State of Florida
Department of Transportation

Instrumentation of Florida's Accelerated Pavement Testing Facility

FDOT Office
State Materials Office

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

EXECUTIVE SUMMARY

The evaluation and validation of new and emerging pavement technologies and innovative concepts require assessing their in-service long-term performance. In-service assessment requires the consideration of the interaction between traffic loading, materials properties, and environmental effects. The Florida Department of Transportation (FDOT) purchased a Heavy Vehicle Simulator (HVS), Mark IV model and initiated an accelerated pavement testing (APT) in 2000. The APT program is housed within the State Materials Research Park in Gainesville. Pavement performance is ultimately measured by the formation of distresses on the pavement surface (e.g., rutting, cracking, raveling, etc.) that limit functionality or capacity. Pavement response such as stress and strain to load and/or environmental conditions is also critical in the assessment of long-term performance. The objective of this document is to provide an overview of the most common instrumentation used in Florida's APT program. This document is not intended to be an endorsement of any particular instrumentation sensor.

The following people may be contacted for additional information regarding the instrumentation presented in this report or Florida's APT program in general:

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INTRODUCTION

The evaluation and validation of new and emerging pavement technologies and innovative concepts require assessing their in-service long-term performance. In-service assessment requires the consideration of the interaction between traffic loading, materials properties, and environmental effects. The primary disadvantage of such an evaluation approach is the extensive time period required to obtain potentially meaningful results. Additionally, it is often difficult, impractical, and/or expensive to obtain or account for all the data and information required from in-service experimental set ups.

The need for faster and more practical evaluation methods under closely simulated in-service conditions prompted the Florida Department of Transportation (FDOT) to consider accelerated pavement testing (APT). APT is generally defined as a controlled application of a realistic wheel loading to a pavement system simulating long-term, in-service loading conditions. This allows the monitoring of a pavement system's performance and response to accumulation of damage within a much shorter time frame. APT can produce early, reliable and beneficial results while improving pavement technology and understanding/prediction of pavement systems performance.

OBJECTIVE

The objective of this document is to provide an overview of the most common instrumentation used in Florida's APT program. Specific information is provided on instrumentation gauges, the data acquisition system, operational guidelines, and data analysis.

FLORIDA'S APT FACILITY

The Florida Department of Transportation (FDOT) recognized the benefits of APT and purchased a Heavy Vehicle Simulator (HVS), Mark IV model in 2000. Important HVS specifications are listed in TABLE 1. Florida's APT program is housed within the State Materials Research Park in Gainesville. The testing site consists of 8 linear test tracks with each test track measuring 150 feet long and 12 feet wide. Two additional test tracks were designed with water table control capabilities within the supporting unbound layers. The HVS is electrically powered (using external electric power source or electricity from an on-board diesel generator), fully automated, and mobile. The APT facility and the HVS are shown in FIGURE 1.

TABLE 1 HVS Specifications

Parameter	Specification
Weight	50+ tons
Length	75 feet
Test section length	20 feet
Width	12 feet
Load range	7 to 45 kips
Wheel speed	2 to 8 mph
Maximum passes per day	14,000 passes (uni-directional)
Maximum rut depth	4 inches
Tire types	1. Goodyear Unisteel G149 RSA, 11R22.5 (Dual Tire) 2. Goodyear G286 A SS, 425/65R22.5 (Super Single) 3. Michelin X One XDA-HT Plus, 445/50R22.5 4. Michelin X One XDA-HT Plus, 455/55R22.5
Tire wander	0 to 30 inches
Environmental control	Insulated panels and heater system

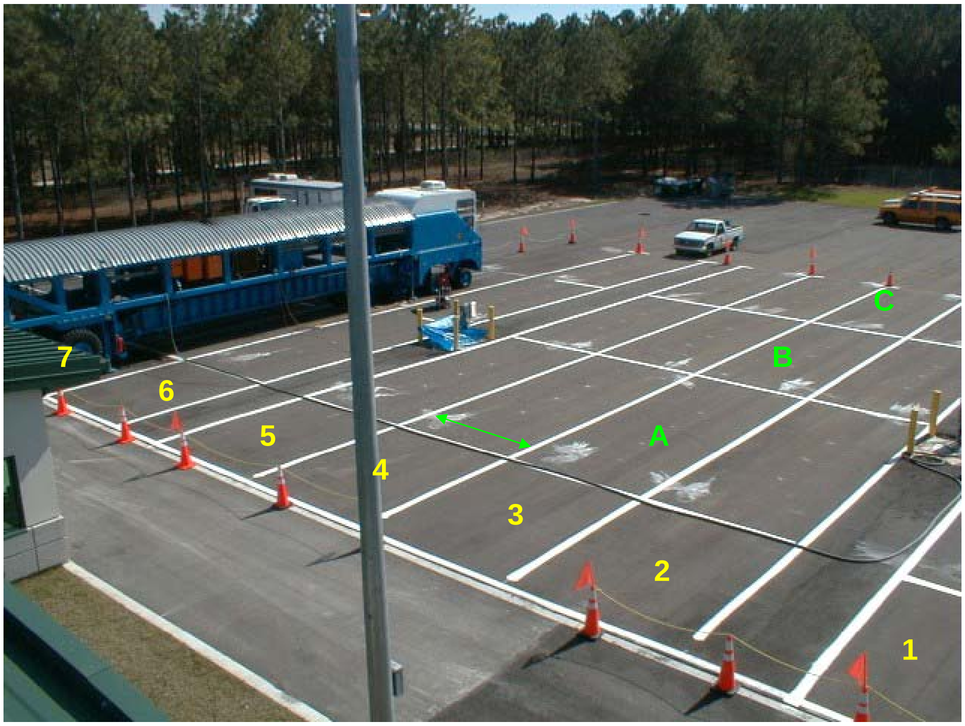

FIGURE 1 Florida's APT facility and test tracks.

DATA ACQUISITION SYSTEM

Most instrumentation is connected to a National Instruments (NI) Data Acquisition System (DAQ) mounted on a custom made chamber trolley. The chamber, shown in FIGURE 2, is temperature controlled and rated for outdoor use (NEMA 4X). A wireless link between the main HVS control room computer and the outdoor DAQ is used so that data acquisition can be controlled from indoors and further processing can be performed using fully-automated NI LabVIEW TM software. TABLE 1 summarizes the DAQ specifications.

FIGURE 2 Instrumentation chamber.

TABLE 2 Data Acquisition System Specifications

Vendor	Model	Description	Quantity
National Instruments	SCXI-1001	12-Slot Chassis	1
National Instruments	SCXI-1314	Front Mounting Terminal Block	4
National Instruments	SCXI-1303	32-Channel Isothermal Terminal Block	1
National Instruments	SCXI-1600	16-bit USB Digitizer	1
Ice Qube	IQ37S4XAC	NEMA 4X SS Enclosure w/1200 BTU/Hr. AC	1

ASPHALT STRAIN

Embedded Asphalt Strain Gauge

The purpose of embedded asphalt strain sensors is to measure the dynamic strain responses at the bottom of the asphalt layer under moving traffic loads. H-gauges are utilized to measure both longitudinal and transverse strain. A typical H-gauge consists of an electrical resistance strain gauge embedded within a strip of glass-fiber reinforced epoxy with transverse stainless steel anchors at each end of the strip to form an H-shape (Figure). It is important that the strip stiffness is approximately the same as the HMA stiffness (*1*). Because the H-gauge measures the average strain between the anchors, the length of the sensor should be three to five times the maximum aggregate size (*2*). H-gauges are designed to withstand the high placement temperatures of asphalt and the compaction loads associated with pavement construction. They incorporate full Wheatstone bridge circuits within the sensor to reduce signal conditioning complexity. There are four active electrical resistance strain gauges incorporated in each sensor: two aligned in the longitudinal direction and two in the transverse direction. FDOT has typically used the Tokyo Sokki KM-100HAS guage shown in FIGURE 3. Specifications for the gauge are listed in TABLE 3. In FDOT’s experience, dynamic strain measurements made with foil resistance strain gauges attached to cores have produced inconsistent results.

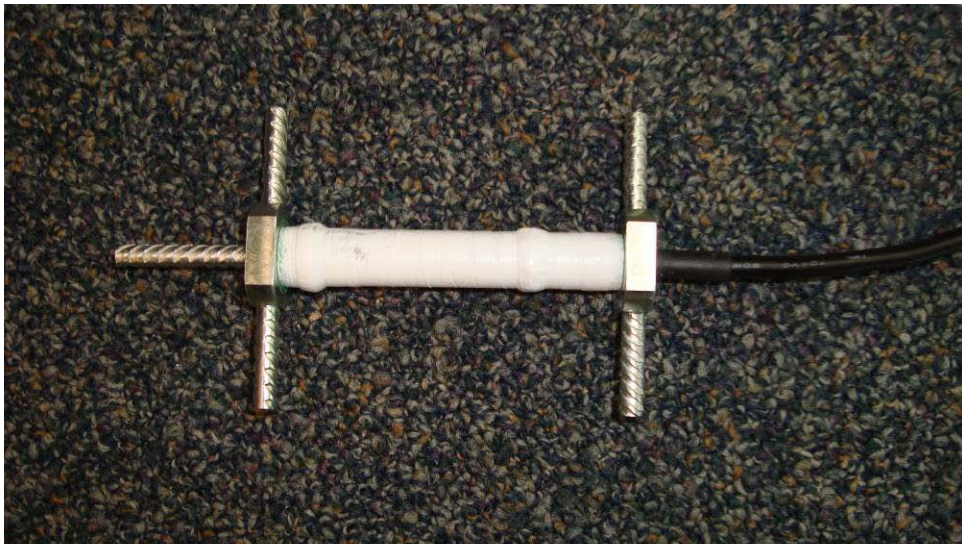

FIGURE 3 Tokyo Sokki KM-100HAS H-guage.

TABLE 3 Tokyo Sokki KM-100HAS specifications.

Parameter	Specification
Gauge length	100 mm
Capacity	± 5000 με
Resistance	350 Ω full bridge
Rated output	~2.5mV/V
Temperature range	-20°C to 180°C

Installation

Embedded H-gauges must survive the heat and compaction effort required to place HMA. Typically, if gauges survive the harsh construction environment, they will continue to perform satisfactorily over the duration of the experiment. The following guidelines are recommended for installation of embedded H-gauges:

1. Prior to installation, connect each H-gauge to the DAQ system to verify functionality. The lead wire may also need to be extended. Specifically, the following measurements should be verified:
    a. Gauge produces an output signal.
    b. Baseline (unloaded) response is stable over several seconds.
    c. Gauge responds as expected to stimulus.
    d. Gauge baseline (unloaded) signal is within acceptable range.
2. Mark locations and gauge orientations on the base or milled pavement surface. Typically, the strain gauges will be placed directly below the wheel path. Use a fixed reference point that will be available before and after paving and measure distance and offset to each strain gauge using string lines or more advanced survey methods.
3. Within the area to be paved, saw cut a path for the gauge wires (FIGURE 4). The path should be the most direct possible to the outside edge of the paving lane to reduce the amount of wire to be paved over.

FIGURE 4 Saw-cut for strain-gauge wire.

4. Place gauges in correct location and orientation (FIGURE 5). Place gauge wires into cut path.

FIGURE 5 Placement of strain gauge and wires.

5. Seal gauge wire path with silicon sealant (FIGURE 6).

FIGURE 6 Sealing gauge wire path with silicone sealant.

6. In the past, thermal reflective tape was placed across strain gauge wire path. Experience has shown that the thermal tape does not typically adhere to the milled surface during construction. This step can be eliminated from future installation efforts.
7. Once the gauges are secured, double-check the functionality of gauges (step 1). This will likely be the last chance to replace nonfunctioning or problematic gauges.
8. Just prior to paving, hand-compact a small sample of the hot-mix to be paved around the gauge (FIGURE 7). Some hot-mix will need to placed under the gauge as well.
9. After construction, confirm each gauge survived by repeating step 1.

FIGURE 7 Placement of gauges prior to paving.

10. Pave the instrumented area using normal practices, with care to minimize disturbance of gauges.
11. After paving, mark the locations of the embedded strain gauges on the pavement surface using the reference points established earlier.
12. Check gauge functionality to make sure the gauges survived the construction process.

Asphalt Surface Strain Gauge

The metallic foil-type strain gauge consists of a grid of wire filament bonded directly to the strained surface by a thin layer of epoxy resin. When a load is applied to the surface, the resulting change in surface length is communicated to the resistor and the corresponding strain is measured in terms of the electrical resistance of the foil wire, which varies linearly with strain. The foil diaphragm and the adhesive bonding agent must work together in transmitting the strain, while the adhesive must also serve as an electrical insulator between the foil grid and the surface.

Each strain gauge wire material has its characteristic gage factor, resistance, thermal properties, and stability. Typical materials include Constantan (copper-nickel alloy), Nichrome V (nickel-chrome alloy), platinum alloys (usually tungsten), Isoelastic (nickel-iron alloy), or Karma-type alloy wires (nickel-chrome alloy), foils, or semiconductor materials (*3*). FDOT currently uses a foil gauge with a copper-nickel (CU-Ni) element and polyester resin backing manufactured by Tokyo Sokki Kenkyujo Co., Ltd. Various sizes have been used, but the 20 mm and 30 mm gauge lengths are the most commonly utilized gauges. Typically, the gauges are placed at various offsets from the tire edge. It is possible to place the gauges in the wheel path and collect reasonable data but the gauges will not last very long. The gauges are shown in FIGURE 8 and their specifications are listed in TABLE 4. A study performed by FDOT showed that strain measurements using these gauges were repeatable under various combinations of tire load, speed, tire pressure, temperature, and offset distance from the tire (*4*).

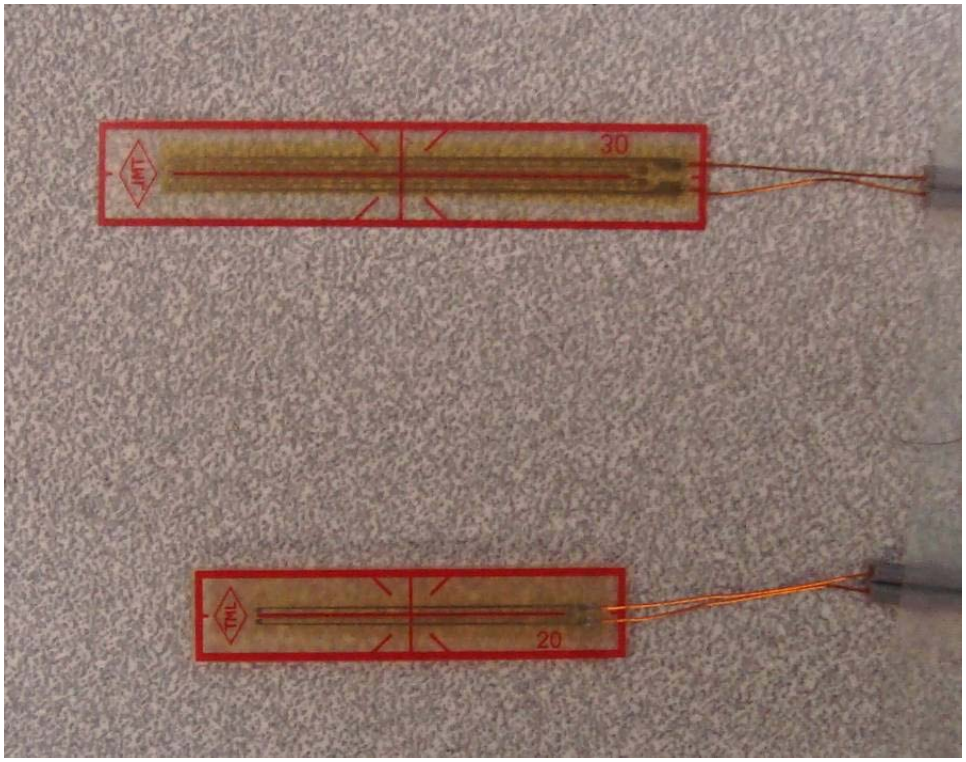

FIGURE 8 Tokyo Sokki PFL-20-11-5L and 30-11-5L gauges.

TABLE 4 Tokyo-Sokki PFL-20-11-5L and 30-11-5L Specifications

Parameter	Specification
Gauge length	20mm and 30 mm
Gauge factor	2.13 ± 1%
Strain limit	2%
Resistance	120 ± 0.5 Ω
Temperature compensation	11 x 10^{-6}/°C
Operational range	-20°C to 180°C
Temperature compensation range	10°C to 180°C
Backing	Polyester
Element	Cu-Ni
Adhesive	CN-E, RP-2

Installation

The surface foil gauges are installed after construction and just prior to testing. The HVS should already be in place. The following guidelines are recommended for the application of surface foil gauges:

1. On the pavement surface, mark the approximate spots that the sensors will be placed. The HVS wheel may need to be lowered and a few passes applied to determine exactly where the wheel path will be located.
2. Grind the surface to remove surface voids and produce a smooth surface (FIGURE 9).

FIGURE 9 Grinding the HMA surface.

3. Clean the grinded pavement surface of all debris and dust. Use a shop rag and alcohol to make sure that all fine dust particles have been removed.
4. Optional: If a considerable number of surface voids are still present, mix two part strain gauge cement and brush onto surface where gauges will be placed. Allow the cement to dry, then roughen the epoxy with steel wool pad and repeat step three.
5. Apply CN strain gauge adhesive (FIGURE 10) liberally to the pavement surface and the underside of the foil gauge.

FIGURE 10 CN strain gauge adhesive.

6. Place the strain gauge on the surface with adhesive. Use the wax paper sheets provided with the gauges to apply pressure by gently rocking back and forth with your fingers. After it adheres (1-2 minutes), leave the wax paper on top (FIGURE 11). Remove the wax paper after the gauges have dried a few more minutes.

FIGURE 11 Wax paper on top of gauge.

7. After all gauges are wired to the DAQ box, neatly bind wires with zip ties and tape them to the surface.
8. Heat wax in a saucer/pot until melted and pour onto wires in order to keep them held in place (FIGURE 11).

FIGURE 12 Melting wax and securing gauge wire.

9. For gauges that will be under the wheel path mix up two part epoxy and coat top of gauge and any wire that will be in the loaded wheel path. This should help prolong the life of the gauge.

Asphalt Strain Analysis

Strain data is typically collected long enough to include three complete loaded passes. The data collection time window may need to be modified if the wheel speed is changed. For standard operation at 8 mph, a time window of 20 seconds is used. Strain data collection is typically set at 10,000 Hz and analyzed and stored by the DAQ system at 100 Hz. Strain data is automatically merged with HVS data and saved to a text file. Asphalt temperature (surface and in-depth) is collected separately and merged at a later date. This file includes the following information:

1. Time of data collection
2. Wheel location
3. Pass number
4. Wheel load
5. Strain information

Typical gauge responses for a single strain profile are shown in FIGURE 13. The strain response is a function of the gauge orientation (longitudinal or transverse), gauge location (near or away from the wheel path) and depth of gauge location (surface or bottom of asphalt layers).

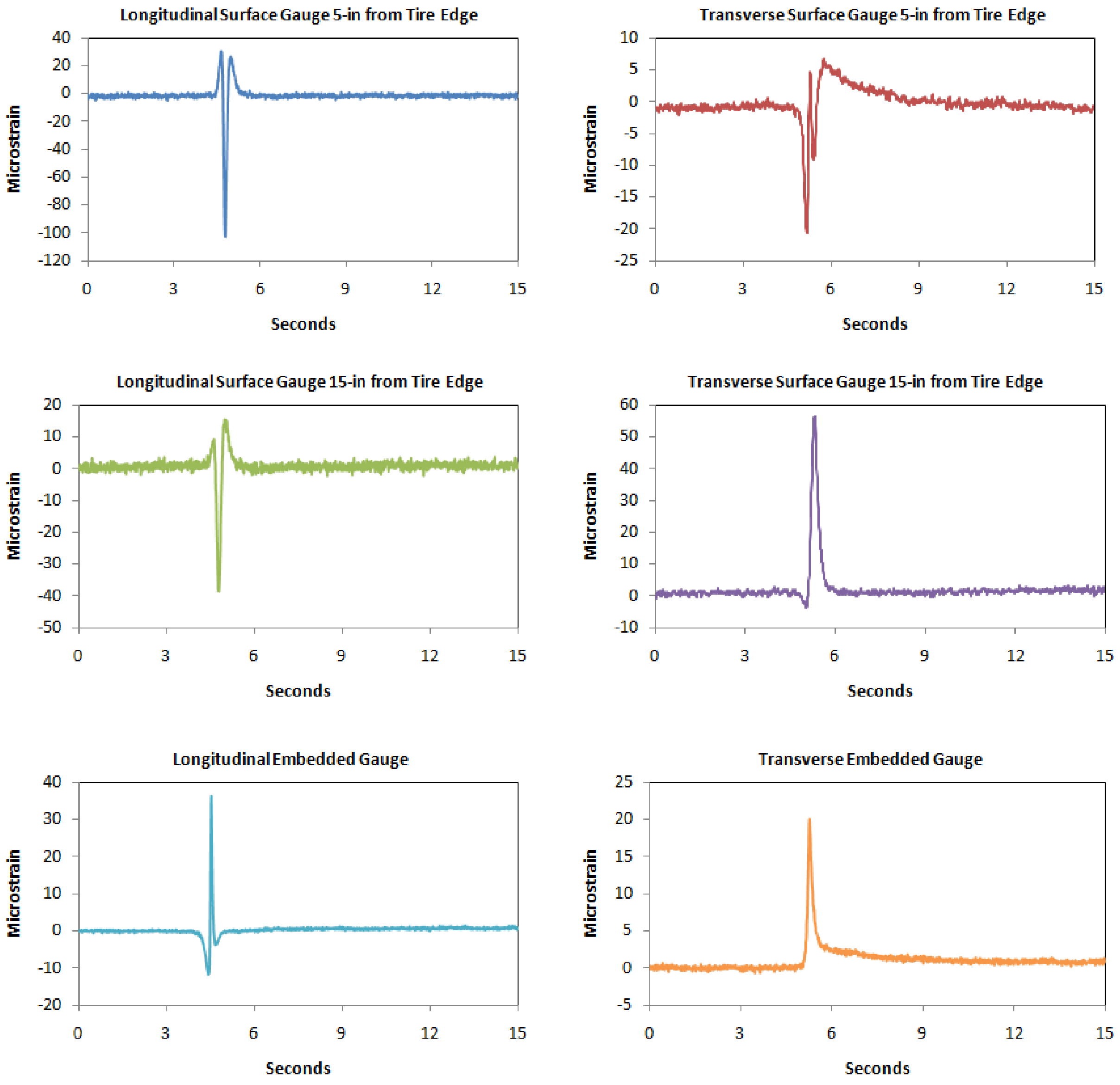

FIGURE 13 Typical strain profiles from surface and embedded gauges.

A typical strain profile from a longitudinal and transverse embedded gauge is shown in FIGURE 14 and FIGURE 15, respectively. Key strain components observed in the longitudinal gauge include compressive strain (ε_{C1}) as the wheel approaches the gauge, tensile strain (ε_t) as the tire passes above the gauge, and a second zone of compression as the tire moved away from the gauge. The strain pulse duration is also identified. The transverse embedded gauge only shows tensile strain. Due to the ambiguity of the trailing portion of the transverse strain pulse, the tensile strain pulse duration of the transverse gauge may be determined as indicated in FIGURE 15.

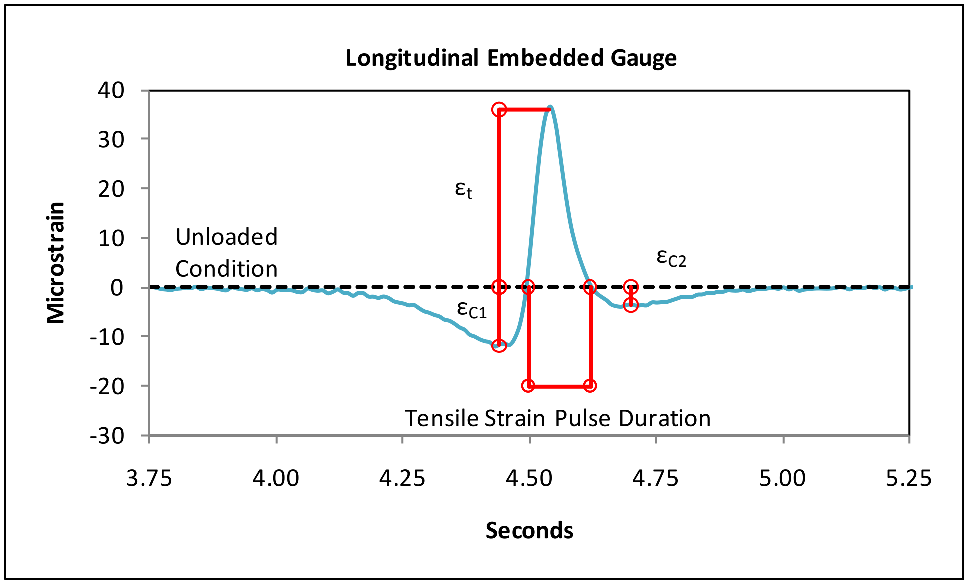

FIGURE 14 Typical longitudinal embedded strain gauge profile.

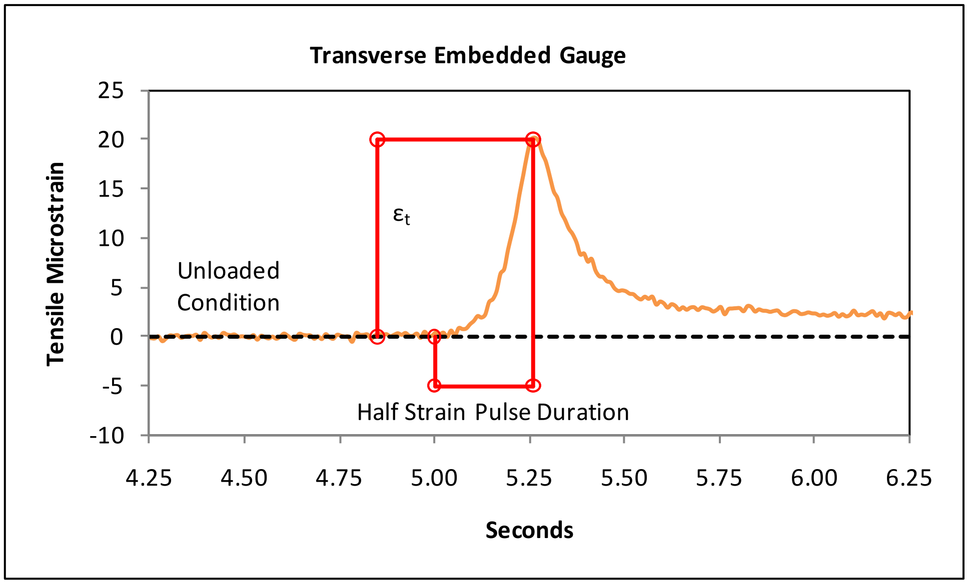

FIGURE 15 Typical transverse embedded strain gauge profile.

FDOT has developed a LabVIEW program that automatically analyzes the recorded strain profile and identifies the critical points. The output of this file includes statistical data for each strain component, wheel position, pass number, wheel load, and pavement temperature.

STRESS IN UNBOUND MATERIALS

Soil pressure sensors are installed in unbound material to measure the dynamic stress generated under moving loads, usually in the vertical direction when used in pavement structures. These sensors are typically two large circular steel plates welded together around their rims to create a closed cell. The space between the plates is completely filled with oil. A steel tube connects the liquid to an electrical pressure transducer where the oil pressure is converted to an electrical signal (*5*). The two most important requirements are the stiffness of the sensor and the ratio between its thickness and diameter (aspect ratio). The stiffness should be high compared to the material that it is to be installed in. The aspect ratio should be less than 0.2 (*1*). Earth pressure cells can be retrieved after use with care. Florida currently uses the Geokon, Inc. model 3510 earth pressure cell. Specifications for this pressure cell are shown in TABLE 5.

TABLE 5 Geokon 3510 Specifications

Parameter	Specification
Transducer Type	Semi Conductor
Output	2m V/V, 0-5 VDC, 4-20mA
Plate diameter	9 inches
Temperature range	-20°C to 80°C
Material	304 Stainless Steel

Installation

1. Prior to installation, connect each pressure gauge to the DAQ system to verify functionality. The lead wire may also need to be extended. Specifically, the following measurements should be verified:
    a. Gauge produces an output signal.
    b. Baseline (unloaded) response is stable over several seconds.
    c. Gauge responds as expected to stimulus.
    d. Gauge baseline (unloaded) signal is within acceptable range.
2. Mark locations on the unbound material surface. Typically, the pressure gauges will be placed directly below the wheel path. Use a fixed reference point that will be available before and after construction and measure distance, offset, and depth to each pressure gauge using string lines or more advanced survey methods.
3. Place a small amount of sand below the pressure cell to protect the components from rocks.
4. Level the pressure cell by pushing or lightly hammering (using a rubber mallet) the raised edge. Cover the pressure cells and lead wire with sand to ensure protection of all components (FIGURE 16).

FIGURE 16 Placing and leveling pressure cells.

5. Confirm the position and elevation of each pressure cell after placement.
6. Once the pressure cells are secured, double-check the functionality (step 1). This will likely be the last chance to replace nonfunctioning or problematic gauges.
7. After construction, confirm each pressure cell survived by repeating step 1.

SURFACE DEFECTS

Surface Deformation

Two 16 kHz frequency lasers are used to measure the surface profile of the trafficked test section. As shown in FIGURE 17, the lasers are mounted 30 inches apart on either side of the load carriage. The lasers, model SLS 5000™ manufactured by LMI Silicon, have a resolution of 0.025 percent of the measurement range. An important factor to consider while selecting laser configuration is the width of the HVS loaded area. To some extent, this is governed by the maximum transverse wander capability, and cannot exceed half of the maximum wander width. Most importantly, the surface profile should be wide enough to accurately map both the wheel path and the adjacent unloaded area.

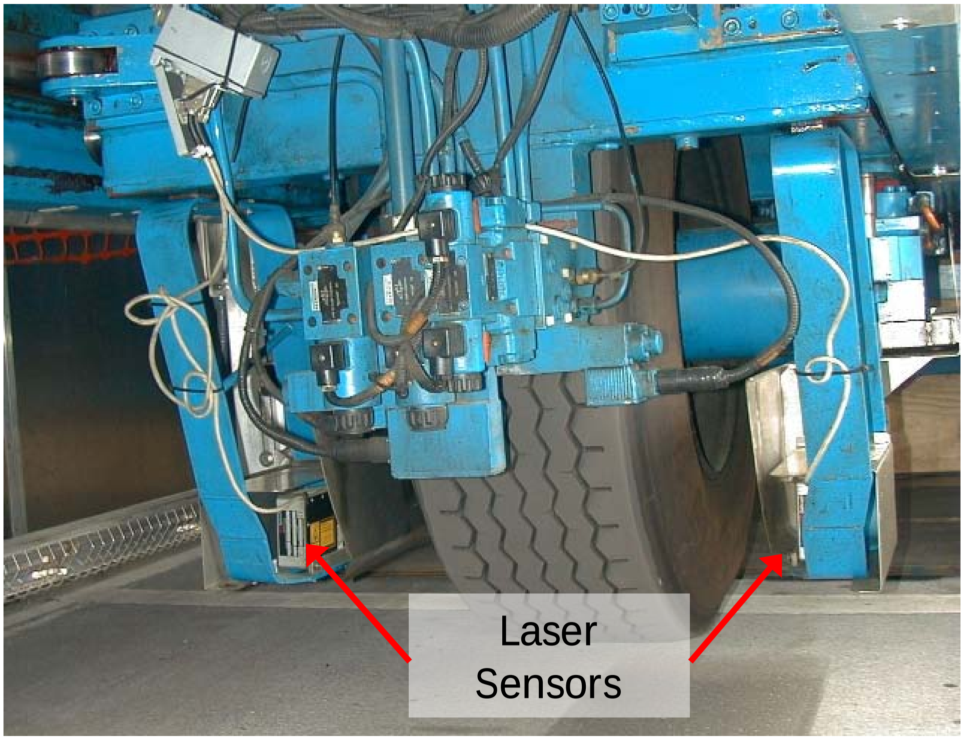

FIGURE 17 HVS laser profiler system.

The data collection and analysis methods were researched and implemented soon after Florida's purchase of the HVS. More detailed information can be found elsewhere (*6*). Data is collected at a 2.5 mph operating speed. One complete profile takes approximately 15 minutes. FIGURE 18 shows a schematic of profile data collection on a representative test section. The wheel carriage starts from the bottom left hand corner and travels longitudinally along the test section to the extreme position on the top left corner. This provides two longitudinal profiles, one from each laser. Due to their positioning on the carriage, the left laser collects data well outside the loaded wheel path while the right laser collects data from the wheel path. One end of the beam (on which the load carriage is mounted) is then kept fixed, while the other end is laterally shifted 25.4 mm (1 in). The wheel carriage then returns along this diagonal path. Again, two longitudinal profiles are generated along this path. The process of longitudinal and diagonal data collection continues as the carriage works its way left to right across the test section. As the carriage approaches the right limits of the profile, the left laser collects data from within the loaded wheel path and the right laser is well outside the wheel path. The lasers have been mounted on the carriage such that at some point in the data collection process, the left laser begins to travel directly over the same legs on the pavement that the right laser has already measured, effectively creating an overlap of longitudinal profiles. Each longitudinal and diagonal profile generates a total of 134 sets of data.

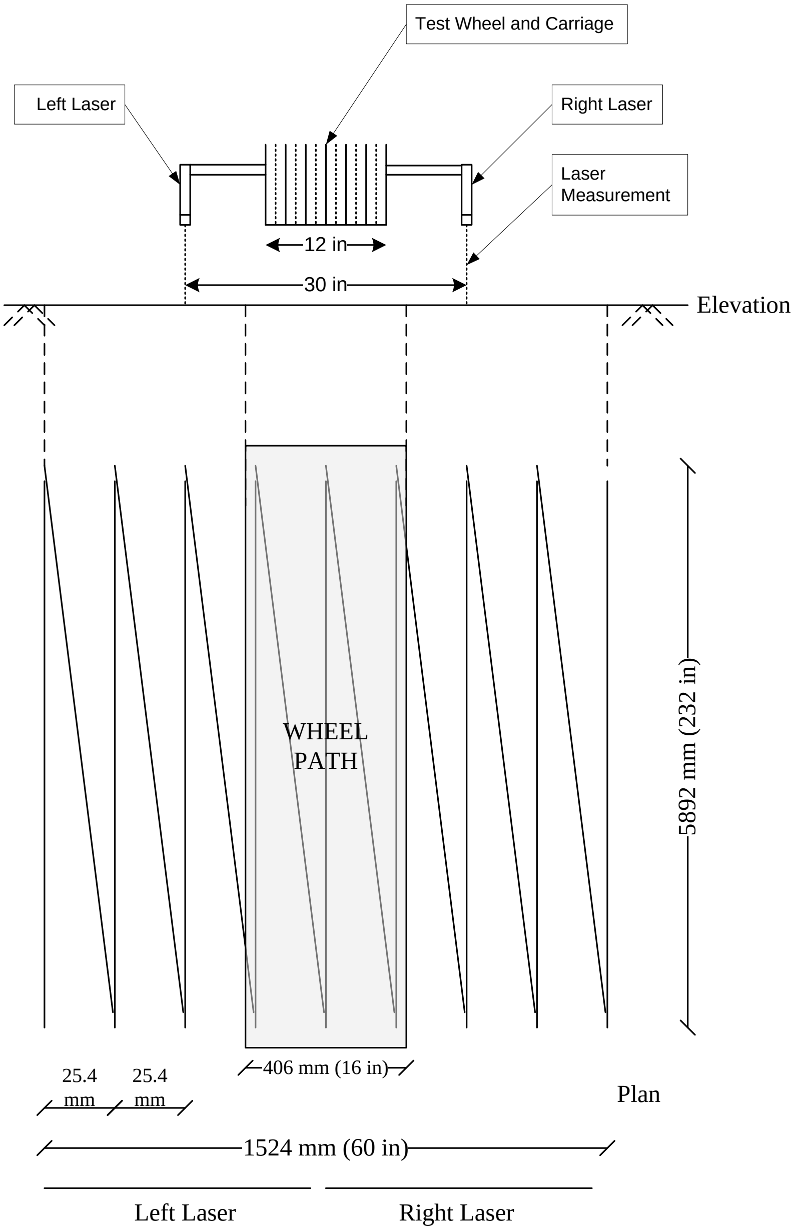

FIGURE 18 Diagram of APT test track laser measurement.

Laser data is averaged by the data acquisition system in real-time at every 4 inches in the longitudinal direction. Thus a total of 58 data points 4 inches apart are collected and recorded from each laser path. The resulting data file comprises of a data array of 58 rows and 134 columns as shown in FIGURE 19, covering approximately 19 feet by 5.5 feet of pavement surface. The raw data is then saved in an ASCII format in a database. At the start of HVS testing, an initial profile is acquired of the unloaded surface. This profile is used as a reference measurement for all subsequent profiles acquired on that pavement test section. Subsequently, the resulting profiles are acquired after every 100 passes up to a total of 1000 passes. Thereafter, the data collection interval is successively increased with increasing number of HVS passes. A series of Visual Basic for Applications (VBA) macros were originally used to automatically process the array of laser data. Later, the code was converted to MATLAB. Currently, data is automatically processed and graphed using LabVIEW. A three-dimensional surface profile is shown in FIGURE 20.

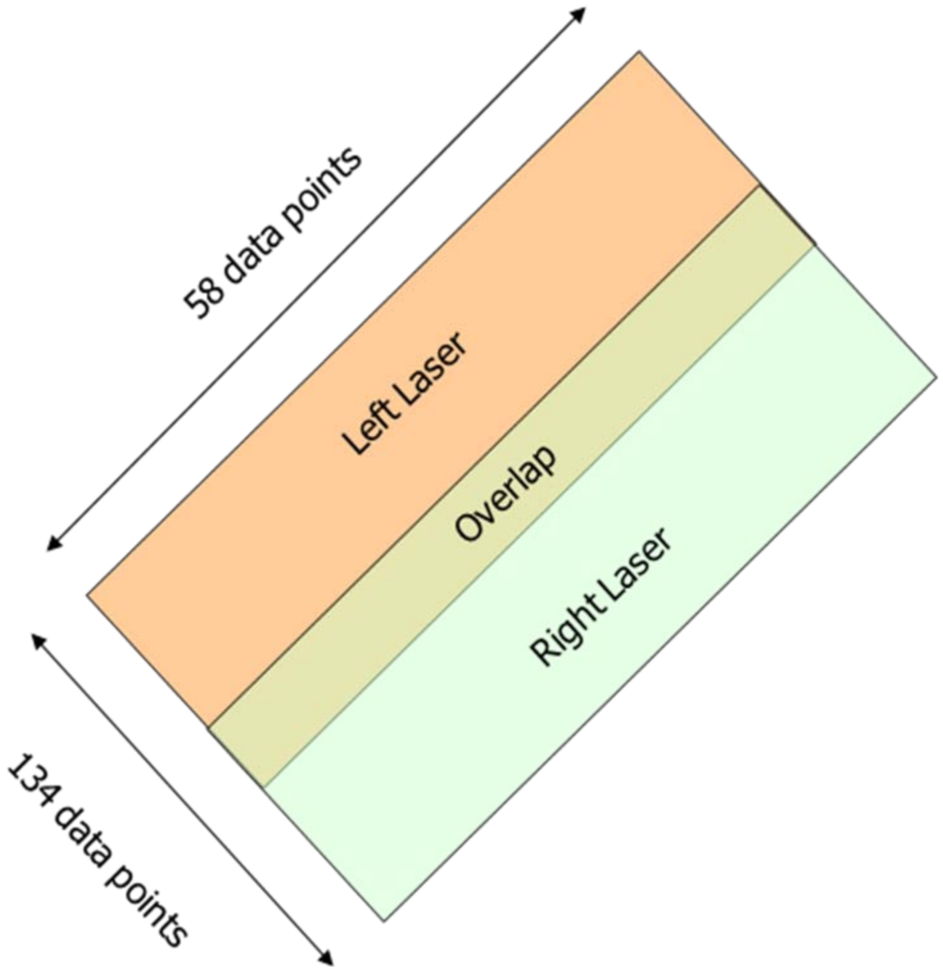

FIGURE 19 Laser profile data array.

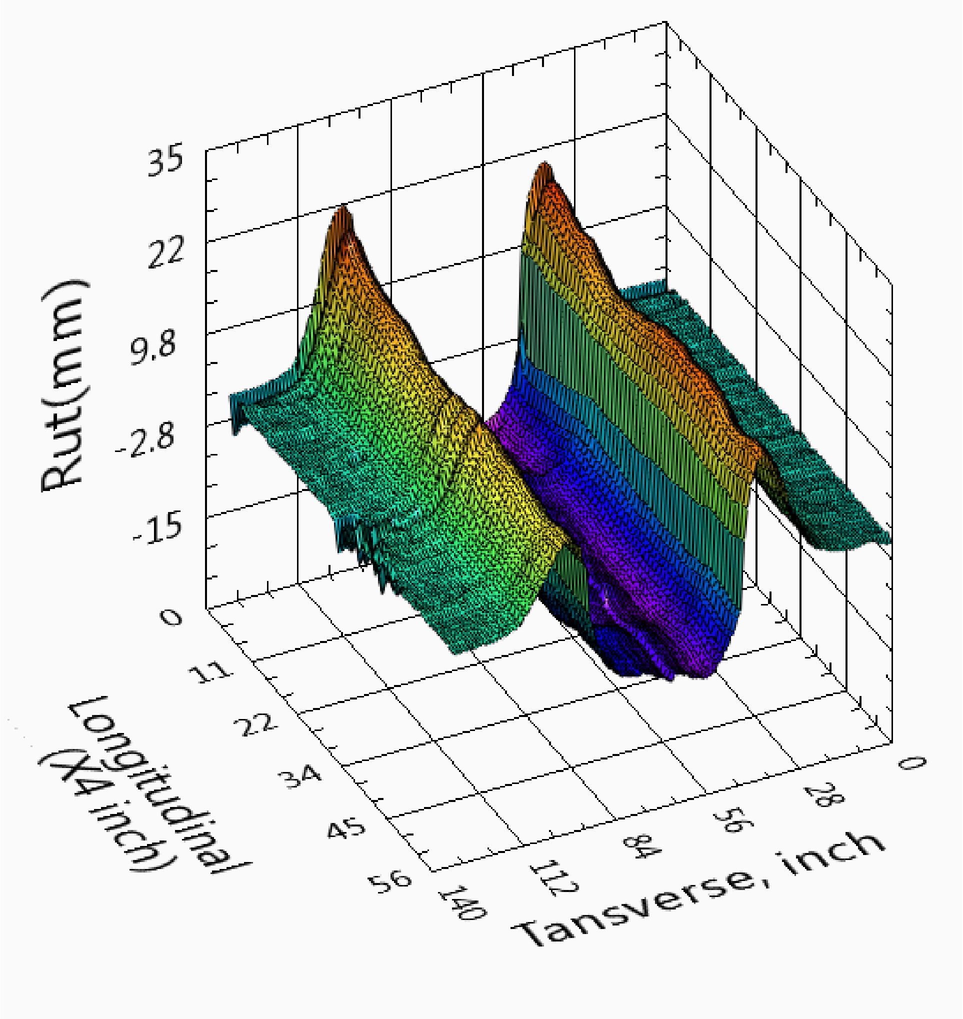

FIGURE 20 Three-dimensional test track surface profile.

Surface Cracking

A camera system was developed in-house to detect and measure development of surface cracks. A National Instruments NI1742 camera is used for the image acquisition and processing. The camera has a built in processor so that the code written in the LabVIEW coding language can be installed directly on the camera. The camera also includes input and output terminals that can be used to trigger the image acquisition or trigger other devices such as lights, valves, or other sensors. The camera is mounted to a bracket installed above the wheel carriage as shown in FIGURE 21. Proximity sensors are used to automatically trigger the camera to collect images at predefined distances to ensure coverage of the entire wheel path. The distance from the pavement and lens focal length were investigated to ensure adequate resolution for detection of cracks. The images are sent over the network to a computer where they are spliced together and are available for further analysis.

FIGURE 21 Camera mounted for crack detection.

Image analysis is performed using LabVIEW. Cracks that are fairly wide and distinct can be detected and measured with no assistance. However, cracks are typically traced with a silver paint pen to guarantee detection and provide better accuracy. Cracks are identified based on an analysis of pixel intensity. The length of the cracks and location along the rut are recorded to an image and transferred to an Excel spreadsheet. FIGURE 22 shows a screen capture of the analysis of a pavement section with several transverse cracks. An image of the total test section spliced together from multiple images (approximately 20 feet long) is recorded so that crack progression can be documented.

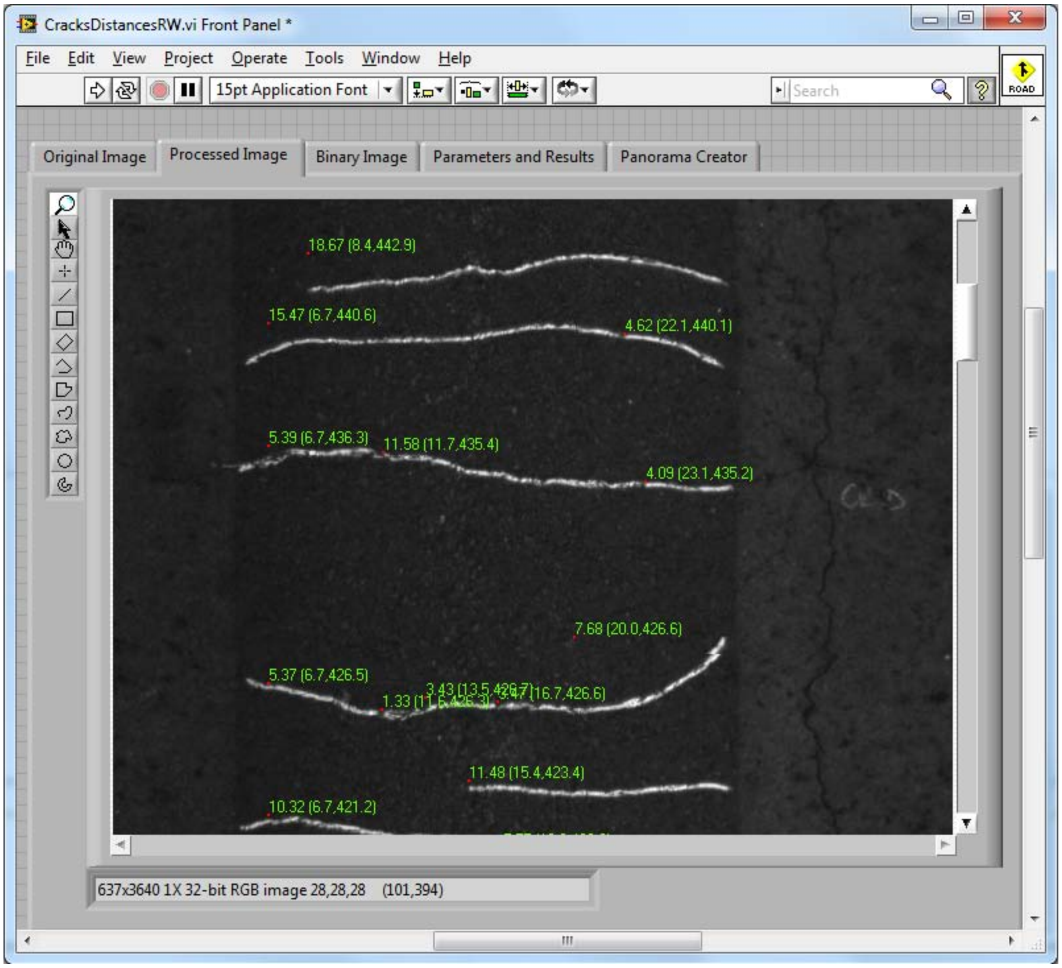

FIGURE 22 Crack detection analysis.

ENVIRONMENTAL SENSORS

Typical environmental parameters that may be useful to pavement related performance include temperature, rainfall, and groundwater elevation. Since APT is conducted under controlled conditions and for relatively short durations HMA temperature is often the only environmental parameter that is measured. Soil moisture is also monitored when the water table is adjusted in the outdoor test pits.

Temperature

Thermocouples are widely used for temperature measurement because of their excellent service life, ease of field installation, and price. A thermocouple is a junction formed from two dissimilar metals. A temperature difference causes a temperature dependent voltage to be developed at the junction. FDOT uses a type K (Ni-Cr/Ni-Al) thermocouple for all asphalt pavement temperature measurements. The particular thermocouple employed by FDOT, shown in FIGURE 23, is custom made by a local vendor and can be manufactured to measure temperatures at multiple depths. Previously, a Type J (Fe/Cu-Ni) thermocouple was used but oxidation of the thermocouples was evident after repeated use.

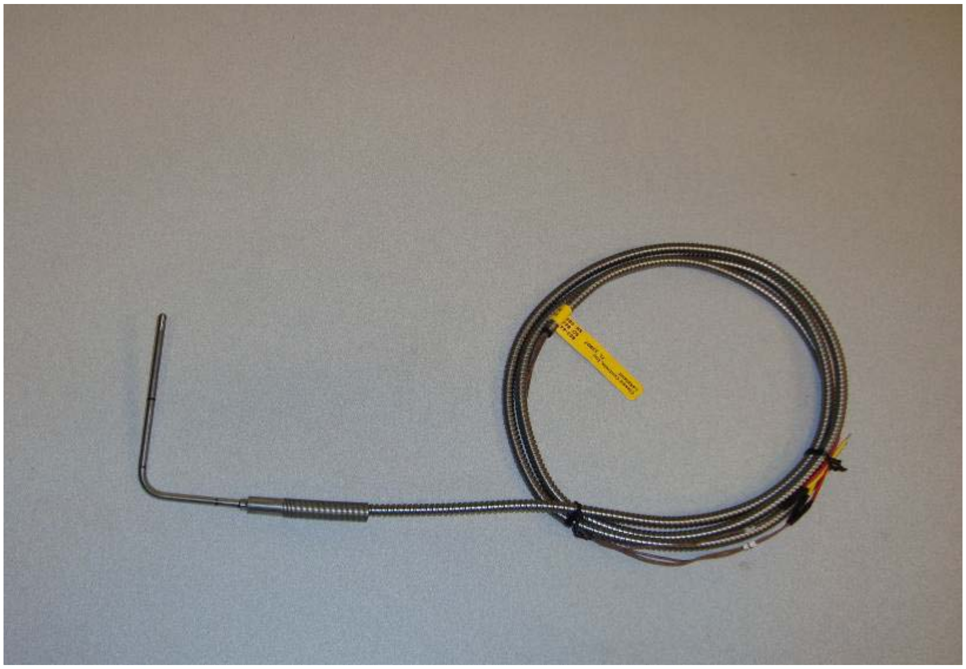

FIGURE 23 Type K thermocouple.

Soil Moisture

Soil moisture is often measured when evaluating pavement materials using the outdoor test pits. Each pit is surrounded by a sump with an interconnecting channel system for controlling the water table. Moisture•Point probes and a data logger system manufactured by Environmental Sensors, Inc. are utilized for this purpose (*7*). These particular probes use time domain reflectometry (TDR) to estimate moisture content. TDR is a method of measuring high-frequency electrical signal propagation times, typically in the nanosecond range (*8*). TDR technology is applied to soils to indirectly measure the average dielectric properties of the soil system. The apparent dielectric constant of a soil system is the average of the dielectric constants of the four major soil components: air, soil, bound water, and free water. Most sands, clays and organic materials have dielectric constants from 2 to 5, while water has a dielectric constant of approximately 81 and air has a dielectric constant of 1 (*8, 9*).

Two Moisture•Point probes and a data logger are shown in FIGURE 24. The probes come in various lengths and estimate the soil moisture in fixed increments of 6 inches. The probe is a rectangular rod constructed of two thin stainless steel bars separated by epoxy. To install the probes, the asphalt is cored and a rigid rod is hammered into the soil and then retracted. The probe is then inserted into the hole. The probe is connected to the data logger when moisture measurements are required (*7*).

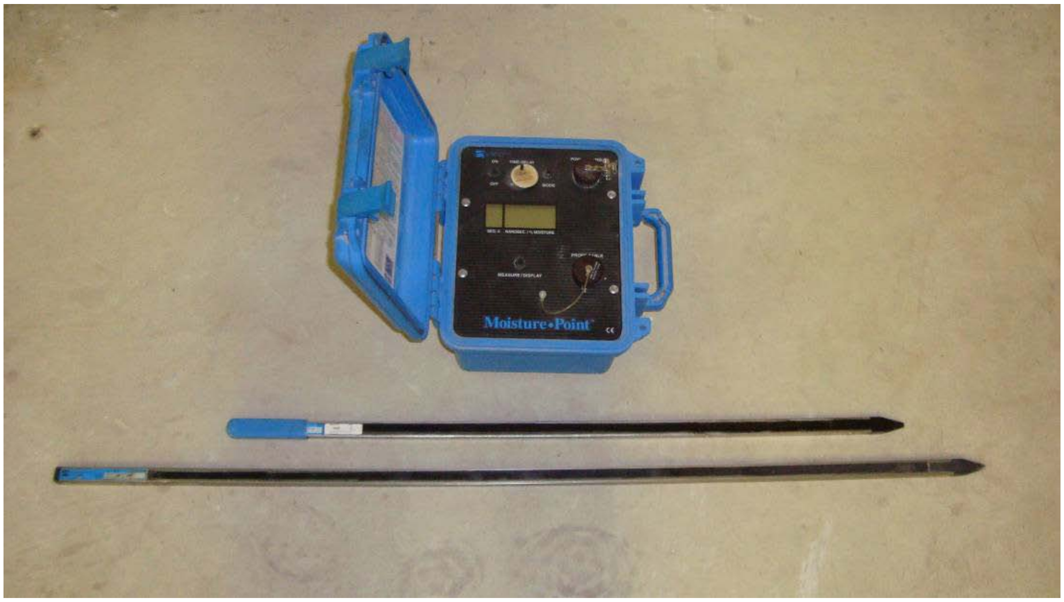

FIGURE 24 Moisture probes and data logger.

OTHER INSTRUMENTATION

Linear Voltage Displacement Transducer

The linear variable displacement transducer (LVDT) is a common type of electromechanical transducer that can convert rectilinear motion into a corresponding electrical signal. The LVDT has been incorporated into a variety of pavement response sensors. The single-depth deflectometer (SDD) and multi-depth deflectometer (MDD) have been used to measure deflection of pavement layers. Joint deflection measurement devices (JDMD) and edge deflection measurement devices (EDMD) have been used to measure deflection of concrete pavement joints and edges due to thermal movement and tire loads.

FDOT has used LVDTs to measure concrete joint movement due to thermal expansion and curling. The LVDTs shown in FIGURE 25 were manufactured by Macro Sensors (model GHSD 750-500). These sensors have a 1 inch range and are constructed of stainless steel and and are hermetically sealed for rugged conditions (*10*). Additional information is shown in TABLE 6 Brackets constructed from Invar 36 (36% Nickel/Iron Alloy) were secured on either side of a concrete pavement joint. Invar 36 was chosen as the bracket material due to its uniquely low coefficient of thermal expansion (COTE). LVDTs were secured to the brackets in a fashion to measure horizontal and vertical movement as shown in FIGURE 25.

FIGURE 25 Measurement of concrete joint movement with LVDTs.

TABLE 6 LVDT Specifications

Parameter	Specification
Range	± 0.5 inch
Input Power	± 15 V DC
Full Scale Output	0 to 10 V DC
Repeatability Error	< 0.000025 inch
Operational Temperature	0°F to 160°F
Construction	Stainless steel, heretically sealed

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