COORDINATION OF LOAD RESPONSE INSTRUMENTATION OF SHRP PAVEMENTS – OHIO UNIVERSITY

FINAL REPORT

OHIO DEPARTMENT OF TRANSPORTATION
And
FEDERAL HIGHWAY ADMINISTRATION

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16. Abstract

The Ohio Department of Transportation constructed an experimental pavement for the Strategic Highway Research Program (SHRP) on U.S. 23 north of Columbus, which included 40 asphalt and concrete test sections in the SPS-1, 2, 8 and 9 experiments. These sections contained various combinations of structural parameters known to affect performance.

To enhance the value of this pavement, sensors were installed in 18 test sections to continuously monitor temperature, moisture and frost within the pavement structure, and 33 test sections were instrumented to monitor strain, deflection and pressure generated by environmental cycling and dynamic loading. Also, two weigh-in-motion systems and a weather station were installed to continuously gather the necessary traffic and climatic information required to properly interpret the performance data. Six universities, including Ohio University which coordinated this effort, were responsible for installing and monitoring the instrumentation. Nondestructive testing conducted with the FWD and Dynaflect, and five series of controlled vehicle tests were performed between 1995 and 1998 to assess the response of these test sections to dynamic loading. This report documents how the instrumentation was installed and monitored, provides details of the controlled vehicle tests, and summarizes results of the nondestructive testing.

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In a project with the size and complexity of the Ohio SHRP Test Road, and with so many agencies involved, it was absolutely vital that all those called upon for assistance shared the vision and completed their assigned tasks accurately and in a timely manner. This cooperation was evident throughout every level of each participating organization. Unfortunately, it will be impossible here to properly acknowledge all those who contributed to the success of this project. We would, however, like to single out individuals and organizations whose efforts were particularly noteworthy.

First and foremost, and without whose support and encouragement this project could not have been initiated, was top management at the Ohio Department of Transportation, including:

Jerry Wray, Director; Ronald L. Zook, Assistant Director and Chief Engineer; Nancy L. Hall, Deputy Director, Office of Executive Management.

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Local industries, no doubt, had reservations from time to time about how the Ohio SHRP Test Road was being designed and constructed, but always took the high road in the interest of the project and the State of Ohio. These include:

Flexible Pavements, Inc., Fred Frecker, Executive Director; Ohio Ready Mixed Concrete Association, Roger Jones, Executive Director; Asphalt Institute, Jorge Villacres, Ohio Office; American Concrete Paving Association, Joe McDaniels, Ohio Office; Ohio Aggregates Association, Bob Wilkinson, Executive Director.

We would like to thank the administration, and students from the universities in the State of

Ohio who completed the instrumentation portion of this project. Last, but not least, we would like to thank Issam S. Khoury, Research Engineer, Ohio University for his effort in the instrumentation of this project.

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CHAPTER 1

INTRODUCTION

In 1987, Congress established the Strategic Highway Research Program (SHRP), a five-year, $150 million research effort to improve the performance of highway pavements and bridges. Eight broad study areas were set up within the program to meet the prescribed goals. One of these areas was defined as Long Term Pavement Performance (LTPP), which was aimed at extending the life of asphalt and portland cement concrete pavements. A series of experiments known as the Specific Pavement Studies (SPS) was developed within LTPP to assess the effect of various structural parameters on pavement performance. A listing is provided in Table 1.1.

Table 1.1 SHRP SPS Experiments

!	SPS-1 A Strategic Study of Structural Factors for Flexible Pavements @
!	SPS-2 A Strategic Study of Structural Factors for Rigid Pavements @
!	SPS-3 A Preventative Maintenance Effectiveness of Flexible Pavements @
!	SPS-4 A Preventative Maintenance Effectiveness of Rigid Pavements @
!	SPS-5 A Rehabilitation of Asphalt Concrete Pavements @
!	SPS-6 A Rehabilitation of Jointed Portland Cement Concrete Pavements @
!	SPS-7 A Bonded Portland Cement Concrete Overlays of Concrete Pavements @
!	SPS-8 A Study of Environmental Effects in the Absence of Heavy Traffic @
!	SPS-9 A Asphalt Program Field Verification Studies @

SHRP convened Expert Task Groups to establish matrices of structural parameters for each SPS experiment which, when constructed and monitored periodically while carrying actual traffic, would define the relative contribution of each parameter to overall pavement performance. State transportation agencies were encouraged to incorporate SPS sections into new and rehabilitated pavements, which met specific climatic, soil, and traffic criteria. The Ohio Department of Transportation (ODOT) wanted to participate, but found it difficult from a public relations standpoint to interrupt traffic on a major highway to construct a series of test sections and return shortly thereafter to replace sections designed for limited service. Additional inconveniences would result from the periodic monitoring required by SHRP.

A 3.5-mile long section of pavement on U.S. 23 in northern Delaware County appeared to be a suitable site for the construction of a series of experimental sections. This was a four-lane facility with an extra wide median constructed in the 1960's to accommodate four additional lanes of divided pavement in the future. By placing SPS sections in the median and having them carry mainline traffic, the original lanes could then be converted into a service road where traffic would be diverted during long term rehabilitation or testing. ODOT management concurred with this concept and construction plans were initiated in 1992.

To obtain maximum benefits from the U.S. 23 site, SPS-1, SPS-2, SPS-8 (AC and PCC), and SPS-9 experiments, consisting of 38 test sections, were designed into the project. By constructing these sections at one location where the climate, soil topography, and to a large extent, traffic were uniform, performance of the individual sections could be compared more directly. During construction, an additional section was incorporated into each of the SPS-2 and SPS-9 experiments, making a total of 40 test sections. Table 1.2 summarizes basic information regarding the project.

The overall objective of the SPS experiment was to evaluate the manner in which various structural parameters affect pavement life. Any premature material failure would seriously impact section performance, thereby tainting the data coming from it and possibly causing it to be removed from the SHRP database. Therefore, to avoid D-cracking in portland cement concrete sections at the U.S. 23 site, rapid testing of local aggregates and aggregates from two sources 40 miles to the

Table 1.2 Project Information

Section Identification	DEL-23-17.48
Construction Project No.	380(94)
Project Length	3.5 miles
Pavement Classification	Major Arterial
No. Lanes	4
Traffic Loading	1,000,000 ESALs/yr.
Topography	Flat
Soil Type	A6 (fine-grained)
Climatic Zone	Wet-Freeze
Total No. of Test Sections	40
Test Section Length	500 ft.
No. Test Sections w/Response Instrumentation	33
No. Test Sections w/SHRP Seasonal Instrumentation	18
Weigh-In-Motion	Mettler-Toledo, IRD

north, which have historically been resistant to D-cracking, were performed by the Iowa Transportation Center prior to sale of the project. As suspected, the northern sources were clearly superior and were pre-qualified for use. Any other sources proposed by the contractor had to be tested and meet the same rigid requirements. One of the pre-qualified sources was used throughout the project.

A $10.3 million contract was awarded to S.E. Johnson Company, Maumee, Ohio as prime contractor for construction of the Ohio SHRP Test Pavement. Paving of the portland cement concrete sections was sub-contracted to Hi-Way Paving Company of Hilliard, Ohio. It was interesting that the second lowest bid for this $10 million project was less than $4,000 above the successful bid.

Over the years, ODOT has sponsored several successful research projects involving the instrumentation of highway pavements to monitor environmental parameters and dynamic response. Therefore, when SHRP announced plans to promote the installation of minimal dynamic instrumentation in four sections of the SPS-1 and SPS-2 experiments, ODOT responded with plans to extensively instrument 33 test sections with dynamic sensors and 18 sections with seasonal sensors meeting SHRP specifications. Data obtained from these sensors would provide designers and researchers with information to better understand how pavements respond to climatic changes and traffic loading. Also, mathematical models can be verified and calibrated. Another benefit will be an early indication as to how the various structural parameters contribute to pavement performance.

To accomplish this enormous undertaking, invitations were forwarded to universities in the State of Ohio to determine if they would like to have some role in the project. Six universities responded positively and tasks were assigned in accordance with the expertise of the participating faculty as summarized in Table 1.3. Each of these universities was awarded a research contract to install and monitor sensors over a two or three year period of time.

Table 1.3 University Faculty Participants

<u>Response Instrumentation</u> Dr. Shad Sargand, Ohio University (Coordinator, load response instrumentation) Dr. Allen Sehn, University of Akron (Pressure Cells) Dr. Andrew Bodocsi, University of Cincinnati (Joint Movement also)
<u>Seasonal Instrumentation</u> Dr. Ludwig Figueroa, Case Western Reserve university (Weather Station also) Dr. William Wolfe, The Ohio State University (Soil Suction also) Dr. Andew Heydinger, University of Toledo (Soil Suction also)

Five series of controlled vehicle tests were conducted on the test pavement with single and tandem axle dump trucks, and a research tank truck from the Canadian National Research Council. As these vehicles traversed the site, sensors embedded in the test sections were monitored to measure the dynamic response of various pavement structures to different speeds, loads, axle configurations, and dual or super single tires. It would have been interesting to monitor these sensors under actual traffic and develop histograms of peak response, but there was insufficient time and resources available to gather these data. Environmental data were collected continuously to determine how temperature and moisture cycle daily and seasonally, and to define conditions at the time controlled vehicle tests and non-destructive tests were performed.

While focusing on seasonal and dynamic instrumentation, this report also documents other data pertinent to the assessment of performance of test sections constructed on the Ohio SHRP Test Pavement. Chapters 1 and 2 provide a general overview of the project. Chapters 3-5 discuss the installation and monitoring of seasonal instrumentation used to measure temperature, moisture and frost depth in these pavement sections. A description of the weather station mounted at the siteis included in Chapter 6. Chapters 7-8 discusses problems encountered during construction of the test road and materials used in the test sections. Chapter 9 provides a general overview of mechanistic pavement design. Chapters 10-15 document the selection, calibration and installation of response instrumentation during construction of the sections and detail how controlled vehicle tests were performed. Chapter 16 briefly summarizes how the test sections performed during their first four years of service and provides detailed data on specific performance parameters.

CHAPTER 2

PROJECT LAYOUT

The Ohio SHRP Test Pavement was constructed approximately five miles north of the city of Delaware, Ohio, on U.S. 23. This site was selected primarily because of the existing median, which was wide enough to accommodate a new four-lane divided pavement. From a research standpoint, this site was ideal because of the flat topography, straight alignment and the relatively uniform A-6 subgrade soil along the three-mile long project. Also, test sections would be exposed to the same environmental conditions and about the same level of traffic in the northbound and southbound lanes. This consistency provides researchers with the opportunity to more directly compare the performance of the various test sections over time.

SHRP assembled knowledgeable people from around the country into Expert Task Groups who defined a series of nine experiments for the Specific Pavement Studies (SPS) and established a matrix of structural parameters for each of these experiments. States were requested to participate by constructing some minimum number of test sections within one or more of these experiments. ODOT designers reviewed the SPS experiments and maximized the effectiveness of the U.S. 23 site by incorporating four of them into one project. These include:

- SPS-1 A Strategic Study of Structural Factors for Flexible Pavements @
- SPS-2 A Strategic Study of Structural Factors for Rigid Pavements @
- SPS-8 A Study of Environmental Effects in the Absence of Heavy Traffic (AC and PCC)@
- SPS-9 A Asphalt Program Field Verification Studies @

The SPS-1 and SPS-9 experiments were located in the southbound lane of the new mainline pavement. The SPS-2 experiment was placed in the northbound lanes of the new mainline pavement, and the AC and PCC sections in the SPS-8 experiment were constructed on a ramp coming south from the village of Norton onto the original southbound lanes of U.S. 23. The new pavement will carry mainline traffic while the original lanes will serve as a service road for local residents. When major testing or rehabilitation of distressed sections is required, traffic can be re-routed back to the original lanes.

Because space was available for more than the required number of test sections in the four SPS experiments, and because ODOT wished to compare the performance of some other sections with the SHRP sections, several state sections were added to the experiment. In all, 14, 19, 4, and 3 test sections were included in the SPS-1, 2, 8, and 9 experiments, respectively, making a total of 40 test sections on the project.

In years preceding development of the Ohio SHRP Test Pavement, ODOT sponsored several successful research projects involving the instrumentation of highway pavements, bridges, and culverts. This experience, coupled with a modest initiative by SHRP to instrument a few SPS-1 and SPS-2 sections for environmental conditions and dynamic response, and the realization that this project offered a unique opportunity to obtain extensive data for mechanistic pavement design, led ODOT to install SHRP environmental instrumentation in 18 test sections, and comprehensive response instrumentation for traffic loading and environmental changes in 16 AC test sections and 17 PCC test sections.

Figure 2.1 shows a layout of the 40 test sections and identifies which were instrumented for environmental and/or response monitoring. This figure is an update from the original construction where Section 803 in SPS-8 contained only dynamic instrumentation and Section 804 contained no

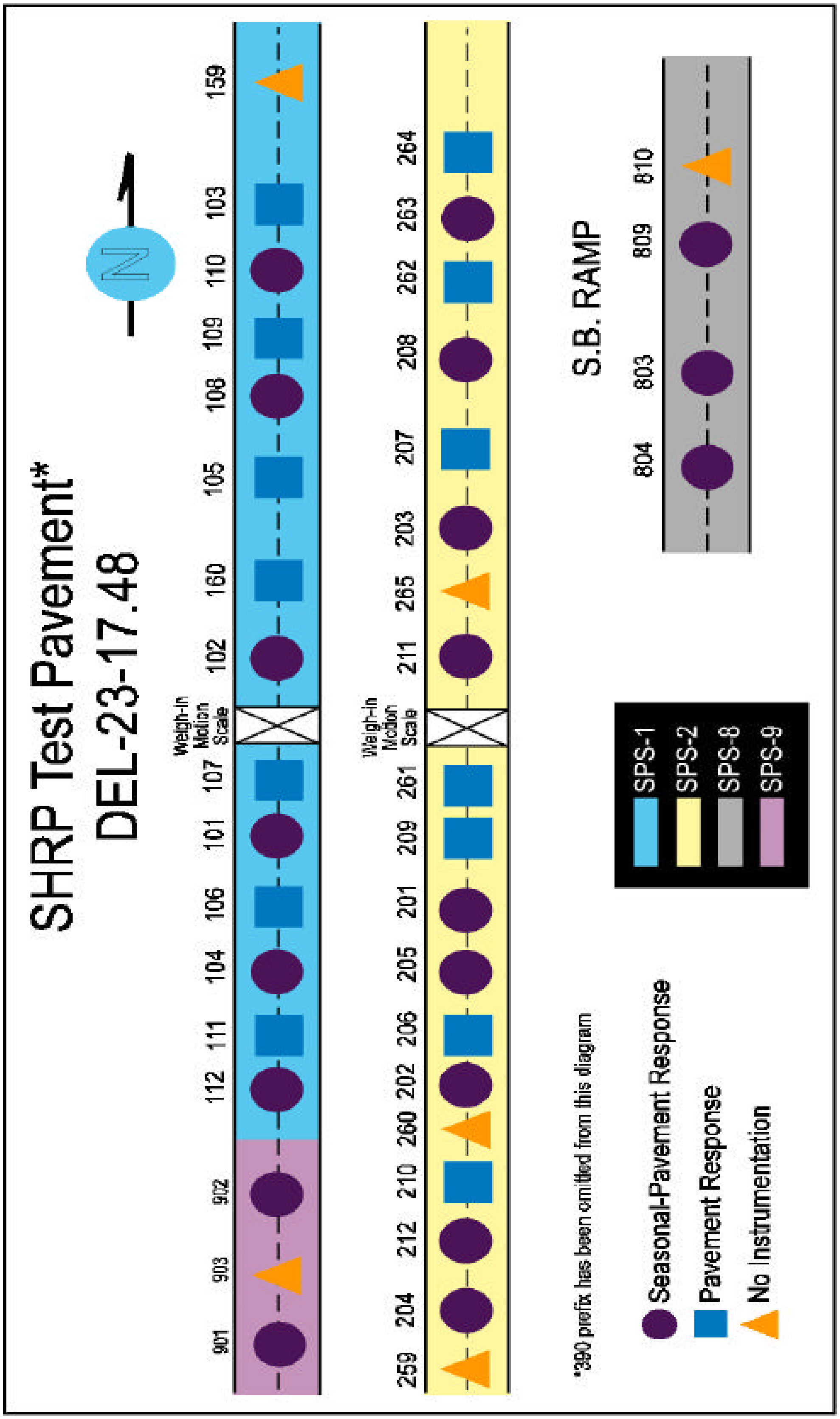

Figure 2.1 Layout of the Ohio SHRP Test Pavement

instrumentation. Severe early rutting in these sections due to a poorly compacted subgrade layer approximately four feet below the pavement surface, excess subgrade moisture and heavy loads applied during the initial series of controlled vehicle tests required they be totally replaced in the Fall of 1997. Environmental and dynamic sensors were added to Sections 803 and 804 at the time of replacement, resulting in a total of 20 environmental sections, 17 response AC sections and 17 response PCC sections.

Tables 2.1 and 2.2 summarize the structural parameters of each test section.

Table 2.1 Portland Cement Concrete Sections

SPS-2 (Northbound)						
Section	Station	PCC Layer		Lane Width (ft.)	Base Type and Thickness	Drain
		Strength (psi)	Thickness (in.)			
390201	343+00-348+00	ODOT	8	12	6" DGAB	No
390202	319+00-324+00	900	8	14	6" DGAB	No
390203	384+00-389+00	ODOT	11	14	6" DGAB	No
390204	275+50-280+50	900	11	12	6" DGAB	No
390205	335+75-340+75	ODOT	8	12	6" LCB	No
390206	327+50-332+50	900	8	14	6" LCB	No
390207	391+25-396+25	ODOT	11	14	6" LCB	No
390208	397+75-402+75	900	11	12	6" LCB	No
390209	350+25-355+25	ODOT	8	12	4" PATB/4" DGAB	Yes
390210	303+50-308+50	900	8	14	4" PATB/4" DGAB	Yes
390211	369+00-374+00	ODOT	11	14	4" PATB/4" DGAB	Yes
390212	294+00-299+00	900	11	12	4" PATB/4" DGAB	Yes
390259	265+50-270+50	900	11	12	6" DGAB	Yes
390260	311+50-316+50	ODOT	11	12	4" PATB/4" DGAB	Yes
390261	357+75-362+75	ODOT	11	14	4" PCTB/4" DGAB	Yes
390262	405+25-410+25	ODOT	11	12	4" PCTB/4" DGAB	Yes
390263	414+50-419+50	ODOT	11	14	6" DGAB	Yes
390264	422+50-427+50	ODOT	11	12	6" DGAB	Yes
390265	376+10-381+10	ODOT	11	12	4" PATB/4" DGAB	Yes

SPS-8 (Ramp)						
Section	Station	PCC Layer		Lane Width (ft.)	Base Type and Thickness	Drain
		Strength (psi)	Thickness (in.)			
390809	25+90-20+90	550	8	11	6" DGAB	No
390810	32+50-27+50	550	11	11	6" DGAB	No

Table 2.2 Asphalt Concrete Sections

SPS-1 (Southbound)				
Section	Station	AC Thickness (in.)	Base Type and Thickness	Drain
390101	355+00-350+00	7	8" DGAB	No
390102	375+00-370+00	4	12" DGAB	No
390103	420_75-415+75	4	8" ATB	No
390104	341+00-336+00	7	12" ATB	No
390105	392+50-387+50	4	4" ATB/4" DGAB	No
390106	348+00-343+00	7	8" ATB/4" DGAB	No
390107	363+00-358+00	4	4" PATB/4"DGAB	Yes
390108	399+75-394+75	7	4" ATB/8" DGAB	Yes
390109	406+50-401+50	7	4" PATB/12" DGAB	Yes
390110	413+50-408+50	7	4" ATB/4" PATB	Yes
390111	333+00-328+00	4	8" ATB/4" PATB	Yes
390112	325+00-320+00	4	12" ATB/4" PATB	Yes
390159	433+00-428+00	4	15" ATB/4" PCTB/6" DGAB	Yes
390160	382+00-377+00	4	11" ATB/4"DGAB	Yes
SPS-8 (Ramp)				
Section	Station	AC Thickness (in.)	Base Type and Thickness	Drain
390803	19+19-14+90	4	8" DGAB	No
390804	13+50-8+50	7	12" DGAB	No
SPS-9 (Southbound)				
Section	Station	AC Thickness (in.)	Base Type and Thickness	Drain
390901	282+5-277+75	4 (AC-20)	12" ATB/4" PATB/6" DGAB	Yes
390902	302+50-297+50	4 (PG58-28)	12" ATB/4" PATB/6" DGAB	Yes
390903	291+00-286+00	4 (PG64-28)	12" ATB/4" PATB/6" DGAB	Yes

Table 2.3 shows the number of test variables contained in each of the SPS experiments on the Ohio SHRP Test Pavement.

Table 2.3 Structural Parameter Distribution

SHRP Experiment	No. Sections	Number of Test Variables					
		Pavement Thickness	Pavement Mixes	Base Thickness	Base Materials	Lane Widths	Drainage
SPS-1	14	2	1	5	6	1	2
SPS-2	19	2	2	2	4	2	2
SPS-8 (AC)	2	2	1	2	1	1	1
SPS-8 (PCC)	2	2	1	1	1	1	1
SPS-9	3	1	3	1	1	1	1

Response instrumentation was placed such that sensors in adjacent sections were located close together, i.e., instrumentation was placed at the south end of one SHRP section and at the north end of the adjacent SHRP section. With this configuration, one data acquisition system could be used to monitor both sections. In-ground, precast concrete pull boxes were located just off the shoulder and approximately mid-way at each instrumented site to store sensor cables, and another pull box placed farther back was spaced mid-way between each pair of pull boxes close to the shoulder. The original plan was to have sensor wires come from the pavement and go underground into the first pull box. Wires from the two adjacent pull boxes would then go through a conduit to the pull box farther back where the data acquisition systems would be located. 120 VAC outlets were provided in each of the far pull boxes to power the data acquisition systems. With 15 or 16 test sections being instrumented on each side of the pavement and with most being located in pairs, nine data acquisition systems were required to monitor all sections on a given side of the pavement concurrently. Test vehicles could be driven the length of the project with dynamic response data being obtained when environmental conditions in the test sections were basically identical.

Instrumented sections were also laid out so those on the northbound side were about across from those on the southbound side. A pull box was installed in the median between these sections with conduits running to the two opposing pull boxes farthest away from the shoulders. Again, the original plan had cables running across the pavement and connecting the two far pull boxes so both traffic directions could be monitored from one side. The data acquisition systems would be set to monitor the northbound side while the test truck was proceeding north and switched to the southbound side as the truck was turning around to go south. This arrangement would permit the monitoring of all 31 instrumented mainline sections at essentially the same time and from the same locations.

Time did not permit the completion of all the necessary wiring to test in this manner. Instead, testing was limited to whatever number of sections could be monitored with the nine available data acquisition systems. To maximize data acquisition efficiency, one system was used to monitor two sections through the use of ribbon cables strung from adjacent pull boxes close to the shoulder to a system placed mid-way between them. AC power was obtained from the far pull box through an extension cord. While this procedure was a bit cumbersome, it provided the necessary flexibility of being able to test anywhere on the project. This was especially important because of the need to test SHRP sections as required, thin sections expected to fail early, and multiple sections on a given side to gather the most information within the limited time available. Specific details of the controlled vehicle tests are provided later in this report.

CHAPTER 3

SEASONAL INSTRUMENTATION

Overview

The seasonal portion of the DEL-23 project involved monitoring of a weather station as well as installation and monitoring of 18 LTPP seasonal sections. Within these 18 sections, instrumentation was placed to measure temperature in the pavement and soil, moisture in the subgrade, and frost depth. Specific sensors were selected by SHRP for use in the SPS experiments to maintain consistency between installations and facilitate data collection. This chapter describes these sensors and explains how they were installed. 110 VAC power was available in pull boxes at each section to facilitate data collection.

Sensor Selection

Soil Moisture

The moisture content of soil is an important pavement design consideration for settlement, resilient modulus, and freeze-thaw capacity. Based on the experiences of other road tests in the U.S., time-domain reflectometry probes (TDR's) manufactured by Campbell Scientific, Inc., were chosen as the best instruments available to monitor volumetric water content (Figure 3.1). Installed every six to twelve inches to a depth of six feet below the top of the base material, TDR's consisted of a 100-foot long coaxial cable with a three-pronged probe at one end.

The two outside rods in the probe act as a shield for the electromagnetic pulse carried along the center rod. These rods expose the electromagnetic pulse to the surrounding material and in turn, allow the signal to be naturally reflected by that material. The dielectric constant of a material (ratio

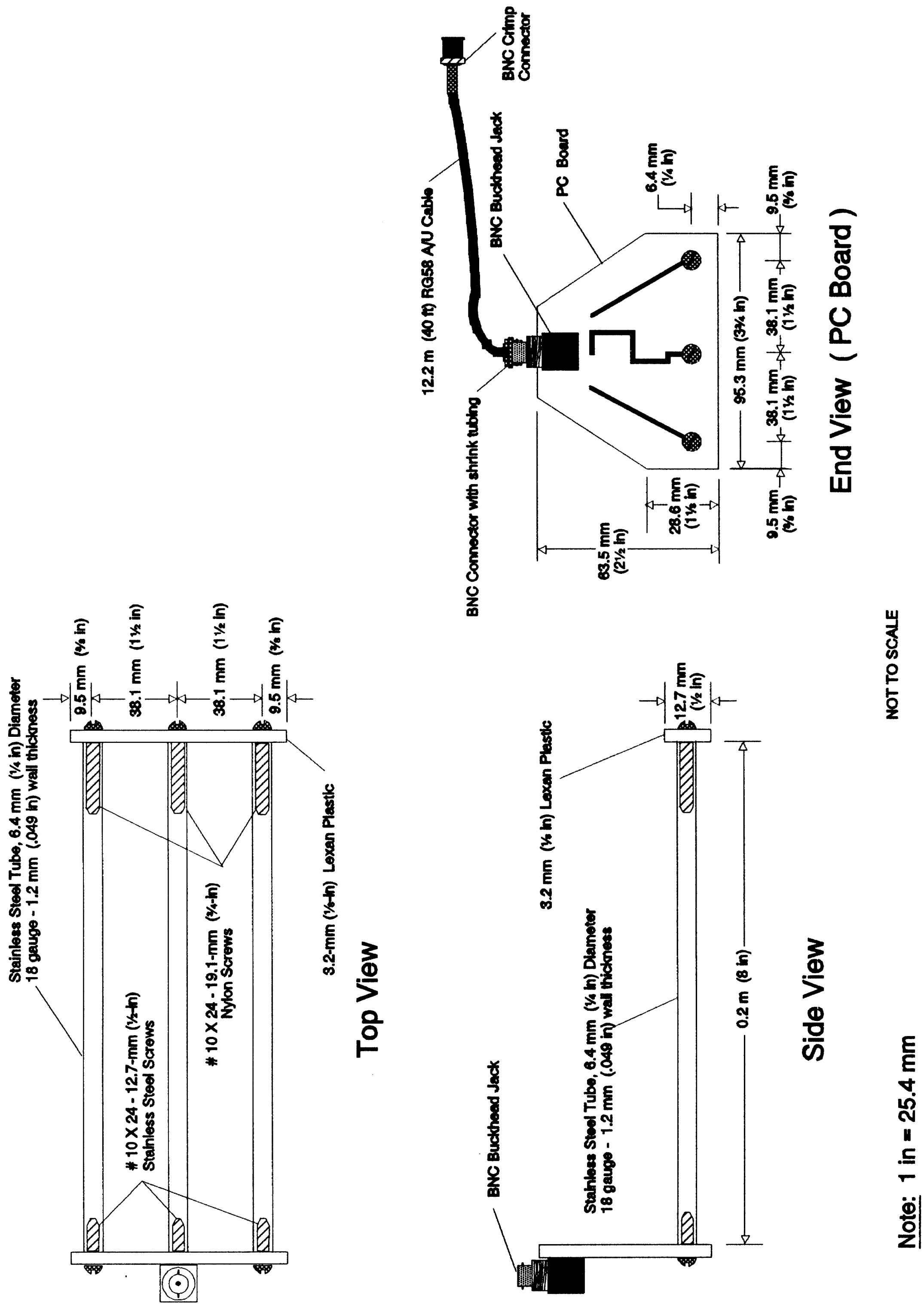

Figure 3.1 FHWA TDR Probe

of the material dielectric permittivity to the permittivity of a vacuum) is generally a function of moisture content. Therefore, as the dielectric constant is measured, soil moisture content can be inferred. This is possible because any change in dielectric constant (as well as open or short circuits in the cable or the rods) creates wave reflections back to the cable tester. These reflections are shown as slope changes along a wave pulse trace, such as that shown in Figure 3.2. This trace shows a rise and fall in return signal strength as the pulse enters the stainless steel rods, and also shows a rise when the pulse reaches the end of the rods. The distance measured along the trace between these two specific points is the apparent length of the probe. Signals sent by a Campbell Scientific CR-10 cable tester propagate slower with higher dielectric constant, thereby increasing the apparent length. The dielectric constant of water is higher than most materials; therefore, the wetter the material, the longer the apparent length. This apparent length and the fixed probe length can be used to determine a dielectric constant and, with this dielectric constant, a soil moisture content as follows:

$$\varepsilon = \left[\frac{(L_a)}{(L)(V_p)} \right]^2 \tag{3.1}$$

Where ε = dielectric constant
L_a = apparent length of probe (horizontal distance between inflection points on trace)
L = actual length of probes (0.203m for FHWA probes)
V_p = phase velocity setting on TDR cable tester (usually 0.99); this is the ratio of the actual propagation velocity to the speed of light

The dielectric constant of soil is calibrated with volumetric moisture content. For preliminary use, this relationship is given in Equation 3.2 (Topp's Equation), and is based on a previously developed regression equation.

$$\theta = (-0.053 + 0.0293\varepsilon - 0.0055\varepsilon^2 + 0.0000043\varepsilon^3) * 100 \tag{3.2}$$

Where θ = volumetric water content, in percent
ε = dielectric constant

Laboratory analyses of soil moisture content for site samples were used to determine the accuracy of this relationship. Using Equation 3.3, this value is easily converted to weight-based moisture

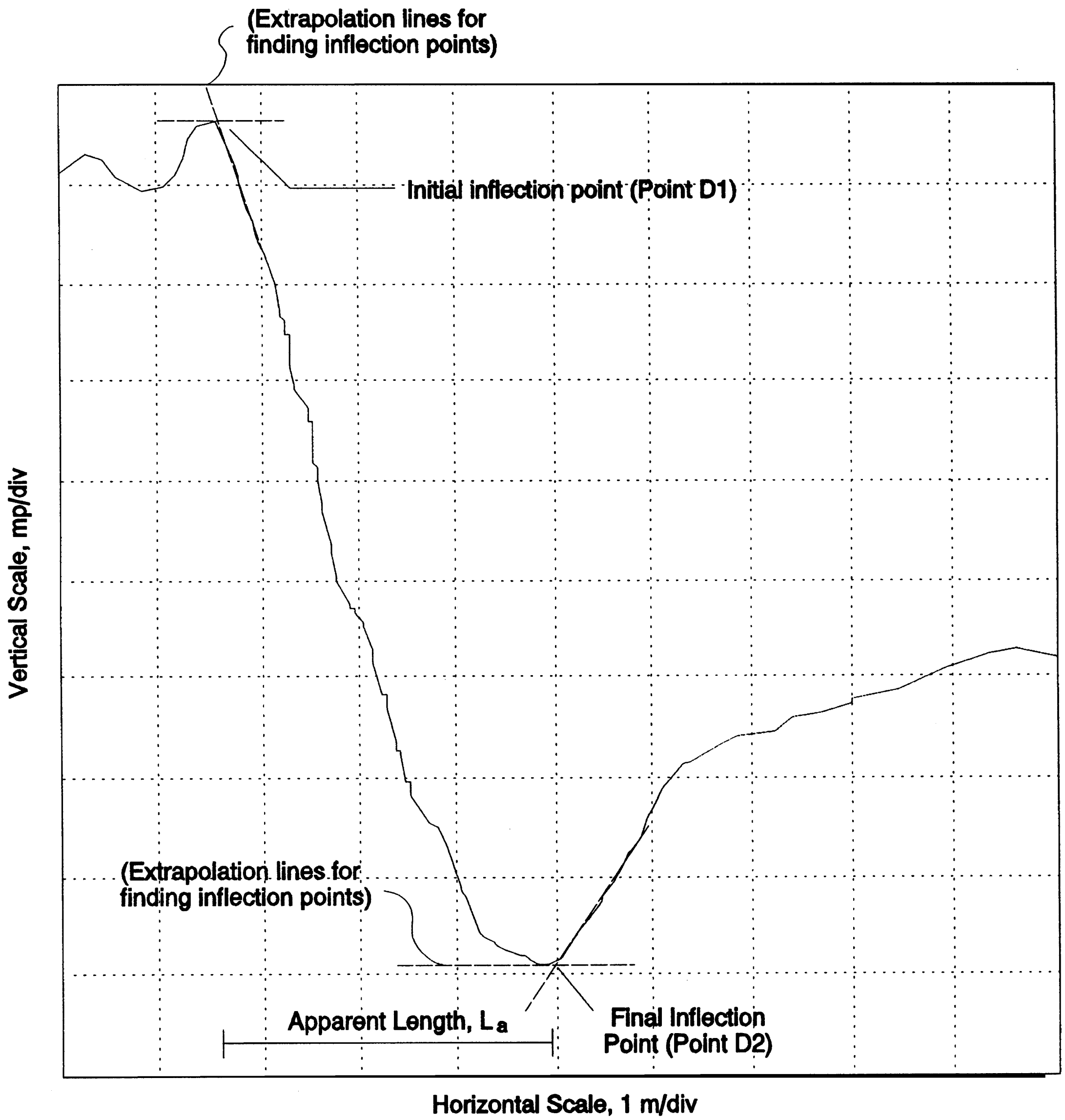

Figure 3.2 Waveform Signal Produced by TDR Probe

content used in most design calculations. The end result is the determination of the change in the degree of saturation of soils throughout the year from which resilient properties of soils may be inferred.

$$w = \theta\left(\frac{P_w}{P_d}\right) \tag{3.3}$$

Where w = gravimetric water content, in percent
θ = volumetric water content, in percent
p_w = density of water, = 1.0 gm/cm^3
p_d = dry density of soil, gm/cm^3

Finally, soil moisture content, in terms of mass, can be derived from volumetric water content using the following equation:

$$W_v = W_s * G \tag{3.4}$$

Where W_v = volumetric water content, volume water/volume solids
W_s = soil moisture content, mass water/mass solids
G = specific gravity of the soil, unit weight of solids/unit weight of water

With volumetric water content and the unit mass of soil known, the soil moisture content is determined using the following formula:

$$W_s = \frac{W_v}{\gamma_s} \tag{3.5}$$

Where γ_s = unit mass of the soil, gm/cm^3

Unit mass (dry density) data provided by ODOT project personnel included 120.5 lb/ft^3 for DGAB material and 123.9 lb/ft^3 for subgrade material. Soil moisture content can be combined with dynamic response data to characterize the seasonal response of pavements.

Raw soil moisture data are grouped under mobile DAT files and can be viewed using any spreadsheet program. Each type of data is stored in single rows of information and in distinct patterns. Soil moisture data are formatted in the following pattern:

1n.yyyy,ddd,hhmm[,(5)](6),(7),(8),(9),1

Where	1n =	record type 1n ($0 \leq n \leq 9$): TDR waveform for sensor (n+1)
	yyyy =	year
	ddd =	day of the year, 1 to 366
	hhmm =	time of day, 0000 to 2359
	(5) =	TDR waveform (251 data points), n.n
	(6) =	Distance to the cursor (meters), n.n.
	(7) =	Distance between waveform points, n.n.
	(8) =	Gain, n.n
	(9) =	Offset, n.n.
	1 =	sample number (always 1 with current software)

The first column of data always signifies the record type. Soil moisture data always begins with record type 10 through 19 (for probes 1 through 10).

A program entitled, AMOBFIELD@, provided by LTPP and described in detail in a report titled " *LTPP Seasonal Monitoring Program: Instrumentation Installation and Data Collection Guidelines, April 1994"* ∗, interprets soil moisture waveform data, determines the apparent length of the probe, and calculates the dielectric constant and volumetric moisture content. Program execution begins by entering AMOBFIELD@ at the CR10 directory prompt. A title screen appears and four selections are provided in the middle of the screen: (1) TDR Data Analysis, (2) Resistance Data Plot, (3) Select Printer Type, and (4) Quit Program. The first option is selected and the program prompts the user to enter the data filename and directory path. After this information is entered, the first TDR probe waveform and calculated information appears on the screen. Each TDR probe trace is viewed by scrolling up or down using the arrow keys. The screen is printed using the F2 key, but the correct printer type must first be selected at the opening screen. A sample printout of the TDR trace screen is shown in Figure 3.3.

∗ SMP data sheets discussed later are also contained in this report.

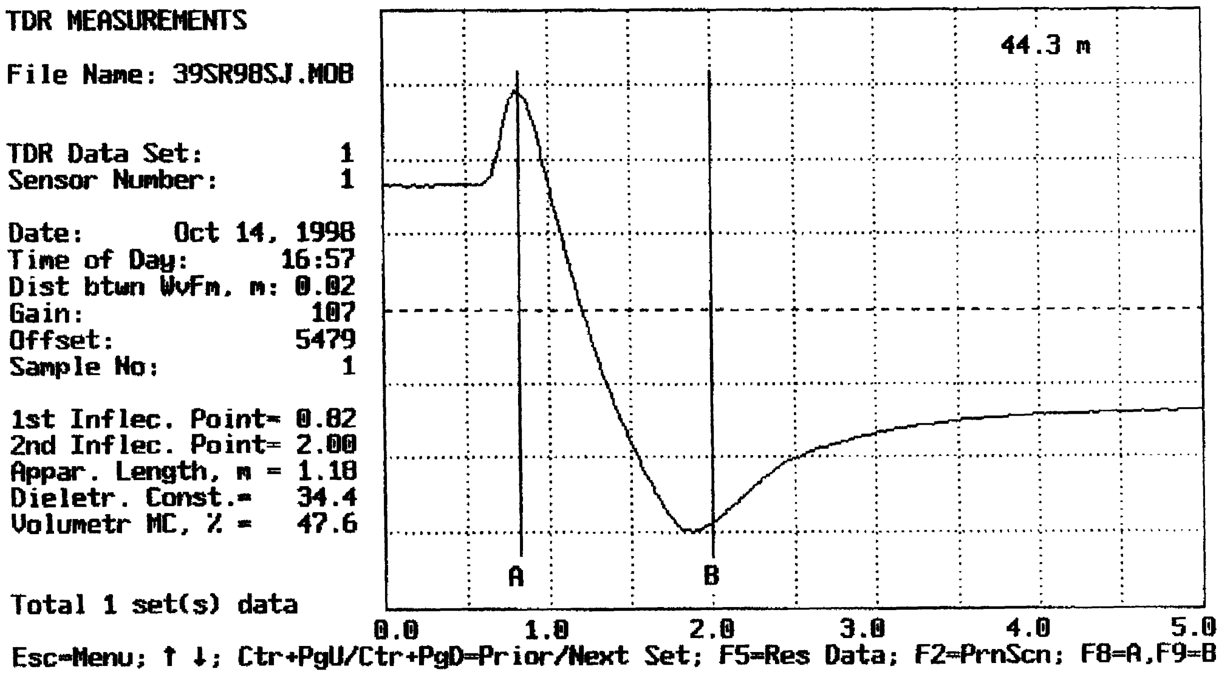

Figure 3.3 Sample TDR Trace

Temperature

As important as moisture content is for subgrade soils, similar is the importance of temperature for stabilized pavement layers above the subgrade. Temperature plays a major role in fatigue life and deflection determination as it directly affects resilient modulus and ultimate tensile strength values for asphaltic materials. For portland cement concrete base and pavement, temperature gradients in the slab cause curling which will accentuate the effect of traffic loads during certain times of the day. Temperature changes also lead to expansion and contraction of slabs that affect load transfer and overall joint performance.

Temperature on the U.S. 23 test road was monitored by TP 101 thermistors, or temperature-sensitive resistors, manufactured by Measurements Research Corporation (MRC) and shown in Figure 3.4. Slight temperature changes create major variations in resistance values of the thermistors.

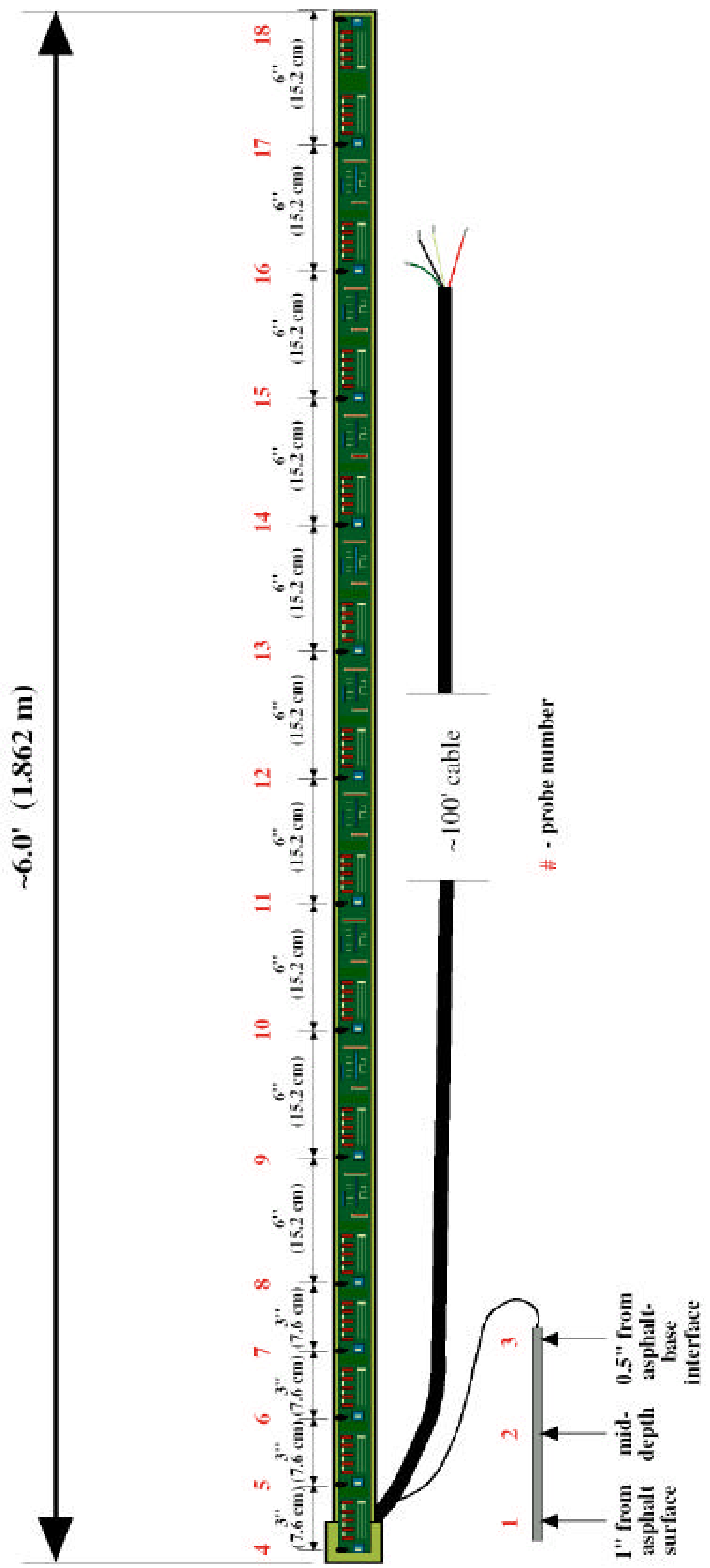

Figure 3.4 MRC Thermistor Probe

To find resistance, a know voltage is applied and the output voltage is read between the thermistors leads. Knowing the change in resistance, Equation 3.6 is used to determine temperature.

$$\frac{1}{T} = C_1 + C_2 \ln R + C_3 (\ln R)^3 \tag{3.6}$$

Where T = absolute temperature, Kelvin
R = resistance, ohms
C_1, C_2, C3 = constants for individual thermistors

These constants are 9.3441 x 10^{-4}, 2.2124 x 10^{-4}, and 1.2665 x 10^{-4}, respectively, for the probes used on the DEL-23 project. This device consists of individual but interconnected probes for both pavement and soil temperature measurements. A variable length metal rod (depending on the pavement thickness) containing three or four thermistors was used for the pavement layer temperature measurements followed by a six-foot long, acrylic pipe that housed 15 thermistors for the subgrade soil temperature measurements.

Temperature data are stored in a slightly different manner than soil moisture. Each hour, two record types are collected. The first record type includes the battery voltage, air temperature, and precipitation for the last hour. Air temperature and precipitation were monitored at the weather station on the Ohio SHRP Test Road, but not at the 18 seasonal sites. The format is as follows:

5,yyyy,ddd,hhmm,b.b,t.t,r.r

Where 5 = record type 5: battery, air temperature, and precipitation
yyyy = year
ddd = day of the year, 1 to 366
hhmm = time of the day, 0000 to 2359
b.b = average battery voltage
t.t = average air temperature, degrees Celsius
r.r = total precipitation, millimeters

The second record type consists of the average temperature readings for the first five MRC thermistors over the last hour. The format is as follows:

6,yyyy,ddd,hhmm[,t.t]

Where	6 =	record type 6: first five MRC soil temperatures
	yyyy =	year
	ddd =	day of the year, 1 to 366
	hhmm =	time of the day, 0000 to 2359
	t.t =	average soil temperature, degrees Celsius

For each 24-hour data set, there should be 24 record Type 5 and 6 readings. At midnight, a complete data set was collected including record Types 1 through 6. Record Types 1 through 4 cover minimum and maximum battery voltage; minimum, maximum, and average air temperature; total precipitation; and minimum, maximum, and average soil temperatures. The following presents the format for record Type 1:

1,yyyy.dd.ba,bx.bx,hhmm,bn.bn,hhmm,ta.ta,txx.tx,hhmm,tn.tn,hhmm,r.r,sss

Where	1 =	record type 1: battery, air temperature, precipitation
	yyyy =	year
	ddd =	day of the year, 1 to 366
	ba =	average battery voltage
	bx =	maximum battery voltage followed by time occurred
	bn =	minimum battery voltage followed by time occurred
	ta =	average air temperature, degrees Celsius
	tx =	maximum air temperature, degrees Celsius, followed by time occurred
	tn =	minimum air temperature, degrees Celsius, followed by time occurred
	r =	total precipitation, millimeters
	sss =	signature, checksum

Record Type 2 is as follows:

2,yyyy,ddd[,t.t]

Where	2 =	record type 2: average soil temperature, degrees Celsius, for all 18 MRC sensors
	yyyy =	year
	ddd =	day of the year, 1 to 366
	t.t =	average soil temperatures, degrees Celsius

Record Type 3 is as follows:

3,yyyy,ddd[,t.t,hhmm]

Where 3 = record type 3: maximum soil temperatures followed by time occurred
yyyy = year
ddd = day of the year, 1 to 366
t.t = maximum soil temperatures, degrees Celsius, followed by time occurred

Record Type 4 is as follows:

4,yyyy,ddd[,t.t,hhmm]

Where 4 = record type 4: minimum soil temperatures followed by time occurred
yyyy = year
ddd = day of the year, 1 to 366
t.t = minimum soil temperatures, degrees Celsius, followed by time occurred

To view a complete set of data, a program must be used to plot the points on a graph. AONSFIELD@, provided by LTPP and described in detail in the aforementioned report, is used for temperature profile data analysis. This program produces data plots for hourly and daily onsite temperatures. The ONSFIELD format is very similar to MOBFIELD and therefore, many of the screens are the same. Program execution begins by entering AONSFIELD@ at the CR10 directory prompt. A title screen appears and five selections are provided in the middle of the screen: (1) Plot Data, (2) Scan Data, (3) Select Printer Type, (4) Edit Scan Parameters, and (5) Quit Program. Option one is selected, and the program prompts the user to enter the data filename and directory path. After this information is entered, six more options are listed at the center of the screen: (1) Daily avg. air temperature and rainfall (RT-1), (2) Daily avg. air, first 5 MRC temp. and rain (RT-1,2), (3) Daily avg. air and all 18 MRC temperature (RT-2), (4) Hourly avg. air, first 5 MRC temp. and rain (RT-5,6), (5) Save export lot files, and (6) Back to Main Menu. Each selection is self-explanatory. The desired selection is entered and a two-graph screen appears. The top graph displays the temperature versus time (in hours) plot for air and/or MRC probe, and the bottom graph provides hourly rainfall data (in millimeters). The screen is printed out using the F2 key - the proper printer must be selected before printing (use option #3 on the main screen). Figure 3.5 provides a sample of the printed graphs using ONSFIELD.

Selection (2) and (4) are used for the Seasonal Monitoring Program (SMP) Check to enter collected data into a database provided by the FHWA.

Frost Depth

Since the DEL-23 project is located in a geographic area that experiences multiple freeze/thaw cycles during the winter months, it is necessary to monitor the depth of frost penetration in the subgrade soil as well as the number of freeze/thaw cycles. This data will be used as input in the assessment of test section performance. Also, since soil stiffness tends to decrease after each freeze/thaw cycle, mechanistic and overlay design procedures will require this information to accurately predict performance.

After studying the methods available for monitoring frost depth, SHRP considered resistivity method to be the most reliable for the SPS experiments. A probe developed by the U.S. Army Corps of Engineers Cold Regions Research and Engineering Laboratory (CRREL) was chosen for this application (Figure 3.6). This probe consists of a 73-inch long solid PVC pipe upon which 36 metal wire electrodes are spaced every two inches. When a function generator creates an AC current in two outer electrodes, voltage drop and resistance are measured and compared across the two inside electrodes.

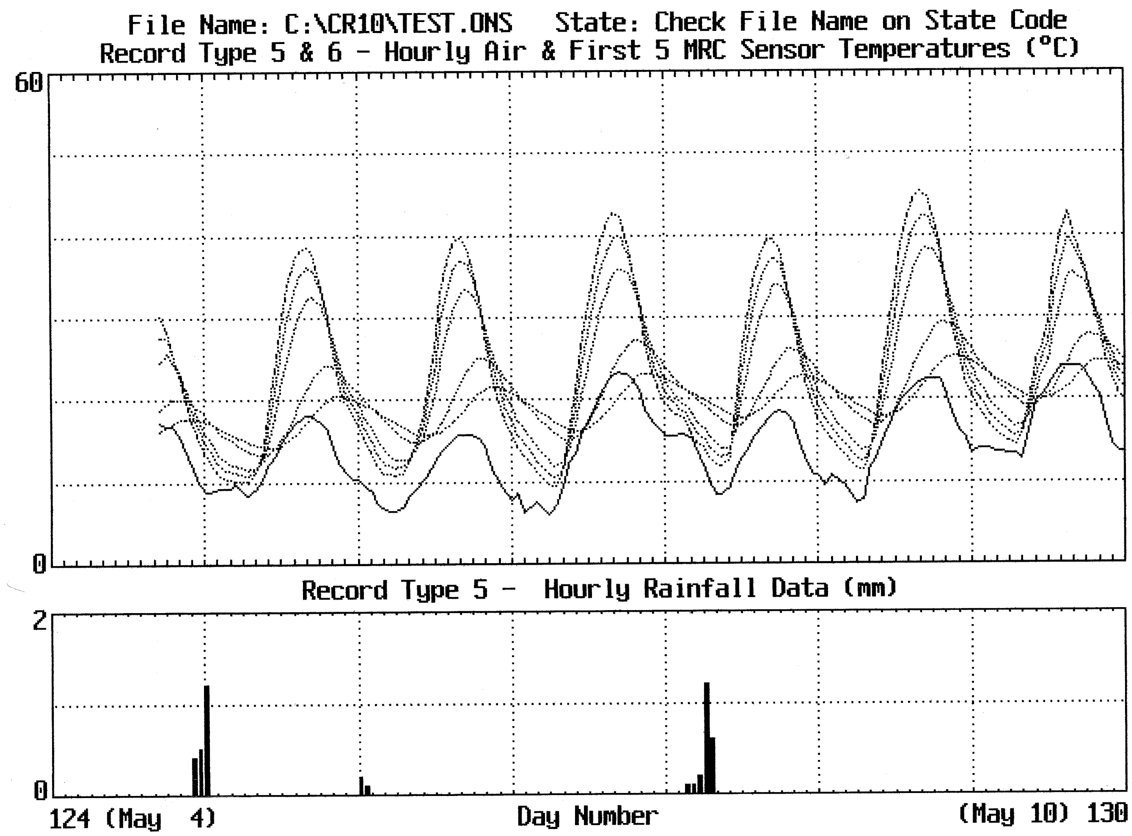

Figure 3.5 MRC Probe Temprature Profile Plots from Onsfield

The resistivity probe is based on the premise that the electrical resistivity of ice is much greater than that of unfrozen pore water. Therefore, the points at which the greatest changes in electrical resistivity occur at the approximate depth of the frost boundary. The resistivity probe is used to find this greatest change by applying a known alternating current (AC) and a measured voltage to two coils at a time. With this current and voltage, the contact resistance of the probe is determined. The resulting data (35 points in all) are plotted and the depths with the largest peaks are considered to be the depths of frost. These depths are determined by taking the distance from the top of the probe to the mid-point of the two coils where a maximum was found, and by adding it to the distance between the top of the probe and the pavement surface.

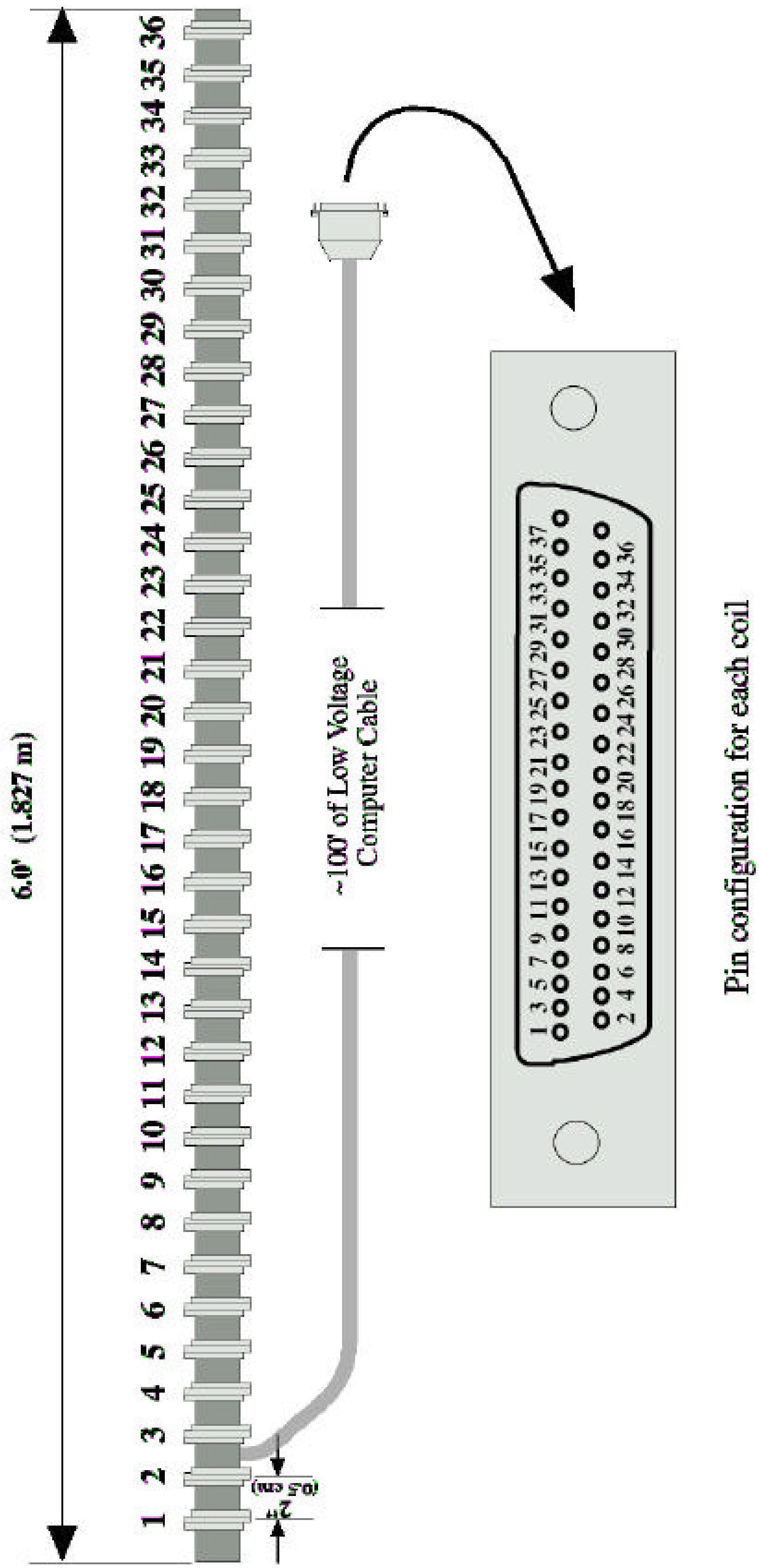

Figure 3.6 CRREL Resistivity Probe

Bulk, or apparent, resistivity can be computed from Equation 3.7.

$$p = G * R = G * \frac{V}{I} \tag{3.7}$$

Where p = bulk electrical resistivity, ohm-meter
G = geometric factor for the electrode array, meters 4πa, for CRREL sensor (a = uniform spacing between electrodes, meters)
R = electrical resistance, ohms
V = voltage, volts
I = current, amps

Since ice has a much greater electrical resistivity than water, areas of high resistivity will correspond to frozen layers in the subgrade soil.

Resistivity probe data are viewed in the same manner as the TDR and MRC probe, but it has its own format. All resistivity data are stored in the following manner:

7,yyyy,ddd,hhmm [,v.v]

Where 7 = record type 7: 35 resistance voltage values
yyyy = year
ddd = day of the year, 1 to 366
hhmm = time of day, 0000 to 2359
v.v = resistance voltage value, millivolts

The datalogger system can be left to automatically collect resistance values every four hours if necessary. The MOBFIELD program used for soil moisture is also used to plot the resistivity probe data. Once the program is executed, selection (2) Resistance Data Plot is entered. The program prompts the user to enter the data filename and directory path, and after this is accomplished, the resistance plot appears on the screen. The graph shows resistivity points 1 through 35 versus voltage. Selecting F2, but first making sure the correct printer setting is selected at the MOBFIELD main screen, prints the screen. A sample printout is provided in Figure 3.7.

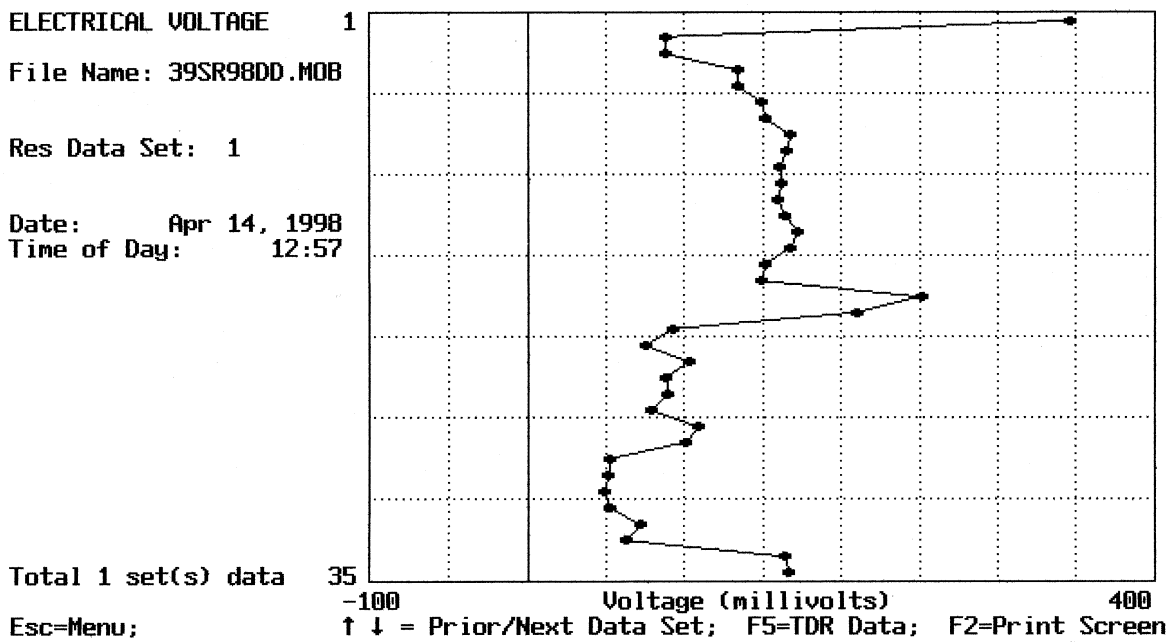

Figure 3.7 CRREL Resistivity Probe Data Plot from Mobfield

Ground Water Table Depth

Fourteen and one-half foot long, slotted observation piezometers were used to measure the depth to the water table along the outside pavement shoulder. Made of two individual 1-inch diameter PVC pipes coupled together, the piezometers were threaded to a metal floor flange and anchored at the bottom of a bore-hole. When necessary, this pipe also serves as a swell-free benchmark for surface level measurements. A total of nine piezometers were installed at the locations shown in Table 3.1.

Table 3.1 Piezometer Locations

Southbound Lane		Northbound Lane	
Section	Station	Section	Station
390103	417+02	390204	279+85
390108	397+00	390212	298+01
390102	372+00	390201	346+00
390104	337+0	390208	401+00
390901	279+50		

Sensor Preparation

TDR Calibration

All TDR probes were run through a series of tests to insure probe accuracy. The first step in this procedure was to set up a Tektronix 1502B Metallic TDR Cable Tester. A thermal printer was installed in front of the unit to obtain a copy of screen readouts. The TDR probe to be calibrated was attached to the cable interface on the cable tester. The signal velocity of propagation was set to 0.99 by adjusting the Vp knobs on the face of the unit and turning it on.

The first calibration procedure was to locate the exact point on the graph where the stainless steel rods were exposed to surrounding mediums. This was achieved by first setting the vertical scale (VERT SCALE) on the cable tester to approximately 172 mp/div (reading at the bottom of the display). Next, the left/right position knobs were adjusted (< > POSITION) to the right until the cursor reading at the top right of the screen was showing approximately 40 m. At this point, the horizontal waveform began sloping up the screen. The TDR probe was then shorted out by placing a flat piece of metal against the middle prong and either of the outside prongs. The piece of metal was placed as close to the potting material as possible. The graph in the screen using the up/down

(Δ∇ POSITION) and left/right (< > POSITION) knobs was fitted while maintaining a short on the probe. The peak of the graph was placed on the left most dotted vertical line and the cursor was moved on top of this dotted line. This gave an exact distance along the cable and probe where the probe began monitoring the surrounding material. After this process was accomplished, the print button was pressed while maintaining a short on the probe, and the sheet was torn off and filled out. The date, probe identification number, and word Ashorted@ was written in the spaces provided. A sample calibration sheet is provided in Figure 3.8. The < > POSITION knobs were not touched for the remainder of the calibration procedure in order to maintain the correct distance along the probe where measurements began.

The next calibration procedure was to obtain the graph of the TDR probe in air. The probe was placed in air at least 12" away from any other object to reduce any chance of signal interference. The Δ∇ POSITION knobs were adjusted to fit the graph in the screen (not disturbing the other knobs), and the print button pressed. The sheet was torn off and completed with appropriate information as with the shorted calibration. With this graph, the dielectric constant of air was calculated. This procedure first entailed drawing lines tangent to the two slopes of the curve approximately where they change concavity. The distance from the cursor to the point where tangents intersect is the apparent length of the probe. Using this length, a dielectric constant was calculated and compared with the true dielectric constant in air (1.0). If the value was within 0.75 to 2.0, the probe passed the first check. An example of an air calibration graph is given in Figure 3.9. The last calibration check required submerging the TDR probe in distilled water and calculating the dielectric constant. The vertical scale of the Tektronix cable tester was set to approximately 74.8 mp/div and the probe was held horizontally at mid-depth in a bucket of distilled water by its cable or potting material. The Δ∇ POSITION knobs were adjusted to fit the graph in the screen and the

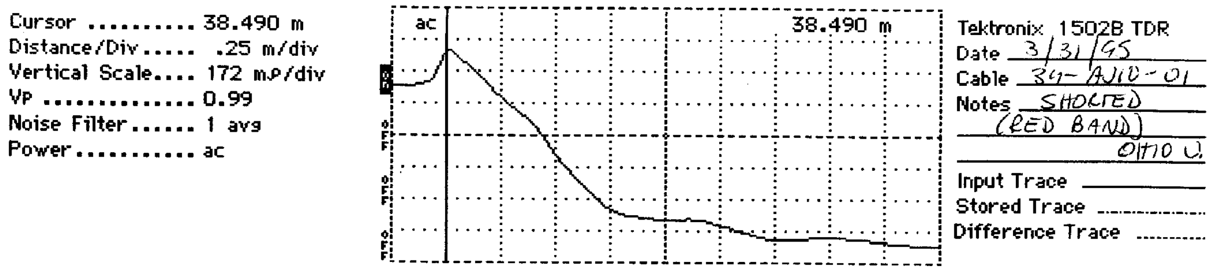

Figure 3.8 Shorted TDR Probe Calibration Sheet

print button was engaged. The sheet was torn off and filled in with the necessary information. The apparent length of the probe in distilled water was determined with the tangent method used for air calibration. Tangents were drawn where the curve moves abruptly upward and the distance from the cursor to the tangent intersection is the apparent length. With the apparent length known, a dielectric

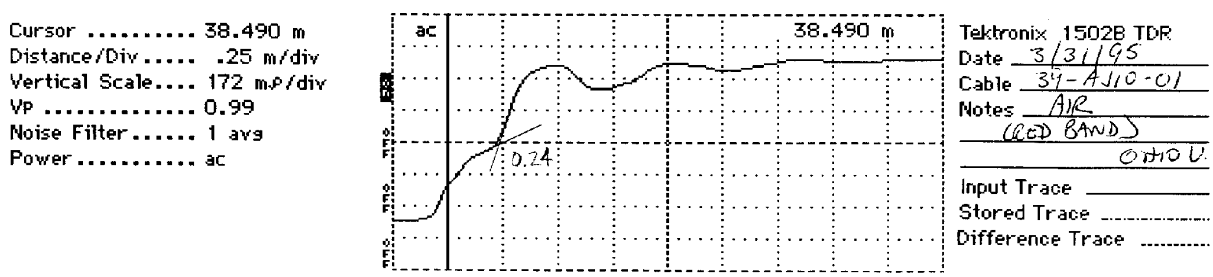

Figure 3.9 TDR Probe in Air Calibration

constant was calculated and compared to the true value of 80. If the calculated dielectric constant fell between 76 and 84, the probe was considered functional and testing was complete. A sample readout of a distilled water calibration graph is presented in Figure 3.10. After the calibration processes were completed, calibration sheets were attached to data sheets labeled Seasonal Monitoring Program (SMP)-C01: TDR Probe Check.

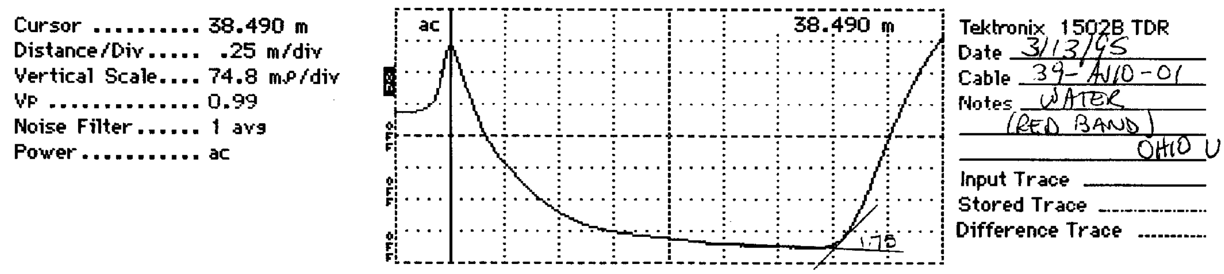

Figure 3.10 TDR Probe in Distilled Water Calibration Sheet

Thermistor Calibration

Thermistors are resistors made of a semiconductor material with a large temperature coefficient of resistance and a high sensitivity to temperature change. The thermistor is read out by applying a known voltage, obtaining the change in voltage, and converting it to a known temperature.

MRC TP101 thermistor probes are not calibrated at the factory. Consequently, they were subjected to three tests to verify that they were functioning correctly prior to installation in the field. Data Sheet SMP-C02: Thermistor Probe Check was completed with this verification procedure. First, the probe was placed in an ice bath along with a thermometer. The two were left to sit and stabilize, and all thermistor readings were compared with the thermometer reading. Second, the probe and thermometer were placed in air, allowed to thermally stabilize, and temperatures were again compared. Finally, the MRC probes were placed in a temperature controlled environment set to +50°F. After a few hours, the controlled-room temperature was compared with every probe reading. If all comparisons for each test fell with ±2°F of each other, the probe was considered to be functional.

A single-point, high temperature asphalt thermocouple, supplied by Measurement Instruments East, Inc., was used to provide a temperature profile only in test sections instrumented to measure dynamic response. This thermocouple is a 2-inch long embedment probe 1/4 inch in diameter. Each probe had 100 feet of Teflon coated T-type (Copper-Constantan) thermocouple wires capable of withstanding temperatures up to 375°F. Temperature measurements were considered vital for the proper interpretation of dynamic response data obtained during the controlled vehicle tests.

The thermocouple is fabricated from two wires of dissimilar metals joined together at the point of measurement. As this measuring point is subjected to any temperature above absolute zero, a small voltage is generated between the wires. This small voltage is proportional to the temperature of the measuring point. In order to avoid creating a second measuring point with a readout unit, a specific readout unit is needed for each type of thermocouple. The readout unit must use similar metals to form a cold junction with the thermocouple wires in order to measure the voltage correctly. For example, metal A and metal B from the thermocouples are connected to two copper wires, which relay the voltage to the readout unit.

One thermocouple was placed in each lift of asphalt concrete as well as in all ATB bases to provide a temperature profile for these materials. No calibration procedure was designated for these probes, but each was checked with a readout unit prior to installation.

Resistivity Probe Check

The CRREL resistivity probe was not calibrated, but checked for continuity between the coil and pin. Data sheet SMP-C03: Resistivity Probe Check was completed with the checking procedure. A voltmeter was first set to read resistance. Next, one of the voltmeter prongs was set on a coil and the other on the corresponding pin in the DB37 pin connector. The voltmeter should show continuity. The prong touching the corresponding coil pin was run along all of the other pins and the connector case. If there was continuity at any other location, the probe had bare wires or pins touching and was considered not functional. Also, the distance between each coil in the probe was measured to be sure they were approximately 2 inches (51 mm) from center to center.

Sensor Labeling

All environmental sections were equipped with ten TDR soil moisture probes designated as 1 through 10 and spaced at 6 or 12-inch intervals to a depth of six feet. TDR probes also had section identification numbers, which were not marked on the probe cable but were recorded on the calibration sheets and other environmental reference documents. The first two digits of this identification number were always 39 (for Ohio). The second segment consisted of two parts - a letter and section shorthand identification code. The letter was either an "A" for asphalt or a "C" for concrete. This was followed by the shorthand code. Finally, the last portion of the identification number was from 01 through 10, which identified the specific probe. An example of the identification number form is 39-AJ10-03 representing asphalt (SPS-1), Section J10 (390110) and probe number three.

MRC probes and CRREL resistivity probes were labeled in the same manner as the TDR probes, but the last two digits were eliminated. Instead, a T or an R was placed to designate temperature or resistivity. An example of this terminology is 39-CJ8-R, representing the resistivity probe for concrete (SPS-2) Section J8 (390208). This identification code was placed at the end of the probe cable. MRC probes had model numbers which were also printed on the probe by the Measurement Research Corporation. These numbers were not unique to the probe and were, therefore, not used as an identification number.

Thermocouples were referenced by color only. Each dynamic-only response section had either three or four thermocouples depending on asphalt concrete thickness and whether an ATB base was present. The number of AC lifts and ATB base determined the color pattern. For sections with three thermocouples, the bottom-most instrument was labeled green, the middle - yellow, and the top

- red. Sections requiring four thermocouples were organized green on bottom, yellow, orange, and red on top. Thermocouples were labeled at the end of their cable with colored tape.

Subsurface Sensor Installation

Overview

SHRP initially recommended that seasonal instrumentation be installed after placement of the pavement. This process involved the drilling of a 12-inch diameter core through the pavement and down to a depth of approximately six feet below the top of the base. Since full depth patches in asphalt and portland cement concrete typically cause premature distress, it is likely the SHRP procedure would result in a bump in the pavement and a source for water intrusion into the base and subgrade at the location of the seasonal sensors. Also, grooves cut in the pavement for the sensor wires would weaken the pavement. Seasonal instrumentation on the Ohio SHRP Test Pavement was installed after completion of the base layers. The pavement was then placed by conventional means with no special provisions being required to protect the sensors.

Borings

Before installation began, all equipment was gathered and brought to the site. A 12-foot long tamper was used to compact the soil as it was replaced around the sensors. This tamper came in 4-foot long sections, which were screwed together at the ends. It was constructed of 2-inch diameter black pipe with flat metal plates welded at each end (one end with a screw, the other tapped to match the screw). The tamper base was fabricated from a half-inch thick steel disk plate, eight inches in diameter, welded to one of the black pipe sections. Two bins were used to collect soil initially along with ten, ten-gallon buckets (with lids) numbered in the order in which the soil was excavated. A large sheet of plywood with a two-foot diameter circle cut at its center was placed around the hole to collect stray soil. A piece of two-inch diameter PVC pipe, eight foot long, cut in half length-wise was inserted in the hole to protect the resistivity coils when tamping. Soil samples were stored in self-sellable plastic bags. Finally, a Tektronix 1502B metallic cable tester with printer was used for post-installation TDR printouts.

First, the environmental sections must be properly located. All environmental response sections were situated along the wheel path (2.5 feet from the pavement edgeline) approximately ten feet away from the deep reference LVDT location closest to the Aenvironmental@ pull box. The exact distance was recorded on Data Sheet SMP-I02.

To begin installation, it was first necessary to auger a 12-inch diameter hole at the desired location. This was done after placement and compaction of the subgrade and base layers. Using the sheet of plywood with a hole cut in the center, the drill rig would bore through the hole and into the soil six to twelve inches at a time. When the auger bit was removed, the recovered soil was scraped off and placed in numbered buckets. This would allow for the soil to be replaced in its original position by backfilling in reverse order. This process was repeated until a depth slightly past the required depth of 74 to 76 inches was reached. When drilling through a dense graded aggregate base, the base material was first excavated by hand and placed in a separate bucket.

Probe Installation

After backfilling the hole and tamping to the required depth for the bottom sensor, the first TDR probe (#10) was lowered to rest horizontally at that level. With this sensor centered in the hole, the resistivity rod and thermistor rod were placed vertically along opposing sides of the hole so they rested on the bottom, but not touching the TDR probe. The tops of the rods were to be located two inches below the surface of the subgrade or dense graded aggregate base, with elevations being recorded on Data Sheets SMP-I02. Cables for all sensors were grouped together on the surface of the base or subgrade, and buried later in a shallow trench leading to the environmental pull box. All probes were installed correctly except for the resistivity and thermistor rods in Section 390204, which were set six inches too deep.

With these sensors correctly positioned, the hole was backfilled in 1.5 inch tamped lifts beginning with soil from the last bucket. Two samples were collected from this bucket for moisture content determinations since accurate estimates of these values are required for use in the TDR equation. A long tamper with a flat round end was used to compact soil. This tamper had a small half-circle removed on one side to fit around the thermistor and resistivity probes during tamping. To protect the resistivity elements further, a section of PVC pipe split longitudinally was used to cover the entire exposed length of the probe, as the hole was backfilled. When the proper elevation was reached, usually at six-inch increments, the next TDR probe was installed on the bottom and two more soil samples were taken as the next lift of backfill was placed in the hole. This process was repeated until the final TDR probe (#1) was placed either six inches below the top of the subgrade or mid-depth in the dense graded aggregate base when this material was used. The top TDR probe was installed so the cables protruded downward to avoid breakage during construction. With this complete, the hole was backfilled to the top of the subgrade or base layer. The depth of all TDR probes was referenced to the top of the resistivity rod and recorded on Data Sheet SMP-I0. A description of each lift of soil replaced in the hole was recorded on Data Sheet SMP-I04. Figure 3.11 shows a typical layout of an environmental sensor installation.

To protect the thermistor probe for later installation in the pavement layer, it was necessary

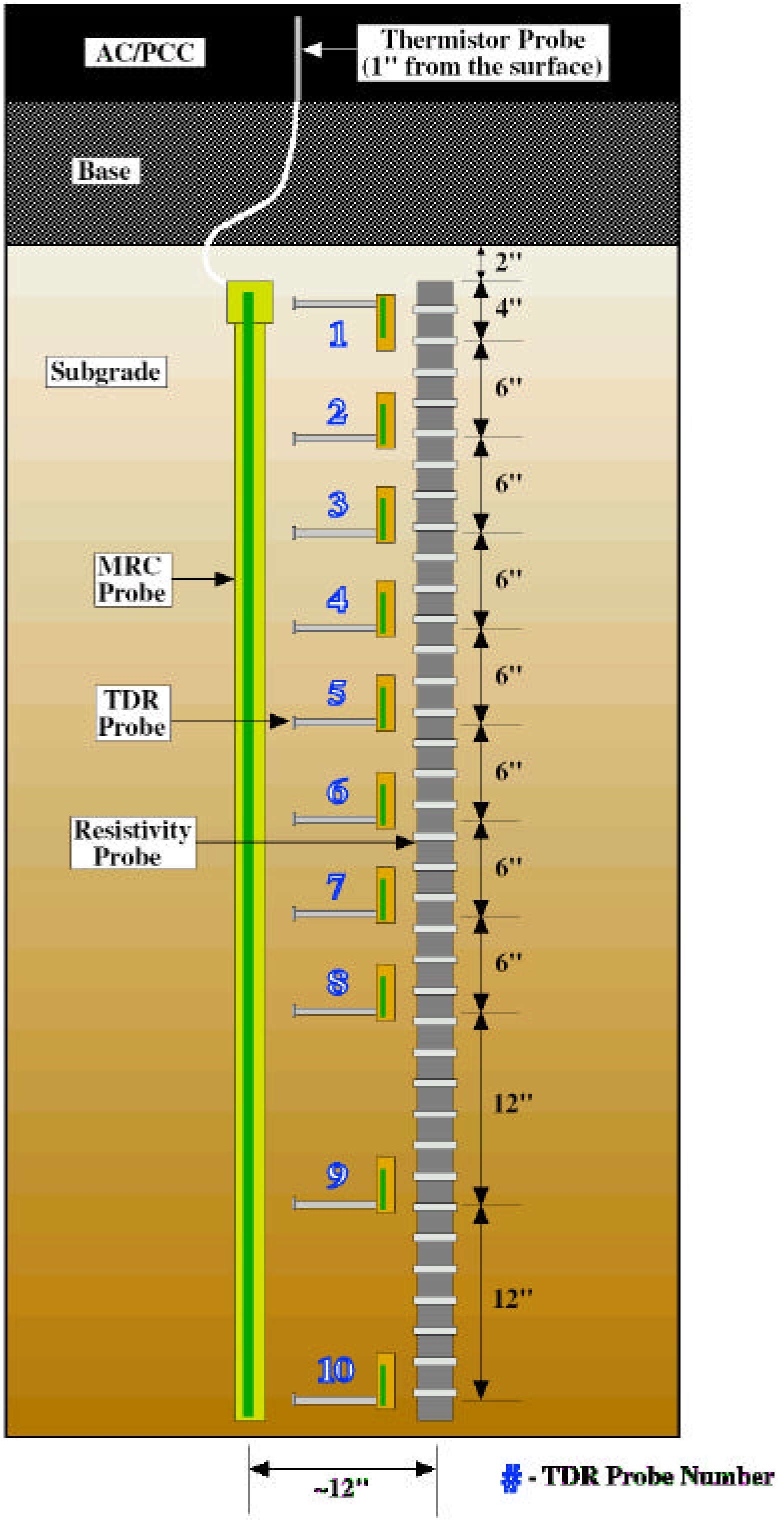

Figure 3.11 Environmental Instrumentation Layout

to temporarily bury it vertically in sand inside of a small rubber hose until paving was either in progress (portland cement concrete) or completed (asphalt cement concrete). The probe was pulled to its proper elevation at that time, affixed in the pavement, and connected for monitoring. To achieve this, the precise location of the probe in its temporary position had to be recorded for later reference. This was accomplished by placing four permanent markers on the existing road (two on each side of the sensor) whose diagonals intersected at the sensor location. Once portland cement concrete paving was past the sensor location, the markers were used to locate it so it could be raised to the surface immediately while the concrete was still green. For asphalt concrete, however, it was necessary to return to the site after construction and bore a 1.5-inch diameter hole at the sensor location. Once the thermistor was carefully raised and positioned, the borehole containing the probe was backfilled with the correct amount of base and AC material.

Cable Installation

With the 12 inch diameter auger hole completely backfilled prior to paving, it was necessary to excavate a trench deep enough to avoid having the cables cut during the final grading. This trench ran from the hole to the edge of the test road. All sensor cables were tied and placed in the trench, which was then backfilled and compacted lightly. A final compaction was completed before paving.

Once paving was completed, the trench was extended from the edge of the road, under the edge drain, and to the environmental pull box where the cable ends would be accessible. Since final grading was not performed beyond the right shoulder and the edge drain was not in place, this trench was excavated to depths of two to three feet using a trenching machine. The cables were again tied and buried in the trench. To protect the exposed cable ends from moisture and debris in the pull box, they were enclosed in a short PVC pipe section having one end capped.

CHAPTER 4

SEASONAL DATA ACQUISITION

Overview

Environmental data was collected continuously at specified time intervals to correlate overall performance of the pavement sections with accumulated traffic and to accurately model the dynamic response of instrumented sections during controlled vehicle tests. The stiffness of asphaltic mixtures is temperature dependent. Moisture content affects base and subgrade support stiffness. Frost depth conditions impact overall stiffness of the pavement structure. The following paragraphs summarize seasonal data acquisition systems and data collection procedures employed on the Ohio SHRP Test Pavement.

Data acquisition equipment used for environmental monitoring includes four major system components: an onsite temperature collection system, a mobile soil moisture, and frost depth data collection system, a personal computer, and a personal computer/cataloger interface.

Onsite Equipment

The onsite temperature collection system consists of individual units wired together and housed in a 14-inch by 12-inch watertight box. The first component in this box is a Campbell Scientific Inc., CR10 programmable datalogger/controller with a wiring interface. It has 64K bytes of Random Access Memory (RAM) used to store information, compile programs, transfer data, and provide memory for entered programs. CR10 units are accessible through a computer, a communication interface, and wiring interface boards containing 49 wire junction ports, a power import, a serial input/output, and ground. An interface wiring schematic for onsite CR10 systems is provided in Figure 4.1. Rather than directly wiring each CR10 to MRC thermistor probe leads, a four-screw terminal block was used as a connecting junction. This terminal was fastened to a block of wood screwed down to the base of the box.

Another components fastened to the onsite box was the battery pack unit, which consists of a rechargeable lead acid 12-volt battery cell, manufactured by Yuasa-Exide, Inc., an interface bracket, and a plug. Positive and negative leads from these battery units were plugged into an external battery socket on the interface bracket. This bracket also contained six-wire junction ports (two charge connections two + 12-volt connections, and two grounds) and an on/off switch which regulated voltage flow from the battery to another independent unit. A Tamura Class 2 transformer (plug) had two leads connected to both charge connections on the interface. This maintained a battery charge using an external AC source. One ground wire and one power wire were used as a connection from the battery interface to the CR10 power import to supply the necessary 12 volts to the CR10 datalogger.

Each environmental section was equipped with an individual onsite data collection system. To set up this system, the MRC probe cable was fed through the box port and each wire was connected with corresponding wires from the CR10 at the screw interface. Transformer wires were also fed through this port to maintain system power while the enclosure was closed. Putty material supplied with each box was used to seal the port to provide a watertight system. The transformer was plugged into an AC outlet supplied in each pull box, and the battery unit was turned on.

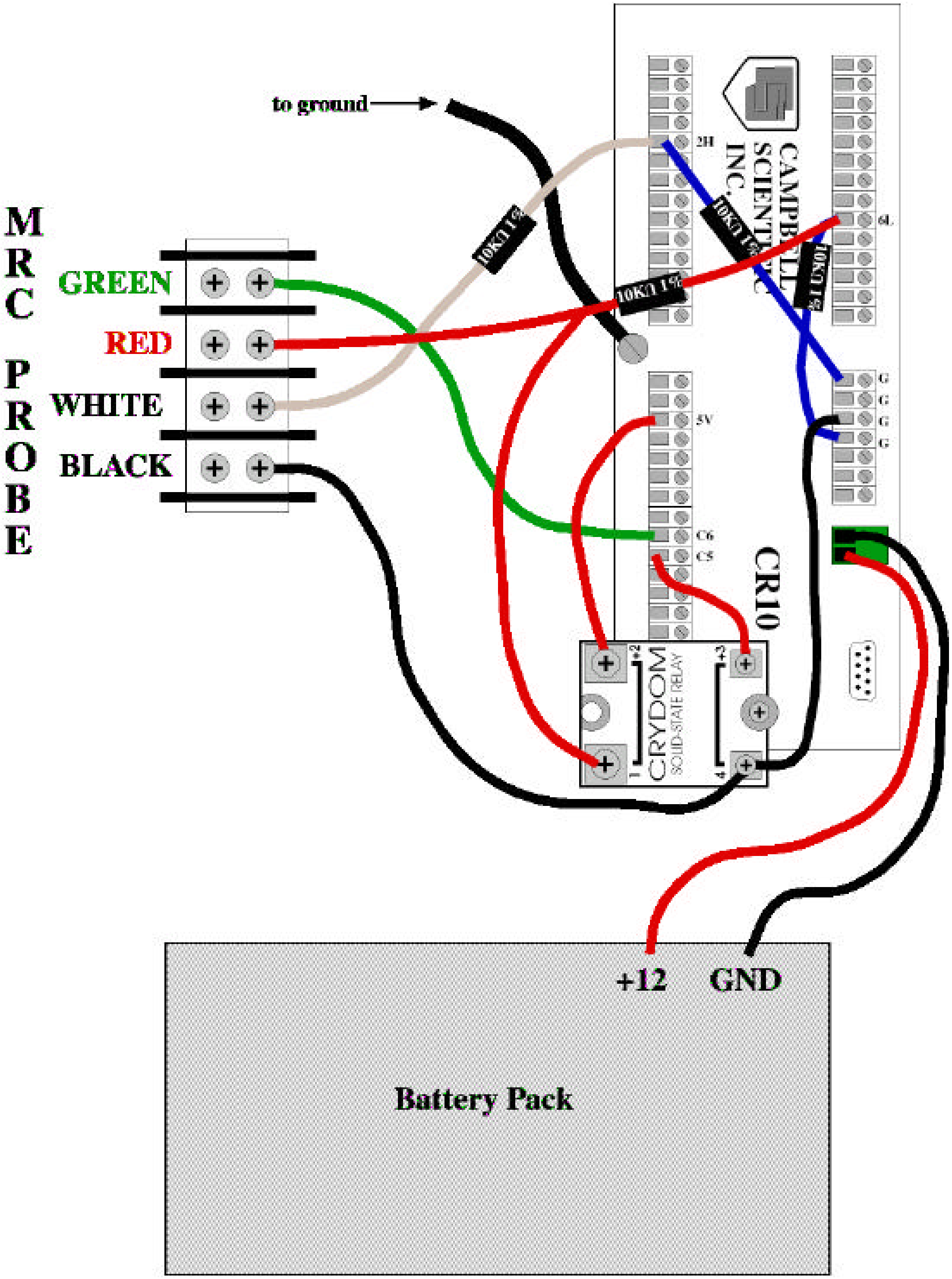

Figure 4.1 Onsite System Wiring Scheme

Mobile Equipment

The mobile data collection system consisted of a number of intricate units linked together with cables to monitor soil moisture and frost depth. This system was sectioned into two watertight enclosure boxes. The first was a 30-inch by 17-inch by 11-inch deep box containing a CR10 datalogger, a battery pack, and a Tektronix 1502B TDR Metallic Cable Tester. The CR10 and battery pack, were set up in a manner similar to the onsite units with the wiring schematic shown in Figure 4.2. A TDR PROM computer chip was installed in the Mobile CR10 datalogger to operate the Tektronix unit during data collection.

The Tektronix TDR cable tester was fastened to a bracket inside the box. This bracket allowed the cable tester to be lifted to view of the oscilloscope. The Synchronous Devices for Measurement (SDM1502) interface was attached to the front of the Tektronix unit. This module regulated TDR multiplexing board activity from the cable-testing unit. The Tektronix unit was powered by the CR10 unit via a PS1502B power interface module in the rear of the cable tester. The CR10 regulates power flow to the cable tester during data collection using this power interface.

The second enclosure was a 12-inch by 10-inch watertight box containing a CRREL multiplexing board, two TDR multiplexing boards, and a bracket to mount both TDR boards. The CRREL multiplexer was mounted on the base of the box and had a female DB37 connector fastened to the TDR board bracket above it to connect the resistivity probe. The TDR multiplexers were mounted on top of a bracket above the CRREL board side by side. The first multiplexer was connected directly to the cable tester via a coaxial cable. A separate cable linked the eighth interface connection on the first multiplexing board to the second board. This configured the first seven probes connected to the first board and the last three to the second board. Figure 4.3 provides a view of both units.

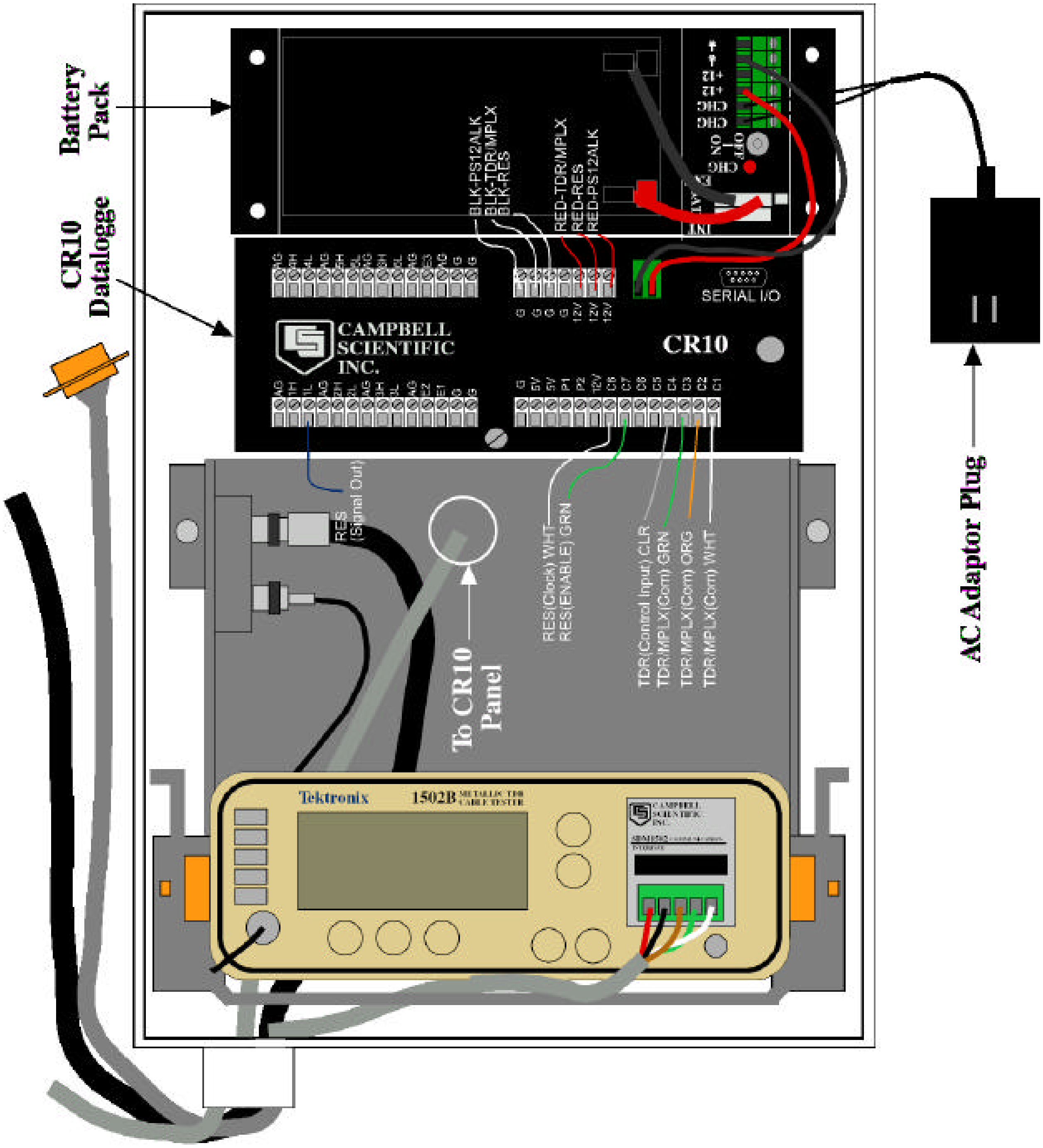

Figure 4.2 Mobile System CR10 Wiring Scheme

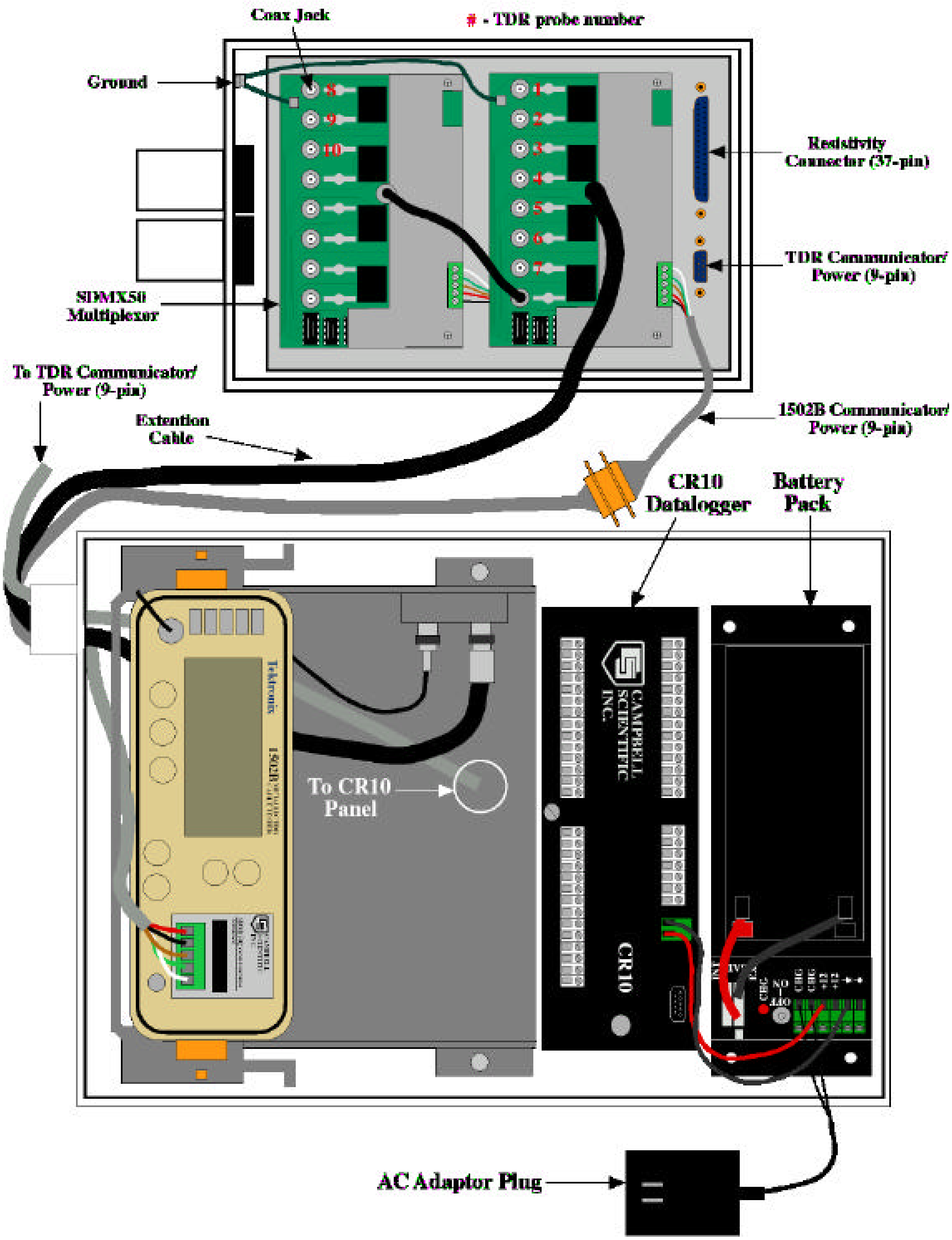

Figure 4.3 Mobile System

Three cables connected the two boxes. First, a cable with a nine pin connection from the CR10 wiring interface was connected to the bracket in the smaller box for TDR communications and power. A second cable connected the SDM 1502 interface with both TDR multiplexing boards. A third shielded coaxial cable connected the cable tester signal generator with the TDR multiplexing boards.

Both the CRREL resistivity cable and TDR coaxial cables were removed from the pull box and set beside the mobile unit. TDR cables numbered 1 through 7 were fastened to multiplexing board number 1. The remaining three cables were connected to the first three interface ports on multiplexing board number 2. The resistivity DB37 connector was attached to its mate in the mobile unit and screwed down on each side. The battery unit was plugged into an AC outlet and turned on. Finally, the Tektronix cable tester was raised out of the enclosure and turned on.

Personal Computer/Datalogger Interface

An IBM compatible laptop computer was used in the field for environmental data collection. All data were saved on the hard drive and backed up on floppy disks after testing was complete. Graph Term software, Version 2.1, provided by Campbell Scientific, Inc., was used to initiate CR10 data collection, upload the data, and view results. This software was installed on each computer used for environmental data collection.

The computer communicates with CR10 dataloggers via an SC32A Campbell Scientific, Inc., Optically Isolated RS232 Interface. One end had a male DB9 connection for a datalogger, and the other end had a female DB25 connection for a computer.

Once the computer was setup, the SC32A communication interface was attached to the COM port via a serial cable. This interface linked the CR10 datalogger to the computer. The interface hookup was the same for both data collection units.

After all data acquisition systems were assembled and determined to be functioning correctly, they were brought to the site for data collection. Onsite units were permanently installed at the designated sections. The computer, interface, and mobile unit were brought to each site for testing. Upon arrival at the site, environmental cables were uncoiled from the pull boxes and preparations made for data collection.

CHAPTER 5

SEASONAL MONITORING PROCEDURES AND DATA ANALYSIS

Overview

To facilitate data collection, and to maintain uniformity and consistency between data collection agencies, SHRP guidelines were followed during site monitoring. These guidelines describe in detail the process for CR10 program setup, sensor monitoring, and data collection.

CR10 Datalogger Setup

Before CR10 dataloggers were used to monitor and store data, a computer program was uploaded to each unit. This program was the main source of communication between the datalogger and the personal computer, and instructed the datalogger to collect, store, and delete data at required intervals. This was necessary for both onsite and mobile units, and was performed with the Graph Term (GT) software package. After starting the program, the source code controlling either the onsite or mobile unit was uploaded to the CR10 following specific instructions shown on the screen. Next, the datalogger clock was set to the computer time, and the system was then ready to monitor the sensors at preset time intervals. This process was performed each time data were taken with the mobile units, since power was cut as the unit was moved from site to site. For the onsite datalogger, however, this process was performed only at initial startup since the datalogger was monitoring and storing soil temperatures continuously. Should a power failure have occurred, the battery attached provided backup power to allow uninterrupted monitoring of temperatures.

Data Retrieval

The onsite data collection procedure required only about three minutes to begin monitoring a temperature profile and two minutes to upload data. The mobile system needs approximately twelve minutes to collect all soil moisture and frost depth data.

Onsite Unit

The first step for onsite data collection was to configure the CR10 directory from C:\> prompt. CR10 software contains a basic documented source code labeled AONSITE.DOC@. A specific copy of this document file must be formed for each environmental section, and the onsite file must be edited using the "edlog onsite @ command. Executing this command lists the onsite program shell and provides options for editing at the top of the screen. First, select ASave@ by entering an AS@. This prompts the user to enter a filename using the format AS@ plus the section identification number. For example, the onsite program for section J10 SPS-1 is entered as S390110. This saves the filename as a document (.DOC) file and also produces a backup file (.BAK). The next step for onsite data collection is to create a download file for the datalogger using a documented source code. This is accomplished by selecting the ADocument .DLD File@ option. The computer compiles a .DLD file and returns to the edlog screen. Finally, the AQuit@ option is selected which, in turn, prompts ASAVE the current file? (Y/N)@. The AY@ selection is entered and the computer returns to the CR10 prompt.

The Graph Term (GT) software controls communications between the computer and the CR10. This software is executed by typing AGT ONSITE@ at the CR10 prompt. The Graph Term screen is displayed providing several options for program execution (see Figure 5.1 for GT screen).

The second step for onsite data collection was to set the clock on the CR10 datalogger. This

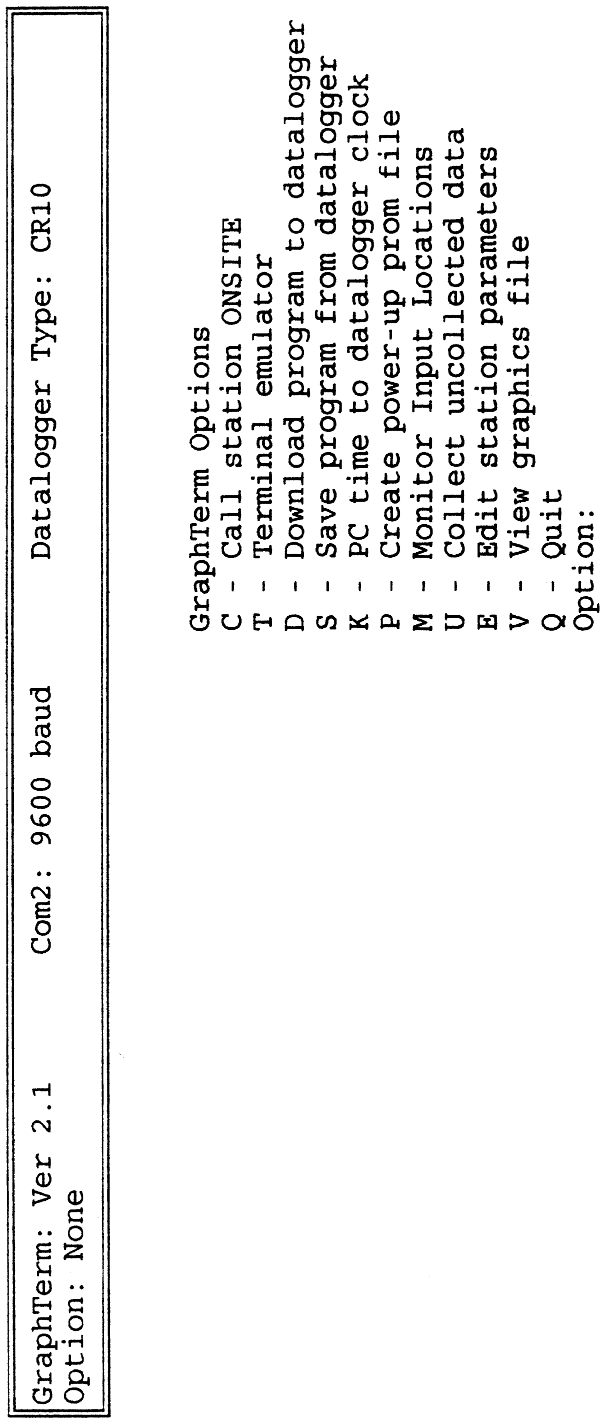

Figure 5.1 Graph Term Screen

is accomplished by entering AK@ at the GT screen and setting the datalogger clock to Personal Computer (PC) time. This allows the CR10 to label all data collected with the correct time.

Next, the data collection program must be loaded into the CR10 unit. Enter AD@ at the GT screen, which, in turn, prompts the user to enter a program filename. The section filename is entered and the computer downloads program information to the CR10.

After setting the clock and downloading the program, the CR10 unit begins following its data collection procedure. To view the temperature profile monitored by the datalogger, enter AM@ to monitor input locations. This displays battery voltage, air temperature (no probe is installed), precipitation total (instrument not installed), and 18 thermistor readings in degrees Celsius (see Figure 5.2). All individual temperature points were sampled every minute. The average of the top five thermistor temperature readings were collected every hour, and the average temperature readings for all eighteen probes were saved at midnight. The maximum and minimum temperatures for all thermistors and times at which they occur were also recorded at midnight.

The last step is to upload temperature data stored in the CR10. Select U "Collect uncollected data@ at the GT screen which initiates the computer to begin uploading data. To avoid saving the same data repeatedly, the datalogger marks the point at the end of the current data file collected, so future collections begin from that point. Data is stored as filename .DAT (i.e., S390110.DAT) in the CR10 directory.

After data collection was completed, the communication cable was removed from the CR10, and the onsite enclosure was closed and set in the pull box. If the CR10 is turned off, the source code will be lost. The datalogger continues to collect temperature data at its assigned intervals as long as power is supplied and the battery does not die or is turned off. After about five weeks of data

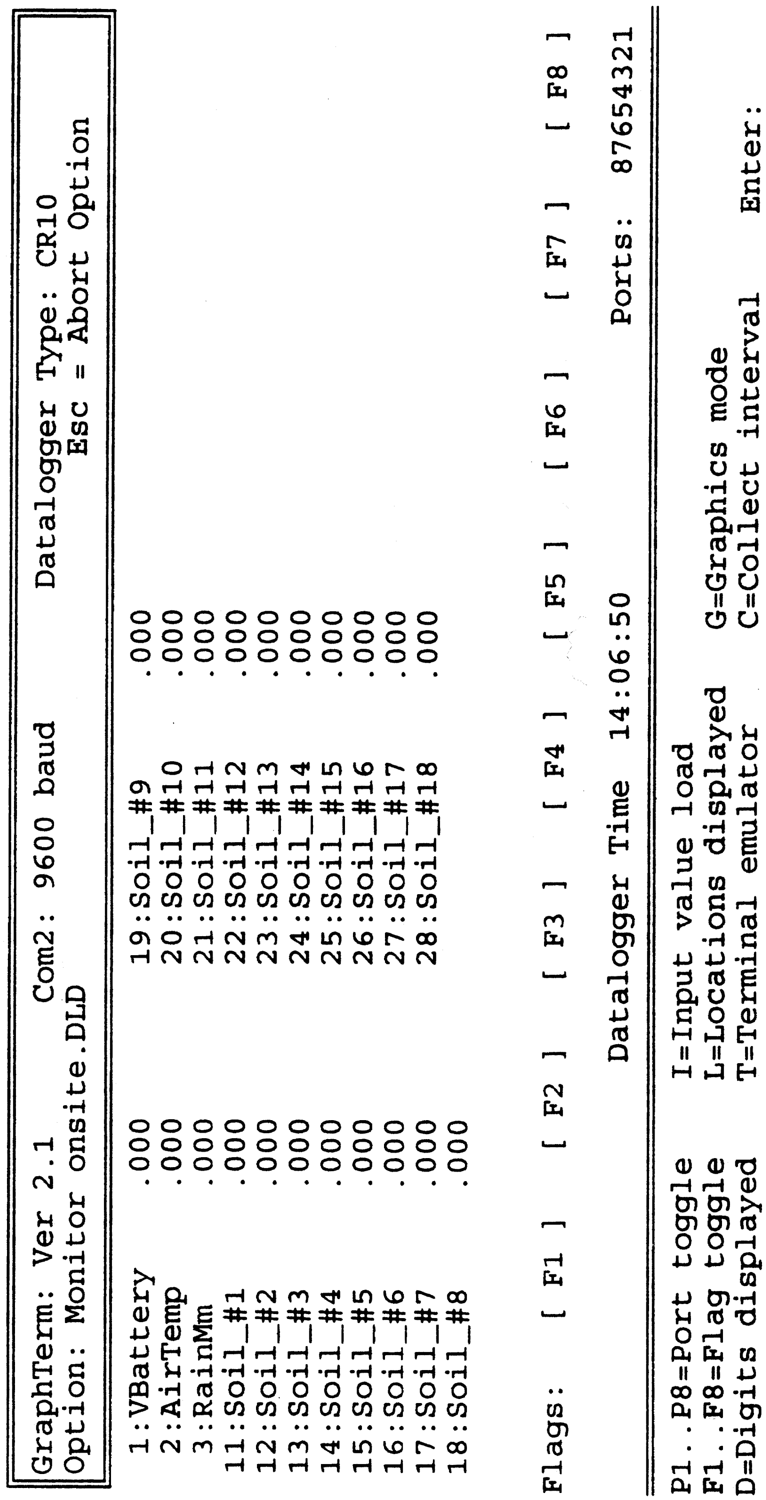

Figure 5.2 Onsite Monitoring System

collection, the CR10 runs out of memory storage space, and the datalogger begins overwriting older data. Therefore, data from the onsite unit must be collected once a month to insure a complete data set is acquired.

Mobile Units

To begin data acquisition with the mobile units, the resistivity and TDR probe cables must first be connected to the multiplexer following the numbered ports. Next, the cable tester is connected to the multiplexer board and the CR10 is linked with the serial cable and interface to the portable computer. The Graph Term program is executed, source code and time are uploaded to the CR10 as before, and the system is ready to monitor.

Much of the onsite data collection procedure is used for the mobile system as well. Mobile system data collection is also performed using programming in the CR10 directory. The MOBILE.DOC file is also edited using the edlog program, which is executed entering Aedlog mobile@. A new .DOC and .DLD file is created in the same manner as with the onsite program, but two alterations must be made. Before anything is created or saved, scroll down through the program until A***7:4 hours - resistivity voltage values@ is in view. The A03:-1 F@ line under this heading must be altered to read A03:1 F@ to enable the program to read resistivity probe data. Also, further along in the program, cable lengths of TDR probes must be modified. Scroll down to A*** TDR data collection and output@ and then to line 49:04. The TDR cable length must be changed to the length recorded at the top right corner on the printouts created during calibration. This alteration is made for the first seven probes, but an additional 0.5 meters is added to the remaining three lengths to compensate for signal travel along the length of cable connecting the two multiplexer boards. With this completed, .DOC and .DLD files are ultimately created using AM@ instead of an AS@ in front of the section identification number (i.e., M390105.DOC).

The Graph Term software is also used to control communications for mobile data collection and is executed by typing AGT MOBILE@ at the CR10 prompt. The same GT screen appears for the mobile program execution as with the onsite (refer to Figure 5.1). Steps followed to edit station parameters, set the clock, and download the program for onsite data collection are also used for mobile data collection. Viewing mobile data is also made possible by selecting the AM@ option on the GT screen. This provides a display of the battery voltage, resistivity values (odd coil numbers 1-35) in milli-volts, timer, and soil moisture waveform values (see Figure 5.3). If the resistivity values are reading -9999 milli-volts, the probe is not correctly attached to the system or the multiplexer is not wired correctly. If the probe is reading -6999 milli-volts, there is a mechanical problem, and its wiring must be checked for damage. Nothing can be determined from values projected on the screen for TDR probes. This information is for the analysis program used to determine soil moisture content. The waveforms can be viewed on the Tektronix oscilloscope as it sends a signal to each TDR probe approximately four minutes after resistivity values are determined.

After the system collects data from the last TDR probe and the timer begins counting again, data must then uploaded from the CR10 at the GT screen by entering a AU@. This uploads mobile data into the CR10 directory as filename with a DAT extension. The datalogger appends all new data to the filename in the same manner as for onsite data collection.

When data collection is completed, the communications cord is removed from the CR10, the battery is shut off, and the transformer unplugged. The Tektronix unit is folded down inside the enclosures, and the larger mobile unit is closed. The resistivity DB37 connector and all TDR coaxial cables are removed from the smaller unit, and the enclosure is latched shut.

As with temperature, resistivity and TDR, data can be checked in the field using the

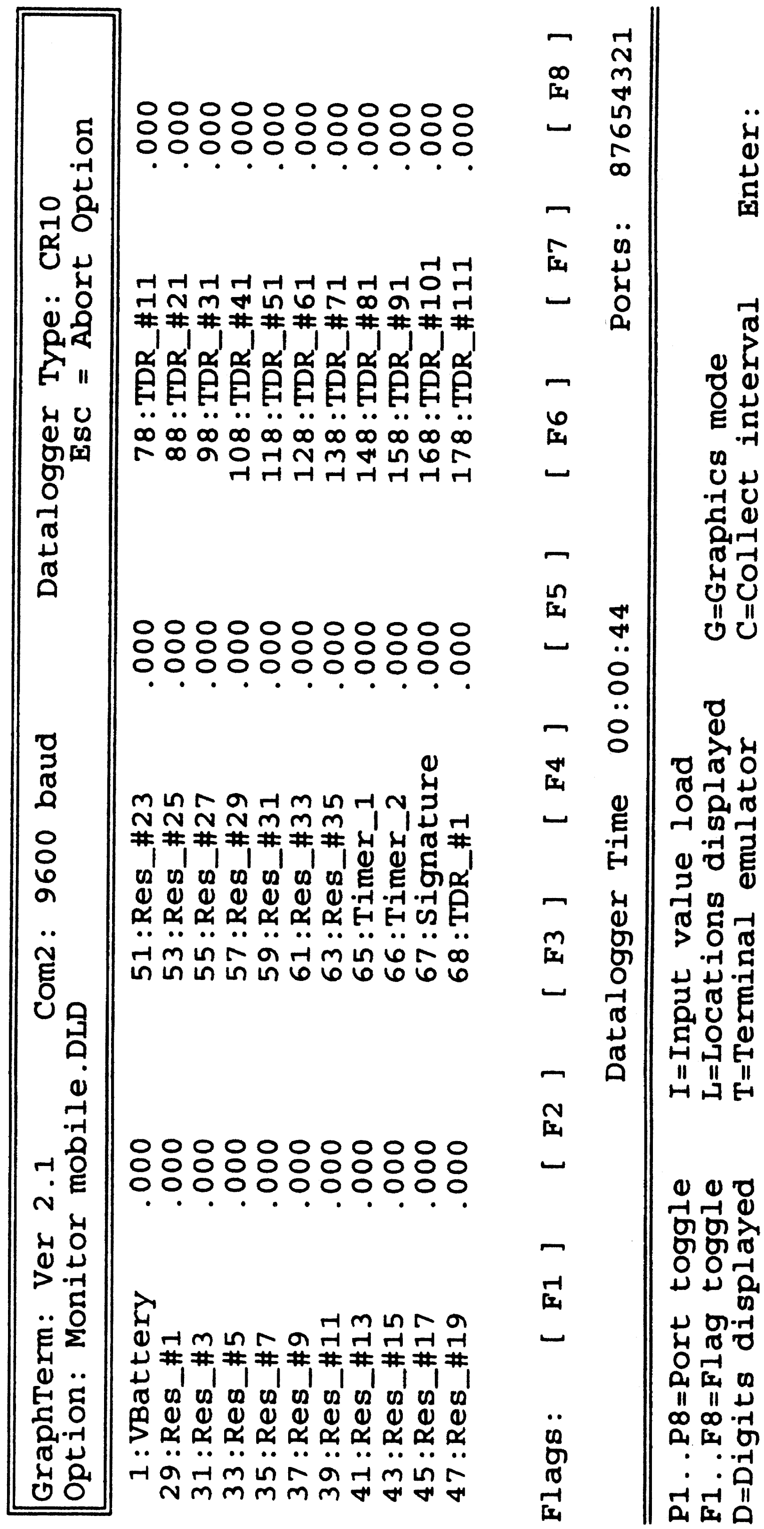

Figure 5.3 Mobile Monitoring Data Screen

MOBFIELD program. All ten TDR traces are displayed as well as a graph of the resistivity values throughout the subgrade. Should problems be immediately visible in the graphs, the user can repeat the monitoring process.

TDR probes were monitored the first time at each site using the mobile units; however, one additional step was necessary to obtain useable readings. The source code provided for upload to the CR10 for each site contains information relating to TDR probe length and cable length. This information was obtained from manually monitoring the TDR probes after their installation in the subgrade. The first time data are collected with the mobile unit, the screen-displayed traces may need to be shifted left or right so the first peak is centered on the vertical axis. This is performed using the EDLOG editor to manually adjust the probe lengths in the source code. The amount of adjustment is determined from the trace display, and the corresponding probe length is increased or decreased accordingly. This process is repeated until every TDR trace is aligned correctly on the cable tester's screen.

Data Analysis

Once data is downloaded from the CR10's at both the seasonal sites and the weather station, it has to be checked and edited for quality. If the data meets quality assurance checks, it is forwarded to LTPP for inclusion in the Data Pave database. From this point, any organization wishing to examine and analyze it can access the data.

To facilitate data analysis, a computer program was written to allow all participants to enter the data in a consistent format. A separate program was created for both seasonal road data and weather station data. The former is known at SMP Check (Seasonal Monitoring Program Check), while the latter is known as AWS Check (Automated Weather Station Check). Both provide a menu-driven front-end that allows for easy use on a DOS platform.

SMP Check Program

The SMP Check Program requires the user to specify a site and to enter relevant installation data such as sensor depth and soil properties specific to that site. The user can then monitor the onsite and mobile data using graphs prepared by the program. In order to meet SHRP specifications, the data must pass a Level D check before it can be sent to the collection site. This check is performed by the program, which alerts the user to the current status. If the data passes all checks, an upload file can be created; whereas, data that fail must be edited for content.

<u>Procedure</u>

Once the SMP Check program is installed and executed, the user is immediately prompted for a specific site identification number that includes state code, site letter designation, and the SHRP number. For Ohio, the SPS1-J2 section is identified as 39P0102. Table 5.1 lists the required name designations for the sites involved in this study. Once the Escape key is pressed, the program creates a subdirectory, in this case 39P, which in itself, contains five subdirectories: CHKFILE, IMSDATA, ONSDATA, MOBDATA, and PROINFO. The user must then copy the individual onsite and mobile data files downloaded from the CR10's into the ONSDATA and MOBDATA directories, respectively. This can be done through the ADOS Shell@ menu choice, or by exiting the program. It is important that these files be previously renamed according to SHRP guidelines, as illustrated below:

ssS#yyab.cde

Where ss = state code (39 for Ohio)
S = AS@ for every data file
# = designation letter as seen in Table 5.1
yy = year that the data was collected

a = identification for each sequential visit: A = 1st, B = 2nd
b = month of data collection; A = January, B = February
cde = file extension; ons for onsite data, mob for mobile data

Once this has been done, the user can return to the program by exiting the DOS shell and then re-enter the site identification section if necessary.

Table 5.1 SHRP Section Identification

Designation	SPS	Section No.	Station	Responsibility
A	SPS-8	390809	20 + 92	ODOT
B	SPS-2	390204	285 + 35	UT
C	SPS-2	390212	302 + 00	CWRU
D	SPS-2	390202	324 + 70	UT
E	SPS-2	390205	341 + 30	CWRU
F	SPS-2	390201	342 + 70	OSU
G	SPS-2	390211	374 + 00	OSU
H	SPS-2	390203	389 + 00	CWRU
I	SPS-2	390208	403 + 75	OU
J	SPS-2	390263	421 + 25	OSU
K	SPS-9 (AC-20)	390901	287 + 00	CWRU
L	SPS-9 (PG58-28)	390902	302 + 25	OSU
M	SPS-1	390112	326 + 50	UT
N	SPS-1	390104	341 + 30	UT
O	SPS-1	390101	355 + 82	UT
P	SPS-1	390102	375 + 80	CWRU
Q	SPS-1	390108	393 + 65	OSU
R	SPS-1	390110	407 + 85	OU

CWRU Case Western Reserve University OU Ohio University

ODOT	Ohio Department of Transportation	UT	University of Toledo
OSU	Ohio State University		

With each site directory created, the DATA PROCESS menu allows the user to enter project data, or to process onsite and mobile data. If the AProject Data@ option is selected, the user has the option to enter one of five types of site data. This includes information collected during sensor installation at each site and recorded on the corresponding data sheets provided by SHRP. The identification number of each sheet corresponds to the number following the available options on the menu, and includes:

1) Instrument Location and TDR Depth (I02)
2) Thermistor Probe Depth (C02)
3) Resistivity Probe Depth (C03)
4) Field Gravimetric Moisture Content (I05), and
5) Field Measured Dry Density (I07)

Once all available data is entered, the computer automatically stores the information in the PROINFO subdirectory where it must now be checked for quality. Choosing the OFFICE CQ option on the main menu, and selecting AC and D Level@ option does this. The program will then check the data for allowable content based on SHRP=s guidelines. A file named SC#*.qc (where SC is the two-digit state code, # is the site ID, and * is AMANUL, ONSIT, MOBLE, or PRJCT@ depending on the type of data being processed) will be created in the CHKFILE subdirectory (SMP Check 1996, 27). Using any editor, the user can view this file to determine if the data has passed Level D status. If not, the user must find and correct any errors made on the data entry screens and execute the quality check again.

With the project identification entered, the user can process onsite, mobile, or manual data that has been collected. Manual data consists of any preliminary readings collected with equipment other than the onsite and mobile dataloggers. If required, all sensors can be monitored with the exception of air temperature probes and rain gauge devices (13). Equipment for other data collection is described in the Seasonal Monitoring Program Guidelines and will not be discussed here.

At this time, the user can process onsite or mobile data. If the AOnsite Data@ option is selected, the program displays all data files available in the site directory for processing. One or all of the files may be selected, whereupon a screen is displayed listing all chosen files and their start and end dates for data collection. Typically, these files will have overlapping dates, which the computer will adjust automatically. If two or more files start on the same day, it is only necessary to select the one file that has the latest end time. If necessary, the user may make time corrections for Daylight Savings Time by adding or subtracting up to two hours from specific days.

With this complete, the program checks the data files, adjusts for overlap and time corrections, and then prepared six graphs that include the following:

1) Daily average, min., max. air temperature and rainfall data
2) Daily average air, rainfall, and first 5 MRC sensors temperature data
3) Daily average all 18 MRC sensors average temperatures
4) Daily average all 18 MRC sensors maximum temperatures
5) Daily all 18 MRC sensors minimum temperatures, and
6) Hourly air temperature, rainfall, and first 5 MRC sensors temperature data

Since this program was developed with other data collection sites in mind, the air temperature and rainfall data will be absent from these graphs in all Ohio Test Road monitoring sites. Typically, each instrumentation site will have its own air temperature and rainfall gauges, whereas, the Ohio SHRP Test Pavement obtains this data through the use of the onsite weather station. This data is viewed and edited with the AWS Check Program described later. Figure 5.4 provides an example of selection 4) above which illustrates daily average temperatures for all eighteen thermistors. Although the sensor number is not visible in the graph, it is seen that temperatures near the surface fluctuate intensely while temperatures deep in the subgrade undergo little change.

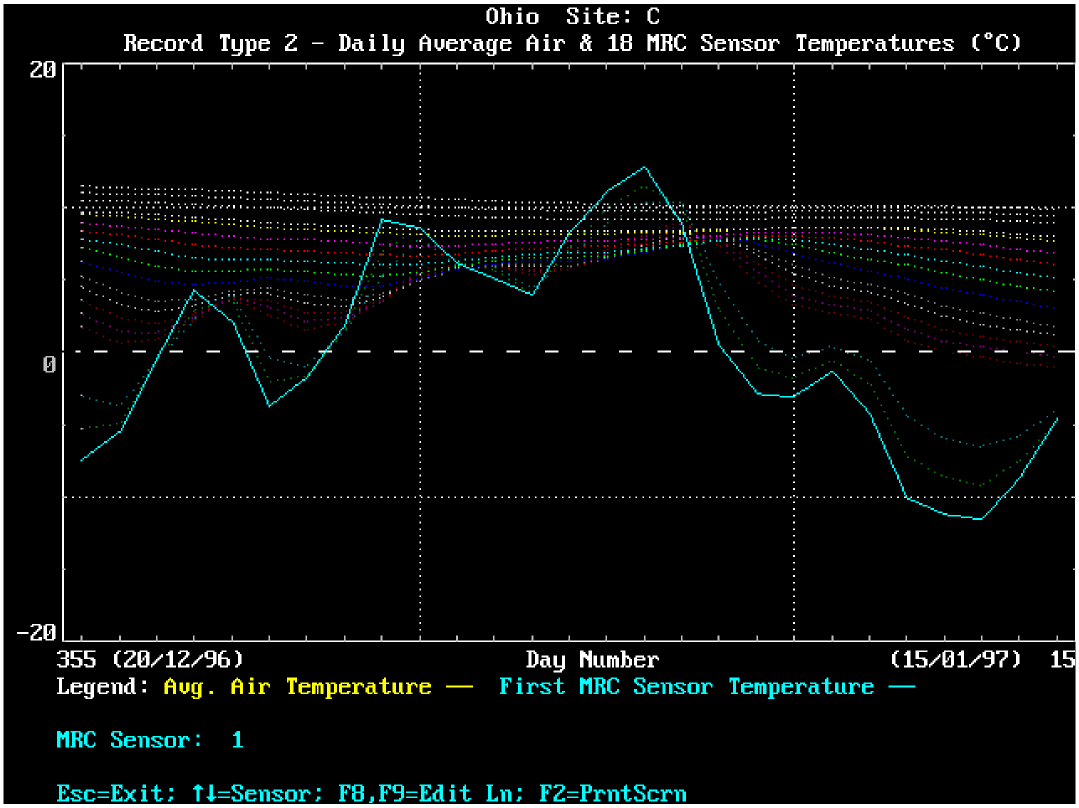

Figure 5.4 Typical SMP Check Display of Daily Average Thermistor Temperature

With the graphs displayed, the user must scan for possible data points that are clearly inaccurate and may reveal an equipment malfunction. If any are found, the editing keys listed on the screen are used to remove the points. With this complete, as with the project data, the onsite data must pass a level D quality check. To do this, the OFFICE QC option is again selected on the main menu, followed by the AC and D Level@ option. Once AOnsite Data@ is chosen, the computer performs a quality check similar to that performed by the user. The results of this check are written to two files, SC#onsit.msg and SC#onsit.qcr (using the same notation described above), that are placed in the CHKFILE subdirectory. When viewed, the *.qcr file lists the status of each type of data field checked by the program. For onsite data and mobile data, the description of every field is listed in Appendix B of the Seasonal Monitoring Program Guidelines. If a field did not pass level D status, as required by SHRP, a description or list of the bad data points is provided so that the user can return to the graphs and remove faulty data. Appendix A of the SMP Check Manual provides sample graphs of acceptable and unacceptable data to help the user identify bad data points. The quality check must be performed each time the data are edited until every field passes Level D. Should the user attempt to create an upload file, any data not passing Level D will be excluded.

Similarly, the mobile data analysis is conducted in the same manner. Once selected, plots of the TDR traces and resistivity values are displayed, as shown in Figure 5.5. For mobile data, however, it is only necessary to choose those plots that are valid by typing the corresponding number under the graph. Appendix B of the SMP Check manual provides samples of acceptable and unacceptable data. The computer will include these plots for processing and quality control when the OFFICE QC option is selected. Again, A SC#moble, msg and a SC#mble.qc file are created displaying selected data and quality control status, respectively. If a file does not pass Level D, the mobile data must be re-evaluated to find the problem.

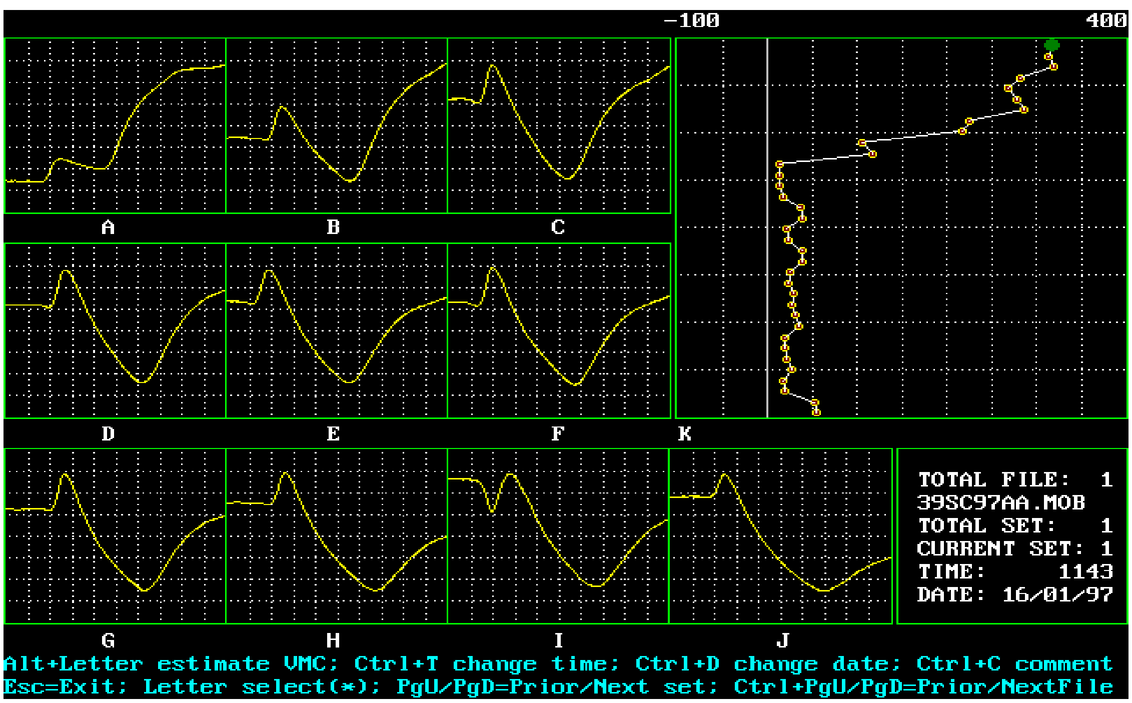

Figure 5.5 Typical SMP Check Display of TDR and Resistivity Data

With all project, manual, onsite, and mobile data passing Level D, it is necessary to create the upload file to be sent to the data storage facility. Selecting the IMS OUTPUT option on the main menu, followed by the ACreate Upload File@ option performs this. A screen appears displaying all of the data available for upload (which has passed Level D), and the user is prompted to select which data to include in the upload file. Any or all of the data can be selected whereupon the computer creates a file in the IMSDATA subdirectory following the format below:

ssmMddyy.UPL

Where ss = LTPP two digit state code in which the test section is located
m = SMP multiple site agency code; A = 1st SMP section, B = 2nd
M = letter designation for month that upload file is created: A = January, B = February
dd = day the upload file was created
yy = last two digits of the year the upload file was created, and
UPL = filename extension used for all upload files (SMP Check ›96, D-1)

Problems

In all, the SMP Check program is straightforward and easy to use. However, a few problems were encountered that did not allow the program to complete execution and prepare the data correctly.

The first of these problems involved a time overlap within some of the onsite files. Although the program was developed to eliminate the overlaps between separate data files, it cannot remove an overlap within one file. Therefore, it was necessary to manually edit the file and delete the repeated data. In addition, many data files began with fields that had been cut in half during data collection because of the ring memory type of storage in the CR10 and, as a result, did not specify a field number. Again, these lines were manually deleted.

Once the program was able to execute properly, several problems were found in the onsite data for every site. These were noticeable while viewing the daily maximum and daily minimum soil temperature graphs. At several days throughout the year, large, unexplained spikes appeared in all of the sensor readings. While this may not be uncommon for sensors in the pavement, sensors in the deeper subgrade soil typically record relatively constant temperatures. It was noticed, however, that these spikes only occurred on days that data was downloaded from the onsite units. It is believed these spikes were created as a result of deleting the station file prior to downloading the data. Because of this, when the datalogger prepared the daily report for this date, it only had several hours of data available to determine highs, lows, and averages.

AWS Check Program

The AWS Check Program used to monitor weather station data follows the same format and procedure for the SMP Check Program previously described. Again, the data are displayed graphically whereupon the user removes corrupt data points, and an upload file is created, providing the data passes the Level D check.

Procedure

Like the SMP Check Program, the user is immediately prompted for the site identification of the weather station that includes the state code, site code, and SHRP section ID. For Ohio, the state code is 39 and the site code is AA@. Site code is determined from the number of weather station sites in the state using AA@ for the first, AB@ for the second, and so on. As for the SHRP section ID, it was assumed that this would be the number for the site closest to the weather station since it was not actually installed at a particular test site. For the Ohio SHRP Test Pavement, the closest section is 390203. Once this has been entered, the computer creates subdirectories much like those described above. The user must copy the collected data files to the newly created AWSDATA directory, and then process the project and weather station data. Project data consists of information relating to weather station positioning at the site such as elevation, latitude, and longitude, and is only entered once for each station.

After selecting the AAW Data@ option under the AData Processing@ menu, the user must select which data files are to be processed. Data files that begin the same date, but end with different end dates, will be combined by the program unless the user specifies which file to use. Again, a correction for Daylight Savings Time is available that allows up to two hours to be added or subtracted from within desired time spans.

With this complete, the AView Selected Data@ option is chosen and the program displays several options for viewing:

1) Daily average, min., max. air temperature and precipitation data
2) Daily relative humidity, solar radiation, and precipitation data
3) Daily wind information
4) Hourly temperature and precipitation data
5) Hourly relative humidity and precipitation data
6) Hourly solar radiation and precipitation data, and
7) Hourly wind information

Figure 5.6 to 5.8 provide samples of selections 2, 3, and 6, respectively. As with Onsite data, the weather station data must be checked for quality and consistency. Options 1 through 3 above, only permit viewing of the data, while options 4 through 7 permit the user to edit the data manually. Obvious Abad@ data, such as extremely high or low temperatures for a season, are removed by selecting a start date and end date, and then deleting the points in between. After all of the data have been checked and edited, if necessary, the AOffice QC@ option is selected from the main menu, followed by the AC&D Level@ option. The computer then checks the data for allowable ranges and writes the status level to a file in the ACHKFILE@ directory. If the status has passed Level D, an upload file may be created, as done with onsite data. If necessary, the user must re-edit the data until it passes Level D.

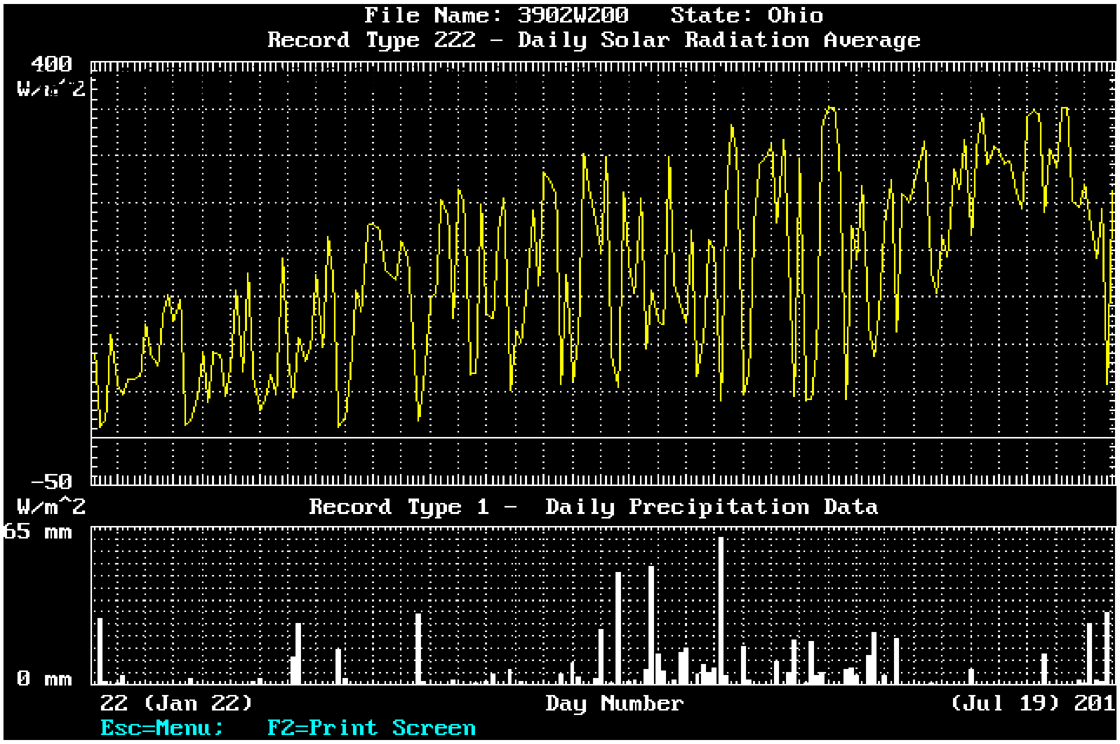

Figure 5.6 Typical AWS Check Display of Hourly Radiation and Precipitation Data

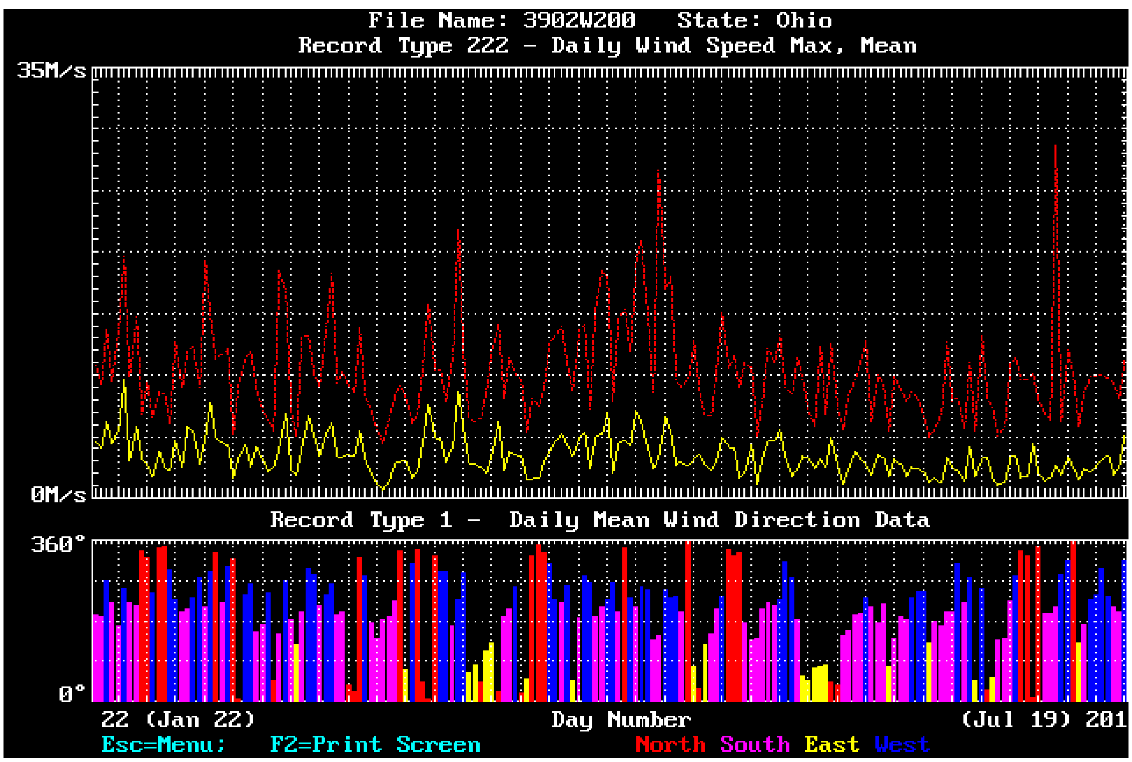

Figure 5.7 Typical AWS Check Display of Daily Wind Information

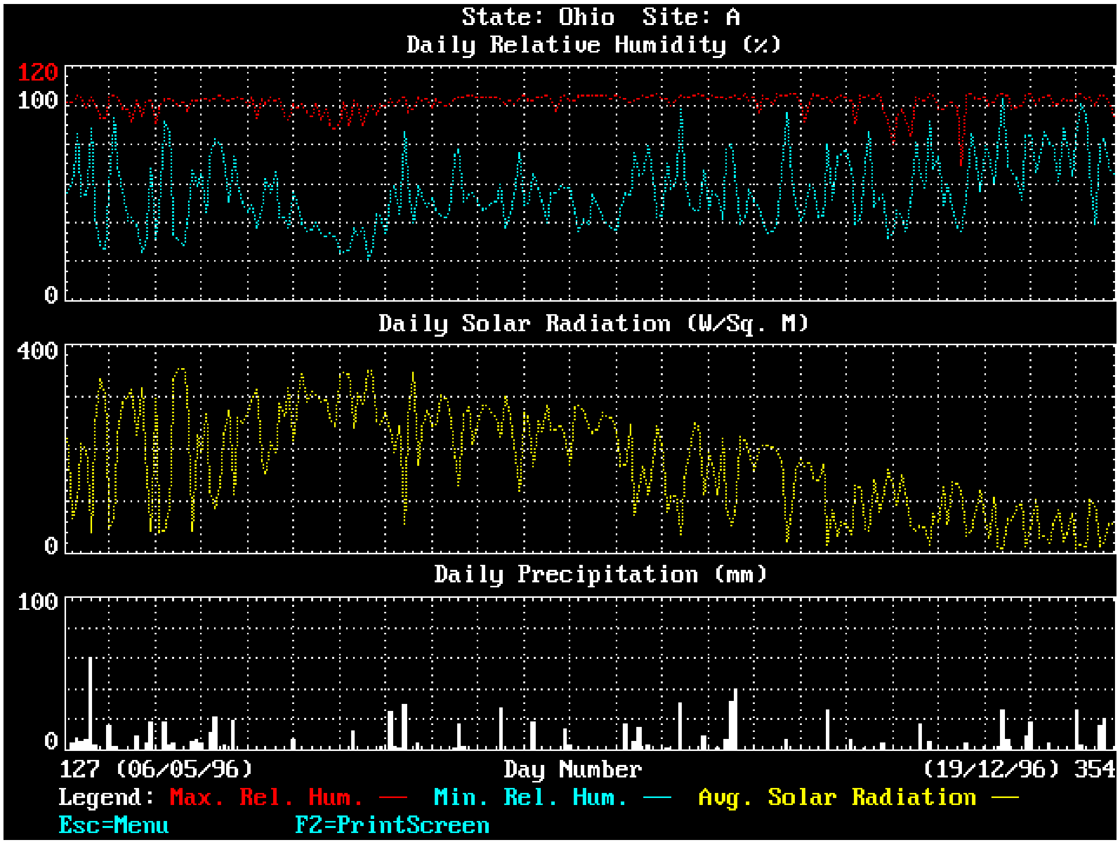

Figure 5.8 Typical AWS Check Display of Daily Humidity, Radiation, and Precipitation Data

Problems

Unlike the SMP Check Program, processing ran smoothly for the weather station data, and an upload file was created with very little editing required. The only problem involved the weather station itself. During the first activation of the station, the selected option in the uploaded program to the CR10 indicated the unit would stop collecting data after all memory had been used, rather than selecting the ring memory option where the oldest data is deleted to provide space for new data. As a result, several weeks of data are missing and appear as a blank area on the graphs. Fortunately, however, this does not affect the data that was obtained. Subsequent operation of the weather station has been performed with the ring memory option which allows for up to approximately six months of data storage without any losses between collection periods.

CHAPTER 6

WEATHER STATION COMPONENTS

Overview

To monitor climate conditions that may enable possible correlation with subsurface temperature and moisture, a weather station was installed near the north end of the test road just east of Section 390203. This station has the capacity to monitor solar radiation, air temperature, wind speed, wind direction, relative humidity, and rainfall.

Air Temperature and Relative Humidity

As with the ground temperature measurements, a thermistor was used to measure air temperature. This thermistor, manufactured by BetaTHERM, was coupled with a capacitive relative humidity sensor manufactured by Vaisala into one probe (Model HMP35C). It was connected to a CR10 mounted in an equipment cabinet on the pole that monitored and stored all weather-related measurements. The working ranges are -33°F to 120°F for the thermistor and 0 to 100% relative humidity for the Vaisala sensor. Figure 6.1 is an illustration of the entire weather station.

Rainfall

To monitor rainfall amounts, a tipping bucket rain gauge was installed a few feet away from the weather station pole. When the level of water reached a calibrated depth, the bucket tipped and sent a pulse to the CR10 datalogger. The water drained after each tip and then returned to its upright position. The number of pulses recorded by the CR10 was used to calculate the total rainfall amounts. The bucket was equipped with a heating device that melted and recorded snowfall.

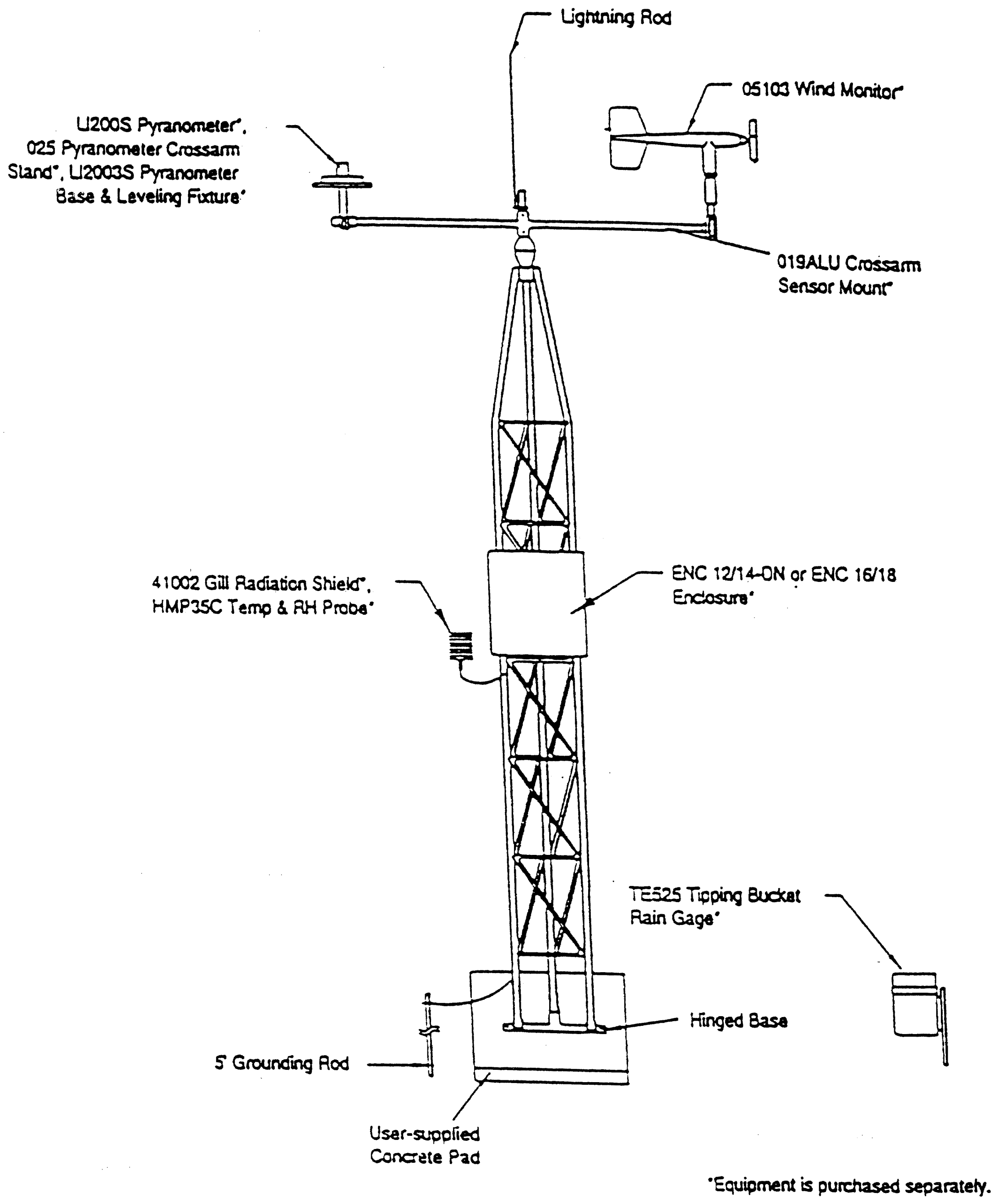

Figure 6.1 UT-3 Weather Station

Wind Speed and Direction

To measure wind speed and direction, a wind monitor manufactured by R.M. Young (Model 05305) was installed on the weather station pole. As the propeller rotates, since wave signals were produced with a frequency proportional to wind speed. Wind direction was determined by the azimuth angle of the vane. As the vane rotated, a potentiometer produced an output voltage proportional to the angle. The CR10 recorded and stored these values.

Solar Radiation

A pyranometer manufactured by LI-COR (Model L1200SZ) was installed on the weather station to monitor incoming solar radiation in terms of energy per surface area. A silicon photovoltaic detector produced an output current based on levels of radiation performed this. A resistor in the cable converted this current to a voltage, which was recorded by the CR10 Datalogger. A cosine correction on the sensor allowed for accurate readings of radiation having incident angles with the surface. For low radiation levels at nighttime, negative readings were common due to system noise and may be set to zero if desired. This sensor should be cleaned regularly to obtain accurate readings.

CHAPTER 7

CONSTRUCTION ISSUES

SPS-1, 2, and 8 experiments were designed to test the structural capacity of pavement sections to carry traffic loads under a range of subgrade and environmental conditions. Upon reaching their structural limits, sections can display various types of distress. Pavement sections were expected to perform up to normal standards and not exhibit premature distress resulting from inferior materials or construction practices. Any problems of this type would jeopardize the validity of data obtained from those particular sections. It was the responsibility of states, therefore, to insure that materials and construction practices being used in the SPS experiments were such that test sections would be capable of reaching their full structural potential.

In Ohio, the primary concern going into the project was to obtain aggregate for the Portland cement concrete pavement sections which was resistant to D-cracking, especially since #57 limestone was being specified. Stone located close to the project had a history of D-cracking susceptibility but, because of its proximity, would likely be selected by the contractor as a matter of economics. Two sources located approximately 40 miles north of the project had shown excellent resistance to D-cracking in the past. With this in mind, ODOT initiated steps to insure the use of D-cracking resistant aggregate.

Time and circumstances did not permit ODOT to conduct its standard test, ASTM C-666, Procedure B, on a large number of aggregates to determine their susceptibility to D-cracking. Instead, samples were obtained from local sources and from the two historically good sources north of the project, and sent to Iowa State University for quality index determinations. This test has been used successfully in Iowa but, thus far, does not seem to be widely accepted. Results of these tests are shown in Table 7.1. As indicated below, the test report received from Iowa State University contained results from two methods for calculating the quality index. The first method, based on X-ray fluorescence (XRF), X-ray diffraction (XRD), and pore index testing, is most commonly used. The second method, based on thermal analysis (TGA), is experimental and should be used cautiously.

Table 7.1 Quality Index Determination for Prospective Aggregate Sources

Source	Quality Index (XFR, XRD and Pore Index)	Quality Index (TGA)
1	4.9	5.6
2	1.0	0.0
3	1.2	0.2
4	1.8	8.3
5	1.6	7.3
6	1.5	4.1
7	2.6	7.2

The Iowa DOT recommends using aggregates with quality indices below 1.5 for high quality pavements. While the two northern sources (2 and 3) qualified in the first method, two other sources were close. Results of the second method, though experimental, showed Sources 2 and 3 to be clearly superior. These results verified past ODOT experience. On this basis, these two aggregate sources were pre-qualified for use in the Portland cement concrete pavement. Contractors were welcome to test other sources and submit the results for approval. As it turned out, all aggregate for the project was obtained from Source 2.

A second concern arose as the project sections were being excavated. There were several areas where poor subgrade material needed to be excavated and replaced with borrow from a pit close to the project. While many of these areas were relatively shallow, a few, thought to be the remnants of old basements, septic tanks, leach beds, cisterns, etc., left behind when the original two-lane pavement was upgraded to a four-lane divided facility in the 1960's, extended to a depth of 9-12 feet. These deep areas were quite localized.

Undercut locations obtained from as-built plans are summarized in Appendix A. Widths and depths shown in the appendix define rectangular cross-sections used by construction inspectors to estimate undercut volume removed and replaced over the limits indicated by the stationing. When more than one rectangle exists for a given station, they may be horizontally or vertically aligned, or entirely separated from each other.

While a detailed description of all undercuts on the project is beyond the scope of this report, a graphical representation of accumulated undercut quantities is shown in Figure 7.1. In general, some undercutting was necessary in the southbound lanes throughout the project, with the largest quantities being recorded between Stations 281 and 290, Stations 322 and 330, and Stations 363 and 410. Undercutting in the northbound lanes was about the same as the southbound lanes, with higher amounts being required from Station 332 to 343, and from Station 364 to 390, and lesser amounts being required at the project ends. This work, performed by change order, is believed to have improved subgrade uniformity on the project. If section failures over time suggest subgrade weakness, Appendix A should be reviewed to determine any possible correlation with undercutting. As-built plans, on file in the ODOT District 6 office, provide precise undercut locations and depths.

A third issue, which emerged, was the SHRP specification on lift thickness. Individual lifts were required to fall within specified tolerances as the pavement was built up. From a research perspective, uniform layer thickness is certainly desirable to simplify modeling, and to improve the consistency of performance within individual test sections and between sections in different locations. From a practical standpoint, however, this requirement can cause a few problems.

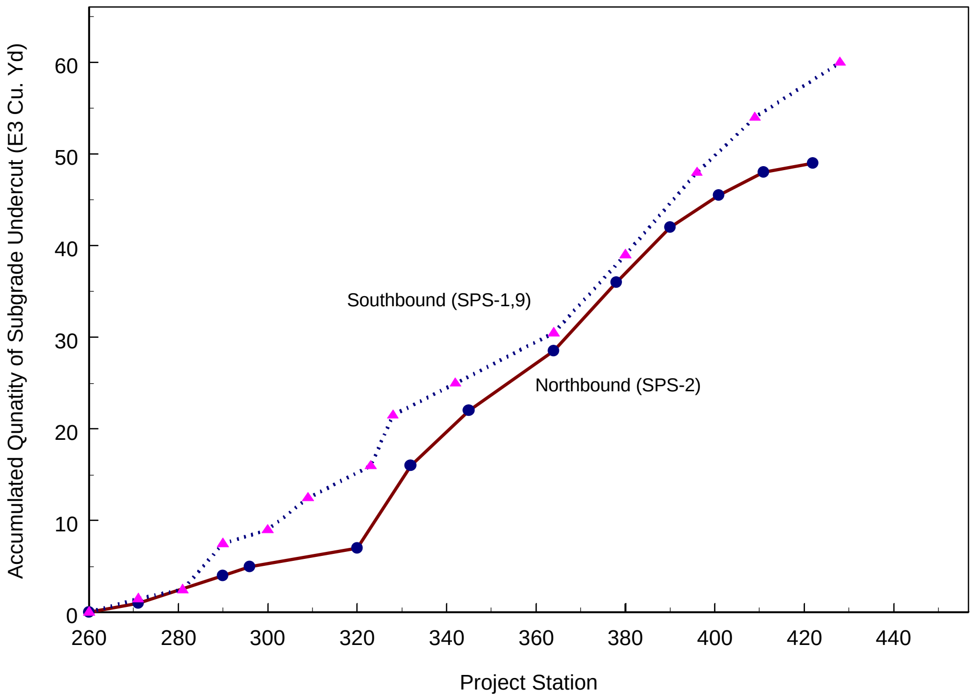

Figure7.1 Accumulated Subgrade Undercutting

Thickness tolerances were monitored by setting up a 50-foot long by 3-foot wide grid in the SPS sections and measuring elevations at the node points after the completion of each construction lift. Corrective action was required whenever the lift thickness calculated by differences in elevation was out of tolerance. The difficulty with this approach is, when tolerances are satisfactory but consistently on the negative side in certain areas and consistently on the positive side nearby, throughout the pavement buildup the final surface can be very uneven. This roughness will result in an uncomfortable ride, potentially reduced payment to the contractor if the smoothness specification is in effect, and vertical dynamic forces being induced into the test sections by heavy trucks as they pass over the pavement surface. This could adversely affect the structural life of the test sections and skew the results of the SHRP experiments. In Ohio, lift tolerances were monitored, but smoothness was considered when directing the contractor to perform corrective action.

A fourth significant problem involved the use of low strength (550 psi) concrete in the SPS-2 and SPS-8 PCC sections, as required by SHRP. The first concrete sections on the Ohio SHRP Test Pavement were placed in the SPS-8 experiment late in the Fall of 1994. It was difficult to develop a low strength concrete mix, which met SHRP requirements, was workable, and appeared to be durable in a wet-freeze environment. The limited time available to develop a suitable mix precluded extensive testing. The contractor finally arrived at a mix containing 350 lbs. of cement and 52 lbs. of Class F fly ash which met the SHRP 550-psi strength requirements and offered reasonable workability. With some minor adjustments at the beginning of placement, the SPS-8 PCC sections were constructed according to specifications. The mix appeared to be quite lean when compared to standard ODOT pavement mixes and there was serious doubt from all involved as to whether the mix would provide long term durability, especially if it were exposed to deicing chemicals soon after placement.

Further doubts about the low strength mixes emerged when compressive tests on cylinders yielded surprisingly high results after the standard 14 days. The SPS-8 low strength PCC sections in Ohio may have much higher strengths than originally planned, but long term durability of the mix in terms of surface scaling or other distress resulting from the action of deicing salts is unknown. These experiences raised serious questions about the basic validity of low strength PCC test sections in wet-freeze environments. Certainly, any material problems that arise should be noted in the SHRP database.

As a result of these concerns, ODOT and SHRP mutually agreed that standard ODOT Class C concrete would be used on low strength SPS-2 sections instead of the 550-psi mix. With a required compressive strength of 4,000-psi after 14 days, the flexural strength of this ODOT mix is expected to be approximately 700-psi. There would still be a sufficient difference in strength between this mix and the 900-psi high strength mix to maintain the intent of the SPS-2 experiment, while avoiding a potentially disastrous situation of having mainline test sections with low strength concrete exhibit premature distress from freeze-thaw deterioration.

CHAPTER 8

MATERIALS

Subgrade

The dominant subgrade soil on the project was brown silty clay classified as AASHTO A-6 with sections of organic present. Consistency was maintained by undercutting where wet or organic material was encountered and replacing it with suitable material from a nearby borrow pit. All subgrade was compacted with rollers, graded and trimmed to the required elevation. Elevation checks were performed by ODOT inspectors at random locations to verify that the subgrade surface was within one-quarter inch tolerance.

Dense Graded Aggregate Base

The majority of test sections have a Dense-Grade Aggregate Base (DGAB) which consists of an ODOT 304 mix of crushed carbonate stone compacted and trimmed to a final elevation. This was always the first base placed atop the subgrade in sections where it was used.

Permeable Asphalt Treated Base

Another base material used in several flexible pavement sections was Permeable Asphalt Treated Base (PATB). This base consisted of #57 stone with of the following gradation and bonded with asphalt cement. It was rolled to a final elevation. PATB is a free-draining material meaning the large voids between the aggregate particles allow water to flow freely. Because PATB is a weaker base structurally and its thickness was limited to no more than four inches, a second base layer was required to help distribute the load. All PATB bases were accompanied by drainage

Gradation of #57 Stone	
% Passing	Sieve Size
95-100	1.0 in.
25-60	0.5 in.
0-10	No. 4
0-5	No. 8

system on the right side of the pavement consisting of a trench lined with a draining fabric and filled with #8 gravel. This drain was installed to remove excess water in the pavement system, and to reduce the opportunity for water to enter other base and subgrade materials.

The amount of asphalt cement in the aggregate mixture was approximately 2.0% of the total weight of the mixture. The maximum compacted thickness of all PATB layers was 4 inches. PATB lifts had to be compacted before the mixture temperature dropped below 100°F (38°C) and to the extent that it could support the weight of machinery used to place the next layer of material. The thickness of PATB layers was specified to be within ± 0.25 inch of the design thickness. The finished surface of the PATB layer was specified to vary not more than 0.25 inch in ten horizontal feet, and be within ± 0.50 inch of the specified plan elevation.

Permeable Cement Treated Base

A Permeable Cement Treated Base (PCTB) was used in one flexible and two rigid pavement sections. Cement treated bases are similar to PATB, except the aggregate is coated with portland cement concrete instead of asphalt cement.

The PCTB, or Cement Treated Free Draining Base (CTFDB), used on U.S. 23 was a mixture of #57 stone, portland cement, and water. The minimum cement content by weight was 250 pounds per cubic yard, and target water to cement ratio of approximately 0.36 was specified. The amount of water was adjusted to provide a workable mix. An approved spreader was required to place the PCTB in widths greater than 12 feet. An air temperature of at least 45°F and dry conditions was required before any material could be placed. Compaction of the PCTB with steel rollers weighing between 6 and 10 tons had to begin within a half-hour of the spreading operation.

Asphalt Treated Base

Another base type used in SPS-1 and SPS-9 was an Asphalt Treated Base (ATB). This material consisted of ODOT 301 bituminous base compacted to its final surface elevation. ATB was placed directly underneath the asphalt concrete pavement layer because of its material composition and integrity.

Lean Concrete Base

Lean Concrete Base (LCB) was a mixture of 2,000 pounds per cubic yard of #57 aggregate and 1,465 pounds per cubic yard of sand with sufficient portland cement to have a compressive strength of between 500-psi and 750-psi after 7 days. LCB is a stiffer material than the Permeable Cement Treated Base. The final surface was specified to have a smooth texture, and the elevation was to be within ± 0.50 inch of the specified plan elevation. This material was placed with a slip form paver. A double layer of wax based curing compound was placed on the surface of the LCB to resist bonding with the PCC pavement.

Asphalt Concrete

SPS-1 and SPS-8 sections consisted of 1-3/4" of ODOT 446, Type 1 asphalt concrete over either 2-1/4" or 5-1/4" of ODOT 446, Type 2 asphalt concrete, depending upon whether the total AC thickness was 4 or 7 inches. Lift thickness for these materials was limited to 3 inches to insure uniform density. The top lift contained a finer graded stone than the bottom lift for a smoother surface finish.

Asphalt concrete in Section 390903 was designed with PG64-28 asphalt cement using Level 1 SuperPave specifications. Standard AC-20 asphalt cement was used in Section 390901, while PG58-28 asphalt cement was used in Section 390902. The mix in Section 390903 was extremely fine, resembling sand-asphalt as it was being placed.

PC Concrete

Because of concerns regarding freeze-thaw durability, the 550-psi concrete mix was only used in the SPS-8 sections. In the six months between construction of SPS-8 and SPS-2, a decision was made with SHRP to replace the 550-psi mix in SPS-2 with ODOT Class C mix. Sections requiring a high strength concrete utilized a 900-psi mix containing Southwestern Type I cement, crushed #57 stone, Class C fly ash, and sand. Water reducers were used as needed.

The ODOT Class C mix, chosen to replace the 550-psi mix, consisted of Type I cement, mixed with #57 stone, Class F fly ash, if required, and sand. In certain sections, water reducers or set retarders were used. Designs for the three concrete mixes used on this project are shown in Table 8.1. Some field adjustments were necessary.

The finished surface elevations of any PCC layer was specified to be within $\pm$ 0.50 inch of the designated plan elevation. Incentives were awarded based upon the rideability or smoothness of the surface. The contractor, to improve the smoothness of the surface, ground down high spots.

Design parameters were carefully chosen for each section to examine specific variables in pavement design. All SHRP concrete sections were Jointed Plain Concrete Pavement (JPCP) with asphalt shoulders. Joint spacing was 15 feet with slab width being either 12 or 14 feet, and pavement thickness being either 8 or 11 inches. Dowel bars were 1.25 inches in diameter in the 8-inch thick pavement sections and 1.509 inches in diameter in the 11-inch thick pavement sections. All dowel bars were placed 12 inches on centers. No. 5 tie bars (0.75-inch diameter) were placed at 30-inch centers along all longitudinal joints.

Table 8.1 Job Mix Formulas for PCC

	Mix Design 1	Mix Design 2	Mix Design 3
FINE AGG. (lbs./cy) Natural Sand (SG 2.58)	1260	950	1316
COURSE AGG. (lbs./cy) Crushed Stone (SG 2.62)	1680	1850	1749
CEMENT (lbs./cy) Type 1 Southwestern	510	750	350
FLY ASH (lbs./cy)	90 (Class F)	113 (Class C)	52 (Class F)
ADMIXTURES (ozs./cy) DARAVAIR WRDA-82 DARATARD	 9.3 18 0	 12.3 43 43	 4 16 0
SLUMP	1-1/4"	¾ - 1-1/4"	2-1/4"
AIR (%)	5.3	6 +/- 1.5	7

Mix Design 1 ODOT specifications (used in 12 sections of the SPS-2 experiment)
Mix Design 2 High Strength Mix (used in 7 sections of the SPS-2 experiment) 900 psi flexural strength @ 14 days
Mix Design 3 Low Strength Mix (used in 2 sections of the SPS-8 experiment) 550 psi flexural strength @ 14 days

Drains

All sections containing a free draining (permeable) base were equipped with a drainage system to remove excess water. Three types of drains were shown in the ODOT DEL-23-17.48 project plans and identified as Detail AA@, AB@, and AC@ in Figure 8.1. The drain depicted in Detail

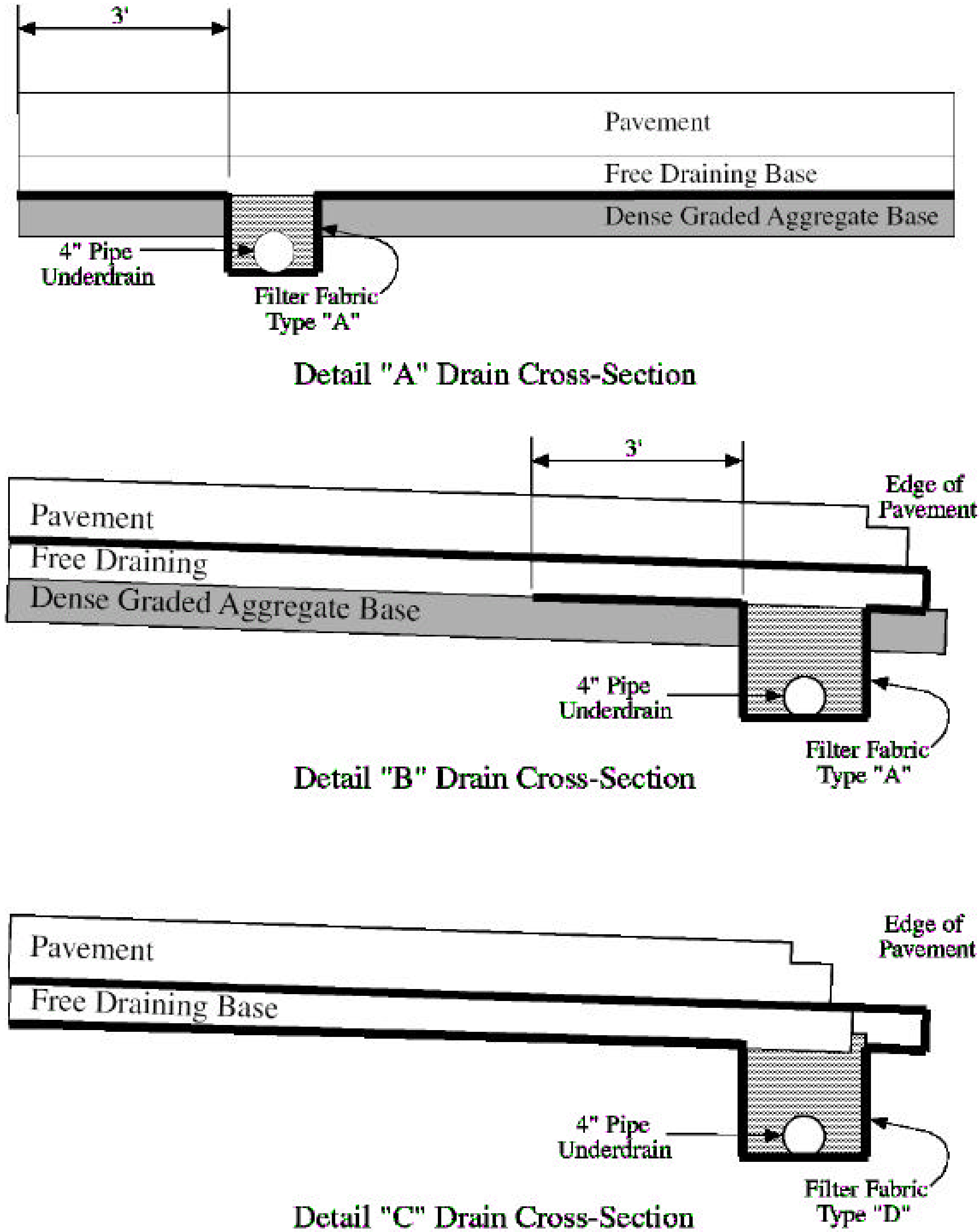

Figure 8.1 Drain Types

AA@ consisted of a rectangular trench excavated through the DGAB base and subgrade along the shoulder. ODOT 712.09, Type A filter fabric was used to line the trench and provide a three-foot extension from the trench edgeline along the DGAB surface. The trench depth varied by section, and these values are listed in Table 8.2. A four-inch diameter drain was set along the length of the trench, and the trench was filled to the top with #8 gravel. Base placement was permitted after the Detail AA@ drain was installed. Detail AA@ drains were designed for portions of the test road with crossovers extending to the existing lanes.

Detail AB@ consisted of a trench excavated through the DGAB base and subgrade at a site-specific depth provided in Table 8.2. ODOT 712.09, Type A filter fabric lined the trench inner walls and extended three feet out toward the middle of the road and to the DGAB edge. A four-inch diameter drain was set along the length of the trench, and the under-drain was filled to the top with #8 grave. The permeable base was placed, and filter fabric wrapped up and over top the permeable base surface extending one foot past the other edge of pavement.

The last type of under-drain at the U.S. 23 site was Detail C. This was installed in the same manner as a Detail AB@ drain, but with a few alterations. First, DOT 712.09, Type D filter fabric was used rather than Type A. Also, due to the fact that Detail C sections does not contain a DGAB base, the filter fabric was extended entirely across the road underneath the permeable base rather than only three feet.

Table 8.2 Drainage Summary

SHRP No.	Section No.	Stationing		Pavement Layout Design	Drain Type	Drain Depth
		From	To			
390901	ODOT	256 + 9.34	286 + 54	4" AC/12" ATB/4" PATB/6" DGAB	B	16", 22"
		286 + 54	286 + 76	(Sensor Location)	B	22"
		286 + 76	294 + 00		A, B	22"
390903	SHRP	294 + 00	301 + 89	4" AC/12"ATB/ 4" PATB/6" DGAB	B	22"
		301 + 89	302 + 11	(Sensor Location)	B	22"
		302 + 11	314 + 00		B	22"
390112	J12	314 + 00	319 + 50	4" AC/12" ATB/ 4" PATB	A, C	22"
		319 + 50	326 + 14		C	22"
		326 + 14	326 + 36	(Sensor Location)	C	22"
		326 + 36	326 + 75		C	22"
390111	J11	326 + 75	327 + 14	4" AC/8" ATB/ 4" PATB	C	26"
		327 + 14	327 + 36	(Sensor Location)	C	26"
		327 + 36	334 + 50		C	26"
390107	J7	356 + 00	356 + 39	4" AC/4" PATB/ 4" DGAB	B	34"
		356 + 39	356 + 61	(Sensor Location)	B	34"
		356 + 61	365 + 30		B	34"
390108	J8	393 + 25	393 + 51	7" AC/4" PATB/ 8" DGAB	B	31"
		393 + 51	393 + 73	(Sensor Location)	B	31"
		393 + 73	400 + 50		B	31"
390109	J9	400 + 50	406 + 79	7" AC/4" PATB/ 12" DGAB	B	31"
		406 + 79	407 + 01	(Sensor Location)	B	31"
		407 + 01	407 + 25		B	31"
390110	J10	407 + 25	407 + 51	7" AC/4" ATB/ 4" PATB	C	27"
		407 + 51	407 + 73	(Sensor Location)	C	27"
		407 + 73	414 + 25		C	27"
390159	K24	421 + 0.14	427 + 50	4" AC/12" ATB/ 4" PCTB/6" DGAB	B	13"
		427 + 50	433 +50	(Possible Sensor Location)	B	13"
		433 + 50	433 + 7.29		B	13"

CHAPTER 9

MECHANISTIC PERFORMANCE

Highway pavements have historically been designed around performance data obtained from the AASHO Test Road and other sources. These procedures have proven to be reasonably adequate over the years, but they rely heavily on empirical relationships, which may or may not reflect actual conditions. A more rational approach would be to accurately model the pavement structure using finite element techniques, apply static or moving wheel loads as theory permits, and predict responses from material properties determined in the laboratory from in-situ non-destructive tests. Long term performance can then be inferred by applying daily and seasonal environmental cycles, estimated traffic loading, and fatigue properties of the materials to the model. The model would need to be verified and calibrated from full-scale measurements under controlled conditions. This is the basis of mechanistic design and verification of these models was the reason the Ohio SHRP Test Pavement was instrumented so extensively.

The long term performance of highway pavement basically depends upon the level of traffic loading, the composition of the pavement structure, and the prevailing environmental conditions. Although performance can be defined in many ways, transportation agencies such as ODOT typically assess pavement performance in terms of life-cycle cost and serviceability to the users. Therefore, the longer a pavement functions or the more traffic is carries per unit of cost, the better it is perceived to be performing.

The manner in which traffic loading affects pavement performance is extremely complex. Obviously, the heavier the traffic in terms of weight or volume, and the more it is concentrated in the wheelpath, the shorter the time a given pavement structure can be expected to function until some type of maintenance activity is required. In fact, the relationship between traffic loading and associated pavement damage is exponential to the fourth power. Except for legal limitations on speed, axle loading, and vehicle configuration, transportation agencies have little control over pavement loading parameters. The location of commercial and industrial developments, and the economic pressures of society largely dictate the volume of trucks and the weight of cargo transported on any particular route. The magnitude of dynamic forces induced by trucks is affected by their configuration, type of suspension, riding quality of the pavement, traffic conditions, and driving habits of operators.

To clearly define pavement loading, the traffic stream must be described in terms of vehicle configuration, weight, volume, speed, and lateral positioning on the pavement. Major categories should be established within each of these parameters and frequencies assigned from the best information available. While some daily, weekly, and seasonal variations do occur with commercial trucking, traffic loading historically has been assumed to be essentially uniform for design purposes. This assumption should be verified and, for example, if substantially higher pavement loading occurs during periods of poor pavement support, actual loading cycles should be taken into account for the prediction of performance. One commonly overlooked load-associated parameter affecting performance is lateral tire wander. The more widely loads are distributed laterally, the less damage there will be per unit volume of traffic. Consequently, to develop accurate mechanistic pavement models, there needs to be a precise definition of the various aspects of traffic loading and the corresponding dynamic response mechanisms taking place in the pavement structure. The Ohio SHRP Test Pavement offered a unique opportunity to measure the effect of several parameters on the response of a number of pavement sections under controlling loading conditions.

Pavement composition refers to the number and thickness of pavement layers with uniquely different material properties, the stiffness of materials comprising these layers, the order in which the layers are placed in the pavement structure, and any appurtenances, such as drainage, added to enhance performance. In general, higher quality materials are placed closer to the surface to resist high stresses and spread the load to lower quality materials deeper in the pavement. While paving materials are generally assumed to be elastic, homogeneous, and isotropic, they do not display these characteristics in many respects. In addition to the inherent variability in naturally occurring materials such as soil and aggregate, environmental conditions at the time of construction, the types of equipment used in construction and construction techniques all impact the in-situ structural properties of paving materials. Sensitivity to changes in temperature, moisture and loading frequency further complicate the engineering properties of certain paving materials during their service lives, as follows:

<u>Temperature</u>

- Bituminous materials - Strength and stiffness varies inversely with temperature. Vertical temperature gradients within these layers result in the formation of numerous sublayers having different stiffness characteristics.
- Cementitious materials - While temperature does not affect strength directly, thermal expansion and contraction does affect how load is transferred across joints and cracks. Also, thermal gradients cause differential expansion/contraction within the layer, which results in curling of the slab and non-uniform pressure distributions on the underlying base.

<u>Moisture</u>

- Fine grained base and subgrade materials. As the moisture increases or decreases from this optimum value, strength decreases. As these materials freeze, strength increases dramatically. However, as the temperature rises and fine-grained materials thaw, they change over to a wet and, potentially, very weak layer.

To properly define the structural properties of paving materials, laboratory and in-situ non-destructive tests must be performed over a range of environmental and dynamic loading conditions. These tests should accurately simulate the manner in which materials respond to traffic loading in the pavement structure. In flexible pavement, particular attention is given to the viscoelastic nature of bituminous materials. Rigid pavement contains discontinuities resulting from joints and cracks, and curling or warping of the cementitious layer which impacts contact pressure on the underlying layer. These discontinuities are best accounted for by mathematical representations of the pavement structure as it experiences moisture and temperature cycling. The engineering properties of materials used on the Ohio SHRP Test Pavement are to be determined by LTPP from samples furnished by ODOT. To date, the results of these tests have not been received. ORITE also conducted tests to determine the physical properties of materials used in these test sections.

Highway pavements are continually exposed to fluctuations in temperature and moisture. Seasonal variations are, in themselves, quite gradual resulting in slow, uniform changes in the pavement layers. In a wet-freeze zone like Ohio, pavements are cool and wet in spring, warm and dry in summer, cool and dry in fall, and cold and wet in winter. As pavements experience periods of subfreezing temperatures in winter and early spring, base and subgrade materials will likely experience a number of freeze/thaw cycles. Daily environmental cycles superimposed on the seasonal cycles throughout the year add substantial complexity to the pavement structure. Because these changes are much more rapid, they also generate thermal and moisture gradients in the pavement which, in effect, add additional sublayers of varying stiffness in asphalt concrete and subgrade materials, respectively, and create various levels of discontinuity around and below cementitious slabs. The manner in which these sublayers are defined depends upon the magnitude of the gradients and the desired level of accuracy of the mathematical representation being used to describe the pavement structure.

CHAPTER 10

RESPONSE SENSOR SELECTION AND CALIBRATION

Two workshops held in Columbus, Ohio in 1993 brought together instrumentation experts from FHWA, universities, several state transportation agencies, and the U.S. Army Corps of Engineers. During these workshops, experiences obtained at Mn/Road, the North Carolina test pavement, I-80 in Iowa, the Denver Airport, U.S. 33 and S.R. 2 in Ohio, and the Alberta Research Council, were shared and discussed. These workshops provided information and background for planning the Ohio SHRP Test Pavement.

Mathematical modeling, such as finite element, boundary element, and finite difference, are essential to any mechanistic design system for highway pavements. There are several mathematical models presently in use to predict the response of rigid and flexible pavement under various loading conditions. Any procedure of this type must be thoroughly calibrated and verified before it can receive wide acceptance. To obtain meaningful data on pavement response, it is vital that appropriate dynamic parameters be measured. Horizontal strain and vertical deflection have long been regarded as the best indicators of performance, with vertical pressure also providing valuable information. Because it is unrealistic to verify models with only one dynamic parameter, all three were monitored on the Ohio SHRP Test Pavement.

Mathematical model predictions are heavily influenced by the engineering properties of materials comprising the pavement structure. Since these properties can vary with temperature, moisture, and stress path, model accuracy will be highly dependent upon the results of laboratory tests used to determine material strength and fatigue characteristics.

Dynamic sensors for monitoring structural response were selected largely from input received at the two 1993 conferences, from successful performance on the U.S. 33 and S.R. 2 projects in Ohio, and from FHWA recommendations. Specific considerations included:

- Material characteristics
- Structural parameters to be measured
- Installation considerations
- Temperature, moisture, and loading environment
- Required response time
- Accuracy and sensitivity
- Durability and fatigue requirements
- Compatibility with data acquisition system
- Cost and time of delivery

Table 10.1 is a summary of dynamic sensors selected for use on the Ohio SHRP Test Pavement. Because distances from the sensor locations to the pull boxes where the data acquisition systems were to be placed were quite varied, all sensors were ordered with 100-foot long lead wires to avoid moisture and potential continuity problems at solder joints.

To minimize any discontinuities within the pavement structure, sensors were installed at the time of construction, as opposed to retrofitting after construction. Consequently, sensors needed to be sufficiently durable to withstand mechanical stresses during the placement of Portland cement concrete and high temperatures and mechanical stresses during the placement and compaction of asphalt concrete.

Horizontal Strain Sensors

The Dynatest PAST-II AC strain gauge was selected for dynamic strain measurements because it fulfilled necessary SHRP criteria, and because of its previous success in earlier ODOT flexible pavement research projects. It is an AH@ shaped precision transducer handcrafted and supplied by Dynatest Consulting, Inc., in Ojai, California. The Past-II AC is four inches (102 mm) in length with three-inch (75-mm) wide arms, is a quarter bridge gauge with a resistance of 120 ohms, and has a gauge factor of 2.0. It has a physical range of up to 1500 microstrains, a thermal range from -22°F to 300°F, and is rated for a 36-month life span. The actual sensor is located inside the longer mid-section encased in a strip of fiberglass reinforced epoxy. It is covered with a PFT sleeve, supported by an antiosmotic base, coated in silicone rubber, and reinforced with a titanium plate to provide protection against chemical and mechanical deterioration. The stainless steel arms are fastened at each end of the mid-section and serve as anchors to the pavement. The entire gauge is coated with an asphalt coating to aid in bonding with asphalt concrete in the pavement. The sensor cable exits the gauge through the middle of one of the stainless steel arms. This cable has a Teflon coating to prevent moisture from damaging the signal and to shield the wire from intense heat of the asphalt concrete during paving. (Figure 10.1)

Table 10.1 Dynamic Response Sensors

Measured Parameter	Sensor
Horizontal AC Strain	Dynatest PAST-II AC Strain Gauge
Horizontal PCC Strain	Dynatest PAST-II PCC Strain Gauge
	TML KM-100B Strain Transducer
	TML PMR-60 Three Axes Rosette
	Carlson A-8 Strain Meter
	Geokon VCE-4200 Vibrating Wire Strain Gauge
	Micro-Measurement EGP-5-120 Strain Gauge
Vertical Deflection	Schaevitz GPD 121-500DC-LVDT
Vertical Pressure	Geokon Model 3500 Pressure Cell

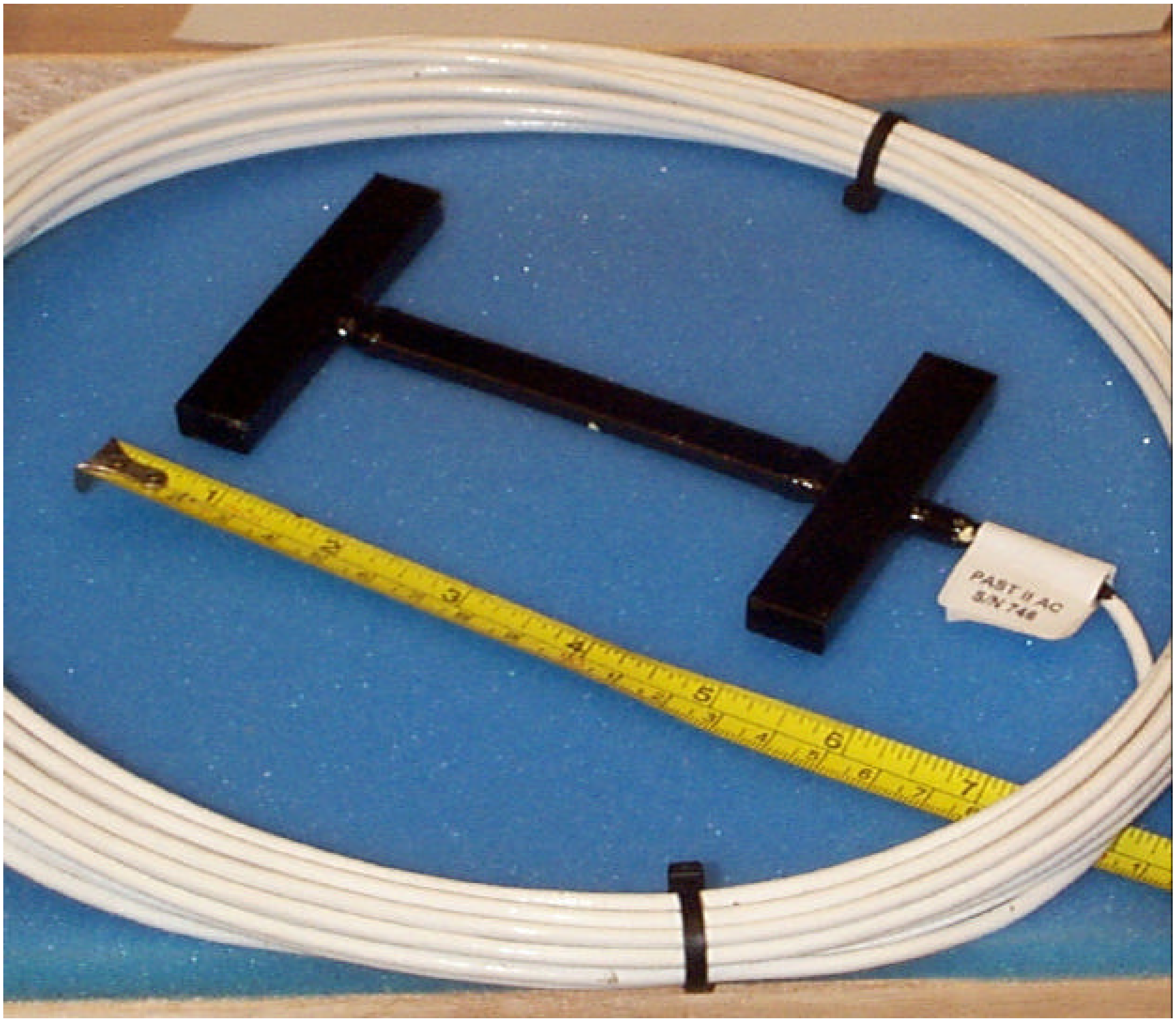

Figure 10.1 Dynatest Past-II AC Strain Gauge

Dynatest gauges produce a strain measurement when the mid-section is compressed or elongated. Therefore, when the asphalt concrete is subjected to a force, the Dynatest mid-section follows any deformation in the material and gives a precise measurement of strain.

The Dynatest PAST-II PCC strain gauge is a handmade gauge also distributed by Dynatest Consulting, Inc., of Ojai, California. It is an H-type gauge very similar to the Dynatest PAST-II AC gauge, but designed for use in rigid pavements. It is set in epoxy, reinforced with fiberglass, and coated with epoxy, silicone, PFT and a titanium plate. The unit is anchored to stainless steel and coated with a granular material to facilitate a mechanical bond to the concrete. The gauge is 4 inches long, 0.4 inches wide, and 0.2 inches thick, operates at a 120 Ω quarter Wheatstone bridge, and has a gauge factor of approximately 2.0. The gauge has an operating temperature range of -22°F to +300°F, a range of ± 1500 μ strain and a service life greater than 36 months. The anchors are 3 inches long, 0.6 inches wide, and 0.3 inches thick (Figure 10.2).

The TML KM-100B strain transducer is manufactured by the Tokyo Sokki Corporation and distributed by Texas Measurements, Inc., of College Station, Texas. This gauge is an embedment gauge, 4 inches long and 0.75 inch in diameter, as shown in Figure 10.3. The gauge operates as a 350 Ω full Wheatstone bridge with a gauge factor of approximately 2.0, and operates in a temperature range of -4°F to +176°F. The gauge has a range of ± 5000 μ strain, is temperature compensated and is specifically designed to measure strain in concrete. Strain is measured using four active gauges, while change in temperature is measured independent of strain using one active gauge and three external resistors. The KM100B is capable of measuring both dynamic and static strain.

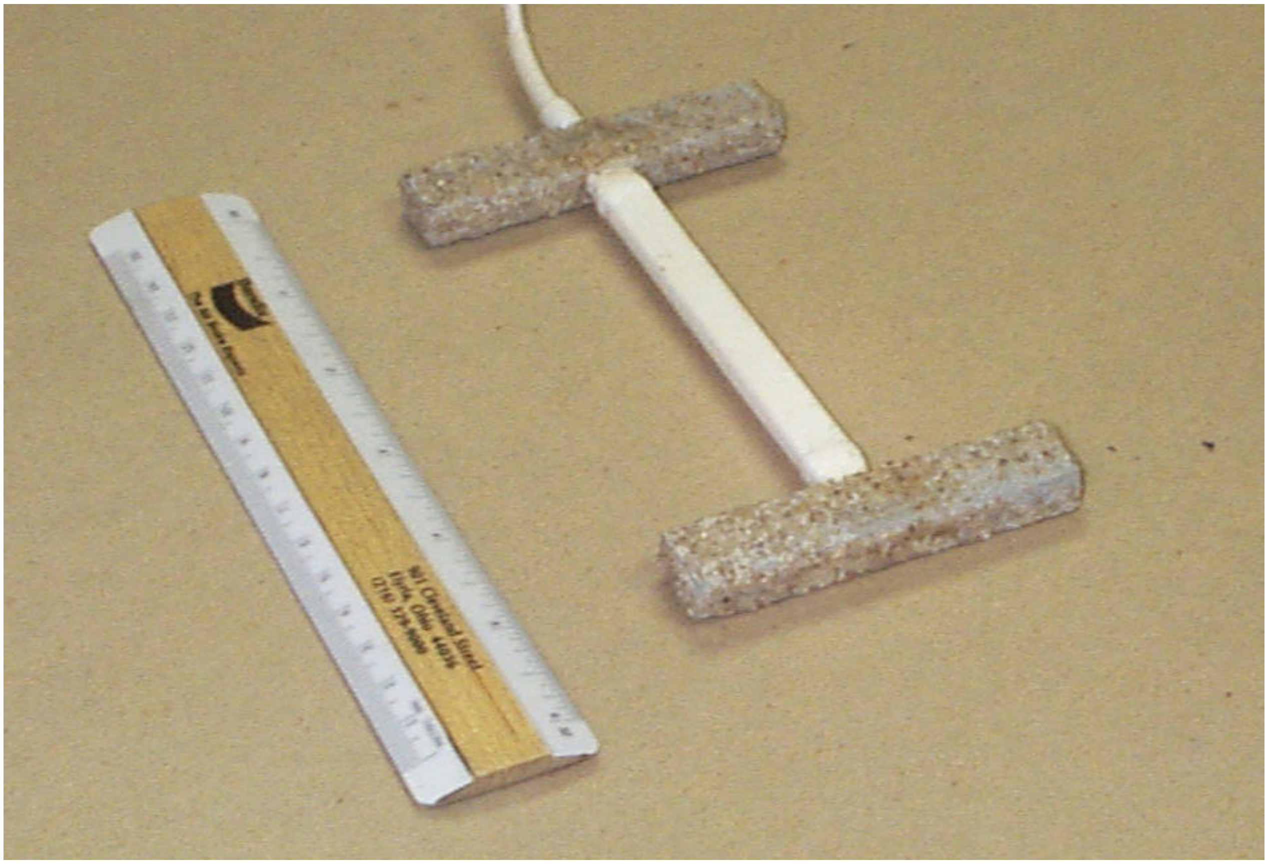

Figure 10.2 Dynatest Past-II PCC Strain Gauge

Figure 10.3 KM-100B Strain Transducer

The TML PMR-60 three axes rosette is also manufactured by the Tokyo Sokki Corporation and distributed by Texas Measurements, Inc., of College Station, Texas. This is a polyester mold embedment gauge, shown in Figure 10.4. The gauge and lead wires are hermetically sealed in epoxy strips and coated with a granular material to facilitate proper bonding to the concrete. The arms of the rosette are offset 45° and each arm is 3.125 inches long, 0.50 inch wide, and 3/16 inch thick. The gauge operates as a 120 Ω quarter Wheatstone bridge with a gauge factor of approximately 2.1, has an operating temperature range of -4°F to +140°F, is not temperature compensated, and is specifically designed to measure dynamic strain in concrete.

The Carlson A-8 strain meter is manufactured by RS Technical Instruments and distributed by B.R. Jones and Associates, Inc., or Normangee, Texas. The gauge is an elastic wire electrical resistance device designed to measure static strain in concrete over long periods of time. The gauge is 8 inches long and 1 inch in diameter (Figure 10.5). It consists of two fine steel wire coils wound on ceramic spools. When strain is induced, one coil increases in length and resistance while the other coil decreases proportionally in length and resistance. The change in resistance ratio of the two coils is proportional to the change in gauge length. A Wheatstone bridge configuration is used with two external resistors to read these sensors.

Geokon, Inc., of Lebanon, New Hampshire, manufactures the VCE-4200 vibrating wire strain gauge. This instrument is specifically designed for long-term temperature and static strain measurement in concrete. It has a limit of $\pm$ 300 μ strain at operating temperatures of -4°F to +176°F. The gauge consists of two parts. The first is a stainless steel tube containing a steel wire, which is tensioned between two end blocks. The second is a small plastic block containing an electromagnetic coil and thermistor. This block slides onto the tube so that the tube and block work together as one unit, as shown in Figure 10.6.

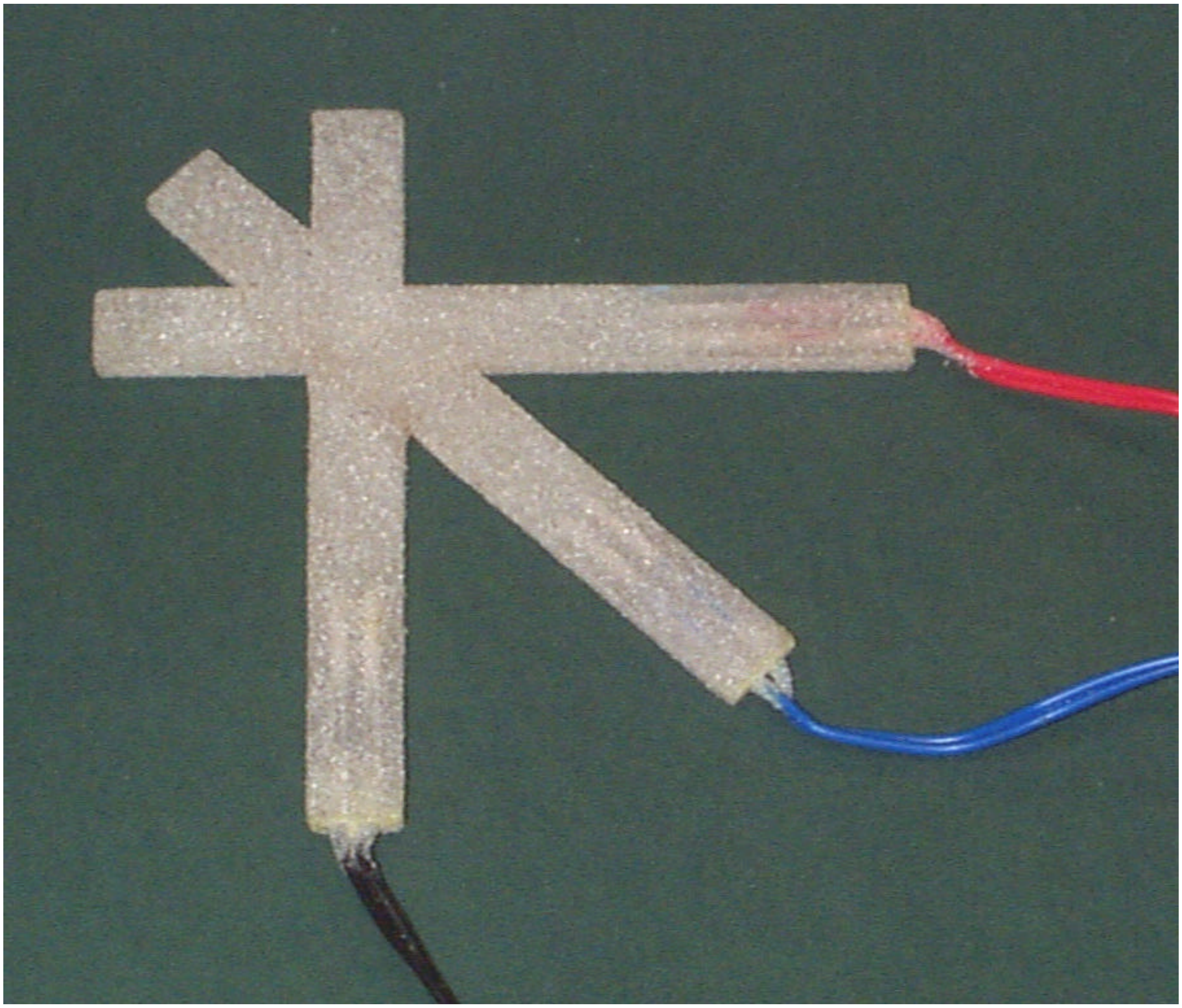

Figure 10.4 TML PMR-60 Rosette

Figure 10.5 Carlson Strain Meter

The Geokon VCE-4200 measures strain using the vibrating wire principle. The electromagnetic coil is used to Apluck@ the steel wire and then read its resonant frequency. Tension in the wire changes as strain occurs, resulting in a different resonant frequency of the wire. Change in resonant frequency is converted to strain through a simple equation. The sensor is also equipped with a thermistor to measure temperature in concrete. The vibrating wire strain gauge is excellent for long-term strain measurement because it does not tend to drift over time like electric strain gauges.

The Micro-Measurements EGP-5-120 embedment strain gauge is manufactured and distributed by the Micro-Measurement Division of Measurements Group, Inc., Raleigh, North Carolina. It is constructed from a strain-sensing grid encased in a corrosion resistant material. The sensing grid is constructed of modified Karma foil on a polyamide backing. The active gauge length is 4 inches, the grid resistance is 120 ohms ± 0.8%, and the gauge factor is 2.05 ± 1.0%. A normal outer body constructed of a polymer/concrete composite provides corrosion protection. The casing measures 5.00 x 0.70 x 0.40 inches (Figure 10.7) and is designated to resist mechanical damage during installation. An operating temperature range of +23°F to +122°F is recommended, but can be extended to -22°F to +149°F. The EGP-5-120 measures dynamic strain.

Vertical Deflection Sensors

Vertical deflection in the asphalt and concrete pavement sections was measured with Schaevitz GPD 121-500 DC and GPD 121-250 DC hermetically sealed Linear Variable Differential Transformers (LVDTs), manufactured by the Lucas Schaevitz Company of Pennsauken, New Jersey. The GPD 121-500 DC LVDT has an all welded AISI 400 series stainless steel casing. The sensor is submersible and the electronics are hermetically sealed. The sensor has a case length of

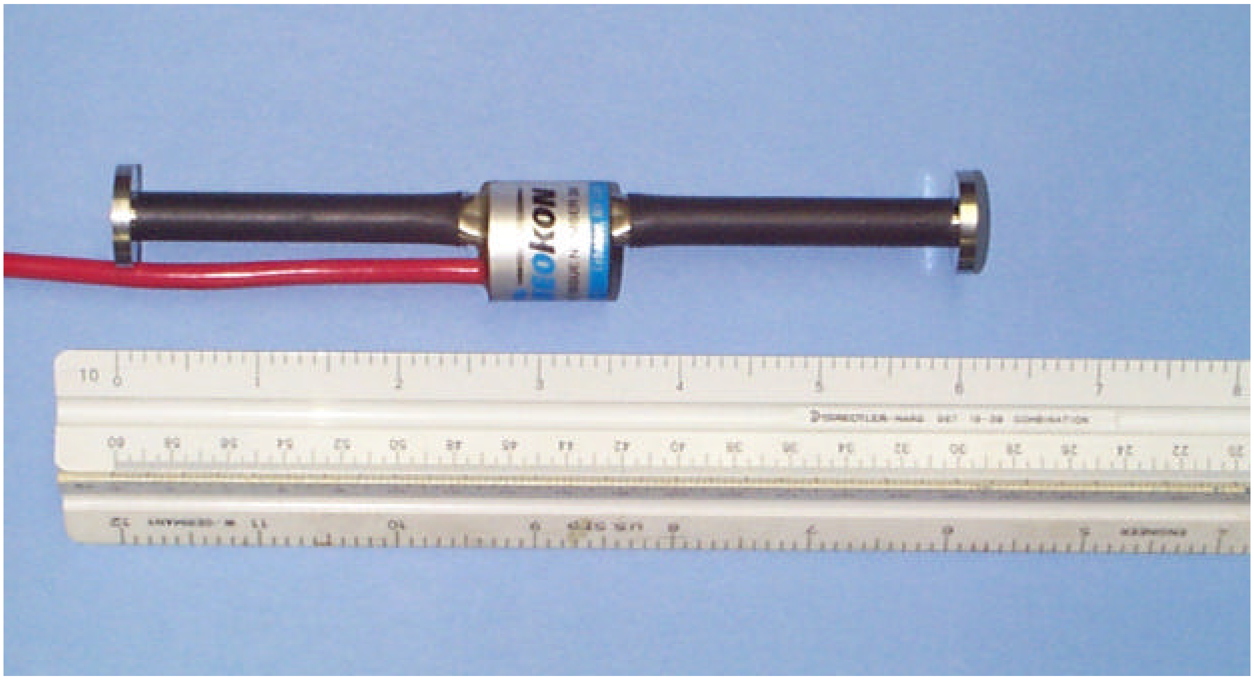

Figure 10.6 Geokon Vibrating Wire Strain Gauge

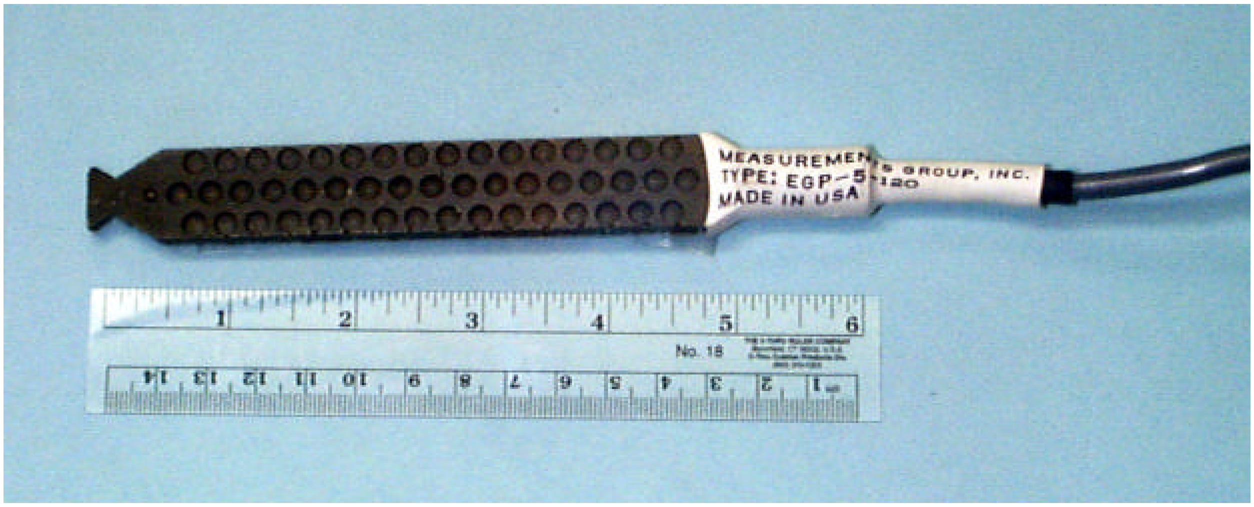

Figure 10.7 Micro-Measurements EGP-5-120 Strain Gauge

5.8 inches, a case and thread length of 9.05 inches, and a fully extended probe length of 11.53 inches. The sensor is 0.75 inches in diameter, weighs 5.50 ounces, and requires a 15V DC excitation. The operating temperature range is from 0°F to +158°F, the gauging range is ± 0.50 inches for a total travel of 1 inch and the sensitivity is approximately 20V/inch. The GPD 121-250DC has similar operating specifications, but is approximately half as long as the GPD 121-500 DC and has a range of ±0.25 inches. Figure 10.8 depicts both LVDTs.

The LVDT consists of a primary coil and two secondary coils symmetrically spaced on a cylindrical form. It produces an electrical output corresponding to the amount of plunger deflection. A free-moving rod-shaped magnetic core inside the soil assembly provides a path for the magnetic flux linking the coils. When the primary coil is energized by an external AC source, voltages are induced in the two secondary coils. These are connected in series opposing so the two voltages are of opposite polarity. Therefore, the net transducer output is the difference between voltages, which is zero, when the core is at the center or null position. When the core is moved from the null position, the induced voltage in the coil toward which the core is moved increases, while the induced voltage in the opposite coil decreases. This action produces a differential voltage output that varies linearly with changes in core position. The phase of this output voltage changes 180° as the core is moved from one side of the null to the other.

LVDT coils were rigidly mounted in the pavement layer while cores were mounted on a rod anchored at some depth in the pavement structure. As pavement deflects vertically, therefore, differential vertical movement of the coil and core was indicative of differences in deflection between the pavement surface and the referenced anchor point. Deflections referenced to points 10-12 feet deep in the pavement may usually be assumed to be total since measurable deflections are not likely to occur at or below this level. At shallower references within the deflected zone, LVDT

Figure 10.8 Lucas Schaevitz GPD LVDTs

measurements represent the difference in deflection between pavement surface and the depth of the anchor. On the Ohio SHRP Test Pavement, each instrumented section had LVDTs referenced to the top of the subgrade and to a depth of 12 feet, with a few asphalt concrete sections also having LVDTs referenced to an intermediate base layer.

The deep reference was a 12-foot long, 0.75-inch diameter steel rod painted to resist corrosion. A 1.5 inch thick, 1.5 inch diameter stainless steep tip was welded at one end of the rod to provide a reference point for the spring loaded LVDT plunger to rest against. Each reference rod was fitted with a 0.5-inch thick square PVC spacer with a 0.75-inch diameter hole in the center. The corners of the square were cut to fit inside a section of two-inch diameter PVC pipe. The PVC spacer was slid up the reference rod just beneath the stainless steel tip. This positioned the rod beneath the stainless steel tip and in the center of the PVC pipe to reduce vibrations due to traffic.

The other type of reference point was a shallow steel plate, one-foot square and one-inch thick painted to resist corrosion. A 1.5-inch diameter stainless steep tip was welded at the center of this plate to serve as the reference point. This tip varied in height due to the various base thickness and the two lengths of LVDTs used. Table 10.2 provides the stainless steel extension rod heights for the instrumented asphalt concrete test sections.

Table 10.2 Stainless Steel Extension Rod Heights for Instrumented AC Sections

Section ID	Shorthand ID	Deep Reference Height (From Subgrade)	Inside Plate Reference Height (From Subgrade)	Outside Plate Referenced Height (From Subgrade)
390901	ODOT	2"	2"	12"
390904	SHRP	2"	2"	12"
390112	J12	2"	2"	6"
390111	J11	2"	2"	2"
390104	J4	5"	5"	*
390106	J6	1"	1"	5"
390101	J1	1"	1"	*
390107	J7	2"	2"	*
390102	J2	2"	2"	*
390160	S7	1"	1"	5"
390105	J5	2"	2"	*
390108	J8	1"	1"	5"
390109	J9	1"	1"	9"
390110	J10	1"	1"	1"
390103	J3	2"	2"	*

* Outside Reference LVDTs were not installed.

Along with the reference points, a pit and holder were required to mount the LVDTs to measure surface deflection. The holder was fabricated from a 1.25 inch inside diameter stainless steel tube with a washer welded to one end. The washer was large enough to allow the LVDT base through. A larger washer was welded to the top of the tube (inside diameter - 1.25 inches, outside diameter - 2.5 inches). The larger washer was machined with three-eighth-inch screw holes for fastening the holder and pit together, and a one-half inch hole for the cable to pass through. This holder provided a fastener to secure the LVDT and obtain accurate deflection readings.

The pit was the section of the deflection unit, which was epoxied to the pavement layer and moved as the pavement moved. It was constructed of a 3.5-inch diameter stainless steel coupler 0.25 inches long. A length of 3.5 inch outside diameter black pipe was welded to the inside of the coupler to provide enough length for the pit to match the pavement thickness. Two sections of one quarter-inch diameter steel rod were welded to the outside of the stainless steel coupler to help anchor it to the pavement. Figure 10.9 provides a photograph of the pit and holder, and Figure 10.10 shows a cross-section of the entire deflection unit.

Vertical Pressure Sensors

The Geokon Model 3500 semi-conductor strain gauge earth pressure cell (Figure 10.11) was selected to measure interface pressures caused by environmental changes and dynamic loading of the pavement. These pressure cells consist of two circular stainless steel plates nine inches in diameter welded together around their periphery. The cavity created between the two plates is filled with an antifreeze solution and connected to a pressure transducer by an 8.5 inch long piece of high-pressure stainless steel tubing. An equal pressure induced by the antifreeze balances external pressures, acting on the cell. This pressure is converted by the transducer into an electrical signal, which is transmitted by a six-conductor shielded cable. The pressure cells purchased for this project were rated from 0 to 50 psi, have a maximum excitation voltage of up to 28 volts DC.

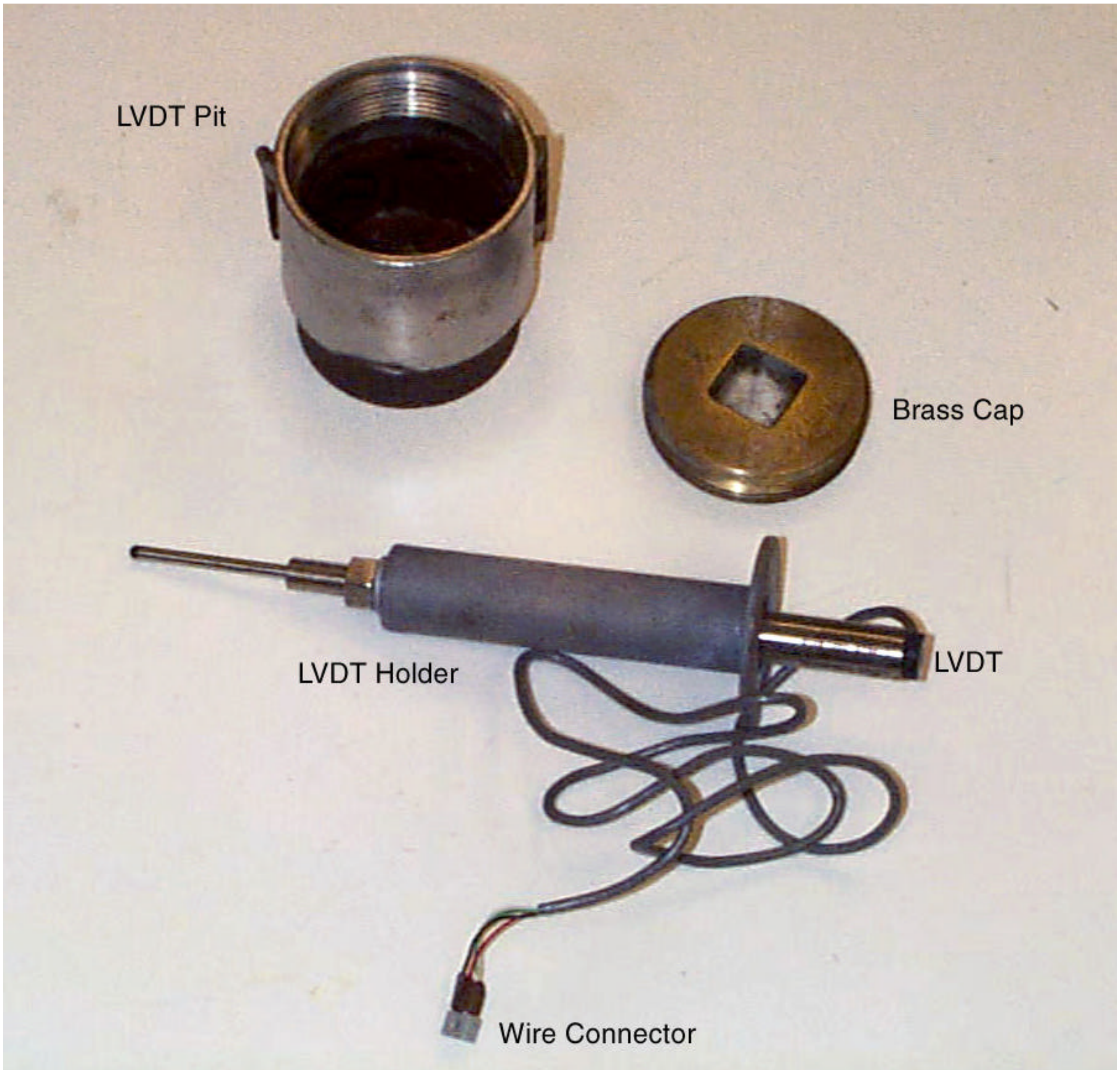

Figure10.9 Photograph of LVDT, Holder, Pit and Cap

Strain Calibration

Because of their physical characteristics, strain gauges used on this project could not be calibrated prior to use. However, continuity and resistance were checked with an ohmmeter during construction and immediately after placement of the asphalt or Portland cement concrete was completed.

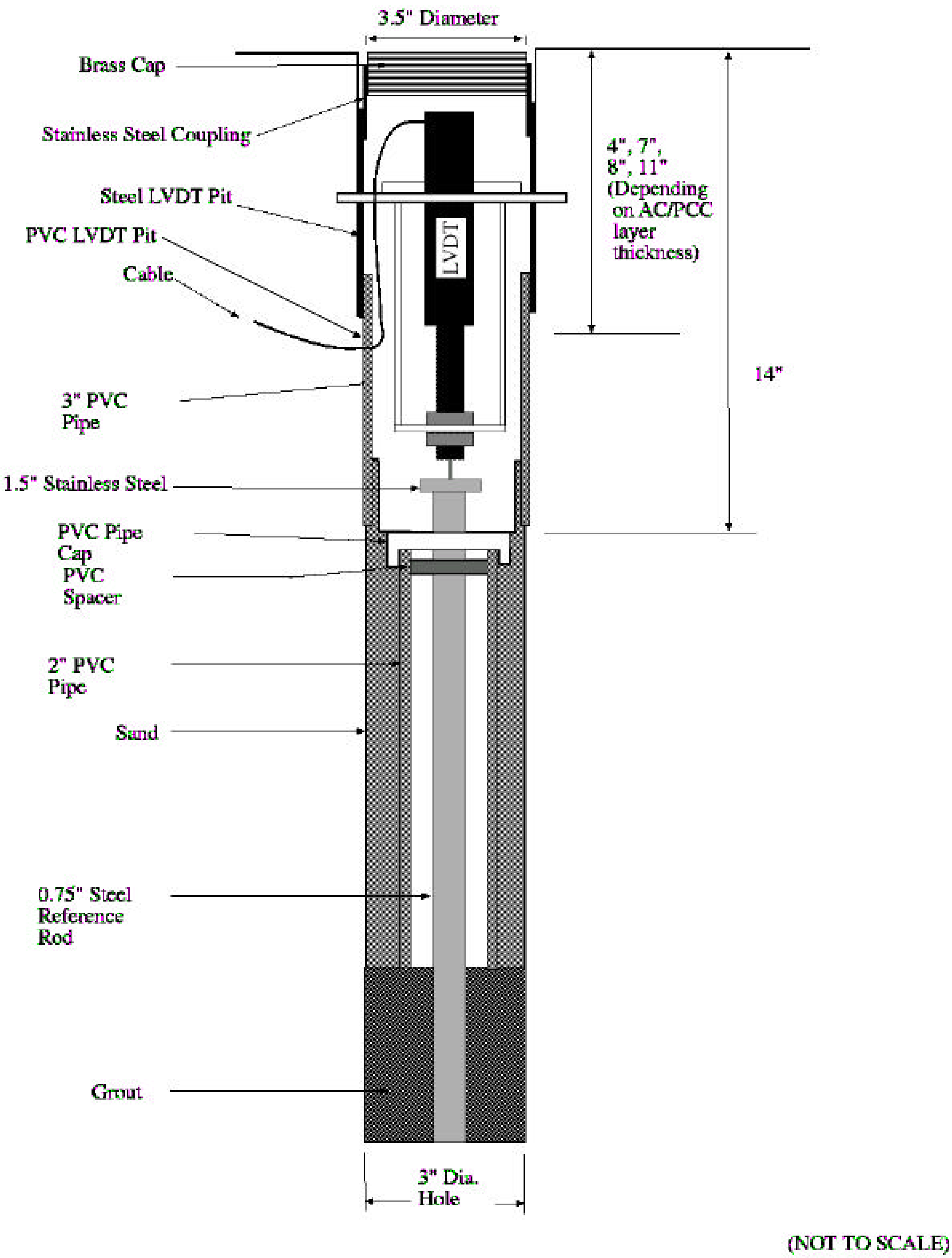

Figure 10.10 Deep Reference Single Layer Deflectometer Profile

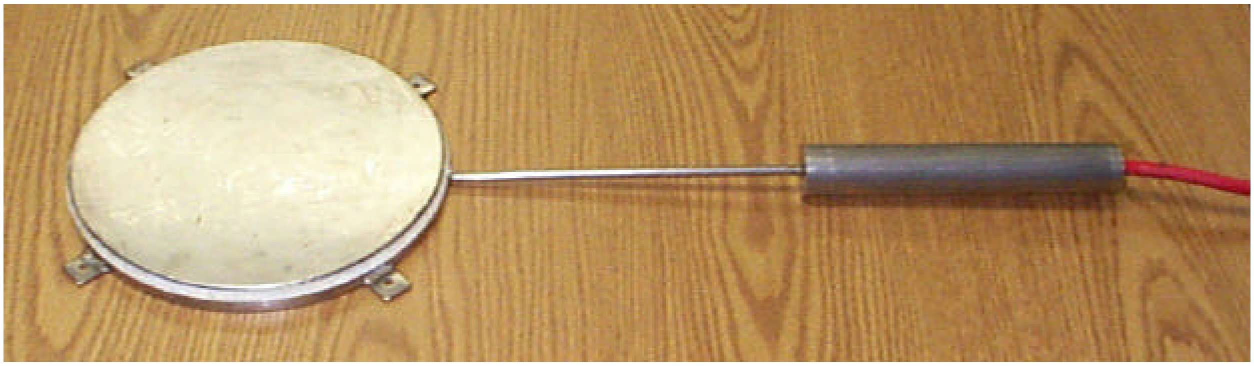

Figure 10.11 Geokon Model-3500 Pressure Cell

LVDT Calibration

Field measurement accuracy depends on the quality of calibration factors established for the sensors. Therefore, a minimum level QA plan must be implemented into the standard calibration procedures. At least two calibration tests must be performed for each pressure cell and LVDT. If two calibration tests are made, relative percent difference (RPD) is the quality indicator, as calculated from:

$$RPD(\%) = \frac{(C_1 - C_2) * 200}{C_1 + C_2} \qquad (10.1)$$

Where C_1 = larger of the two observed calibration factors and C_2 = smaller of the two observed calibration factors. If three or more calibration tests are repeated, relative standard deviation (RSD) is the quality indicator, as calculated by:

$$RSD(\%) = \frac{100}{C} * \sqrt{\sum_{i=1}^{n} \frac{\left(C_i - \overline{C}\right)^2}{m-1}} \qquad (10.2)$$

Where C = mean of the observed calibration factors, n = total number of calibration tests, and C_1 = calibration factor from the I th calibration test. For pressure cells, the acceptable limit of RPD and RSD values is 2%. For LVDTs, the acceptable limit is 0.5% for both RPD and RSD. If these criteria are not satisfied, appropriate action must be taken to resolve the problem.

Equipment required to calibrate LVDTs include an LVDT calibration stand, a precision micrometer, and a data acquisition system. Before field installation, the LVDTs were calibrated twice using a digital micrometer and an Optim Megadac 5000 Series Data Acquisition System. The following calibration procedure was followed for each LVDT with the relative percent difference of the results being within ± 1.0% for acceptance.

1. The LVDT was installed in the calibration stand.
2. The LVDT was connected to the power supply/data acquisition system, allowing 10 to 15 minutes warm up time for the electronics to stabilize.
3. The LVDT core was set at null. The output voltage and micrometer readings were recorded.
4. The LVDT core was compressed in small increments. Both the micrometer and the LVDT output voltage readings were recorded at each step. This process was repeated through half of the full-scale range.
5. The LVDT core was repositioned to null. The output voltage and micrometer reading should return to the value recorded in Step 3.
6. The LVDT core was extended in small increments. Both the micrometer and the LVDT output voltage readings were recorded for each increment. This process was repeated through half of the full-scale range.
7. A plot correlating LVDT core displacement with output voltage from the LVDT was developed, as shown in Figure 10.12.
8. A linear regression analysis was made to obtain a linear slope and the correlation coefficient.
9. The slope calculated was compared with the value supplied by the manufacturer. If the percent difference calculated was within ±1.0% the LVDT was accepted.
10. All data and plots were maintained on file for future auditing.

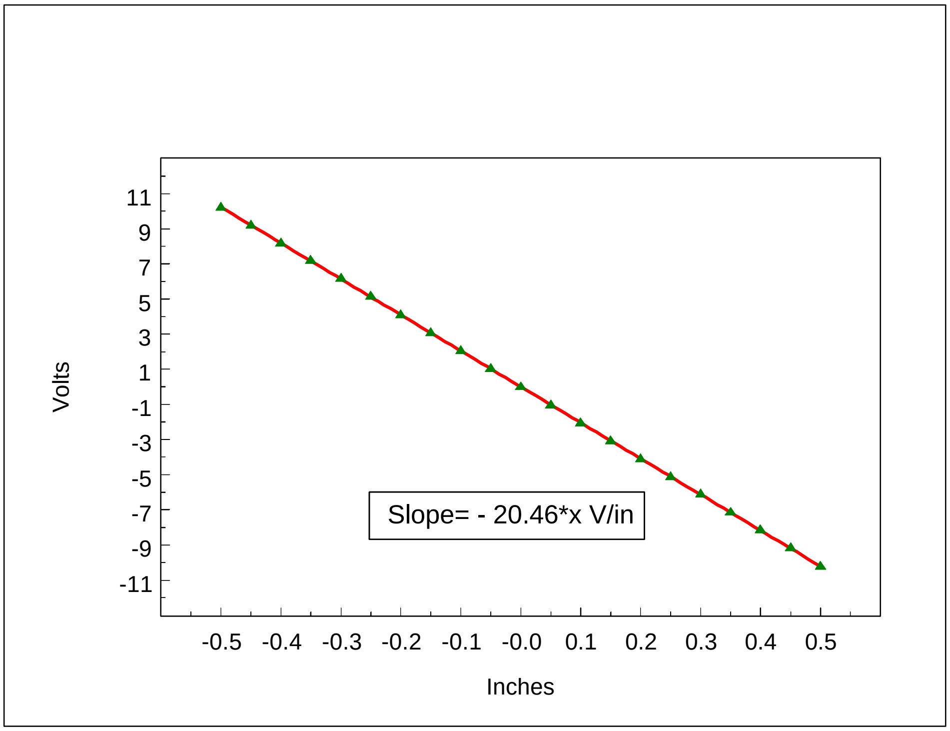

Figure 10.12 Sample LVDT Calibration Curve

Pressure Cell Calibration

Pressure cell manufacturer usually performs a calibration test under hydrostatic pressure conditions for determining calibration constants for each cell. This procedure does not represent conditions in a highway pavement where the cell is surrounded by subgrade, base and pavement materials. In order to obtain relatively accurate measurements of earth pressure, the pressure cells must be carefully calibrated in the laboratory under simulated field installation and loading conditions. A special calibration test box was built for this purpose. Inside the box, crushed limestone backfill material was compacted in lifts. Figure 10.13 shows a typical setup used in calibrating pressure cells with flexible membranes in the laboratory. Similar calibration tests were tried by Selig (1981) and by Felio and Bauer (1986).

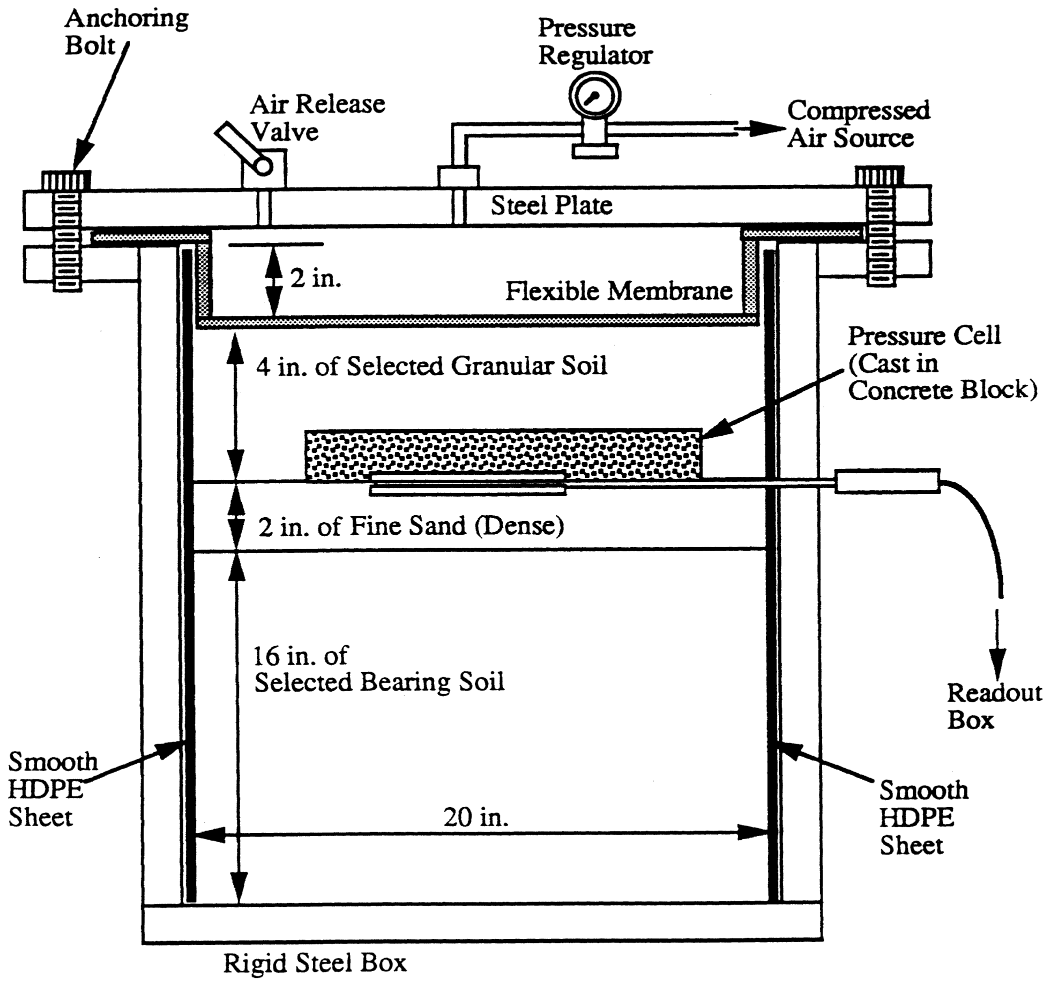

Figure 10.13 Typical Pressure Cell Calibration Test Setup

Pressure in the flexible membrane was increased in increments, and frequency of the transducer was recorded with a readout unit. Two calibration tests were performed on each pressure cell at room temperature. The value of correlation coefficient squared (r^2) was close to 1.00 between applied air pressure (p) and change in transducer readings (ΔR) in all cases, and a good agreement was observed between the two test data for each cell.

CHAPTER 11

SENSOR LOCATION AND LABELING

Because the majority of vehicle loading occurs in wheelpaths, the right wheelpath (2.5 feet in from the edgeline of the right lane) is where most of the dynamic instrumentation was installed on the Ohio SHRP Test Pavement. A few sensors were installed along the centerline and in the left wheelpath to provide ancillary response data as loads were applied to the pavement. Figure 11.1 provides a legend for sensors used on the project. Figure 11.2 shows the location of sensors in flexible pavement sections, while Figure 11.3 shows the sensor locations in rigid pavement sections. All dynamic instrumentation was located outside the 500-foot section length constructed for SHRP.

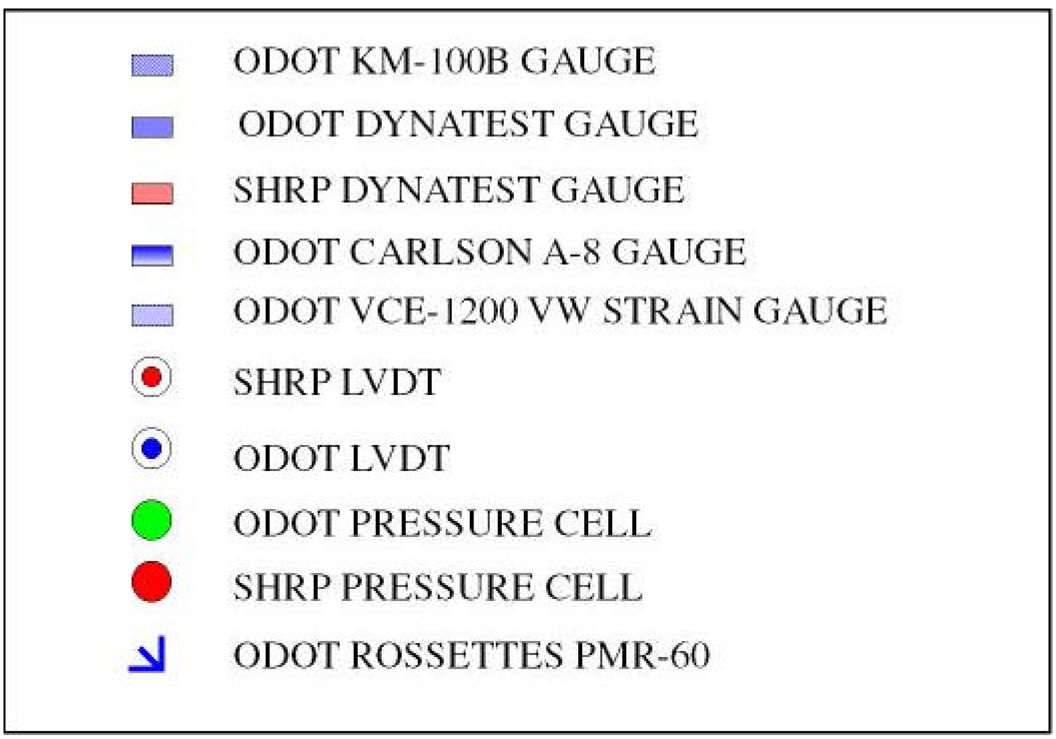

Figure 11.1 Legend for Structural Response Instrumentation

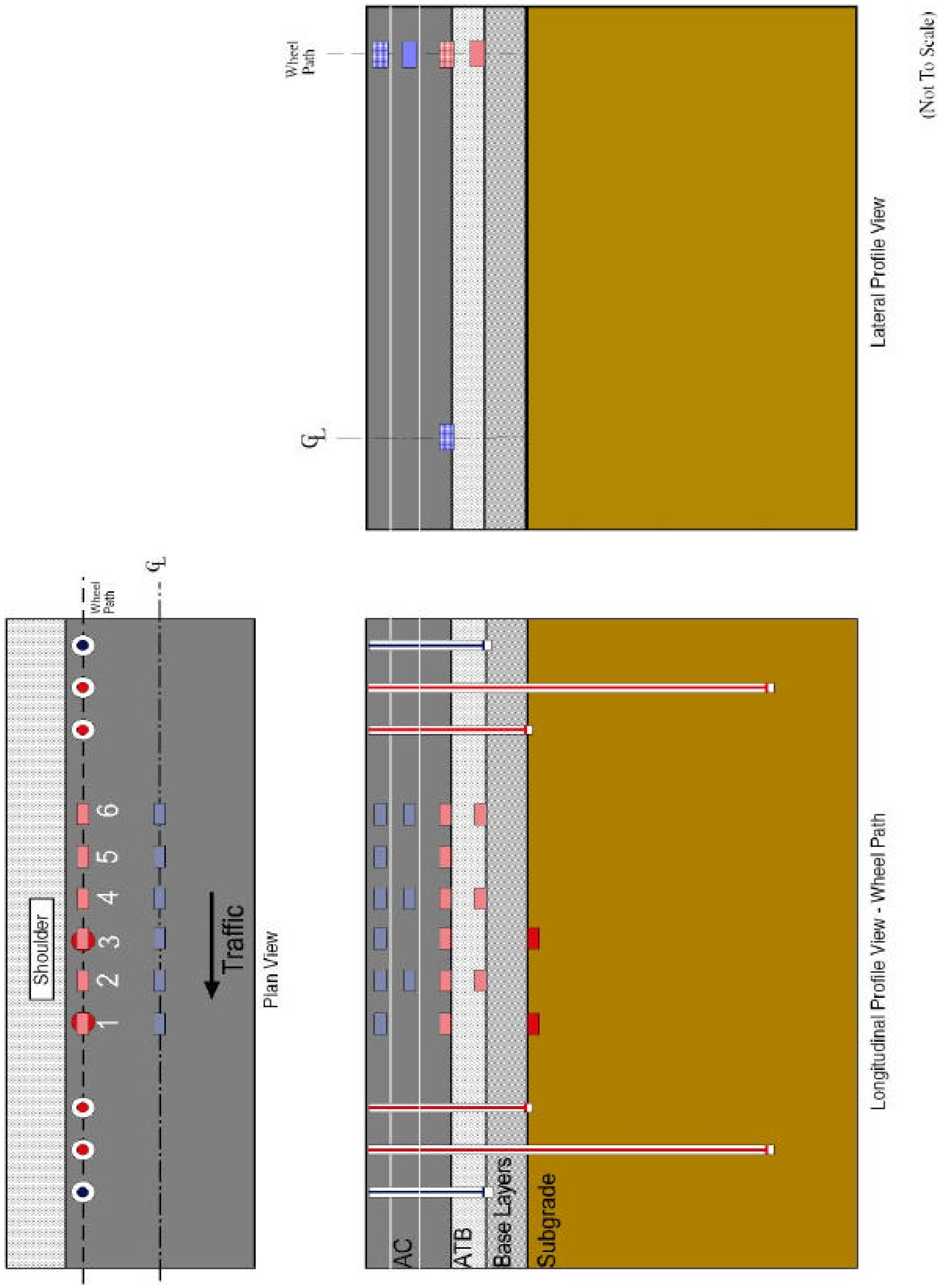

Figure 11.2 Typical Structural Response Sensor Placement in AC Test Sections

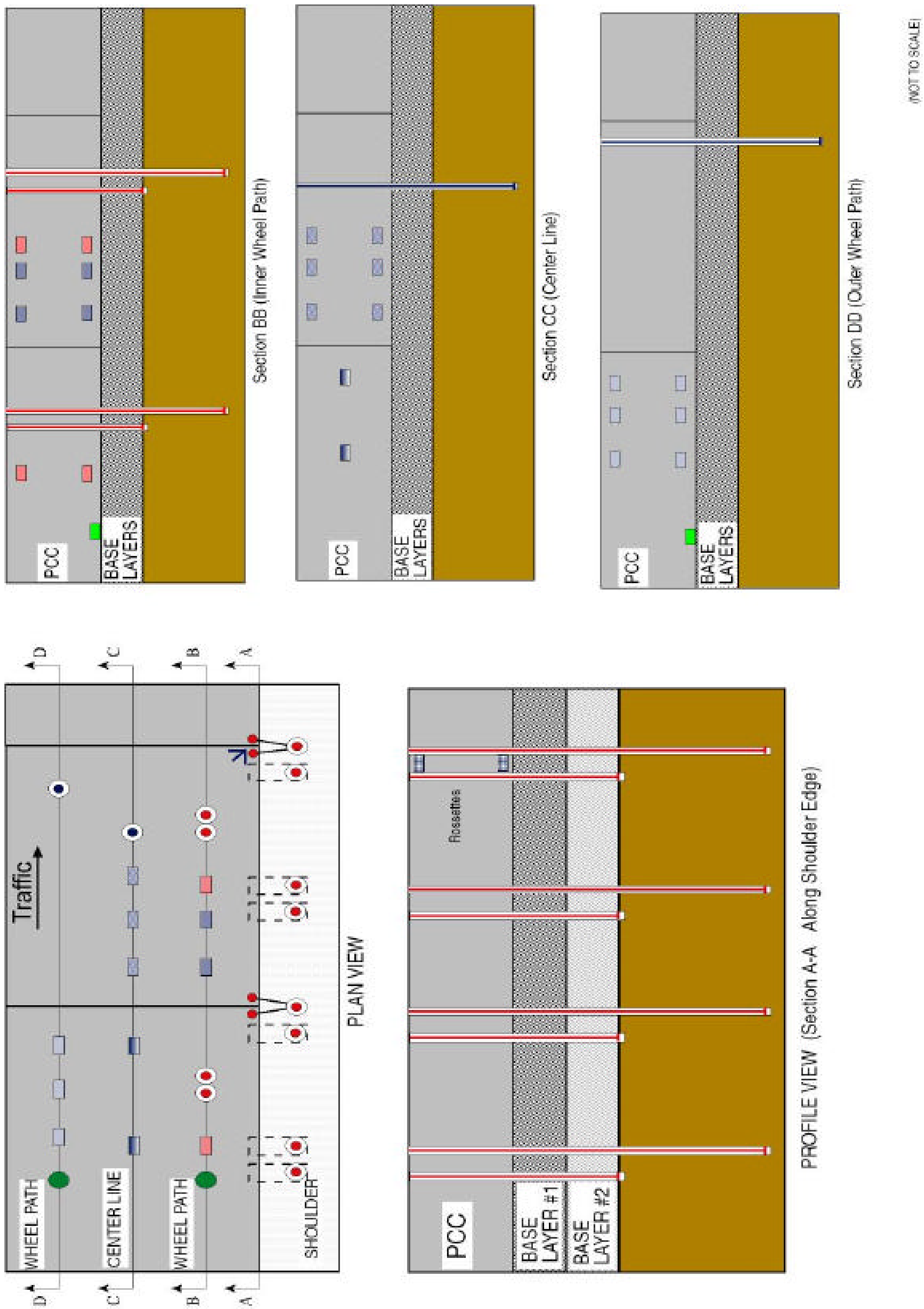

Figure 11.3 Typical Structural Response Sensor Placement in PCC Test Sections

Dynatest gauges were installed approximately one inch from the top and bottom of all pavement layers with some being added at the mid-depth of AC pavement sections requiring three lifts. Gauges in AC sections were positioned in the right wheelpath four feet away from shallow LVDT pits and spaced at two-foot intervals. Dynatest gauges 1, 3, and 5 were positioned transversely with respect to traffic flow and Dynatest gauges 2, 4, and 6 were situated longitudinally, as indicated by the direction of the lines in the symbol for these gauges. All symbols shown in red in Figures 11.1 and 11.2 were included in the dynamic instrumentation plan proposed by SHRP. These sensors only needed to be installed in the four core sections in SPS-1 and SPS-2. ODOT added the black sensors to the core sections and installed the entire sensor arrays shown in 25 additional test sections.

A sufficient number of sensors were placed to replicate dynamic response measurements two or three times. This was considered to be important because of the uncertainty of how well the sensors would withstand the rigors of construction, traffic loading, and environmental cycling. Actually, they held up better than expected and the replicated measurements can then be averaged to improve precision of the sensor output.

Instrumentation Labeling

Proper labeling of the instrumentation was crucial to this project. After instruments were installed in the pavement, the only way to easily identify them was to develop a method of marking not only at the end of each probe cable, but also spaced along its length. This was done to provide sensor identification in the event cables were accidentally cut. The following method of identification was used for each probe placed in the flexible pavement sections. Similar procedures were used for the rigid pavement sections.

The cable extension for LVDT units was only three feet long; therefore, a length of six conductor shielded cable from Alpha Wire Corporation was cut and soldered to provide enough length to reach to the pull box and allow for easy access. The LVDTs were numbered 1 through 4 or 1 through 6 (depending on the section layout) in the direction opposite of traffic flow. The word ALVDT@, LVDT number, and section identification number were typed on four pieces of heat shrink labeling tube. One piece was placed on each end of the cable length and two were spaced evenly in the mid-section.

All strain gauges were labeled using a color and number system for easy identification. Groups were numbered in the direction opposite traffic flow. The six gauges in the top AC lift along the wheelpath were designated Ared@, bottom lift - Ablue@, and middle lift (for seven inch asphalt pavement only) - Aorange@. Six gauges along the centerline were designated as Ayellow@. Finally, if there was an ATB base layer, the gauges installed there were labeled as Agreen@. Each gauge and its proper color and number were taped at approximately 15-foot intervals along the cable. Also, the color, number, and section identification number were typed on a heat shrink tube and attached at the end of the cable.

Pressure Cell Labeling

Each pressure cell has its unique identification number provided by Geokon, Inc., sealed at the end of the lead cable. Also, this identification number was spaced along the length of the cable at approximately 20-foot intervals.

CHAPTER 12

SENSOR INSTALLATION

Subgrade Preparation

Before the installation of any sensors, the subgrade had to be properly prepared. Tight construction controls were enforced during preparation of the subgrade, base, and pavement layers. These controls helped limit the number of variables that would need to be accounted for in the evaluation and comparison of different sections. The S.E. Johnson Construction Company and the PCC sub-contractor, Hi-Way Paving Company, under the supervision of ODOT, were responsible for proper construction of the subgrade layer. Before any preparation could take place, the roadway was surveyed and staked out by S.E. Johnson personnel. A grade line was then set up by Hi-Way Paving personnel as a reference for elevations. This grade line helped the contractor target the thickness and surface elevation for each pavement layer. The subgrade had to meet elevation, crown, density, and moisture requirements, and drains had to be cut in appropriate sections.

The subgrade surface had to be within $\pm$ 0.50 inch of the specified plan elevation. Cut and fill techniques were used to meet this specification. The quality of fill material brought to the site was consistent with material on the project because it came from a borrow pit located adjacent to the project. A rough elevation was achieved with the use of graders, and a final elevation was reached with the use of a trimmer referencing elevation from a string line. The elevation of the subgrade was checked and verified by ODOT personnel. Elevation shots were taken every 50 feet within a SHRP section and every 25 feet outside of SHRP section. For a section to be approved, 85% of the shots had to be within the plan specifications. The subgrade was crowned with the peak at the centerline and sloped 0.1875 inch per foot laterally toward both shoulders.

Density and moisture requirements had to be maintained until the base layer was placed on the subgrade. The moisture content of the compacted subgrade had to be kept between 85% and 120% of the optimal moisture content. Edge drains were cut along the subgrade boundaries to remove excess water before any base material was placed on the subgrade. Final approval of the subgrade was the responsibility of ODOT.

LVDT Reference

Once the subgrade was approved for a particular section, sensor locations were staked out. LVDT reference rods and environmental instrumentation were installed prior to placement of base material. Installation of LVDT references was similar for AC and PCC sections. The following description is for a typical PCC section, but applies to AC sections as well. A short length of pavement was located just outside each 500-foot long SHRP sections in each section and designated for response instrumentation. Ohio University and ODOT personnel determined the specific locations. A pull box was located near the center of each array of sensors to store cables. Station markers were located 14 feet from the edge of the pavement and spaced 25 feet apart. Nails were driven in the top and side of the stakes to provide precise stationing and elevations.

Because the contractor was permitted to place station markers within $\pm$ 6 inches, the construction joint between two instrumented slabs on PCC sections was located first, and subsequent measurements were made from that location. At the appropriate location, a 3/4-inch diameter x 30 inch long steel reference pin was hammered into the ground leaving approximately 18 inches of the pin exposed. From this point, a transit was set up to lay out the middle joint and locate the reference pin on the opposite side of the road. A 90-degree angle was then turned to locate the joint at the end of one slab. In this line of sight, 15 feet was measured from the reference pin and an end joint reference pin was placed. After turning a 180-degree angle on the transit, the reference pin for the end of the other slab was placed using the same procedure. Using a tape measure and measuring off the middle joint reference pin in the passing lane shoulder, the remaining reference pins were located on the opposite side of the road. This reference pin setup was checked and confirmed to have the correct dimensions, and painted with a highly visible paint to avoid being hit or removed by the contractor. String lines were tied to the reference pins to simulate the three transverse joints and define the instrumented PCC slabs.

A string line connecting the nails on top of the survey stakes was used as a reference from which to make measurements. Following the simulated transverse joints, appropriate measurements were taken from the survey stake line to locate the edge of the pavement, both wheelpaths and the center of the slab. At the correct distance along the joint, a plumb bob was used to locate the proper points, which were marked with a nail and highly visible paint. The measuring tape was then extended to 16.5 feet from the wheelpath closest to the edge of the pavement, 20 feet for the center of the slab, and 23.5 feet for the outer wheelpath. At each location, the previously mentioned procedure was used to identify sensor locations. The same measurements and procedures were used along the remaining two transverse joints to mark off the shoulder LVDTs, wheelpaths, and center of slab.

After all nails were placed, a pattern jig was used to locate all LVDT positions. The jig was lightweight and portable, constructed from two pieces of steel 2 inches wide, 7.50 feet long, and 0.25 inch thick. The two pieces were joined lengthwise by a steel plate for a combined length of 15 feet, the exact length of one concrete slab. The pattern was fitted with handles to facilitate positioning and moving, painted to resist corrosion, and precise distances were marked off directly on the jig. These marks correlated to precise locations in both rigid and flexible pavement sections. Different colors were used for each instrumented slab. A green mark referred to slab one and a red mark referred to slab two. The jig saved time and assured that the layout of sensors in every section would be consistent.

Once the LVDT positions were marked, a drill rig was brought in to bore the deep reference holes, as shown in Figure 12.1. The holes were bored with a 3-inch diameter auger bit to a depth of approximately 10.5 feet. To achieve an accurate hole location, two references were measured off and marked from the nail identifying the LVDT location. The auger bit was started in the soil, but before the boring was continued, the references were checked to assure that the hole was being dug in the correct place. After a hole was bored and the measurements were checked to be correct, a reference rod was placed in the hole. The reference rod consisted of a 0.75-inch diameter, 12-foot long steel rod with a 1.50-inch diameter, 1-inch long stainless steel tip welded to the end to provide a smooth, clean surface for the LVDT.

To permanently fix the rod in the hole, a spacer cut from 0.75-inch thick plastic was slid onto the rod and positioned just under the tip. The rod was then dropped into the center of the hole and driven approximately one-foot into the subgrade placing the tip at the proper elevation. A non-shrinking grout was placed in the bottom of the hole using a large funnel and 10-feet of 1.5-inch diameter plastic hose to anchor the rod in place. The grout was poured to a depth of only one-foot leaving 10 feet of the steel rod exposed. After 24 hours, a 10 foot long piece of 2-inch PVC pipe was placed around the rod and spacer assembly, lowered to just below the stainless steel tip, and centered in the hole by filling the gap around the pipe with cement sand.

Figure 12.1 ODOT Drill Rig

Sand was vibrated around the pipe to assure all gaps were filled and proper compaction was achieved. A 3-inch to 2-inch plastic reducer was placed on the end of the PVC pipe. The opening of the reducer was taped off to prevent base material from falling into the pipe during the construction of subsequent pavement layers.

Reference plates for the shallow LVDTs were constructed of one-foot square by one-inch thick steel plate with a 1.50-inch diameter stainless steep tip welded in the middle on one side. The tips were not located at the same elevation in all sections. Tip elevation was determined by the thickness of the concrete and base layers. Because the top surface of the plates rested evenly with the surface of the subgrade, the distance to the top of the pavement varied.

The LVDT was placed in a Single Layer Deflectometer (Figure 12.2) mounted in the concrete. Because of the way the LVDT was mounted, 11-inches placed the LVDT at its

Figure 12.2 Single Layer Deflectometer

approximate zero point, or at least within a workable range for testing. Tips requiring up to 3-inches of elevation were constructed solely from stainless steel. However, when a tip had to be 4-inches or longer, the tip was welded to the top of a 0.75-inch diameter steel rod. Reference plates placed in locations with two base layers had to have the tips tapped and screwed in after the placement of the base layers because the bases were placed in 4-inch lifts. Before the plate was placed in the subgrade, the assembly was painted to resist corrosion. The top of the plate was centered at the correct location in the subgrade and the outline of the plate was marked in the subgrade with paint. The plate was removed leaving a painted square outline. Subgrade material inside the square outline was dug out by hand to a depth of one- inch. A thin layer of concrete sand was placed on the bottom of the cutout to aid in leveling of the plate. The plate was placed in the cutout square and leveled with a bubble level in both longitudinal and transverse directions. Broken up subgrade material, which had been removed from the cutout, was compacted around any loose edges of the plate to secure the plate position. A string line was pulled across the tops of both deep rods and shallow plates in the shoulder or wheelpath to make sure all tips lined up. Any plate or rod that did not line up was subsequently repositioned in its proper location. After the placement of LVDT references was complete, the subgrade was finished and the base layers were placed.

Sections with a stabilized base required one final step before construction could continue. Because of the nature of the treated bases, and the fact they extended under both the pavement and shoulder and were placed at one time, wooden boxes with the outer dimensions of the shoulder pits and the heights of the base layers were positioned and anchored over the shoulder reference locations prior to the placement of the treated base layers.

Base Construction

DGAB layers were placed with dump trucks, graders and rollers. The aggregate was hauled in from the quarry by truck and dumped in front of a grader. The grader spread the aggregate in 3 to 4-inch thick lifts and cut it to the approximate elevation before compaction. A roller compacted the aggregate to the proper density. If the proper elevation was not achieved, high spots were cut with a trimmer and low spots were filled and recompacted.

PATB material was mixed at an asphalt plant in Marion, Ohio, hauled in by truck, and placed with an asphalt paver, as shown in Figure 12.3. The driving lane was paved first, the passing lane shoulder second, and the driving lane last. The material was placed at a depth greater than 4 inches, and compacted by at least two passes of the roller to the proper density and thickness.

Figure 12.3 Asphalt Paver

If the PATB layer rutted under construction loading, filling was permitted by ODOT.

LCB was mixed at the on-site batch plant and placed with a slip form paver (Figure 12.4). Trucks hauled the mix and deposited it in front of the paver.

PCTB was placed in the same manner as the LCB under both asphalt and concrete sections. After the PCC concrete slabs were completed, PCTB was placed in the shoulders with a smaller paver designed for short slab width.

Preparation of the Base

Before any sensors could be installed, the base layer had to be properly graded and compacted. LVDT references and all other sensors were located in the concrete slabs. Shoulder LVDT locations were left alone until the slabs were completed and it came time to place the asphalt shoulders. To begin the sensor location, transverse joints were laid out, and the wheelpaths and center of the slab were located the same as they were on the subgrade.

Figure 12.4 Slip Form Paver

The same jig was used to locate all gauges. Sensor positions were marked with a painted cross (Figure 12.5) to aid in the proper placement of the gauges. LVDT locations were marked with paint because the reference rods and plates had to be uncovered. In DGAB material, a hole was dug at the paint mark with a pick and cleaned with a vacuum cleaner. The top of the rod or plate was located first to limit the size of the hole to approximately 4 inches in diameter.

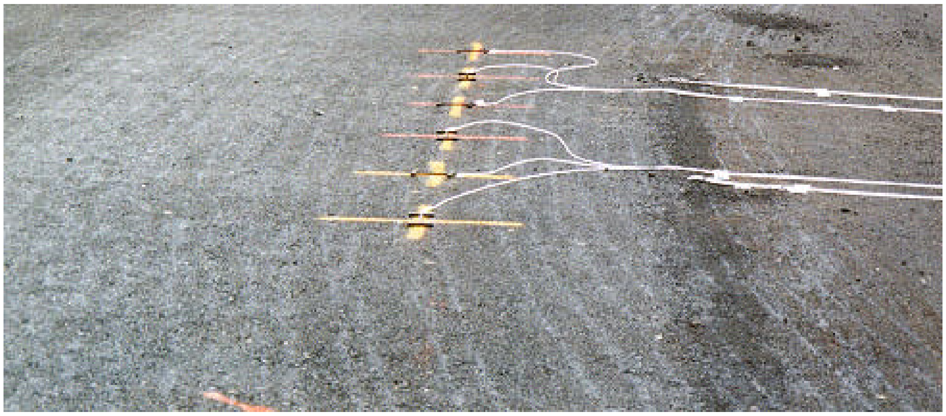

Figure 12.5 Painted Sensor Locations

In PATB material, a hole was dug with a hammer and chisel. The tip of the rod or plate was again located first, and the hole was cut approximately 4 inches in diameter and cleaned with a vacuum cleaner. In LCB and PCTB material, the hole had to be cored around the tip. Precise measuring became very important because the 4 inch core bit had to be placed as close to the center as possible during the drilling process. Ideally, a hole was cored leaving the tip of the rod or plate in the center of the hole. When this was not achieved, the hole was shaved to center the tip. Because water was used to lubricate and cool the bit as it cut into the LCB or PCTB, the hole was cleaned with a wet-dry vacuum. Once the base layers were properly prepared, installation of the sensors could begin.

PCC Sensor Installation

Sensors for measuring pavement strain made up the largest group of sensors. The group was comprised of Dynatest PAST-II, TML KM-100B, TML PMR 60, Carlson A-8, Geokon VWSG, and a few Micro-Measurements EGP-5-120 strain gauges. All strain gauges in PCC sections were held in position with a specially designed stand unit. Except in the case of the TML PMR 60 rosette, which required only one stand, two stands made up a unit. These stands were constructed of 0.25-inch diameter cold rolled steel. Each type of strain gauge had its own special stand, which placed the gauge at its proper depth in the concrete. The two stands in the unit were independent of one another to give the gauges freedom of motion to respond in concert with the PCC layer whenever strains were induced, as shown in Figure 12.6. The Maiden and Jenkins Construction Company of Nelsonville, Ohio manufactured the stands.

Before a strain gauge could be affixed to the unit, the stands had to be set in their proper positions and anchored to the base. Except for the TML PMR-60 rosette stand, all stands were

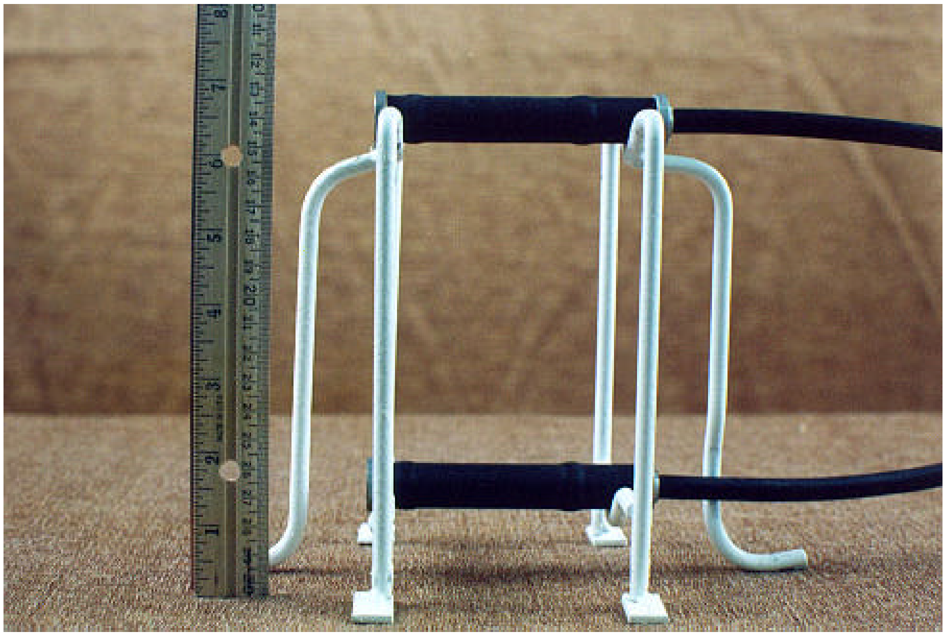

Figure 12.6 Stands to Hold Strain Gauges

oriented such that the strain gauges would lie longitudinally in the roadway (Figure 12.7).

Figure 12.7 Gauge Orientation

In DGAB and PATB, a 6 inch long, 0.25-inch diameter steel spike was hammered into the base and hooked onto the stand. In LCB and PCTB, a non-shrinking, fast setting grout was poured over the feet of the stands. The gauge anchors were secured to the stands with plastic cable ties at the middle around the strain gauge portion of the sensors (Figure 12.8). Special care was taken to assure that the strain gauge rested on the stands and that it was not being stressed in any way.

TML KM-100B strain transducers were placed one-inch from both the top and bottom of the PCC layer in the center lane of the second slab. The two transducers per location were identified by another color scheme with red being the top transducer and blue the bottom transducer. Stands designed for the KM-100B had a half-circular bend designed to cradle the transducers.

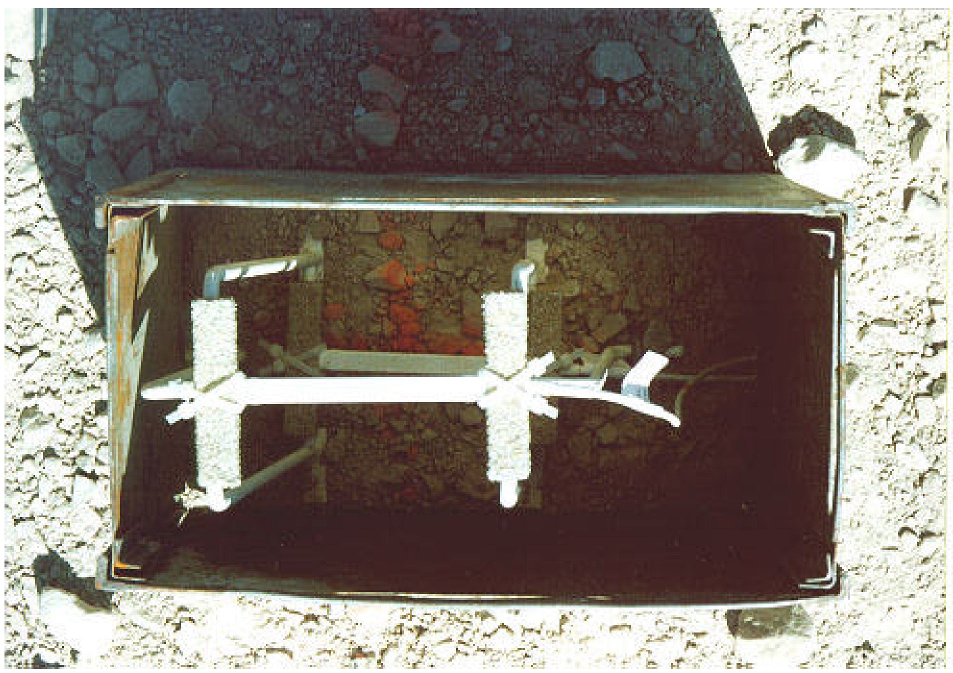

Figure 12.8 Dynatest Strain Gauge Setup for PCC Pavement

Transducers were placed in the stands so the ends extended approximately 0.75-inch past the support and the lead wire would be pushed toward the transducer by the paver. This permitted the ends of the transducers to be completely embedded in the concrete. The transducers were affixed to the stands with plastic cable ties in a criss-cross pattern (Figure 12.9).

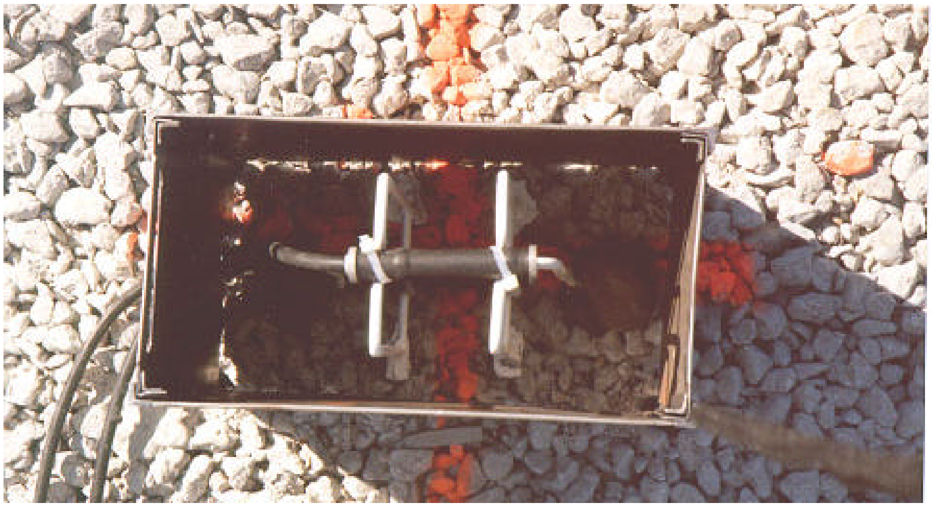

Figure 12.9 KM-100B Setup

Two TML PMR-60 three axis rosettes were held in position with one stand. The rosettes were not labeled by color. Rather, they were labeled as top and bottom. The top gauge sat one inch from the surface of the concrete, and the bottom gauge rested an inch above the base of the concrete, 18 inches away from the driving shoulder and the third transverse joint. The stand had three fingers spaced 45 degrees apart, which supported the three strain gauges of the rosette. The stand was oriented such that the lead wire of the rosette would be pushed toward the gauge by the paver. The gauges were affixed to the stand with a plastic cable tie (Figure 12.10).

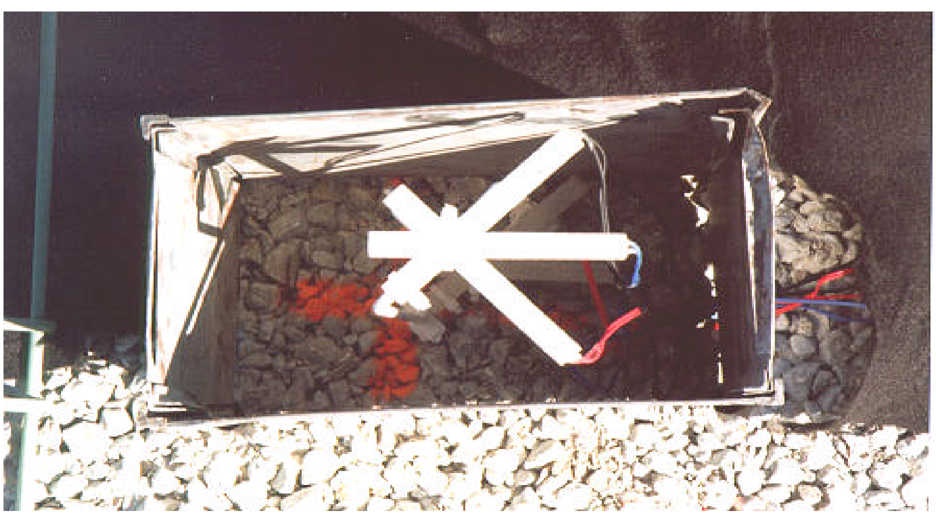

Figure 12.10 PMR-60 Rosette Setup

One Carlson A-8 strain meter was used per location. With only one gauge per pair of stands, no color scheme was needed, rather the gauges in each slab were labeled 1 and 2. The gauge was placed at mid height in the PCC layer and in the center lane of the first slab. The stands used a half-circular notch to support the gauge. The stands were located such that approximately one-inch of the gauge would extend over each stand. This allowed for the ends of the gauge to be securely embedded in the concrete. The Carlson gauges were placed on the stand so the lead wire would be pushed in the direction of the gauge by the paver. Plastic cable ties were used to secure the gauges to the stands (Figure 12.11).

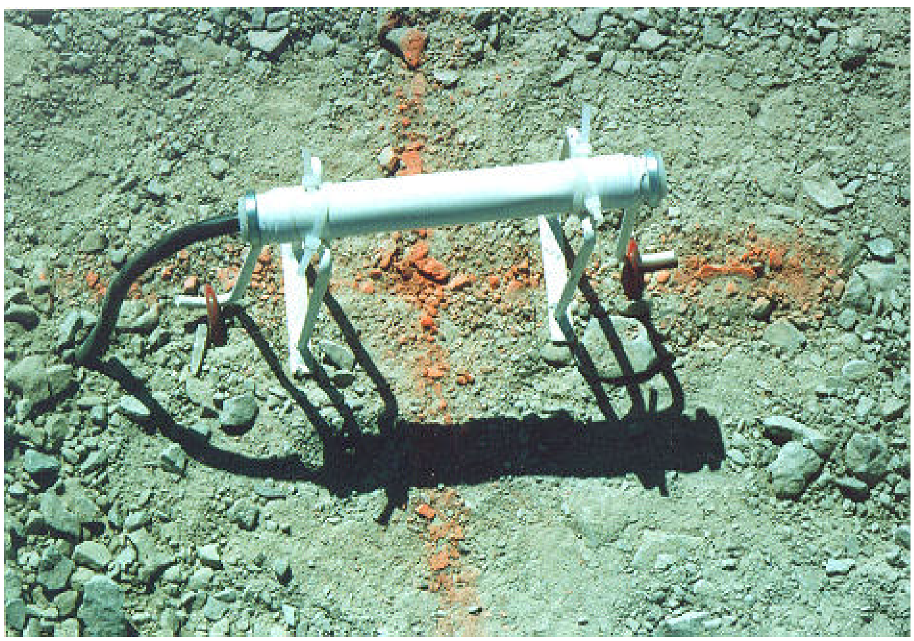

Figure 12.11 Carlson A-8 Strain Meter Setup

Geokon Vibrating Wire Strain Gauges (VWSG) were placed one-inch from the top and bottom of the concrete in the inside wheelpath of the first concrete slab. The VWSG positions mirrored the locations of the Dynatest gauges in the second slab. With two VWSG being used per location, red identified the top gauge and white identified the bottom gauge. The stands supporting the VWSG had a small notch, which seated the center of the steel anchor at its proper elevation. The anchor rested on the stands with approximately 0.75-inch of overhang past the stands to permit proper bonding to the concrete. The steel anchor was secured to the stands with plastic cable ties (Figure 12.12). The electromagnetic coil was then secured onto the steel anchor with a steel clamp in such a way that the lead wire was pushed in the direction of the coil by the paver. Care was also taken to assure that the coil was affixed in such a way to allow overall maximum coverage of the VWSG gauge.

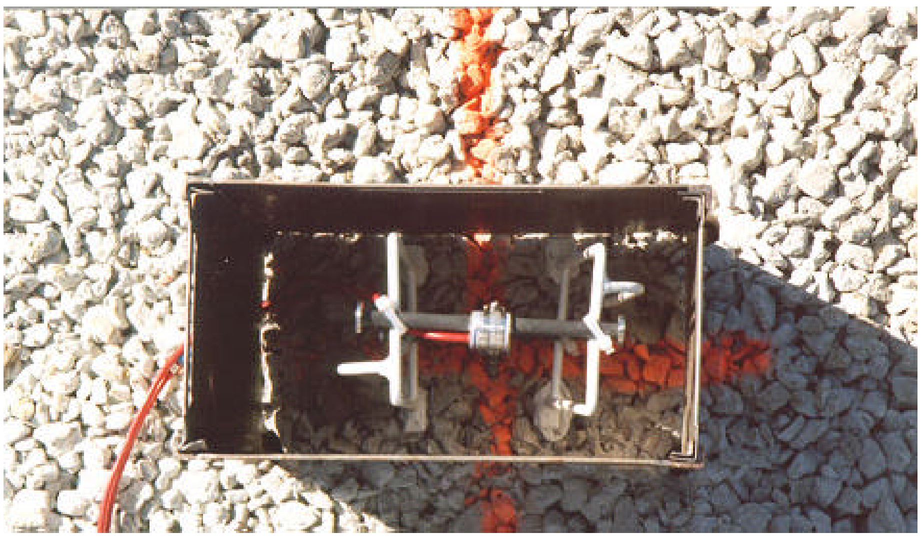

Figure 12.12 Geokon VWSG Setup

Micro-Measurements EGP 5-120 embedment strain gauges were only specified in certain sections where a third slab was utilized. The EGP 5-120 gauges were placed in the driving lane, 1 inch from the top and the bottom of the PCC layer in the outside wheelpath. Gauge locations in the third slab were exactly the same as the Dynatest gauge locations in the second slab. With two gauges per location, red identified the top gauge and blue identified the bottom gauge. The stands designed to support the EGP 5-120 gauges utilized a flat surface for the gauge to rest on and plastic cable ties secured the gauge to the stands (Figure 12.13). The gauges were oriented so the lead wire was pushed in the direction of the gauge by the paver.

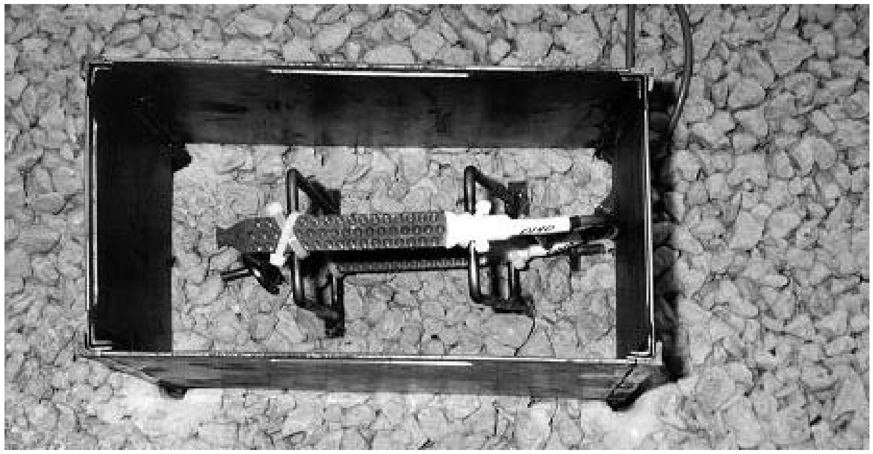

Figure 12.13 Micro Measurement EGP-5-120 Gauge Setup

From previous projects, it is known that forces exerted during paving were sufficient to move the sensors. Two basic methods were used to prevent sensor displacement. LVDTs, Carlson gauges, pressure cells, thermocouples and thermistors, were protected by piling green concrete around them when the spreader was approximately two slabs away from the instrumented section. An amount of concrete from a cement truck was dumped in front of the paver in one of the passing lane slabs. The concrete was shoveled by hand to the instrument location, gently piled around the instrument, and vibrated with a portable vibrator to assure consolidation. This process was continued until the instrument was completely covered with concrete.

Dynatest gauges, KM-100B gauges, VWSGs and PMR-60 rosettes required a greater degree of protection. Ohio University designed a special box constructed of sheet metal and 0.50 inch angle iron. Each box was 1-foot long, 6 inches wide, and either 7.5 inches or 10.5 inches high, depending upon the thickness of the PCC layer. The angle iron corners acted as anchors into the base and support for the sheet metal sides.

The box was designed to be rigid during the paving process, yet come apart for removal. A box was placed around sensors at each location prior to paving and set so the top was slightly below the elevation of the pavement surface. Anchoring the boxes to the base materials proved to be an awkward task. It was facilitated with the use of a hammer drill, a 0.50-inch drill bit, and a pattern that identified anchor positions. Holes were drilled 4-inches deep into the base material and the anchors of the box were set directly into them. The narrowness of the hole provided a sufficient amount of friction to hold the box in place during paving, and still, the degree of friction was small enough to allow for relatively easy removal of the boxes after paving. Just before the spreader reached the instrumented slabs, green concrete was placed in all the boxes by hand to prevent any damage that might have occurred to the gauges from the weight of the concrete being dropped or shoved against them. The concrete was vibrated to assure consolidation. This process continued until the vibrated concrete filled the box. Once this was done, excess concrete was shoveled on top and around the sides of the box for added protection. After these steps were completed, at all sensor locations, the instrumented section was ready for paving.

After passage of the spreader and paver, but before final finishing and texturing of the PCC, the boxes were removed one side at a time and the integrity of the gauges was checked. To complete this task, a 32-foot aluminum platform resting on wooden horses was used to span the freshly paved concrete lanes and provide researchers with direct access to each instrument location (Figure 12.14). Due to the relatively close proximity of the top of the boxes to the surface of the concrete, they could be easily located for removal.

Figure 12.14 Pulling Protective Boxes

Using a pair of channel lock pliers to grasp the top of the walls of the box, the 6-inch ends were removed first, followed by the one-foot long sides. The location of the top gauge was then verified to be in the proper position by gently removing a small amount of the concrete directly over it. If the position of the gauge was incorrect, the portable vibrator was used to liquefy the concrete in the immediate area surrounding the gauge while the position was corrected by hand. Any gauge damaged during the paving operation was replaced at this time.

Researchers monitored the gauges continuously during the paving process. Once the gauge was in proper position, it was covered with concrete. The area was vibrated thoroughly to assure proper consolidation and the surface was smoothed with a trowel. After all boxes were removed and all the sensor locations were verified, the instrumented sections were returned to contractor personnel for finishing and texturing.

Personnel from the Hi-Way Paving Company were extremely cooperative during this operation. While any delays resulting from sensor placement was minimal, their assistance made it go smoothly. They helped place concrete around the sensors ahead of the spreader, took care not to step on the sensors, and provided necessary labor and tools to get the job done. This type of cooperation is essential if a project of this magnitude is to be successful.

Pressure Cells

The Geokon Model 3500 earth pressure cell was used to measure pressure. Ohio University personnel installed the pressure cells in SPS-8; however, pressure cell installation in the other SPS sections fell under the responsibility of the University of Akron. For SPS-8, two pressure cells were calibrated in the Ohio University lab. The cells were set in concrete with a face of the pressure cell flush with the surface of the concrete. The pressure cell/concrete structures were placed in pre-dug holes with the exact dimensions of the concrete block. The exposed pressure cell surface faced down in both wheelpaths of the second slab (Figure 12.15). Sand was used to level the pressure cell, and

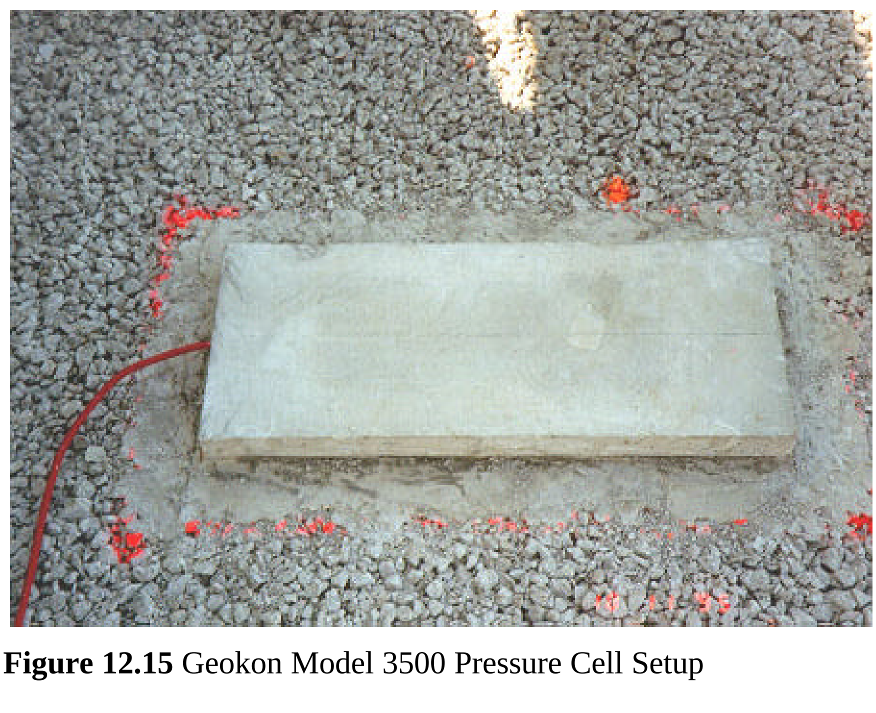

Figure 12.15 Geokon Model 3500 Pressure Cell Setup

loose aggregate was compacted around the edges of the concrete block to hold it in place. In SPS-2 sections, pressure cells were placed in both wheelpaths of the first slab, and in SPS-1 sections, two pressure cells were placed in the right wheelpath.

Temperature Sensors

Temperature on SPS-2 sections was measured with thermocouples sticks tied to the dowel bar baskets. Individual sensors were located in the right wheelpath at different elevations to measure slab gradients. Additional sensors were located in the center of the slab. To properly position these sensors, a 0.25-inch diameter round spike, approximately 15-inches long, was driven into the base material. The sensors were then tied to the spike with plastic cable ties.

In SPS-1 sections, single thermocouples were placed at the top and bottom of AC or base lift.

AC Sensor Installation

The positioning of Dynatest gauges and thermocouples in ATB and AC layers follows the same procedures. Therefore, the method of installation described below for Dynatest gauges was also used for the thermocouples.

As asphalt mixtures were placed, Dynatest gauges and thermocouples were prepared for the section being paved and situated in their correct locations. The three green labeled Dynatest gauges were placed longitudinally along the wheelpath. As the asphalt paver approached, exact locations of each Dynatest gauge were staked out and marked with fluorescent paint. Asphalt concrete was taken from the paver and sieved through 0.25-inch mesh hardware cloth into a wheelbarrow to remove large aggregate, which might damage the gauge during rolling. This sieved material was taken to the paint marks and laid 1-inch thick on the base. Next, the Dynatest gauges were situated atop the sieved asphalt layer exactly over the paint marks (Figure 12.16).

Figure 12.16 Sensor Placement in AC Pavement Sections

Each gauge was positioned horizontally with its cable pointing toward the paver and rollers. Additional sieved AC was placed over the gauge and compacted lightly to maintain postion.

The four-inch thick AC layer was placed in two lifts - the bottom lift was 2.25 inches thick, and the top lift was 1.75 inches thick. Before the bottom lift was in place, preparation was necessary for instrumentation installation.

The locations of blue and yellow Dynatest gauges were painted on the base surface. As the paver approached the section, each Dynatest gauge and thermocouple (when applicable) was installed using the same procedure as for ATB bases. The thermocouple was situated between Dynatest gauges 3 and 4 and between the centerline and wheelpath. All cables were maneuvered around the instruments, brought straight out to the edge of the pavement, and taped down to the surface. This distributed all cables out and avoided leaving too many wires in one area creating weak spots in the asphalt. The gauges were checked for correct resistance values with a voltmeter before, during, and after the paving operation. The thermocouples were also checked with the hand-held readout unit after pavement placement.

The top-lift Dynatest gauges and thermocouples (when applicable) were installed similar to the bottom lift, but because the lift thickness and gauge location were different, a slightly different procedure was used. The red Dynatest gauges and the thermocouple were situated atop 0.75-inch of sieved asphalt rather than a full inch. This situated the gauge one-inch from the pavement surface.

Seven-inch thick AC layers were placed in three lifts. The bottom lift was 3-inches thick, the middle lift was 2.25-inches thick, and the top lift was 1.75-inches thick. The only difference in instrumentation installation from the 4-inch thick pavement was placement of the middle lift. Orange Dynatest gauges and thermocouples (when applicable) were situated atop a half-inch thickness of sieved asphalt concrete. This established the orange gauges at the middle of the AC pavement layer. All other procedures for Dynatest gauge and thermocouple installation were the same.

After the asphalt concrete had been placed, the cables were routed to the pull boxes, the wires were covered with sieved asphalt concrete, and the data acquisition connectors were fixed to the cable ends. The cables were then buried to a sufficient depth in trenches to the pull boxes. The trench was dug deep enough near the pull box to fit all cables through a hole created with a hammer drill in the pull box wall. Soil was replaced overtop the cables in the trench and tampered.

After this was accomplished, cables exiting the pavement shoulder were then covered with asphalt concrete. This helped protect the wires from stray vehicles running off the pavement. All cables were organized and fitted with connectors for easier hook-up to data acquisition systems. These connectors were constructed by first tipping each wire with gold plated pins using an air-compressed crimping machine. The pins were pushed into a male DB37 connector in a set configuration. The female end was configured in the same manner and linked to a data acquisition system. This use of connectors saved time while hooking up gauges to the data acquisition systems.

Also, connectors insure a more solid signal junction.

Shoulder Work

The shoulders in the DEL-23-17.48 project were all asphalt concrete (AC). The shoulders for all PCC sections were placed after the PCC had cured. The passing lane shoulder was 4 feet wide and the driving lane shoulder was 10 feet wide.

Protection was needed for the lead wires from the hot AC mix and from forces generated while placing and compacting the AC layers. In sections paved directly on DGAB or PATB, shallow trenches were dug. The wires were placed in these trenches and covered up with loose aggregate. The entire area was then compacted to assure that the integrity of the base under the shoulder was intact. Instrumented sections placed on LCB or PCTB utilized a shallow trench and a length of PVC pipe. The wires were either strung through a 1-inch diameter, 10-foot long PVC pipe or placed under a 2-inch diameter, 10-foot long piece of PVC pipe which had been sawed in half lengthwise. The covered wires were placed in shallow trenches and taped to the surface of the base with duct tape to secure their position. Once the wires were out of the shoulder, they were placed in a deeper trench. This trench was cut from the existing locations of the wires in the shoulder directly to the pull box where the wires were then stored. Burying the wires provided protection from damage during future grading operations.

The shoulder LVDTs in instrumented SPS-2 sections were of concern during the paving of the AC shoulders. Researchers were faced with the problem of providing a square or rectangle hole at the edge of the pavement to house the shoulder LVDT boxes. A circular saw could not be used to cut the hole after the shoulder was paved because the blade would cut into the PCC or tear up the base while cutting the edges of the hole. The shoulder box itself could not be installed because the shoulder was placed in three lifts. It was decided that wooden boxes having the outside dimensions of the pit with the heights of the individual lifts would be used. To install the wooden boxes, the shoulder LVDT reference rods and plates were uncovered. The box was butted against the edge of the pavement and covered the reference tip of the plate or rod. The box was then anchored to the base layer with 50-penny nails. After the box was anchored, one or two holes, depending on the type of pit, were drilled through the back edge of the box. Lead wires were strung through these holes for connection to the LVDTs at a later date. After each lift was placed, the boxes were uncovered and another box with the height of the next lift was nailed to the top of the box on the bottom. Due to the thickness of the final lift, 0.25-inch particleboard cutouts were nailed to the top of the existing structure to the surface of the PCC. Once the entire shoulder was completed, the wood pieces and anchors were removed leaving a square or rectangular hole for the shoulder boxes to slide into.

LVDT Installation

Prior to testing a section, the LVDTs had to be installed in both the slabs and the shoulder. Working on the concrete slabs required considerable care so as not to damage the surface. The shoulder work required installing the shoulder boxes as well as the LVDTs.

Installing the LVDTs in the concrete slabs first required locating the positions of the Single Layer Deflectometers (SLDs) buried in the concrete. To obtain a close approximation of the locations, measurements were taken from the edge of the pavement along the transverse joints. At the appropriate distances, the wheelpaths and center of the slabs were marked. The jig used to lay out the instruments was again used to mark the SLD positions. To uncover the SLD, a drill with a 0.50-inch drill bit was used to locate the brass cap of the SLD. Once the brass cap was located, the rest of the cap was uncovered by carefully chipping away the concrete covering the cap. Care was taken to provide a hole directly over the SLD, which would not have a greater diameter than the brass cap itself. After the cap was uncovered, it was removed to allow installation of the LVDT. Lead wires from the LVDT were soldered to the wire extending out of the SLD. The soldered connections were protected individually with heat shrink and the entire connection was also protected with heat shrink. The LVDT was then installed in the SLD as close to the zero position as possible.

To prevent chipping away the PCC surface around the SLD, individual brass caps were specially constructed for each individual SLD. Each specially designed cap enabled the top of the SLD to be flush with the PCC surface.

Installing the shoulder pits and LVDTs required a greater degree of effort. Installing the shoulder pit had to be completed before the LVDTs could be installed. Each pit was placed in its hole left by the wooden box. For the pit to sit properly, the front edge had to rest flush against the edge of the pavement, the reference tip of the rod or plate had to be correctly surrounded, and the top of the pit had to rest as close to flush with the surface of the shoulder as possible. After the proper position was determined, the pit had to be epoxied to the shoulder. First, an amount of sand was placed around the outside of the pit in part to wedge the pit in position and in part to prevent epoxy from seeping under the pit and filling up the inside of the pit. Epoxy was then poured around the pit up to the surface and allowed to set. Once the pits were set in place, the LVDTs were installed. They were soldered and protected using the same procedures used in the concrete slabs. The LVDTs were mounted to brackets, which were securely anchored to the edge of the PCC. The LVDTs were set as close to the zero position as possible and the pit was closed.

Instrumentation Coordinate System

An instrumentation coordinate system for each section was constructed to reference each

gauge in an organized and simple manner. An LVDT cap was a good origin to begin from because it was exposed and easy to locate. The x-axis runs longitudinally along the wheelpath, the y-axis runs perpendicular to the x-axis and laterally across the road surface, and the z-axis runs vertically into the ground. The northern-most reference rod LVDT cap was selected as the origin, and anything north of that cap was given a negative x value. Locations toward the center of the road were considered positive y value, and locations in the pavement structure were negative z values. LVDT coordinates were selected at their reference location (i.e., deep reference rods are at -10' along the z-axis).
In special cases, due to construction needs minor adjustments were made in the field to sensor locations. This data will be available in the Ohio database with sensor response data.

CHAPTER 12

SENSOR INSTALLATION

Subgrade Preparation

Before the installation of any sensors, the subgrade had to be properly prepared. Tight construction controls were enforced during preparation of the subgrade, base, and pavement layers. These controls helped limit the number of variables that would need to be accounted for in the evaluation and comparison of different sections. The S.E. Johnson Construction Company and the PCC sub-contractor, Hi-Way Paving Company, under the supervision of ODOT, were responsible for proper construction of the subgrade layer. Before any preparation could take place, the roadway was surveyed and staked out by S.E. Johnson personnel. A grade line was then set up by Hi-Way Paving personnel as a reference for elevations. This grade line helped the contractor target the thickness and surface elevation for each pavement layer. The subgrade had to meet elevation, crown, density, and moisture requirements, and drains had to be cut in appropriate sections.

The subgrade surface had to be within $\pm$ 0.50 inch of the specified plan elevation. Cut and fill techniques were used to meet this specification. The quality of fill material brought to the site was consistent with material on the project because it came from a borrow pit located adjacent to the project. A rough elevation was achieved with the use of graders, and a final elevation was reached with the use of a trimmer referencing elevation from a string line. The elevation of the subgrade was checked and verified by ODOT personnel. Elevation shots were taken every 50 feet within a SHRP section and every 25 feet outside of SHRP section. For a section to be approved, 85% of the shots had to be within the plan specifications. The subgrade was crowned with the peak at the centerline and sloped 0.1875 inch per foot laterally toward both shoulders.

Density and moisture requirements had to be maintained until the base layer was placed on the subgrade. The moisture content of the compacted subgrade had to be kept between 85% and 120% of the optimal moisture content. Edge drains were cut along the subgrade boundaries to remove excess water before any base material was placed on the subgrade. Final approval of the subgrade was the responsibility of ODOT.

LVDT Reference

Once the subgrade was approved for a particular section, sensor locations were staked out. LVDT reference rods and environmental instrumentation were installed prior to placement of base material. Installation of LVDT references was similar for AC and PCC sections. The following description is for a typical PCC section, but applies to AC sections as well. A short length of pavement was located just outside each 500-foot long SHRP sections in each section and designated for response instrumentation. Ohio University and ODOT personnel determined the specific locations. A pull box was located near the center of each array of sensors to store cables. Station markers were located 14 feet from the edge of the pavement and spaced 25 feet apart. Nails were driven in the top and side of the stakes to provide precise stationing and elevations.

Because the contractor was permitted to place station markers within ± 6 inches, the construction joint between two instrumented slabs on PCC sections was located first, and subsequent measurements were made from that location. At the appropriate location, a 3/4-inch diameter x 30 inch long steel reference pin was hammered into the ground leaving approximately 18 inches of the pin exposed. From this point, a transit was set up to lay out the middle joint and locate the reference pin on the opposite side of the road. A 90-degree angle was then turned to locate the joint at the end of one slab. In this line of sight, 15 feet was measured from the reference pin and an end joint reference pin was placed. After turning a 180-degree angle on the transit, the reference pin for the end of the other slab was placed using the same procedure. Using a tape measure and measuring off the middle joint reference pin in the passing lane shoulder, the remaining reference pins were located on the opposite side of the road. This reference pin setup was checked and confirmed to have the correct dimensions, and painted with a highly visible paint to avoid being hit or removed by the contractor. String lines were tied to the reference pins to simulate the three transverse joints and define the instrumented PCC slabs.

A string line connecting the nails on top of the survey stakes was used as a reference from which to make measurements. Following the simulated transverse joints, appropriate measurements were taken from the survey stake line to locate the edge of the pavement, both wheelpaths and the center of the slab. At the correct distance along the joint, a plumb bob was used to locate the proper points, which were marked with a nail and highly visible paint. The measuring tape was then extended to 16.5 feet from the wheelpath closest to the edge of the pavement, 20 feet for the center of the slab, and 23.5 feet for the outer wheelpath. At each location, the previously mentioned procedure was used to identify sensor locations. The same measurements and procedures were used along the remaining two transverse joints to mark off the shoulder LVDTs, wheelpaths, and center of slab.

After all nails were placed, a pattern jig was used to locate all LVDT positions. The jig was lightweight and portable, constructed from two pieces of steel 2 inches wide, 7.50 feet long, and 0.25 inch thick. The two pieces were joined lengthwise by a steel plate for a combined length of 15 feet, the exact length of one concrete slab. The pattern was fitted with handles to facilitate positioning and moving, painted to resist corrosion, and precise distances were marked off directly on the jig. These marks correlated to precise locations in both rigid and flexible pavement sections. Different colors were used for each instrumented slab. A green mark referred to slab one and a red mark referred to slab two. The jig saved time and assured that the layout of sensors in every section would be consistent.

Once the LVDT positions were marked, a drill rig was brought in to bore the deep reference holes, as shown in Figure 12.1. The holes were bored with a 3-inch diameter auger bit to a depth of approximately 10.5 feet. To achieve an accurate hole location, two references were measured off and marked from the nail identifying the LVDT location. The auger bit was started in the soil, but before the boring was continued, the references were checked to assure that the hole was being dug in the correct place. After a hole was bored and the measurements were checked to be correct, a reference rod was placed in the hole. The reference rod consisted of a 0.75-inch diameter, 12-foot long steel rod with a 1.50-inch diameter, 1-inch long stainless steel tip welded to the end to provide a smooth, clean surface for the LVDT.

To permanently fix the rod in the hole, a spacer cut from 0.75-inch thick plastic was slid onto the rod and positioned just under the tip. The rod was then dropped into the center of the hole and driven approximately one-foot into the subgrade placing the tip at the proper elevation. A non-shrinking grout was placed in the bottom of the hole using a large funnel and 10-feet of 1.5-inch diameter plastic hose to anchor the rod in place. The grout was poured to a depth of only one-foot leaving 10 feet of the steel rod exposed. After 24 hours, a 10 foot long piece of 2-inch PVC pipe was placed around the rod and spacer assembly, lowered to just below the stainless steel tip, and centered in the hole by filling the gap around the pipe with cement sand.

Figure 12.1 ODOT Drill Rig

Sand was vibrated around the pipe to assure all gaps were filled and proper compaction was achieved. A 3-inch to 2-inch plastic reducer was placed on the end of the PVC pipe. The opening of the reducer was taped off to prevent base material from falling into the pipe during the construction of subsequent pavement layers.

Reference plates for the shallow LVDTs were constructed of one-foot square by one-inch thick steel plate with a 1.50-inch diameter stainless steep tip welded in the middle on one side. The tips were not located at the same elevation in all sections. Tip elevation was determined by the thickness of the concrete and base layers. Because the top surface of the plates rested evenly with the surface of the subgrade, the distance to the top of the pavement varied.

The LVDT was placed in a Single Layer Deflectometer (Figure 12.2) mounted in the concrete. Because of the way the LVDT was mounted, 11-inches placed the LVDT at its

Figure 12.2 Single Layer Deflectometer

approximate zero point, or at least within a workable range for testing. Tips requiring up to 3-inches of elevation were constructed solely from stainless steel. However, when a tip had to be 4-inches or longer, the tip was welded to the top of a 0.75-inch diameter steel rod. Reference plates placed in locations with two base layers had to have the tips tapped and screwed in after the placement of the base layers because the bases were placed in 4-inch lifts. Before the plate was placed in the subgrade, the assembly was painted to resist corrosion. The top of the plate was centered at the correct location in the subgrade and the outline of the plate was marked in the subgrade with paint. The plate was removed leaving a painted square outline. Subgrade material inside the square outline was dug out by hand to a depth of one- inch. A thin layer of concrete sand was placed on the bottom of the cutout to aid in leveling of the plate. The plate was placed in the cutout square and leveled with a bubble level in both longitudinal and transverse directions. Broken up subgrade material, which had been removed from the cutout, was compacted around any loose edges of the plate to secure the plate position. A string line was pulled across the tops of both deep rods and shallow plates in the shoulder or wheelpath to make sure all tips lined up. Any plate or rod that did not line up was subsequently repositioned in its proper location. After the placement of LVDT references was complete, the subgrade was finished and the base layers were placed.

Sections with a stabilized base required one final step before construction could continue. Because of the nature of the treated bases, and the fact they extended under both the pavement and shoulder and were placed at one time, wooden boxes with the outer dimensions of the shoulder pits and the heights of the base layers were positioned and anchored over the shoulder reference locations prior to the placement of the treated base layers.

Base Construction

DGAB layers were placed with dump trucks, graders and rollers. The aggregate was hauled in from the quarry by truck and dumped in front of a grader. The grader spread the aggregate in 3 to 4-inch thick lifts and cut it to the approximate elevation before compaction. A roller compacted the aggregate to the proper density. If the proper elevation was not achieved, high spots were cut with a trimmer and low spots were filled and recompacted.

PATB material was mixed at an asphalt plant in Marion, Ohio, hauled in by truck, and placed with an asphalt paver, as shown in Figure 12.3. The driving lane was paved first, the passing lane shoulder second, and the driving lane last. The material was placed at a depth greater than 4 inches, and compacted by at least two passes of the roller to the proper density and thickness.

Figure 12.3 Asphalt Paver

If the PATB layer rutted under construction loading, filling was permitted by ODOT.

LCB was mixed at the on-site batch plant and placed with a slip form paver (Figure 12.4). Trucks hauled the mix and deposited it in front of the paver.

PCTB was placed in the same manner as the LCB under both asphalt and concrete sections. After the PCC concrete slabs were completed, PCTB was placed in the shoulders with a smaller paver designed for short slab width.

Preparation of the Base

Before any sensors could be installed, the base layer had to be properly graded and compacted. LVDT references and all other sensors were located in the concrete slabs. Shoulder LVDT locations were left alone until the slabs were completed and it came time to place the asphalt shoulders. To begin the sensor location, transverse joints were laid out, and the wheelpaths and center of the slab were located the same as they were on the subgrade.

Figure 12.4 Slip Form Paver

The same jig was used to locate all gauges. Sensor positions were marked with a painted cross (Figure 12.5) to aid in the proper placement of the gauges. LVDT locations were marked with paint because the reference rods and plates had to be uncovered. In DGAB material, a hole was dug at the paint mark with a pick and cleaned with a vacuum cleaner. The top of the rod or plate was located first to limit the size of the hole to approximately 4 inches in diameter.

Figure 12.5 Painted Sensor Locations

In PATB material, a hole was dug with a hammer and chisel. The tip of the rod or plate was again located first, and the hole was cut approximately 4 inches in diameter and cleaned with a vacuum cleaner. In LCB and PCTB material, the hole had to be cored around the tip. Precise measuring became very important because the 4 inch core bit had to be placed as close to the center as possible during the drilling process. Ideally, a hole was cored leaving the tip of the rod or plate in the center of the hole. When this was not achieved, the hole was shaved to center the tip. Because water was used to lubricate and cool the bit as it cut into the LCB or PCTB, the hole was cleaned with a wet-dry vacuum. Once the base layers were properly prepared, installation of the sensors could begin.

PCC Sensor Installation

Sensors for measuring pavement strain made up the largest group of sensors. The group was comprised of Dynatest PAST-II, TML KM-100B, TML PMR 60, Carlson A-8, Geokon VWSG, and a few Micro-Measurements EGP-5-120 strain gauges. All strain gauges in PCC sections were held in position with a specially designed stand unit. Except in the case of the TML PMR 60 rosette, which required only one stand, two stands made up a unit. These stands were constructed of 0.25-inch diameter cold rolled steel. Each type of strain gauge had its own special stand, which placed the gauge at its proper depth in the concrete. The two stands in the unit were independent of one another to give the gauges freedom of motion to respond in concert with the PCC layer whenever strains were induced, as shown in Figure 12.6. The Maiden and Jenkins Construction Company of Nelsonville, Ohio manufactured the stands.

Before a strain gauge could be affixed to the unit, the stands had to be set in their proper positions and anchored to the base. Except for the TML PMR-60 rosette stand, all stands were

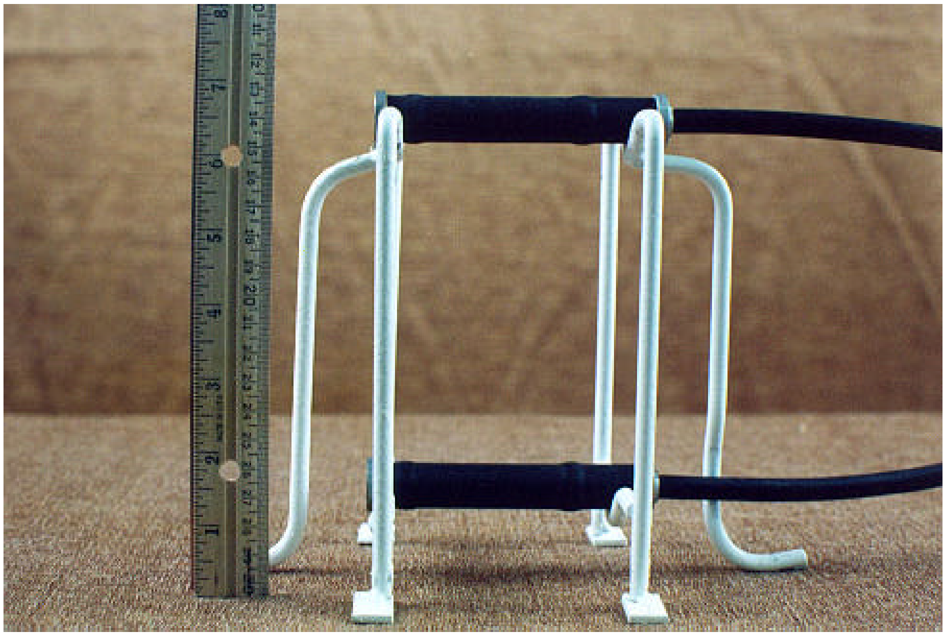

Figure 12.6 Stands to Hold Strain Gauges

oriented such that the strain gauges would lie longitudinally in the roadway (Figure 12.7).

Figure 12.7 Gauge Orientation

In DGAB and PATB, a 6 inch long, 0.25-inch diameter steel spike was hammered into the base and hooked onto the stand. In LCB and PCTB, a non-shrinking, fast setting grout was poured over the feet of the stands. The gauge anchors were secured to the stands with plastic cable ties at the middle around the strain gauge portion of the sensors (Figure 12.8). Special care was taken to assure that the strain gauge rested on the stands and that it was not being stressed in any way.

TML KM-100B strain transducers were placed one-inch from both the top and bottom of the PCC layer in the center lane of the second slab. The two transducers per location were identified by another color scheme with red being the top transducer and blue the bottom transducer. Stands designed for the KM-100B had a half-circular bend designed to cradle the transducers.

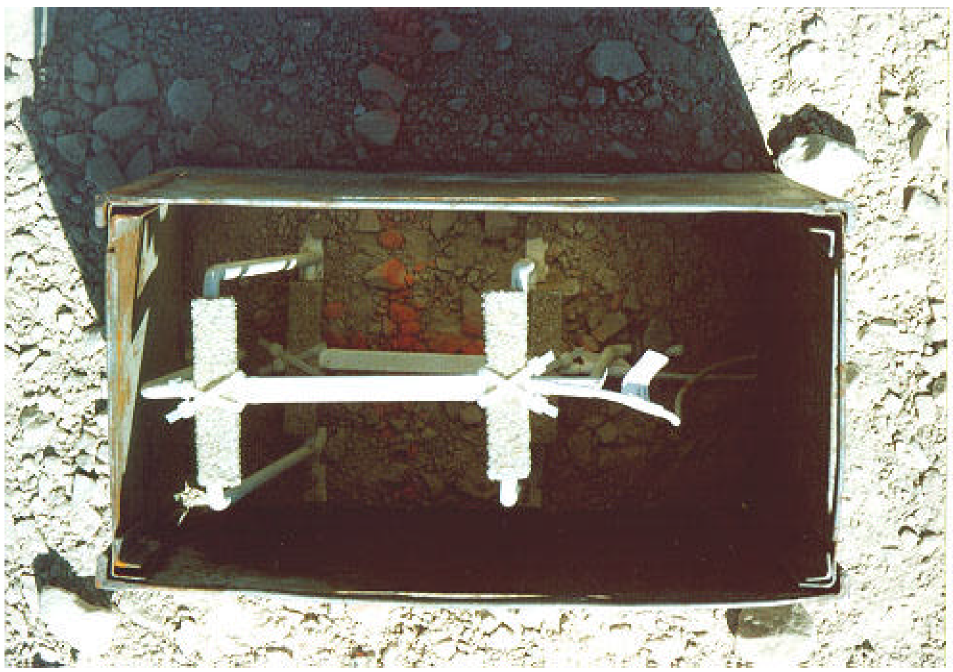

Figure 12.8 Dynatest Strain Gauge Setup for PCC Pavement

Transducers were placed in the stands so the ends extended approximately 0.75-inch past the support and the lead wire would be pushed toward the transducer by the paver. This permitted the ends of the transducers to be completely embedded in the concrete. The transducers were affixed to the stands with plastic cable ties in a criss-cross pattern (Figure 12.9).

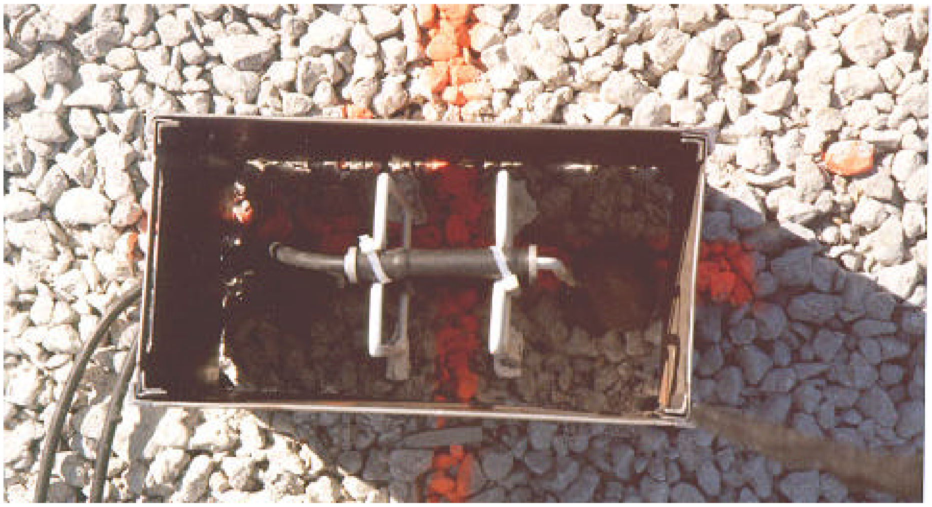

Figure 12.9 KM-100B Setup

Two TML PMR-60 three axis rosettes were held in position with one stand. The rosettes were not labeled by color. Rather, they were labeled as top and bottom. The top gauge sat one inch from the surface of the concrete, and the bottom gauge rested an inch above the base of the concrete, 18 inches away from the driving shoulder and the third transverse joint. The stand had three fingers spaced 45 degrees apart, which supported the three strain gauges of the rosette. The stand was oriented such that the lead wire of the rosette would be pushed toward the gauge by the paver. The gauges were affixed to the stand with a plastic cable tie (Figure 12.10).

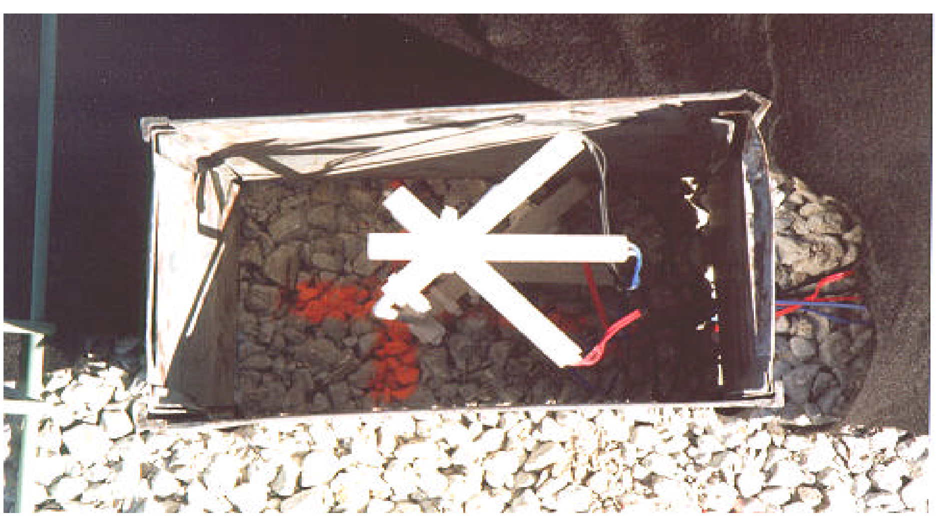

Figure 12.10 PMR-60 Rosette Setup

One Carlson A-8 strain meter was used per location. With only one gauge per pair of stands, no color scheme was needed, rather the gauges in each slab were labeled 1 and 2. The gauge was placed at mid height in the PCC layer and in the center lane of the first slab. The stands used a half-circular notch to support the gauge. The stands were located such that approximately one-inch of the gauge would extend over each stand. This allowed for the ends of the gauge to be securely embedded in the concrete. The Carlson gauges were placed on the stand so the lead wire would be pushed in the direction of the gauge by the paver. Plastic cable ties were used to secure the gauges to the stands (Figure 12.11).

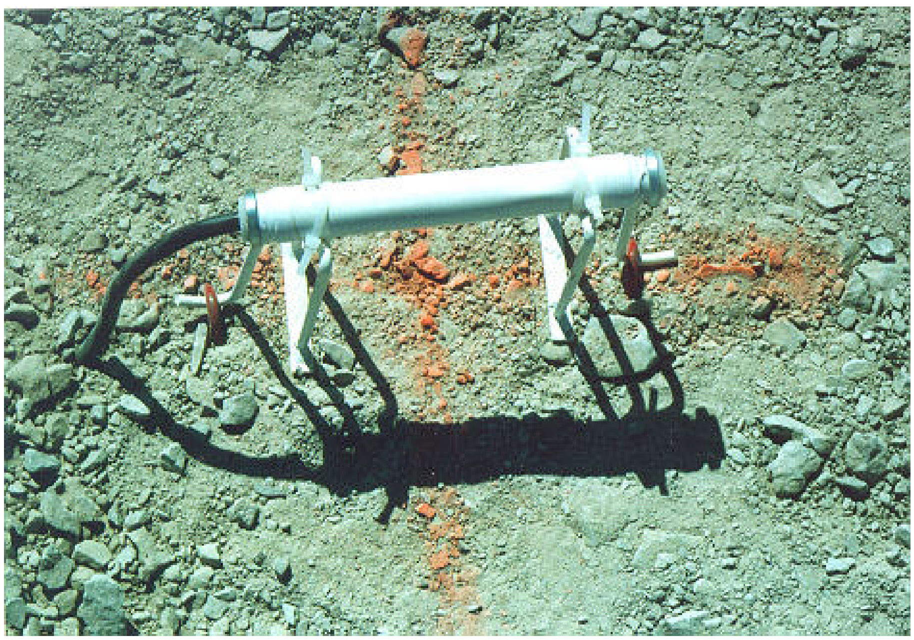

Figure 12.11 Carlson A-8 Strain Meter Setup

Geokon Vibrating Wire Strain Gauges (VWSG) were placed one-inch from the top and bottom of the concrete in the inside wheelpath of the first concrete slab. The VWSG positions mirrored the locations of the Dynatest gauges in the second slab. With two VWSG being used per location, red identified the top gauge and white identified the bottom gauge. The stands supporting the VWSG had a small notch, which seated the center of the steel anchor at its proper elevation. The anchor rested on the stands with approximately 0.75-inch of overhang past the stands to permit proper bonding to the concrete. The steel anchor was secured to the stands with plastic cable ties (Figure 12.12). The electromagnetic coil was then secured onto the steel anchor with a steel clamp in such a way that the lead wire was pushed in the direction of the coil by the paver. Care was also taken to assure that the coil was affixed in such a way to allow overall maximum coverage of the VWSG gauge.

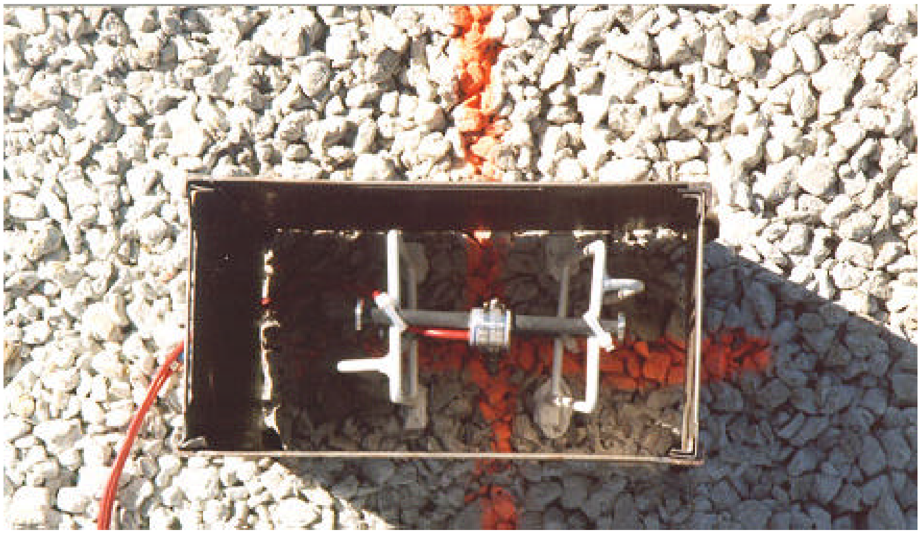

Figure 12.12 Geokon VWSG Setup

Micro-Measurements EGP 5-120 embedment strain gauges were only specified in certain sections where a third slab was utilized. The EGP 5-120 gauges were placed in the driving lane, 1 inch from the top and the bottom of the PCC layer in the outside wheelpath. Gauge locations in the third slab were exactly the same as the Dynatest gauge locations in the second slab. With two gauges per location, red identified the top gauge and blue identified the bottom gauge. The stands designed to support the EGP 5-120 gauges utilized a flat surface for the gauge to rest on and plastic cable ties secured the gauge to the stands (Figure 12.13). The gauges were oriented so the lead wire was pushed in the direction of the gauge by the paver.

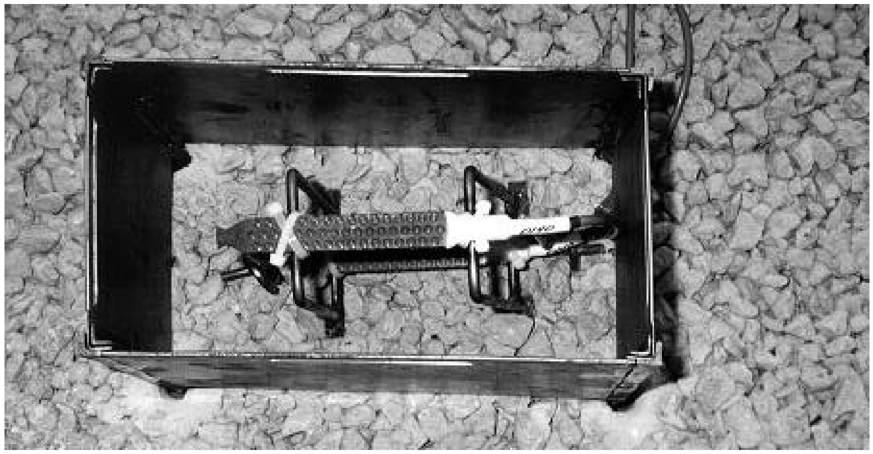

Figure 12.13 Micro Measurement EGP-5-120 Gauge Setup

From previous projects, it is known that forces exerted during paving were sufficient to move the sensors. Two basic methods were used to prevent sensor displacement. LVDTs, Carlson gauges, pressure cells, thermocouples and thermistors, were protected by piling green concrete around them when the spreader was approximately two slabs away from the instrumented section. An amount of concrete from a cement truck was dumped in front of the paver in one of the passing lane slabs. The concrete was shoveled by hand to the instrument location, gently piled around the instrument, and vibrated with a portable vibrator to assure consolidation. This process was continued until the instrument was completely covered with concrete.

Dynatest gauges, KM-100B gauges, VWSGs and PMR-60 rosettes required a greater degree of protection. Ohio University designed a special box constructed of sheet metal and 0.50 inch angle iron. Each box was 1-foot long, 6 inches wide, and either 7.5 inches or 10.5 inches high, depending upon the thickness of the PCC layer. The angle iron corners acted as anchors into the base and support for the sheet metal sides.

The box was designed to be rigid during the paving process, yet come apart for removal. A box was placed around sensors at each location prior to paving and set so the top was slightly below the elevation of the pavement surface. Anchoring the boxes to the base materials proved to be an awkward task. It was facilitated with the use of a hammer drill, a 0.50-inch drill bit, and a pattern that identified anchor positions. Holes were drilled 4-inches deep into the base material and the anchors of the box were set directly into them. The narrowness of the hole provided a sufficient amount of friction to hold the box in place during paving, and still, the degree of friction was small enough to allow for relatively easy removal of the boxes after paving. Just before the spreader reached the instrumented slabs, green concrete was placed in all the boxes by hand to prevent any damage that might have occurred to the gauges from the weight of the concrete being dropped or shoved against them. The concrete was vibrated to assure consolidation. This process continued until the vibrated concrete filled the box. Once this was done, excess concrete was shoveled on top and around the sides of the box for added protection. After these steps were completed, at all sensor locations, the instrumented section was ready for paving.

After passage of the spreader and paver, but before final finishing and texturing of the PCC, the boxes were removed one side at a time and the integrity of the gauges was checked. To complete this task, a 32-foot aluminum platform resting on wooden horses was used to span the freshly paved concrete lanes and provide researchers with direct access to each instrument location (Figure 12.14). Due to the relatively close proximity of the top of the boxes to the surface of the concrete, they could be easily located for removal.

Figure 12.14 Pulling Protective Boxes

Using a pair of channel lock pliers to grasp the top of the walls of the box, the 6-inch ends were removed first, followed by the one-foot long sides. The location of the top gauge was then verified to be in the proper position by gently removing a small amount of the concrete directly over it. If the position of the gauge was incorrect, the portable vibrator was used to liquefy the concrete in the immediate area surrounding the gauge while the position was corrected by hand. Any gauge damaged during the paving operation was replaced at this time.

Researchers monitored the gauges continuously during the paving process. Once the gauge was in proper position, it was covered with concrete. The area was vibrated thoroughly to assure proper consolidation and the surface was smoothed with a trowel. After all boxes were removed and all the sensor locations were verified, the instrumented sections were returned to contractor personnel for finishing and texturing.

Personnel from the Hi-Way Paving Company were extremely cooperative during this operation. While any delays resulting from sensor placement was minimal, their assistance made it go smoothly. They helped place concrete around the sensors ahead of the spreader, took care not to step on the sensors, and provided necessary labor and tools to get the job done. This type of cooperation is essential if a project of this magnitude is to be successful.

Pressure Cells

The Geokon Model 3500 earth pressure cell was used to measure pressure. Ohio University personnel installed the pressure cells in SPS-8; however, pressure cell installation in the other SPS sections fell under the responsibility of the University of Akron. For SPS-8, two pressure cells were calibrated in the Ohio University lab. The cells were set in concrete with a face of the pressure cell flush with the surface of the concrete. The pressure cell/concrete structures were placed in pre-dug holes with the exact dimensions of the concrete block. The exposed pressure cell surface faced down in both wheelpaths of the second slab (Figure 12.15). Sand was used to level the pressure cell, and

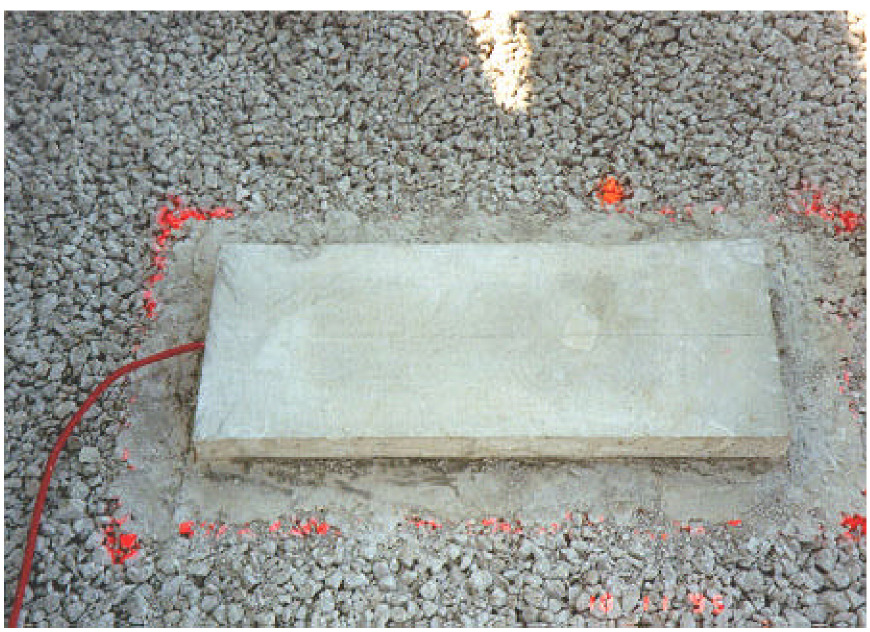

Figure 12.15 Geokon Model 3500 Pressure Cell Setup

loose aggregate was compacted around the edges of the concrete block to hold it in place. In SPS-2 sections, pressure cells were placed in both wheelpaths of the first slab, and in SPS-1 sections, two pressure cells were placed in the right wheelpath.

Temperature Sensors

Temperature on SPS-2 sections was measured with thermocouples sticks tied to the dowel bar baskets. Individual sensors were located in the right wheelpath at different elevations to measure slab gradients. Additional sensors were located in the center of the slab. To properly position these sensors, a 0.25-inch diameter round spike, approximately 15-inches long, was driven into the base material. The sensors were then tied to the spike with plastic cable ties.

In SPS-1 sections, single thermocouples were placed at the top and bottom of AC or base lift.

AC Sensor Installation

The positioning of Dynatest gauges and thermocouples in ATB and AC layers follows the same procedures. Therefore, the method of installation described below for Dynatest gauges was also used for the thermocouples.

As asphalt mixtures were placed, Dynatest gauges and thermocouples were prepared for the section being paved and situated in their correct locations. The three green labeled Dynatest gauges were placed longitudinally along the wheelpath. As the asphalt paver approached, exact locations of each Dynatest gauge were staked out and marked with fluorescent paint. Asphalt concrete was taken from the paver and sieved through 0.25-inch mesh hardware cloth into a wheelbarrow to remove large aggregate, which might damage the gauge during rolling. This sieved material was taken to the paint marks and laid 1-inch thick on the base. Next, the Dynatest gauges were situated atop the sieved asphalt layer exactly over the paint marks (Figure 12.16).

Figure 12.16 Sensor Placement in AC Pavement Sections

Each gauge was positioned horizontally with its cable pointing toward the paver and rollers. Additional sieved AC was placed over the gauge and compacted lightly to maintain postion.

The four-inch thick AC layer was placed in two lifts - the bottom lift was 2.25 inches thick, and the top lift was 1.75 inches thick. Before the bottom lift was in place, preparation was necessary for instrumentation installation.

The locations of blue and yellow Dynatest gauges were painted on the base surface. As the paver approached the section, each Dynatest gauge and thermocouple (when applicable) was installed using the same procedure as for ATB bases. The thermocouple was situated between Dynatest gauges 3 and 4 and between the centerline and wheelpath. All cables were maneuvered around the instruments, brought straight out to the edge of the pavement, and taped down to the surface. This distributed all cables out and avoided leaving too many wires in one area creating weak spots in the asphalt. The gauges were checked for correct resistance values with a voltmeter before, during, and after the paving operation. The thermocouples were also checked with the hand-held readout unit after pavement placement.

The top-lift Dynatest gauges and thermocouples (when applicable) were installed similar to the bottom lift, but because the lift thickness and gauge location were different, a slightly different procedure was used. The red Dynatest gauges and the thermocouple were situated atop 0.75-inch of sieved asphalt rather than a full inch. This situated the gauge one-inch from the pavement surface.

Seven-inch thick AC layers were placed in three lifts. The bottom lift was 3-inches thick, the middle lift was 2.25-inches thick, and the top lift was 1.75-inches thick. The only difference in instrumentation installation from the 4-inch thick pavement was placement of the middle lift. Orange Dynatest gauges and thermocouples (when applicable) were situated atop a half-inch thickness of sieved asphalt concrete. This established the orange gauges at the middle of the AC pavement layer. All other procedures for Dynatest gauge and thermocouple installation were the same.

After the asphalt concrete had been placed, the cables were routed to the pull boxes, the wires were covered with sieved asphalt concrete, and the data acquisition connectors were fixed to the cable ends. The cables were then buried to a sufficient depth in trenches to the pull boxes. The trench was dug deep enough near the pull box to fit all cables through a hole created with a hammer drill in the pull box wall. Soil was replaced overtop the cables in the trench and tampered.

After this was accomplished, cables exiting the pavement shoulder were then covered with asphalt concrete. This helped protect the wires from stray vehicles running off the pavement. All cables were organized and fitted with connectors for easier hook-up to data acquisition systems. These connectors were constructed by first tipping each wire with gold plated pins using an air-compressed crimping machine. The pins were pushed into a male DB37 connector in a set configuration. The female end was configured in the same manner and linked to a data acquisition system. This use of connectors saved time while hooking up gauges to the data acquisition systems.

Also, connectors insure a more solid signal junction.

Shoulder Work

The shoulders in the DEL-23-17.48 project were all asphalt concrete (AC). The shoulders for all PCC sections were placed after the PCC had cured. The passing lane shoulder was 4 feet wide and the driving lane shoulder was 10 feet wide.

Protection was needed for the lead wires from the hot AC mix and from forces generated while placing and compacting the AC layers. In sections paved directly on DGAB or PATB, shallow trenches were dug. The wires were placed in these trenches and covered up with loose aggregate. The entire area was then compacted to assure that the integrity of the base under the shoulder was intact. Instrumented sections placed on LCB or PCTB utilized a shallow trench and a length of PVC pipe. The wires were either strung through a 1-inch diameter, 10-foot long PVC pipe or placed under a 2-inch diameter, 10-foot long piece of PVC pipe which had been sawed in half lengthwise. The covered wires were placed in shallow trenches and taped to the surface of the base with duct tape to secure their position. Once the wires were out of the shoulder, they were placed in a deeper trench. This trench was cut from the existing locations of the wires in the shoulder directly to the pull box where the wires were then stored. Burying the wires provided protection from damage during future grading operations.

The shoulder LVDTs in instrumented SPS-2 sections were of concern during the paving of the AC shoulders. Researchers were faced with the problem of providing a square or rectangle hole at the edge of the pavement to house the shoulder LVDT boxes. A circular saw could not be used to cut the hole after the shoulder was paved because the blade would cut into the PCC or tear up the base while cutting the edges of the hole. The shoulder box itself could not be installed because the shoulder was placed in three lifts. It was decided that wooden boxes having the outside dimensions of the pit with the heights of the individual lifts would be used. To install the wooden boxes, the shoulder LVDT reference rods and plates were uncovered. The box was butted against the edge of the pavement and covered the reference tip of the plate or rod. The box was then anchored to the base layer with 50-penny nails. After the box was anchored, one or two holes, depending on the type of pit, were drilled through the back edge of the box. Lead wires were strung through these holes for connection to the LVDTs at a later date. After each lift was placed, the boxes were uncovered and another box with the height of the next lift was nailed to the top of the box on the bottom. Due to the thickness of the final lift, 0.25-inch particleboard cutouts were nailed to the top of the existing structure to the surface of the PCC. Once the entire shoulder was completed, the wood pieces and anchors were removed leaving a square or rectangular hole for the shoulder boxes to slide into.

LVDT Installation

Prior to testing a section, the LVDTs had to be installed in both the slabs and the shoulder. Working on the concrete slabs required considerable care so as not to damage the surface. The shoulder work required installing the shoulder boxes as well as the LVDTs.

Installing the LVDTs in the concrete slabs first required locating the positions of the Single Layer Deflectometers (SLDs) buried in the concrete. To obtain a close approximation of the locations, measurements were taken from the edge of the pavement along the transverse joints. At the appropriate distances, the wheelpaths and center of the slabs were marked. The jig used to lay out the instruments was again used to mark the SLD positions. To uncover the SLD, a drill with a 0.50-inch drill bit was used to locate the brass cap of the SLD. Once the brass cap was located, the rest of the cap was uncovered by carefully chipping away the concrete covering the cap. Care was taken to provide a hole directly over the SLD, which would not have a greater diameter than the brass cap itself. After the cap was uncovered, it was removed to allow installation of the LVDT. Lead wires from the LVDT were soldered to the wire extending out of the SLD. The soldered connections were protected individually with heat shrink and the entire connection was also protected with heat shrink. The LVDT was then installed in the SLD as close to the zero position as possible.

To prevent chipping away the PCC surface around the SLD, individual brass caps were specially constructed for each individual SLD. Each specially designed cap enabled the top of the SLD to be flush with the PCC surface.

Installing the shoulder pits and LVDTs required a greater degree of effort. Installing the shoulder pit had to be completed before the LVDTs could be installed. Each pit was placed in its hole left by the wooden box. For the pit to sit properly, the front edge had to rest flush against the edge of the pavement, the reference tip of the rod or plate had to be correctly surrounded, and the top of the pit had to rest as close to flush with the surface of the shoulder as possible. After the proper position was determined, the pit had to be epoxied to the shoulder. First, an amount of sand was placed around the outside of the pit in part to wedge the pit in position and in part to prevent epoxy from seeping under the pit and filling up the inside of the pit. Epoxy was then poured around the pit up to the surface and allowed to set. Once the pits were set in place, the LVDTs were installed. They were soldered and protected using the same procedures used in the concrete slabs. The LVDTs were mounted to brackets, which were securely anchored to the edge of the PCC. The LVDTs were set as close to the zero position as possible and the pit was closed.

Instrumentation Coordinate System

An instrumentation coordinate system for each section was constructed to reference each gauge in an organized and simple manner. An LVDT cap was a good origin to begin from because it was exposed and easy to locate. The x-axis runs longitudinally along the wheelpath, the y-axis runs perpendicular to the x-axis and laterally across the road surface, and the z-axis runs vertically into the ground. The northern-most reference rod LVDT cap was selected as the origin, and anything north of that cap was given a negative x value. Locations toward the center of the road were considered positive y value, and locations in the pavement structure were negative z values. LVDT coordinates were selected at their reference location (i.e., deep reference rods are at -10' along the z-axis). In special cases, due to construction needs minor adjustments were made in the field to sensor locations. This data will be available in the Ohio database with sensor response data.

CHAPTER 13

DATA ACQUISITION

Data acquisition systems play an integral role in the level of success of any instrumentation experiment. This chapter describes the data acquisition systems used on the Ohio SHRP Test Pavement.

Dataloggers

Two types of dataloggers manufactured by Campbell Scientific Inc., of Logan, Utah, controlled the data acquisition systems used for seasonal monitoring and environmental factors monitoring in this study. The operation and capabilities of these systems are very similar. They are both fully programmable dataloggers/controllers, capable of collecting and storing data over extended periods of time. A data acquisition system consists of a datalogger and additional equipment needed to collect data. Each component of the system is described in this section.

CR7 dataloggers were used to collect data from KM100B strain transducers, Carlson strain meters, LVDTs and thermocouples. The CR7 consists of a control module, an I/O module, integral keyboard and display, and a battery, all enclosed in a rugged fiberglass case.

Control module capabilities include real-time task initiation, measurement processing, data storage, and keyboard/display interaction. An I/O module handles all analog and pulse signal measurements, as well as analog and digital control output functions. The I/O module contains its own processor card, a 16-bit analog interface card, and seven card slots for any combination of I/O cards. For these tests, the following cards were used: 723 analog input card, 723-T analog input card with RTD, and 725 excitation card. Sensor leads are connected to I/O cards at screw terminals.

Figure 13.1 illustrates the setup of a CR7 system. A laptop computer equipped with Campbell Scientific, Inc., PC 208 software is used to communicate with CR7 through an SC32A interface device. AM416 relay multiplexers from Campbell Scientific Inc., enable the CR7 to read strain and temperature from up to 16 KM100B strain transducers, vertical deflection from up to 32 LVDTs and strain from up to 16 Carlson strain meters. The setup also includes a $\pm$ 15 volt direct current power supply to provide excitation for LVDTs. This is necessary because the CR7 is only capable of delivering $\pm$ 5 volts excitation. A set of three 350 Ω precision resistors complete the full bridge for KM100B temperature measurement. Precision resistors also form a voltage dividing circuit to reduce the $\pm$ 10 volt DC output reading from the LVDTs to within $\pm$ 2.5 volt range of the CR7 and complete the full bridge Carlson strain meter circuit. The multiplexers, power supply, and bridge completion circuits are enclosed in an environmentally sealed box.

The CR10 system setup is illustrated in Figure 13.2. A personal computer with PC208 software is used for two-way communication with the datalogger. An SC32A interface device links the computer to the CR10. A multiplexer enables the CR10 to read from as many as sixteen vibrating wire strain gauges. An AVW vibrating wire interface connects the CR10 to the strain gauges. The constant 12V power required by the datalogger is provided by an external DC power supply. All components of this system are mounted in an environmental box to guarantee a moisture free atmosphere during operation. Components of the CR7 and CR10 data acquisition systems are discussed below.

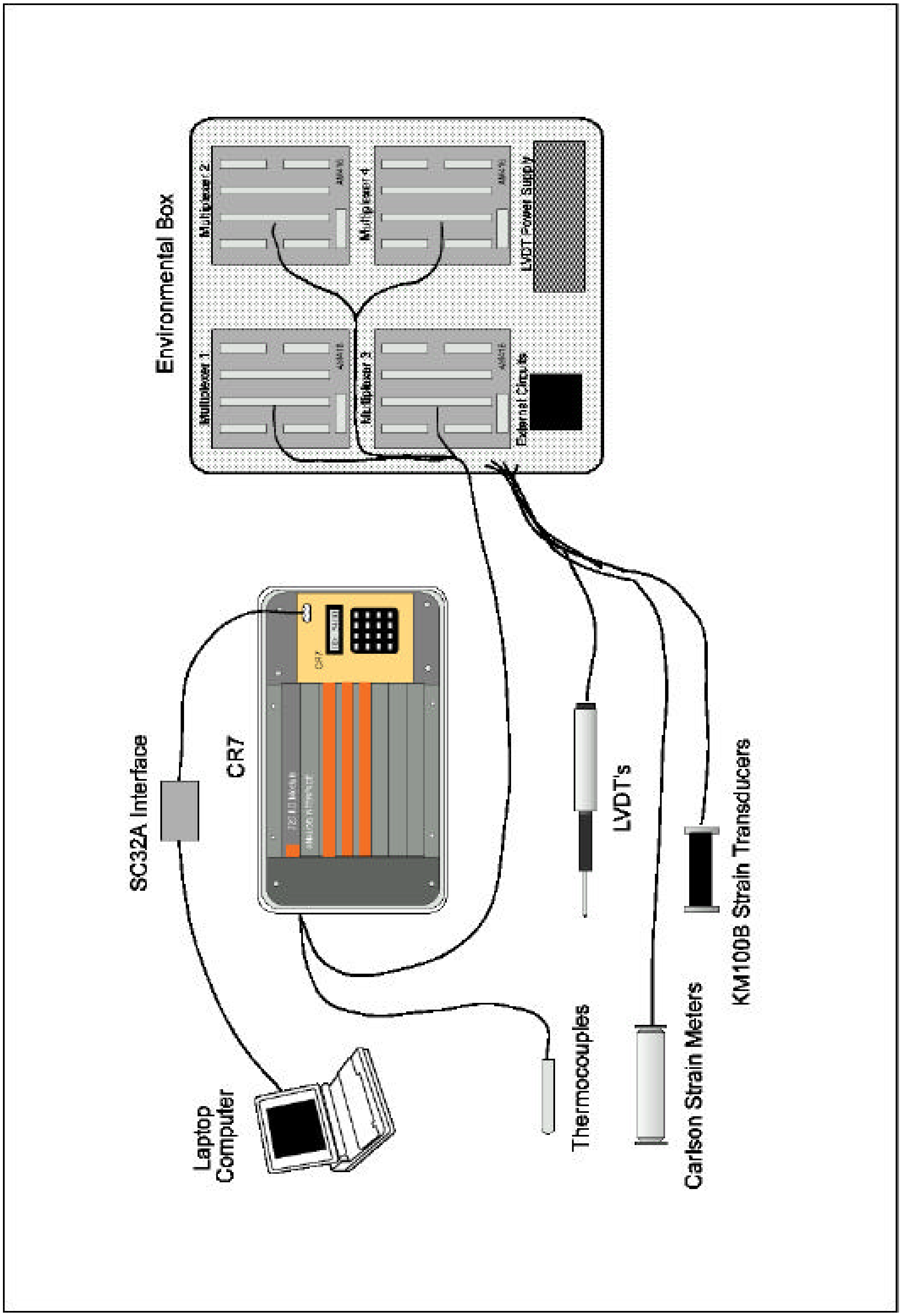

Figure 13.1 CR7 Data Acquisition System

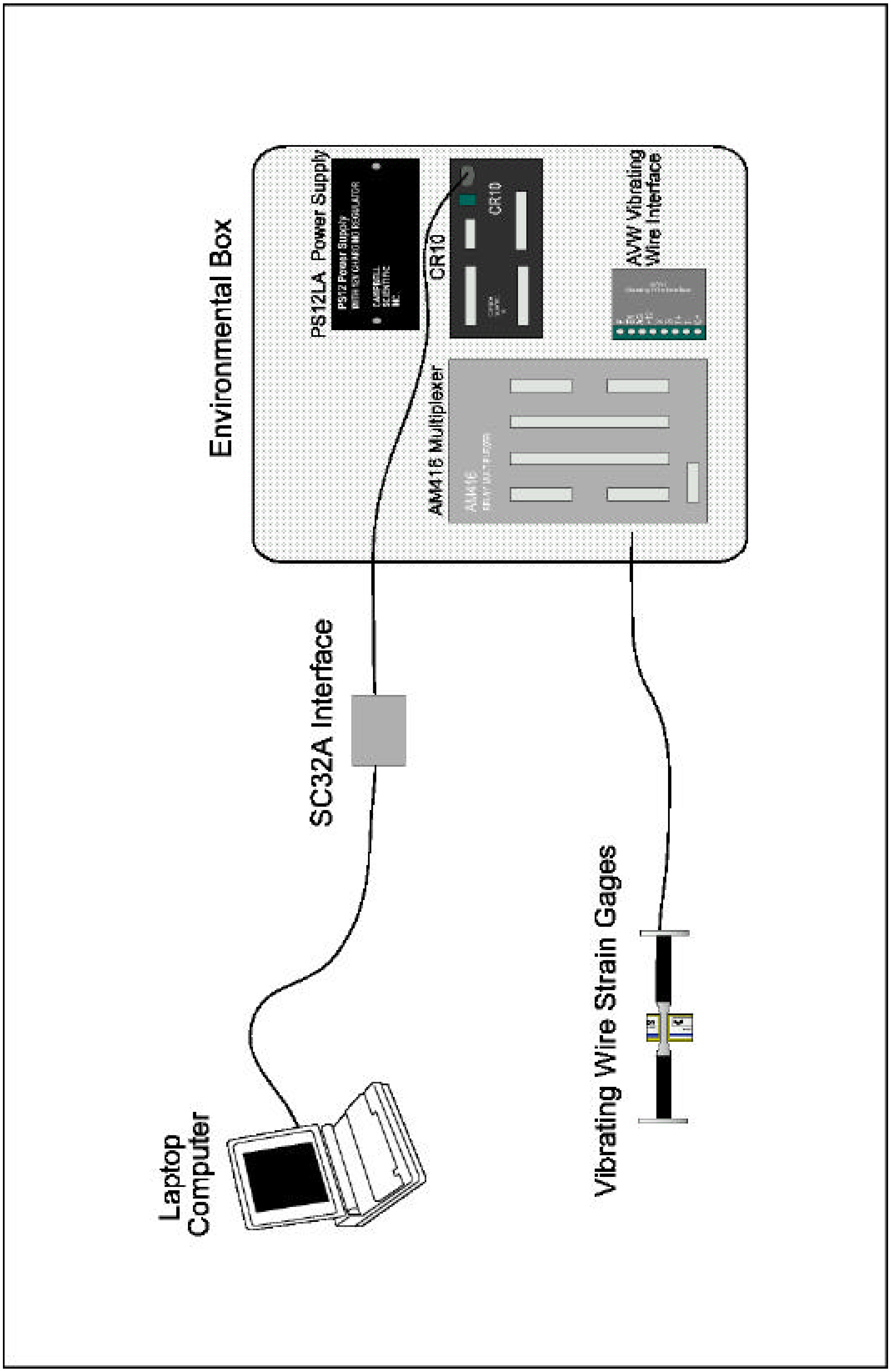

Figure 13.2 CR10 Data Acquisition System

Data Acquisition Components

The PS121LA power supply regulates 12 VDC power to the CR10 and serves as a backup power source if AC power is interrupted. It includes a 12-Volt, 7.0 amp-hour lead acid battery, and AC transformer, and a temperature compensated charging circuit with a charge indicating diode.

Multiplexers must be used on this project for two reasons. First, the large number of sensors in each section is more than the number of channels available on the dataloggers. AM416s allows several sensors to be monitored by one CR7 or CR10 channel. Multiplexers also allow one bridge completion or voltage dividing circuit to be used for several sensors, reducing the number of precision resistors needed and the time required assembling the circuits.

The multiplexer is positioned between the datalogger and the sensor. Mechanical relays inside the multiplexer switch the desired sensor signals to the datalogger. The AM416 is divided into sixteen sets or channels, each consisting of four lines (this is where the name A(nalog) M(ultiplexer) 4(lines) x 16(channels) originates). When signaled by the datalogger, the multiplexer switches from one channel to the next. A total of 64 lines may be multiplexed. These lines may include up to 32 differential sensors that do not require excitation from the datalogger (LVDTs and thermocouples) or 16 differential sensors that require excitation (full bridge circuits and vibrating wire sensors).

The AVW vibrating wire interface is used in combination with the CR10 to read vibrating wire strain gauges. This instrument provides the following signal conditioning functions:

1. Completion of thermistor bridge for temperature measurements.
2. Convert the swept frequency excitation from 2.5 volts peak to 12 volts peak.
3. Provide transformer isolation and consequent noise reduction for vibrating wire signal.
4. Provide additional transient protection for temperature and strain measurements.

The SC32A interface device allows two-way communication between a computer and

Campbell Scientific datalogger. The interface is plugged into the communication port of a computer. The other end of the interface is plugged into the nine pin serial I/O port on the datalogger. This device enables programs to be written, edited, and stored on the computer and then downloaded to the datalogger.

The DC LVDTs used in this project require + 15 and - 15 volt excitation. Since the CR7 can deliver a maximum excitation of 5 volts, an external power supply was required. The power supply used on this project was the Sola Model SLD13-3030-15 that required 120VAC power. LVDTs were wired directly to the power supply.

PC208 software by Campbell Scientific, Inc., was used in two applications on this project. First, the AEdlog@ function provided a quick and convenient way of developing and modifying programs. Programs included information on gauge types being monitored, data collection interval, and some simple data manipulation functions. The second application involved the AGraph Term@ function, which aids in communication with the datalogger. This function allowed programs to be downloaded to the system and data to be collected from the system quickly and easily. It was also useful for troubleshooting if a problem develops in the datalogger.

Data Acquisition Circuits

The components discussed previously all work together to collect data from the sensors. This section describes how the components were connected to form systems and how the sensor leads were connected to these systems.

The KM100B strain transducer has the ability to measure both strain and temperature using electric strain gauges. These measurements require two multiplexers (one for strain and one for temperature) and three external precision resistors, as shown in Figure 13.3. The CR7 first reads strain by taking a four-wire full bridge measurement from each KM100B wired to multiplexer one. The datalogger then measures temperature by taking a full bridge measurement from each KM100B on multiplexer two using the external completion circuit.

The LVDT data acquisition circuit is shown in Figure 13.4. Two LVDTs were connected to each channel on the multiplexer because an external power supply was used. Two sets of external precision resistors were used to divide the LVDT output voltage by a factor of four so that it could be measured by the CR7 (CR7 input voltage cannot exceed 2.5V). When reading LVDT output voltages, the CR7 takes differential voltage measurement between the H1 and L12 ports, followed by the H2 and L2 ports of each channel on the multiplexer. One set of voltage dividing resistors is needed for each of these measurements.

The Carlson strain meter cannot be directly connected to the CR7 due to the nature of the sensor. Again, an external circuit is needed to allow the datalogger to take strain readings. Using the circuit shown in Figure 13.5, the CR7 was able to read the sensor as a six-wire full bridge.

Thermocouple Data Acquisition Circuit

A multiplexer is not required for reading thermocouples in a typical section since there are a maximum of six thermocouples per section. The leads of these thermocouples were wired directly into the 723-T analog input card. This card was equipped with a platinum resistance thermistor (PRT). The CR7 takes differential voltage measurements from the thermocouples and calculates temperature using the PRT as a reference.

A multiplexer is required to read the additional thermocouples on section S5 SPS-2. In this

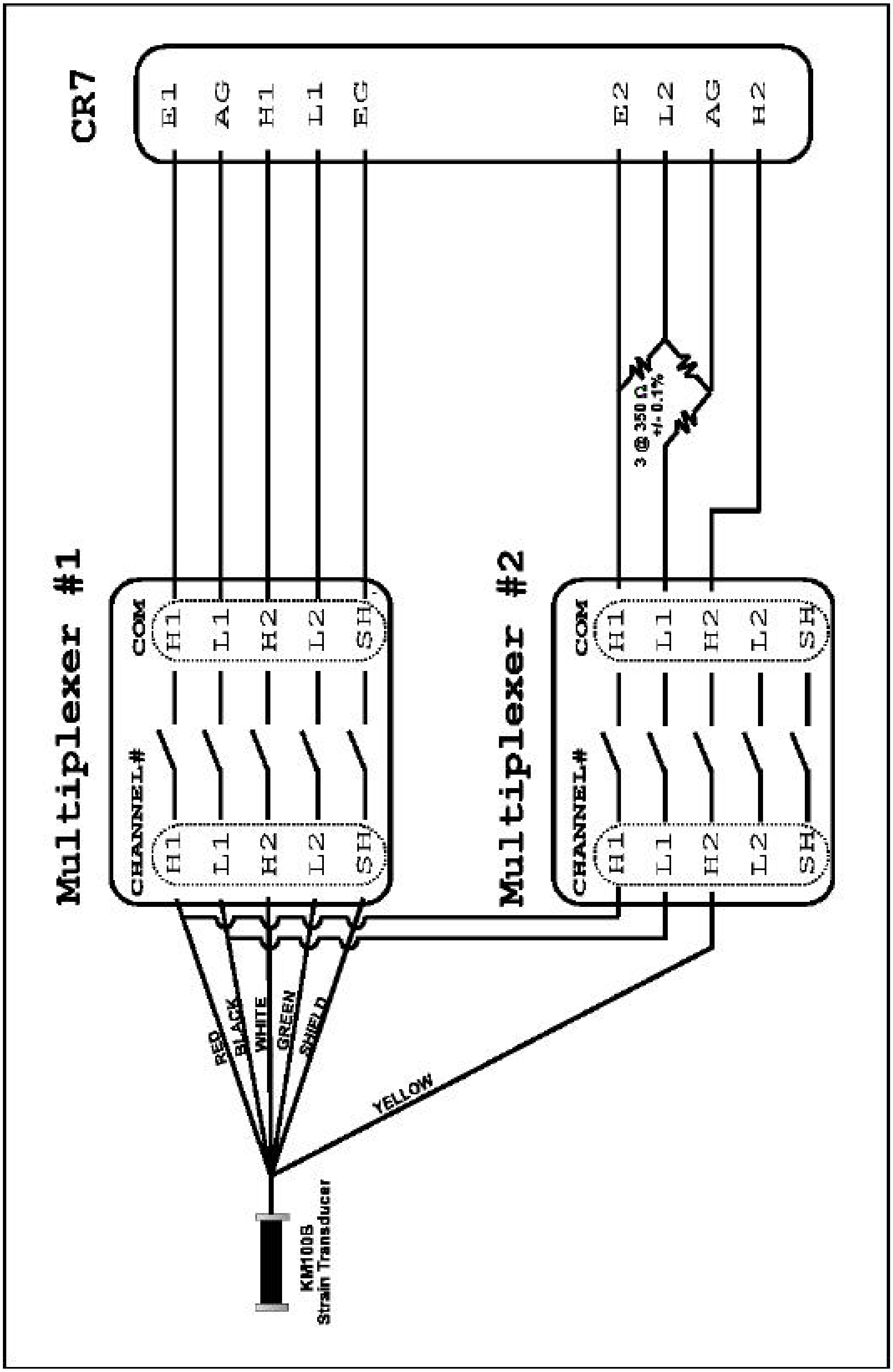

Figure 13.3 KM100B Data Acquisition Circuit

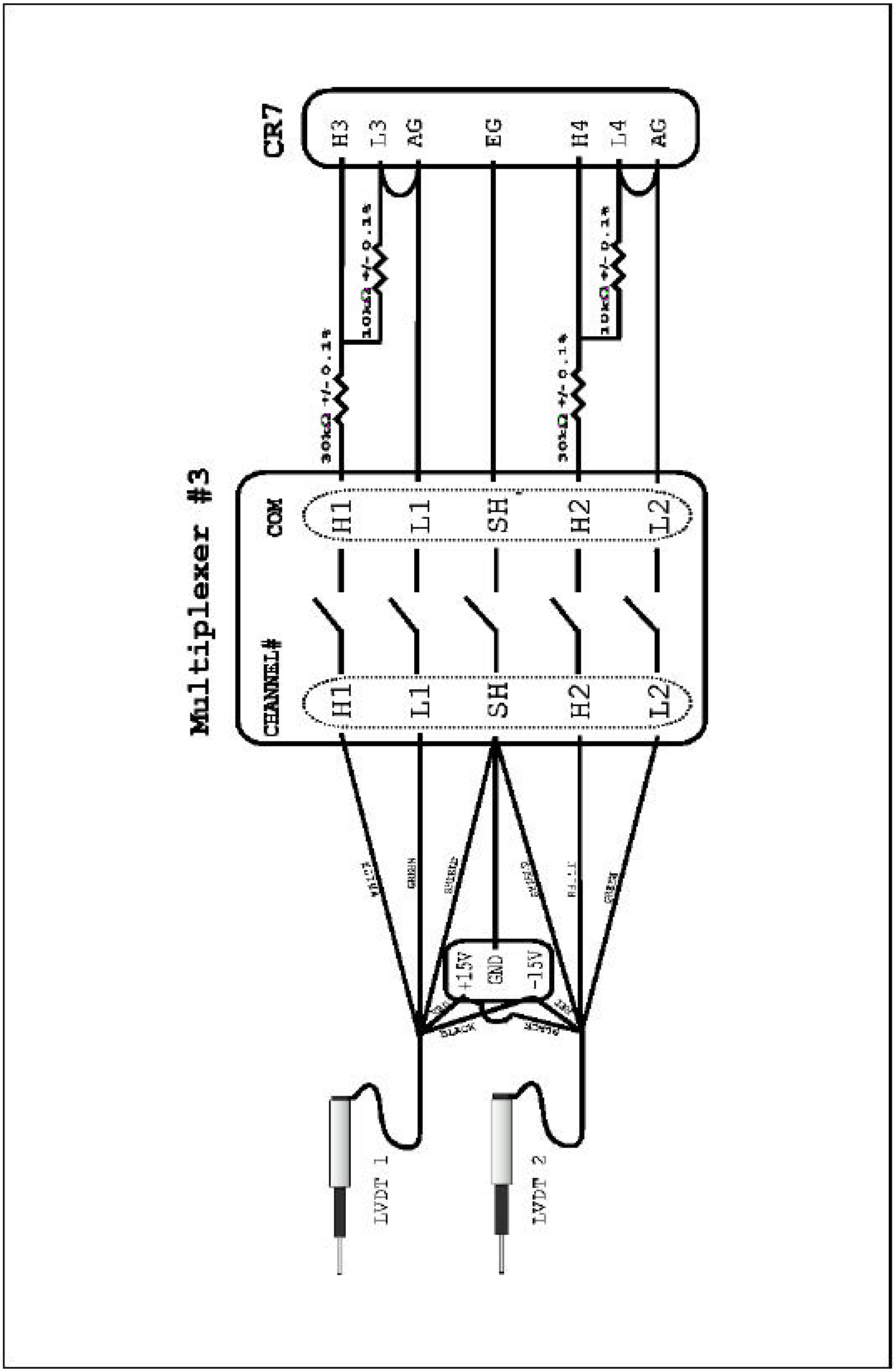

Figure 13.4 LVDT Data Acquisition Circuit

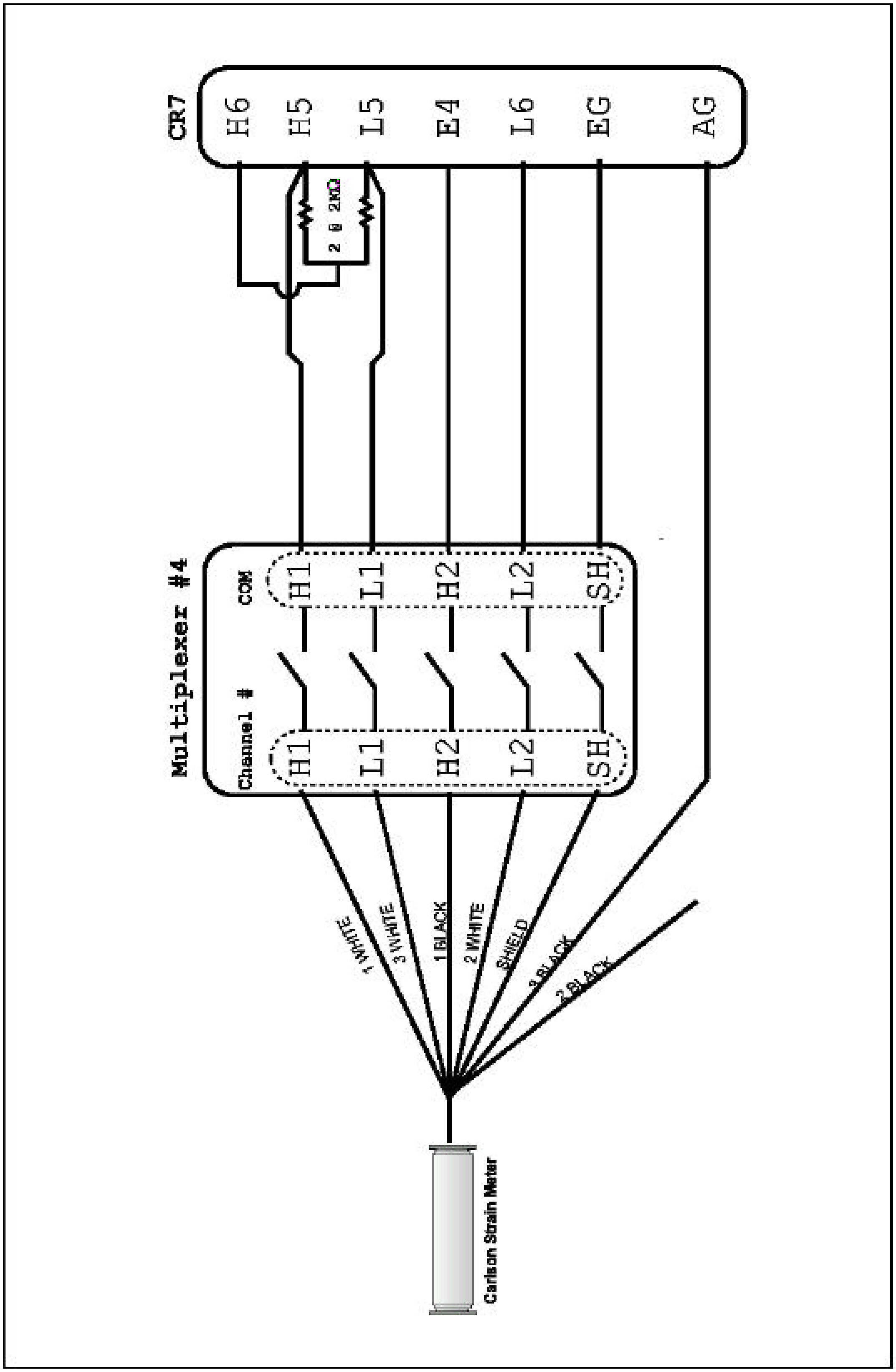

Figure 13.5 Carlson A-8 Strain Meter Data Acquisition Circuit

case, the CR7 takes a voltage reading between ports H1 and L1 on multiplexer channel one, then reads between ports H2 and L2 on the same channel. The datalogger then advances the multiplexer to the next channel. These measurements are converted to temperature as described above.

Vibrating wire strain gauges measure temperature using an internal thermistor and strain using the vibrating wire principle. A multiplexer and vibrating wire interface are needed for these measurements, as shown in Figure 13.6. The datalogger first reads the thermistor on the first channel, followed by the strain on the first channel, then advances to the next channel.

Software

Before dynamic testing was initiated, programs were developed to operate the dataloggers in the field. Campbell dataloggers use a programming language developed specifically for this purpose. Programs were written and tested at Ohio University prior to use in the field. In the field, the programs were downloaded from a computer to dataloggers using Campbell Scientific software and the SC32A interface devices. CR7 and CR10 programs used for this study are listed in Appendix B.

Data Acquisition System

The data acquisition system had to be capable of performing in the field under a variety of environmental conditions from extreme heat, cold, dry or humid conditions. Following recommendations from the Federal Highway Administration (FHWA), a Megadac 5108A data acquisition system, manufactured by Optim Electronics Corporation of Germantown, MD, was chosen to monitor and record dynamic sensor responses on the Ohio SHRP Test Pavement (Figure 13.7).

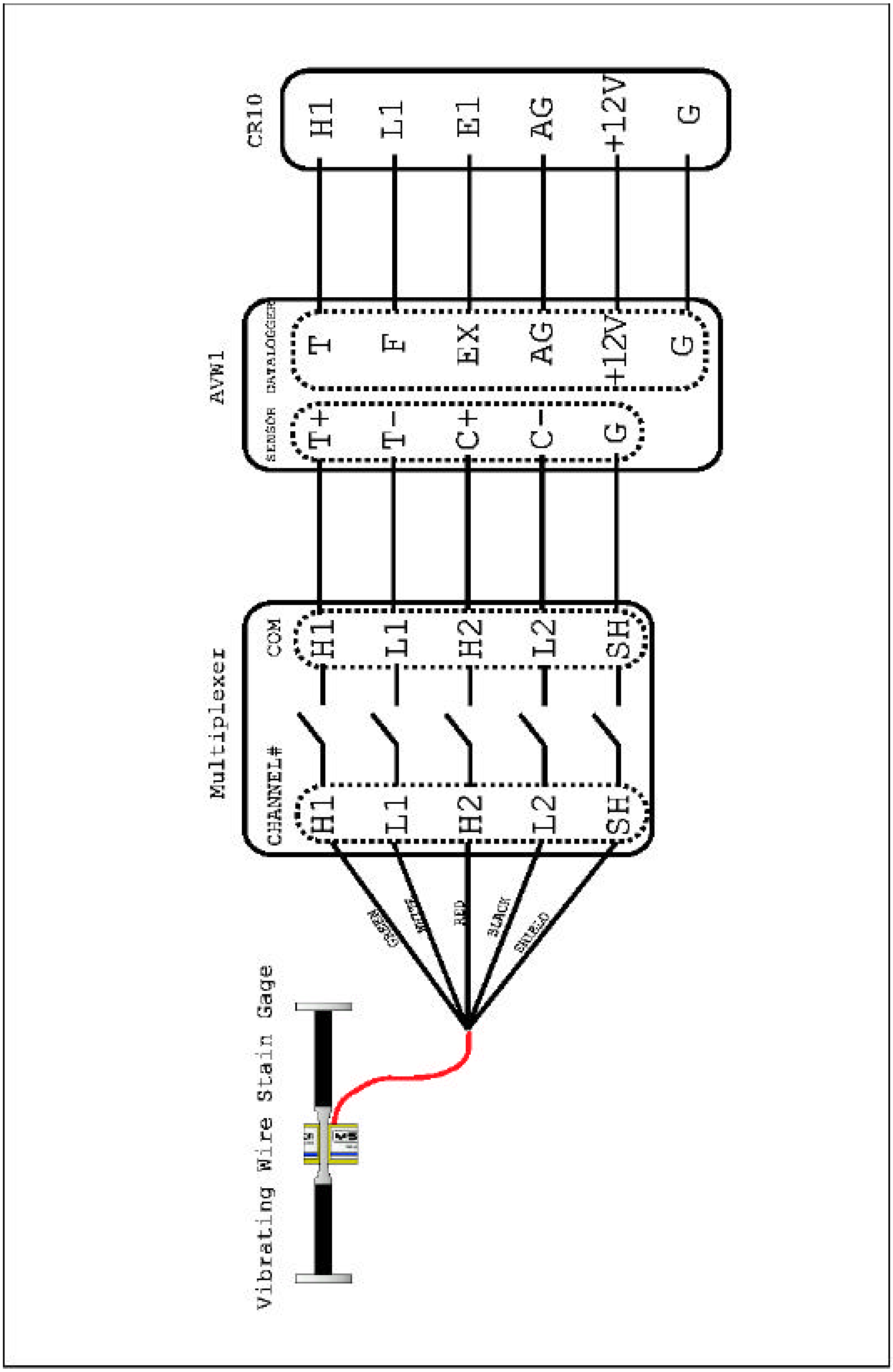

Figure 13.6 Vibrating Wire Strain Gauge Data Acquisition Circuit

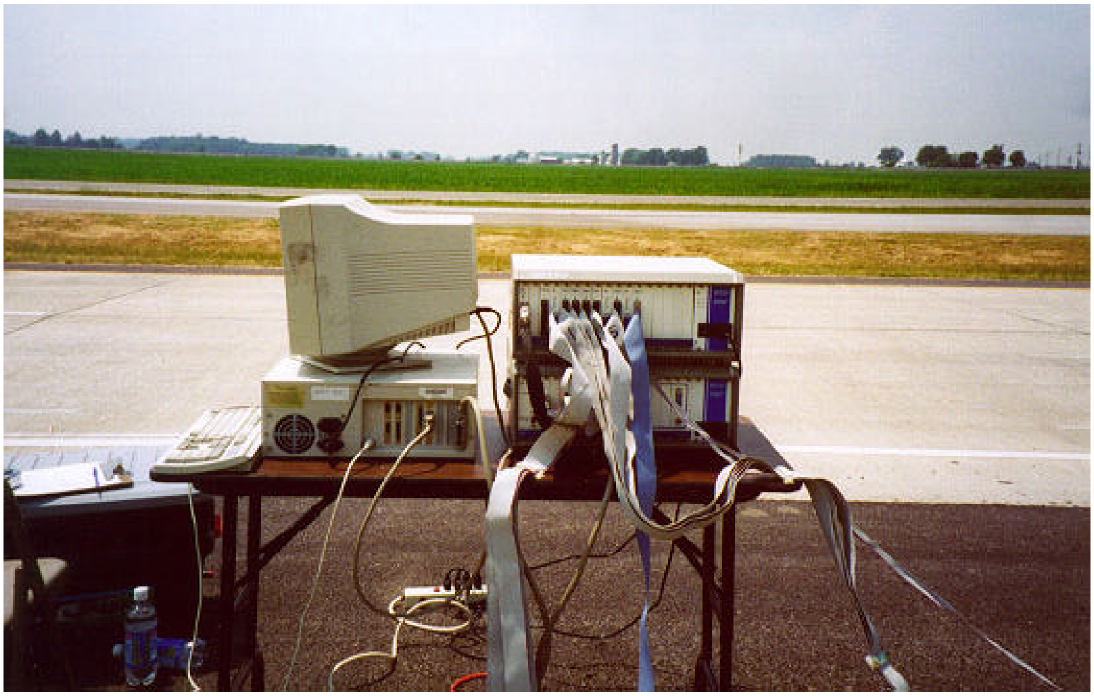

Figure 13.7 Optim Electronics Megadac 5108AC

The Megadac 5108AC is a 16-bit system with 4 megabytes of acquisition and storage memory. Data were collected at 2000 points per second per sensor and filtered at 100Hz. A 486-66DX IBM compatible computer was used to operate the system. The self-contained Megadac data acquisition system was controlled through an interactive IEEEE-488 communications bus. Optim provided its own Test Control Software (TCS) for the data acquisition system. TCS was a menu-driven, software package, which simplified test setup, sensor identification and data confirmation.

To begin a test series, the analog input and output modules had to be identified. Two analog input modules were required to handle the test requirements. The AD-1 808FB-1 Analog Input Module was used for interacting with the Dynatest PAST-II, KM-100B, Rosette and Micro-Measurements EGP-5-120 strain gauges. Each 808FB-1 had eight independent channels for measuring one-quarter, one-half, and full bridge strain gauges. This module operated as two groups of four channels. The groups were divided into channels 0-3 and 4-7, with each channel receiving the same gain, excitation and voltage. Each parameter was jumper selectable. Jumper settings provided for addressing 2, 5, or 10-volt excitation voltage sources, calibration voltage, gain and filter frequency for each bank of channels along with other parameters. The AD 808D-1 Analog Input Module was used in conjunction with LVDT and Geokon Model 3500 Earth Pressure Cells. Each 808D-1 had eight independent channels for measuring voltage. AD 808D-1 modules were broken up into two banks of 4 channels (0-3 and 4-7). Jumpers were set to determine address, calibration, voltage, gain and filter frequency. Every 808D-1 module worked in conjunction with a CB 100 signal-conditioning module. The CB 100 was a fused source of + 5 volts and $\pm$ 15 volts at 0.5 amps.

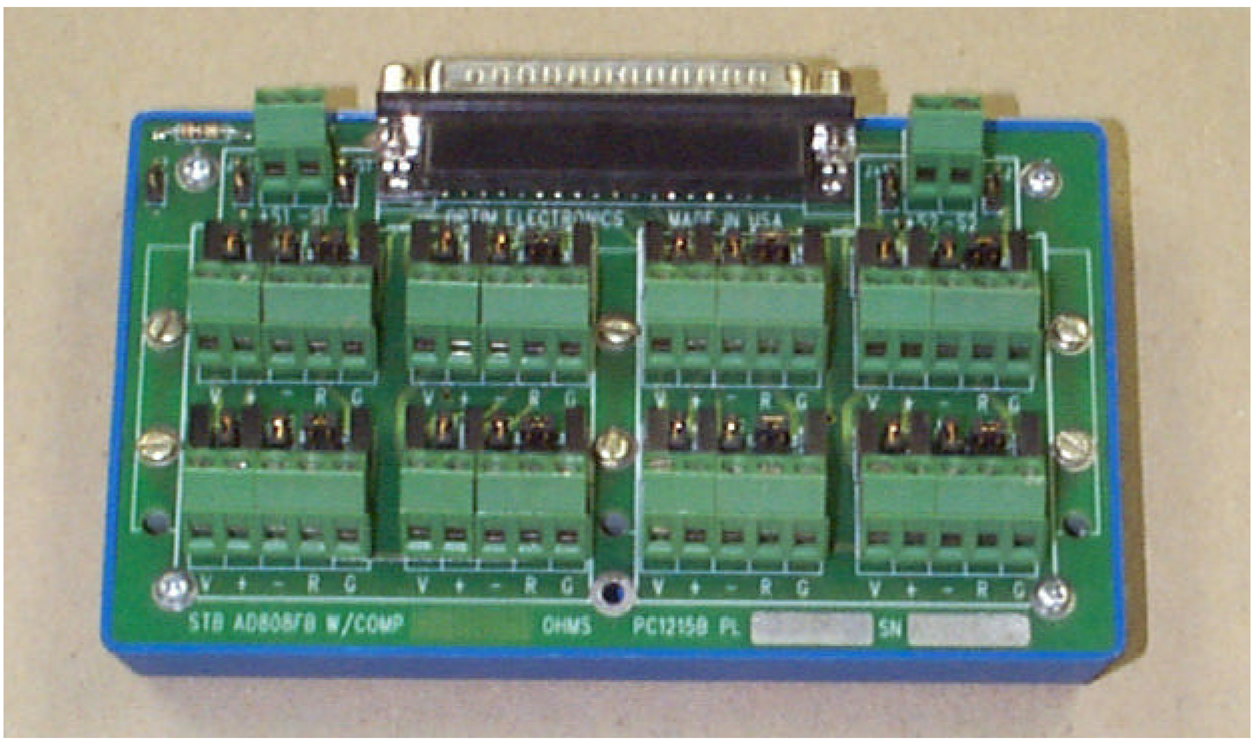

Figure 13.8 808FB-1 STB

Each analog input module required a Screw Terminal Block (STB). STBs provided for an easy connection between the sensors and the analog input cards. The STB 808FB-1 (Figure 13.8) had two major functions. First, it allowed for an interface between the lead wire of the one-quarter, one-half and full bridge strain gauges. Second, it provided for bridge completion of the one-quarter and one-half bridge strain gauges. Interfacing was provided for eight channels. Five screw terminals were allocated for each channel. Each channel required that jumpers be set for either one-quarter, one-half or full bridge application. Both the 120 Ω and 350 Ω versions of the STB, designated STB 808FB1/120 and STB 808FB1/350, were used. The STB 808D1 connected to both the AD 808D1 Analog Input Module and the CB 100 signal conditioning module. The CB 100 provided excitation voltage while the AD 808D1 measured signal voltage. Eight channel interfaces were allocated with five screw terminals per channel and sense terminal for every two channels. Jumper settings allowed for either 5 or 15-volt excitation.

Testing Setup

Before testing could begin, the appropriate arrangement of analog input modules had to be installed in the Megadac chassis. Due to the number of instruments in SPS-2 experiments, an expansion chassis was utilized. Analog input modules were allocated for one type of instrument only. One basis module arrangement was used for SPS-2 experiments with minor adjustments incorporated for sections with extra instruments. See Table 13.1 for module allocations.

Table 13.1 Module Allocation

Sensor	AD 808FB-1	AD 808D-1	CB 100
Schaevitz 121-500 DC LVDT	-	2	2
Geokon Model 3500 Earth Pressure Cells	-	1	1
Dynatest PAST-II PCC Strain Gauge	1	-	-
TML KM-100B Strain Gauge	1	-	-
TML PM-60 Rosette	1	-	-
MM EGP-5-120 Strain Gauge	1	-	-

All dynamic tests performed on any PCC section required a specialized TCS test. A test encompassed all information regarding a specific testing application. Because different sections were tested under the same conditions with the same testing equipment, many tests outlined the same parameters. To identify a specific test, each test was given a unique title. A test outlined test requirements including recording parameters. The parameters included recording speed, trigger type, along with pre and post trigger time, and where to record data. Extended parameters could also be set. The extended parameter utilized for DEL-23-17.48 included digital monitors, plots and peak detection under monitoring and identifying the ADC 5615 module for the Megadac. Next, tags and channels had to be assigned. Tag and channel menus were used to identify measurables. Tags identified specific sensors and allocated them to channels. Sensor definitions provided basic information about sensors that were connected to specific channels and labeled as a tag. Sensor definition included sensor name, recording units, analog input module type, sensitivity, resistance, and gain.

Due to the large amount of sensors to be monitored, and to make the wiring process easier and faster, connectors were attached to the end of the sensor wires. A connector box, shown in Figure 13.9, was designed with slots for connectors on each side. The STBs were pre-wired to connectors and the assembly was fastened into the connector box. To set up the data acquisition system, wire ribbons are connected from the analog input modules to the connector box and the field wiring is connected to the connectors on the opposite side of the box. Wiring diagrams of gauge wires, field wires, and connector box wires connected to the STB terminals for each gauge type used in dynamic testing were generated to verify that all connections were sound.

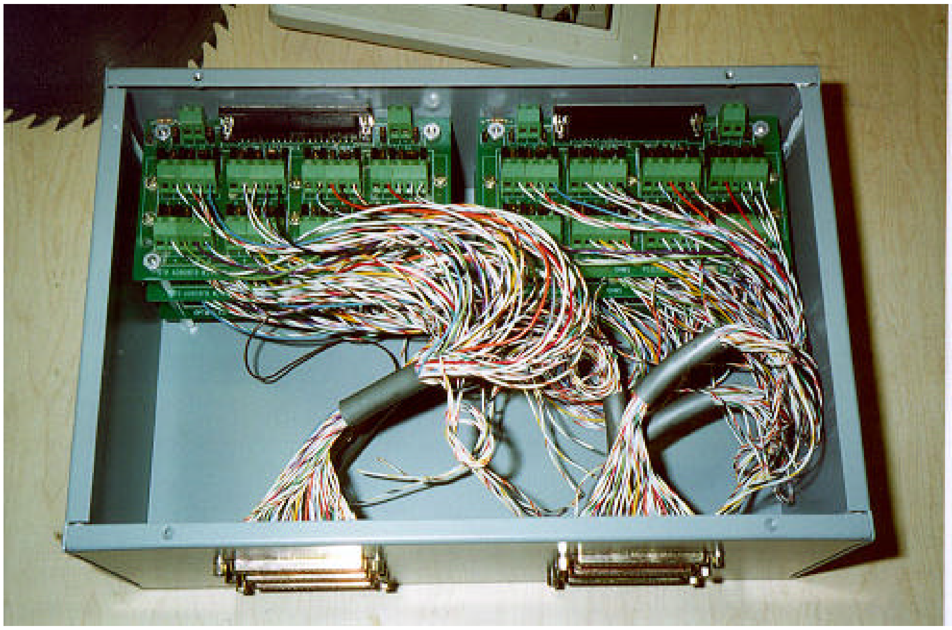

Figure 13.9 Connector Box

Data

Figures 13.10 and 13.11 show typical plots of strain and deflection, respectively, as the tandem axle research tank truck from the Canadian National Research Council passed over the sensors. The strain plot includes the sensor one-inch from the top of a PCC slab and its counterpart one-inch from the bottom of the slab. The LVDTs did not respond fast enough to clearly separate the individual truck axles. Similar plots are available for all sensors in each test section monitored during each truck pass for the five series of controlled vehicle tests. Because of the enormity of this database, individual strain and deflection peaks have been identified and stored separately for analysis.

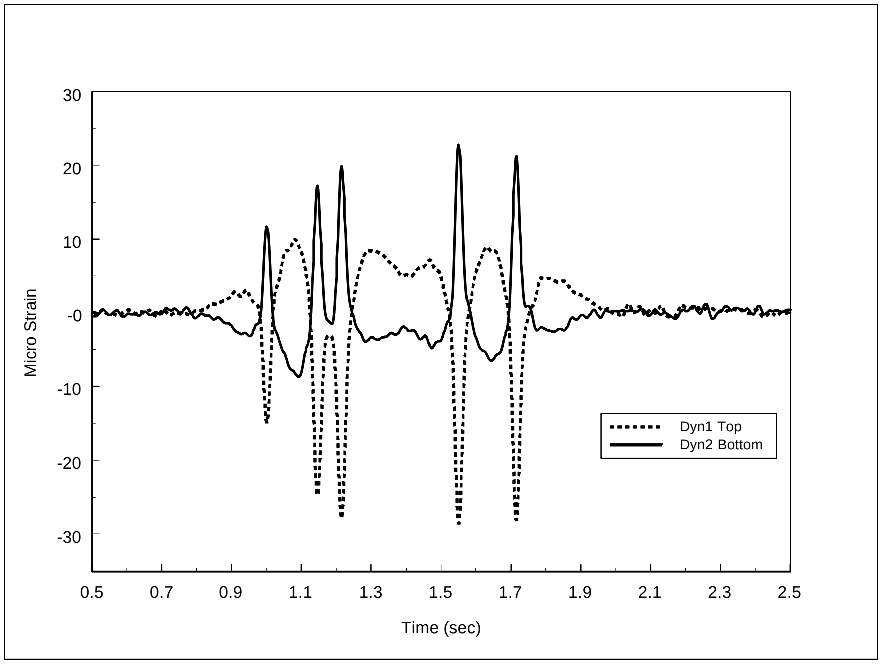

Figure 13.10 Typical Strain Gauge Response Graph

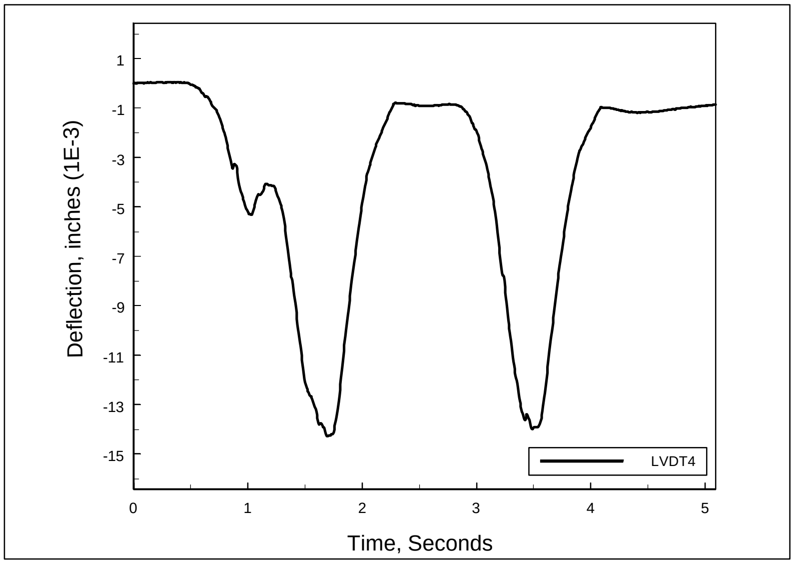

Figure 13.11 Typical LVDT Response Graph

Data Recording and Processing

Any analysis of PCC pavement performance must be based on good data. For data to be labeled good, it had to be recorded properly. Hence, a recording procedure was designed and adhered to during controlled vehicle testing. The procedure began by checking the test validity with the Test and Control Software. Before any data was recorded, the Megadac was set to automatically balance all instruments being monitored. Then, the record test data option was selected from the menu. The operator was given a choice of monitoring options. The preferred option was selected and data was ready to be recorded. Test trials were initiated and concluded with a keyboard trigger. Once a trial was concluded, the operator selected the review test data option. This option allowed the operator to download the freshly recorded data to the hard drive of the computer and freed up the Megadac memory for the next trial. After data from a particular trial was downloaded, researchers were able to evaluate that trial with their choice of monitors before the next trial began. This procedure continued until a particular test was finished. The flexibility of the Megadac allowed for multiple tests to be performed in one day and shortened the time required in the field.

Filtering was performed in the frequency domain with a linear-phase filter. The frequency response of the filter was obtained from the Fourier transform of an ideal low-pass impulse response, truncated and windowed by a Kaiser window function. The Kaiser window can be optimized for both the transition bandwidth and the maximum error in the frequency response. The filter is typically designed to stop frequencies above 55-Hz in order to eliminate the 60-Hz noise, and to pass frequencies up to 20-50 Hz, depending on truck speed.

Data Processing/Storage

The binary data files were copied from the data-acquisition computers to a portable hard disk. The files were then copied from the hard disk to two sets of 2.3-GB optical disks for archival in two separate locations. A third copy was made to optical disk for further processing. A custom program was used to verify the original files and insure the copies are identical. The third copy was processed by proprietary software which read the binary data, scaled it, filtered it, found peaks, and wrote three kinds of output files: unfiltered text, filtered text, and tables of peaks. The filtered and unfiltered text files were used to produce plots of sensor response. The peak tables, sensor locations and other pertinent data will be stored in a database.

CHAPTER 14

CONTROLLED VEHICLE TESTING

Highway vehicles are extremely varied in terms of size, weight and axle configuration. FHWA has divided the more common configurations into 13 separate classifications, with one additional classification being used for non-standard configurations. Considering that vehicle speed, vehicle dynamics, tire configuration, tire pressure, lateral position on the pavement, and many other factors affect the dynamic response of highway pavements, the size of a matrix required to examine all load associated response parameters in a series of controlled vehicle tests becomes unwieldy. Time and funding typically limit testing of this type to a few of the more significant parameters.

SHRP targeted four core sections in each of the SPS-1 and SPS-2 experiments for the installation of sensors to monitor dynamic pavement response during controlled vehicle testing. These sections included J2 (390102), J4 (390104), J8 (390108), and J10 (390110) in SPS-1; and J1 (390201), J5 (390205), J8 (390208), and J12 (390212) in SPS-2. Tests were to be performed with a single-axle and tandem-axle dump truck. The rear axle on the single-axle truck was to be loaded to approximately 18 and 22 kips, while total load on the rear axles of the tandem-axle dump truck was to be approximately 32 and 42 kips. Both trucks were to run over the instrumented sections at 50 (30), 65 (40), and 80(50) km/hr (mph) in the morning and afternoon. Tests were conducted twice a day to gather information on how temperature differences in the pavement layer affect response. With a minimum of three repetitions being required for each cell in the matrix, a total of 72 runs were necessary to complete a single series of SHRP tests with the two trucks.

SHRP requested states to perform these tests in the spring and summer when moisture conditions in the base and subgrade, and temperature in the pavement layer are typically quite different. The ODOT goal was to follow the SHRP testing protocol on all core sections and to include as many of the other 25 instrumented sections as possible at the time these tests were being run. ODOT also wished to conduct additional tests with a research tank truck operated by the Canadian National Research Council to gather supplementary information on the effects of tridem axles, axle spacing, and dual versus super single tires.

As of the date of this report, five series of controlled truck tests had been completed on the pavement. Each series followed a similar pattern with regard to how the tests were setup and conducted, as indicated by the general steps listed below:

Test Series Design

1. Select the sections to be monitored.
2. Select trucks to be used in the tests and establish the test matrix.
3. Check strain gauge resistance and install and balance LVDTs.

Setup

1. Adjust truck tires to desired pressure.
2. Load trucks to achieve the approximate desired axle weight.
3. Weigh trucks by individual tire or by set of duals and measure all tires for print width and geometric positioning on the pavement.
4. Connect a data acquisition system to each section or pair of adjacent pavement sections to be monitored.

Test Procedure

1. Spread a thin layer of fine, damp sand in the right tire path at LVDT caps to measure the lateral position of the truck as it passes over the sensors (Figure 14.1).
2. Turn the data acquisition system on as the truck approaches the sensors and turn it off as the truck passes the sensors. Collect data at a minimum rate of 400 points per sensor per second.
3. Determine the lateral offset distance of the truck by measuring from the outer edge of the outermost tire print in the sand to the center of the LVDT cap.
4. Check data recorded on the data acquisition system and, if acceptable, move the file to the computer hard disk.

Figure 14.1 Tire Marks on Sand Patches

For the layout of sections on U.S. 23, the most efficient procedure for performing controlled vehicle tests was to operate two trucks simultaneously. One truck would run the length of the project and pass over the sections being monitored. As that truck was returning on the other side of the highway, the second truck would start its run. As the second truck returned, the first truck would make another pass. This pattern continued until the desired number of runs was completed for the day (typically 12 per truck). In general, it was easier to run the heavier loads first and dump material to achieve the lighter load than to go back to the garage and increase the load. Slower speeds were run first to acquaint drivers with the layout of the sections being monitored and to facilitate their understanding of how the truck should be positioned during the runs.

Tests were conducted with the right rear tires of the trucks either passing over or, in some runs with dual tires, straddling the sensors. Several schemes were used to assist drivers maintain the correct lateral position at the sensors. In all cases, it proved helpful to paint a dashed line approximately 200 to 300 feet long in the right wheelpath leading to the sensor array in each section. This aided drivers in positioning the vehicle properly as they approached the sensors. The best drivers, including the one from CNRC, needed nothing more than the line to maintain a proper alignment. It helped some drivers to have a piece of black electrical tape on the hood of the truck to align with the line on the pavement. In other situations, it was necessary for someone to ride along and observe the rear tire positioning with respect to the dashed line on the pavement through a rear-view mirror on the right side of the truck. They would then verbally instruct the drivers to adjust right or left as they neared the sensors.

An automated guidance system was devised for use on the ODOT dump trucks prior to testing. This system, designed and fabricated by AMT, Inc., of Columbus, consisted of a video camera mounted on the right side of the truck and focused on the pavement edge line, which was placed with a strict alignment specification to insure a uniform distance from the sensors in all instrumented sections. A computer inside the truck monitored the location of the edge line in the video image. Conceptually, the function of the computer was to automatically maintain a constant distance between the truck and the edge line by making necessary alignment corrections through a drive motor attached to the steering column in the truck. A safety manual override was provided for the driver to take control of the truck at any time either by releasing a dead-man switch, or by grabbing the steering wheel and applying minimal torque. Although time did not permit the successful completion of the entire system, enough of it was finished to allow a passenger watching the alignment on a video monitor in the truck to make steering corrections by turning a potentiometer knob on a hand-held box. A second video camera was mounted under the truck and directed at the pavement in front of the right rear tire(s). This camera was connected to a video recorder, also in the truck, and provided confirmation of lateral positioning as the tires passed over the sensors. This automated guidance system was mounted in the ODOT tandem-axle dump truck and worked reasonably well for a prototype.

Table 14.1 summarizes the basic parameters included in each of the five series of controlled vehicle tests and the following text describes each series in some detail.

Series I Testing - CNRC (12/95 and 3/96)

Toward the end of 1995, FHWA requested permission to conduct a series of controlled vehicle tests on one AC and one PCC section in the SPS-8 experiment constructed and instrumented the previous year. They were in the process of preparing a document on size and weight regulations for commercial trucks in which axle configuration and types of tires were to be included. Dynamic response data obtained from these sections would provide valuable input as to how these parameters

Table 14.1 Controlled Vehicle Parameters

Controlled Vehicle Tests											
Test Date	Test Series	Truck	No. Passes	Sections Monitored		Dynamic Parameters					
				AC	PCC	Load	Speed	No. Axles	Axle Spac.	Tires	Veh. Dyn.
12/95 3/96	I**	CNRC	144	1	1	X	X	X	X	X	
8/96	II	Single	85	6	5	X	X				
		Tandem	87								
6/97	III	CNRC	127	7	8	X	X	X	X	X	X**
		Tandem	122	7	8	X	X				
7/97 8/97	IV	Single	77	12	14	X	X				
		Tandem	77								
10/98	V	Single	72	8	9	X	X				
		Tandem	60								

* Pavement Temperature, soil moisture and lateral truck position are inherent variables within each series of test
**Funded by FHWA

affect pavement performance. ODOT agreed and a special research truck was brought down from the Canadian National Research Council (CNRC) to perform the tests. This truck, shown in Figure 14.2, can be configured with tandem or tridem axles on the trailer. Axle spacing can be adjusted and either dual or super single tires can be mounted on the trailer axles. Specified axle weights are achieved by filling selected tanks in the trailer with water and by adjusting lead weights on the rear of the trailer.

For this series of tests, tandem axles were typically spaced 48 inches on centers with a few tests being run at a 96 and 114-inch spacing. A tridem axle configuration was achieved by lowering the lift axle and spacing it 54 inches in front of the 48-inch spaced tandem axles. Standard dual tires were used with the tandem configuration, and both standard dual and super single tires were used with the tridem configuration. Tire pressure was set at 100 psi for all tests. In gathering dynamic response information, data acquisition systems were turned on as the truck approached the sensors and turned off when the truck passed the sensors.

Figure 14.2 Canadian National Research Council Test Truck

The resulting traces for each sensor represented a continuous record of response during this window of time. Lateral position of the truck was determined from imprints made in sand spread around the sensors. Figures in Appendix C show the relative geometry of how tires were spaced on the CNRC tractor when dual and super single tires were mounted on the trailer. This information is necessary to properly correlate output of the dynamic response sensors with the passage of each tire or set of tires. Individual wheel loads were obtained in the ODOT District 6 garage with loadometer scales. Tables showing these weights are included in Appendix D.

FHWA contracted with Battelle of Columbus, Ohio, to coordinate the testing, and Ohio University was contracted to collect and process the data. Drs. James Kennedy and Shad Sargand were the principal investigators, respectively. A test matrix of loading parameters was developed to investigate the effects of load, speed, axle configuration, and tire configuration on pavement response. Harsh winter conditions and limited time did not permit the completion of the entire matrix. Tables14.2 and 14.3 summarize test parameters actually run and the order of testing. Offset distances measured during these tests are available, but too voluminous to include in this report.

Table 14.2 Series I Test Parameters - CNRC Tandem Test Truck

Date	Axle Spacing (inches)	Tire Type	Nominal Load (K)	Rear Axle Loads (K)		Nominal Speed (mph)	Load I.D.	Run No.
				Lead	Rear			
12/5/95	48	Duals	36	18.00	18.30	Sand Cal.	A	1-12
12/6/95	48	Duals	36	18.00	18.30	45	A	13-18
12/6/95	48	Duals	38	19.80	20.00	45	B	1-5
12/7/95	48	Duals	34	17.10	17.40	15,30,45	C	1-19
12/8/95	114	Duals	40	21.40	21.40	15,30,45	D	1-13
12/11/95	96	Duals	38	19.80	20.00	15,30,45	E	1-10
12/14/95	96	Duals	38	19.80	20.00	15,30,45	E	11-24

SPS-8 sections monitored: 390803 (AC) and 390809 (PCC)

Table 14.3 Series I Test Parameters - CNRC Tridem-Axle Test Truck

Date	Axle Spacing (inches)	Tire Type	Nominal Load (K)	Rear Axle Loads (K)			Nominal Speed (mph)	Load I.D.	Run No.
				Lead	Mid	Rear			
12/15/95	54-48	Duals	42	14.30	14.30	14.40	15,30,45	F	1-12
12/15/95	54-48	Duals	54	18.10	18.20	18.60	15	G	1
3/13/96	54-48	Duals	48	16.10	16.40	16.70	15.45	H	1-9
3/13/96	54-48	Duals	54	18.10	18.20	18.60	15.45	I	1-8
3/14/96	54-48	Duals	54	18.10	18.20	18.60	45	I	9-11
3/15/96	54-48	Super Singles	54	17.90	18.10	18.40	,15,30,4	J	1-15
3/16/96	54-48	Super Singles	42	14.40	14.00	14.20	15,45	K	1-8
3/16/96	54-48	Super Singles	48	16.20	16.10	16.60	15,45	L	1-9

SPS-8 sections monitored: 390803 (AC) and 390809 (PCC)

Series II Testing - ODOT Single and Tandem Axle-Dump Trucks (8/96)

ODOT planned to conduct a series of basic SHRP controlled vehicle tests on the SPS-1 and SPS-2 core sections using ODOT single and tandem-axle dump trucks prior to their opening to traffic. Because of the anticipated early distress in Sections J5 (390105) and J7 (390107), however, they were added to this test series so data could be obtained before those gauges became inoperative and the sections failed completely. Test sections in the SPS-1 and SPS-9 experiments were opened to main-line traffic on August 14, 1996. The SPS-2 sections were opened one day later. Approximately three weeks after being opened to traffic, Sections J1 (390101), J2 (390102), and J7 (390107) in the SPS-1 (asphalt concrete) experiment began to exhibit measurable wheelpath rutting. Tables 14.4 and 14.5 summarize the variables included in this series of tests. Tire spacing, sensor coverage, and wheel loads are shown in Appendices C and D.

Table 14.4 Series II Truck Parameters - ODOT Single-Axle Dump Truck

Date	Nominal Load (K)	Rear Axle (K)	Nominal Speed (mph)	Load I.D.	Run No.
8/6/96	18	18.45	C,30,40,50	C	1-14
8/7/96	18	18.45	C,30,40,50	C	1-14
8/9/96	22	22.23	C,30,40,50	C	1-13 (1)
SPS-1 (AC) sections monitored: 390102, 390104, 390105, 390107, 390108, 390110					
8/12/96	22	22.23	C,30,40,50	A	1-30 (2)
8/13/96	22	22.23	C,30,40,50	A	1-27 (2)
8/14/96	18	18.10	30,40,50	B	1-15 (3)
SPS 2 (PCC) sections monitored: 390201, 390205, 390208, 390209, 390212					

(1) No morning runs for 22K on SPS-1
(2) Run numbers include single and tandem-axle trucks
(3) No afternoon runs for 18K load on SPS-2

Table 14.5 Series II Truck Parameters - ODOT Tandem-Axle Dump Truck

Date	Nominal Load (K)	Rear Axle Loads (K)		Nominal Speed (mph)	Load I.D.	Run No.
		Lead	Rear			
8/2/96	32	16.62	16.23	C,30,40,50	A	1-17
8/3/96	32	16.62	16.23	C,30,40,50	A	1-15
8/5/96	42	21.14	21.38	C,30,40	B	1-11
8/6/96	42	21.14	21.38	30,40,50	B	1-16
SPS-1 (AC) sections monitored: 390102, 390104, 390105, 390107, 390108, 390110						
8/12/96	42	21.14	21.38	C,30,40,50	A	1-30 (1)
8/13/96	42	21.14	21.38	C,30,40,50	A	1-27 (1)
8/14/96	32	16.54	16.00	(2)	B	(2)
SPS-2 (PCC) sections monitored: 390201, 390205, 390208, 390209, 390212						

(1) Run numbers include single and tandem-axle trucks
(2) Tandem-axle dump truck broke down; no data available

Series III Testing - CNRC and ODOT Tandem-Axle Dump Truck (6/97)

Because of the high quality of pavement response data obtained on the two SPS-8 sections during Series I testing with the CNRC truck in 1996, and because 31 additional instrumented test sections were available on the mainline pavement, ODOT contracted with the Canadian National Research Council to bring their research tank truck back to Ohio for an expanded series of tests in June 1997. One month of testing was believed to be adequate to complete a comprehensive matrix of truck parameters, including number of axles, axle spacing, load, speed, tire configuration, and lateral position on the pavement. FHWA also funded the monitoring of vehicle dynamics on the CNRC truck for a few runs during this series of tests. Unfortunately, this was an extremely wet time in Ohio and testing could not be performed while it was raining because of the data acquisition systems being exposed to the elements. Even most of the weekends were wet.

It soon became apparent the planned testing sequence would have to be modified to accommodate the weather and still obtain the maximum benefits from the CNRC truck within the allotted time. The first step taken was to select the optimum number of sections in SPS-1 and SPS-2 that could be monitored simultaneously with the nine data acquisitions available. There was not going to be sufficient time to conduct one complete series of tests on SPS-1 and another on SPS-2 as originally planned. By monitoring sections as the truck traveled northbound and southbound, seven and eight of the highest priority sections in SPS-1 and SPS-2 could be monitored within a few minutes of each other.

Because the ODOT tandem-axle dump truck would be involved in routine SHRP testing as long as the pavement sensors remained functional, it was also run in the Series III tests to serve as a control vehicle for comparison with the CNRC truck. Axle load and speed on the ODOT truck were adjusted to simulate conditions for the CNRC truck as close as possible. With this arrangement, the CNRC truck would make a pass on one set of SPS sections and pass over the other SPS sections as it returned. The ODOT truck would follow behind in such a way as to be traveling in one direction as the CNRC truck was traveling in the other direction. Pavement response was monitored on both sides of the highway. The time differential between comparable runs for the two vehicles was typically less than 10 minutes.

For the CNRC truck, it was most efficient to perform all tests with the same arrangement of lead weights on the back of the trailer. Consequentially, three of the four boxes of weights were evenly distributed across the back of the truck throughout the Series III tests. Tests were grouped to minimize the movement of axles and changing of tires. Tanks of water were filled at the District 6 garage so the heaviest load would be run first. One or two tanks were then emptied into a catch basin at the site in preparation for the next heaviest axle load. This procedure minimized the necessity of having to return to the district garage to fill tanks. Similarly, the ODOT tandem-axle dump truck was loaded heavy in the morning at a nearby maintenance garage and unloaded as necessary by returning to this garage. While not as efficient as dumping material at the site, this process reduced the potential problem of having to find an equipment operator at the garage to load the truck during the day when most everyone was out. Unloading typically takes less time than loading. Also, the trucks were gassed up either in the morning or at the end of the day to reduce down time. Wheel loads on the trucks were weighed with portable PAT scales in the test lane where any effects of pavement slope would be taken into account.

Tables 14.6, 14.7, and 14.8 summarize CNRC and ODOT truck configurations used in Series III. Tire spacing, tire coverage of sensors, and tire loads are shown in the appendices.

Table 14.6 Series II Truck Parameters - ODOT Tandem-Axle Dump Truck

Date	Nominal Load (K)	Rear Axle Loads (K)		Nominal Speed (mph)	Load I.D.	Run No.
		Lead	Rear			
6/4-5/97	40	20.80	19.10	C,30,40,50	A	1-12
6/9-10/97	32	16.90	16.20	C,30,40,50	B	1-12
6/9-10/97	32	16.90	16.20	C,30,40,50	BA	1-13 (1)
6/19/97	32	16.90	16.20	C,30,40,50	Y	1-12
6/20/97	32	16.90	16.20	C,30,40,50	Z	1-13
6/23/97	32	16.90	16.20	C,30,40,50	C	1-12
6/24/97	32	16.90	16.20	C,30,40,50	D	1-10
6/24/97	20	10.00	9.50	C,30,40,50	E	1-10
6/25/97	20	10.00	9.50	30,40,50	F	1-9
6/25/97	12	6.60	6.00	30,40,50	G	1-9
6/26/97	12	6.60	6.00	C,30,40,50	H	1-10

7 SPS-1 (AC) sections monitored 390101, 390104, 390105, 390106, 390108, 390111, 390112
8 SPS-2 (PCC) sections monitored: 390201, 390202, 390205, 390206, 390209, 390210, 390212, 390261
(1) 7 SPS-1 sections only

Table 14.7 Series III Truck Parameters - CNRC Tandem Test Truck

Date	Axle Space (inches)	Tire Type	Nominal Load (K)	Rear Axle Load (K)		Nominal Speed (mph)	Load I.D.	Run No.
				Lead	Rear			
6/4-5/97	48	Duals	50	25.70	25.50	C,30,40,50	A	1-12
6/9-10/97	48	Duals	36	18.10	18.20	C,30,40,50	B	1-12
6/9-10/97	48	Duals	36	18.10	18.20	C,30,40,50	BA	1-13 (1)
6/17/97	48	Super Single	36	18.10	17.90	Sand Cal.	XA	1-5 (2)
6/19/97	48	Super Single	36	18.10	17.90	C,30,40,50	Y	1-12
6/20/97	146	Super Single	40	20.20	19.70	C,10,30,50	Z	1-13
6/23/97	96.5	Super Single	40	18.90	18.80	C,10,30,50	C	1-12
6/25/97	48	Super Single	32	16.20	16.00	30,40,50	F	1-9
6/25/97	48	Super Single	26	13.30	13.50	30,40,50	G	1-9
6/26/97	48	Duals	26	13.60	13.80	C,30,40,50	H	1-10

7 SPS-1 (AC) sections monitored: 391010, 390104, 390105, 390106, 390108, 390111, 390112
8 SPS-2 (PCC) sections monitored: 390201, 390202, 390205, 390206, 390309, 390210, 390212, 390261
(1) 7 SPS-1 sections only
(2) SPS-1 sections 390104, 390105, and 390111 only

Table 14.8 Series III Truck Parameters - CNRC Tridem Test Truck

Date	Axle Spacing (inches)	Tire Type	Nominal Load (K)	Rear Axle Loads (K)			Nominal Speed (mph)	Load I.D.	Run No.
				Lead	Mid	Rear			
6/24/97	54-48	Super Singles	50	16.60	16.90	17.10	C,10,30,50	D	1-10
6/24/97	54-48	Super Singles	32	11.50	11.60	11.60	C,30,40,50	E	1-10

7 SPS-1 (AC) sections monitored: 391010, 390104, 390105, 390106, 390108, 390111, 390112
8 SPS-2 (PCC) sections monitored: 390201, 390202, 390205, 390206, 390309, 390210, 390212, 390261

Series IV - ODOT Single and Tandem Axle Dump Trucks (7/8/97)

The fourth series of truck tests were performed mainly to fulfill the requirements of SHRP. However, it was also an excellent opportunity to monitor a number of other pavement sections along with the core sections. To complete these tests, 12 sections in the SPS-1 experiments were monitored first. Single and tandem-axle dump trucks were loaded with the light load, and all speeds and repetitions were run in the morning and afternoon of July 2, 1997. The load was increased on July 3 and the same test sequence was performed. A similar procedure was followed for 14 sections in the SPS-2 later in July and early August. Tables 14.9 and 14.10 summarize the test parameters for this series of tests. Tire spacing, sensor coverage, and tire loads are shown in the appendices.

Table 14.9 Series IV Truck Parameters - ODOT Single-Axle Dump Truck

Date	Nominal Load (K)	Rear Axle (K)	Nominal Speed (mph)	Load I.D.	Run No.
7/2/97	18	17.35	C,30,40,50	K	1-20
7/3/97	22	24.95	C,30,40,50	L	1-18
SPS-1 (AC) sections monitored: 390103, 390104, 390105, 390106, 390108, 390109, 390110, 390111, 390112, 390160 SPS-9 (AC) sections monitored: 390901, 390902					
7/29/97	18	21.45	C,30,40,50	M	1-10
7/30/97	18	21.45	30,40,50	N	1-9
7/30/97	22	25.35	30,40,50	O	1-9
8/6/97	22	25.35	C,30,40,50	P	1-11
SPS-2 (PCC) sections monitored: 390201, 390202, 390203, 390204, 390205, 390206, 390207, 390208, 390210, 390211, 390212, 390262, 390263, 390264					

Table 14.10 Series IV Truck Parameters - ODOT Tandem-Axle Dump Truck

Date	Nominal Load (K)	Rear Axle Load (K)		Nominal Speed (mph)	Load I.D.	Run No.
		Lead	Rear			
7/2/97	32	16.90	16.10	C,30,40,50	K	1-20
7/3/97	42	25.15	24.30	C,30,40,50	L	1-18
SPS-1 (AC) sections monitored: 390103, 390104, 390105, 390106, 390108, 390109, 390110, 390111, 390112, 390160 SPS-9 (AC) sections monitored: 390901, 390902						
7/29/97	32	18.35	17.50	C,30,40,50	M	1-10
7/30/97	32	18.35	17.50	30,40,50	N	1-9
7/30/97	42	23.05	22.05	30,40,50	O	1-9
8/6/97	42	23.05	22.05	C,30,40,50	P	1-11
SPS-2 (PCC) sections monitored: 390201, 390202, 390203, 390204, 390205, 390206, 390207, 390208, 390210, 390211, 390212, 390262, 390263, 390264						

Series V - ODOT Single and Tandem Axle Dump Trucks (10/98)

The Series V controlled vehicle tests were also performed for SHRP. All core sections, with the exception of Section 390102, which was removed and replaced earlier, were included along with a few additional sections to obtain supplementary data. By the time these tests were run, there had been a significant drop in the number of sensors that were still operable. In the thinner SPS-1 sections, very few strain gauges were functional, except for replacement Section 390162, which was constructed in the Fall of 1997. Overall, the pressure cells appeared to be performing satisfactorily and 90% of the LVDTs, which had been removed after the last series of truck tests and remounted for these tests, provided valid data. As noted in the earlier tests, a higher percentage of sensors were operational in the thicker pavement sections.

In the PCC sections (SPS-2), the number of operable pressure cells and LVDTs was comparable to that in the thicker AC sections. None of the rosettes, about half of the Dynatest gauges, and approximately 90% of the KMB-100 gauges were operational.

The full SHRP matrix of load parameters was completed on nine SPS-2 sections. Because of time constraints and mechanical problems with the tandem-axle truck, only a few runs were completed on the eight AC sections being monitored. Tables 14.11 and 14.12 summarize the runs monitored during the fifth series of controlled vehicle tests.

Table 14.11 Series V Truck Parameters - ODOT Single-Axle Dump Truck

Date	Nominal Load (K)	Rear Axle (K)	Nominal Speed (mph)	Load I.D.	Run No.
10/19/98	22	24.00	C,30,40,50	98E	1-24 (1)
10/20/98	18	20.65	C,30,40,50	98F	1-12
SPS-1 (AC) sections monitored: 390104, 390106, 390108, 390109, 39011, 390162, 390165 SPS-9 (AC) sections monitored: 390902					
10/9/98	18	18.40	C,30,40,50	98A	1-24 (1)
10/14/98	18	18.40	C,30,40,50	98B	1-24 (2)
10/14/98	22	24.00	C,30,40,50	98C	1-24 (2)
10/15/98	22	24.00	C,30,40,50	98D	1-24 (2)(3)
SPS-2 (PCC) sections monitored: 390201, 390204, 390205, 390208, 390209, 390210, 390121, 390261, 390262					

(3) Even numbers (4) Odd numbers (5) One creep run along pavement edge

Table 14.12 Series V Truck Parameters - ODOT Tandem-Axle Dump Truck

Date	Nominal Load (K)	Rear Axle Loads (K)		Nominal Speed (mph)	Load I.D.	Run No.
		Lead	Rear			
10/19/98	32	19.60	18.75	C,30,40,50	98E	1-24 (1)
SPS-1 (AC) sections monitored: 390104, 390106, 390108, 390109, 39011, 390162, 390165 SPS-9 (AC) sections monitored: 390902						
10/9/98	32	16.55	15.75	C,30,40,50	98A	1-24 (1)
10/14/98	32	16.55	15.75	C,30,40,50	98B	1-24 (2)
10/14/98	42	19.60	18.75	C,30,40,50	98C	1-24 (2)
10/15/98	42	19.60	18.75	C,30,40,50	98D	1-24 (2)
SPS-2 (PCC) sections monitored: 390201, 390204, 390205, 390208, 390209, 390210, 390212, 390261, 390262						

(1) Odd numbers (2) Even numbers

Summary

Techniques used to install response sensors in the SPS-1, SPS-2, SPS-8, and SPS-9 pavement sections were quite successful with over 95% surviving construction, over 90% of those still functional after one year, and a significant number of surviving in the thicker pavement sections after two years. Sensors failed quickest in the thinner SPS-1 (AC) sections where there was no drainage. Repeated heavy loads applied by mainline traffic on these sections over-stressed the transducers and caused visible distress in the pavement after a rather short period of time. Table 14.13 summarizes the instrumented sections monitored in each of the first five series of controlled vehicle tests conducted on the Ohio SHRP Test Pavement.

Table 14.13 Instrumented Pavement Sections Monitored During Controlled Vehicle Tests

Asphalt Concrete (AC)						**Portland Cement Concrete (PCC)**					
Section No.	**Test Series/Date**					**Section No.**	**Test Series/Date**				
	I 12/95 3/96	**II 8/96**	**III 6/97**	**IV 7/97**	**V 10/98**		**I 12/95 3/96**	**II 8/96**	**III 6/97**	**IV 7/97 8/97**	**V 10/98**
SPS-1						**SPS-2**					
390101			X	**	**	390201*		X	X	X	X
390102*		X				390202			X	X	
390103				X		390203				X	
390104*		X	X	X	X	390204				X	X
390105		X	X	X	**	390205*		X	X	X	X
390106			X	X	X	390206			X	X	
390107		X		**	**	390207				X	
390108*		X	X	X	X	390208		X		X	X
390109				X	X	390209		X	X		X
390110*		X		X	X	390210			X	X	X
390111			X	X		390211				X	
390112			X	X		390212*		X	X	X	X
390160				X		390261			X		X
390162***					X	390262				X	X
390165***					X	390263				X	
						390264				X	
SPS-8											
390803	X					390809	X				
SPS-9											
390901				X							
390902				X	X						

* SHRP Core Section
** Section failed/removed from service
*** Replacement section

CHAPTER 15

EARLY PERFORMANCE OF SPS SECTIONS

Projected Performance

In general, SPS-1 and SPS-2 test sections on the Ohio SHRP Test Pavement were placed so those expected to fail early were located toward the middle of the project, except where construction sequencing required sections containing some unique design feature or material be put in the same area. Sections with the longest life expectancy were located at the ends of the project where traffic control at the intersection of the old and new lanes would be difficult during rehabilitation or replacement.

Projected services lives of SPS-1 and SPS-2 sections included in the original SHRP matrix are shown in Table 15.1 in terms of ESALs. These preliminary estimates were derived from AASHTO equations prior to construction using assumed structural properties for materials being incorporated into the pavement sections. By coincidence, the ESAL count on U.S. 23 at the project location was estimated to be about one million annually, thereby making the ESALs to failure count (in millions) shown in Table 15.1 the approximate number of years of expected structural service, assuming no unusual environmental conditions or material degradation. Sections are listed in their order of location on U.S. 23 with the top of the table being the north end of the project. Service lives projected in the table were subject to considerable error due to design assumptions involved and, quantitatively, the actual values shown are not as significant as the relative order of predicted failure. Obviously, the extremely long lives predicted for some of the stiffer sections are unrealistic. Material properties, in-situ stiffness and environmental data obtained after construction brought the calculated service lives of the failed sections much closer to observed performance. State sections added by

ODOT to the SPS-1 and SPS-2 experiments were designed to provide performance information for standard ODOT lives.

Table 15.1 Projected Design Lives of SHRP Test Sections

SPS-1		**SPS-2**	
Section No.	ESAL (million)	Section No.	ESAL (million)
390103	7.2	390208	36.5
390110	10.0	390207	12.2
390109	15.5	390203	10.7
390108	6.4	390211	36.9
390105	1.6	390209	3.2
390102	0.9	390201	0.9
390107	0.2	390205	1.1
390101	2.4	390206	7.8
390106	75.2	390202	6.7
390104	215.4	390210	23.2
390111	17.2	390212	112.2
390112	118.1	390204	32.7

Visual Distress; SPS-1

Construction of the SPS-1 and SPS-9 sections was functionally complete and mainline traffic was moved onto the test pavement on August 14, 1996. Within a few days, noticeable rutting was detected in Sections 390102 and 390107 in SPS-1, and there was concern these sections might deteriorate rapidly over the upcoming Labor Day weekend. Fortunately, there were no serious problems, but there was considerable doubt as to whether the sections would remain intact during the spring thaw. The prospect of having to perform emergency repairs on a major highway during the winter or early spring while the weather was cold and wet, and access to materials was limited prompted the consideration of some type of immediate remedial repair. After some deliberation, it was decided to remove the 4-inch thick AC pavement layer and some base material from both sections and replace these materials with a thicker layer of temporary AC pavement to get them through the winter. The southbound lanes were closed on September 3, 1996 to complete this work. A total removal of the temporary pavement and replacement with more robust supplemental sections of interest to the state was planned for 1997. While the distress in Sections 390102 and 390107 occurred somewhat earlier than expected using ODOT design parameters, the AASHTO equations did forecast these sections to be the first to fail.

During the rehabilitation of Section 390107, a portion of the underdrains originally installed to drain the pavement were observed to be not connected to outlet pipes, thus making the section partially drained and partially undrained. SHRP was notified of this oversight so it would be properly documented and perhaps the section removed from the database.

Shortly after placement of the temporary pavement in Sections 390102 and 390107, and ropening of the southbound lanes on September 11, 1996, rutting also began to develop in Section 390101. To avoid a midwinter or early spring failure in this section and to preserve the integrity of dynamic response sensors in the thinner AC sections for the 1997 controlled vehicle tests, these lanes were closed again on December 3, 1996, and not re-opened until November 11, 1997.

During the winter of 1996-97, plans were prepared for removal of the three distressed SPS-1 sections and installation of heavier sections similar to those in SPS-9. Replacement of two distressed SPS-8 AC sections was included in the same contract. Prior to preparation of the construction drawings, ODOT contacted SHRP to see if there was any interest in having the sections rehabilitated in some particular way to further achieve their goals. ODOT was informed that SHRP had no follow-up plans for distressed sections in SPS-1 or SPS-2.

Visual observations of the three distressed SPS-1 sections indicated severe rutting throughout, with localized areas also exhibiting wheelpath cracking. Because it was not possible visually to determine the specific causes of the distress, ODOT personnel and ORITE staff and students conducted a forensic investigation to more clearly define the failure mechanism in Section 390101. Judging by the nature and timing of distress in the other two sections, their modes of failure were likely to be very similar. Results of the forensic study showed the following:

1. Subgrade moisture was consistently higher throughout the short life of the section.
2. Essentially all of the rutting could be attributed to the base and subgrade, with none being observed in the AC layers.
3. AC debonding was observed in the most severely distressed areas. The AC lifts were not tacked together during construction.

As this report was nearing completion, a sudden and rather dramatic failure occurred at Station 2+30 in Section 390105. Within a few hours after the distress was first reported to ODOT by passing motorists on May 29, 1998, considerable AC material from an area approximately 20 feet long and covering the right half of the right lane had been removed by traffic and scattered along the roadside. The two lifts of AC had debonded from the ATB and from each other over a 3-foot wide by 6-foot long oval at the center of the failed area. The ATB was also broken and in danger of being removed at that point. Away from the most distressed area, debonding was still evident, but less severe. Heavy rain on the day before likely precipitate the failure.

Over the next few days, an ODOT maintenance crew shut the driving lane down in Section 390105 only, removed the severely debonded AC over a 6-foot wide by 40-foot long area in the right side of the lane, and patched it with hot mix AC. Severe rutting was noted in other areas of the section and in the instrumented area immediately preceding the section. Consequently, other portions of the section were expected to fail in a short period of time. FWD and Dynaflect measurements obtained three weeks prior to this failure confirmed the area between Stations 2+00 and 2+50 to be particularly weak in the right wheelpath, with mid-lane measurements showing good uniformity throughout the section length.

Section 390105 was removed and replaced with a pavement identical to Section 390108, but with the addition of underdrains and Geogrid, a geosynthetic fabric, on the surface of the finished subgrade. That is, a 7-inch thick asphalt concrete pavement (1-3/4" ODOT 446, Type I AC/5-1/4" ODOT 446, Type II AC) on a 12-inch thick base (4" PATB/8" DGAB) on Geogrid laid on the subgrade. The Geogrid was not stapled or otherwise affixed to the subgrade prior to installation of the base. To facilitate construction and permit completion of a fifth series of controlled truck tests, the entire test pavement was shut down and traffic diverted back to the original lanes between September 8 and October 20, 1998. This replacement section was identified as Section 390164.

Visual Distress; SPS-2

The SPS-2 test sections were opened to traffic on August 15, 1996. Traffic was moved back to the original lanes on December 2, 1996 for testing and rehabilitation of distressed SPS-1 sections. To facilitate completion of the fifth series of controlled vehicle tests, traffic was removed from the SPS-2 sections between September 8 and October 20, 1998.

During the 1998 truck tests, early signs of distress were observed in Sections 390205 and 390206, the two 8-inch thick PCC sections with a lean concrete base. Among the types of distress noted were transverse cracks, faulting, and pumping at the pavement/shoulder interface. Specifically, they included the following:

Table 15.2 Visual Distress in SPS-2

Section No.	Project Station	SHRP Station	Slab No. (1)	Distress	Severity
390205	335+7	0+02	1	Transverse cracks, shoulder to half way across right lane	Low
	338+35	2+60	18	Mid-slab pumping stain at shoulder	Low
	339+91	4+16	28/29	Minor faulting at joint	Slight
	339+97	4+22	29	Transverse crack across right lane	Low
	340+13	4+38	30	Transverse crack across right lane with spalling	Medium
	340+14	4+38	30	Transverse crack across passing lane	Low
	342+04	N.A. (2)	42	Transverse crack across right lane	Slight
390206	330+83	3+32	23	Mid-slab pumping stain at shoulder with spalling	Medium
	331+78	4+27	29	Mid-slab pumping stain	Slight
	331+91	4+40	30	Mid-slab pumping stains	Slight
	332+74	N.A. (2)	36	Pumping/spalling at pavement edge	Low
	334+16	N.A. (2)	45	Pumping stain at pavement edge	Low

(1) Slab in which SHRP section started (0+00) is Slab No. 1
(2) Outside SHRP section

Various aspects of the distresses outlined above are of interest. As noted above, both sections have a 6-inch thick lean concrete base. Section 390205 has a 12-foot lane width and ODOT Class C concrete, while Section 390206 has a 14-foot lane width and high strength concrete. Both show evidence of pumping. Also, the pumping stains were located between contraction joints and on both lane widths and both concrete strengths. The location of the crack at SHRP Station 4+38 in Section 39205 appears to correspond to the location of a crack noted in the lean concrete base prior to placement of the PCC pavement. Further observations will be made to see if there is any correlation between cracks in the base and cracks in the pavement. These sections will likely deteriorate further over the 1998-99 winter.

Visual Distress; SPS-8

The four test sections in SPS-8 were opened to traffic on November 18, 1994. Sections 390803 and 390804 (AC) displayed premature rutting very quickly. While these sections were exposed to a very low volume of truck traffic during 1995, the Series I controlled vehicle tests performed for FHWA in December 1995 and March 1996 accelerated the rutting process through the repeated application of some very heavy loads. ORITE staff completed a set of Cone Penetrometer Tests (CPT) tests along both sections and discovered a layer of poorly consolidated clay subgrade approximately four feet below the pavement surface. This was the depth of undercutting required in the area during construction, and the level at which the first lift of material was replaced and compacted. CPT tests suggested the compaction effort on this first lift was inadequate. Also, the subgrade under the SPS-8 sections was undrained and appeared to be quite wet most of the time. The presence of excessive moisture, the poorly compacted subgrade layer, and the truck tests performed for FHWA all contributed to the premature rutting on these sections.

In August of 1997, Sections 390803 and 390804 were removed and replaced with sections similar to the original SPS-8 AC construction. The only differences were that the subgrade was undercut to a greater depth and treated with lime as it was replaced, and the surface and leveling courses were both constructed of ODOT Type 1 asphalt concrete. An array of response sensors similar to those incorporated in the other AC sections was installed just outside both replaced sections, and one additional environmental array was placed near the interface of the two sections. Because of pavement geometry on the ramp where this SPS-8 experiment was located, only local traffic could use Section 390809 and 390810 while Sections 390803 and 390804 were being replaced. This included some construction traffic. The ramp was re-opened on October 15, 1998.

Visual Distress; SPS-9

The three SPS-9 sections were constructed with a 22-inch thick base to provide extended service. The only difference between these sections was the grade of asphalt cement used in the 4-inch thick pavement layer. Section 390901 contained standard AC-20, Section 390902 contained PG 58-28, and Section 390903 contained PG 64-28. The AC surface course mix designed for Section 390903 with Superpave Level I specifications resulted in an extremely fine mix resembling sand asphalt. Skid resistance, as measured with the ODOT K.J. Law Skid Trailer, has remained satisfactory on these sections and about the same as the standard ODOT mix used on the SPS-1 sections. Aside from the fine texture on the pavement surface, there have been no indications of distress in the SPS-9 sections. Dates when these sections have been opened and closed to traffic are the same as sections in the SPS-1 experiment as discussed earlier in this chapter.

Non-Destructive Testing

Falling Weight Deflectometer (FWD) measurements obtained on the finished subgrade are an important indicator of how pavements are likely to perform in the future. Because preliminary borings taken prior to construction suggested a relatively uniform soil structure throughout the U.S. 23 site, subgrade stiffness was expected to be reasonably similar in all of the test sections. However, the remains of old basements, wells, cisterns and other abandoned structures left when U.S. 23 was upgraded from a two-lane to a four-lane facility in the 1960's, and the occurrence of a few other localized areas where the naturally occurring soil was wet (all undiscovered during the preliminary investigation, but uncovered during construction) would, if left in place, have resulted in a highly variable subgrade stiffness through these SPS experiments. In an attempt to improve subgrade uniformity, substantial undercutting was performed to remove these features. Even then, actual subgrade stiffness measurements obtained with the FWD still varied dramatically between sections and even within certain sections.

All FWD deflections shown in this report have been normalized to 1,000 lbs. for easier comparison with other FWD data and to facilitate any comparisons with Dynaflect data where deflections were obtained with a uniform 1,000 lb. sinusoidal loading. While the magnitude of FWD loading can be approximated by mounting specified weights on the trailer and by adjusting the drop height of the weights, actual applied load is affected by the stiffness of the pavement structure. For a given combination of weights and drop height, measured load will tend to increase with increasing pavement stiffness.

By the very nature of the SPS experiments, there should be a dramatic difference in non-destructive deflection measurements between the various test sections once construction was complete. This variation was due to the wide range in stiffness designed into the SPS experiments and any inherent differences in the subgrade. As on the subgrade, FWD data on finished pavement are an important indicator of how well sections can be expected to perform under traffic. Sections designed for limited service are less stiff and give much higher deflections than the more robust sections. Tables E-1, E-2, and E-3 in Appendix E summarize FWD results obtained at the time the subgrade was finished, when the test sections were completed and ready for opening to traffic, and again in May 1998 after the sections had been in service for about two years. Table E-4 and E-5 show Dynaflect data obtained at the same time on all sections just prior to opening and in May 1998.

Test sections were typically constructed in groups by location on the project, by the types of material being used or by some particular design feature common to the sections. As the subgrade was finished, the FWD was brought in for testing. This process was repeated for each lift of material as sections were built up and completed throughout the project. Because FWD test dates for the various layers and sections are quite different, any comparison of deflections between sections must be made cautiously. The most obvious variable throughout the season is subgrade moisture, which has a significant impact on FWD measurements. Temperatures within the AC or PCC pavement layer can also affect these data. While both the driving and passing lanes were constructed identically, all SHRP sections were located in the right hand or driving lane. Deflection data were obtained in the right wheelpath and in the centerline of this right lane.

FWD testing on the complete subgrade consisted of two drops at each of four load ranges at 50-foot intervals along the sections. The highest loads on the subgrade ranged between 4,000-6,000 lbs. Data in Table E-1 represent an average deflection at the center of the load plate for the two drops at this level. A profile of this deflection along the section length is indicative of subgrade uniformity. With the exception of Sections 390159 and 390264, which were not finished until the following year, the subgrade for all SPS-1 and SPS-2 sections was completed and tested in the summer of 1995. Table E-1 shows subgrade stiffness to be highly variable between sections and, in some instances, within individual sections. FWD deflections obtained on the subgrade under Sections 390159 and 390264 are much higher than the remaining sections constructed one year earlier. These data illustrate how, even on projects with such a high visibility as this SHRP project, current ODOT specifications are limited in their ability to ensure the construction of uniform pavement subgrades.

Stiffness-based specifications based on non-destructive testing (FWD/Dynaflect) might provide a better method for controlling subgrade uniformity than density-based specifications using nuclear density techniques.

While Table E-1 shows considerable variability within the subgrade, Table D-2, with data obtained when the sections were completed but not yet opened to traffic indicates that, as expected, much of this variability is masked once a pavement is placed over the subgrade. Also, the degree of masking is dependent upon the stiffness of the overlying pavement structure. Specifically, 1) the addition of any pavement structure will bridge over localized areas of subgrade weakness to some extent and reduce stiffness variability within the total structure, and 2) stiffer pavement structures provide more bridging action, thus reducing variability to a greater extent. As any pavement structure carries traffic, however, internal stresses will be higher in areas of diminished subgrade support. These areas will fatigue faster than the remaining pavement, and variability will begin to emerge again as a problem in the structure, both in terms of stiffness and visible distress.

FWD testing of the newly finished pavement sections in June 1996 consisted of one drop at each of three load levels in the centerline and right wheelpath of the right lane. The sensor under the load plate (Df1) was used as the indicator of stiffness in Table D-2 for the middle drop, being 9,000-11,000 lbs. on AC sections and 11,000-14,000 lbs. on PCC sections. This difference in load range on the two types of pavement was due to the effect of pavement stiffness on the response of the FWD. On AC sections, readings were taken every 50 feet in both test paths. On PCC sections, mid-slab readings were taken at about 50-foot intervals along the centerline and, in the right wheelpath, joint measurements were obtained every 100 feet.

Joint measurements taken with the FWD and Dynaflect are defined as either being joint approach or joint leave. In joint approach measurements, the joint is centered midway between the first and second sensors on the Dynaflect and midway between the second and third sensors on FWD, while joint leave measurements are taken with the load wheels or load plate located just past the joint. Load Transfer (LT) is defined as W2/W1 (Dynaflect) or Df3/Df2 (FWD) in the joint approach configuration, while the Joint Support Ratio (JSR) is defined as W1 Leave/W1 Approach (Dynaflect) or Df1Leave/Df1Approach (FWD). These parameters are not included in Tables E-2 and E-3, but they are indicative of how PCC joints are performing. Low LT suggests an inability in the pavement joint to distribute load effectively to adjacent slabs. Typically, load transfer will increase as temperature increases and PCC slabs expand to provide more aggregate interlock. High JSR suggests different levels of support on the two sides of the joint with excess moisture or a void usually present under the leave slab.

It is interesting to note from Table E-2 that the first four sections to fail (390101, 390102, 390105, and 390107) were new pavement sections with the highest normalized Df1 deflection (1.62, 3.36, 1.38, and 1.90 mils, respectively). Also, the area in Section 390101 with the most severe distress at the time of the forensic investigation was Station 2+65 which was close to the station in that section with the highest initial normalized deflection (2.17 mils). As would be expected, mid-lane and right wheelpath measurements were quite similar on these new AC pavement sections.

The May 1998 FWD readings were taken in a manner similar to those taken in June 1996. One drop at each of three heights was made at 50-foot intervals throughout the test sections. Time did not permit the completion of both mid-lane and right wheelpath measurements in all sections. Because readings at the center of the load plate (Df1) were quite erratic and often less than those at the edge of the plate (Df2) on the PCC sections, Df1 is shown for the SPS-1 sections and Df2 is shown for SPS-2 sections. It is interesting to note that the average normalized deflection on Section 390105 was 1.52 mils and the normalized deflection at Station 2+50 was 2.76 mils less than four weeks before failure occurred on May 29. Table E-3 in Appendix E summarizes these data.

Tables E-4 and E-5 in Appendix E show Dynaflect data comparable to that shown for the FWD in Tables E-2 and E-3. It is noteworthy that Sections 390101, 390102, 390105, and 390107 again have the highest average deflections (1.10, 1.48, 0.99 and 1.15 mils, respectively) when the sections were new. Also, the Dynaflect identified Station 2+50 as being the weakest location in Section 390101 when it was new, Section 390105 as being the weakest location in that section. Overall, the correlation between FWD and Dynaflect measurements appears to be excellent for ranking pavement stiffness or identifying areas of weakness. For a more precise comparison of FWD and Dynaflect data, differences in the geometry of the loaded areas and in distances from the load to the sensors must be taken into account.

Another non-destructive test parameter necessary for the back-calculation of layer moduli is the shape of the deflection basin generated by the FWD and Dynaflect. Tables F-1 and F-2 in Appendix F show average FWD basin profiles for the SPS-1 (AC) sections when they were new in June 1996 and again in May 1998. Tables F-3 and F-4 summarize the same data for the SPS-2 (PCC) sections. Tables F-5 to F-8 provide comparable information obtained with the Dynaflect. When reviewing these data, the following should be noted:

1. Spreadability (SPR) is the average normalized deflection for a basin profile and is expressed as a percent. It is defined as the average deflection of all sensors being considered divided by the sensor in the group nearest the center of the loaded area. This parameter is indicative of stiffness in that stiffer pavements have higher spreadability. The last five sensors (Df3-Df7) were used for the FWD here because they most closely simulate the positioning of the Dynaflect sensors.

2. Average deflections shown in Tables F-1 to F-4 for the FWD were obtained at a

higher load than average deflections listed in Tables E-2 and E-3. While non-linearity does not appear to be a significant problem on these test sections, sensor readings under the load plate (Df1) are slightly different in Appendices E and F because of this difference in load. W1 measurements with the Dynaflect in Tables F-5 to F-8 should be the same as those shown in Tables E-4 and E-5.

Surface Roughness

Another indicator of pavement performance is the manner in which surface roughness increases over time. As pavements degrade, they tend to become rougher and more uncomfortable for vehicle drivers and passengers. A K.J. Law Non-Contact Profilometer was used by ODOT at the completion of the SPS sections and periodically thereafter to monitor section roughness. Data shown in Tables 15.3 and 15.4 represent a summary of section roughness in Mays and psi numbers when the pavement was new and at various times after it had been open to traffic. Unfortunately, rutting of the pavement surface may not be reflected in the roughness measurements.

Skid Resistance

Skid resistance is a measure of the macro-texture and micro-texture of the pavement surface. AC surfaces tent to exhibit higher skid resistance soon after being opened to traffic as the bituminous coating wears off the aggregate, and then a gradual decrease over time as the aggregate particles loose their sharp edges. PCC surfaces typically have high initial skid resistance, which decreases as the texture, and particles wear over time. Table 15.5 summarizes skid resistance data obtained to date at 40 mph. The differences observed may be due to the various skid units used to

Table 15.3 Roughness of Ohio SHRP Test Pavement-Mays

Section No.	Mays Ride Number								
	8/16/96	35304	9/18/96	10/28/96	11/28/97	6/4/98			
SPS-1									
390159	Data Not Available (DNA)								
390103	Data Not Available								
390110	68.1	68.8	71.6	72.9	64.8	79.3			
390109	43.0	43.3	45.0	46.3	49.7	61.6			
390108	53.3	53.4	55.9	67.6	72.4	87.1			
390105	57.3	60.6	75.1	75.9	97.7	126.3			
390164									
390160	63.1	65.8	65.0	69.4	110.1	108.2			
390102	83.1	146.0							
390161					58.4	48.6			
390107	70.4	81.5							
390162					49.5	45.8			
390101	86.8	111.8	134.7	189.2					
390163					75.3	64.8			
390106	71.2	71.3	73.9	76.7	140.9	123.0			
390104	45.2	47.2	48.0	46.8	74.0	91.2			
390111	44.3	45.5	46.8	45.3	58.9	64.1			
390112	53.7	53.0	53.8	52.3	71.2	83.3			
SPS-2									
390259	Data Not Available								
390204	51.4	61.2	53.4	50.9	55.2	49.3			
390212	67.9	71.3	62.2	60.7	68.3	74.9			
390210	65.3	73.1	61.5	58.7	66.9	71.6			
390260	66.6	73.4	64.0	61.1	66.3	68.1			
390202	71.6	79.1	70.7	71.4	80.7	86.9			
390206	76.3	70.1	69.6	68.0	79.3	86.0			
390205	69.8	68.3	67.1	65.9	69.5	66.6			
390201	71.8	70.8	71.9	71.4	79.1	78.0			
390209	59.9	58.3	58.9	57.0	64.9	65.7			
390261	76.3	75.8	76.1	74.4	87.8	93.4			
390211	85.6	83.1	80.1	80.3	86.4	84.1			
390265	84.0	81.3	82.5	80.1	86.6	86.4			
390203	63.1	61.1	60.1	56.2	65.5	65.6			
390207	80.0	77.1	74.8	74.5	76.8	84.7			
390208	79.9	79.1	79.0	75.1	81.8	89.3			
390262	75.0	73.1	73.6	66.1	74.6	78.7			
390263	Data Not Available								
390264	Data Not Available								
SPS-8									
390810 (PCC)	Data Not Available								
390809 (PCC)	Data Not Available								
390803 (AC)	Data Not Available								
39A803 (AC)					DNA	DNA			
390804 (AC)	Data Not Available								
39A804 (AC)					DNA	DNA			
SPS-9									
390902	47.4	47.2	48.0	47.5	45.7	49.6			
390903	41.7	40.8	41.6	41.0	45.9	49.1			
390901	46.7	46.5	47.9	47.0	46.1	48.5			

Table 15.4 Roughness of Ohio SHRP Test Pavement - PSI

Section No.	Present Serviceability Index (PSI)								
	8/16/96	35304	9/18/96	10/28/96	11/28/97	6/4/98			
SPS-1									
390159	Data Not Available								
390103	Data Not Available								
390110	3.97	3.99	3.94	3.94	4.07	3.79			
390109	4.18	4.20	4.17	4.19	4.28	4.02			
390108	4.09	4.13	4.07	3.98	4.15	3.83			
390105	4.00	4.01	3.81	3.80	3.67	3.28			
390164									
390160	4.04	4.04	4.00	4.00	4.09	3.81			
390102	3.92	3.22							
390161					4.57	4.31			
390107	4.06	3.84							
390162					4.43	4.28			
390101	3.92	3.62	3.35	2.77					
390163					4.41	4.12			
390106	3.95	3.98	3.94	3.95	3.85	3.68			
390104	4.05	4.04	4.03	4.08	4.08	3.90			
390111	4.10	4.10	4.06	4.11	4.15	3.99			
390112	3.93	3.96	3.94	3.96	4.01	3.86			
SPS-2									
390259	Data Not Available								
390204	4.08	3.88	4.05	4.07	4.05	4.12			
390212	3.94	3.90	4.05	4.06	3.96	3.91			
390210	3.92	3.85	4.00	4.06	3.96	3.89			
390260	3.86	3.76	3.93	4.00	3.91	3.89			
390202	4.02	4.00	4.07	4.11	4.06	4.00			
390206	3.85	3.96	3.97	3.99	3.91	3.82			
390205	3.96	4.00	4.03	4.06	4.03	4.00			
390201	4.02	4.05	4.02	4.06	4.03	4.05			
390209	4.05	4.09	4.08	4.12	4.06	4.07			
390261	3.94	3.97	3.97	4.00	3.93	3.90			
390211	3.81	3.85	3.89	3.90	3.87	3.88			
390265	3.77	3.83	3.82	3.89	3.80	3.79			
390203	3.96	4.01	4.02	4.08	4.01	3.98			
390207	3.81	3.86	3.88	3.89	3.90	3.80			
390208	3.77	3.79	3.82	3.87	3.82	3.76			
390262	3.82	3.88	3.84	4.01	3.86	3.85			
390263	Data Not Available								
390264	Data Not Available								
SPS-8									
390810 (PCC)	Data Not Available								
390809 (PCC)	Data Not Available								
390803 (AC)	Data Not Available								
39A803 (AC)									
390804 (AC)	Data Not Available								
39A804 (AC)									
SPS-9									
390902	3.89	3.95	3.93	3.95	4.08	3.95			
390903	4.15	4.19	4.17	4.22	4.26	4.13			
390901	3.95	3.98	3.96	3.97	4.25	4.02			

Table 15.5 Skid Resistance on Ohio SHRP Test Pavement

Section No.	Skid Number (SN40) on Date								
	8/16/96	5/6/97	5/5/98	10/27/98					
SPS-1									
390159	DNA	50.3	53.2	48.9					
390103	DNA	67.3	54.0	55.3					
390110	DNA	69.7	56.3	57.5					
390109	DNA	70.0	54.4	54.9					
390108	DNA	69.0	55.8	55.3					
390105	DNA	72.0	53.1						
390164				52.9					
390160	DNA	71.0	57.2	49.0					
390102	DNA	68.0							
390161			54.9	34.0					
390107	DNA	63.0							
390162			52.0	38.9					
390101	DNA	72.0							
390163			52.6	41.9					
390106	DNA	70.3	56.1	54.8					
390104	DNA	65.7	55.4	53.6					
390111	DNA	69.7	55.7	55.3					
390112	DNA	71.7	56.4	53.8					
SPS-2									
390259	39.7	49.3	39.9	32.2					
390204	45.0	52.3	41.9	30.0					
390212	46.0	58.7	47.4	33.3					
390210	49.3	60.7	49.0	32.3					
390260	52.0	61.0	53.5	41.0					
390202	32.0	54.0	40.7	26.0					
390206	39.3	54.0	42.5	28.6					
390205	49.3	61.0	53.9	41.6					
390201	40.3	59.7	47.6	36.2					
390209	44.3	59.7	49.9	39.6					
390261	43.3	58.3	48.9	38.2					
390211	43.0	57.0	50.0	37.4					
390265	48.3	59.3	50.1	40.3					
390203	45.3	59.0	48.1	38.7					
390207	47.7	57.3	54.3	43.4					
390208	35.0	54.0	37.6	30.3					
390262	47.7	58.3	56.3	45.2					
390263	45.0	58.0	50.4	40.2					
390264	38.3	55.3	53.4	43.9					
SPS-8									
390810 (PCC)	Data Not Available		61.8	57.6					
390809 (PCC)	Data Not Available		63.1	56.9					
390803 (AC)	Data Not Available								
39A803 (AC)			67.8	64.6					
390804 (AC)	Data Not Available								
39A804 (AC)			64.6	62.5					
SPS-9									
390902	DNA	67.0	52.9	55.7					
390903	DNA	74.0	58.0	56.5					
390901	DNA	69.3	57.8	57.4					

obtain the data, although some minor seasonal effects are known to exist.

Replacement Sections

As of the date of this report, a total of six test sections had failed. Four of these sections in SPS-1 were replaced with more robust sections of interest to ODOT. Two AC sections in the SPS-8 experiment were replaced with identical designs, except that lime was added to the subgrade to improve stiffness. Table 15.6 summarizes the pavement buildup, design features and station limits of these replacement sections.

Table 15.6 Design and Station Limits of Replacement Sections

SHRP Section New	SHRP Section Replaced	500 ft SHRP Station Limits		Pavement Buildup	Design Feature
		Start	End		
39A803	390803	19+90	14+90	1.75” TI/ 2.25” TII/ 8” DGAB	No Recycled Material
39A804	390804	13+50	8+50	1.75” TI/ 5.25” TII/ 12” DGAB	No Recycled Material
390161	390102	375+00	370+00	1.25” TI/ 1.75” TII/ 12”ATB/ 4” PATB/ 6” DGAB	SUPERPAVE Level I Design & 20% RAP in both TI and TII
390162	390107	363+00	358+00	1.25” TI/ 1.75” TII/ 12”ATB/ 4” PATB/ 6” DGAB	No Recycled Material & Gravel Coarse Agg. In Both T1 and TII
390163	39010	355+00	350+00	1.25” TIH/ 1.75” TII/ 12”ATB/ 4” PATB/ 6” DGAB	No Recycled Material in TIH, Polymer added to TIH
390164	390105	392+50	387+50	1.75” TI/ 5.25” TII/ 4”PATB/ 8”DGAB/ Geogrid	See Note Below

TI Asphalt Concrete Surface Course
TII Asphalt Concrete Intermediate Course
ATB Asphalt Treated Base
PATB Permeable Asphalt Treated Base
DGAB Dense Graded Aggregate Base
Geogrid Tensar BX1100

Note: Special Design Considerations for section 3901064

PG 64-28 will be the binder used in both TI and TII. The section will have underdrains installed. Bituminous Prime Coat will be used between the PATB and the TII. Tack Coat will be used between the TII and TI. No reclaimed material will be used in the TI or TII mix. Geogrid will be placed between the subgrade and DGAB.

Accumulated Traffic

Figure 15.1 is a plot of accumulated Equivalent Single Axle 18 Kip loads measured by the weigh-in-motion scales mounted in the pavement.

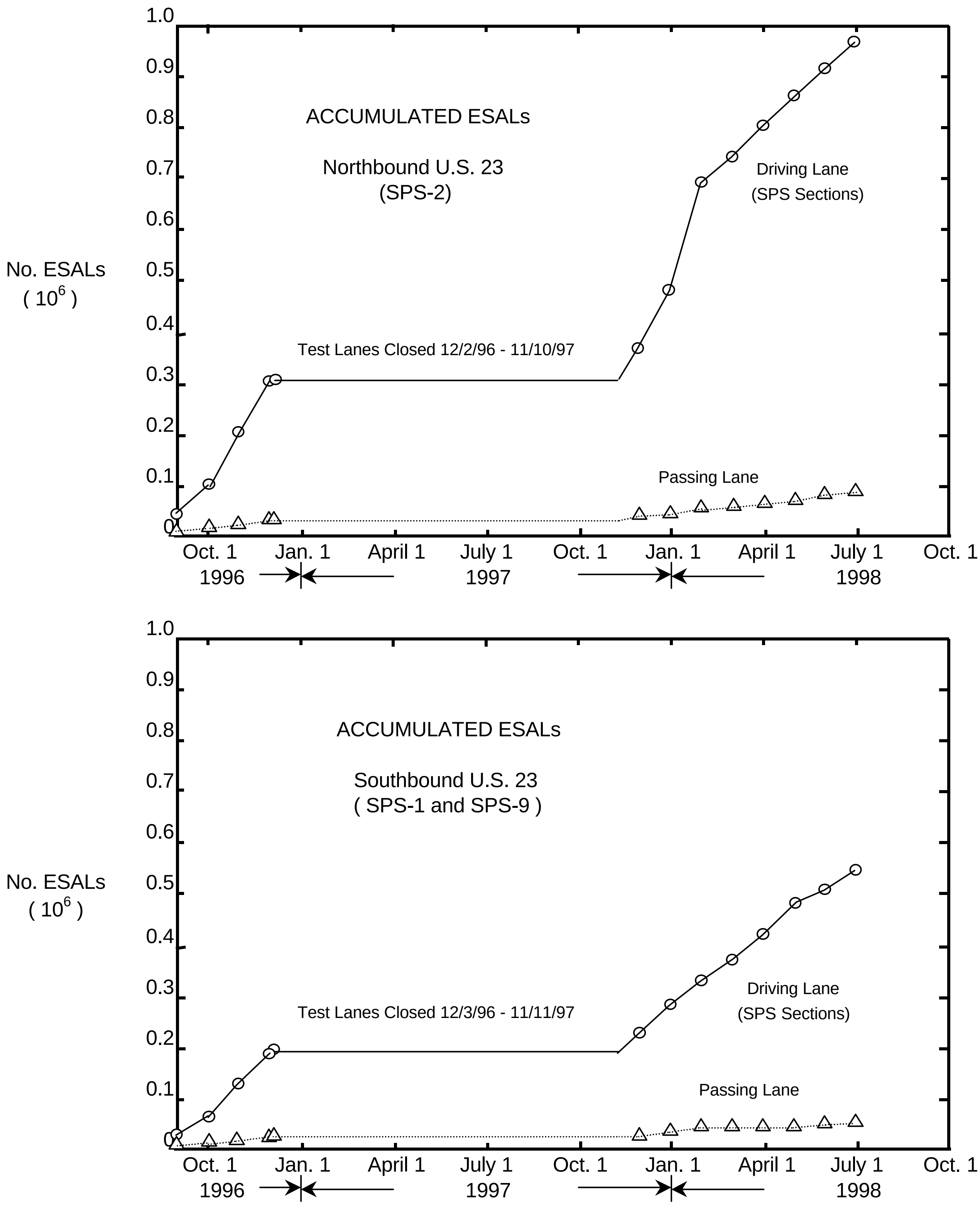

Figure 15.1 Accumulated Equivalent Single Axle 18 Kip Loads

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Appendix A

Ohio SHRP Test Pavement Subgrade Undercuts

OHIO SHRP TEST PAVEMENT
Subgrade Undercuts

Station	Direction	Width (Feet)	Depth (Feet)	Quantity (Cubic Yard)
260+25-261+50	SB	31	2.50	359
264+25-264+70	SB	12	3.00	60
264+70-266+25	SB	25	3.00	431
265+20-271+00	Both	96	0.75	1547
270+20-271+00	NB	20	3.00	222
271+00-277+00	Both	38	0.75	633
277+00-281+00	Both	38	0.75	422
280+60-282+00	NB	38	2.00	384
280+50-281+00	Center	76	1.00	141
281+00-281+75	Center	76	1.20	263
281+00-290+00	SB	38	1.50	1900
281+00-290+00	NB	38	1.00	1267
284+30-286+30	SB	38	5.00	1407
287+80-289+80	SB	38	4.25	1196
290+00-291+85	SB	38	4.00	1041
291+10-291+85	NB	38	3.00	317
291+35-291+85	NB	20	3.00	111
290+00-292+00	NB	38	1.25	352
290+00-300+00	SB	38	0.75	1013
294+00-295+00	NB	38	4.25	598
295+00-295+75	NB	38	2.20	232
301+00-302+00	NB	38	1.00	141
300+00-304+50	SB	38	1.00	633
300+00-305+00	NB	38	0.75	528
305+50-307+00	SB	38	1.00	211
305+61-306+04	SB	23	3.00	79
307+00-309+15	SB	38	9.00	999
307+75-309+00	SB	38	9.00	200
304+50-314+00	SB	38	0.75	1003
312+95-313+70	SB	27	4.00	296
314+80-316+40	SB	16-36	3.50	794
314+50-318+00	NB	38	1.00	493
314+60-318+00	SB	38	1.00	479
318+30-320+00	NB	38	2.00	479
318+70-323+00	SB	38	2.67	1616
321+15-322+00	NB	38	4.00	479
318+50-325+00	SB	38	0.75	686
322+00-324+00	NB	38	4.00	1126
323+00-326+00	SB	38	3.25	1372
324+00-326+00	NB	38	4.00	1126
326+00-330+00	SB	38	4.00	2252
326+00-329+00	NB	38	4.00	1689
318+50-331+00	NB	38	0.75	1319
329+00-331+00	NB	38	4.00	1126
331+00-335+00	NB	38	0.75	422

331+00-332+00	NB	38	4.00	563
325+00-341+00	SB	38	0.75	1689
335+30-339+00	SB	38	3.20	1666
335+00-336+00	NB	38	3.75	528
336+00-340+00	NB	38	3.75	211
340+50-342+00	SB	38	2.25	475
335+00-347+50	NB	38	0.50	880
341+20-342+00	NB	38	3.00	338
342+00-342+80	NB	38	2.50	281
340+00-341+00	NB	38	3.75	525
341+75-342+15	NB	38	1.50	84
342+15-342+25	NB	38	0.50	7
345+20-346+80	SB	38	25.00	563
343+80-345+20	NB	38	3.00	591
346+80-347+17	SB	48	4.00	263
347+25-351+00	NB	38	25.00	1619
347+68-347+98	NB	10	2.00	22
346+80-347+13	NB	47	4.00	230
334+20-353+00	SB	38	0.50	1323
347+20-380+00	SB	38	2.25	887
350+00-352+50	SB	38	2.50	880
351+00-353+00	NB	38	2.25	633
347+50-353+00	NB	38	1.50	1161
353+90-354+02	SB	20	1.50	13
354+50-356+50	SB	38	1.95	494
358+00-363+50	SB	38	3.13	2863
363+85-364+15	NB	60	1.67	111
363+85-364+15	Center	100	1.00	111
357+00-363+85	NB	38	3.29	3172
363+50-367+00	SB	38	1.14	562
367+00-377+00	SB	38	1.90	2674
377+00-377+40	SB	55	2.00	163
364+00-369+00	NB	38	2.74	1928
369+50-377+40	SB	38	2.00	2274
369+00-377+80	NB	50	4.00	5926
392+00-394+50	SB	19	0.60	103
377+80-378+58	NB	28	4.00	324
377+80-378+58	NB	78	4.00	324
377+80-378+44	SB	94	4.00	891
377+50-386+00	NB	38	0.75	897
378+20-380+00	SB	60	3.00	1200
			1.00	400
380+00-382+77	SB	50	1.75	898
			1.21	621
378+20-378+70	NB	80	3.00	444
378+70-382+77	NB	38	2.25	1193
378+40-386+00	SB	38	0.75	760
383+50-389+00	SB	8	3.00	178
284+25-384+60	SB	23	2.50	75
387+40-387+00	NB	38	0.75	866

386+00-395+85	SB	38	0.75	1040
383+50-390+00	NB	38	2.00	1830
390+00-394+00	NB	38	2.60	1464
383+50-395+00	SB	38	2.80	4497
394+00-395+80	NB	38	3.75	950
392+00-394+50	NB	19	0.60	106
396+50-398+50	SB	38	2.50	704
			1.00	281
396+00-414+00	SB	38	0.75	1875
395+30-396+32	SB	27	4.00	380
396+00-401+00	NB	38	1.00	633
396+00-416+00	NB	38	0.75	2055
395+77-396+36	NB	16-31	4.00	347
398+50-401+00	SB	38	2.75	968
401+50-402+00	SB	38	2.00	281
402+00-404+00	NB	38	3.25	915
405+25-406+00	SB	38	2.00	211
403+50-408+50	SB	38	2.30	1619
404+50-408+50	NB	38	0.75	369
409+50-411+50	SB	38	1.00	281
408+50-409+50	SB	38	2.25	317
409+50-411+35	NB	38	2.00	521
408+50-409+50	NB	38	2.60	369
409+25-414+00	SB	38	0.75	501
411+50-412+00	SB	38	2.00	141
414+00-427+00	SB	38	0.75	1372
413+00-420+00	SB	18	2.00	933
415+75-417+50	NB	18	0.75	204
416+00-422+15	SB	38	1.50	1298
416+00-427+00	NB	38	0.75	1161
414+00-420+00	NB	38	1.20	1013
420+00-421+70	NB	38	1.00	239
422+50-423+58	SB	30	1.50	180
423+58-423+81	SB	16	1.50	20
421+00-423+00	SB	18	1.75	367
424+00-427+00	SB	15	1.50	250
425+03-428+00	SB	30	1.50	487

Appendix B

CR7 and CR10 Programs used for Environmental Factors Monitoring

CR7 Program

```
Program:cr7main (CR7 program for standard section)
Reads KM100B strain & temp, LVDT, Carlson, & Thermocoup
Flag Usage:
Input Channel Usage:
Excitation Channel Usage:
Continuous Analog Output Usage:
Control Port Usage:
Pulse Input Channel Usage:
Output Array Definitions:


*      1        Table 1 Programs
  01: 60.0      Sec. Execution Interval

01:  P92        If time is
  01: 0         minutes into a
Time Interval for Taking Readings:
  02: 30        minute interval
  03: 30        Then Do

02:  P78        Resolution
  01: 1         High Resolution

03:  P87        Beginning of Loop
  01: 0         Delay
  02: 5         Loop Count
Begin KM100B Strain Reading

04:  P20        Set Port
  01: 1         Set high
  02: 1         EX Card
  03: 1         Port No.

05:  P87        Beginning of Loop
  01: 0         Delay
  02: 12        Loop Count

06:  P86        Do
  01: 72        Pulse Port 2

07:  P6         Full Bridge
  01: 1         Rep
  02: 13        15 mV fast Range
  03: 2         IN Card
  04: 1         IN Chan
  05: 1         EX Card
  06: 1         EX Chan
  07: 1         Meas/EX
  08: 2500      mV Excitation
  09: 1--       Loc [:strain_#1]
  10: 1.0       Mult
  11: 0.0       Offset

08:  P95        End
```

```
09:  P20       Set Port
  01: 0        Set low
  02: 1        EX Card
  03: 1        Port No.
End KM100B Strain Reading
Begin KM100B Temperature Reading

10:  P20       Set Port
  01: 1        Set high
  02: 1        EX Card
  03: 3        Port No.

11:  P87       Beginning of Loop
  01: 0        Delay
  02: 12       Loop Count

12:  P86       Do
  01: 74       Pulse Port 4

13:  P6        Full Bridge
  01: 1        Rep
  02: 15       150 mV fast Range
  03: 2        IN Card
  04: 2        IN Chan
  05: 1        EX Card
  06: 2        EX Chan
  07: 1        Meas/EX
  08: 2500     mV Excitation
  09: 18--     Loc [:KMtemp_#1]
  10: 1.0      Mult
  11: 0.0      Offset

14:  P95       End

15:  P20       Set Port
  01: 0        Set low
  02: 1        EX Card
  03: 3        Port No.
End KM100B Temperature Reading
Begin Thermocouple Readings

16:  P17       Panel Temperature
  01: 1        IN Card
  02: 35       Loc [:ref_temp ]
```

```
17:  P14       Thermocouple Temp (DIFF)
  01: 6        Reps
  02: 13       15 mV fast Range
  03: 1        IN Card
  04: 1        IN Chan
  05: 1        Type T (Copper-Constantan)
  06: 35       Ref Temp Loc ref_temp
  07: 36       Loc [:TC_temp#1]
  08: 1.0      Mult
  09: 0.0      Offset
End Thermocouple Readings
Begin LVDT Readings

18:  P20       Set Port
  01: 1        Set high
  02: 1        EX Card
  03: 5        Port No.

19:  P87       Beginning of Loop
  01: 0        Delay
  02: 16       Loop Count

20:  P86       Do
  01: 76       Pulse Port 6
LVDT H1,L1

21:  P2        Volt (DIFF)
  01: 1        Rep
  02: 18       5000 mV fast Range
  03: 2        IN Card
  04: 3        IN Chan
  05: 43--     Loc [:LVch1_#1 ]
  06: 1.0      Mult
  07: 0.0      Offset
LVDT H2,L2

22:  P2        Volt (DIFF)
  01: 1        Rep
  02: 18       5000 mV fast Range
  03: 2        IN Card
  04: 4        IN Chan
  05: 60--     Loc [:LVch2_#1 ]
  06: 1.0      Mult
  07: 0.0      Offset

23:  P95       End

24:  P20       Set Port
  01: 0        Set low
  02: 1        EX Card
  03: 5        Port No.
End LVDT Reading
Begin Carlson Reading
```

```
25:  P20      Set Port
  01: 1       Set high
  02: 1       EX Card
  03: 7       Port No.

26:  P87      Beginning of Loop
  01: 0       Delay
  02: 4       Loop Count

27:  P86      Do
  01: 78      Pulse Port 8

28:  P9       Full BR w/Compensation
  01: 1       Rep
  02: 8       5000 mV slow EX Range
  03: 4       50 mV slow BR Range
  04: 2       IN Card
  05: 5       IN Chan
  06: 1       EX Card
  07: 4       EX Chan
  08: 1       Meas/EX
  09: 2000    mV Excitation
  10: 77--    Loc [:carl#1   ]
  11: 1.0     Mult
  12: 0.0     Offset

29:  P95      End

30:  P20      Set Port
  01: 0       Set low
  02: 1       EX Card
  03: 7       Port No.
End Carlson Reading

31:  P32      Z=Z+1
  01: 82      Z Loc [:counter  ]

32:  P89      If X<=>F
  01: 82      X Loc counter
  02: 3       >=
  03: 5       F
  04: 10      Set high Flag 0 (output)

33:  P77      Real Time
  01: 110     Day,Hour-Minute

34:  P71      Average
  01: 80      Reps
  02: 1       Loc strain_#1

35:  P95      End
```

```
36:  P30      Z=F
  01: 0       F
  02: 82      Z Loc [:counter  ]

37:  P95      End

38:  P        End Table 1


*     2       Table 2 Programs
  01: 0.0000  Sec. Execution Interval

01:  P        End Table 2


*     3       Table 3 Subroutines

01:  P        End Table 3


*     4       Mode 4 Output Options
  01: 00      (Tape OFF) (Printer OFF)
  02: 00      Printer 300 Baud


*     A       Mode 10 Memory Allocation
  01: 82      Input Locations
  02: 450     Intermediate Locations


*     C       Mode 12 Security
  01: 00      Security Disabled
  02: 0000    Security Code
```

Input Location Assignments (with comments):

Key:
T=Table Number
E=Entry Number
L=Location Number

```
T:  E:  L:
1:  7:  1:  Loc [:strain_#1]
1: 13: 18:  Loc [:KMtemp_#1]
1: 16: 35:  Loc [:ref_temp ]
1: 17: 36:  Loc [:TC_temp#1]
1: 21: 43:  Loc [:LVch1_#1 ]
1: 22: 60:  Loc [:LVch2_#1 ]
1: 28: 77:  Loc [:carl#1   ]
1: 31: 82:  Z Loc [:counter  ]
1: 36: 82:  Z Loc [:counter  ]
```

Page 7   Input Location Labels:

1:strain_#1	22:__________	43:LVch1_#1	64:CARL #
2:__________	23:__________	44:__________	65:__________
3:__________	24:__________	45:__________	66:__________
4:__________	25:ref_temp	46:__________	67:__________
5:__________	26:TC_temp #	47:__________	68:__________
6:__________	27:TC_Temp #	48:LV_CH2 #	69:counter
7:__________	28:TC_Temp #	49:__________	70:__________
8:__________	29:TC_Temp #	50:__________	71:__________
9:__________	30:TC_Temp #	51:__________	72:__________
10:__________	31:TC_Temp #	52:__________	73:__________
11:__________	32:LV_CH1 #	53:__________	74:__________
12:__________	33:__________	54:__________	75:__________
13:KM_Temp #	34:__________	55:__________	76:__________
14:__________	35:ref_temp	56:__________	77:carl#1
15:__________	36:TC_temp#1	57:__________	78:__________
16:__________	37:__________	58:__________	79:__________
17:__________	38:__________	59:__________	80:__________
18:KMtemp_#1	39:__________	60:LVch2_#1	81:__________
19:__________	40:__________	61:__________	82:counter
20:__________	41:__________	62:__________	83:__________
21:__________	42:__________	63:__________	84:__________

CR10 Program

```
Program:cr10vw
(CR10 program for standard and additional sections)
Reads vibrating wire strain gage strain and temperature
Flag Usage:
Input Channel Usage:
Excitation Channel Usage:
Control Port Usage:
Pulse Input Channel Usage:
Output Array Definitions:


*      1        Table 1 Programs
  01: 60.0     Sec. Execution Interval

01:  P92       If time is
  01: 0        minutes into a
Time Interval for Taking Readings:
  02: 30       minute interval
  03: 30       Then Do

02:  P87       Beginning of Loop
  01: 0        Delay
  02: 5        Loop Count
Begin Vibrating Wire Temperature Readings

03:  P86       Do
  01: 41       Set high Port 1

04:  P87       Beginning of Loop
  01: 0        Delay
  02: 14       Loop Count

05:  P86       Do
  01: 72       Pulse Port 2

06:  P78       Resolution
  01: 0        Low Resolution

07:  P4        Excite,Delay,Volt(SE)
  01: 1        Rep
  02: 15       2500 mV fast Range
  03: 1        IN Chan
  04: 1        Excite all reps w/EXchan 1
  05: 1        Delay (units .01sec)
  06: 2500     mV Excitation
  07: 1--      Loc [:tempR #  ]
  08: 0.001    Mult
  09: 0.0      Offset
```

```
08:  P55      Polynomial
  01: 1       Rep
  02: 1--     X Loc tempR #
  03: 15--    F(X) Loc [:temp_#   ]
  04: -104.78 C0
  05: 378.11  C1
  06: -611.59 C2
  07: 544.27  C3
  08: -240.91 C4
  09: 43.089  C5
End Vibrating Wire Temperature Readings
Begin Vibrating Wire Strain Readings

09:  P78      Resolution
  01: 1       High Resolution

10:  P28      Vibrating Wire (SE)
  01: 1       Rep
  02: 2       IN Chan
  03: 1       Excite all reps w/EXchan 1
  04: 24      Starting Freq. (units=100 Hz)
  05: 31      End Freq. (units=100 Hz)
  06: 500     No. of Cycles
  07: 500     Rep delay (units=.01sec)
  08: 29--    Loc [:read_#   ]
  09: 1.0     Mult
  10: 0.0     Offset

11:  P95      End

12:  P86      Do
  01: 51      Set low Port 1
End Vibrating Wire Strain Readings

13:  P32      Z=Z+1
  01: 48      Z Loc [:counter  ]

14:  P89      If X<=>F
  01: 48      X Loc counter
  02: 3       >=
  03: 5       F
  04: 10      Set high Flag 0 (output)

15:  P77      Real Time
  01: 110     Day,Hour-Minute

16:  P71      Average
  01: 28      Reps
  02: 15      Loc temp_#

17:  P95      End
```

```
18:  P30      Z=F
  01: 0       F
  02: 0       Exponent of 10
  03: 48      Z Loc [:counter  ]

19:  P95      End

20:  P        End Table 1


*     2       Table 2 Programs
  01: 0.0000  Sec. Execution Interval

01:  P        End Table 2


*     3       Table 3 Subroutines

01:  P        End Table 3


*     A       Mode 10 Memory Allocation
  01: 71      Input Locations
  02: 200     Intermediate Locations
  03: 0.0000  Final Storage Area 2


*     C       Mode 12 Security
  01: 0       LOCK 1
  02: 0       LOCK 2
  03: 0000    LOCK 3
```

Input Location Assignments (with comments):

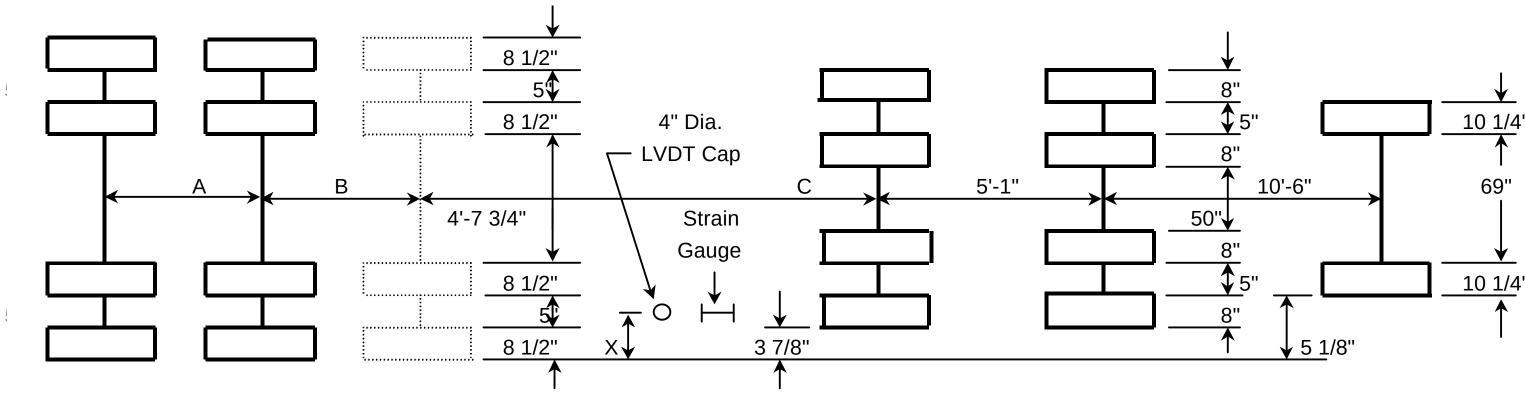
```
Key:
T=Table Number
E=Entry Number
L=Location Number

T:  E:  L:
1:  7:  1:  Loc [:tempR #  ]
1:  8: 15:  F(X) Loc [:temp_#   ]
1: 10: 29:  Loc [:read_#   ]
1: 13: 48:  Z Loc [:counter  ]
1: 18: 48:  Z Loc [:counter  ]
```

Page 5   Input Location Labels:

1:tempR #	15:temp_#	29:read_#	43:TC_Temp_#
2:_________	16:_________	30:_________	44:_________
3:_________	17:_________	31:_________	45:_________
4:_________	18:temp_#	32:_________	46:_________
5:_________	19:_________	33:_________	47:_________
6:_________	20:_________	34:_________	48:counter
7:_________	21:_________	35:read #	49:_________
8:_________	22:_________	36:_________	50:_________
9:_________	23:_________	37:_________	51:_________
10:_________	24:read #	38:_________	52:_________
11:_________	25:_________	39:_________	53:_________
12:_________	26:_________	40:_________	54:_________
13:_________	27:_________	41:_________	55:counter
14:_________	28:_________	42:_________	56:_________

Appendix C

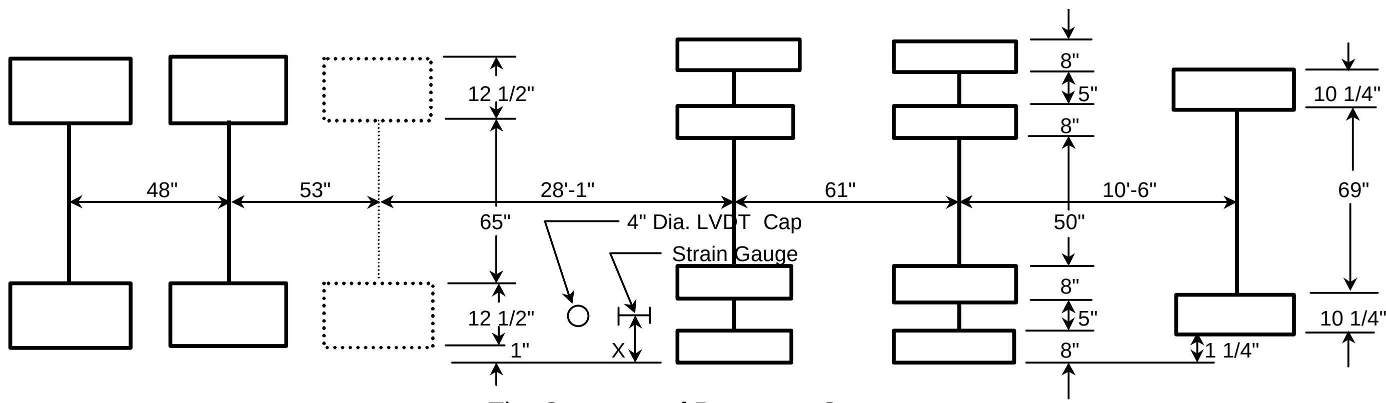
Relative Geometry of Tire Spacing



Tire Coverage of Pavement Sensors

Trailer Axles		Tractor Axles		Steering Axle	
Offset X (in.)	Tire Position	Offset X (in.)	Tire Position	Offset X (in.)	Tire Position
Longitudinal Strain Gauges					
<0	Dual tires inside gauge	< 3 7/8	Dual tires inside gauge	< 5 1/8	Tire inside gauge
0 to 8 1/2	Outer tire over gauge	3 7/8 to 11 7/8	Outer tire over gauge	5 1/8 to 15 3/8	Tire over gauge
8 5/8 to 13 3/8	Dual tires straddle gauge	12 to 16 3/4	Dual tires straddle gauge	> 15 3/8	Tire outside gauge
13 1/2 22	Inner tire over gauge	16 7/8 to 24 7/8	Inner tire over gauge		
> 22	Dual tires outside gauge	> 24 7/8	Dual tires outside gauge		
LVDT Caps					
< -1 7/8	Dual tires inside cap	< 2	Dual tires inside cap	< 3 1/4	Tire inside cap
- 1 7/8 to 1 7/8	Partial coverage, outer edge, outer tire	2 to 5 3/4	Partial coverage, outer edge, outer tire	3 1/4 to 7	Partial coverage, outer edge
2 to 6 1/2	Full coverage, outer tire	5 7/8 to 9 7/8	Full coverage, outer tire	7 1/8 to 13 3/8	Full coverage
6 5/8 to 10 3/8	Partial coverage, inner edge, outer tire	10 to 13 3/4	Partial coverage, inner edge, outer tire	13 1/2 to 17 1/4	Partial coverage, inner edge
10 1/2 to 11 1/2	Dual tires straddle cap	13 7/8 to 14 7/8	Dual tires straddle cap	> 17 1/4	Tire outside cap
11 5/8 to 15 3/8	Partial coverage, outer tire, inner tire	15 to 18 3/4	Partial coverage, outer edge, inner tire		
15 1/2 to 20	Full coverage, inner tire	18 7/8 to 22 7/8	Full coverage, outer tire		
20 1/8 to 23 7/8	Partial coverage, inner edge, inner tire	23 to 26 3/4	Partial coverage, inner edge, inner tire		
> 23 7/8	Dual tires outside cap	> 26 3/4			

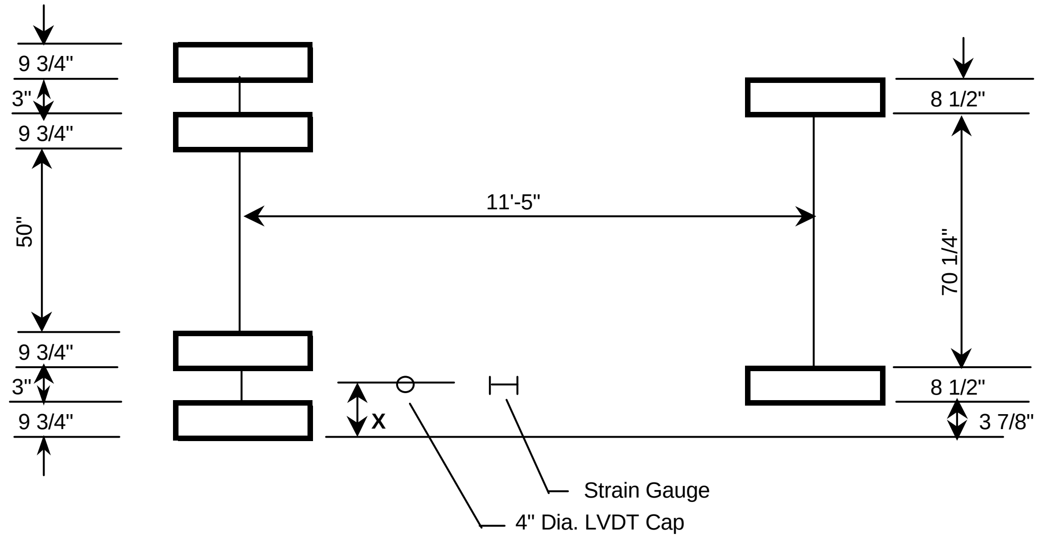
Figure C1 Tire Spacing and Coverage - CNRC Truck with Tandem/Tridem Axles and Dual Tires



Tire Coverage of Pavement Sensors

Trailer Axles		Tractor Axles		Steering Axle	
Offset X (in.)	Tire Position	Offset X (in.)	Tire Position	Offset X (in.)	Tire Position
Longitudinal Strain Gauges					
< 1	Tire inside gauge	< 0	Dual tires inside gauge	< 1 1/4	Tire inside gauge
1 to 13 1/2	Tire over gauge	0 to 8	Outer tire over gauge	1 1/4 to 11 1/2	Tire over gauge
> 13 1/2	Tire outside gauge	8 1/8 to 12 7/8	Dual tires straddle gauge	> 11 1/2	Tire outside gauge
		13 to 21	Inner tire over gauge		
		> 21	Dual tires outside gauge		
LVDT Caps					
< -7/8	Tire inside cap	< -1 7/8	Dual tires inside cap	< -5/8	Tire inside cap
-7/8 to2 7/8	Partial coverage, outer edge	-1 7/8 to 1 7/8	Partial coverage, outer edge, outer tire	-5/8 to 3 1/8	Partial coverage, outer edge
3 to 11 1/2	Full coverage	2 to 6	Full coverage, outer tire	3 1/4 to 9 1/2	Full coverage
11 5/8 to 15 3/8	Partial coverage, inner edge	6 1/8 to 9 7/8	Partial coverage, inner edge, outer tire	9 5/8 to 13 3/8	Partial coverage, inner edge
> 15 3/8	Tire outside cap	10 to 11	Dual tires straddle cap	> 13 3/8	Tire outside cap
		11 1/8 to 14 7/8	Partial coverage, outer edge, inner tire		
		15 to 19	Full coverage, inner tire		
		19 1/8 to 22 7/8	Partial coverage,inner edge, inner tire		
		> 22 7/8	Dual tires outside cap		

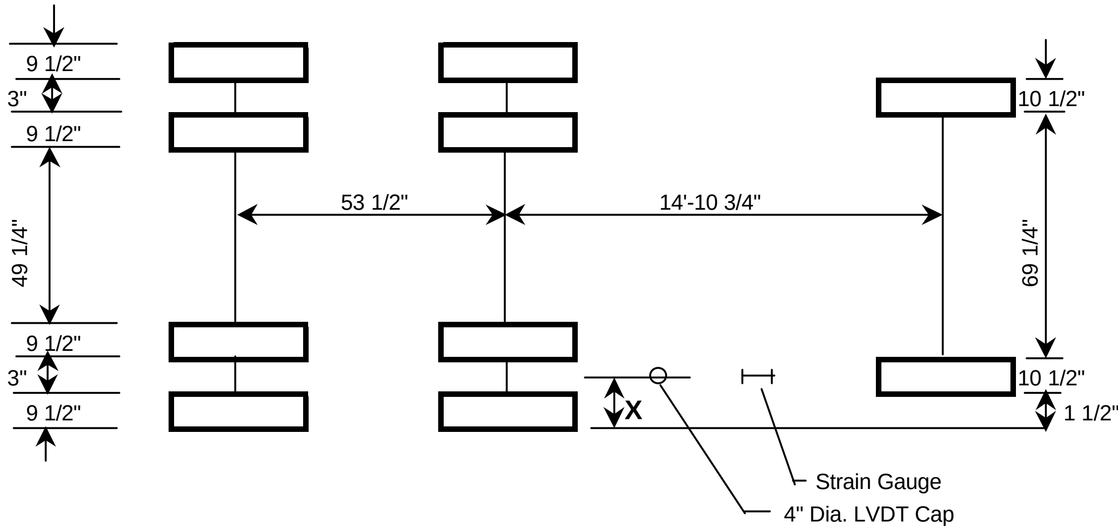
Figure C2 Tire Spacing and Coverage - CNRC Truck with Tandem/Tridem Axles and Super Single Tires



Tire Coverage of Pavement Sensors

Rear Axle		Steering Axle	
Offset X (in.)	Tire Position	Offset X (in.)	Tire Position
Longitudinal Strain Gauges			
< 0	Dual tires inside gauge	< 3 7/8	Tire inside gauge
0 to 9 3/4	Outer tire over gauge	3 7/8 to 12 3/8	Tire over gauge
9 7/8 to 12 5/8	Dual tires straddle gauge	> 12 3/8	Tire outside gauge
12 3/4 to 22 1/2	Inner tire over gauge		
> 22 1/2	Dual tires outside gauge		
LVDT Caps			
< -1 7/8	Dual tires inside cap	< 1 3/4	Tire inside cap
-1 7/8 to 1 7/8	Partial coverage, outer edge, outer tire	1 3/4 to 5 1/2	Partial coverage, outer edge
2 to 7 3/4	Full coverage, outer tire	5 5/8 to 10 1/8	Full coverage
7 7/8 to 10 3/4	Partial coverage, inner edge, outer tire	10 1/4 to 14	Partial coverage, inner edge
10 7/8 to 11 5/8	Partial coverage, both tires	>14	Tire outside cap
11 3/4 to 14 5/8	Partial coverage, outer edge, inner tire		
14 3/4 to 20 1/2	Full coverage, inner tire		
20 5/8 to 24 3/8	Partial coverage, inner edge, inner tire		
> 24 3/8			

Figure C3 Tire Spacing and Coverage - ODOT Single-Axle Dump Truck



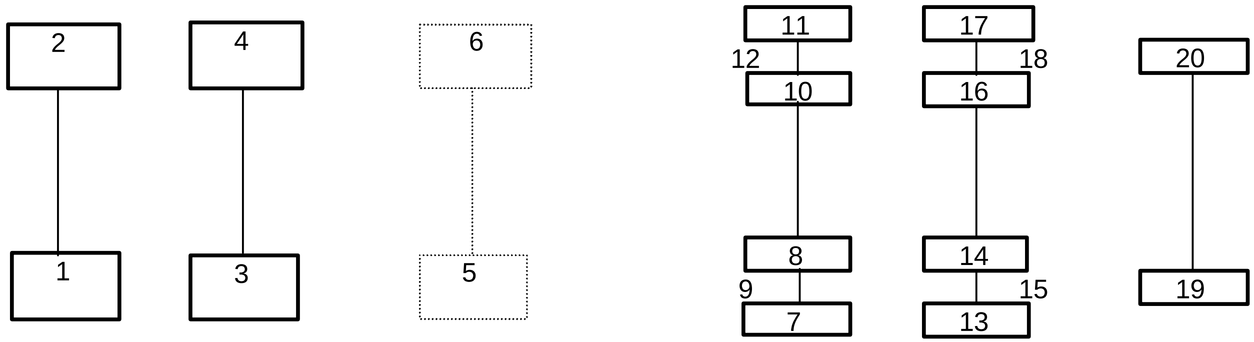
Tire Coverage of Pavement Sensors

Rear Axles		Steering Axle	
Offset X (in.)	Tire Position	Offset X (in.)	Tire Position
Longitudinal Strain Gauges			
< 0	Dual tires inside gauge	< 1 1/2	Tire inside gauge
0 to 9 1/2	Outer tire over gauge	1 1/2 to 12	Tire over gauge
9 5/8 to 12 3/8	Dual tires straddle gauge	> 12	Tire outside gauge
12 1/2 to 22	Inner tire over gauge		
> 22	Dual tires outside gauge		
LVDT Caps			
< -1 7/8	Dual tires inside cap	< -3/8	Tire inside cap
-1 7/8 to 1 7/8	Partial coverage, outer edge, outer tire	-3/8 to 3 3/8	Partial coverage, outer edge
2 to 7 1/2	Full coverage, outer tire	3 1/2 to 10	Full coverage
7 5/8 to 10 1/2	Partial coverage, inner edge, outer tire	10 1/8 to 13 7/8	Partial coverage, inner edge
10 5/8 to 11 3/8	Partial coverage, both tires	> 13 7/8	Tire outside cap
11 1/2 to 14 3/8	Partial coverage, outer edge, inner tire		
14 1/2 to 20	Full coverage, inner tire		
20 1/8 to 23 7/8	Partial coverage, inner edge, inner tire		
> 23 7/8	Dual tires outside cap		

Figure C4 Tire Spacing and Coverage - ODOT Tandem-Axle Dump Truck

Appendix D

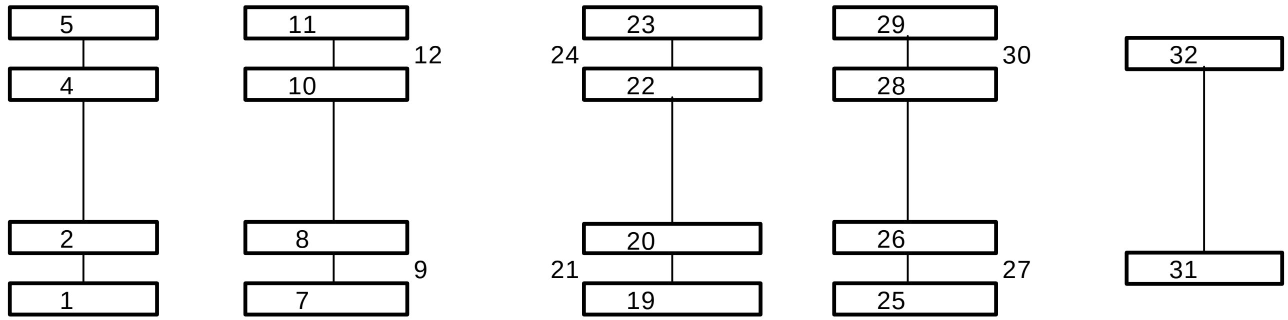
Truck Weights



Test Series	Date	Load I.D.	Wheel Load (K)																			
			1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
			Tandem																			
3	6/17,19/96	XA,Y	9850	8000	9650	8400			6600	6950	13550			11200	6400	7650	14050			11850	6700	6750
3	6/20/96	Z	10650	9050	10700	9500			6250	6650	12900			11450	6400	6700	13100			11750	6900	7100
3	6/23/96	C	9900	8850	10150	8750			6550	6550	13100			11900	6600	6550	13150			12250	6550	6950
3	6/25/96	F	8400	7600	8400	7750			3000	2900	5900			5400	3100	3150	6250			5100	5850	6300
3	6/25/96	G	6900	6550	7150	6150			1850	1650	3500			3250	1800	1600	3400			3300	5550	5700
			Tridem																			
1	3/15/96	J	8650	9700	9250	8800	10100	7750			7100*			7100*			7125*			7125*	5700*	5700*
1	3/16/96	K	7150	7000	7225	6800	7100	7250			11700			13550			12450			10200	5750	7050
1	3/16/96	L	8700	7900	8100	8000	8000	8200			5000			4925			5400			5175	5100	5400
3	6/24/96	D	8950	8150	8750	8100	9000	7550	3900	3750	7650			7000	3800	4350	8150			6850	5650	5950
3	6/24/96	E	6000	5600	5950	5650	6100	5350	2700	2450	5150			4700	2650	2900	5550			4650	5400	5600

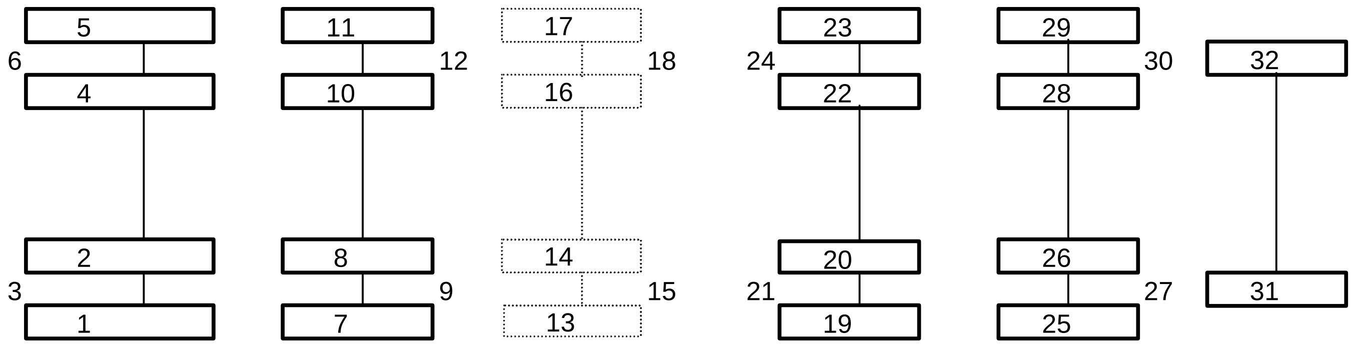
* One half of reported axle load

Figure D1 Tire Loads - CNRC Truck with Tandem/Tridem Axles and Super Single Tires



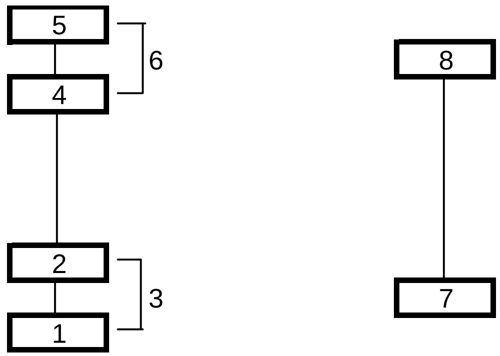
Test Series	Date	Load I.D.	Wheel Load (K)											
			1	2	3	4	5	6	7	8	9	10	11	12
1	12/5,6/95	A	4600	5200	9800	4725	3800	8525	4625	4725	9350	4750	3900	8650
1	12/6/95	B	4850	5350	10200	5050	4000	9050	4500	5300	9800	5200	3700	8900
1	12/7/95	C	4400	4700	9100	4650	3650	8300	4400	4600	9000	4750	3300	8050
1	12/8/95	D	5650	5500	11150	5700	4500	10200	5300	6150	11450	5950	3900	9850
1	12/11,14/95	E	4950	5375	10325	5200	4400	9600	4750	5450	10200	5225	4350	9575
3	6/4,5/97	A	6400	7050	13450			12050	6600	6950	13550			12150
3	6/9,10/97	B,BA	4550	5300	9850			8300	4850	4950	9800			8300
3	6/26/97	H	3350	3850	7200			6550	3550	3650	7200			6350
			19	20	21	24	25	26	27	30	31	32		
1	12/5,6/95	A			11000	9700			9500	11300	6250	6075		
1	12/6/95	B			9700	9725			9900	10050	6150	6450		
1	12/7/95	C			11050	10350			10350	11400	6025	6225		
1	12/8/95	D			13200	11250			10750	13700	6600	6150		
1	12/11,14/95	E			11000	9000			9500	9000	5650	5650		
3	6/4,5/97	A	8000	8550	16550	14750	7500	8300	15800	14750	6900	7500		
3	6/9,10/97	B,BA	6650	6800	13450	12100	6450	7350	13800	12650	6200	6600		
3	6/26/97	H	1800	1700	3500	3400	2050	1950	4000	3300	5300	5500		

Figure D2 Tire Loads - CNRC Truck with Tandem Axles and Dual Tires



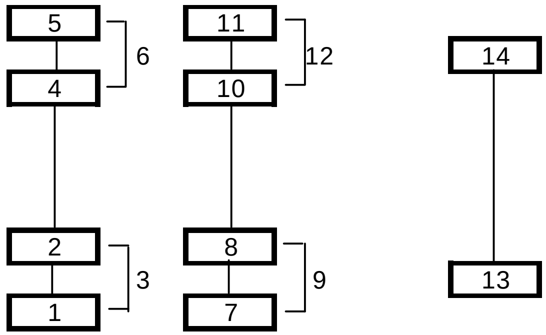
Test Series	Date	Load I.D.	Wheel Load (K)																	
			1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
1	12/15/95	F	3200	3600	6800	3600	4000	7600			6850			7400	3350	3500	6850	3650	3800	7450
1	12/15/95	G			8875			9750			8900			9250			9875			8250
1	3/13/96	H			7850			8850			8225			8175			8800			7250
1	3/13,14/96	I			8875			9750			8900			9250			9875			8250
			19	20	21	22	23	24	25	26	27	28	29	30	31	32				
1	12/15/95	F			####			####			####			####	5650	6950				
1	12/15/95	G			6750			7450			7450			6800	5450	5950				
1	3/13/96	H			5200			4800			5400			5100	5350	5700				
1	3/13,14/96	I			6750			7450			7450			6800	5450	5950				

Figure D3 Tire Loads - CNRC Truck with Tridem Axles and Dual Tires



Test Series	Test Date	Load I.D.	Wheel Load (K)									
			1	2	3	4	5	6	R. Axle	7	8	F. Axle
2	8/2,3/96	A			3770			3840	7610			
2	8/5,6/96	B			9150			9335	18485	4690	4660	9350
2	8/6,7/96	C			8870			9580	18450	4760	4850	9610
2	8/9/96	D			10680			11550	22230	4760	4850	9610
2	8/12/96	A			10680			11550	22230	4760	4850	9610
2	8/13/96	A			10930			10160	21090			
2	8/14/96	B			9290			8810	18100	4690	4820	9510
4	7/2/97	K	3300	5400	8700			8650	17350	4250	4300	8550
4	7/3/97	L	5350	7750	13100			11850	24950	4450	4450	8900
4	7/29,30/97	M,N	4950	6350	11300			10150	21450	3650	3600	7250
4	7/30,8/6/97	O,P	5700	7550	13250			12100	25350	3950	3750	7700
5	10/9,14/98	98A,B	4150	5300	9450	4850	4100	8950	18400	4750	4650	9400
5	10/14,15/98	98C,D	5300	6750	12050	6700	5250	11950	24000	4800	4600	9400
5	10/19/98	98E	5300	6750	12050	6700	5250	11950	24000	4800	4600	9400
5	10/20/98	98F	4650	5800	10450	6000	4200	10200	20650	4900	4750	9650

Figure D4 Tire Loads - ODOT Single-Axle Dump Truck



Test Series	Date	Load I.D.	Wheel Load (K)													
			1	2	3	4	5	6	7	8	9	10	11	12	13	14
2	8/2,3/96	A			8050			8180			8120			8500	7360	7850
2	8/5,6/96	B			10220			11160			10550			10590	8220	8770
2	8/12,13/96	A			10220			11160			10550			10590	8220	8770
2	8/14/96	B			7750			8250			8010			8530	7030	7680
					3159			3158			3050			3030		
					11350			10700			11800			10300		
3	6/4,5/97	A	6700	3250	9950			9500	4650	6450	11100			9700	8150	8050
3	6/9,10,19/97	B,BA,Y	4000	4350	8350			7800	4250	4600	8850			8000	6600	6450
3	6/20,23,24/9	Z,C,D	3800	4500	8300			7800	3950	5150	9100			7800	6700	6500
3	6/24,25/97	E,F	2200	2700	4900			4550	2400	3400	5800			4200	6000	5800
3	6/25,26/97	G,H	1200	1750	2950			3000	1550	2150	3700			2900	5500	5500
4	7/2/97	K	3900	4950	8850			7250	4200	5250	9450			7450	7300	7200
4	7/3/97	L	5500	7100	12600			11700	5700	7050	12750			12400	8400	8600
4	7/29,30/97	M,N	4050	5200	9250			8250	4350	5400	9750			8600	7550	7550
4	7/30,8/6/97	O,P	5300	6000	11300			10750	5900	6350	12250			10800	8350	8250
5	10/9,14/98	A,B	3750	3650	7400	5600	2750	8350	3100	5300	8400	5150	3100	8250	6700	6850
5	10/14,15/98	C,D	4600	4550	9150	6200	3400	9600	3650	5850	9500	6100	4000	10100	7500	7500
5	10/19/98	E	4600	4550	9150	6200	3400	9600	3650	5850	9500	6100	4000	10100	7500	7500

Figure D5 Tire Loads - ODOT Tandem-Axle Dump Truck

Appendix E

Falling Weight Deflectometer and Dynaflect Test Results

Table E1 Normalized FWD Profile of New AC Test Sections

Section No.	Test Date	Pvt. Surf. Temp (*F)	Test Path	Avg. Load (K)	Normalized Df1 Deflection (mils) at Station											Average Midlane (mils)	Average RWP (mils)
					0+00	0+50	1+00	1+50	2+00	2+50	3+00	3+50	4+00	4+50	5+00		
Southbound SPS-1																	
390101	6/11/96	75	Midlane	9.23	1.39	1.60	1.50	1.66	1.56	1.59	2.08	1.51	1.53	1.85	1.85	1.65	
			RWP	9.18	1.46	1.52	1.48	1.53	1.50	1.61	2.17	1.50	1.49	1.68	1.71		1.60
390102	6/11/96	74	Midlane	9.49	3.14	2.78	3.25	3.70	4.00	3.54	3.68	3.13	3.06	4.38	3.87	3.50	
			RWP	9.42	3.36	2.82	3.02	3.36	3.63	3.68	3.61	2.74	2.55	3.51	3.11		3.22
390103	6/10/96	86	Midlane	9.52	1.22	1.04	1.18	1.09	1.12	0.98	1.03	1.09	1.16	1.15	0.96	1.09	
			RWP	9.48	1.42	1.20	1.36	1.27	1.26	1.21	1.19	1.22	1.32	1.26	1.06		1.25
390104	6/11/96	75	Midlane	9.41	0.46	0.41	0.47	0.46	0.47	0.48	0.42	0.48	0.43	0.43	0.41	0.45	
			RWP	9.32	0.46	0.42	0.41	0.51	0.48	0.50	0.48	0.47	0.46	0.44	0.48		0.46
390105	6/11/96	70	Midlane	9.67	1.39	1.27	1.30	1.33	1.20	1.46	1.31	1.26	1.25	1.55	1.61	1.36	
			RWP	9.47	1.55	1.35	1.26	1.29	1.33	1.47	1.41	1.20	1.34	1.59	1.48		1.39
390106	6/11/96	75	Midlane	9.35	0.61	0.59	0.60	0.52	0.56	0.53	0.56	0.52	0.49	0.56	0.54	0.55	
			RWP	9.26	0.68	0.64	0.60	0.58	0.58	0.53	0.56	0.53	0.58	0.55	0.58		0.58
390107	6/11/96	75	Midlane	9.21	1.90	1.96	2.35	2.09	2.37	1.99	1.87	2.30	1.93	2.34	2.21	2.12	
			RWP	9.19	1.77	1.74	2.25	1.77	2.19	1.74	1.79	1.75	1.79	2.07	2.04		1.90
390108	6/11/96	68	Midlane	9.81	1.11	1.03	1.10	0.85	0.93	0.79	0.86	1.02	0.96	0.77	1.12	0.96	
			RWP	9.80	1.14	1.06	1.09	0.91	0.98	0.85	0.87	0.88	0.91	0.77	1.10		0.96
390109	6/11/96	68	Midlane	10.06	1.02	1.07	0.88	0.88	1.10	1.02	0.91	0.88	0.94	1.01	1.10	0.98	
			RWP	9.78	0.99	1.01	0.92	1.02	1.23	1.20	1.02	0.90	0.94	1.00	1.04		1.02
390110	6/10/96	94	Midlane	9.45	0.99	0.86	0.85	0.94	0.85	0.94	1.00	1.01	1.02	1.10	1.12	0.97	
			RWP	9.65	1.03	0.95	0.95	0.97	1.02	0.97	1.12	1.01	1.04	1.16	1.14		1.03
390111	6/11/96	72	Midlane	9.20	0.54	0.62	0.68	0.61	0.63	0.66	0.74	0.71	0.76	0.82	0.73	0.68	
			RWP	9.22	0.56	0.64	0.68	0.65	0.68	0.71	0.73	0.72	0.77	0.82	0.75		0.70
390112	6/11/96	72	Midlane	9.32	0.51	0.57	0.55	0.53	0.57	0.55	0.52	0.48	0.53	0.49	0.52	0.53	
			RWP	9.37	0.44	0.50	0.52	0.51	0.51	0.53	0.49	0.49	0.52	0.46	0.41		0.49
390159			Midlane														
			RWP														
390160	6/11/96	70	Midlane	9.85	0.51	0.59	0.52	0.48	0.48	0.48	0.46	0.40	0.59	0.46	0.56	0.50	
			RWP	9.98	0.56	0.62	0.51	0.45	0.46	0.49	0.44	0.37	0.57	0.48	0.55		0.50
390161	11/5/97	42	Midlane	9.55	0.36	0.43	0.28	0.31	0.29	0.29	0.28	0.29	0.28	0.37		0.32	
(390102)			RWP	9.39	0.29	0.30	0.34	0.29	0.33	0.32	0.32	0.30	0.32	0.28	0.32		0.31
390162	10/27/97	41	Midlane	10.00	0.27	0.29	0.29	0.31	0.29	0.28	0.27	0.27	0.28	0.25		0.28	
(390107)			RWP	9.47	0.29	0.29	0.33	0.34	0.35	0.31	0.29	0.31	0.28	0.30	0.29		0.31
390163	10/27/97	41	Midlane	9.62	0.30	0.24	0.29	0.26	0.30	0.29	0.26	0.29	0.31	0.36		0.29	
(390101)			RWP	9.76	0.29	0.26	0.25	0.28	0.26	0.28	0.32	0.29	0.34	0.34	0.34		0.30
390164	10/2.98	47	Midlane	9.10	1.52	1.53	1.25	1.13	1.05	1.22	1.13	1.46	1.65	1.42		1.34	
(390105)			RWP	9.23	1.49	1.49	1.40	1.40	1.05	1.21	1.12	1.32	1.49	1.43	1.48		1.35

Ramp SPS-8																	
390803	11/16/94	50	Midlane	9.52	2.35	2.06	2.01	2.45	1.93	2.03	1.76	1.81	2.01	1.97		2.04	
			RWP	9.80	2.46	2.29	2.10	2.49	2.07	2.01	2.00	1.56	2.13	1.96	1.94		2.09
390804	11/16/94	50	Midlane	9.70	1.22	1.11	1.07	1.02	1.11	1.13	1.11	1.02	1.11	1.09		1.10	
			RWP	9.85	1.15	1.15	1.07	1.00	1.11	1.09	1.05	1.04	1.05	1.05	1.04		1.07
39A803			Midlane														
(390803)			RWP														
39A804			Midlane														
(390804)			RWP														
Southbound SPS-9																	
390901	6/11/96	72	Midlane	9.35	0.45	0.37	0.45	0.42	0.37	0.38	0.38	0.37	0.39	0.39	0.43	0.40	
			RWP	9.29	0.40	0.43	0.46	0.41	0.39	0.39	0.40	0.38	0.42	0.37	0.45		0.41
390902	6/11/96	72	Midlane	9.36	0.41	0.38	0.46	0.46	0.49	0.50	0.49	0.45	0.44	0.43	0.41	0.45	
			RWP	9.34	0.43	0.39	0.50	0.46	0.46	0.49	0.47	0.43	0.43	0.44	0.45		0.45
390903	6/11/96	72	Midlane	9.60	0.42	0.45	0.50	0.49	0.52	0.44	0.44	0.44	0.42	0.40	0.45	0.45	
			RWP	9.58	0.44	0.44	0.45	0.49	0.49	0.46	0.43	0.48	0.44	0.40	0.48		0.45

Table E2 Normalized FWD Profile of New PCC Test Sections

Section No.	Test Date	Pvt. Surf. Temp (*F)	Test Path	Avg. Load (K)	Normalized Df1 Deflection (mils) at Station											Average Midlane (mils)	Average RWP (mils)
					0+00	0+50	1+00	1+50	2+00	2+50	3+00	3+50	4+00	4+50	5+00		
Northbound SPS-2																	
390201	6/12/96	80	Midlane	12.08	0.72	0.51	0.59	0.71	0.61	0.47	0.56	0.58	0.58	0.52	0.52	0.58	
			RWP-Jt*	12.00	.51/.58		.70/.75		.71/.75		.62/.69		.65/.70		.70/.72		.65/.70
390202	6/12/96	74	Midlane	12.18	0.49	0.62	0.54	0.46	0.44	0.54	0.61	0.50	0.54	0.58	0.57	0.54	
			RWP-Jt*	12.24	.50/.53		.59/.62		.46/.47		.62/.61		.75/.72		.53/.60		.58/.59
390203	6/19/96	76	Midlane	11.46	0.31	0.33	0.36	0.32	0.31	0.30	0.30	0.28	0.33	0.32	0.28	0.31	
			RWP-Jt*	11.39	.34/.35		.47/.43		.37/.37		.37/.40		.41/.46		.38/.38		.39/.40
390204	6/12/96	64	Midlane	12.22	0.35	0.25	0.29	0.26	0.24	0.24	0.27	0.26	0.27	0.26	0.28	0.27	
			RWP-Jt*	11.94	.47/.48		.49/.49		.50/.48		.52/.48		.46/.51		.49/.49		.49/.49
390205	6/12/96	77	Midlane	12.12	0.52	0.43	0.40	0.47	0.46	0.46	0.38	0.47	0.57	0.41	0.51	0.46	
			RWP-Jt*	12.20	.41/.41		.36/.41		.42/.46		.32/.30		.44/.44		.41/.41		.39/.41
390206	6/12/96	77	Midlane	12.17	0.49	0.54	0.50	0.50	0.31	0.55	0.52	0.30	0.34	0.44	0.60	0.46	
			RWP-Jt*	12.18	.47/.52		.49/.48		.38/.43		.50/.53		.35/.38		.41/.44		.43/.46
390207	6/19/96	76	Midlane	11.87	0.26	0.20	0.20	0.16	0.18	0.18	0.24	0.22	0.23	0.27	0.21	0.21	
			RWP-Jt*	12.19	.24/.29		.31/.28		.19/.18		.22/.23		.25/.24		.18/.25		.23/.25
390208	6/19/96	82	Midlane	11.57	0.21	0.29	0.25	0.20	0.30	0.22	0.22	0.24	0.28	0.25	0.24	0.25	
			RWP-Jt*	11.57	.25/.26		.32/.34		.30/.28		.27/.25		.26/.25		.24/.26		.27/.27
390209	6/19/96	74	Midlane	12.93	0.45	0.43	0.43	0.37	0.45	0.41	0.32	0.40	0.42	0.42	0.39	0.41	
			RWP-Jt*	12.37	.55/.54		.55/.59		.50/.53		.44/.50		.52/.59		.44/.45		.50/.53
390210	6/12/96	69	Midlane	12.43	0.51	0.36	0.42	0.42	0.39	0.40	0.39	0.41	0.37	0.40	0.37	0.40	
			RWP-Jt*	12.22	.64/.75		.49/.51		.51/.65		.52/.54		.47/.51		.43/.44		.51/.57
390211	6/19/96	76	Midlane	11.97	0.28	0.28	0.26	0.27	0.25	0.29	0.26	0.27	0.25	0.31	0.26	0.27	
			RWP-Jt*	11.89	.41/.46		.43/.53		.32/.41		.44/.44		.35/.41		.34/.39		.38/.44
390212	6/12/96	68	Midlane	11.78	0.30	0.27	0.25	0.26	0.28	0.25	0.30	0.31	0.30	0.29	0.29	0.28	
			RWP-Jt*	12.26	.38/.39		.39/.42		.35/.42		.38/.41		.39/.43		.38/.40		.38/.41
390259	6/12/96	64	Midlane	13.42	0.31	0.30	0.24	0.24	0.24	0.29	0.29	0.25	0.28	0.27	0.25	0.27	
			RWP-Jt*	13.21	.43/.59		.44/.41		.42/.43		.45/.39		.43/.39		.47/.41		.44/.44
390260	6/12/96	69	Midlane	12.07	0.28	0.27	0.28	0.27	0.26	0.28	0.30	0.26	0.29	0.29	0.27	0.28	
			RWP-Jt*	12.18	.36/.34		.35/.37		.30/.32		.35/.38		.29/.35		.29/.33		.32/.35
390261	6/19/96	74	Midlane	12.18	0.20	0.21	0.23	0.21	0.25	0.23	0.22	0.24	0.23	0.23	0.25	0.23	
			RWP-Jt*	11.90	.42/.42		.28/.29		.27/.30		.30/.36		.28/.30		.33/.34		.31/.34
390262	6/19/96	82	Midlane	11.84	0.20	0.22	0.20	0.20	0.20	0.25	0.23	0.27	0.25	0.27	0.26	0.23	
			RWP-Jt*	11.98	.27/.27		.29/.28		.29/.30		.30/.29		.36/.33		.34/.32		.31/.30
390263	6/19/96	82	Midlane	11.67	0.33	0.29	0.32	0.31	0.29	0.29	0.33	0.28	0.30	0.34	0.32	0.31	

			RWP-Jt*	11.48	.41/.40		.38/.39		.39/.37		.37/.38		.37/.37		.40/.39		.39/.38
390264			Midlane														
			RWP-Jt*														
390265	6/19/96	76	Midlane	11.34	0.28	0.28	0.26	0.23	0.28	0.29	0.26	0.31	0.28	0.28	0.35	0.28	
			RWP-Jt*	11.25	.43/.33		.30/.35		.36/.40		.36/.42		.35/.38		.40/.39		.35/.38
Ramp SPS-8																	
390809	10/19/94	62	Midlane	12.51	0.45	0.51	0.55	0.52	0.45	0.48	0.43	0.51	0.65	0.52		0.51	
			RWP-Jt*														
390810	10/19/94	58	Midlane	12.53	0.39	0.42	0.43	0.29	0.29	0.33	0.29	0.31	0.33	0.33		0.34	
			RWP-Jt*														

* Df1A/Df1L at joint closest to station

Table E3 Dynaflect Profile of New AC Test Sections

Section No.	Test Date	Pvt. Surf. Temp. (*F)	Test Path	Deflection (mils) at Station											Average Midlane (mils)	Average RWP (mils)
				0+25 0+00	0+75 0+50	1+25 1+00	1+75 1+50	2+25 2+00	2+75 2+50	3+25 3+00	3+75 3+50	4+25 4+00	4+75 4+50	5+00		
Southbound SPS-1																
390101	6/10/96	84	Midlane	0.92	1.02	1.34	1.07	0.89	1.12	1.30	1.03	1.03	1.28	1.19	1.11	
		80	RWP	1.01	1.05	1.15	0.97	0.93	1.30	1.04	1.02	1.10	1.17	1.10		1.08
390102	6/10/96	70	Midlane	1.34	1.27	1.34	1.59	1.68	1.61	1.50	1.43	1.41	1.35	1.62	1.47	
		80	RWP	1.42	1.34	1.51	1.52	1.61	1.58	1.51	1.44	1.42	1.39	1.61		1.49
390103	6/10/96	67	Midlane	0.77	0.70	0.70	0.74	0.74	0.67	0.66	0.65	0.69	0.69	0.59	0.69	
			RWP	0.86	0.74	0.74	0.78	0.73	0.69	0.70	0.71	0.74	0.67	0.58		0.72
390104	6/10/96	86	Midlane	0.41	0.34	0.43	0.43	0.43	0.45	0.40	0.40	0.42	0.40	0.37	0.41	
			RWP	0.41	0.34	0.44	0.46	0.44	0.46	0.41	0.41	0.43	0.42	0.39		0.42
390105	6/10/96	70	Midlane	0.97	0.94	0.96	0.95	0.88	0.92	0.92	0.91	0.95	1.06	1.22	0.97	
			RWP	1.03	0.99	0.99	0.92	0.94	0.95	0.93	0.89	1.00	1.08	1.15		0.99
390106	6/10/96	86	Midlane	0.54	0.51	0.55	0.48	0.48	0.50	0.50	0.44	0.43	0.48	0.47	0.49	
			RWP	0.51	0.56	0.55	0.48	0.47	0.49	0.53	0.45	0.45	0.47	0.48		0.49
390107	6/10/96	81	Midlane	1.18	1.08	1.34	1.16	1.33	1.15	1.14	1.37	1.20	1.35	1.52	1.26	
		82	RWP	1.17	1.22	1.18	1.11	1.27	1.04	1.07	1.02	1.09	1.24	1.24		1.15
390108	6/10/96	70	Midlane	0.75	0.66	0.68	0.54	0.61	0.54	0.56	0.67	0.63	0.52	0.71	0.62	
			RWP	0.74	0.69	0.68	0.59	0.63	0.53	0.57	0.58	0.56	0.58	0.72		0.62
390109	6/10/96	67	Midlane	0.63	0.63	0.57	0.56	0.68	0.67	0.60	0.58	0.57	0.65	0.67	0.62	
		70	RWP	0.63	0.65	0.63	0.58	0.68	0.63	0.62	0.56	0.54	0.64	0.68		0.62
390110	6/10/96	67	Midlane	0.55	0.49	0.50	0.56	0.55	0.60	0.58	0.58	0.61	0.69	0.66	0.58	
			RWP	0.53	0.48	0.52	0.57	0.57	0.65	0.64	0.62	0.60	0.70	0.69		0.60
390111	6/10/96	86	Midlane	0.46	0.57	0.56	0.55	0.54	0.60	0.64	0.62	0.67	0.67	0.67	0.60	
			RWP	0.44	0.56	0.57	0.55	0.54	0.59	0.64	0.63	0.66	0.68	0.66		0.59
390112	6/10/96	86	Midlane	0.43	0.48	0.49	0.45	0.50	0.51	0.47	0.44	0.43	0.42	0.43	0.46	
			RWP	0.41	0.49	0.53	0.49	0.52	0.54	0.48	0.47	0.49	0.44	0.48		0.49
390159			Midlane													
			RWP													
390160	6/10/96	70	Midlane	0.53	0.52	0.47	0.43	0.40	0.38	0.40	0.34	0.49	0.38	0.45	0.44	
			RWP	0.54	0.46	0.45	0.38	0.40	0.37	0.39	0.49	0.38	0.41	0.43		0.43
390161 (390102)																
390162 (390107)																

390163 (390101)																
390164 (390105)																
Ramp SPS-8																
390803																
390804																
39A803 (390803)																
39A804 (390804)																
Southbound SPS-9																
390901	6/10/96	89	Midlane	0.34	0.35	0.36	0.37	0.39	0.39	0.40	0.39	0.42	0.43	0.44	0.39	
		90	RWP	0.43	0.45	0.48	0.49	0.46	0.46	0.46	0.46	0.44	0.43	0.41		0.45
390902	6/10/96	86	Midlane	0.30	0.31	0.41	0.38	0.41	0.47	0.42	0.35	0.35	0.35	0.39	0.38	
		87	RWP	0.30	0.31	0.39	0.38	0.45	0.46	0.35	0.35	0.37	0.36	0.38		0.37
390903	6/10/96	87	Midlane	0.44	0.48	0.47	0.46	0.44	0.45	0.44	0.47	0,45	0.42	0.38	0.45	
		86	RWP	0.36	0.35	0.37	0.38	0.35	0.36	0.38	0.38	0.47	0.48	0.43		0.39

Table E4 Dynaflect Profile of New PCC Test Sections

Section No.	Test Date	Pvt. Surf. Temp. (*F)	Test Path	Deflection (mils) at Station 0+25 / 0+00	0+75 / 0+50	1+25 / 1+00	1+75 / 1+50	2+25 / 2+00	2+75 / 2+50	3+25 / 3+00	3+75 / 3+50	4+25 / 4+00	4+75 / 4+50	5+00	Average Midlane (mils)	Average RWP (mils)
Northbound SPS-2																
390201	6/11/96	78	Midlane	0.39	0.37	0.43	0.43	0.42	0.32	0.44	0.45	0.43	0.36	0.38	0.40	
			RWP-Jt*	.58/.56		.52/.52		.49/.58		.48/.55		.68/.64		.52/.64		.55/.58
390202	6/11/96	75	Midlane	0.41	0.44	0.38	0.33	0.37	0.39	0.41	0.38	0.40	0.38	0.38	0.39	
			RWP-Jt*	.46/.48		.44/.52		.38/.47		.47/.51		.45/.52		.51/.55		.45/.51
390203	6/12/96	78	Midlane	0.26	0.31	0.28	0.26	0.27	0.27	0.26	0.29	0.32	0.26	0.25	0.28	
	6/28/96	75	RWP-Jt*	.38/.40		.52/.54		.55/.57		.48/.47		.49/.49		.36/.37		.46/.47
390204	6/11/96	69	Midlane	0.25	0.23	0.25	0.35	0.26	0.23	0.26	0.44	0.25	0.26	0.34	0.43	
			RWP-Jt*	.27/.26		.31/.29		.34/.35		.47/.48		.38/.36		.36/.36		.36/.35
390205	6/11/96	78	Midlane	0.34	0.26	0.33	0.33	0.34	0.27	0.24	0.27	0.41	0.30	0.33	0.31	
			RWP-Jt*	.29/.32		.34/.42		.33/.39		.26/.32		.38/.43		.27/.35		.31/.37
390206	6/11/96	76	Midlane	0.30	0.31	0.32	0.35	0.36	0.36	0.32	0.34	0.35	0.33	0.30	0.33	
			RWP-Jt*	.32/.36		.32/.35		.34/.39		.33/.37		.35/.42		.29/.34		.33/.37
390207	6/12/96	78	Midlane	0.18	0.19	0.22	0.14	0.15	0.17	0.20	0.16	0.18	0.22	0.18	0.18	
	6/28/96	76	RWP-Jt*	.37/.37		.33/.31		.31/.31		.32/.34		.32/.33		.27/.27		.32/.32
390208	6/12/96	78	Midlane	0.19	0.22	0.22	0.17	0.25	0.17	0.20	0.20	0.19	0.23		0.20	
	6/28/96	78	RWP-Jt*	.28/.31		.38/.39		.33/.35		.33/.33		.28/.28		.36/.35		.33/.34
390209	6/11/96	79	Midlane	0.37	0.43	0.38	0.35	0.37	0.32	0.29	0.35	0.39	0.36	0.35	0.36	
			RWP-Jt*	.40/.46		.43/.49		.40/.44		.37/.33		.43/.50		.35/.36		.40/.45
390210	6/11/96	70	Midlane	0.43	0.34	0.32	0.32	0.34	0.34	0.32	0.32	0.35	0.30	0.29	0.33	
		75	RWP-Jt*	.47/.55		.38/.47		.40/.45		.38/.46		.39/.45		.32/.39		..39/.46
390211	6/12/96	60	Midlane	0.26	0.26	0.34	0.26	0.27	0.30	0.26	0.26	0.25	0.28	0.26	0.27	
		67	RWP-Jt*	.36/.37		.38/.39		.39/.45		.32/.34		.32/.35		.29/.28		.35/.36
390212	6/11/96	69	Midlane	0.26	0.28	0.23	0.20	0.24	0.22	0.24	0.28	0.29	0.27	0.24	0.25	
			RWP-Jt*	.30/.30		.31/.28		.26/.30		.28/.25		.34/.46		.30/.33		.30/.32
390259	6/11/96	69	Midlane	0.30	0.31	0.25	0.26	0.28	0.32	0.31	0.31	0.32	0.30	0.27	0.29	
			RWP-Jt*	.36/.35		.36/.32		.31/.26		.33/.35		.37/.37		.32/.35		.34/.33
390260	6/11/96	75	Midlane	0.28	0.23	0.23	0.21	0.22	0.26	0.23	0.20	0.25	0.22	0.22	0.23	
			RWP-Jt*	.26/.31		.27/.32		.22/.28		.28/.35		.24/.30		.25/.30		.25/.31
390261	6/11/96	79	Midlane	0.21	0.21	0.21	0.22	0.23	0.24	0.22	0.26	0.24	0.22	0.24	0.23	
		80	RWP-Jt*	.29/.36		.25/.28		.26/.29		.30/.33		.29/.36		.27/-		.28/.32
390262	6/12/96	79	Midlane	0.22	0.21	0.20	0.21	0.22	0.21	0.24	0.27	0.21	0.25	0.22	0.22	
	6/28/96	79	RWP-Jt*	.31/.32		.34/.36		.37/.36		.36/.39		.42/.45		.37/.37		.36/.38
390263	6/12/96	78	Midlane	0.29	0.29	0.28	0.28	0.33	0.29	0.29	0.28	0.31	0.34	0.31	0.30	
	6/28/96	82	RWP-Jt*	.44/.45		.47/.46		.57/.58		.53/.53		.49/.49		.48/.47		.50/.50

390264			Midlane RWP-Jt*													
390265	6/12/96	67 69	Midlane RWP-Jt*	0.21 .25/.27	0.22	0.21 .20/.22	0.21	0.21 .26/.25	0.23	0.27 .20/.30	0.25	0.23 .25/.28	0.23	0.30 .20/.27	0.23	.23/.27
Ramp SPS-8																
390809																
390810																

* W1A/W1L in vicinity of station

Appendix F

FWD Basin Profiles

Table F1 Normalized FWD Profile of Subgrade in AC Test Sections

Section No.	Test Date	Midlane RWP	Avg. Load (K)	Normalized Df1 Measurements (mils) at Station											Average Midlane (mils)	Average RWP (mils)	Section Average (mils)
				0+25	0+75	1+25	1+75	2+25	2+75	3+25	3+75	4+25	4+75				
				0+00	0+50	1+00	1+50	2+00	2+50	3+00	3+50	4+00	4+50	5+00			
Southbound SPS-1																	
390101	8/29/95	Midlane	5.10	4.06	3.55	3.20	4.55	6.39	6.73	4.18	5.98	18.41	15.59		7.26		
		RWP	5.12	8.13	7.16	8.83	10.03	5.41	11.81	9.00	3.41	6.50	16.33	15.26		9.26	8.31
390102	8/29/95	Midlane	5.78	2.43	3.84	4.62	4.78	5.77	9.57	2.90	2.13	2.07	4.10		4.22		
		RWP	5.67	2.83	3.10	3.82	7.21	7.19	8.73	3.22	2.18	4.88	2.43	3.17		4.43	4.33
390103	8/24/95	Midlane	4.90	5.28	5.01	3.22	5.17	4.26	6.70	4.94	4.94	4.00	6.73		5.03		
		RWP	4.99	7.32	4.12	3.00	3.58	5.96	4.99	4.38	4.34	3.64	4.15	13.33		5.35	5.19
390104	7/19/95	Midlane	5.81	5.67	4.57	6.13	10.94	7.74	5.32	6.61	4.58	2.55			6.01		
		RWP	5.79	6.98	4.49	9.41	4.54	5.84	2.90	4.18	2.11	4.14	2.49	5.27		4.76	5.32
390105	8/28/95	Midlane	5.26	5.77	5.97	4.37	4.32	3.95	4.03	4.15	4.39	4.71	5.02		4.67		
		RWP	5.29	4.10	5.26	3.21	3.68	3.65	4.91	5.51	6.22	5.95	5.83	6.05		4.94	4.81
390106	8/13/95	Midlane	5.51	(1)	(1)	11.50	4.12	5.18	3.07	3.49	3.74	3.00	5.19		4.91		
		RWP	5.63	(1)	(1)	(1)	6.08	5.43	5.82	5.05	3.44	4.98	2.73	2.75		4.54	4.72
390107	8/29/95	Midlane	5.82	9.37	3.71	6.12	4.00	3.31	3.16	6.66	3.33	7.54	7.36		5.46		
		RWP	5.84	3.99	2.53	3.79	3.35	4.19	5.02	3.19	3.57		9.64	7.97		4.72	5.09
390108	8/28/95	Midlane	5.65	3.41	2.58	3.90	3.90	3.74	4.43	(2)	(2)	2.88	3.10		3.49		
		RWP	5.55	4.93	2.58	4.55	5.98	4.53	4.41	(2)	(2)	6.03	2.42	3.33		4.31	3.92
390109	8/25/95	Midlane	4.62	6.60	5.57	5.66	2.78	18.81	3.79	4.48	5.77	5.36	5.77		6.46		
		RWP	4.27	11.64	11.85	4.74	8.18	14.41	18.55	6.74	8.11	18.05	5.08	6.69		10.37	8.51
390110	8/25/95	Midlane	4.77	4.60	14.32	4.56	6.98	4.30	5.47	3.30	5.35	5.18	6.94		6.10		
		RWP	4.71	8.40	11.50	14.71	6.89	8.18	4.21	3.27	3.28	8.08	5.74	8.06		7.48	6.82
390111	7/19/95	Midlane	5.57	3.41	3.93	5.93	6.02	17.33	9.66	6.69	3.60	3.20	2.26		6.20		
		RWP	5.60	2.01	2.36	3.58	5.39	6.81	19.73	5.26	5.29	2.97(3)	4.34	3.00		5.52	5.85
390112	7/20/95	Midlane	5.62	3.73	6.76	6.33	3.52	9.33	4.85	26.49	3.64	9.36	5.33		7.93		
		RWP	5.62	2.60	10.30	9.64	5.02	3.74	4.01	5.25	4.68	11.19	5.90	12.54		6.81	7.34
390159	6/28/96	Midlane	3.86	6.29	23.77	22.88	21.88	13.69	24.60	27.58	14.67	12.63	15.99		18.40		
		RWP	3.85	9.13	6.89	26.83	26.95	23.60	29.02	17.25	8.59	9.07	8.36	9.03		15.88	17.08
390160	8/28/95	Midlane	5.28	3.80	6.75		3.09	4.96	2.74	6.70	3.66	(2)	(2)		4.53		
		RWP	5.45	2.94	5.89	4.13	3.98	2.37	3.99	4.59	3.54	(2)	(2)	4.31		3.97	4.22
390161 (390102)	10/2/97	Midlane	4.93	6.25	6.98	10.09	12.84	6.03	11.99	7.99	4.27	5.03	5.28		7.68		
		RWP	4.88	9.42	10.86	11.07	11.50	9.10	11.34	6.57	4.62	7.35	5.05	7.72		8.60	8.14
390162 (390107)	10/6/97	Midlane	4.51	2.88	2.38	6.46	9.21	5.21	3.11	2.88	2.68	1.41	1.61		3.26		
		RWP	4.67	3.09	1.86	4.65	2.94	2.30	2.75	2.61	3.99	3.32	5.20	1.53		3.11	3.19
390163 (390101)	10/3/97	Midlane	4.55	1.99	1.31	3.65	4.55	2.66	2.54	4.05	4.52	5.48	3.62		3.44		
		RWP	4.47	4.49	3.94	2.87	2.92	2.12	1.75	3.20	3.44	5.38	23.28	8.32		5.61	4.53
390164 (390105)	9/17/98	Midlane	2.87	35.64	23.88	26.79	24.09	34.77	17.83	22.08	37.18	46.27	54.78		32.33		
		RWP	2.94	23.56	16.79	21.45	22.49	25.67	33.97	23.59	22.57	29.56	34.10	43.87		27.06	29.70
Ramp SPS-8																	
390803	10/31/94	Midlane	4.24	5.42	4.57	6.76	4.56	5.30	6.99	6.31	5.83	8.35	3.75		5.78		
	11/7/94	RWP	4.34	6.50	4.72	4.53	3.65	4.49	5.96	6.36	5.84	6.69	5.84	6.60		5.56	5.67
390804	10/31/94	Midlane	4.34	6.10	6.67	9.37	4.65	6.00	5.81	6.46	6.79	5.08	4.23		6.12		
	11/8/94	RWP	4.28	6.03	12.77	7.39	11.12	8.27	8.26	8.23	5.83	7.05	5.65	7.17		7.98	7.05
39A803 (390803)	10/3/97	Midlane	4.46	2.54	2.49	3.17	4.41	1.79	1.70	1.88	1.82	2.50	4.21		2.65		
		RWP	4.25	2.05	2.43	3.32	3.37	1.95	2.42	2.20	2.58	2.26	2.35	4.08		2.64	2.65
39A804 (390804)	10/3/97	Midlane	4.18	4.41	3.31	3.49	4.58	3.64	4.59	9.94	6.08	3.70	3.59		4.73		
		RWP	4.73	3.75	8.31	5.18	6.05	3.54	4.02	24.90	14.89	6.36	11.58	26.90		10.49	7.61
Southbound SPS-9																	
390901	8/1/95	Midlane	5.58	5.61	4.82	3.05	1.72	1.29	1.20	3.36	4.18	2.81	2.76		3.08		
		RWP	5.38	6.84	8.31	4.46	2.01	1.75	1.88	2.32	4.86	3.61	4.46	3.06		3.96	3.54
390902	7/20/95	Midlane	5.14	5.78	3.30	4.22	3.08	5.39	3.75	2.43	5.72	7.47	10.64		5.18		
		RWP	5.39	11.23	9.57	7.78	5.47	5.46	4.60	6.71	6.80	4.40	5.69	8.47		6.93	6.09
390903	7/20/95	Midlane	5.19	3.88	5.62	2.72	4.66	4.30	3.36	2.36	7.47	10.12	7.08		5.16		
		RWP	5.19	4.76	4.41	4.54	4.35	4.50	4.07	3.08	6.86	11.14	15.78	14.44		7.08	6.17
																Average	7.03

(1) Subgrade in test section not entirely finished
(2) Crossroad
(3) Df3 > Df2> Df1

Table F2 Normalized FWD Profile of Subgrade in PCC Test Sections

			Avg.	Normalized Df1 Measurements (mils) at Station											Average	Average	Section
Section	Test	Midlane	Load	0+25	0+75	1+25	1+75	2+25	2+75	3+25	3+75	4+25	4+75		Midlane	RWP	Average
No.	Date	RWP	(K)	0+00	0+50	1+00	1+50	2+00	2+50	3+00	3+50	4+00	4+50	5+00	(mils)	(mils)	(mils)
Northbound SPS-2																	
390201	8/1/95	Midlane	5.44	5.97	23.61	8.88	5.15	8.66	4.36	5.48	6.04	(2)	(2)		8.52		
		RWP	4.93	11.38	7.65	21.94	7.10	18.47	9.62	15.12	9.64	(2)	(2)	(2)		12.62	10.57
390202	7/11/95	Midlane	5.50	2.02	2.09	2.04	4.68	6.37	6.99	4.30	5.05	9.93	22.30		6.58		
	7/10/95	RWP	5.41	2.23	3.50	4.52	3.51	6.50	4.84	4.65	4.30	16.71	10.83	4.27		5.99	6.27
390203	8/22/95	Midlane	5.12	4.44	6.22	3.36	4.70	4.38	5.34	3.28	5.88	6.70	4.82		4.91		
		RWP	4.96	4.78	3.03	8.65	5.95	4.92	4.91	7.07	5.10	5.85	5.33	5.38		5.54	5.24
390204	6/26/95	Midlane	5.29	3.61	2.82	3.40	2.54	3.99	1.23	1.97	1.40	7.21	1.80		3.00		
		RWP	5.69	4.01	4.96	4.29	3.89	2.68	2.38	1.50	1.46	2.76	3.31	3.13		3.12	3.06
390205	7/19/95	Midlane	4.92	5.96	16.58	19.16	5.96	5.50	19.02	8.24	4.51	5.92	6.20		9.71		
		RWP	4.62	7.63	19.68	23.57	34.35	18.09	6.00	28.20	9.83	3.42	6.21	5.07		14.73	12.34
390206	7/19/95	Midlane	5.23	8.11	9.72	17.44	5.00	3.21	5.57	3.24	4.43	3.64	6.89		6.73		
		RWP	5.03	7.84	24.39	10.04	23.98	4.82	5.35	3.94	8.27		12.50	3.70		10.48	8.60
390207	8/23/95	Midlane	4.52	5.61	3.56	4.30	5.18	5.96	5.42	5.67	7.04	4.40	3.11		5.03		
		RWP	4.82	2.73	2.80	3.67	3.95	3.37	3.75	4.66	7.60	3.39	6.72	(2)		4.26	4.64
390208	8/23/95	Midlane	4.70	5.72	6.26	3.83	3.47	2.29	3.46	4.23	2.81	4.17	6.81		4.31		
		RWP	4.83	3.98	5.57	7.22	5.29	5.75	5.76	3.90	5.23	3.87	6.02	7.17		5.43	4.90
390209	8/23/95	Midlane	4.31	7.34	13.23	11.62	12.08	24.44	26.72	20.33	3.93	3.77	2.96		12.64		
		RWP	4.43	5.66	16.85	11.89	19.98	30.22	25.44	10.54	5.23	4.92	2.72	3.07		12.41	12.52
390210	6/26/95	Midlane	4.32	17.70	20.09	4.49	9.23	7.38	8.95	9.84	8.62	9.83	24.18		12.03		
		RWP	4.67	18.84	5.86	6.06	8.83	6.58	7.20	5.34	5.81	3.99	5.69	4.52		7.16	9.48
390211	8/23/95	Midlane	5.02	5.70	4.00	3.60	3.55	3.79	4.25	4.48	4.52	5.12	4.51		4.35		
		RWP	4.89	4.87	5.36	4.70	5.95	3.58	4.60	3.91	5.85	4.41	4.56	7.70		5.04	4.71
390212	6/26/95	Midlane	4.90	4.15	3.00	3.47	4.28	2.04	2.94	2.96	3.14	3.95	4.28		3.42		
	8/17/95	RWP	4.93	7.42	7.96	5.32	5.14	5.74	2.71	4.42	3.19	3.04	4.81	2.31		4.73	4.11
390259	7/11/95	Midlane	5.24	7.46	4.15		5.45	4.02	4.37	10.40	10.76	9.57	7.77		7.11		
	7/19/95	RWP	5.31	5.61	5.57	3.79	4.72	6.33	5.76	9.53	28.24	13.58	5.29	22.17		10.05	8.73
390260	7/10/95	Midlane	5.31	5.24	4.21	5.23	3.81	5.26	(2)	17.84	9.72	3.94	6.94		6.91		
		RWP	5.41	2.56	4.27	6.89	3.86	4.36	(2)	(2)	4.45	22.94	4.91	7.49		6.86	6.88
390261	8/23/95	Midlane	5.18	8.00	5.89	4.78	3.84	2.65	4.66	4.72	3.50	3.49	3.49		4.50		
		RWP	5.15	22.14	4.02	4.29	2.89	2.28	3.78	4.07	5.06	3.68	3.52	3.75		5.41	4.98
390262	8/23/95	Midlane	4.69	3.80	4.44	4.33	5.51	2.31	3.21	7.15	6.23	5.68	6.73		4.94		
		RWP	4.63	4.85	4.92	5.31	5.29	2.67	3.63	5.78	6.46	4.46	8.97	12.75		5.92	5.45
390263	8/23/95	Midlane	4.53	6.50	18.84	5.97	7.03	3.39	3.58	3.71	4.27	3.61	4.08		6.10		
		RWP	4.37	10.31	7.56	10.15	8.29	20.16	4.85	5.57	9.65	4.55	6.91	2.91		8.26	7.23
390264	6/20/96	Midlane	4.97	9.08	15.29	19.37	18.00	5.96	14.95	18.82	19.93	19.93	18.07		15.94		
		RWP	3.69	10.21	14.59	18.03	26.31	14.56	23.83	14.61	21.95	13.18	14.99	24.51		17.89	16.96
390265	8/22/95	Midlane	5.27	(1)	(1)	(1)	(1)	(1)	7.51	4.94	6.00	4.46	4.72		5.53		
		RWP	5.26	(1)	(1)	(1)	(1)	(1)	(1)	7.26	6.96	4.45	5.31	7.36		6.27	5.90
Ramp SPS-8																	
390809	9/27/94	Midlane	4.19	7.87	3.31	3.74	9.05	12.85	8.12	5.07	4.80	19.04	27.78		10.16		
	10/6/94	RWP	4.26	5.51	4.50	4.35	4.62	8.62	8.16	7.87	4.94	8.07	16.80			7.34	8.75
390810	9/27/94	Midlane	4.15	5.65	8.64	14.69	11.47	5.23	9.80	14.37	7.05	5.35	6.48		8.87		
	9/31/94	RWP	3.84	14.81	32.68	19.70	11.35	5.66	4.50	6.00	5.28	7.50	7.54			11.50	10.19
															Average		7.33

(1) Subgrade in test section not entirely finished
(2) Crossroad