Long-Term Pavement Performance Seasonal Monitoring Program: Instrumentation Selection and Installation

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The operational theory of and the installation procedures for the instrumentation selected to monitor changes in internal pavement moisture and thermal regimes and external climate at test sections in the Long-Term Pavement Performance seasonal monitoring study are described. The instrumentation includes time-domain reflectometry probes to measure the moisture contents of unbound materials, thermistor sensors to measure pavement temperature gradients and air temperature, electrical resistivity probes to measure frost locations, a piezometer to measure the depth to the groundwater table, and a tipping bucket rain gauge to measure precipitation. These measurements of the external climate and the resulting changes in the pavement material will be coupled with monthly or more frequent deflection measurements, bimonthly roughness measurements, elevation profiles, and distress surveys to study the causes and effects of seasonal changes in the structural response of pavement. Preliminary results from the instrumentation pilot studies illustrating these types of seasonal effects are presented.

It is widely recognized that temperature- and moisture-related changes in pavement structures, within a day or over the course of a year, can have a significant impact on the structural characteristics of the pavement layers, thereby affecting the response of the pavement to traffic loads and, ultimately, the life of the pavement. The magnitudes of these effects and the relationships involved, however, are not well understood, making it difficult to address them with any degree of confidence in the design and evaluation of pavements.

The primary objective of the seasonal monitoring program within the Strategic Highway Research Program's (SHRP's) Long-Term Pavement Performance (LTPP) studies is to provide the data needed to attain a fundamental understanding of the magnitude and impact of temporal variations in pavement response and properties resulting from the separate and combined effects of temperature and moisture variations. The products of this effort will provide (a) the means to link pavement response data obtained at random points in time to critical design conditions, (b) the means to validate models for the relationships between environmental conditions (e.g., temperature and precipitation) and the in situ structural properties of pavement materials, and (c) expanded knowledge of the magnitude and impact of the changes involved.

Resource limitations make it impossible to monitor all of the approximately 3,000 LTPP test sections scattered across North America on a seasonal basis. As a result, a two-tiered program has been established to maximize the number of sections studied and, therefore, the applicability of the results. The first tier, referred to as the *core experiment*, includes 64 LTPP test sections selected to obtain a balance of key pavement factors (Table 1). The second tier, referred to as *supplemental studies*, was conceived in response to the strong desire on the part of several states to contribute to this effort by instrumenting and monitoring additional LTPP test sections. The final number of supplemental sections is not yet known.

Sixty of the targeted 64 sites have been identified and accepted for inclusion into the core experiment (Figure 1). The necessary instrumentation has been installed at 28 sites, and the remaining 36 sites will be operational by late 1994. Monitoring has started and will continue through at least three full yearly cycles.

Moisture and temperature will be monitored continually. The following tests will be conducted at least once a month:

- Deflection basin testing, for evaluating temporal variations in structural properties;
- Load transfer testing on joints and cracks in rigid pavements, for monitoring load transfer conditions; and
- Joint faulting and joint opening measurements, for determining the effects of temperature variations on joint condition.

In addition, the following tests will be performed at least once each season:

- Surface elevation measurements, for evaluating the effects of frost heave and swelling soil;
- Transverse and longitudinal profile measurements, for characterizing pavement rutting and roughness; and
- Distress surveys, for monitoring the progression of pavement distresses over time.

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TABLE 1 Core Experiment: Experimental Design Cells and Target Number of Sections

Pavement Type	Subgrade Soil	No Freeze		Freeze	
		Dry	Wet	Dry	Wet
Flexible - Thin AC (< 127 mm (5 in.)) Surface	Fine	1 (3)	2 (3)	3 (3)	4 (3)
	Coarse	5 (3)	6 (3)	7 (3)	8 (3)
Flexible - Thick AC (> 127 mm (5 in.)) Surface	Fine	9 (3)	10 (3)	11 (3)	12 (3)
	Coarse	13 (3)	14 (3)	15 (3)	16 (3)
Rigid - Jointed Plain Concrete (JPC)	Fine	17 (1)	18 (1)	19 (1)	20 (1)
	Coarse	21 (1)	22 (1)	23 (1)	24 (1)
Rigid - Jointed Reinforced Concrete (JRC)	Fine	25 (1)	26 (1)	27 (1)	28 (1)
	Coarse	29 (1)	30 (1)	31 (1)	32 (1)

Note: First number in each cell represents the identification number assigned to the cell. The second number, in parentheses, represents the target number of sections within the cell.

The collection of deflection, profile, and distress data is being accomplished by using LTPP equipment and testing protocols. To gather many of the remaining data, the seasonal monitoring program is relying on instrumentation permanently installed at the test sections. Time-domain reflectometry (TDR) probes and thermistor probes are being used to monitor changes in subsurface moisture and temperature, electrical resistivity probes are being used for frost-thaw depth measurements, and piezometers are being used to determine the depth to the groundwater table. In addition, air temperature probes and tipping-bucket rain gauges are being used to monitor ambient temperature and precipitation.

INSTRUMENTATION SELECTION

The instrumentation developed for the seasonal monitoring program will seek to measure changes in internal pavement moisture content, surface and subsurface temperatures, frost depth, depth

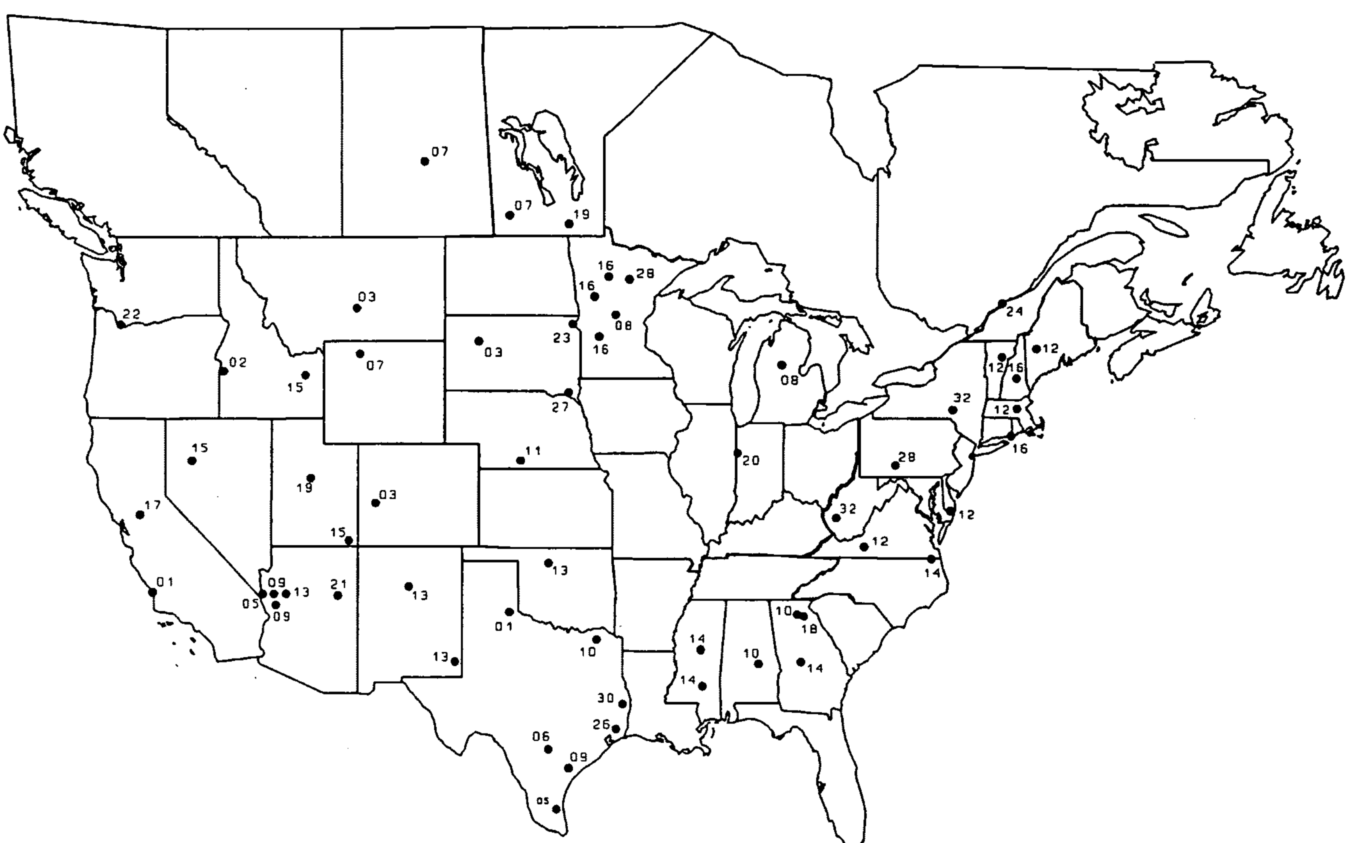


FIGURE 1 Geographical distribution of core experiment sites.

to the groundwater table, and climate over time. The installation of these types of sensors within the pavement structure is still a developing field, and little is known about their performances under field conditions, installation techniques, and costs.

Hence, the available literature was reviewed and manufacturers were contacted to determine which sensors would best fit the needs of the program. In addition, advice was solicited and obtained from the SHRP In Situ Instrumentation Expert Task Group. After careful consideration of the several types of sensors identified, the following alternative instrumentations were selected for further consideration:

- TDR probes or frequency-domain probes for monitoring internal moisture,
- Thermistors or thermocouples for monitoring pavement subsurface temperature,
- Electrical resistivity probes for monitoring frost-thaw depth, and
- Piezometers for monitoring the depth to the groundwater table.

A clear-cut decision could not be reached on the subsurface moisture and temperature sensors, so two pilot studies were initiated to identify the sensors best suited for the program and to investigate installation methods. The first pilot installation of sensors was completed in October 1991 on a flexible test section near Syracuse, N.Y. (*1*). The second pilot installation was completed in November 1991 on a rigid test section west of Boise, Idaho (*2*). The following sensors were installed at these pilot sites:

- Four TDR probe models—flat two-prong, flat three-prong, curved three-prong, and curved three-prong probe models—and an access hole for the Troxler frequency-domain moisture probe.
- Thermocouple and thermistor temperature sensor strings.
- An electrical resistivity probe.
- A piezometer.

These sensors were monitored at least monthly through May 1992. On the basis of the findings obtained at both sites, the TDR probes were selected because of (a) the more reasonable and reliable moisture contents that they provided, (b) concerns over the effects of salinity on the Troxler measurements, (c) problems encountered in maintaining the integrity and water tightness of the access hole in the wheelpath, and (d) the fact that the Troxler probe, although simpler to install, requires the operator to stand on the road, obstructing the deflection measurement operations, and requires traffic control. The flat-three prong TDR probe model was selected because it provided a superior signal strength and quality. The curved TDR sensors were found to be more difficult to install since they had to be held against the auger hole wall during compaction.

The thermistors were selected over the thermocouple strings used in the pilot study for temperature measurements because they provided the most consistent and accurate temperature readings under field conditions. The thermistor unit also used lower-cost and easier-to-operate readout equipment.

After the final equipment selections were made, equipment was installed at an additional pilot site, near Billings, Mont. (*3*), to investigate the effects of placing all pavement sensors in the same hole and to refine the installation procedures. The results provided much valuable information regarding the installation of seasonal instrumentation, particularly the finding that only one pavement hole is required for the installation of the in-pavement sensors. Also, the installation of sensors can be completed in 1 day and not 2 days, as was originally anticipated.

It is important to note that the instrumentation selected for the seasonal monitoring program is not without limitations; for example, the relationship between dielectric constant and moisture content is limited to a very small area of influence around the TDR probe rods; the temperature measured by the thermistor probe is that of the thermistors, and hence, unless they are in close contact with the soil, the readings may not be representative; and external factors such as the presence of salts in the soil can have an impact on the electrical resistivity probe measurements.

DESCRIPTION OF SENSORS

TDR Probes

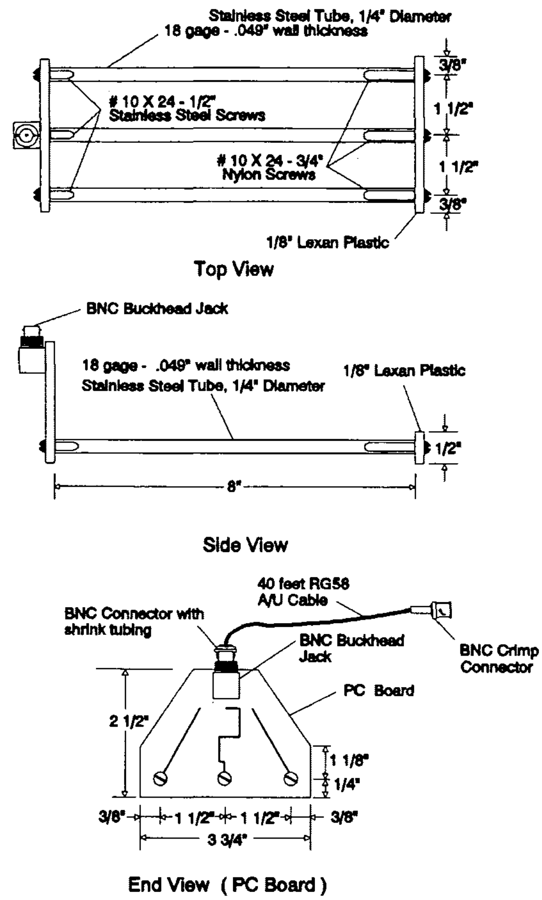
The moisture content of the subgrade soil and unbound materials is an important parameter that influences their behaviors; however, it is one of the most difficult to measure. Several approaches for measuring moisture content have been developed, but each suffers from various limitations. The method selected for use is TDR.

The principle of the TDR system is similar to that of radar. In the TDR method, a wave is transmitted along a shielded coaxial metallic cable that acts as a waveguide. (A dual-lead antenna wire can also be used; however, the coaxial cable-connector assembly was chosen because it is more rugged.) The velocity of the wave is a function of the dielectric constant (ϵ) of the material surrounding the central conductor. Changes in the dielectric constant, as well as open or short circuits in the cable, create wave reflection or wave loss points indicated by slope changes in the pulse of the return wave recorded by the TDR readout unit. A short circuit in the system will reduce the return signals from beyond that point, whereas an open circuit will generally result in an increase in the return signal.

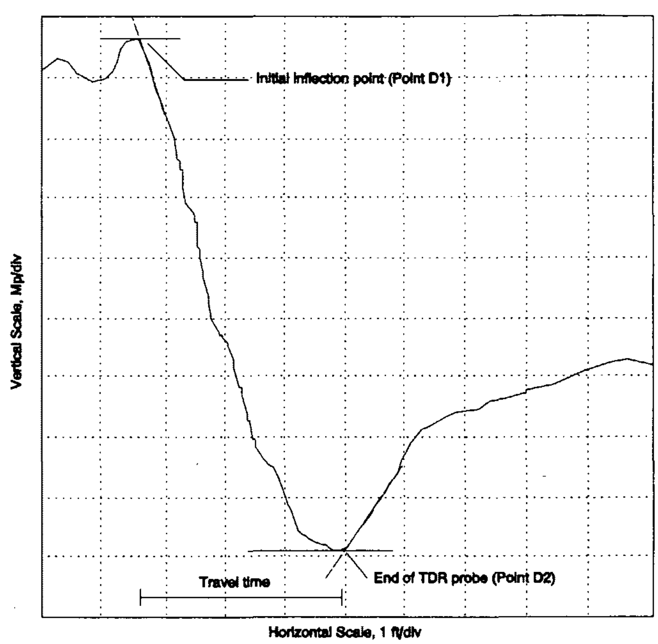
For soil moisture applications, the coaxial cable center conductor is connected to the center stainless steel rod on the probe. The cable's outer shielding is connected to the outer two rods. In essence, the probe becomes an electrical extension of the cable. Figure 2(*a*) shows the TDR probe that was refined and fabricated by FHWA for use in the LTPP seasonal monitoring program. The TDR readout device displays a rise and fall in the return signal strength as the electromagnetic wave enters and exits the probe rods, as illustrated in Figure 2(*b*). The distance between the initial inflection point (point D1) and the end of the TDR probe (point D2) is known as the *apparent length* of the probe (L_a).

This technique works well in most soil applications because the dielectric constant of soils is primarily a function of their moisture content. The dielectric constant of water is approximately 80, whereas that of dry soil particles is typically between 3 and 5, depending on the soil type and density. (The dielectric constant of air is defined as 1.) Thus, the dielectric constant of water dominates the measured value of the dielectric constant for the soil-moisture-air mixture between the conducting rods of a TDR probe. The dielectric constant of a soil-water-air mixture is computed as follows:

$$\epsilon = \left[\frac{(L_a)}{(L)(V_p)}\right]^2 \qquad (1)$$



a. TDR Probe



b. TDR Trace

FIGURE 2 TDR probe (*a*) and TDR trace (*b*). (1 ft/div = 0.3 m/div). Mρ/div is millirhos per division.

where

ϵ = dielectric constant;
L_a = apparent length of probe;
L = actual length of probe (TDR trace units); and
V_p = phase velocity setting on TDR readout instrumentation (usually 0.99).

The relationship between the volumetric moisture content and the dielectric constant can be determined by using a regression equation or a theoretical formulation. In the absence of specific relationships for pavement materials, Topp's equation (*4*) will initially be used as an indication of the moisture content from TDR readings until more refined relationships can be developed. Topp's calibration regression equation is

$$\theta = -0.053 + 0.0293\epsilon - 0.00055\epsilon^2 + 0.0000043\epsilon^3 \quad (2)$$

where θ is the volumetric water content, in decimal.

To convert soil moisture from a volume to a weight basis, as used in pavement engineering applications, it is essential that reasonably accurate dry density estimates are available, since this transformation is based on the ratio of the dry density of the material to the density of water. To develop calibration curves between the moisture content and the dielectric constant of the materials included in the study, field moisture samples at the time of sensor installation and 18.9-L (5-gal) samples of the base, subbase, and subgrade materials are obtained.

Thermistor Probes

The temperature sensor selected for use in the seasonal monitoring program is the thermistor. Thermistors are thermally sensitive resistors usually made of a semiconductor material that has an extremely large temperature coefficient of resistance. Hence, very small changes in temperature result in directly related large changes in resistance (hundreds to thousands of ohms).

Thermistors that measure a variety of temperature ranges are available in a variety of sizes and shapes, for example, rods, disks, spheres, metal sheaths, glass beads, and plastic coated. For the LTPP seasonal monitoring program, the Measurement Research Corporation TP101 thermistor probe is being used to sense the temperature gradient through the pavement. Each probe consists of three thermistor sensors in a 330-mm (13-in.)-long metal tube filled with plastic and a string of 15 thermistors encased in a 25-mm (1-in.)-diameter by 1.8-m (6-ft)-long clear plastic rod. The thermistors in the plastic rod are mounted on an electrical circuit board containing multiplexing circuitry. The three sensors in the metal rod are for installation into the pavement surface layer at an angle so that measurements at approximately 25-mm (1-in.)

deep, middepth, and 25-mm (1-in.) above the bottom of the layer can be made. By varying the angle, the rod can be used in pavements of different thicknesses. A schematic of the thermistor probe, including the spacing between the thermistor sensors, is shown in Figure 3.

The resistance of each thermistor is found by applying a known current and reading the voltage across the thermistor's leads. The resistance reading is then converted to temperature by using a calibration equation. The most common calibration equation is Steinhart's model (*5*), which is given by the following equation:

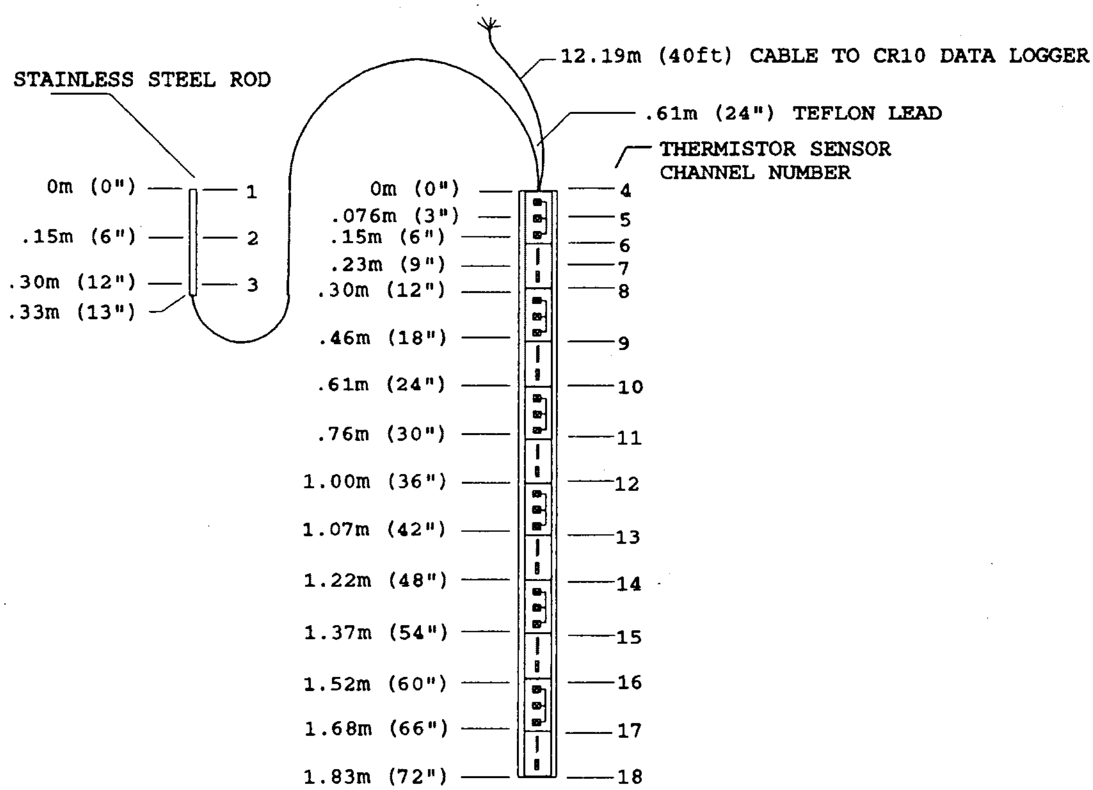
$$\frac{1}{T} = C_1 + C_2 \ln R + C_3(\ln R)^3 \quad (3)$$

where

T = absolute temperature (degrees Kelvin);
R = resistance (ohms); and
C_1, C_2, and C_3 = constants for the individual thermistor. The constants can be determined by calibrating the thermistors at three known temperatures; however, manufacturers typically develop temperature resistance curves for each thermistor batch and guarantee curve accuracy over specified temperature ranges.

Electrical Resistivity Probes

Temperature gradients have traditionally been used to determine the depth of frost penetration into a soil. This method can be unreliable, since deicing chemicals can depress the freezing point and during thaw periods an isothermal temperature regime can exist to the maximum frost depth. Presently, the most reliable method appears to be the use of electrical resistance measurements.



NOTES:

Dimensions:
Probe: 1.83m x .03m (72" x 1") OD
External Sensors: .33m x 6mm (13" x 1/4") OD

TP101
Manufactured by Measurement Research Corporation
Total of 18 Thermistors
Degree of accuracy +/-0.1 degree C
External .33m (13") Lead attached by .61m (24") of Teflon Wire
.08m (3") spacing from .30m (12") to 1.83m (72")
.15m (6") spacing for the External Lead

FIGURE 3 Thermistor probe.

Electrical resistivity probes are composed of a series of equally spaced electrodes mounted on a nonconducting rod. An individual lead wire is connected to each electrode. The probes used in the LTPP program consist of 36 metal wire electrodes, spaced 51 mm (2 in.) apart and mounted on a solid polyvinyl chloride (PVC) rod. The lead wires run along a groove in the side of the rod that is sealed with potting compound. The lead wires are connected to a computer type DB37 pin connector. The length of the cable holding the lead wires is 12.2 m (40 ft) long from the top of the probe to the connector. Figure 4 presents an illustration of the electrical resistivity probes used in the LTPP program. These probes have been manufactured by the U.S. Army Corps of Engineers' Cold Regions Research and Engineering Laboratory (CRREL).

The electrical resistivities of most soil minerals are very high, and for practical purposes they can be considered infinite. Virtually all electrical current flow through a soil is carried by free ions in the pore water. Thus, the electrical resistivity of soil depends primarily on its porosity, the degree of pore water saturation, and the electrical resistivity of the pore water. Because the electrical resistivity of ice is much greater than that of unfrozen pore water, the formation of ice in the pore space causes a net decrease in the effective porosity and a corresponding increase in the apparent or bulk electrical resistivity.

Electrical resistance can be measured with an ohmmeter, or the ohmmeter function can be measured with multipurpose electrical meters (called multimeters). An ohmmeter works by injecting an electrical current (I) through a specimen and measuring the resulting voltage drop (V) across the specimen. Resistance (R), voltage, and current are related to each other according to Ohm's law. Electrical resistivity is a property of a material in which the resistance to current flow through the material is related to a geometric factor. The electrical resistivity of a material can be measured by a four-point technique in which current is input into two outside electrodes and the voltage across two separate inside electrodes is read.

To measure the electrical resistance or resistivity of a soil, a function generator is used to supply an electric current in the form

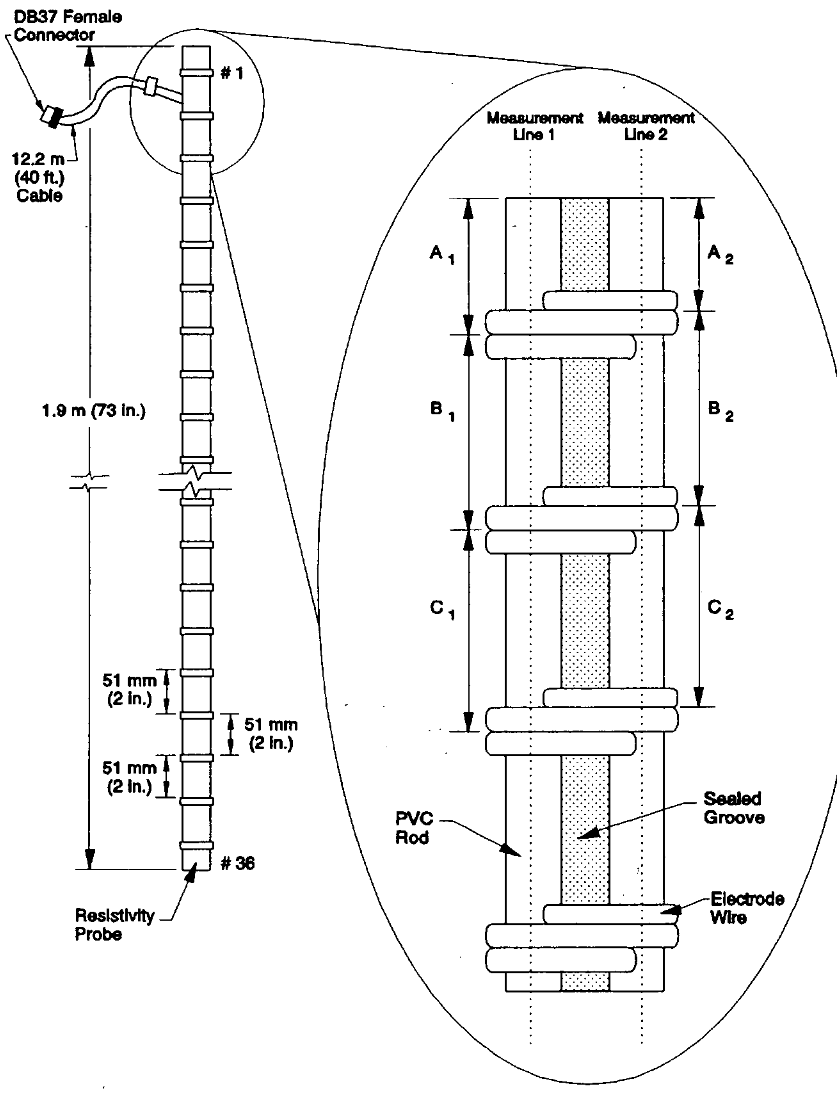


FIGURE 4 Electrical resistivity probe.

of a low-frequency alternating current (ac). This helps to minimize the current electrode's polarizing effects on the ions in the pore water. By keeping the frequencies low enough to avoid inductive and ac coupling effects, the direct current resistance equation can be used without a loss of accuracy.

For the electrical resistivity probe used in this program, contact resistance is measured by transmitting the electrical current through two adjacent electrodes and measuring the current flow and voltage. The contact resistances are measured between each adjacent electrode pair sequentially down the probe. Ohm's law is used to compute the contact resistance. Four-point electrical resistivity measurements will also be performed on some test sections for comparison. Contact resistances are plotted on a graph as a function of the average depth of the electrode pair. The location of frost is determined by comparing the unfrozen resistance profile with the frozen resistance profile. Frost areas are identified by relatively large increases in the resistance profiles. The temperature profile is generally plotted adjacent to the resistance profile to aid in the interpretation.

Piezometer Well, Air Temperature Probe, and Tipping-Bucket Rain Gauge

The depth of the groundwater table is being measured through piezometers, which have been designed to also serve as a frost- and swell-free benchmark for use as a reference point for elevation measurements. Air temperature and rainfall are being measured by using an air temperature probe and a tipping-bucket rain gauge placed next to the site equipment cabinet on a pole assembly. Figure 5 illustrates the equipment cabinet and pole assembly. The air temperature probe, manufactured by Campbell Scientific, Inc., consists of two parts. The first is a thermistor temperature probe, which has a temperature measurement range of from −35°C to 50°C. The second is a solar radiation shield that protects the temperature probe from various environmental conditions. The tipping-bucket rain gauge, manufactured by Texas Electronics, measures the amount of rainfall in 0.1-mm (0.01-in.) increments. When the rain reaches a calibrated level, the bucket tips, actuating a switch. The numbers of switch pulses are counted by the circuitry of the on-site data logger. Once the bucket tips, the water is funneled out through the base of the gauge.

Other Related Equipment

In addition to the sensors just described, the other equipment used at each seasonal monitoring site includes the following:

- An equipment cabinet to house the cable leads and switches, data loggers, and other equipment needed for seasonal monitoring.

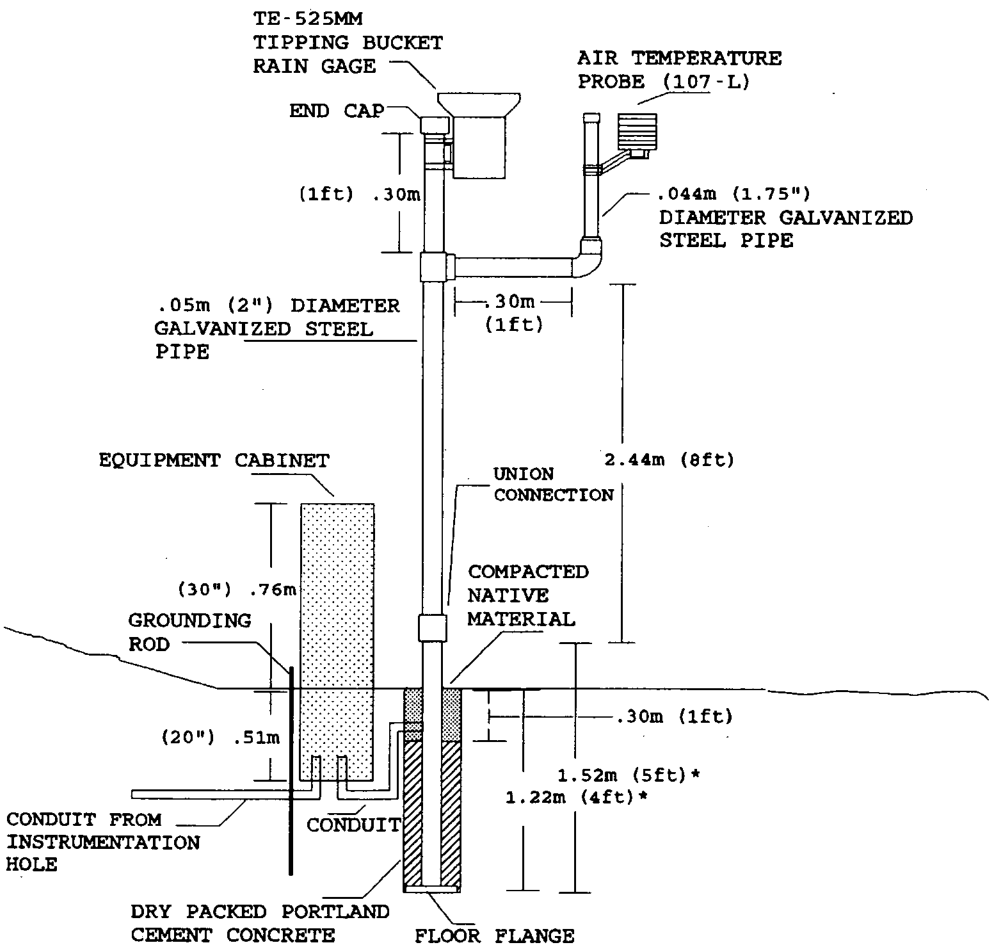


FIGURE 5 Tipping-bucket rain gauge and air temperature probe.

• Equipment used to perform moisture content measurements: (a) a Tektronix 1502B cable tester for TDR measurements and (b) a system developed by Campbell Scientific, Inc., in which the Tektronix 1502B cable tester is coupled with a CR10 data logger and multiplexers to provide for automated measurements.

• Equipment used to perform subsurface temperature measurements: (a) an on-site CR10 data logger that provides for sequential measurements of the 18 thermistors in the probe and that converts the output voltages to temperature and (b) a handheld temperature readout unit for manual readout of the thermistor probe, as a backup to the automated system.

• Equipment used to perform frost depth measurements: (a) a function generator capable of supplying a square wave signal at 100 Hz with 10 V (p-p) output into 600 Ω or equivalent, (b) two digital multimeters—one to measure the ac and the other to measure the ac voltage, (c) an automated multiplexer for making contact resistance measurements, and (d) a manual switchboard with connectors for the function generator, digital multimeters, and probe, as a backup to the automated system.

Data acquisition for the seasonal instrumentation is handled by a programmable Campbell Scientific, Inc. CR10 measure-and-control module, more commonly referred to as a *data logger*. An on-site data logger provides hourly and daily records of the measurements of the TDR probes, the air temperature probe, the thermistor probe, the tipping-bucket rain gauge, and potentially, for a few select sites, the electrical resistivity and water tables. A mobile data logger along with the Tektronix 1502B cable tester and multiplexer circuitry for the TDR moisture probes and electrical resistivity probes are used to collect moisture and frost-thaw data at the time of deflection testing.

INSTRUMENTATION INSTALLATION

Overview

The layout for a typical installation of the seasonal monitoring instrumentation is illustrated in Figure 6. The TDR probes, thermistor sensors, and electrical resistivity probe are placed in one hole, located in the outer wheelpath [0.6 to 0.9 m (2 to 3 ft) from the edge of the lane] and at least 1.2 m (4 ft) away from joints or cracks to avoid surface moisture infiltration. Figure 7 illustrates the installation of the three types of sensors in the instrumentation hole. The instrumentation hole extends approximately 2.1 m (7 ft) beneath the bottom of the bound pavement layers.

Both the thermistor and electrical resistivity probes are placed approximately 51 mm (2 in.) below the bottom of the lowest stabilized layer to minimize the likelihood of damage to the sensors from traffic applications. The 10 TDR probes are placed at the following depths: (a) if the top granular base or subbase level is more than 305 mm (12 in.), the first TDR probe is placed 152 mm (6 in.) below the bottom of the lowest stabilized layer; otherwise, the probe is placed at middepth of the top granular base; (b) the next seven TDR probes are placed at 152-mm (6-in.) in-

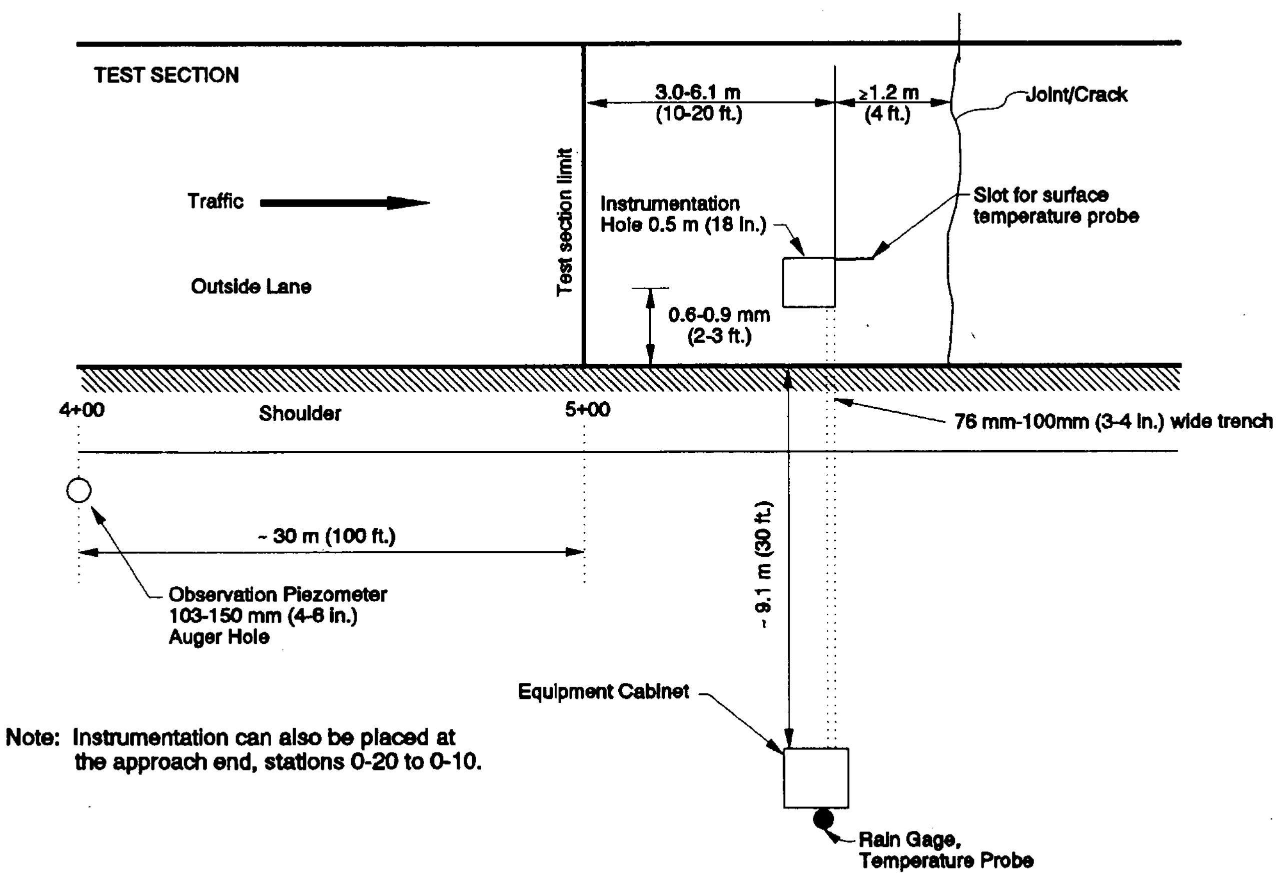


FIGURE 6 Typical instrumentation layout on asphalt concrete (AC) pavement.

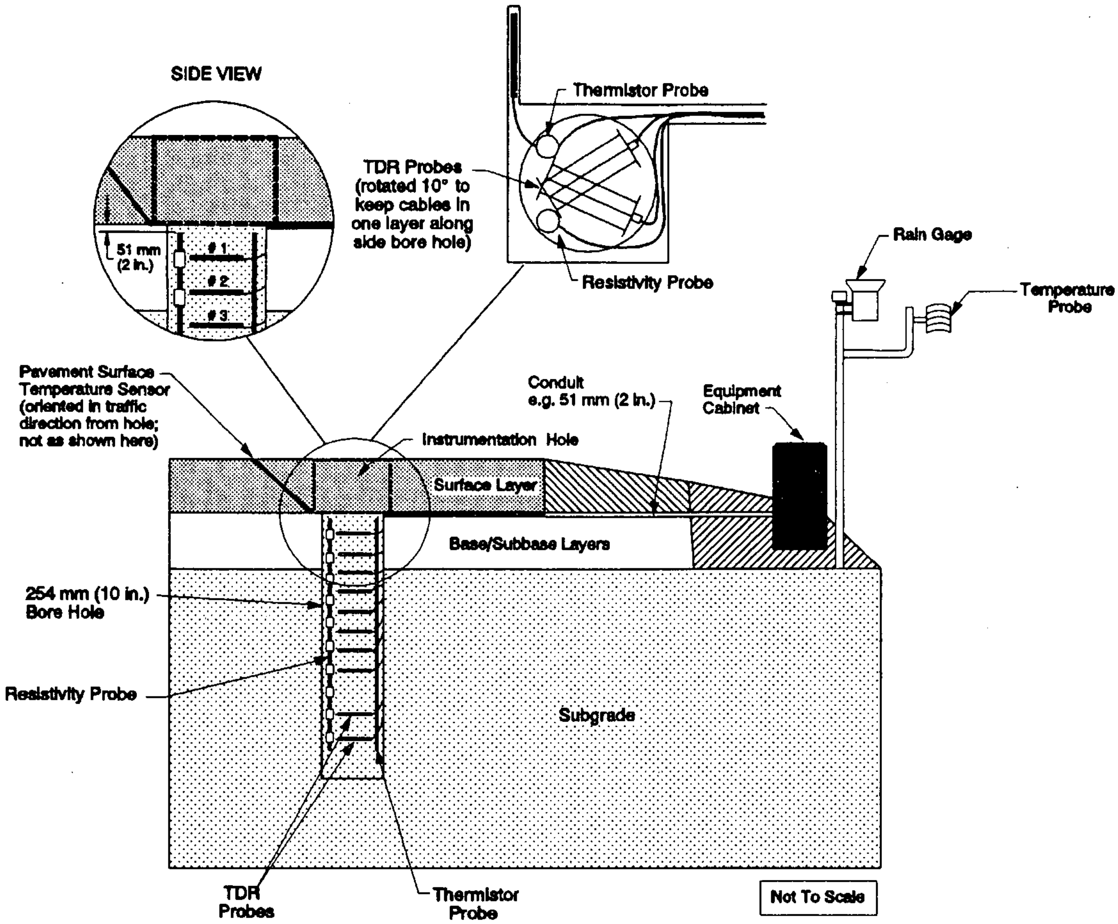


FIGURE 7 Instrumentation installation.

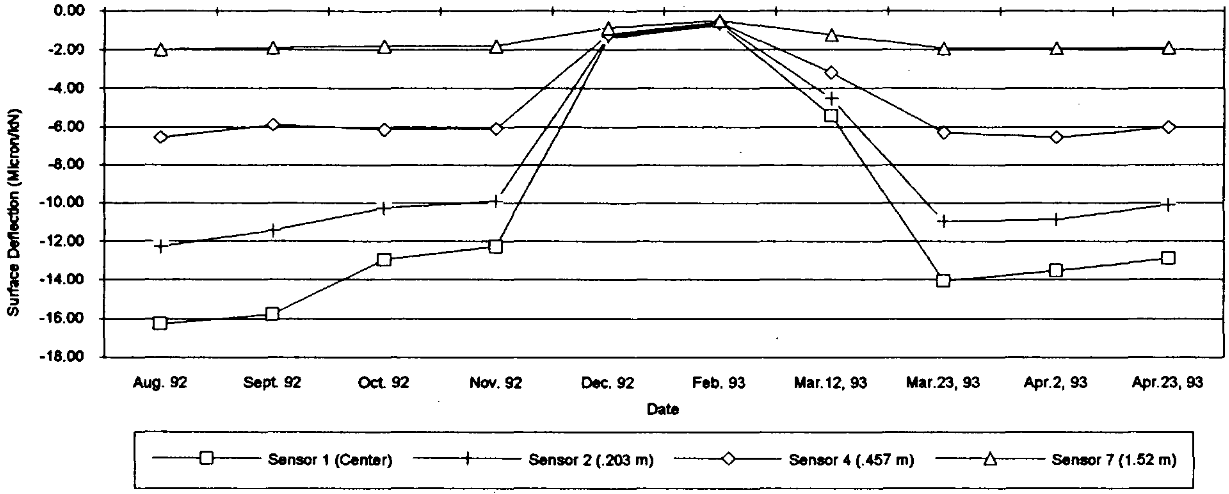
tervals; and (c) the last two TDR probes are placed at 305-mm (12-in.) spacing intervals.

Wires leading from the installed probes are placed in a 51-mm (2-in.)-diameter flexible steel conduit and buried in a 76-mm (3-in.)-wide trench leading to the equipment cabinet. The equipment cabinet and climatic sensors are located approximately 9.1 m (30 ft) away from the edge of the travel lane. In addition, the piezometer is placed adjacent to the test section, but outside the shoulder.

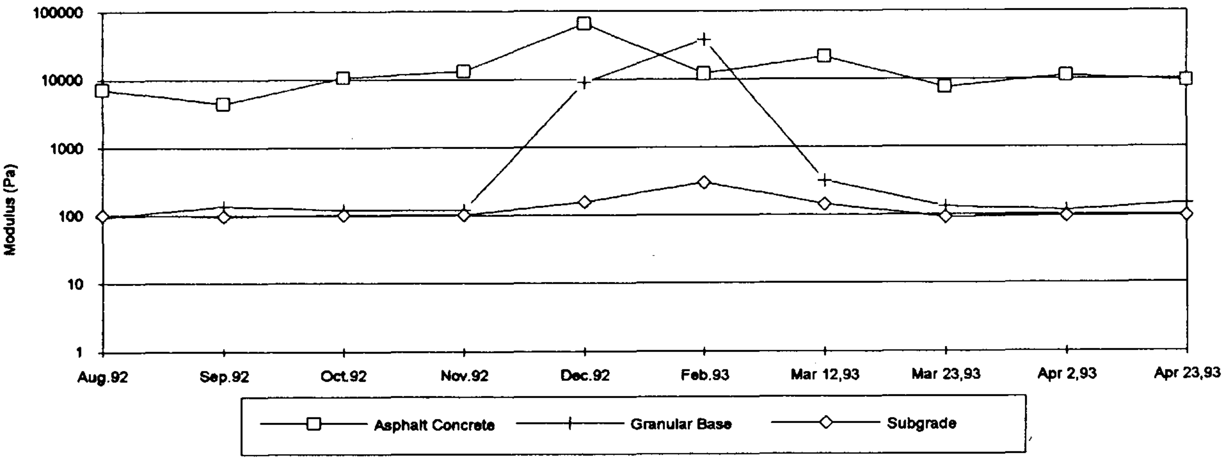
Installation Activities

Installation of the seasonal instrumentation is completed in one 8-hr day, with a second day used to perform the initial readings and measurements. The procedure followed in the installation of the piezometer is typical of that used by many highway agencies; detailed guidelines are given elsewhere (*6*). For the installation of the sensors in the pavement structure, the general procedure described here is followed:

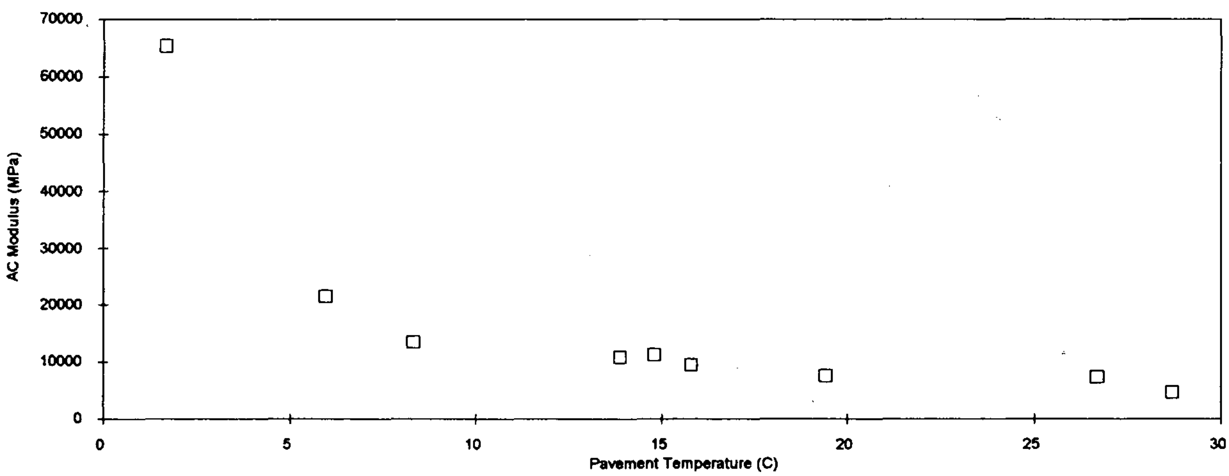
1. Lay out the location of instrumentation hole and trench.
2. Cut a 305-mm (12-in.)-diameter installation hole.
3. Cut a 76- to 102-mm (3- to 4-in.)-wide, full depth trench 76 mm (3 in.) below the bound pavement surface layers through the pavement and shoulder.
4. Cut a groove in the surface layer for installation of the pavement surface temperature probe.
5. Auger through the base and subgrade to a depth of approximately 2.1 m (7 ft) below the top of the unbound base or the bottom of the last bound pavement layer.
6. Replace and compact material in the hole (in reverse order from extraction) to approximate desired sensor depths.
7. Position the electrical resistivity and thermistor probes such that the top of the probes are 51 mm (2 in.) below the top of the first unbound base layer.
8. Place the TDR probe in the hole at the desired depth, measure the depth from the pavement surface, take two moisture samples from the material that is placed around it, and compact material carefully around the sensors.
9. Add and compact additional material needed to reach the next desired TDR sensor elevation.
10. Repeat Steps 8 and 9, rotating the orientations of the probes about 10 degrees to keep the lead wires in one layer along the side of the hole. Continue this process until all TDR sensors and material are placed in the hole.
11. Place surface temperature probe in the groove in the pavement surface and seal with sealant.
12. Run sensor lead cables through the conduit and place in the trench.



8a. Seasonal FWD Deflection Basin Profile



8b. Backcalculated Modulus of Surface, Base and Subgrade Layers



8c. Elastic Modulus of Asphalt Concrete Surface Layer versus Pavement Temperature

FIGURE 8 Seasonal deflection profiles and estimated moduli on the Montana pilot test section. FWD is falling weight deflectometer.

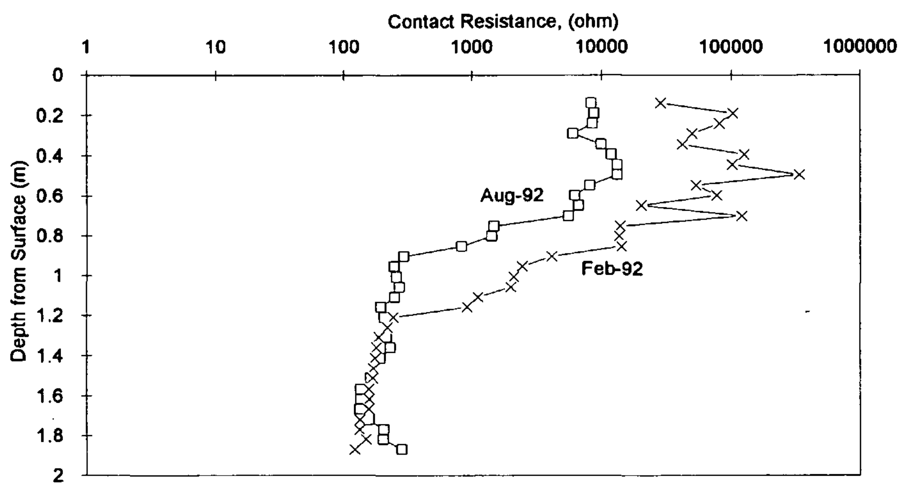
Before installation, the TDR probes are checked by performing measurements in air and distilled water. The dielectric constants computed from these measurements should be within the range of 0.75 to 2.0 for air and 76 to 84 for water. In addition, during installation and compaction of the material around the TDR probes, the probes are connected to the TDR recording unit and monitored to detect any faults that may have been produced during compaction.

The equipment cabinet, which houses the cable leads and switches, data loggers, and other equipment needed for seasonal monitoring, is positioned approximately 9.1 m (30 ft) from the instrumentation hole. Finally, the pole assembly supporting the air temperature probe and rain gauge is positioned within 1 m (3 ft) of the equipment cabinet.

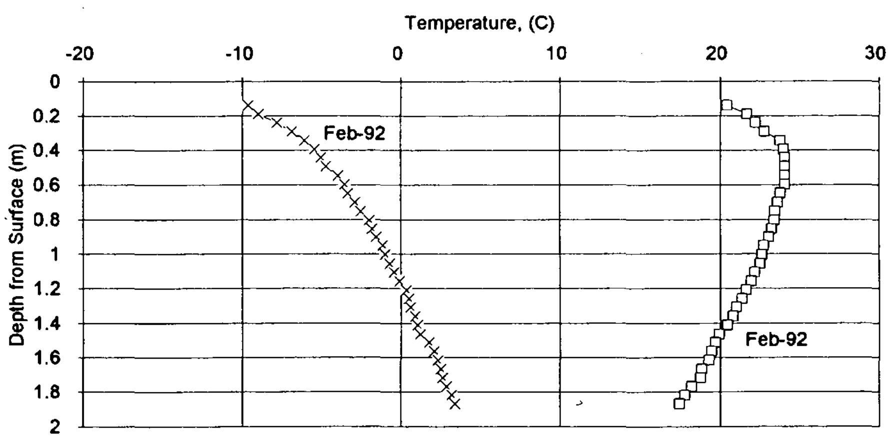
The last installation activity is restoration of the site. The desired practice is to replace and bond original core back into the hole. Regardless of the procedure, it is imperative that the pavement surface be restored to a watertight condition.

EARLY RESULTS: PILOT STUDIES

The results of an analysis of the deflection and instrumentation data from the Montana pilot test section are shown in Figures 8 and 9. In Figure 8(*a*), the seasonal variation in the deflection basin from a single point on the test section is shown; only the deflections for Sensors 1 (center of the load plate), 2 [0.203 m (8 in.) from the load], 4 [0.457 m (18 in.) from the load], and 7 [1.52 m (60 in.) from the load], normalized for load, are shown. Monthly deflections obtained from August 1992 to December 1992 are shown and bimonthly measurements obtained in March and April 1993 are shown. Deflection testing was not performed in January



9a. Plot of Resistance Profiles with Pavement Depth



9b. Plot of Temperature Depth Profiles

FIGURE 9 Indication of frost penetration into the Montana pavement structure.

because of winter storm conditions at the site. The dramatic decrease in deflections during the winter months can clearly be seen.

In Figure 8(*b*), the backcalculated layer moduli for the deflection basins illustrated in Figure 8(*a*) are shown. These moduli were computed by using the MODULUS4 program and are not corrected for temperature. The pavement structure at this site consists of approximately 89 mm (3.5 in.) of asphalt concrete surface material over a 610-mm (24-in.)-thick crushed aggregate base on a sandy clay subgrade material. An underlying rigid layer was not found within 6.1 m (20 ft). The increase in the elastic modulus of the asphalt concrete during the colder months can be seen. Of particular interest is the dramatic increase in the elastic modulus of the granular base layer from December through February. As will be shown, this increase is due to the formation of frost in the base layer. The subgrade elastic modulus was relatively constant.

In Figure 8(*c*), the backcalculated elastic modulus of the asphalt concrete surface layer is plotted as a function of the average pavement temperature. These results display a relatively good relationship between temperature and the elastic modulus of asphalt concrete except for the one outlier at subzero temperatures. This point occurred for the deflections taken in February 1993. Its result is probably more of an anomaly produced by the assumptions used in the backcalculation rather than a reflection of the underlying relationship between temperature and elastic modulus. It can be seen in Figure 8(*b*) that the moduli from the February deflections yielded a higher modulus for the granular base than for the asphalt concrete surface layer.

In Figure 9(*a*), the contact resistance profile is shown for August and February 1992. The dramatic increase in the resistance at a point 1.2 m (4 ft) from the surface of the pavement indicates that this is the probable depth of the frost in February. Thus, it can be reasoned that the dramatic increase in the elastic modulus of the aggregate base layer is due to a relatively deep frost penetration into the pavement structure.

SUMMARY AND CONCLUSIONS

The instrumentation for monitoring the test sections included in the LTPP seasonal study has been selected on the basis of three pilot installations. This instrumentation includes TDR sensors and thermistor probes for monitoring changes in subsurface moisture and temperature, electrical resistivity probes for frost-thaw depth measurements, piezometers for determination of the depth to the groundwater table, and air temperature probes and tipping-bucket rain gauges for monitoring ambient temperature and rainfall.

The standard procedures that were developed for installation of the seasonal instrumentation and that are implemented at several program sites show that the pavement sensors can be placed into one hole in the pavement without noticeable interaction effects. In addition, with proper planning, installation of the sensors can be completed in one 8-hr day.

Preliminary data show that the selected instrumentation is operating satisfactorily and yielding reasonable results. It appears that these sensors will indeed provide many of the data needed to attain a fundamental understanding of the magnitude and impact of temporal variations in pavement response and properties caused by the effects of and interactions between temperature, moisture, and traffic loadings; this was clearly illustrated in the sample data in the paper.

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