to be covered with more than one type surface distress.

Distribution Analysis. The analysis process reviews the problem locations and their influence length in order to find any PPT applicable locations in a section. The process includes (1) determination of Distress Coverage of Unit Analysis Length (DCUAL); (2) application of allowable DCUAL; and (3) determination of PPT applicable locations.

The distress coverage for each unit analysis length UAL (1 mile) is calculated using Equation 4.2. For example, if the frequency of data collection is 10 ft., the first distress coverage of UAL is for a section is between 0 ft to 5280 ft (1 mile) away from the beginning of the section. Accordingly, the second UAL for the section is between 10 ft to 5290 ft away from the beginning of the section. The allowable $DCUAL_i$ for the PPT applications varies by the type of a test section. Any locations with $DCUAL_i$ equal or less than the allowable coverage is determined to be adequate for the application PPT as shown in Table 4.5.

$$DCUAL_i = \frac{\sum_i^{i+j} S_i}{j} \times 100 \qquad (4.2)$$

Where,

$DCUAL_i$ (i=0, 1, …, n-1-j) = distress coverage of unit analysis length at i^{th}

i = 0, 1, …, n-1-j, where n is the total number of data for a test section

j = total number of data in unit analysis length (UAL, 1 mile long)

S = distress index (i.e., presence of distress for 1 and non-presence of distress for 0)

4.3 iSub Overview

The evaluation software "INDOT Pavement Subsurface Condition Evaluation (iSub)" (see Figure 4.5) was developed as part of the JTRP/SPR-3507: Subsurface Condition Evaluation for Asphalt Surface to aid the pavement subsurface condition evaluation. The software is entirely based on the "Guidelines of subsurface condition evaluation for pavement preservation." Thus, iSub provides user-friendly system which helps to follow the hierarchy of evaluation steps. Furthermore, iSub automatically calculates the overall condition of the pavement subsurface as severity rating for each laboratory test result was implemented into the software. However, it should be noted that iSub does not determine core sampling location nor analyze GPR and surface distress survey data. The guideline should be used in core sampling location determination and iSub aids the subsurface condition determination process based on laboratory test results. For additional details, please refer to the iSub user manual (Appendix F).

4.4 iMoisture Overview

The evaluation software "INDOT Water Stripping Severity Evaluation (iMoisture)" (see Figure 4.6) was developed to aid the water stripping severity evaluation and incorporate INDOT subsurface condition evaluation process. Asphalt mixture is primarily composed of asphalt and aggregate. Aggregates should be completely coated by asphalt. Thus, the uncoated aggregate is an index of water stripping, iMoisture detects uncoated aggregates and quantifies the area in a sample by employing the digital image analysis technology. For additional details, please refer to the iMoisture user manual (Appendix G).

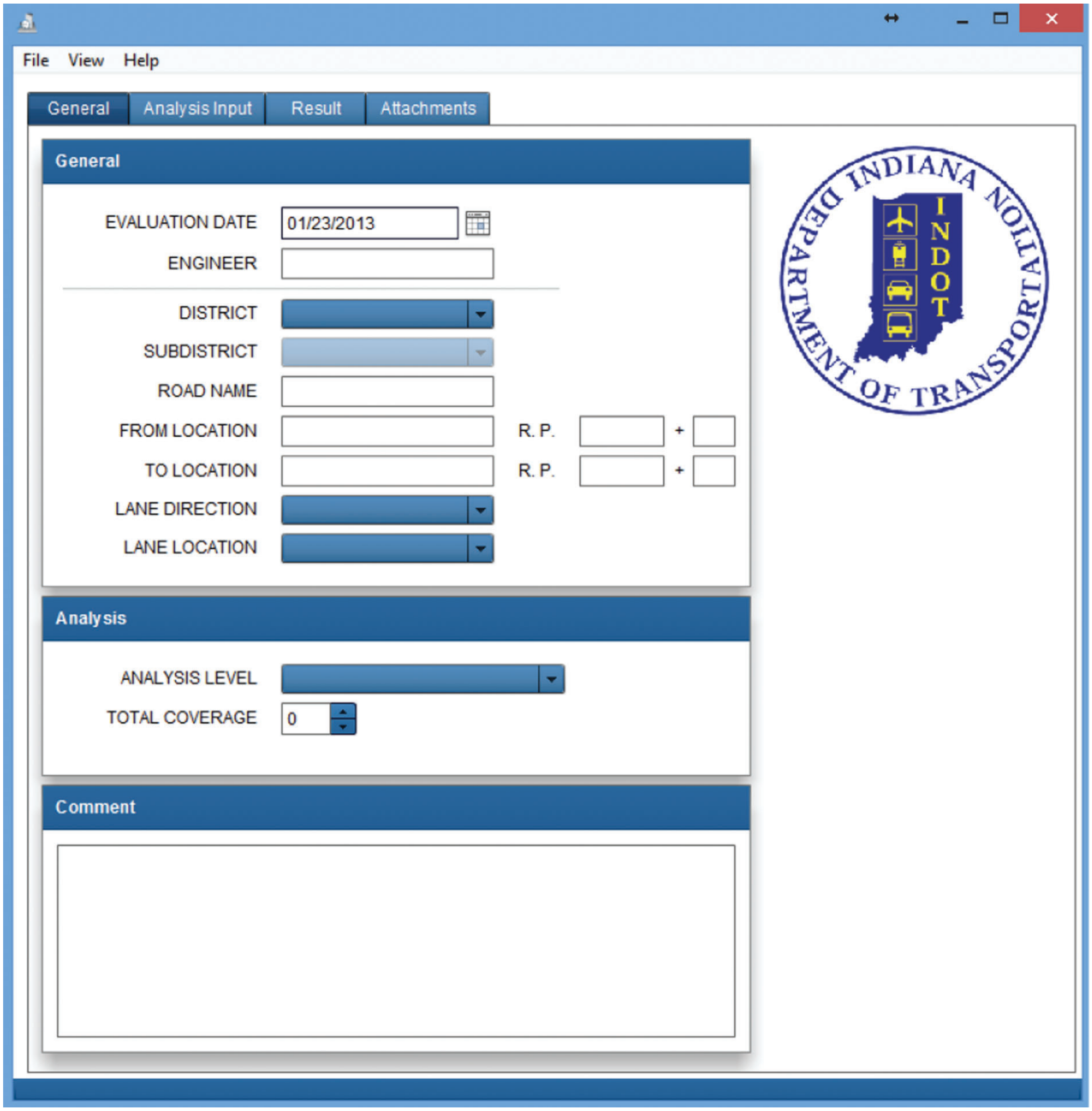


Figure 4.5 iSub: INDOT Subsurface Condition Evaluation Software.

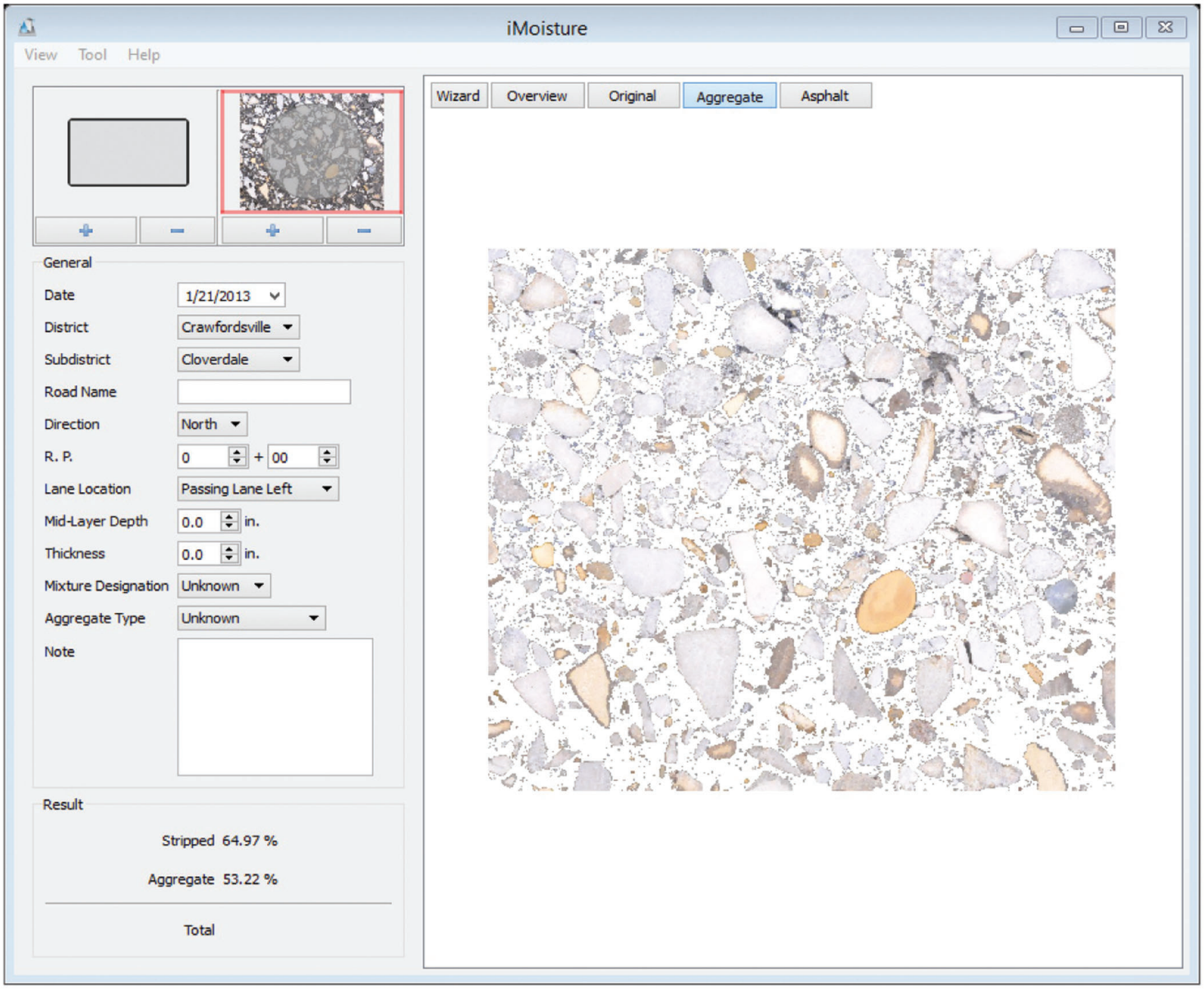


Figure 4.6 iMoisture: INDOT Water Stripping Severity Evaluation Software.

5. EXAMPLE APPLICATION OF GUIDELINE

A guideline for evaluation of subsurface condition for applicability of Indiana pavement preservation treatments (PPTs) was developed and presented in Ch. 4. Specifically, the guideline, utilizing GPR measurements, surface distress, and laboratory tests, estimates the pavement subsurface condition for PPT applicability to aid decision making. The evaluation provides severity of subsurface distresses, quantifies their coverage (extent), and distribution in a project. This chapter presents the analysis results conducted on the SR-70 test section. Two different evaluation methods presented in the guideline were applied, GPR based (Level 1) and surface distress based (Level 2). A summary of the case study is the following.

5.1 Level 1 Analysis (GPR Analysis–Based Result)

Table 5.1 presents the summary of the subsurface condition evaluation based on GPR analysis. Overall, 11.81 % of Layer 1 and 2, and 16. 96 % of Layer 3 in the test section was determined to be problematic. According to the average laboratory test results at the problem locations, the condition of Layer 1 and Layer 3 were the poorest and the best, respectively. In detail, Layer 1 showed the highest average air voids and lowest average tensile strength. Layer 3 showed the highest average water stripping severity.

Table 5.2 summarizes the subsurface condition evaluation based on the non-problem locations. Overall, 92.19 % of Layer 1 and 2, and 83.04 % of Layer 3 in the test section were covered with non-problem locations.

TABLE 5.1
Laboratory test results in GPR problem locations

Layer	Avg. air voids [%]	Avg. tensile strength [psi]	Avg. water stripping severity [%]	Coverage [%]
1	12.4 (Poor)	57 (Poor)	10.7 (Good)	11.81
2	8.2 (Fair)	152 (Good)	53.1 (Poor)	
3	3.7 (Good)	128 (Good)	29.6 (Fair)	16.96

In addition, generally, the non-problem locations had better subsurface conditions comparing to the problem locations. Thus, in comparison, the average air voids and the average water stripping severities in the non-problem locations were lower, and the average tensile strengths were higher for all layers except higher Layer 3 with higher air voids and Layer 1 with higher water stripping severity.

The findings from Table 5.1 and Table 5.**2** confirm that the evaluation method with GPR is valid for interpreting the subsurface condition. P-values from t-test, as shown in Table 5.3, generally, supports the finding. In other words, the laboratory test results at the GPR based problem locations are significantly different from that at the non-problem locations at 5% significance level except the average air voids and tensile strength in Layer 2.

The lab test results were converted to scores using the guidelines (refer to Ch. 4. 9. 2). The overall scores for the problem locations were 42 with the coverage of 20.5 %. The coverage of non-problem locations was 79.5% and its overall subsurface condition score was 76.

As the overall scores for problem and non-problem locations indicate, the test section showed non-uniform distribution, thus the subsurface distress distribution anlaysis along the test section was evaluated (refer to Ch. 4.9.4). The DCUAL analysis showed that the entire test section was determined to be not applicable for the pavement preservation treatment based on the allowable coverage for state road (DCUALj $\leq$ 20%) as shown in Figure 5.1.

5.2 Level 2 Analysis (Surface Distress–Based Result)

According to the surface distress survey using the digital image acquisition system, the main distresses on SR-70 were longitudinal cracks, fatigue cracks, and potholes. The longitudinal crack was the most widely distributed distress (among the three distress types) with 22% of lane length in the 2-mile test section. Furthermore, more distresses were shown on R.P. 3-4 than on R.P. 4-5.

Based on the water stripping test results and the core visual observations, it was confirmed that the test section on SR-70 had the water stripping problem. In addition, overall, there was no subsurface condition difference between left wheel and right wheel paths.

As summarized in Table 5.4, based on condition ratings from the laboratory test results at the test section locations with the surface distresses, generally, each layer showed different subsurface condition. Specifically, Layer 1 was determined to be the poorest condition and Layer 3 to be the best condition according to their air voids. The average tensile strengths indicated good condition in all three layers. Based on the water stripping severities, Layer 2 was in the poorest condition.

Table 5.5 summarizes condition ratings from the laboratory test results at the test section locations without the surface distresses. When the results are compared to that with surface distresses in Table 5.4, average air voids and water stripping severities decrease and average tensile strengths increase. The observation confirms that the evaluation process using the surface distress is valid for understanding the subsurface

TABLE 5.2
Laboratory test results in non-problem locations

Layer	Avg. air voids [%]	Avg. tensile strength [psi]	Avg. water stripping severity [%]	Coverage [%]
1	10.7 (Poor)	177 (Good)	17.3 (Good)	92.19
2	7.8 (Good)	159.4 (Good)	31.1 (Fair)	
3	5.2 (Good)	100.3 (Good)	33.4 (Fair)	83.04

TABLE 5.3
T-test results for laboratory test results in problem and non-problem locations

Layer	Avg. air voids [%]	Avg. tensile strength [psi]	Avg. water stripping severity [%]
1	0.045	0.0043	0.046
2	0.79	0.61	0.009
3	0.0001	0.042	0.23

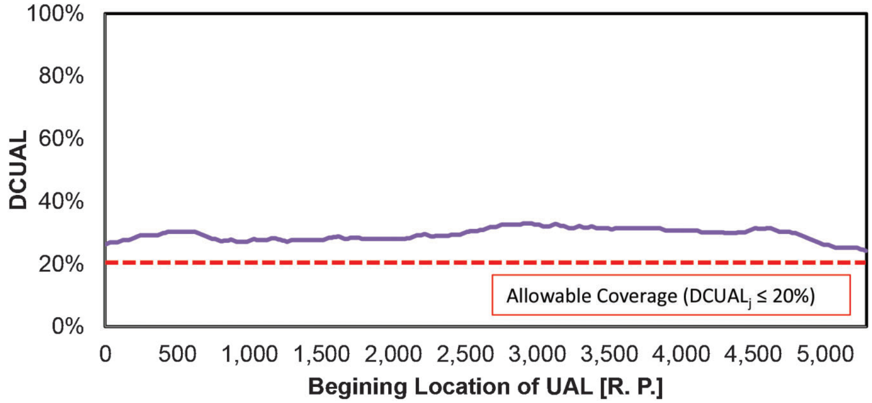


Figure 5.1 Distress distribution analysis of SR-70 based on GPR analysis.

condition. However, P-values from t-test, as shown in Table 5.6, generally, result in the laboratory test results at the test section locations with surface distresses are not significantly different from that without surface distresses at 5% significance level.

The lab test results were again converted to scores using the guidelines. The overall score of the test section covered with the surface distresses by 28% was 56. Thus, the extent level of subsurface distresses was determined to be fair. In addition, the overall score for the test section without surface distresses was 78, which is good condition.

The subsurface condition conducted using Level 2 analysis also showed that the test sections had non-uniform distribution. A DCUAL distribution along the test section is shown in Figure 5.2. The overall 28% of the test section was covered with surface distress; however, the distress was densely populated in the first half-mile test section. Considering the allowable distress coverage for state roads (DCUALj $\leq$ 20%), a specific test section located between 1,860 ft and 8,320 ft from R. P. 3 can be determined to be applicable for the pavement preservation treatment.

TABLE 5.4
Laboratory test results with surface distresses

Layer	Avg. air voids [%]	Avg. tensile strength [psi]	Avg. water stripping severity [%]	Coverage [%]
1	12.1 (Poor)	87.4 (Good)	18.1 (Fair)	28
2	9.6 (Fair)	152 (Good)	44.8 (Poor)	28
3	4.5 (Good)	117 (Good)	37.4 (Fair)	28

TABLE 5.5
Laboratory test results without surface distresses

Layer	Avg. air voids [%]	Avg. tensile strength [psi]	Avg. water stripping severity [%]	Coverage [%]
1	10.4 (Poor)	163 (Good)	10.9 (Good)	72
2	6.8 (Good)	161 (Good)	32.2 (Fair)	72
3	5.2 (Good)	96 (Good)	24.8 (Fair)	72

TABLE 5.6
T-test results for the laboratory test results with and without surface distresses

Layer	Avg. air voids [%]	Avg. tensile strength [psi]	Avg. water stripping severity [%]
1	0.14	0.19	0.16
2	0.014	0.48	0.21
3	0.23	0.13	0.11

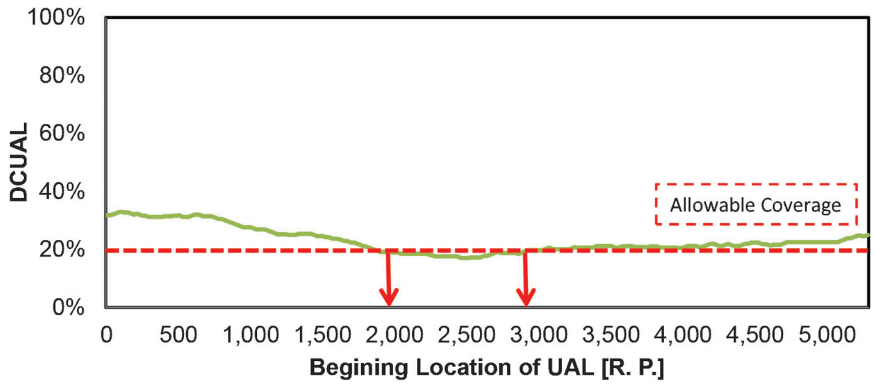


Figure 5.2 DCUAL distribution analysis of SR-70 based on surface distress.

6. SUMMARY AND CONCLUSION

6.1 Evaluation of Subsurface Condition Test Methods

- A new method for quantifying the water stripping severity was developed with computer software using the digital image analysis. The new method can provide a consistent and rational engineering indicator for the measurement of water stripping severity.
- When the laboratory test results with the surface distresses or in the GPR-based problem locations were compared to that without the surface distresses or in the GPR-based non-problem locations, in general, average air voids and water stripping severities decrease and average tensile strengths increase. Accordingly, it was concluded that both the surface distresses survey and the GPR measurement were reliable method to determine the core sampling locations to evaluate the subsurface condition.
- In addition, core samples with poor conditions, based on the laboratory tests, were correctly matched to the problem locations determined by the distress survey and GPR measurement. The observation confirms that the laboratory evaluation processes are applicable for evaluating the subsurface condition.
- The FWD results had a weak correlation with the laboratory test results possibly due to fairly long testing interval (i.e., 328 ft). The current FWD test protocol should be improved for evaluating the subsurface condition in pavement preservation application.

6.2 Guideline of Subsuface Condition Evaluation

- A methodology for evaluating subsurface condition of pavement was developed utilizing the findings from the study on SR-70. A concept of hierarchy was used in the methodology by taking project importance and available resources into consideration. A tool including guidelines, computer software (e.g., iSub and iMoisture), and its manual was also developed based on the methodology as a research product. The tool can help a consistent and rational decision making process for project level or district level pavement preservation program.

6.3 Example Application of Guideline on SR-70

- The main distresses on SR-70 were longitudinal cracks, fatigue cracks, and potholes. The longitudinal crack was the most widely distributed distress with 22% of lane length in the 2-mile test section among the three distress types. Furthermore, more distresses were shown on R.P. 3-4 than on R.P. 4-5. Based on the water stripping severity test results and the visual observations of core samples, it was confirmed that the test section on SR-70 had the water stripping problem. In addition, there was no significant subsurface condition difference between left wheel and right wheel paths. In general, the Layer 1 was in the poorest condition based on the laboratory test results.
- The conditions were converted into the overall scores scaled from 0 to 100. Layers with a score closer to 100 are in better subsurface condition. As a result, the 28% of the test section length with was determined to have the fair subsurface condition by the level 2 evaluation with surface distress. The rest 72% of the test section without surface distresses was estimated to have the good subsurface condition. Similarly, 20.5% of the test section length contained the problem locations with the fair subsurface condition and the rest 79.5 % of the length had the good subsurface condition.

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APPENDIX A. CORE LABORATORY TEST RESULTS

ID	Mid-Layer Depth [in.]	Layer No.	Location [mile]	Location [ft]	Wheel Path	Gmb	Air Voids [%]	Tensile Strength [psi]	Water Stripping Severity [%]
1	0.95	1	0.004	21.12	R	2.12	13.46	185.2	27.47
2	2.9	2	0.004	21.12	R	2.26	9.30	144.2	7.14
3	4.9	3	0.004	21.12	L	2.20	8.33	0.0	13.86
4	6.6	3	0.004	21.12	L	2.32	4.22	116.7	0.00
5	8	3	0.004	21.12	L	2.35	3.05	100.2	0.00
6	1.05	1	0.198	1045.44	R	2.23	9.05	206.1	27.58
7	3.05	2	0.198	1045.44	R	2.33	6.54	220.2	0.00
8	4.95	2	0.198	1045.44	L	2.36	5.36	158.9	0.00
9	6.8	2	0.198	1045.44	R	2.34	6.19	168.6	28.13
10	1	1	0.227	1198.56	R	2.24	8.57	203.4	0.00
11	2.9	2	0.227	1198.56	R	2.33	6.61	186.9	0.00
12	4.8	2	0.227	1198.56	R	2.33	6.53	139.0	36.97
13	6.7	2	0.227	1198.56	R	2.39	3.93	110.6	44.02
14	8.7	2	0.227	1198.56	R	2.38	4.35	93.7	17.43
15	11.05	2	0.227	1198.56	R	2.37	4.74	95.8	46.25
16	0.5	1	0.317	1673.76	R	2.20	10.29	0.0	20.92
17	1.55	2	0.317	1673.76	R	2.26	9.09	176.1	28.52
18	3.15	3	0.317	1673.76	R	2.38	1.43	167.7	17.88
19	5.15	3	0.317	1673.76	L	2.37	2.24	151.1	31.17
20	6.85	3	0.317	1673.76	L	2.40	0.69	135.5	24.84
21	0.6	1	0.387	2043.36	L	2.16	11.72	152.2	19.66
22	2.1	2	0.387	2043.36	L	2.24	9.98	134.0	12.95
23	3.95	3	0.387	2043.36	L	2.38	1.55	158.3	26.31
24	5.95	3	0.387	2043.36	R	2.29	5.42	82.3	35.21
25	8	3	0.387	2043.36	R	2.28	5.60	86.1	44.77
26	9.7	3	0.387	2043.36	R	2.29	5.21	82.7	61.94
27	0.65	1	0.515	2719.2	L	2.13	13.20	0.0	50.14
28	2.2	2	0.515	2719.2	L	2.29	8.01	116.7	0.00
29	4.1	3	0.515	2719.2	L	2.28	5.65	96.3	0.00
30	6	3	0.515	2719.2	R	2.25	7.15	79.2	56.88
32	0.65	1	0.543	2867.04	R	2.16	11.76	0.0	54.89
33	2.3	2	0.543	2867.04	R	2.25	9.53	162.2	34.24
34	3.95	3	0.543	2867.04	R	2.30	5.07	135.2	83.93
35	5.4	3	0.543	2867.04	R	2.30	5.07	122.6	70.00
36	6.9	3	0.543	2867.04	R	2.25	7.07	89.7	38.32
38	0.75	1	0.551	2909.28	R	2.20	10.34	141.6	54.50
39	2.45	2	0.551	2909.28	R	2.21	11.14	172.7	43.36
40	4.35	3	0.551	2909.28	R	2.26	6.72	97.7	38.07
41	6.05	3	0.551	2909.28	R	2.21	8.64	92.3	35.93
44	0.75	1	0.697	3680.16	L	2.21	9.79	239.2	35.38
45	2.5	2	0.697	3680.16	L	2.25	9.54	172.3	60.92
46	4.45	3	0.697	3680.16	L	2.34	3.25	130.5	45.53
47	6.25	3	0.697	3680.16	R	2.30	5.03	95.7	37.01
50	0.55	1	1.275	6732	R	2.14	12.53	155.3	28.03
51	2.05	2	1.275	6732	R	2.24	10.16	153.8	46.46
52	3.7	2	1.275	6732	R	2.39	3.87	155.6	49.22
53	5.35	3	1.275	6732	R	2.28	5.60	133.4	32.29
56	0.65	1	1.282	6768.96	R	2.15	12.18	146.7	24.78
57	1.85	2	1.282	6768.96	R	2.19	12.17	153.8	51.14
58	3.1	2	1.282	6768.96	R	2.27	8.68	144.4	31.62
59	4.6	3	1.282	6768.96	R	2.38	1.66	143.8	55.41
62	0.6	1	1.55	8184	R	2.18	10.96	164.9	0.00
63	1.9	2	1.55	8184	R	2.27	8.76	202.8	37.14
64	3.35	2	1.55	8184	R	2.33	6.35	196.9	27.49
65	4.75	2	1.55	8184	L	2.35	5.56	194.9	0.00
66	6.35	3	1.55	8184	L	2.29	5.33	127.2	41.16
67	8.15	3	1.55	8184	R	2.29	5.15	98.2	29.73

Table continued on p. 44.

TABLE
(Continued)

ID	Mid-Layer Depth [in.]	Layer No.	Location [mile]	Location [ft]	Wheel Path	Gmb	Air Voids [%]	Tensile Strength [psi]	Water Stripping Severity [%]
68	0.55	1	1.65	8712	R	2.13	12.94	157.5	23.04
69	1.7	2	1.65	8712	L	2.11	15.23	150.5	0.00
70	3	2	1.65	8712	L	2.27	8.97	172.6	17.96
71	4.4	3	1.65	8712	R	2.28	5.57	110.7	38.28
72	5.95	3	1.65	8712	R	2.27	6.12	100.7	57.72
74	0.75	1	1.926	10169.28	R	2.13	13.04	0.0	31.62
75	2.35	2	1.926	10169.28	R	2.31	7.09	154.6	21.23
76	3.8	3	1.926	10169.28	R	2.32	4.05	102.8	25.24
77	4.9	3	1.926	10169.28	R	2.33	3.55	94.5	21.97

APPENDIX B. PRELIMINARY ASSESSMENT

APPENDIX C. INDOT GUIDELINE OF SUBSURFACE CONDITION EVALUATION FOR PAVEMENT PRESERVATION TREATMENT

APPENDIX D. INDOT PAVEMENT SUBSURFACE CONDITION EVALUATION SOFTWARE (ISUB)

APPENDIX E. INDOT WATER STRIPPING SEVERITY EVALUATION SOFTWARE (IMOISTURE)

APPENDIX F. INDOT PAVEMENT SUBSURFACE CONDITION EVALUATION SOFTWARE (ISUB) MANUAL

APPENDIX G. INDOT WATER STRIPPING SEVERITY EVALUATION SOFTWARE (IMOISTURE) MANUAL

Appendices B through G are available for download here: http://dx.doi.org/10.5703/1288284315187

About the Joint Transportation Research Program (JTRP)

On March 11, 1937, the Indiana Legislature passed an act which authorized the Indiana State Highway Commission to cooperate with and assist Purdue University in developing the best methods of improving and maintaining the highways of the state and the respective counties thereof. That collaborative effort was called the Joint Highway Research Project (JHRP). In 1997 the collaborative venture was renamed as the Joint Transportation Research Program (JTRP) to reflect the state and national efforts to integrate the management and operation of various transportation modes.

The first studies of JHRP were concerned with Test Road No. 1—evaluation of the weathering characteristics of stabilized materials. After World War II, the JHRP program grew substantially and was regularly producing technical reports. Over 1,500 technical reports are now available, published as part of the JHRP and subsequently JTRP collaborative venture between Purdue University and what is now the Indiana Department of Transportation.

Free online access to all reports is provided through a unique collaboration between JTRP and Purdue Libraries. These are available at: http://docs.lib.purdue.edu/jtrp

Further information about JTRP and its current research program is available at: http://www.purdue.edu/jtrp

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