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16. Abstract

In this project a system for monitoring construction of flexible pavement layers by using an accelerometer mounted on a smooth-drum vibratory compactor was tested on numerous TxDOT projects. Projects tested included untreated subgrade, lime-treated subgrade, cement-treated subgrade, and flexible base. Results showed the roller measurements relate to the stiffness of the pavement foundation layer. The relationship between the roller drum displacement and pavement layer stiffness properties must be calibrated at the jobsite. This report presents a brief summary of the test system, example results, and draft construction specifications and a draft test procedure.

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PILOT IMPLEMENTATION OF INSTRUMENTED ROLLERS FOR MONITORING FLEXIBLE PAVEMENT CONSTRUCTION

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ACKNOWLEDGMENTS

This project was made possible by the Texas Department of Transportation and the Federal Highway Administration. Special thanks must be extended to Zhiming Si, P.E., for serving as the implementation director, and Caroline Hererra, P.E., for serving as the program coordinator.

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CHAPTER 1

INTRODUCTION TO THE RAM SYSTEM

SUMMARY

The roller accelerometer monitor (RAM) system consists of an accelerometer that mounts onto the vibrating arm of a compaction roller and a computer system for collecting and processing the roller drum vibration data. By double-integrating the measured accelerations, the system documents the amplitude of the roller drum displacement, termed the instrumented roller value (IRV). The purpose of the system essentially is to use the vibratory roller as a rolling stiffness meter. Ideally, the roller drum displacements relate to pavement layer properties so that the roller data can provide a useful quality control or quality assurance function. The relationship between the roller drum displacement and pavement layer properties must be calibrated at the jobsite. This report describes the basics of using the roller system, example field results, and a draft construction specification and test procedure for using the RAM system for testing flexible pavement construction projects.

PRINCIPLE OF OPERATION

Figure 1.1 illustrates example data from the RAM system. The top graph shows the roller drum position with distance. Filtering out the low frequencies (pavement roughness) produces the lower graph, which shows the roller response to the pavement system without the influence of pavement roughness.

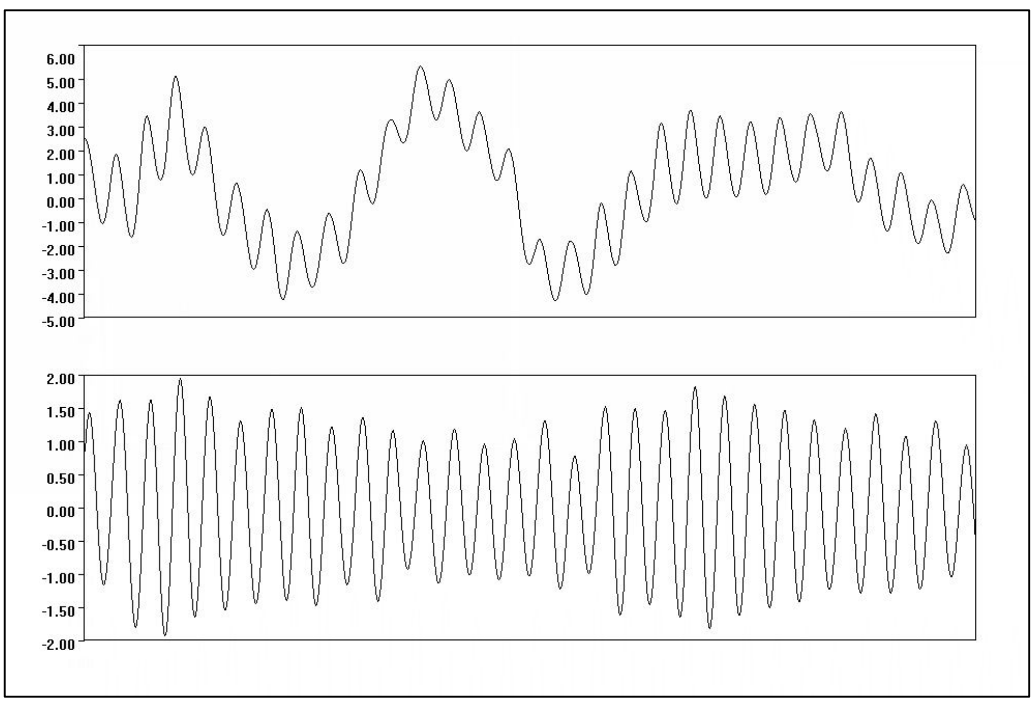

Figure 1.1. Example Raw (top) and Filtered (bottom) Roller Drum Displacement Data.

Using the filtered data, the amplitude of the roller drum displacement waveform can be determined and plotted with distance. Figure 1.2 shows an example of this plot from two repeat tests at a short pavement section at Texas A&M's Riverside Campus. The plot also shows the subgrade modulus with distance as measured with a portable falling weight deflectometer (PFWD). The data show that the roller drum displacement increases with higher pavement stiffness. Essentially, the roller "bounces" more off of a stiffer pavement foundation. It is this dependency on pavement stiffness that enables the roller to provide a measurement function.

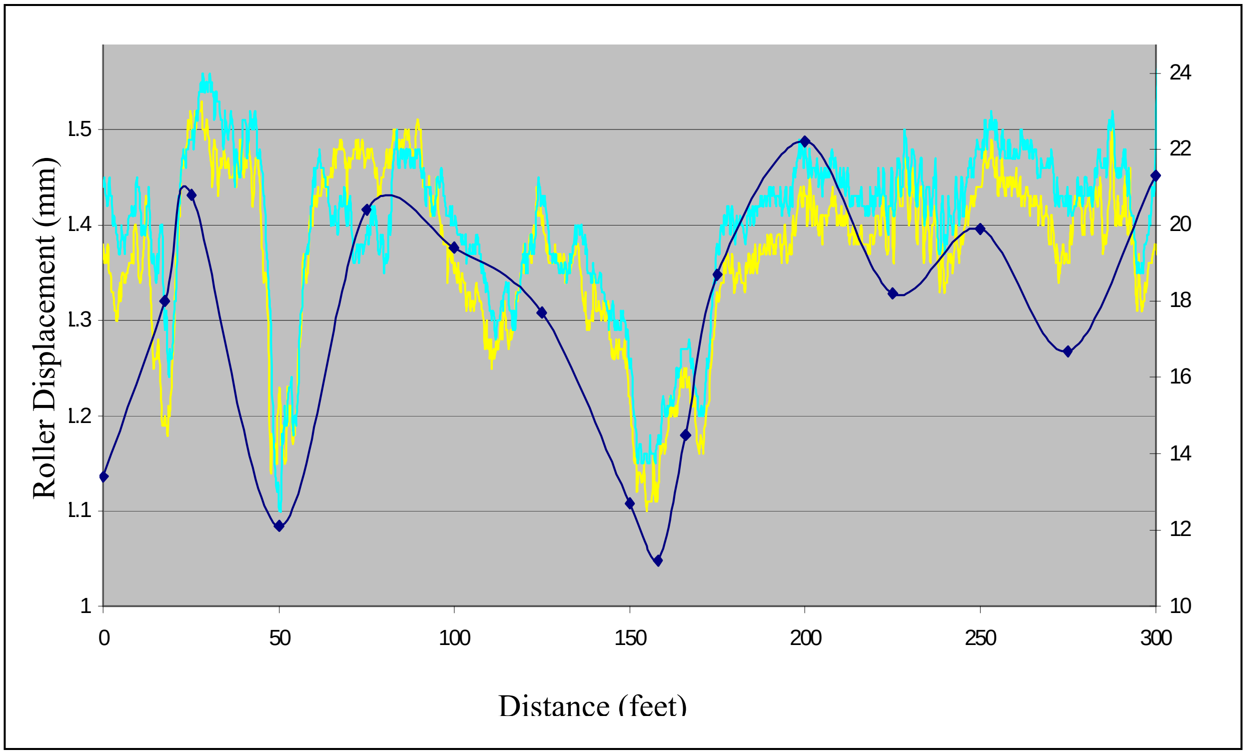

Figure 1.2. Roller Drum Displacement and Pavement Layer Stiffness with Distance.

HARDWARE COMPONENTS

The RAM system consists of an accelerometer, accelerometer mount, signal conditioner, distance measuring instrument (DMI), DMI mount, computer system, computer mount, data acquisition card, battery, power inverter, and necessary connection and power cables. Figure 1.3 shows the primary system components. The current RAM system still uses a distance encoder for positional referencing. Integration of submeter accuracy GPS should be feasible with the system; however, this integration was not possible within the pro-forma expenses anticipated for acquiring the other critical components of the RAM systems.

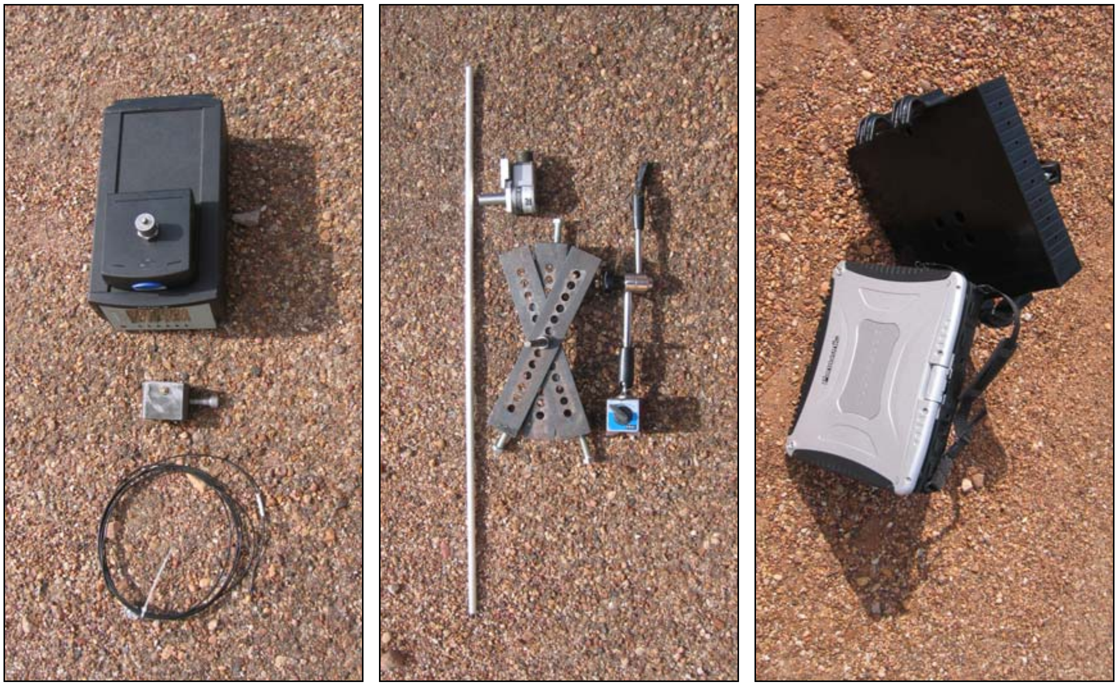

Figure 1.3. RAM System Components.
L to R: accelerometer components, DMI components, and computer components

SYSTEM INSTALLATION

Product 5-4774-01-P2, available from the Texas Transportation Institute (TTI), contains detailed procedures and video of how to install and operate the RAM system. Product 5-4774-01-P1 contains a detailed written user's manual. In summary, installation requires the user to:

- Attach the DMI mount and DMI to the hub of one of the paver wheels.
- Stabilize the DMI using the stabilizer assembly.
- Attach the accelerometer mount on the vibrating arm of the roller drum.
- Attach the accelerometer to the accelerometer mount.
- Secure the signal conditioner, computer system, and battery on the operator's platform.
- Connect the accelerometer to the signal conditioner using the connection cable.
- Connect the signal conditioner to the computer using the data transfer cable.
- Connect the power cord between the battery and the computer system.

CHAPTER 2

TYPICAL FIELD TEST RESULTS

SUMMARY

Testing the RAM system on numerous projects revealed that the roller drum measurements relate to the stiffness of the foundation layer. Data collected on projects ranging from untreated subgrade, lime-treated subgrade (LTS), cement-treated subgrade, and flexible base led to this conclusion. The sections below present example data from projects tested.

SH 21 UNTREATED SUBGRADE

On this project, after screening a section of the prepared untreated subgrade with the instrumented roller, nuclear density and dynamic cone penetrometer (DCP) tests performed showed the roller did not correlate to density or the stiffness of the surface layer. Rather, the roller correlated with the stiffness of the subsurface foundation layer. Figures 2.1 through 2.3 illustrate these results. A Cat CS 433, with a 66-inch drum, an operating weight of 14,875 pounds, and a vibration frequency of 32 Hz was used at a travel speed of approximately 2-4 mph.

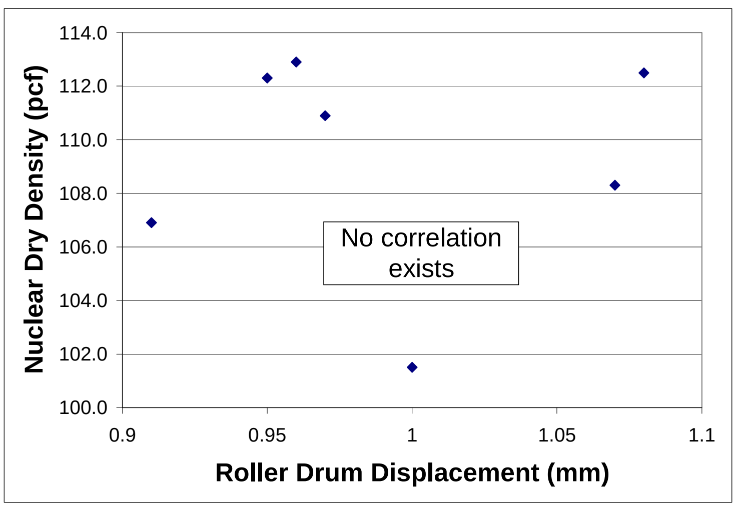

Figure 2.1. Density vs. Roller for SH 21.

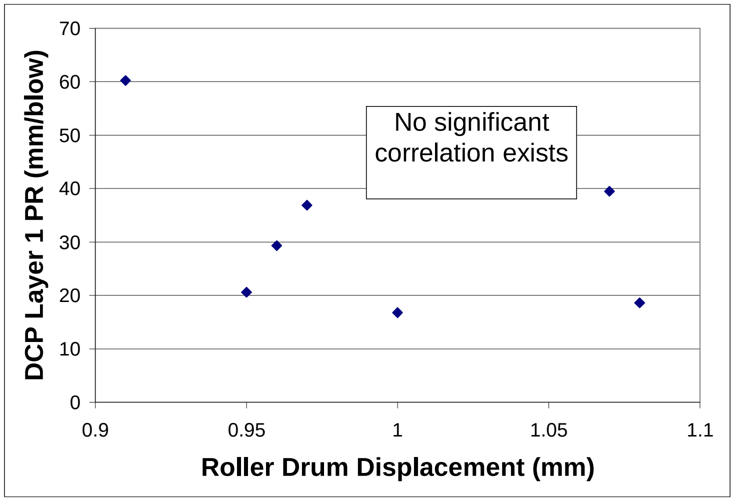

Figure 2.2. DCP Layer 1 Penetration Rater (PR) vs. Roller for SH 21.

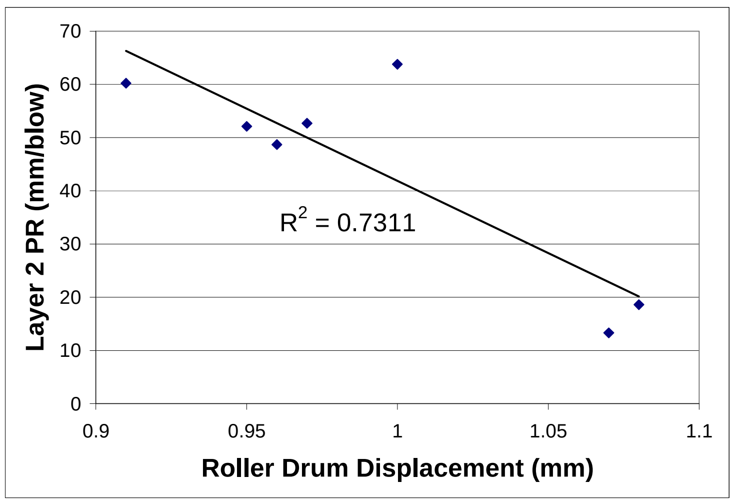

Figure 2.3. Layer 2 PR vs. Roller for SH 21.

To further validate these findings, Table 2.1 presents summary data from the locations with the highest and lowest roller drum displacements. The data show:

- The weakest location based on the roller had a surface layer stiffness equal to the stiffest location. However, beyond 9 inches in depth, the stiffness at Station 97+04 deteriorates substantially. Therefore, the roller is responding primarily to this foundation layer.
- Both nuclear and laboratory density show negligible differences in moisture content or density among the two test locations.
- Laboratory resilient modulus tests confirm the roller accurately identified the location of weaker foundational stiffness.

Table 2.1. Summary of SH 21 Untreated Results.

Station	IRV (mm)	DCP Data				Nuclear Data**		Lab Shelby Tube Data			
		Layer	Thickness (inches)	PR (mm/blow)	E (ksi)	Dry Density (pcf)	Percent Moisture	Dry Density (pcf)	Percent Moisture	Lab E (ksi)***	PI
97+04	0.95	1	8.9	20.6	11	111.5	17.7	109.3	17.7	11.4	32
		2	20.4	52.1	5.7						
97+38	1.08	1	29.9*	18.6	11.9	112	17.6	110.9	17.2	59	26

*No distinct layer breaks identified

**Average of 6 and 12 inch readings, which differed by at most 1.6 pcf and 0.2 percent moisture

***Tested from Shelby tube samples obtained at 2 to 4 foot depth with 5 psi confining stress and 15 psi deviator stress

SH 21 LIME-TREATED SUBGRADE

On this project, the roller screened a section of lime-treated subgrade. The same Cat CS 433 roller previously described was used. Follow-up work revealed the roller data did not correlate to properties of the LTS. Instead, the roller correlated to the stiffness of the foundation layer beneath the LTS. Figure 2.4 shows typical DCP data from the project, and Figures 2.5 and 2.6 illustrate the relationship between the roller data and DCP properties for the pavement layers.

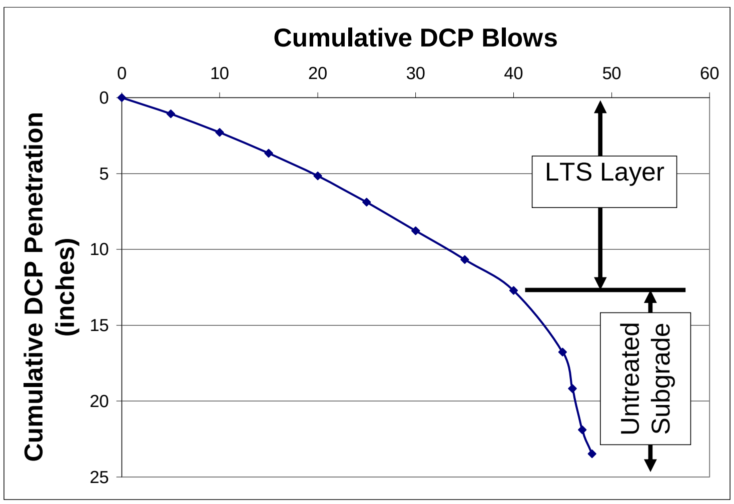

Figure 2.4. Typical DCP Pattern for SH 21 LTS.

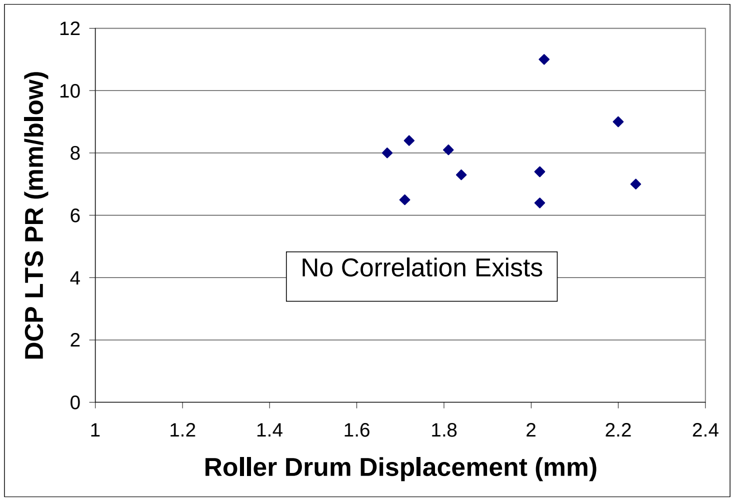

Figure 2.5. LTS Penetration Rate vs. Roller for SH 21 LTS.

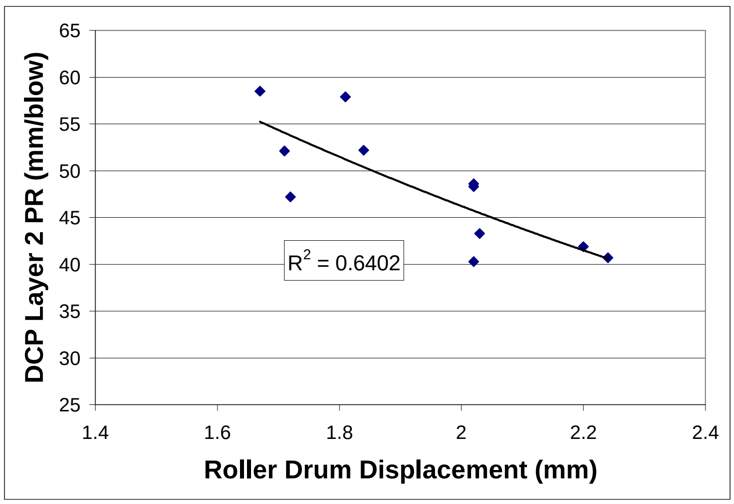

Figure 2.6. Layer 2 PR vs. Roller for SH 21 LTS Section.

SH 130 UNTREATED SUBGRADE

On this project, the roller screened a section of untreated subgrade then researchers performed follow-up tests with nuclear density, dirt seismic pavement analyzer (DSPA), PFWD, and DCP spot tests. The results again showed that the roller data did not correlate to density, and the roller correlated to the stiffness properties of the foundation material. A Cat CS 563-E roller was used at low vibration amplitude and an operating speed of approximately 2 mph. This roller has an operating weight of 24,520 pounds, an 84-inch-wide drum, and a vibration frequency of 32 Hz.

Figure 2.7 shows roller data collection in progress. At this site, the pavement system consisted of three distinguishable layers, as Figure 2.8 illustrates. The data revealed the roller correlated to stiffness properties of the lowest identified foundation layer and did not correlate to the top layer of fill at the project site. Figures 2.9 through 2.13 show the correlation (or lack thereof) between the roller data and various spot test devices for the pavement layers.

Figure 2.7 Collecting Roller Drum Displacement Data on SH 130.

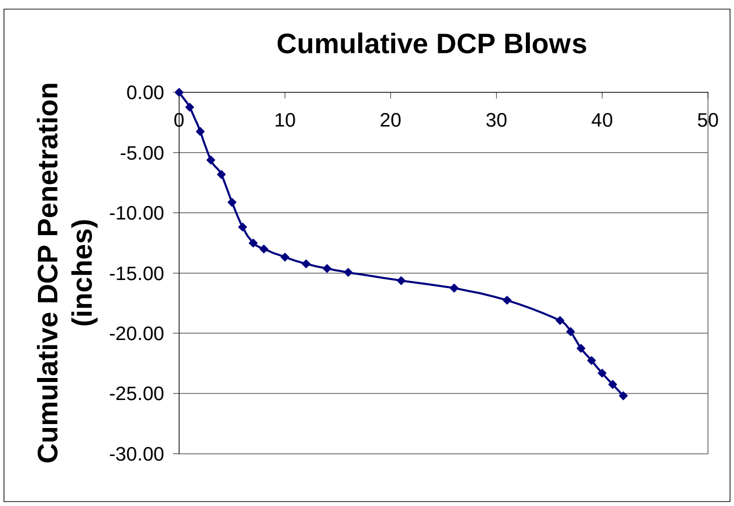

Figure 2.8. Typical DCP Pattern on SH 130.

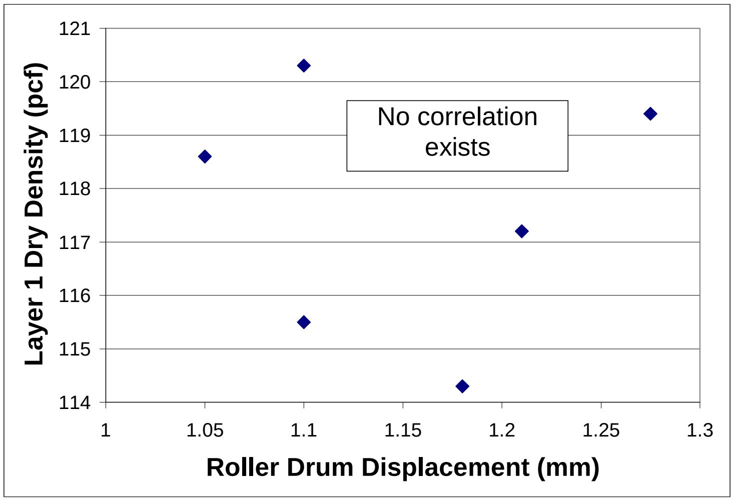

Figure 2.9. Layer 1 Density vs. Roller for SH 130 Untreated Subgrade.

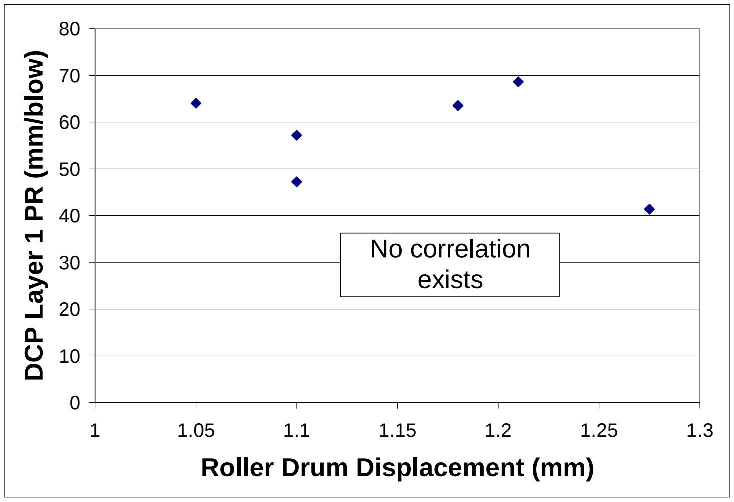

Figure 2.10. Layer 1 PR vs. Roller for SH 130 Untreated Subgrade.

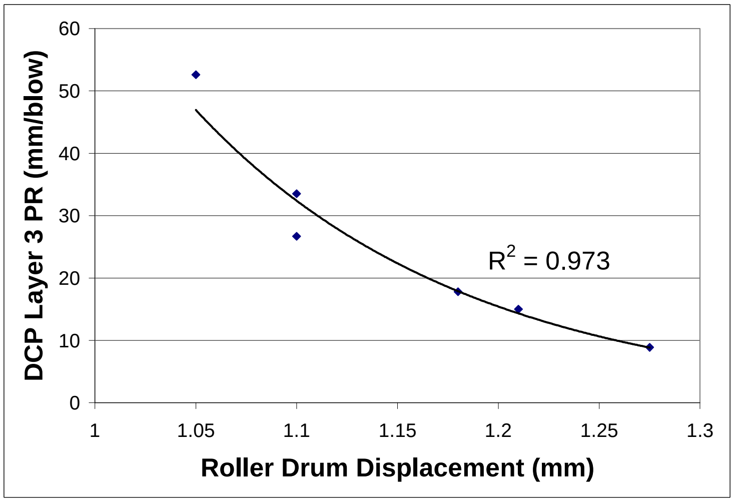

Figure 2.11. Foundation Layer PR vs. Roller for SH 130 Untreated Subgrade.

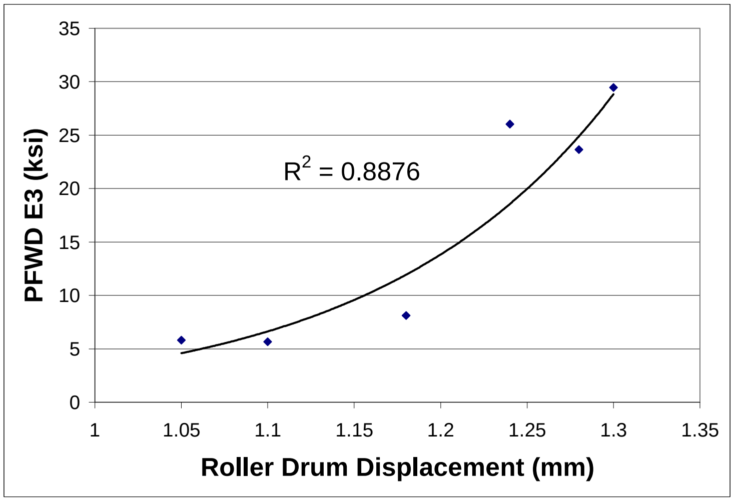

Figure 2.12. Foundation Layer PFWD Modulus vs. Roller for SH 130 Untreated Subgrade.

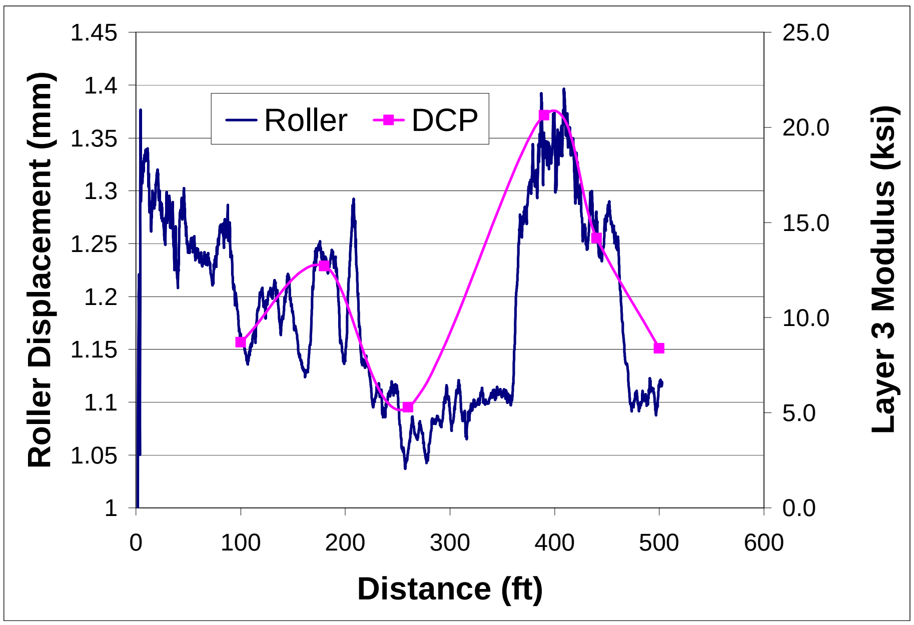

Figure 2.13. Roller Drum Displacement and DCP Foundation Layer Modulus vs. Distance for SH 130 Untreated Subgrade.

SH 130 CEMENT-TREATED SUBGRADE

After cement treatment, the DCP data still showed patterns similar to that illustrated by Figure 2.8. As before, the data did not show a correlation to the density of the top layer. Figures 2.14 and 2.15 illustrate these findings. The roller used was the Cat CS 563-E previously described.

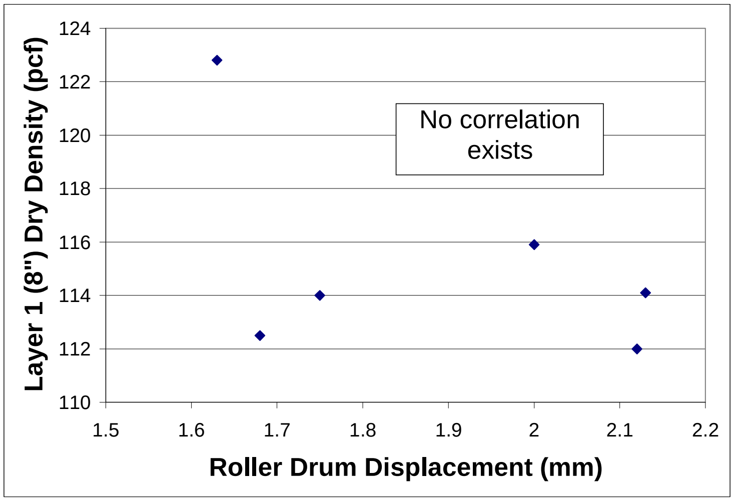

Figure 2.14. Layer 1 Density vs. Roller for SH 130 Cement-Treated Subgrade.

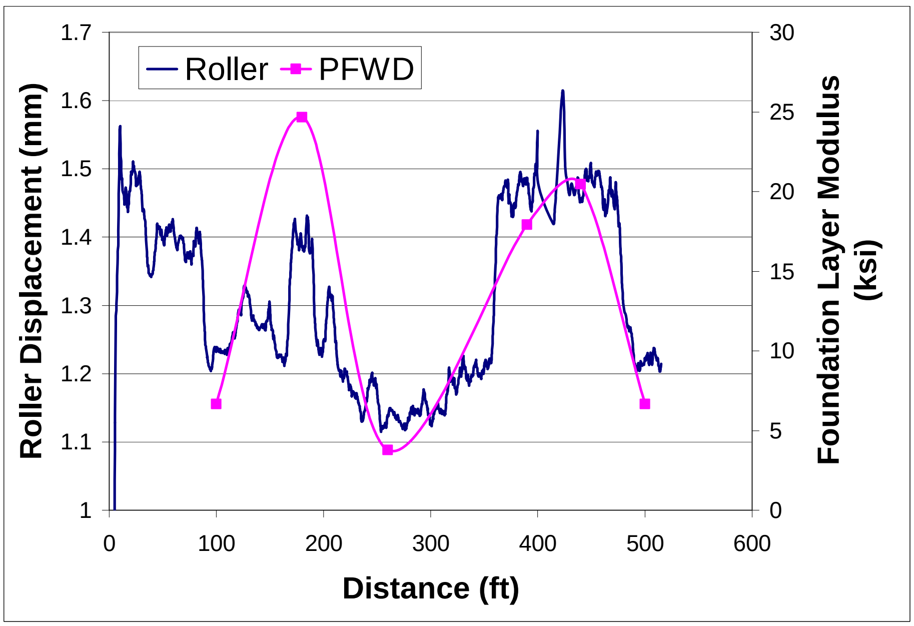

Figure 2.15. Roller Drum Displacement and PFWD Foundation Layer Modulus vs. Distance for SH 130 Cement-Treated Subgrade.

CHAPTER 3

CONCLUSIONS AND RECOMMENDATIONS

In this project, researchers tested the RAM system on a spectrum of field construction projects and used various spot tests including the nuclear density gauge, DCP, and PFWD to evaluate what the instrumented roller system measures. Unfortunately, the data indicate the roller drum displacements do not correlate to density or stiffness properties of the top pavement layer. Instead, the roller response depends primarily on the stiffness of the foundation material. On the projects tested with a typical 12-ton roller, this foundation material typically lies at least 12 inches below the test surface. Therefore, attempts to use this technology for compaction acceptance are discouraged. From the results of this pilot implementation, two potential uses currently exist for further implementation of this system:

1. Use as a proof roller.

At its simplest, the instrumented roller can be used to detect the weak areas in the pavement system. This application would involve screening a section with the roller and spot testing the locations with the lowest roller drum deflection.

2. Use as a compaction monitor to determine when to stop rolling.

Figure 3.1 shows the roller drum displacement with distance for a sequence of three passes over the same section on SH 130. As long as the roller drum displacement increases with additional passes, the pavement system is increasing in stiffness. Therefore, in this application, when the roller drum displacement does not increase with additional roller passes, the operator can stop rolling.

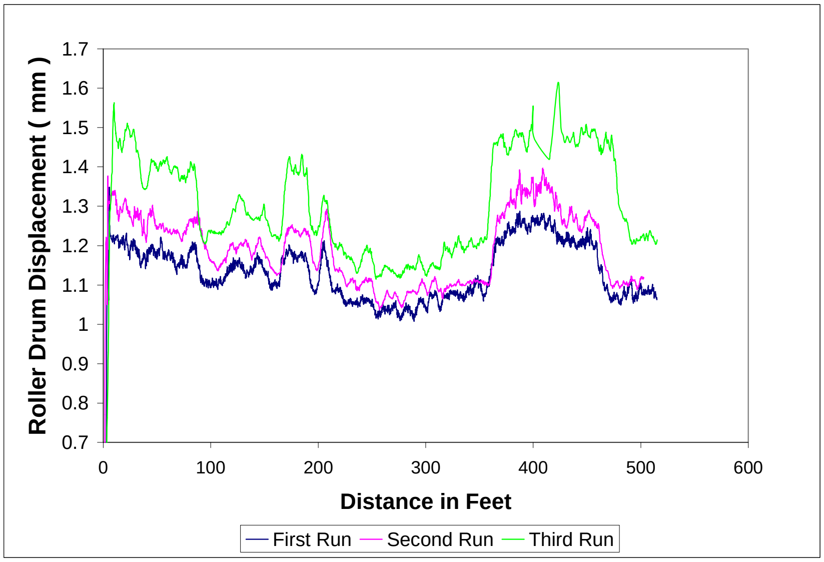

Figure 3.1. Roller Response from Three Runs on SH 130.

Appendix A of this report presents the hardware specifications for the RAM system. Appendix B presents draft construction specifications for using instrumented rollers for proof rolling and compaction monitoring. Appendix C provides a draft test procedure to accompany instrumented rolling.

To help TxDOT implement the RAM technology, this project sought to deliver three units to TxDOT. As of this report date, all components have been procured; however, due to unexpected delays in delivery of certain hardware devices, a repeatability analysis among the three units has not yet been conducted. Therefore, the units have not yet been delivered to the Texas Department of Transportation (TxDOT), and the project director along with TTI are seeking support for a small project for fiscal year 2008 to complete the repeatability testing of the systems.

A side topic of this project was a trial of a non-nuclear moisture probe made by Vertek. Figure 3.2 shows the probe and an example relationship between the true oven-dried moisture content and the probe readings for a sandy subgrade soil. Although the ordinary-least squares slope is 0.77, based upon the degrees of freedom and the standard error of the slope estimate, the slope does not statistically differ from 1.0. Therefore, at least for this material, the Vertek probe provided unbiased moisture readings. Although promising for unconsolidated or extremely poorly compacted soil layers, installation of this probe into compacted pavement layers led the research team to abandon continued testing with the device.

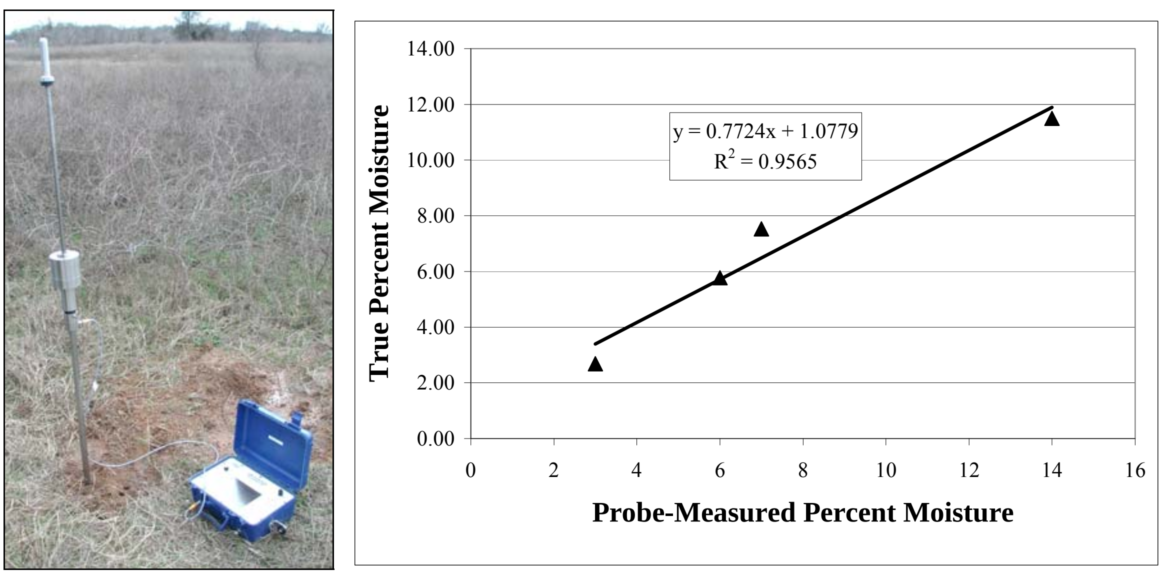

Figure 3.2. Vertek Moisture Probe and Example Calibration Curve.

APPENDIX A

HARDWARE SPECIFICATIONS FOR RAM

Computer Specifications:
Processor speed: 1.8 GHz
Memory: 512 Mb, DDR2, 533 MHz 1 DIMM
Hard drive: 60 GB 5400 RPM SATA
Video Card: Integrated ATI Radeon X1150 or equivalent
Operating System: Windows XP
I/O: 1 USB 2.0

Distance Measuring Instrument Specifications:
Housing configuration: square flange
Shaft loading: up to 40 lb axial and 40 lb radial
Flat on shaft: 0.75 x 0.03 deep
Shaft diameter: 0.37
Shaft seal
Starting torque at 25 °C: 2.5 in-oz maximum with shaft seal
Bearing life: 1.5×10^9 revolutions at rated load
Maximum RPM: 8000
Moment of inertia: 2.0×10^{-4} oz-in-sec^2
Code: incremental
Output format: dual channels with index and complementary output
Cycles per shaft turn: 120
Supply voltage: 5 to 28 VDC
Current requirements: 100 mA typical + output load, 250 mA (max)
Voltage/Output: Vout = Vin
Protection level: reverse, overvoltage, and output short circuit
Frequency response: 100 kHz
Output termination: MS3102R18-1P
Enclosure rating: NEMA 4 & 13 (IP66)
Operating temperature: 0° to 70 °C
Storage temperature: -25° to 90 °C
Shock: 50 g's for 11 msec duration
Vibration: 5 to 2000 Hz @ 20g's
Humidity: 98% RH without condensation

Accelerometer Specifications:
Sensitivity charge (pC/ms-2): 10
Frequency range (Hz): 0.1 to 4800
Mounted resonance frequency (kHz): 16
Temperature range: -100 to 482 °F
Transverse sensitivity maximum (at 30 Hz, 100 ms-2): < 4% reference sensitivity
Transverse resonance frequency (kHz): 4
Maximum operational shock: ± 2000 g peak
Maximum continuous sinusoidal: 2000 g peak
Temp transient sensitivity (3 Hz low lim. Frq. [-3dB, 6 dB/oct]): 0.02 ms^{-2}/°C
Magnetic sensitivity (50 Hz, 0.038 T): 1 ms^{-2}/T
Acoustic sensitivity (154 dB SPL): 0.001 ms^{-2}

Base strain sensitivity (at 250 με in base plane): 0.003 ms^{-2}/με
Humidity: 90% RH non-condensing
Electrical connector: 10 – 32 UNF-2A
Mounting thread: 10 – 32 UNF-2B
Mounting surface flatness: < 3 μm

Signal Conditioner Specifications:
Input type: charge input
Connector: TNC
Input grounding: single-ended or floating
Max Input:
    Differential charge: 10 nC (peak)
    Common mode voltage: 4.2 V (peak)
Common mode rejection ratio: > 50 dB
Amplifier gain: 0.1 mV/pC to 10 V/pC
Transducer sensitivity range: 10^{-19} to 10^{-6} C/MU
Calibrated output:
    Selectable in 10 dB steps. 100 dB attenuator range
    10^{-15} to 10^{7} V/MU ±1% for 0 °C ≤ T_a ≤ 40 °C and ±2% for -10 °C ≤ T_a ≤ 55 °C
    Frequency range from 5 x f_l to 0.2 x f_u where
    f_l = lower frequency limit: 0.1, 1.0, or 10 Hz
    f_u = upper frequency limit: 0.1, 1, 3, 10, or 100 kHz
Frequency range:
    Acceleration: 0.1 Hz to 100 kHz (transducer cable length < 10m)
    Velocity (optional): 1.0 Hz to 10 kHz
    Displacement (optional): 1.0 Hz to 10 kHz
Low pass filter: 0.1, 1, 3, 10, 22.4, 30, or 100 kHz, attenuation slope 40 dB/decade
High pass filter:
    Acceleration: 0.1, 1.0, or 10 Hz
    Velocity (optional): 1.0 or 10 Hz
    Displacement (optional): 1.0 or 10 Hz
Inherent noise (2 Hz to 22.4 kHz):
    < 5 fC referred to input, -10 °C ≤ T_a ≤ 40 °C
    < 10 fC referred to input, 40 °C ≤ T_a ≤ 55 °C
Harmonic distortion and noise (2 Hz to 22.4 kHz, Q_{in} ≤2 nC peak, V_{out} ≤3.16 V peak): < 0.003% for amplifier gain ≤0.1 V/pC
Environmental susceptibility:
    Magnetic field: <0.2 fC/(A/m)
    Electromagnetic field: <20 fC/(V/m) or <4 fC/V
    Vibration (10 to 500 Hz): <30 fC/(m/s^2)
Output connector: BNC
Output grounding: single-ended or floating
Output impedance: 50 ohm//500 pF
Max output (differential voltage): 3.16 V peak
Max DC offset: ± 25 mV, typically <2 mV

Output protection:

Differential voltage: ≤50 V (peak)

Common mode voltage: ≤15 V (peak)

Common mode rejection: >50 dB (50 to 60 Hz) for common mode voltage ≤2 V peak

Output drive capacity:

100 m of cable length (100 pF/m) to 20 kHz

1000 m of cable length (100 pF/m) to 2 Khz

Channel separation: better than -100 dB at 1 kHz

APPENDIX B
DRAFT CONSTRUCTION SPECIFICATIONS

Instrumented Rolling (Proof Rolling)

1. **Description.** Proof roll earthwork, base, or both to locate unstable, non-uniform, or low density areas.

2. **Equipment.** Provide machinery, tools, and equipment necessary for the proper execution of the work. Provide a minimum 12 ton smooth drum vibratory roller and an accelerometer-based instrumentation system.

   A. **Roller-Vibratory.** Provide a Drum (Type C) roller, with a static weight $\geq$ 12 tons, with a vibration frequency between 28 and 40 Hz, meeting the requirements of Item 210, "Rolling."

   B. **Instrumentation System.** Provide an accelerometer-based instrumentation system, capable of measuring and displaying the roller drum vibration amplitude with distance or GPS location in real time, and capable of saving all data for retrieval by project personnel.

3. **Construction.** Perform proof rolling as directed. Operate the roller at speeds that will produce at least 10 blows per foot unless otherwise shown on the plans or approved. Use the low amplitude setting on rollers with variable amplitude. Overlap passes by 1 to 2 ft.

   - Install the instrumentation system according to the manufacturer's instructions.
   - Initiate data collection and proof roll the section.
   - Provide the data collected to the Engineer for interpretation and spot testing.
   - If an unstable, non-uniform, or low density area is found, correct the area in accordance with the applicable Item.

4. **Measurement.** Rolling will be measured by the hour operated on the surface to be tested.

5. **Payment.** The work performed and equipment furnished in accordance with this Item and measured as provided under "Measurement" will be paid for at the unit price bid for "Instrumented Rolling (Proof Rolling)." This price is full compensation for furnishing and operating equipment and for labor, materials, tools, and incidentals.

Instrumented Rolling (Compaction Monitoring)

1. **Description.** Perform instrumented rolling during compaction of earthwork, base, or both, to evaluate when to stop rolling and where to focus additional compaction efforts.

2. **Equipment.** Provide machinery, tools, and equipment necessary for the proper execution of the work. Provide a minimum 12 ton smooth drum vibratory roller and an accelerometer-based instrumentation system.

   A. **Roller-Vibratory.** Provide a Drum (Type C) roller, with a static weight ≥ 12 tons, with a vibration frequency between 28 and 40 Hz, meeting the requirements of Item 210, "Rolling."

   B. **Instrumentation System.** Provide an accelerometer-based instrumentation system, capable of measuring and displaying the roller drum vibration amplitude with distance or GPS location in real time, and capable of saving all data for retrieval by project personnel.

3. **Construction.** Perform instrumented rolling to evaluate when to stop rolling and where to focus additional compaction efforts.

   - Install the instrumentation system according to the manufacturer's instructions.
   - Initiate and collect instrumented roller data during each pass of the compaction operation.
   - Cease rolling when the instrumentation data show the roller drum displacement does not increase with additional roller passes, or when density tests on the section pass.
   - Provide the instrumented roller data to the Engineer.

4. **Measurement and Payment.** The work performed, materials furnished, equipment, labor, tools, and incidentals will not be measured or paid for directly but will be subsidiary to pertinent items.

APPENDIX C
DRAFT TEST PROCEDURE

Setting Target IRV for Instrumented Rolling

Contents:

Section 1

Overview

This method determines the relationship between the pavement layer modulus and the instrumented roller value (IRV) for purposes of setting the target IRV if desired for assisting with interpretation of proof rolling or compaction monitoring with an instrumented roller system. This Test Procedure must take place in the field during the compaction operations of the pavement layer surface to be tested.

Section 2

Definitions

This test method references the following terms and definitions:

- Instrumented Roller Value (IRV) – the amplitude of the vibration waveform of the compactor drum in millimeters.
- Target IRV – the IRV value at which the compaction process produces the specified pavement layer stiffness.

Section 3

Apparatus

The following apparatus is required:

- Roller - a Drum (Type C) roller, with a static weight ≥ 12 tons, with a vibration frequency between 28 and 40 Hz, meeting the requirements of Item 210, “Rolling.”
- Instrumentation System - an accelerometer-based instrumentation system capable of measuring and displaying the roller drum vibration amplitude with distance or GPS location in real time, and capable of saving all data for retrieval by project personnel.
- Stiffness Measuring Device - a spot test device including either a dynamic cone penetrometer (DCP), portable falling weight deflectometer (PFWD) or portable seismic pavement analyzer (PSPA) for measuring pavement layer modulus.

Section 4

Procedure

The following table lists the steps necessary to determine the relationship between IRV and pavement layer stiffness.

Setting Target IRV for Instrumented Rolling	
Step	**Action**
1	At the construction site, select a pavement area at least 3500 ft^2 to perform the test. For a typical roller this equates to 500 linear feet.
2	Install the instrumentation system according to the manufacturer's instructions.
3	During the compaction process, collect instrumented roller data on the test section.
4	Initiate data collection at the start of the test section. Operate the roller on low amplitude at a speed to produce at least 10 blows per foot.
5	After the instrumented roller traverses the test section, review the plot of IRV with distance for the section. Select a minimum of five spot test locations representing observed low, average, and high IRV values from within the section.
6	Perform a spot test with an approved stiffness measuring device at the centerline of each test location selected. Conduct these tests in accordance with the device manufacturer's instructions and the current state of the practice for the device used. For more reliable results, collect three tests evenly spaced across the roller's width at each test location.
7	Repeat Steps 3 through 6 as the layer compacts to the specified density.

Section 5

Calculations

Calculate the pavement layer modulus value from the stiffness measuring device according to the current state of the practice. If the stiffness measuring device used detects distinct pavement layers, calculate the modulus and thickness of each layer according to the current state of the practice. If more than one test was performed at each location, average the values from that spot.

Using the IRV data in conjuction with the pavement layer modulus measured by the stiffness device, use regression tools to predict the IRV from the layer modulus. Select the function that provides the best fit. If the stiffness measuring device used detects distinct pavement layers, perform this regression for each pavement layer.

Calculate the target IRV by inputting the target layer modulus into the regression equation developed. Obtain the target layer modulus either from plans or from the project Engineer.

Section 6

Test Record

Record the project identification, test location, test date, layer tested, and other relevant project information for future reference. Record the spot test data for each spot test location.

Graph

Plot the IRV versus the pavement layer modulus as Figure B.1 shows. When the stiffness measuring device discerns different pavement layers, plot a separate graph for each pavement layer.

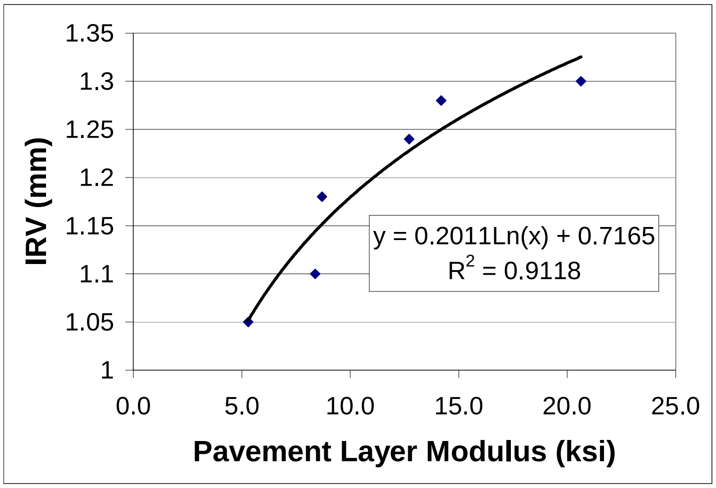

Figure B.1. Example IRV vs. Pavement Layer Modulus.

Plot the IRV and the layer modulus with distance as Figure B.2 shows. When the stiffness measuring device discerns different pavement layers, plot a separate graph for each pavement layer.

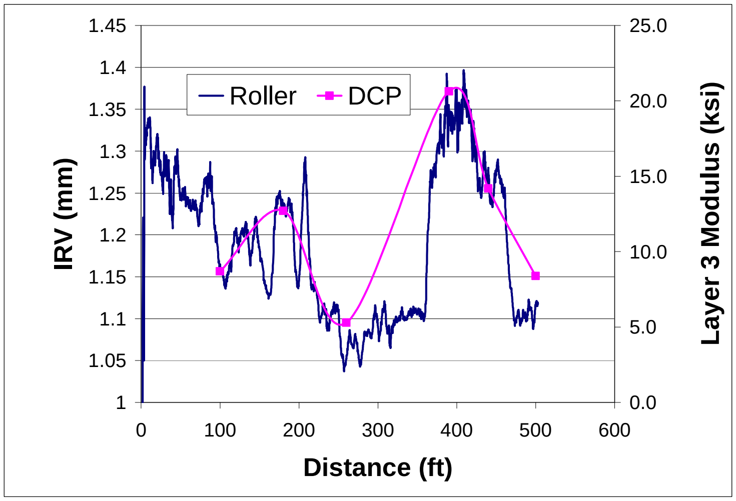

Figure B.2. Example IRV and Layer Modulus with Distance.

Section 7

Reporting Test Results

Report the following:

- equations and R^2 between IRV and pavement layer modulus values, and
- target IRV value to the nearest tenth of a millimeter.