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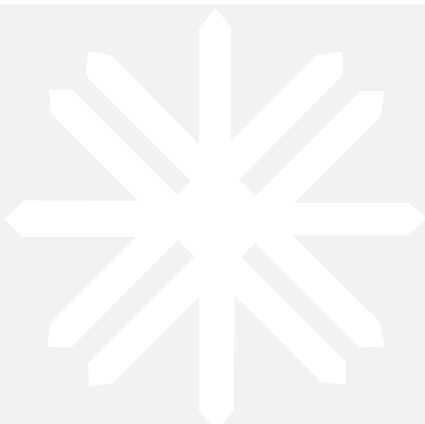
Forest Service

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Development
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July 2001



Using Time Domain Reflectometry (TDR) and Radio Frequency (RF) Devices to Monitor Seasonal Moisture Variation in Forest Road Subgrade and Base Materials



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Executive Summary/Abstract

The U.S. Department of Agriculture Forest Service and the U.S. Army Cold Regions Research and Engineering Laboratory have been evaluating a quantitative technique for the application and removal of load restrictions by observing relationships among pavement stiffness, pavement damage, soil moisture, and seasonal freezing and thawing. Laboratory tests of the Time Domain Reflectometry and Radio Frequency sensors showed both to be reasonably accurate and repeatable when compared to known moisture values in several soil types. Laboratory tests of the probes under repeated adverse freeze-thaw cycling showed the probes to be durable. Analysis of field data collected at seven locations on four national forests showed that permanently installed sensors strategically located on a forest road network can provide an affordable method for quantitatively determining the beginning and end of critical periods of pavement weakening associated with spring thaw. This information would be useful in administering periods of spring thaw load restriction.

The following report outlines the laboratory and field test programs conducted to monitor soil moisture and pavement stiffness and describes instrumentation used for the study. It discusses observations, analyses, and results from the laboratory and field tests as part of an overall effort to develop a reliable, objective, cost-effective method to determine when to place and remove load restrictions associated with periods of critical pavement weakening (i.e., spring thaw). The technique is applicable to any secondary road subjected to seasonal freezing.

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Background

The U.S. Department of Agriculture (USDA) Forest Service (FS) has management responsibility for more than 380,000 miles of road. These generally “low-volume” roads have various surface types ranging from thin, hot-mix asphalt cement and bituminous surface treatments (BSTs) to crushed gravel and native soils. Historically, the major heavy vehicle use of these roads has been for log haul during timber sales. A large portion of the total mileage is located in areas subjected to seasonal freezing and thawing or seasonal wet/dry climates. The potentially detrimental effect of heavy vehicles on thaw-weakened or saturated pavement structures is well known (figure 1). In an effort to reduce road surfacing maintenance costs and extend pavement life, it has been a common practice within the FS to restrict heavy vehicle use during periods of severe seasonal weakening. Decisions on the timing of when to place and lift load restrictions are generally made by local road managers and are based on visual distress indicators, past experience, and local economic impacts. Short of observing actual damage occurring to pavement structures, objective data demonstrating structural weakening is usually not available.

Current spring-thaw load restriction practices, including the level of restriction, correct timing, and length of restricted haul, vary appreciably

among road maintenance agencies (Kestler et al. 2000). During the past 15 years, several forests in the northwestern United States have installed subsurface temperature monitoring probes under paved roads to help determine periods of thaw-weakened conditions (figure 2). The probes consist of thermistors, spliced into a multistrand cable that is encapsulated into casting resin within a clear, small-diameter plastic tube several feet long. The tube is placed into a drilled hole through the pavement and backfill is compacted around it. Temperatures at depths below the road surface are monitored at the end of the instrumented cable. The readout end of the cable terminates in a small, weatherproof, electrical type box at the side of the road, often nailed to a tree. Readings have been taken both manually, with a digital thermometer unit, and with automated data loggers (figure 3). Current practice when using the thermistors is to place load restrictions when thawing below the asphalt is indicated by subsurface temperatures above 32 °F. Based on past limited studies of paved roads with nonplastic, coarse granular subgrades, the restrictions were generally maintained until all ground ice has melted (McBane and Hanek 1986a,b). While the use of thermistor probes have been effective in determining the beginning of strength loss and when to initiate load restrictions, the timing of strength recovery and restriction removal is less well-defined.



Figure 1—Examples of pavement damage due to thaw weakening.



Figure 2—Taking subsurface temperatures at a typical thermistor probe installation. Sites like this exist on many national forests in the northwestern United States.



Figure 3—The Handar 555 data-logger is used for auto-logging of thermistor probe readings. Data-logger is shown installed inside a weather-tight utility box.

Purpose

This report documents a project intended to investigate and better define the interrelationship that occurs in freeze/thaw and wet/dry climates among subsurface temperature, moisture, and pavement load capacity. In cooperation with the U.S. Army Cold Regions Research and Engineering Laboratory (CRREL), the FS investigated the feasibility of using Time Domain Reflectometry (TDR) and Radio Frequency (RF) soil moisture sensors in conjunction with thermistor probes to better define periods of seasonal weakening at seven field test sites located on four national forests in the northwestern and northeastern United States (figure 4). In particular, this study focused on determining if these technologies would be helpful in assessing when the hauling of heavy loads can be resumed on low-volume roads following seasonal load restrictions.



Figure 4—Field monitoring sites.

Project Overview

In 1993, a proposal was made to the FS Roads Technology Development Program (RTDP) to investigate the feasibility of using TDR technology to monitor real-time changes in moisture content of road base and subgrade materials. The proposal was subsequently approved and funded by the FS RTDP and U.S. Department of Transportation, Federal Highway Administration (FHWA), Federal Lands Highway Coordinated Technology Implementation Program (CTIP). A cooperative agreement was reached with CRREL for assistance because they had substantial experience with both the TDR and RF technologies. Interest in these relatively new technologies (new in terms of use for measuring soil moisture) was high, since no

easy-to-use, rugged, reliable method for nondestructive, in situ, real-time measurement of subsurface moisture contents at multiple depths existed.

A secondary objective of this study was to provide field based information on the timing, duration, and magnitude of seasonal strength and moisture changes in road base and subgrade materials for use in pavement design. Mechanistic-empirical pavement designs generally require an estimation of seasonal strength and/or moisture variations (Uhlmeier et al. 1996). Field measured data of this sort is extremely limited, and the results from this study added to the limited database.

Commercially available TDR and RF soil moisture probes were investigated, evaluated in the laboratory, and installed at field sites. Laboratory programs consisted of calibration testing and freeze-thaw cycling of the probes. The purpose of the laboratory testing was to evaluate the operational characteristics of the devices with respect to the planned field applications. Field installations occurred at sites on four national forests: the Willamette National Forest in western Oregon, the Ochoco National Forest in central Oregon, the Kootenai National Forest in northwestern Montana, and the White Mountain National Forest in New Hampshire. Sites were monitored 1 or more years. Additional site instrumentation included thermistor probes for monitoring subsurface, pavement, and air temperatures; and open well standpipes for monitoring groundwater levels. Falling Weight Deflectometer (FWD) testing was performed periodically at all sites.

Instrumentation

TDR

TDR probes were used to monitor seasonal variations of in situ moisture contents of road base and subgrade soils at multiple depths. TDR probes (figure 5) determine a soil's volumetric water content by measuring its apparent dielectric constant (K_a). A material's dielectric constant is a function of the ratio between the speed of light in a vacuum, (c), and the velocity (v) of an electromagnetic pulse through the material of interest. It can be written as $K_a = (c/v)^2$

Since the length of the tines of the waveguide probes (length the pulse travels), (L), is known, the equation can be rewritten as $K_a = (ct/L)^2$

where t is the transit time of the electromagnetic pulse along the probe tines. The TDR device, similar to radar, transmits an electromagnetic pulse through a cable to the waveguide probe. The transit time of the pulse along the probe length is measured, and the dielectric constant of the material surrounding the probe is calculated using the above equation. The dielectric constants of air, dry soil, ice, and water are approximately 1, 3–5, 3–4, and 80, respectively. Because the dielectric constant of water is so much greater than that of dry or frozen soil, the contribution of liquid water to the overall soil-water-air mixture dominates the dielectric constant, and consequently, the percentage of water, by volume, can be determined. Additional detail on theory is provided in a number of references (Baker 1990; Klemunes 1998; Look and Reeves 1992; Topp et al. 1980; Topp et al. 1994).



Figure 5—Soilmoisture Equipment Corp. TDR buriable probe and testing unit.

TDRs have previously been used for geotechnical and pavement monitoring applications (Cramer 1995; Kane 1986). Both two- and three-tine probes have been permanently buried in the soil or structure to be monitored. Probes are available commercially from a number of companies or can be fabricated in any machine shop. Probes can be read by using a Tektronix (or similar) cable-testing unit or by a commercially available special TDR readout unit. The cable testing units require more time and effort than TDR readout units for waveform analysis to determine K_a . The TDR readout unit used on this project was a TRASE Model 6050X1 built by Soilmoisture Equipment Corp. of Santa Barbara, CA (figure 6). The \$8,800 cost was more expensive than a standard Tektronix cable-testing unit, but the TRASE device provides direct volumetric water content values. Individual probes cost less than \$100 each. Literature for the project TDR equipment is available from Soilmoisture Equipment Corp. (Soilmoisture Equipment Corp. 1993).



Figure 6—TRASE TDR unit taking moisture content reading from probe installed below pavement. The weather-tight utility box shown is used to protect TDR probe cable ends between readings.

RF

RF probes were also used to monitor in situ seasonal changes in subgrade moisture content at multiple depths. RF probes (figure 7), developed by Dartmouth College and CRREL, are now commercially produced by Vitel, Inc. of Chantilly, VA (Atkins et al. 1998; Campbell 1988; Kestler et al., in preparation). The Vitel RF probes used in this study allow measurements of both the real and imaginary dielectric constants. The frequency of operation of the probes is 50 MHz, which minimizes the effects of soil salinity and reduces

the need for soil specific calibrations. All required electronics for K_a determination are contained within the buriable probes. Four output voltages from the probes can be read with standard multimeters and automated data acquisition systems. Software provided with the equipment can be used for determination of a soils salinity, volumetric moisture content, and temperature. The cost of a probe, connector, and 50 feet of cable was approximately \$300 and a portable readout unit was approximately \$750 (figure 8). Typical manufacturer's literature on the RF probes and the readout unit are provided by Vitel, Inc. (Vitel 1994a,b).



Figure 7—Vitel, Inc. RF probe and reader.



Figure 8—Vitel, Inc. RF reader is shown inside a weather-tight utility box. It is used to protect cable ends between readings.

Thermistor Strings

Thermistor probes were installed at the test sites to measure air, pavement, and subsurface temperatures for determining the timing and depth of freezing and thawing. Thermistor probes for the project were constructed by Intercity Engineering Inc. of Springfield, OR to FS specifications using YSI 44004 thermistors from Yellow Springs Instrument Co., Inc. The probes were of various lengths, depending on site climate, and consisted of 9 to 14 individual thermistors, spliced into a multistrand cable that was encapsulated using casting resin into a small-diameter clear plastic tube. A thermistor lead was also provided to monitor pavement temperature, and another thermistor, on a separate cable, monitored air temperatures. A typical probe costs approximately \$300. Both a manually operated switchbox (built by Intercity Engineering, Inc., at a cost of approximately \$92), in combination with a commercial digital thermometer (Tegam, Inc. Model 865, at a cost of approximately \$190), as well as an automated data logger system (Handar, Inc., Model 555A, at a cost of approximately \$1,850) were used to collect site temperatures. As previously mentioned, similar probes are currently used by several national forests in the northwestern United States to assist in determining critical periods of weakening during spring thaw (Baichtal 1990; Barcomb 1989; Collins 1991; DeJean et al. 1991; McBane and Hanek 1986a,b; Utterback 1995).

Standpipes

Open well standpipes were installed to monitor seasonal fluctuations of groundwater at the sites. Standpipes for the project consisted of geotextile wrapped, slotted, 1-inch-diameter PVC water pipe placed into multiple geotechnical exploration drill holes at each site. The drill holes were continued until bedrock was encountered or the hole was approximately 20 feet in depth, whichever occurred first. Groundwater levels were monitored manually using an electronic water meter from Slope Indicator Co. of Seattle, WA.

FWD

FWD testing (figure 9) was performed at each site to monitor seasonal changes in pavement stiffness, allowing calculations to be made of seasonal changes in load carrying capacity and pavement damage potential. The FWD device applies a falling weight load to the pavement surface, and the resulting deflection basin is measured by velocity transducers or linear variable displacement transducers (LVDTs) at preselected distances from the applied load. Internal integration (or direct readout in the case of the LVDTs) yields displacement, which can be used to manually determine pavement layer moduli via backcalculation (FHWA 1994).



Figure 9a—FWD used at Willamette, Ochoco, and Kootenai National Forest sites.



Figure 9b—FWD used at White Mountain National Forest site.

The FWD testing for the three western United States locations, each location with two test sites, was contracted with Pavement Services, Inc. of Portland, OR. The device used was a KUAB 2m Model 150 FWD. A 5.91-inch-diameter segmented plate transferred the load pulse to the pavement. Deflections were recorded by seven LVDTs that measured the displacement of the sensor body relative to an internally suspended damped mass that acts as an inertial reference. The LVDTs had a measurement range of 0 to 200 mils within the accuracy tolerances of American Society of Testing and Materials (ASTM) D 4694. The FWD load and deflection measurement system was calibrated at the Strategic Highway Research Program's (SHRP) Western Region Calibration Center prior to the project (calibration date October 18, 1994) and again prior to the start of testing on the Kootenai National Forest sites (calibration date October 19, 1995). FWD testing of the White Mountain National Forest site was performed by a Dynatest device, provided by CRREL, that had previously been calibrated at the Pennsylvania Department of Transportation (DOT) SHRP calibration center in Harrisburg (calibration date December 3, 1997).

The FWD testing was conducted by first applying a "seating" drop of approximately 12,000 pounds. After the seating drop, three drops were applied at each of the target loads of 6,000, 9,000, and 12,000 pounds. Peak load and deflection values were recorded for all drops except the seating drop. In addition, deflection and load time histories were recorded for the three drops targeted at 9,000 pounds. Deflection sensor spacing varied depending on the project test site and local structural and environmental conditions.

EVERCALC, a backcalculation computer program developed for the Washington State Department of Transportation (WSDOT), was used for the backcalculation of pavement moduli for this study (FHWA 1994; WSDOT 1995a,b). EVERCALC is a mechanistic pavement analysis program based on the program CHEVRON. It uses an iterative approach to match measured and theoretical surface deflections calculated from assumed moduli, and the root mean square (RMS) value is minimized. It can handle up to five layers with or without a rigid base. Seed moduli can be estimated

based on relationships among layer moduli, load, and a variety of deflection basin parameters. It should be noted that one of backcalculations recognized weaknesses is its questionable accuracy during thawing, particularly with frozen and thawed layers during spring freeze-thaw cycling. Backcalculation does not adequately consider thin layers well nor does it handle soft (thawed) layers between two stiffer (frozen) layers. However, it is believed the backcalculated moduli values determined here were reasonable.

Laboratory Tests

Laboratory testing was a dual-phase program. The first phase consisted of laboratory tests performed to evaluate the durability, accuracy, and repeatability of TDR and RF moisture contents determined using the manufacturer supplied calibration curves. Measurements were compared to known gravimetric values determined in large-scale soil molds using four different soil types (figure 10).

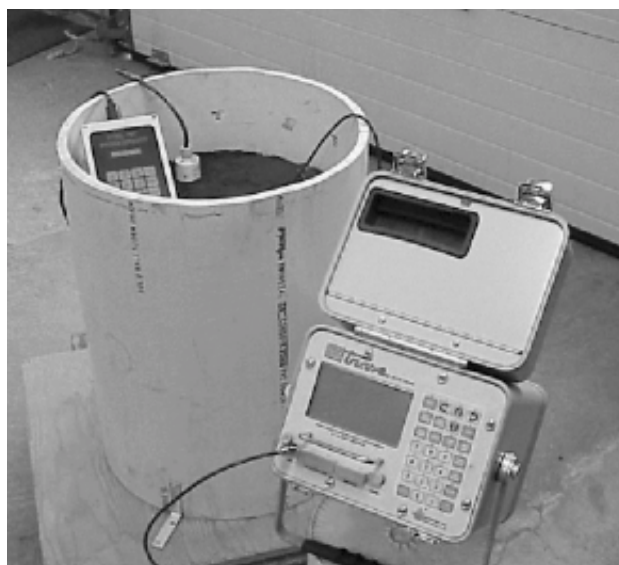


Figure 10—Large diameter soil mold used in calibration testing.

The second phase required the development of a simple inexpensive laboratory freeze-thaw moisture sensor testing device (figure 11) used to evaluate repeatability and accuracy of the probes when subjected to freeze-thaw cycling (Kestler et al. 1997).

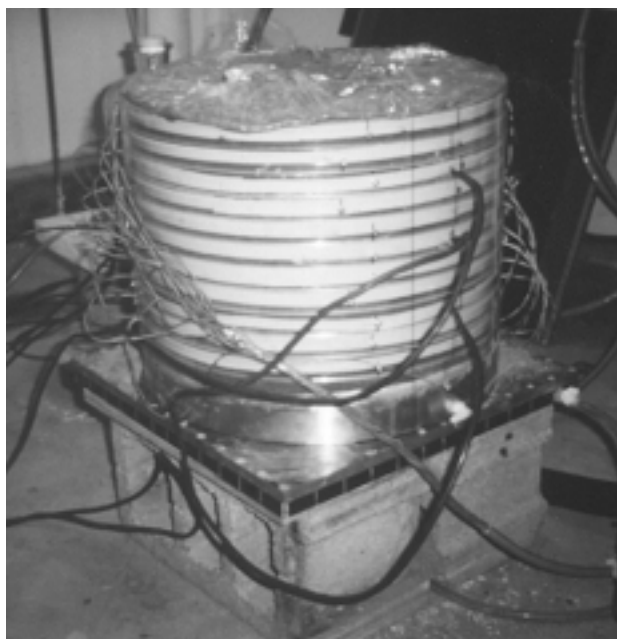


Figure 11—Soil mold developed by CRREL for repeated freeze/thaw testing of TDR and RF probes.

Field Sites – General

Instrumentation was installed at two test sites each on the Willamette National Forest, the Ochoco National Forest, and the Kootenai National Forest. A single test site was instrumented on the White Mountain National Forest as part of a larger unassociated road drainage study conducted by CRREL. Details in the instrumentation and monitoring activities varied slightly among the sites and will be discussed in the respective site-specific sections that follow. In general, each site consisted of a road segment approximately 80-feet long. One or two thermistor probes, depending on the site, were installed at each location with the probes generally near either end of the site. Near the middle of the site, a vertically spaced series of TDR probes were installed in a horizontal orientation, either into the side of a borehole or within the borehole backfill. Similarly, in a second borehole, a series of vertically spaced RF probes were installed. The depth of the instrumented vertical profile varied from site to site and was intended to slightly exceed the anticipated frost depth. Five FWD impact points, 20-feet apart, were located along the length of each site and marked to allow repeated testing on the same spots. In general, the FWD impact points were located between the wheel paths. Measurements of all

instrumentation were taken at the time of each FWD test, as well as periodically between tests.

Pavement structures at the sites are representative of typical paved and aggregate surfaced FS collector and arterial roads. All of the test sites, except the two on the Willamette National Forest, had asphalt surfacing. The asphalt thickness varied from 3.0 to 5.5 inches, depending on the site. Asphalt quality varied from new hot-mix asphalt on the White Mountain National Forest, to a moderately aged hot-mix asphalt on the Ochoco National Forest, to a composite asphalt surface consisting of several types of asphalt treatment (bituminous surface treatments, cold mix, chipseals) placed over a period of many years on the Kootenai National Forest. Both sites on the Willamette National Forest had crushed aggregate surfacing. The Willamette National Forest aggregate surfaced sites were chosen to investigate the potential for utilizing moisture monitoring devices for road management of unpaved roads in nonfrost climates.

The range of subgrade soils at the test sites is typical of those found in mountainous terrain and representative of FS roads. Subgrade soils, under the Unified Soil Classification System, varied widely including silty sands (SM), silty-sandy gravels (GM), clayey sands (SC), silts (ML), and elastic silts (MH).

Climates among the sites are representative of the wide range of conditions commonly found on mountainous FS roads throughout the United States. Climates ranged from a wet but nonfrost condition at the Willamette sites, to a mild and relatively dry climate with repeated freeze/thaw cycling on the Ochoco National Forest, to relatively severe, wet, deep frost at the Kootenai and White Mountain sites.

The Willamette, Ochoco, and White Mountain sites were instrumented in the fall of 1994. Site monitoring and associated FWD testing occurred for approximately 1 year following instrumentation, with additional data collected in subsequent years at the White Mountain site. The Kootenai sites were instrumented in the fall of 1995 with monitoring and FWD testing occurring during 1995 and 1996.

Laboratory Testing Program

The laboratory testing program was a multi-phase program. The first phase, conducted by the Willamette National Forest Materials Laboratory, was initiated for the purpose of gaining familiarity with the operational aspects of the TDR and RF equipment in the range of soil types and moisture and density conditions expected at the field test sites. The second phase of the testing program, conducted by CRREL, evaluated the TDR and RF probes when subjected to freeze-thaw cycling (Kestler et al. 1997). Both studies evaluated the durability, accuracy, and repeatability of probes and provided information for installation procedures and limitations of the equipment.

The TRASE TDR equipment utilizes the “Topp” correlation equation programmed into the TDR unit to relate the dielectric constant to the volumetric moisture content (Soilmoisture Equipment Corp. 1993). The Topp equation is an experimentally derived third degree equation based on laboratory tests of silts and clays. The equation is as follows:

$$\theta_v = -0.053 + 0.0292 K_a - 5.5 \times 10^{-4} K_a^2 + 4.3 \times 10^{-6} K_a^3, \text{ where}$$

θ_v = the volumetric moisture content of a soil expressed as a percent, and

K_a = the dielectric constant of the soil.

The soil types, bulk densities, and moisture contents used to develop the Topp equation were typical of agricultural soils. The Topp equation has been shown to adequately address these soil types as a “universal” correlation equation (Topp et al. 1994).

The Vitel RF equipment utilizes experimentally derived polynomial equations for three standard soil types (sand, silt, and clay) in correlating the volumetric moisture content to the dielectric constant. The equations for each soil type can be formulated using the following generic equation and the coefficients shown below.

$$\theta_v = a + b K_a + c K_a^2 + d K_a^3, \text{ where}$$

Soil Type	a	b	c	d
Sand	-8.63	3.216	-0.0954	0.001579
Silt	-13.04	3.819	-0.09129	0.007342
Clay	-20.93	6.553	-0.2464	0.0032414

Some of the road building materials, in which the gauges for this study were installed, were outside the range of soil types used to derive these equations. This testing procedure was initiated to determine the appropriate relationship between the dielectric constant and moisture for common road building materials.

Soil Types Tested

Four soils were tested in the first phase of the laboratory testing program. The Rexius Loam was selected because it was similar to an agricultural soil used in the derivation of the Topp equation. The Rexius Loam was 1/2-inch-minus with 48.4 percent passing the #200 sieve, nonplastic, and a classification of SM.

The aggregate soil was selected because probes were planned for installation in roadbase aggregate, as well as forest soils that are more granular than agricultural soils. The aggregate selected was 1/2-inch-minus with 9.6 percent passing the #200 sieve. Aggregate base material is typically 1-inch-minus or coarser, but the spacing of the RF gauge’s probe tines were only 0.47 inches. The finer aggregate was used to allow for better material contact around the probe tines. The other two soils were subgrade soils from the Willamette and Ochoco field test sites. These materials were an elastic silt and silty sand, respectively. The Ochoco soil was 1/2-inch-minus with 47.8 percent passing the #200 sieve, had a liquid limit of 39 percent, a plasticity index of 4 percent, and a classification of SM. The Willamette soil was 3/8-inch-minus with 72 percent passing the #200 sieve, a plasticity index of 6 percent, and a classification of MH.

Subgrade soil from the White Mountain National Forest test site was used for the laboratory freeze/thaw testing by CRREL. The soil was a nonplastic GM under the Unified Soil Classification System. It contained 15 percent gravel, 53 percent sand, and 32 percent fines passing the #200 sieve.

Test Procedures

During testing at the Willamette Laboratory, the experimental procedure consisted of placing both TDR and RF wave-guides in a large mold with soil compacted to a specific moisture content and density. The mold was constructed from a 24-inch-long section of 18-inch-diameter PVC pipe (id of 17.44 inch) mounted onto a plywood base. The mold was scribed horizontally on the inside every 3 inches. Soil was batched to the specified moisture content and kept in sealed buckets. A specified weight of the soil-water mixture was placed in the mold and compacted in 3-inch lifts to meet the specified density. Compaction was accomplished with a 5.5-inch-diameter vibratory plate. Moisture contents were obtained before, during, and after compaction with testing on approximately every other lift to assure quality control.

Tests were performed on each of the four soils at a density of approximately 85 percent of the maximum density as defined by AASHTO T-99 and at various moisture contents above and below optimum moisture. This density level was selected to facilitate insertion of the probes into the soil.

The RF probes consist of four 0.16-inch-diameter by 2.3-inch-long tines. Three of the tines were spaced at 120 degrees along a 0.50-inch-radius circle with the fourth tine at the center of the circle (figure 7). The RF probes were pushed vertically into each layer approximately 3.5 inches from the outside of the mold at 90 degree increments.

Various configurations of probes or waveguide connectors are available with the TRASE TDR equipment. This study used both a connector-type and buriable-type waveguide. The connector probe had two 0.25-inch-diameter by 5.9-inch-long detachable tines spaced 2.1 inches apart. The buriable probe had three 0.13-inch-diameter by 7.9-inch-long tines spaced 1 inch apart. The

connector probe was made to be installed vertically from the soil surface, while the buriable probe is made to be buried horizontally in a soil, but can be pushed vertically. Generally, the buriable probes were installed horizontally. Typically, the TDR connector probes were pushed vertically into every other lift (6 inches) approximately 3.5 inches from the outside of the mold, 180 degrees apart. TDR and RF probes were placed in the same lift, but were placed away from each other as not to affect the readings. Initially, the buriable probes were placed at the layer interfaces. This resulted in some problems with erratic readings. It was believed the problems were due to density variations caused by uneven compaction around the probe. The procedure was then modified by scarifying the bottom layer prior to placing the probe and upper layer. This appeared to improve the situation, but more consistent results were obtained when a probe was placed at middepth of an uncompacted layer. The last of these methods was employed for this study.

The CRREL testing program consisted of determining the freeze-thaw behavior of a 17-inch-diameter soil sample subjected to three freeze-thaw cycles instrumented with temperature, RF, and TDR sensors. The test apparatus and general testing procedure were modeled after CRREL's frost susceptibility laboratory test. The purpose of the program was to determine the reliability and durability of the sensors when subjected to repeated freeze-thaw behavior.

The White Mountain test site subgrade soil was compacted by CRREL into a 17-inch-diameter cell in 9 lifts, 90 to 95 percent of the optimum density as defined by AASHTO T-99. The test apparatus cell consisted of 12 clear plastic rings approximately 1.1-inches high, placed on top of a porous plate and an aluminum base plate. The base plate allowed water entry into the sample from a reservoir. Cold plates at the top and bottom of the sample enabled control of a thermal gradient across the soil sample. The test apparatus can be seen in figure 11. The sample was instrumented with three TDR sensors, three RF sensors, thermistors, thermocouples, and screws mounted into the clear plastic rings for monitoring frost heave.

Test Results

During the Willamette Laboratory calibration check testing, with the TDR buriable probe installed horizontally, readings of volumetric moisture were taken after the construction of every lift. The connector probe was installed vertically, read, then removed and reinstalled after every lift. The RF probes were also inserted vertically, read for K_a , then removed and reinstalled after every lift. The volumetric moisture results for a given probe type and orientation were averaged for a test setup (soil type, density, and moisture content). The volumetric moisture content was converted to the gravimetric moisture content of the test point by the following relationship:

$$\theta_g = \theta_v \times \gamma_w / \gamma_d, \text{ where}$$

θ_g = the gravimetric moisture content,

θ_v = the volumetric moisture content,

γ_w = the unit weight of water, and

γ_d = the dry density of soil.

The RF K_a data was converted to the volumetric moisture content (and then gravimetric moisture content using the above relationship) using the correlation equations for sand, silt, and clay. Figures 12 through 15 show the lab measured gravimetric moisture contents versus those calculated from the gauge readings with the 1:1 line indicating no deviation between measured and calculated values.

As shown in the figures, the RF results were all close to the 1:1 line. For the Willamette site soil (Lowell Silty Clay), the RF values for the “clay” curve are essentially on the 1:1 line, as was the “silt” curve values for the Rexius Loam. For the Ochoco soil, the “silt” and “clay” curves are very close to the 1:1 line. The aggregate results were farther from the 1:1 line, but still good. In all cases, the graphs plotted approximately parallel to the 1:1 line, indicating good correlation between changes in gravimetric and volumetric moistures.

The TDR results, with the exception of the aggregate soil and the Ochoco silt, generally varied more from the 1:1 line than the best RF fits, but were still reasonably close. The TDR results were

better for the Rexius Loam and Ochoco soils as they are more similar to the silty soils modeled by the Topp curve. As with the RF probe, the TDR data generally plotted approximately parallel to the 1:1 line.

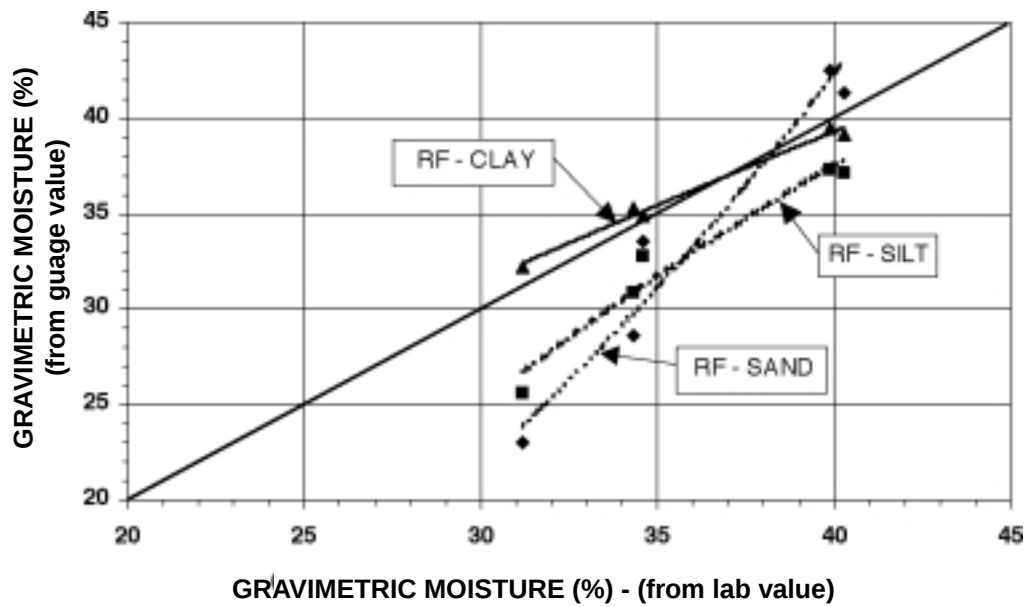
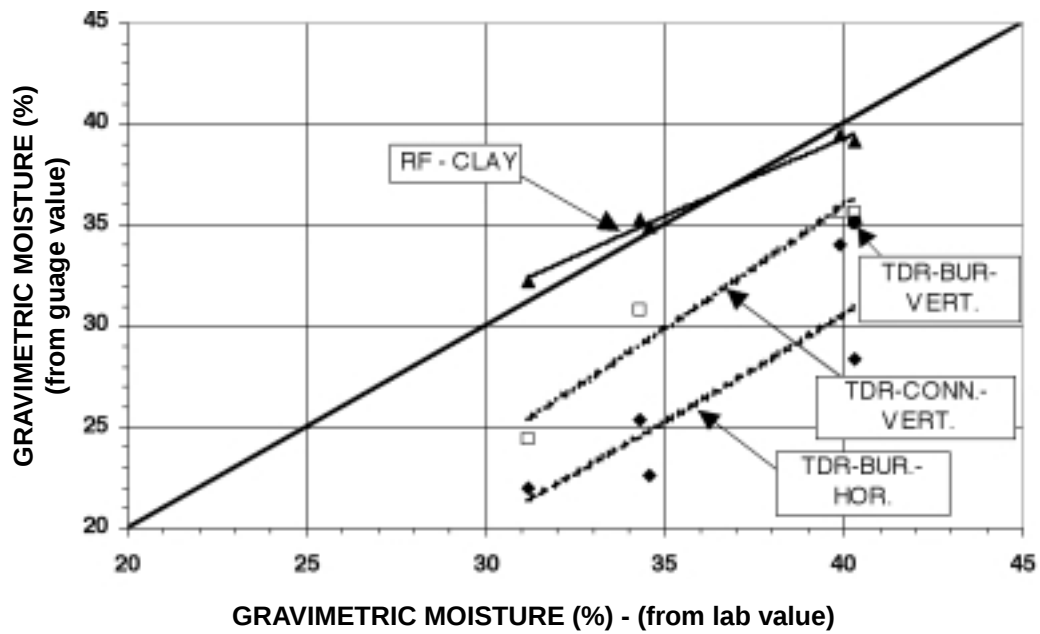
During the CRREL freeze-thaw testing, the frost penetration rate was fairly constant and was selected to be similar to the rates expected at the Montana and New Hampshire sites. The frost heave after the first cycle was minimal, probably due to the position of the water reservoir being below the base of the actual sample. The level was raised for cycles 2 and 3 and the sample heaved by 2.5 inches or nearly 15 percent.

The initial moisture contents for each probe type measured by the three TDR probes or three RF probes were close to one another, but the RF values were different than the TDR values. This is because the RF probes were installed in frozen soil and inserted into the mass while the TDR probes were compacted into the mass. After the freeze-thaw cycles, the TDR and RF values approached one another as expected.

The relationships between frost penetration, frost heave, and water added to the system were anticipated. The total frost heave corresponded well to frost penetration and to the water added to the system. Sharp increases and decreases in volumetric water contents also correspond well with the freezing front. The reader is referred to the previously referenced paper (Kestler et al. 1997) for additional details on this portion of the study.

Conclusions on Lab Testing

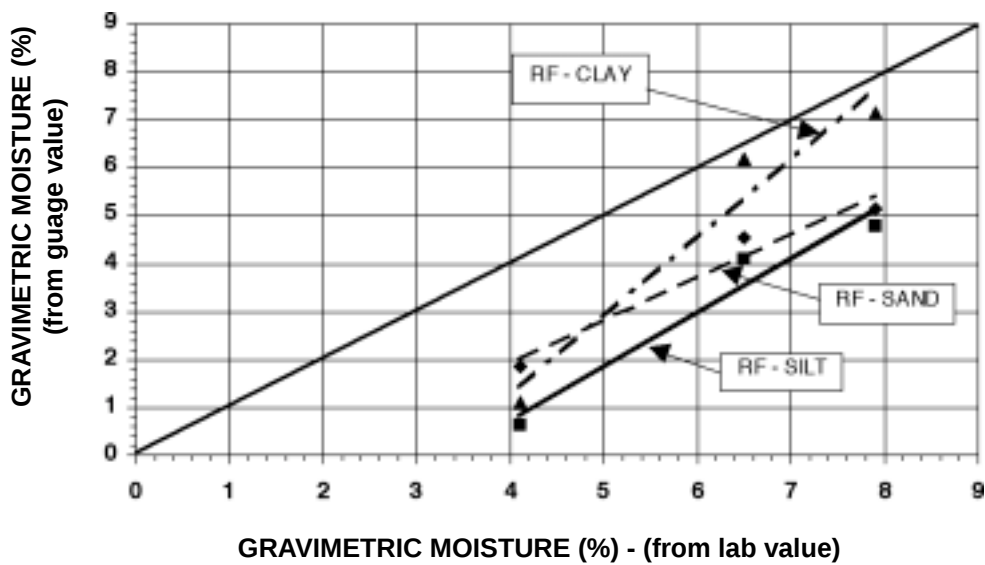
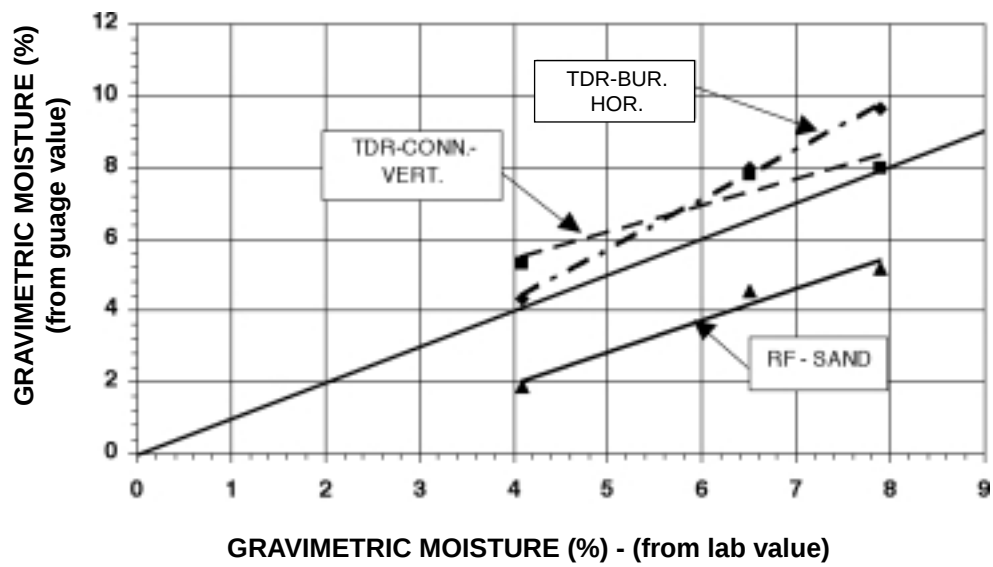
1. During the Willamette Laboratory testing, both gauges did reasonably well correlating K_a to moisture. The RF did slightly better, probably because of the separate curves for various soil types.
2. The internal RF calibration was a poor choice for the aggregate test soil, probably because of the difficulties obtaining soil compaction between the tines.



a) Lab Testing: Lowell Silty Clay

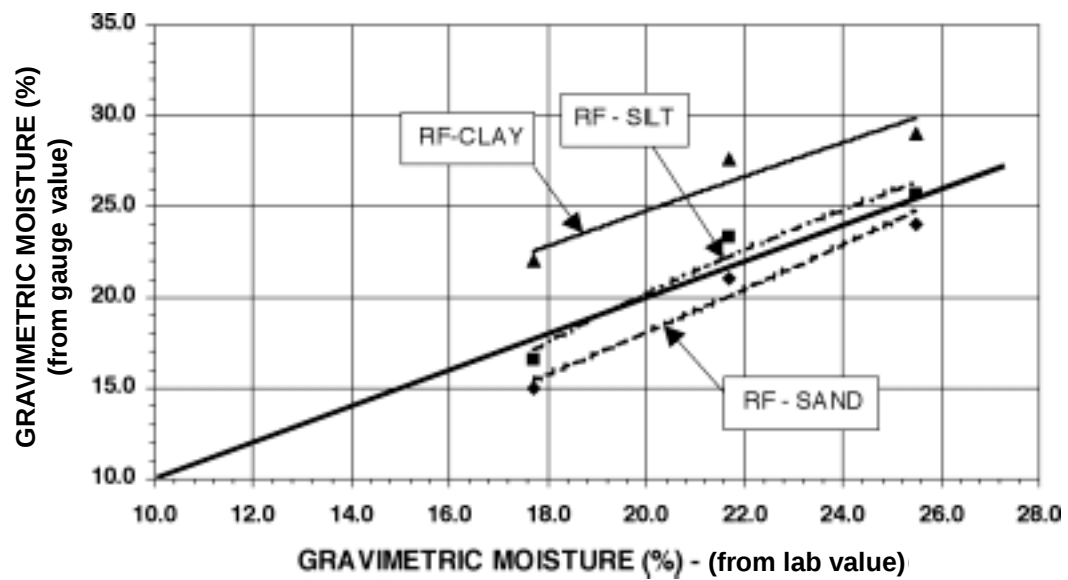
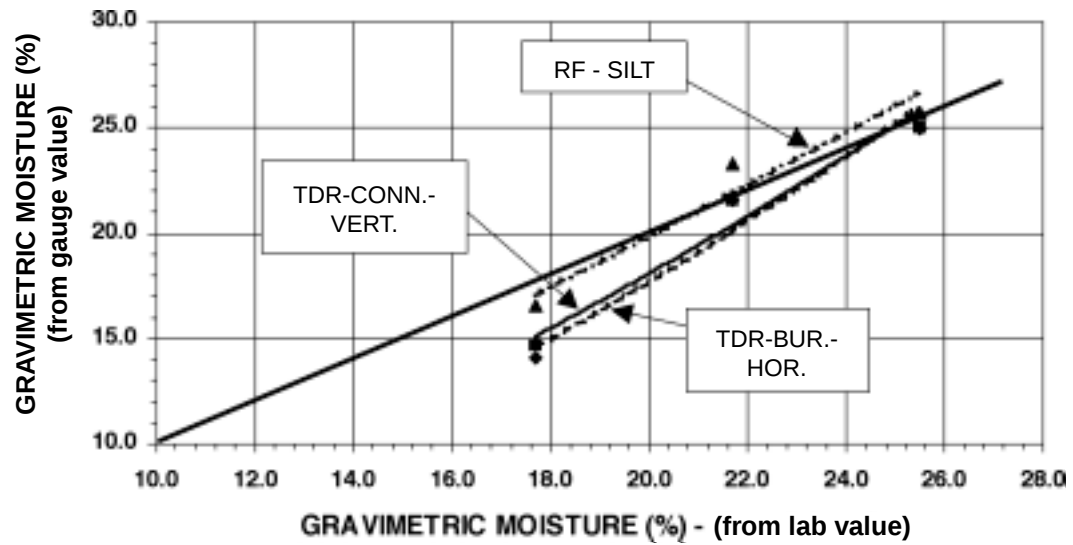
b) Lab Testing: Lowell Silty Clay RF Calibration

Figure 12—TDR and RF results compared with laboratory determined values—Lowell Silty Clay.



- a) Lab Testing: Aggregate
- b) Lab Testing: Aggregate—RF Calibration

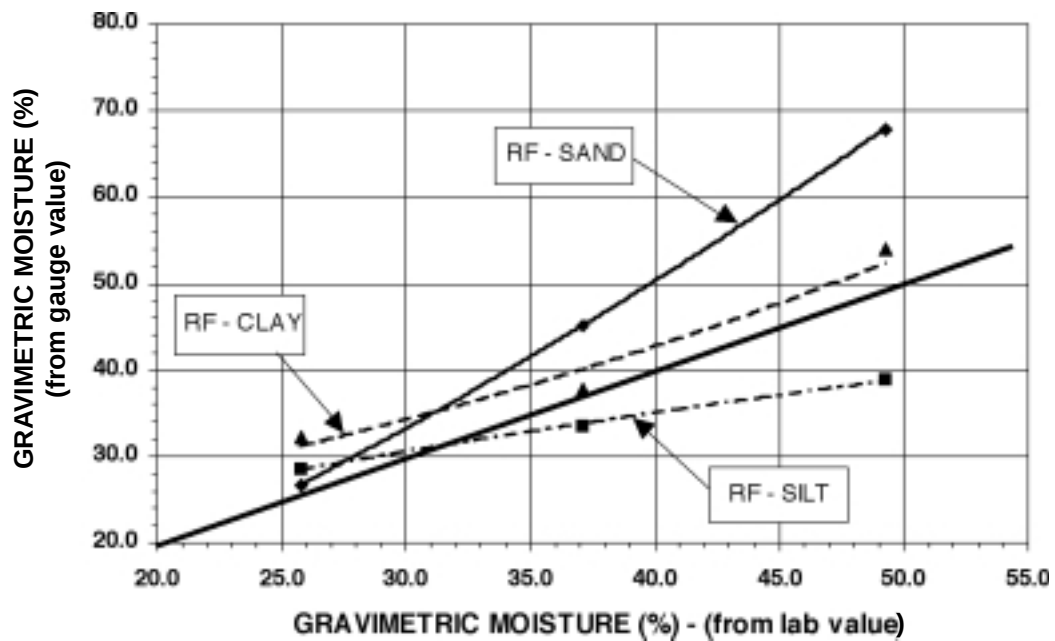
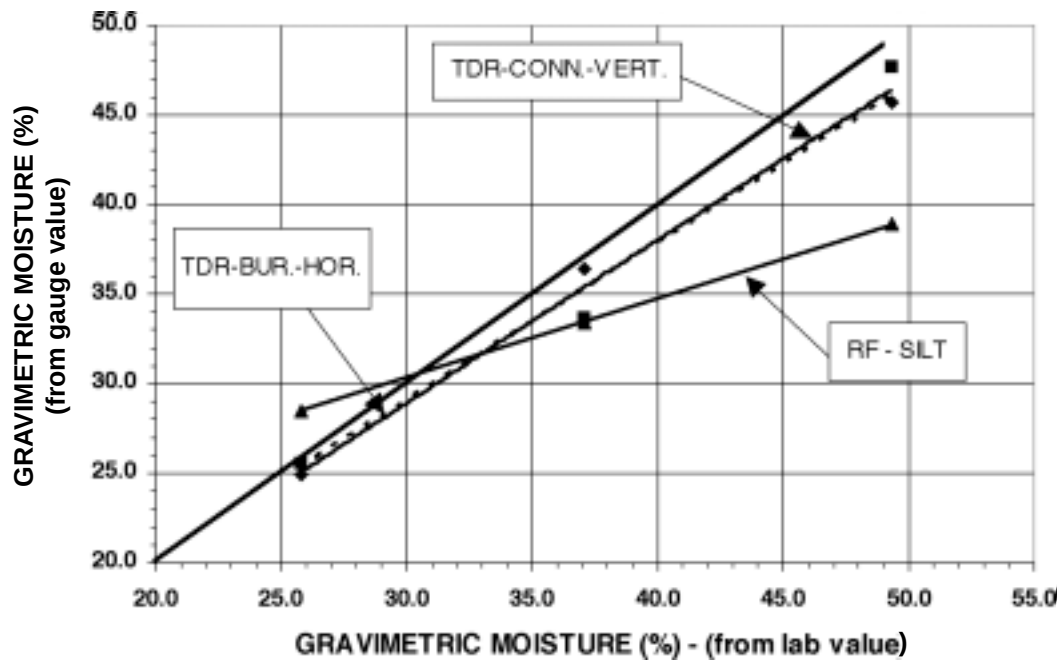
Figure 13—TDR and RF results compared with laboratory determined values—Aggregate.



a) Lab Testing: Rexius Loam

b) Lab Testing: Rexius Loam—RF Calibration

Figure 14—TDR and RF results compared with laboratory determined values—Rexius Loam.



a) Lab Testing: Ochoco Silt

b) Lab Testing: Ochoco Silt—RF Calibration

Figure 15—TDR and RF results compared with laboratory determined values—Ochoco Silt.

3. Both the TDR and RF results tended to approximately parallel best-fit 1:1 correlation lines. This indicates that small soil-specific correction values could be developed, if needed, to further improve the correlation accuracy.
4. During freeze-thaw testing, rapid decreases and increases in the apparent water content were observed as the freezing front advanced and retreated. These observations showed that TDR and RF moisture sensors are good indicators of frozen versus thawed conditions.
5. Laboratory testing demonstrated that TDR and RF probes are reliable, repeatable, and durable when used to measure unfrozen water contents in soils subjected to freeze-thaw cycling.

Willamette Field Sites Location and General Layout

The Willamette National Forest test sites were located on the Lowell Ranger District, Forest Service Road No. 1821190 at milepost 0.6. Road 1821190. Typical of forest roads west of the Cascade, it is a single-lane road with turnouts, side-hill construction, aggregate surface, and road grades between 6 and 12 percent (figure 16). The climate west of the Cascades is maritime, with mild temperatures and a distinct rainy and dry season. Average annual precipitation measured at the closest weather station (Lookout Point Dam, approximately 13 miles west of the site) is 40 inches, delivered primarily as rainfall between November and May.



Figure 16—Willamette National Forest test site during instrumentation installation. The narrow, aggregate surfaced road is typical of many western Oregon FS roads.

The test site location was within the road segment used for a road sedimentation study (Foltz and Truebe 1994) and an aggregate thickness design study (Truebe and Evans 1994) that were monitored between 1992 and 1994. The two sites were approximately 50 feet apart and set up similarly. Each site had five FWD test location points spaced 20 feet apart. Instrumentation points for TDR, RF, and thermistor sensors were located between the FWD tests location points as shown in figures 17 and 18.

The TDR and RF probes were installed horizontally in the sidewall of the augered holes when possible. The Willamette sites were the first sites instrumented in this study and the installation equipment consisted of simple pry bars. Some of the probes had to be compacted in the backfill because of these limitations. Specialized pry bar heads were constructed for the Ochoco and Kootenai sites, and more probes were consequently installed into the sides of the augered holes (figure 19).

Site Surfacing Structure and Material Properties

The Willamette sites were aggregate surfaced road segments over an elastic silt subgrade (ML to MH). The surfacing material was a good quality 1-inch-minus, dense graded, crushed aggregate ranging in thickness from 10 to 11 inches at site 1, and 11 to 12 inches at site 2. A thin layer (2 to 5 inches) of an older, 4-inch-minus aggregate was encountered at some locations at site 1.

A subsurface investigation was performed at each site for the purpose of determining the depth to a material change or “hard layer” and for monitoring groundwater fluctuations. Two drive probe points (depths up to 27 feet) and one augured hole (depths up to 17 feet) were installed at each site. Standpipes were placed in all of the holes for water level monitoring.

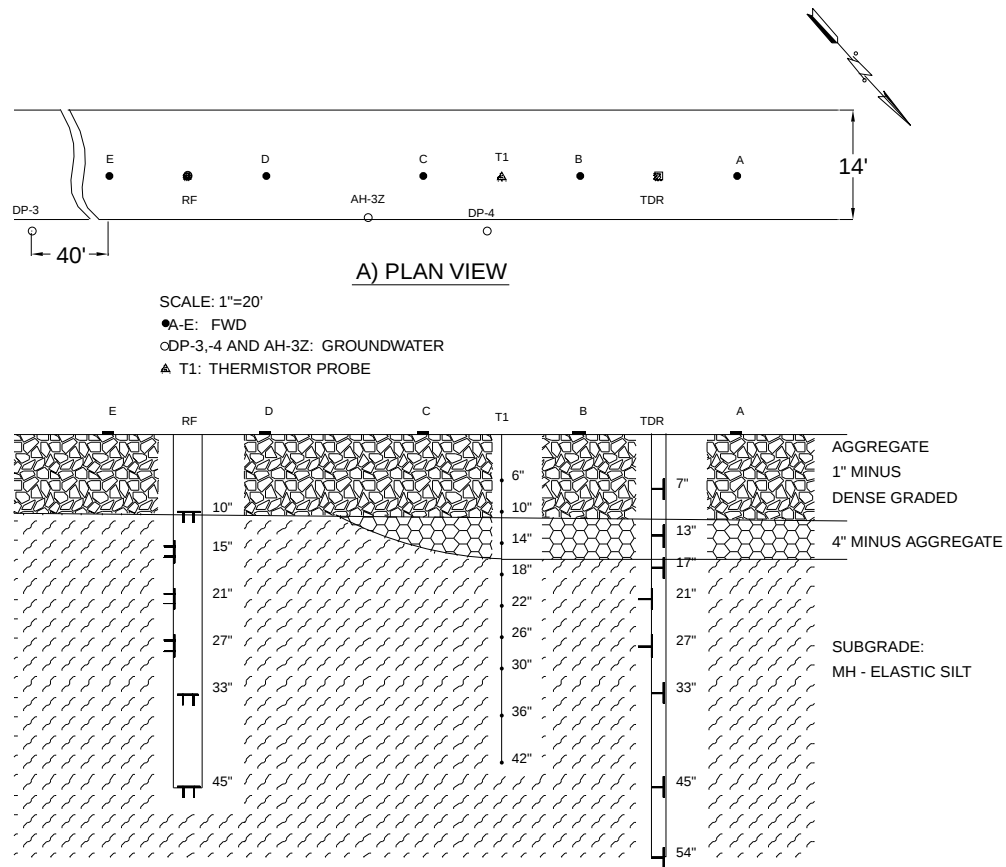
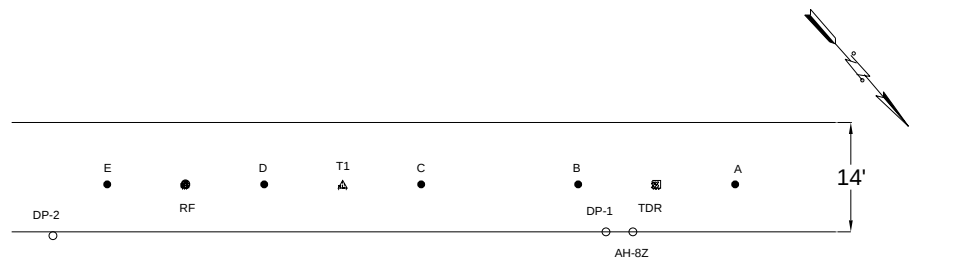


Figure 17—Instrument Layout: Willamette National Forest—Site 1.



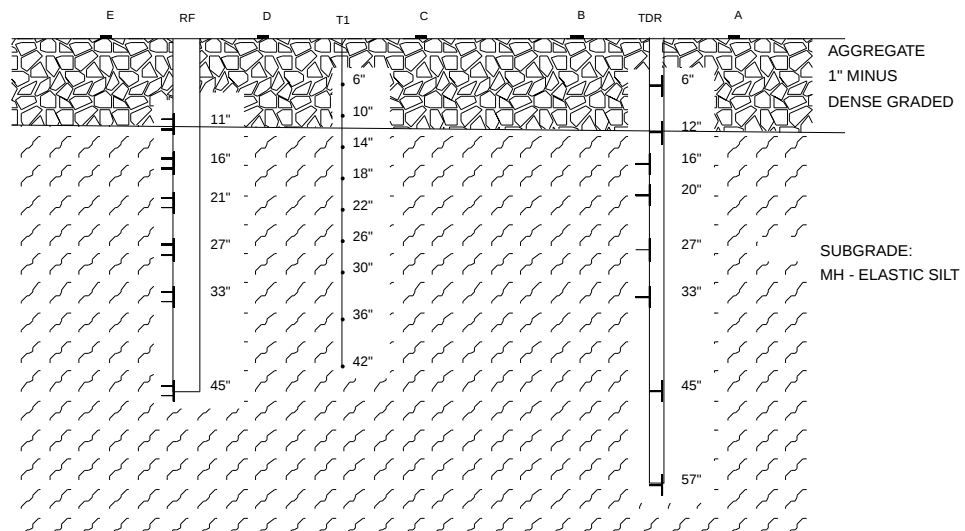
A) PLAN VIEW

SCALE: 1"=20'

● A-E: FWD

○ DP-1, -2 AND AH-8Z: GROUNDWATER

▲ T1: THERMISTOR PROBE

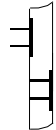


B) PROFILE VIEW

NOTES:

1 - PROFILE VIEW SHOWS PLACEMENT DEPTHS OF INSTRUMENTATION

2 -



PROBE INTO SIDE OF BOREHOLE

PROBE COMPACTED INTO BOREHOLE BACKFILL

3 - BOREHOLE DIAMETER IS NOT DRAWN TO SCALE

4 - HORIZONTAL SCALE: 1"=20'

VERTICAL SCALE: 1"=20"

Figure 18—Instrument Layout: Willamette National Forest—Site 2.

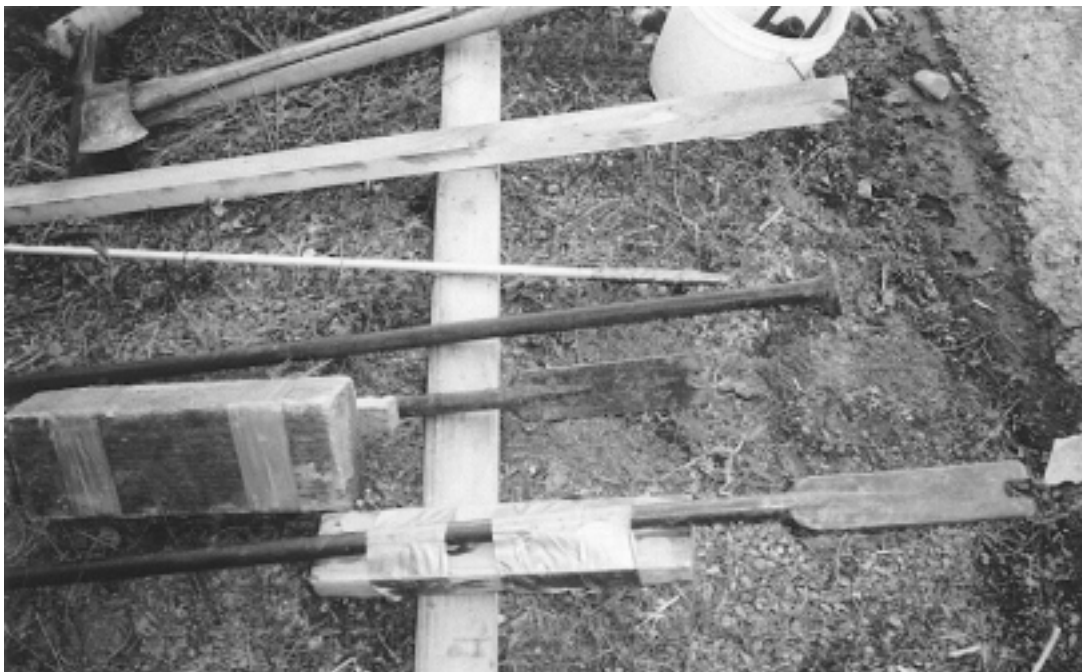


Figure 19a—Modified (slotted ends) pry bars are used for inserting probes into the side of a borehole.

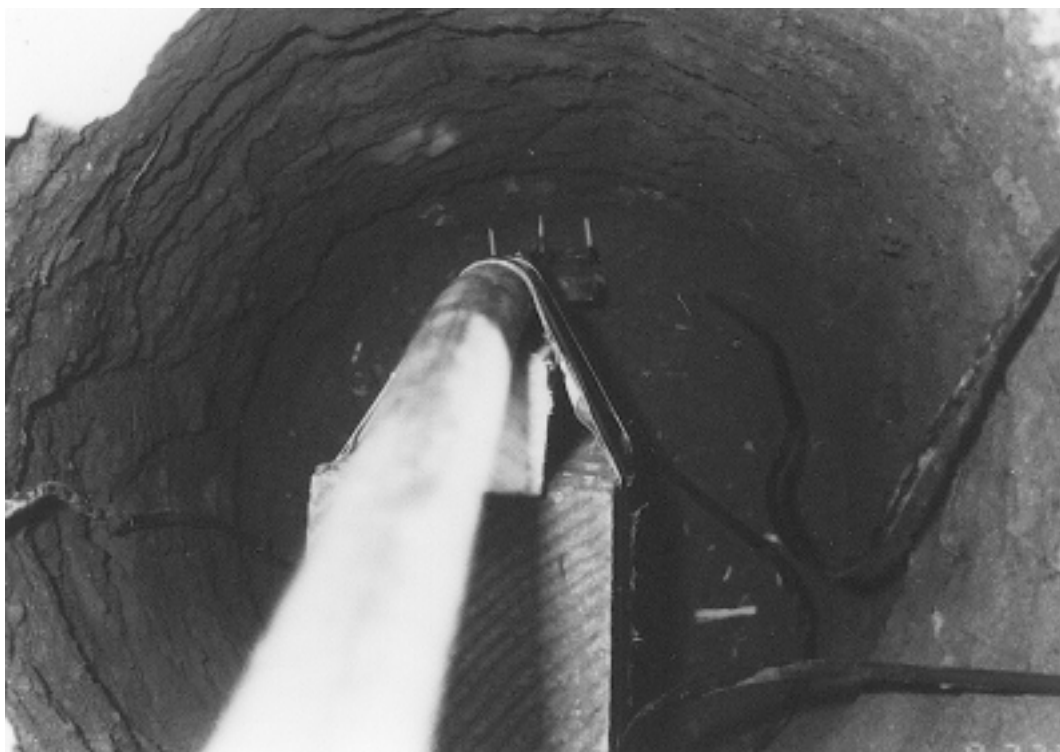


Figure 19b—Using a pry bar with an attached wooden block, the TDR probe is inserted into the side of a borehole.

TDR, RF, and Thermistor Instrumentation

The TDR probes were installed in 10-inch-diameter augured holes. Soil and aggregate was saved from specific depths of the excavation and reused as backfill at corresponding depths. In some instances, extra material was necessary to backfill the hole. An effort was made to push the probes into the sides of the boreholes, but when this was not possible, probes were installed in the backfill. All TDR probes were installed horizontally and rotated approximately 45 degrees from the probe installed immediately below. Depths and installation method of the TDR probes are shown in figures 17 and 18.

The RF probes were installed in 6-inch-diameter augured holes. Soil and aggregate was conserved and utilized similar to the TDR holes. Similar to the TDR sites, an effort was made to install the RF probes into the sides of the augured holes. When this was not possible, the probes were installed vertically into the backfill. Depths and installation method of the RF probes were also shown in figures 17 and 18.

The thermistor strings were installed with 9 thermistors located between depths of 6 and 42 inches and a 10th thermistor located to monitor air temperatures.

Data Collection and FWD Testing Program

Data was collected for temperature (thermistors) and weather conditions, moisture content (TDR and RF), and groundwater from August 19, 1994 through August 29, 1995. Readings were obtained at least every month during the dry season and at least twice per month during the wet time of the year. All readings were obtained manually. Additional information was recorded and stored in the TDR and RF units for review and data verification purposes.

FWD data was obtained throughout the year for the purpose of determining material layer strengths and seasonal strength variations. Data was obtained every other month from October 1994 through August 1995. Temperature and moisture data was always collected on these test dates.

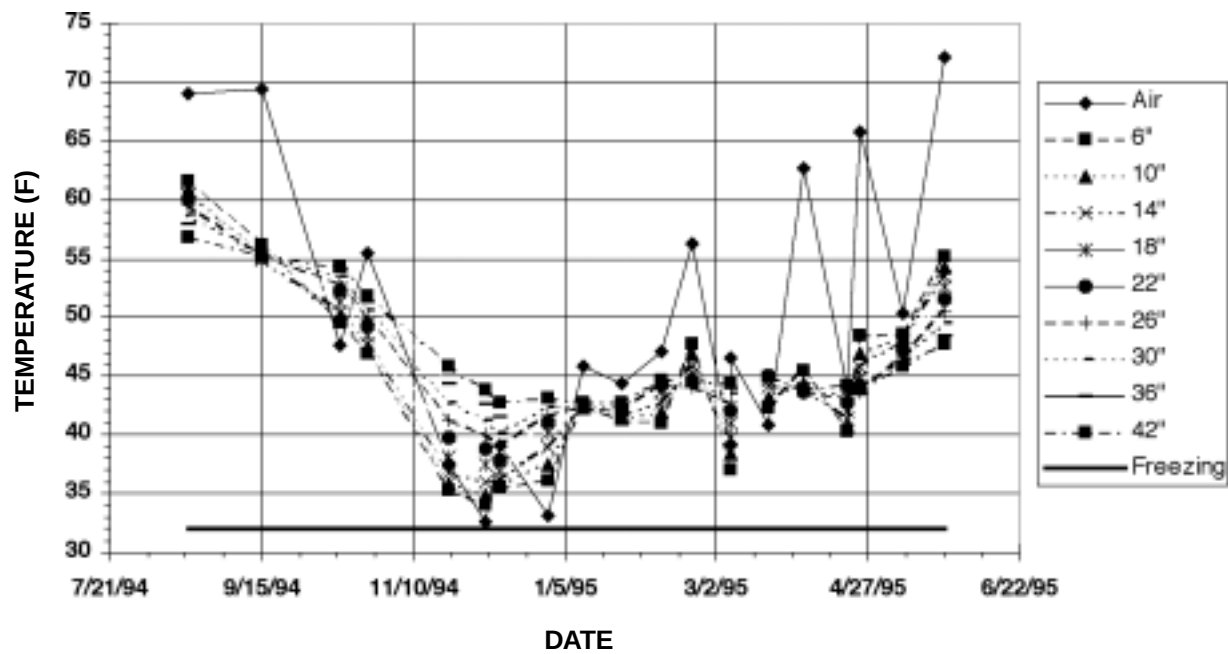
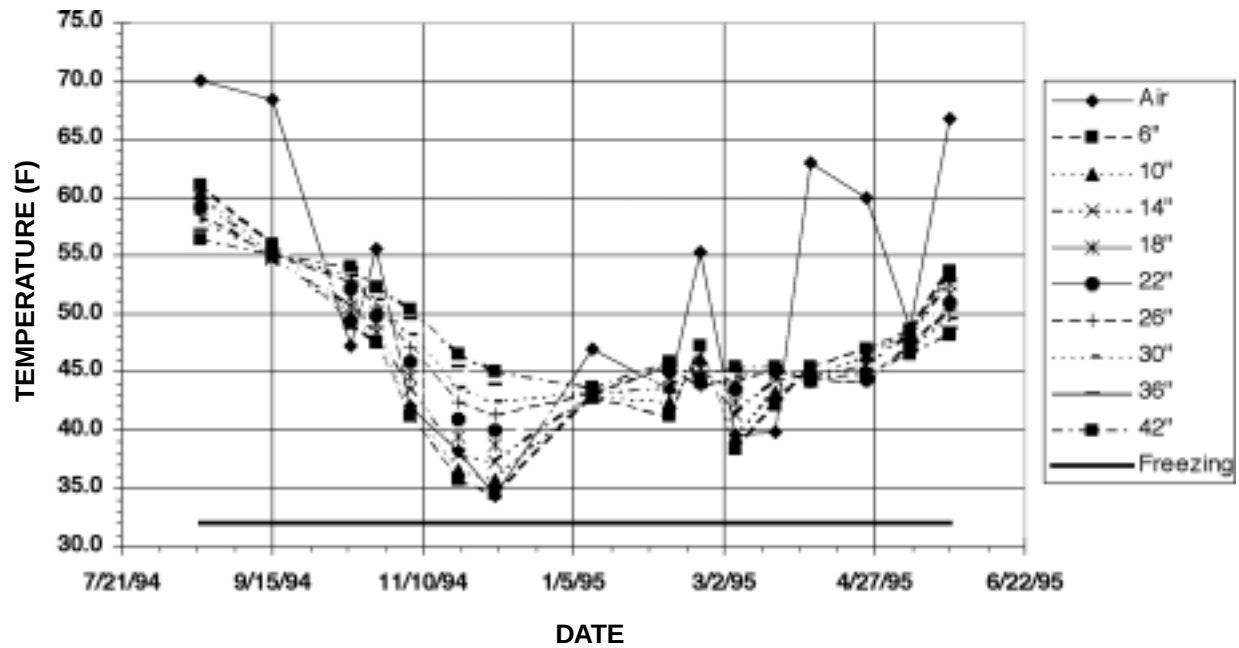
Analysis and Results

Temperature

Subsurface and air temperatures were monitored at the Willamette sites from July 1994 through May 1995. Temperatures were read manually at least monthly, generally late in the morning or in the afternoon as shown in figure 20. All measured temperatures were above 32 °F. The lowest temperature measured in the ground was 34.5 °F at a 6 inch depth. At a depth of 10 inches (top of subgrade), the lowest temperature measured was 35.7 °F. The average minimum monthly temperatures (1961 to 1990) at the nearest weather station (Lookout Point Dam, approximately 13 miles west of the site) were 37.4, 30.6, 29.5, and 34.7 °F for November through February. Based on the measured temperatures and historic averages, it was likely the air temperatures on some nights had dropped below freezing, but it was unlikely for freezing of more than the top 1 or 2 inches of the aggregate to have occurred.

TDR and RF

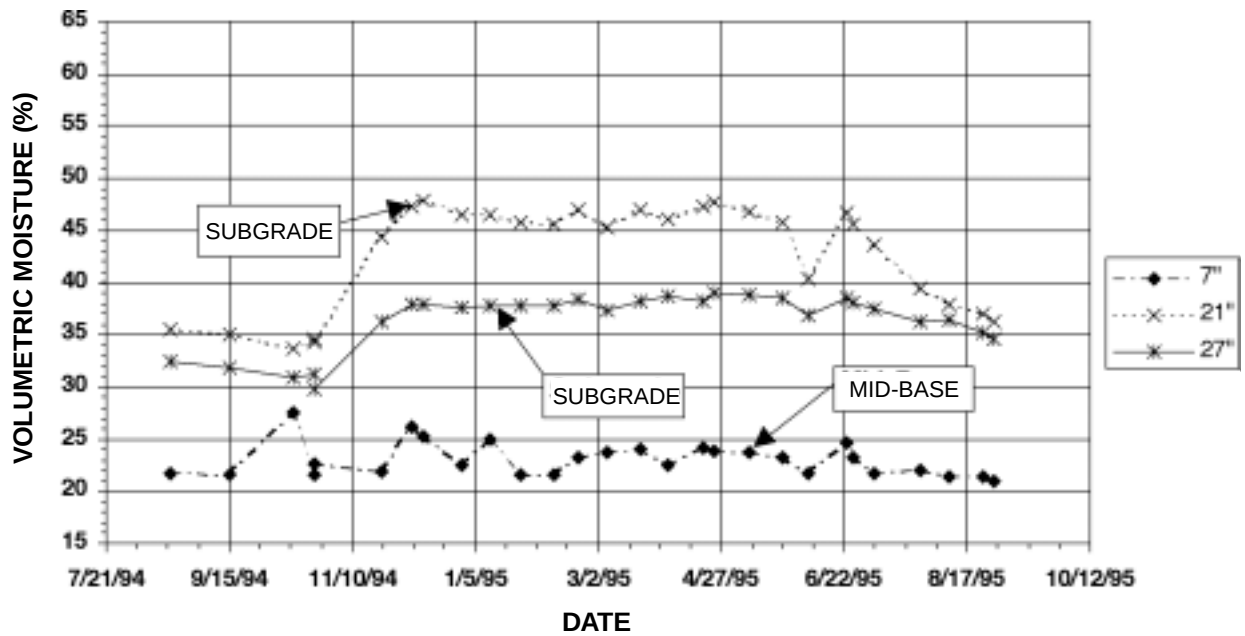
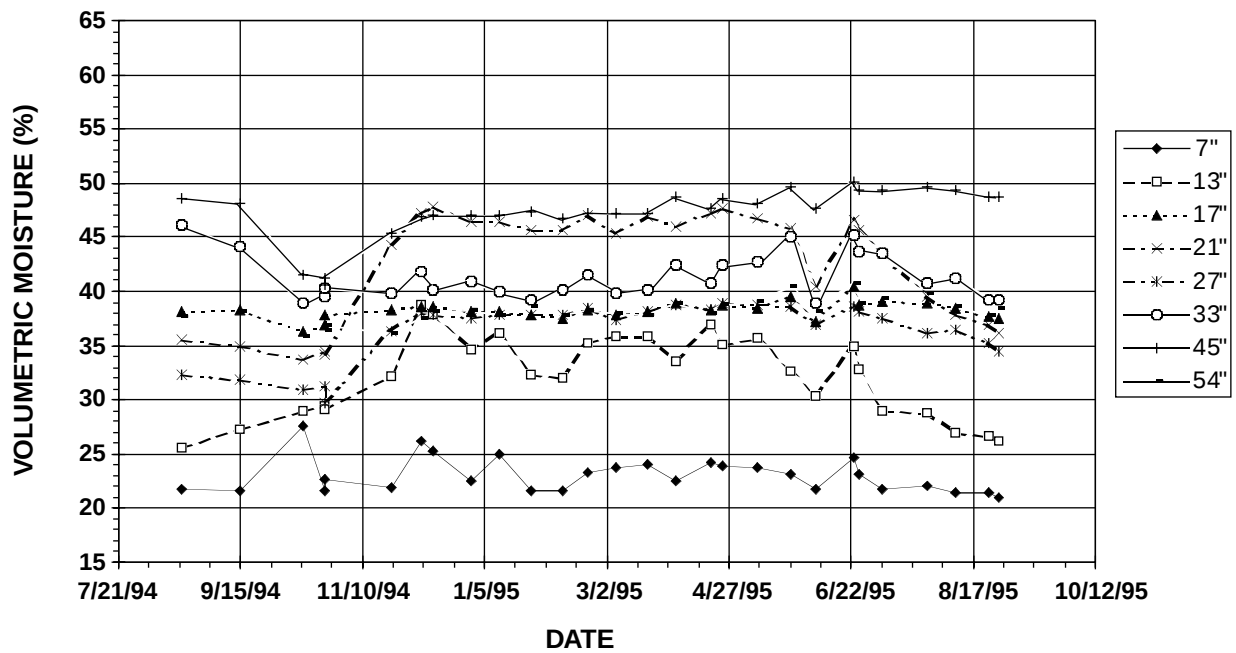
The volumetric moisture contents as shown in figures 21 through 24 do not show a rapid increase or decrease in moisture such as would be expected during freezing and thawing. The TDR figures show small but gradual decreases in moisture from summer to the beginning of the wet season, which began in November. The moisture contents remained fairly stable throughout the winter and then decreased back to the summer values starting in June. This trend, however, was not as clear when viewing the RF results. The Willamette sites were the first sites where the RF probes were installed in the field. Problems with erratic readings were experienced. This was determined to be the result of corrosion of the aluminum connectors. These connectors were replaced with copper connectors on March 6 and 7, 1995.



a) Temperatures Willamette—Site 1.

b) Temperatures Willamette—Site 2.

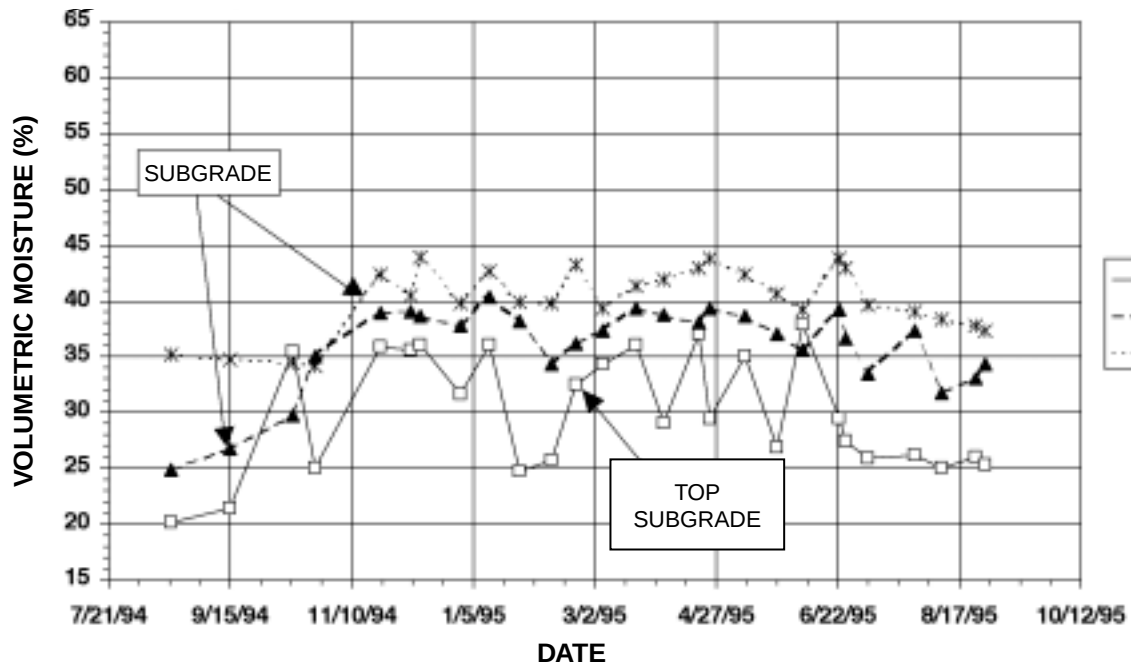
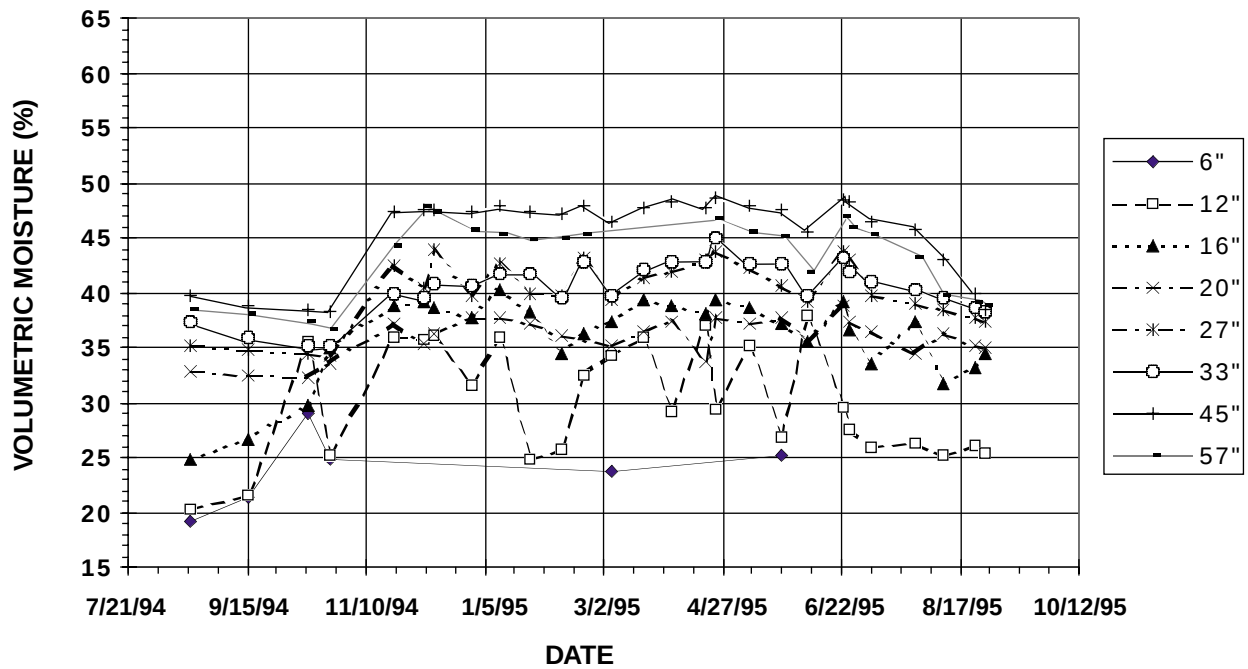
Figure 20—Willamette seasonal temperature variations. Legend shows depth below road surface of individual thermistor sensors within probe.



a) TDR Volumetric Moisture: Willamette—Site 1.

b) Selected TDR Volumetric Moisture: Willamette—Site 1.

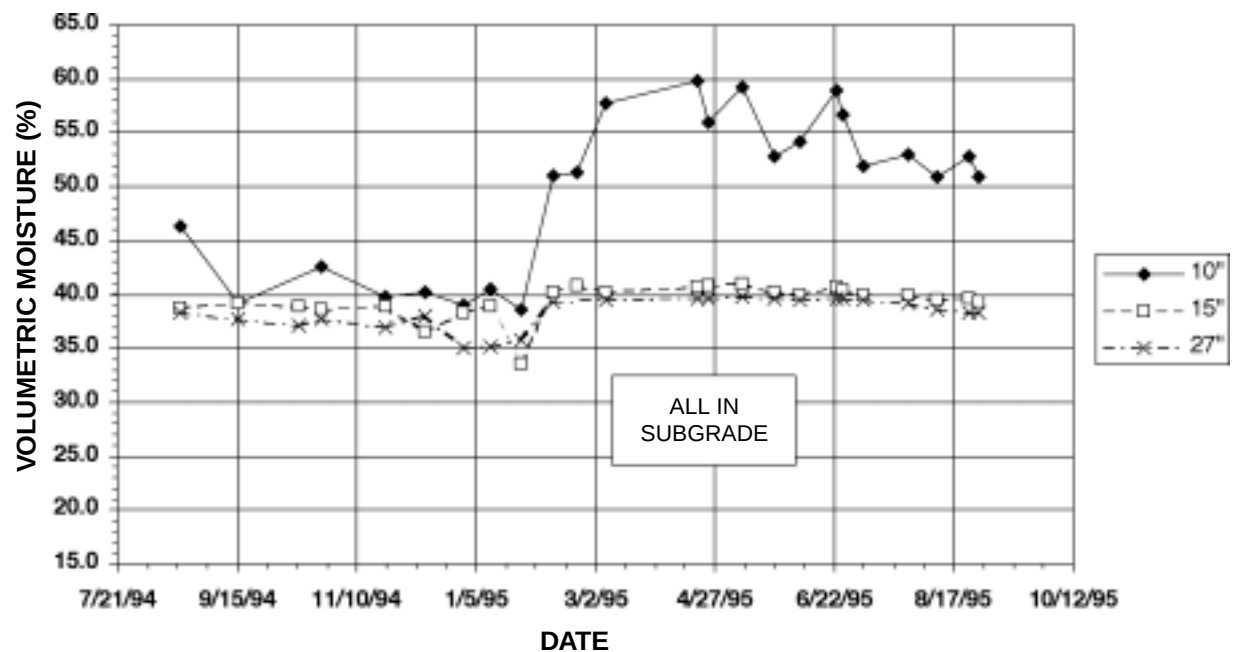
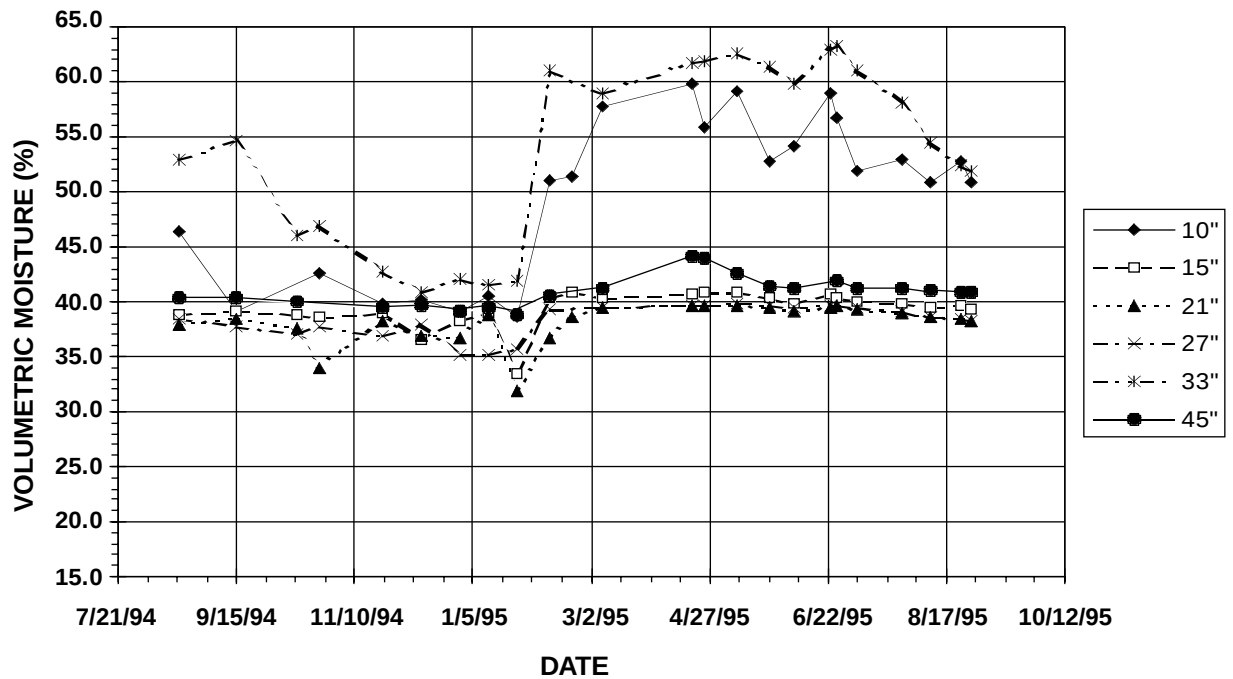
Figure 21—Seasonal variation in TDR measured moisture. Legend shows probe depth below road surface.



a) TDR Volumetric Moisture: Willamette—Site 2.

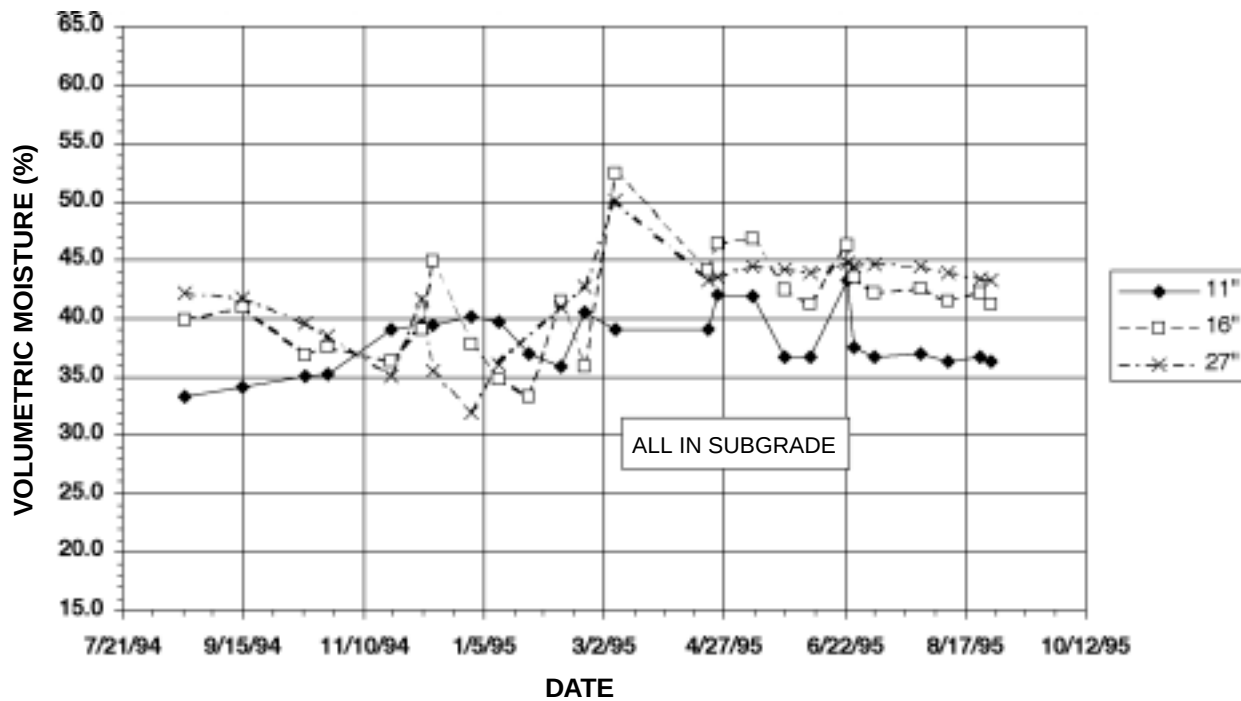
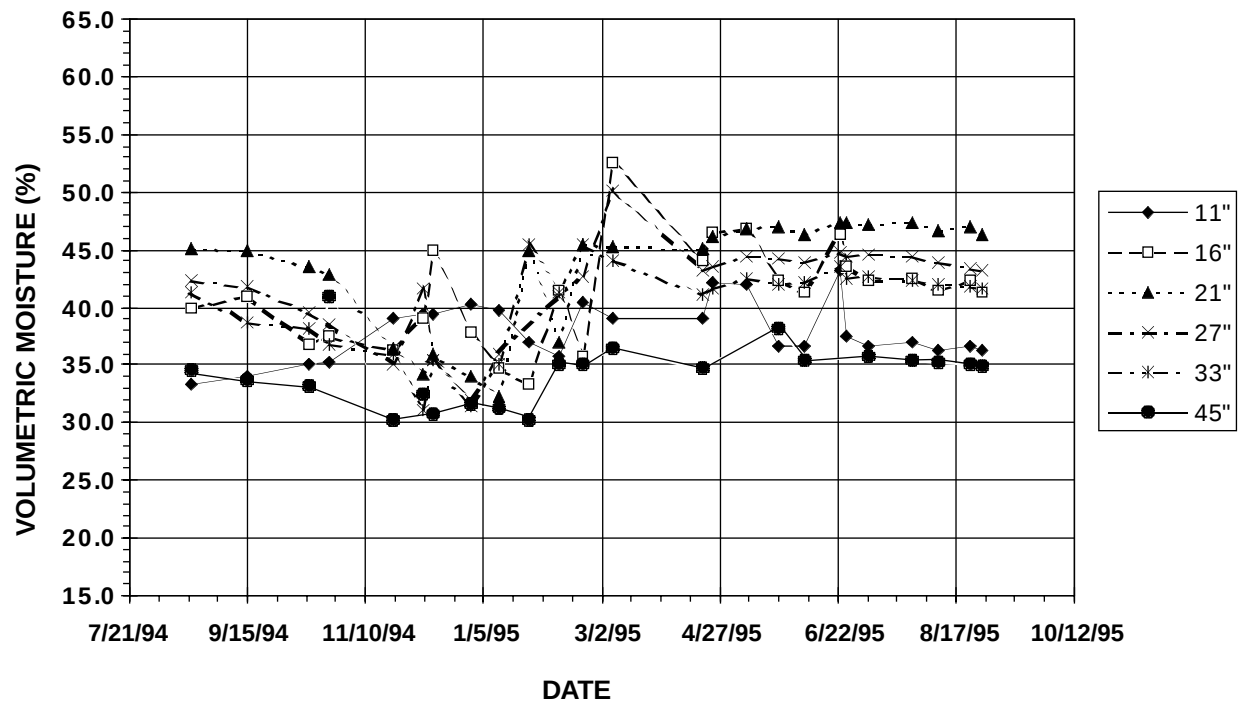
b) Selected TDR Volumetric Moisture: Willamette—Site 2.

Figure 22—Seasonal variation in TDR measured moisture at indicated depths below road surface.



- RF Volumetric Moisture: Willamette—Site 1.
- Selected RF Volumetric Moisture: Willamette—Site 1.

Figure 23—Seasonal variation in RF measured moistures at indicated depths below road surface.



a) RF Volumetric Moisture: Willamette—Site 2.

b) Selected RF Volumetric Moisture: Willamette—Site 2.

Figure 24—Seasonal variation in RF measured moistures at indicated depths below road surface.

n viewing the average TDR results from both sites, the average subgrade volumetric moisture content during the dry season was 31 percent, while the volumetric moisture content averaged 41 percent during the wet season. This corresponded to gravimetric moisture contents of 23 and 30 percent, respectively. The percent saturation for the dry and wet season was 61 and 81 percent using a dry density of 82 pounds per cubic foot (average value measured at these sites in 1993) and assuming the specific gravity of the solids was 2.60. The average wet season subgrade moisture content, measured as part of the previously mentioned sediment study at these sites during 1993, was 37 percent (gravimetric), which is reasonably close to the gravimetric value correlated from the TDR readings.

Groundwater

Groundwater levels were monitored in the three open standpipes installed at each site. As seen in figure 25, the groundwater fluctuations at each site were similar, occurring at essentially the same times. In general, the groundwater appeared to fluctuate at each site during the wet season from a depth of 7 to 17 feet.

Area Parameter

The area parameter is an index of the overall stiffness of a pavement section. The larger the area parameter, the stiffer the pavement section (FHWA 1994). It is defined as the normalized area of the deflection basin divided by the maximum deflection. The area parameter was calculated as follows:

$$A_p = 6[d_0 + 2d_1 + 2d_2 + d_3]/d_0, \text{ where}$$

A_p is the area parameter,

d_0 is the deflection measured at the center of the applied load,

d_1 is the deflection measured at a distance of 1 foot, and

d_2 is the deflection measured at a distance of 2 feet, and

d_3 is the deflection measured at a distance of 3 feet.

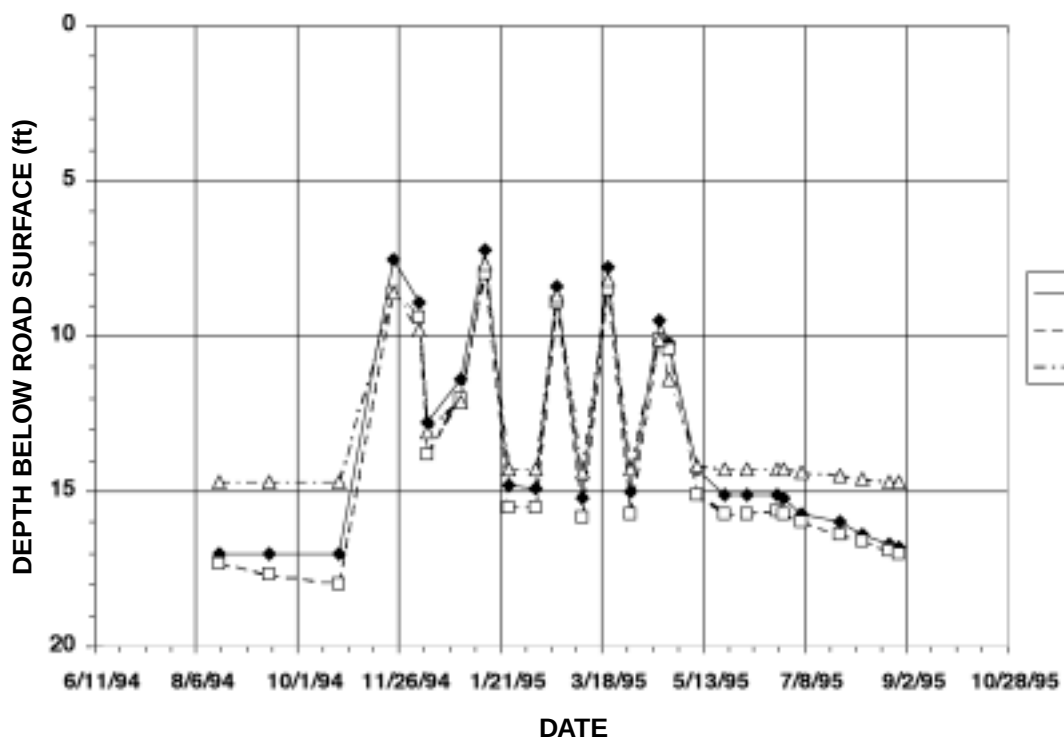
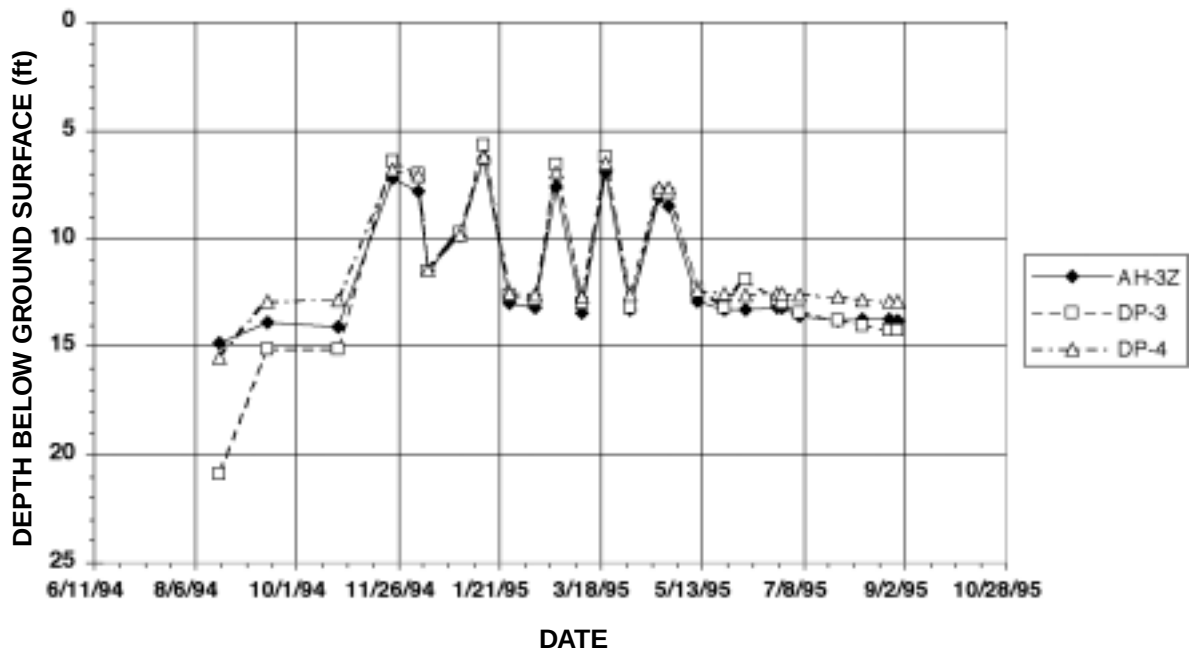
The maximum possible value of 36 (i.e., $d_0=d_1=d_2=d_3$) would indicate an extremely stiff pavement system. Low values would suggest the pavement is not much different from the underlying subgrade.

As shown in figure 26, the area parameters for the Willamette sites are fairly constant from October 1994 to May 1995 and then increase by approximately 10 percent during the dry season.

Layer Moduli

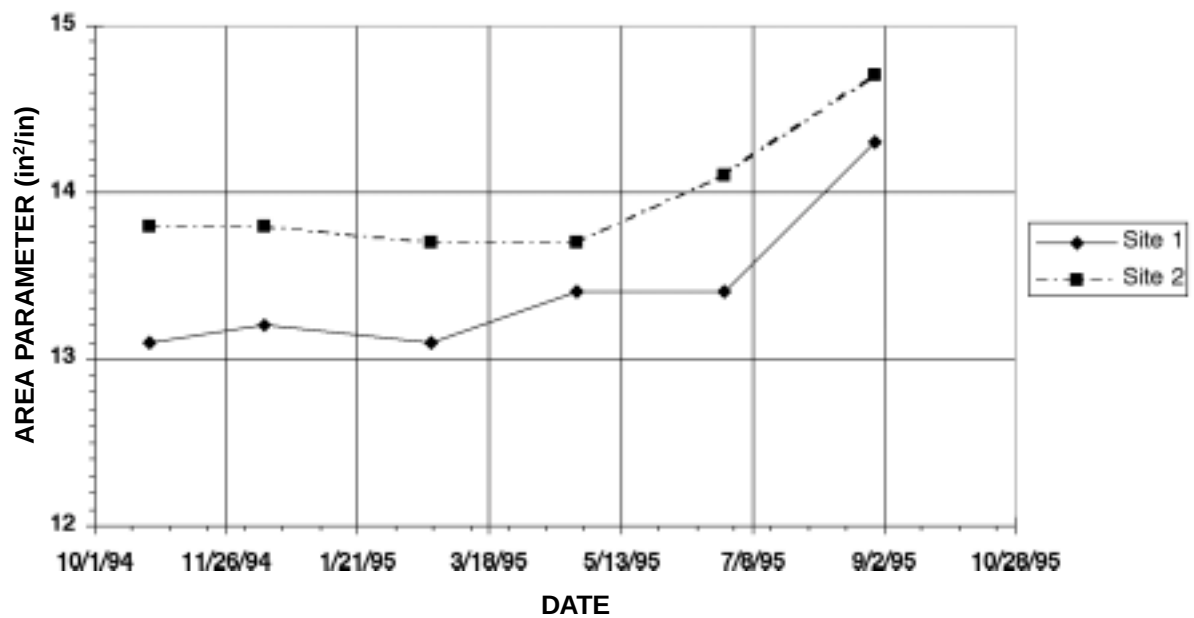
The subgrade moduli were backcalculated for each FWD testing point from the deflection data using EVERCALC (version 5.11), the WSDOT elastic-layered analysis procedure. The pavement structure was modeled as a four layer system, with layers 1 and 2 each being half the total aggregate thickness (including the 4-inch-minus aggregate where present). Layer 3 was modeled as the subgrade soil to the top of the stiff layer. The top of the stiff layer ranged between 75 and 80 inches, defined by an increase in driving resistance of the drive probe. The RMS error ranged from 0.13 to 4.22 percent and was typically in the range of 1 to 2 percent. The RMS error is slightly higher than desired (<1 percent), but considered acceptable since the tests were performed on aggregate surfaced roads as opposed to an asphalt pavement.

As shown in the graphs of subgrade modulus versus date in figure 27, the moduli ranges from 8 to 30 ksi at site 1 and 8 to 19 ksi at site 2. At a given test location, there was a trend of the moduli decreasing from the dry season to the wet season and increasing again during the summer. The moduli values were fairly constant through the wet winter months, again reflecting the higher moisture contents from rainfall as opposed to any effects of freeze-thaw.



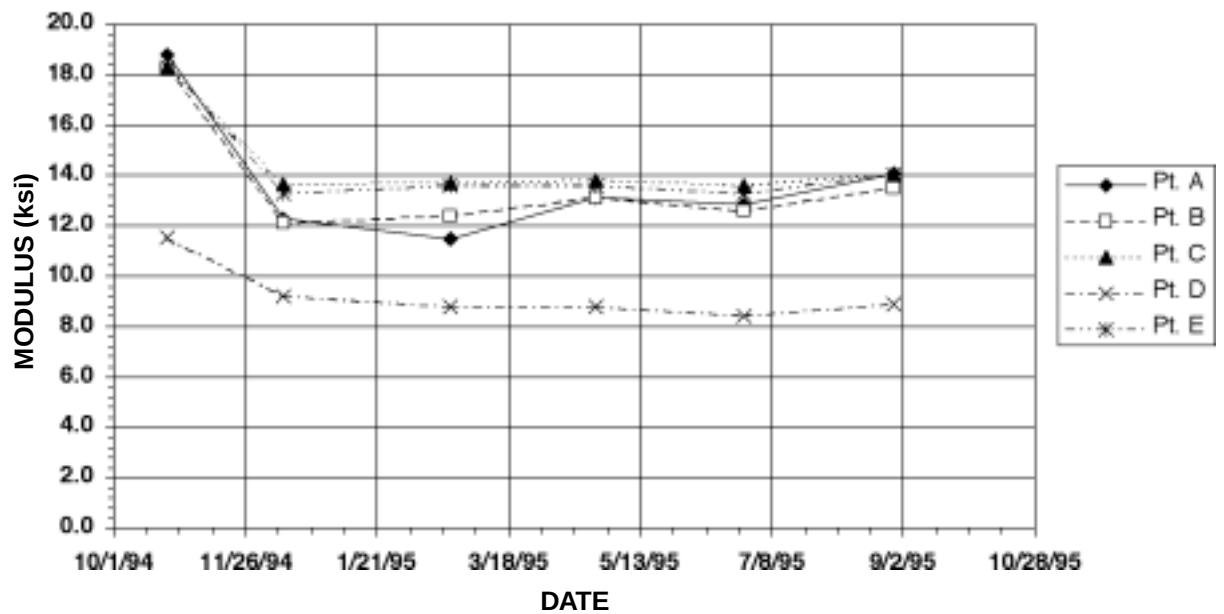
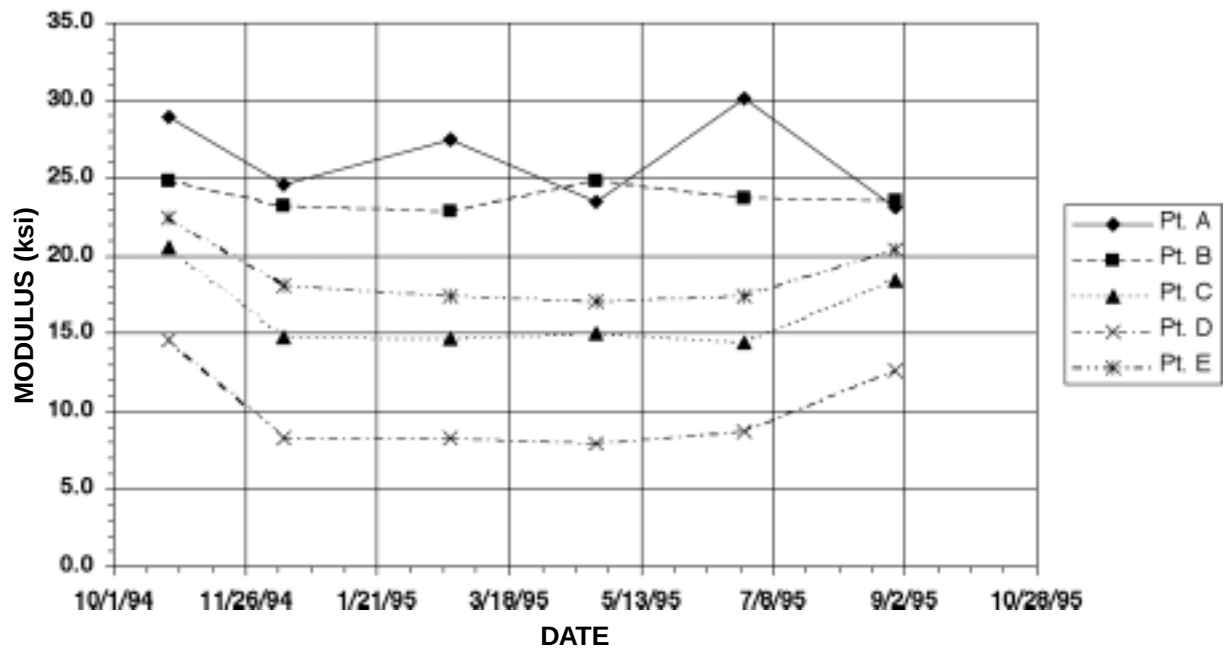
- a) Groundwater Depth: Willamette—Site 1.
- b) Groundwater Depth: Willamette—Site 2.

Figure 25—Seasonal groundwater variation.



Area Parameter (D0-D36): Willamette—Sites 1 and 2

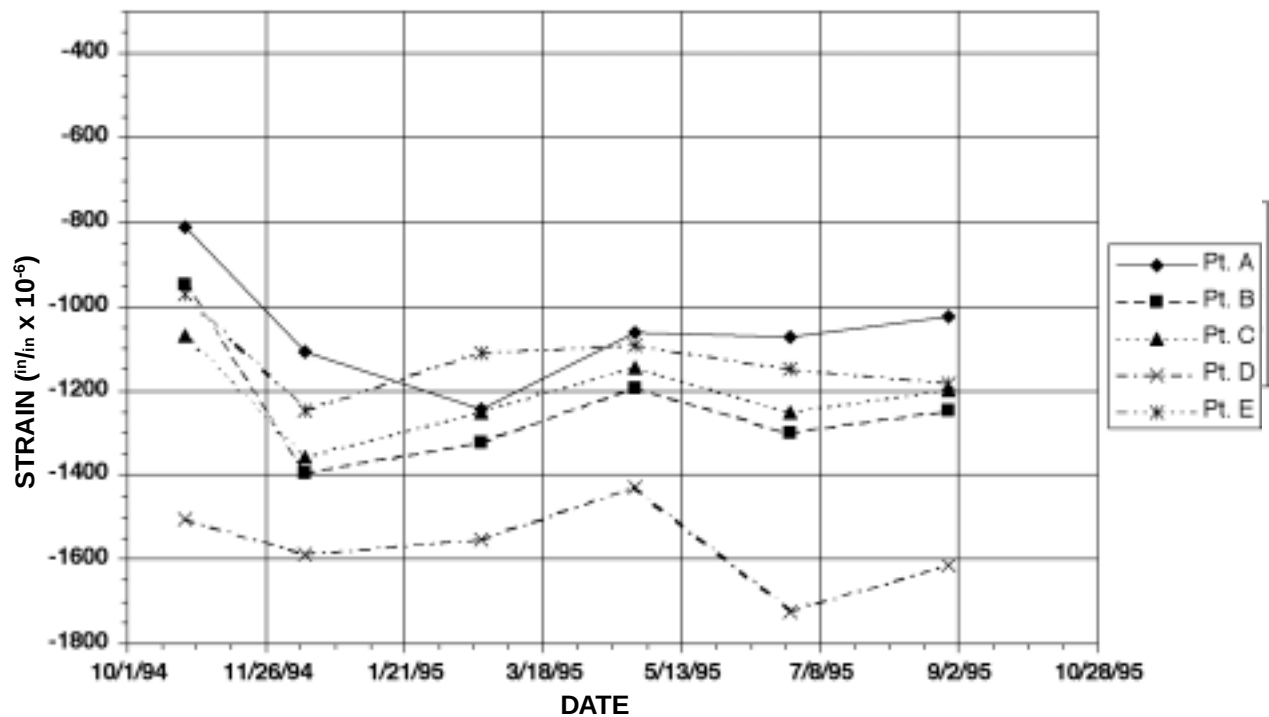
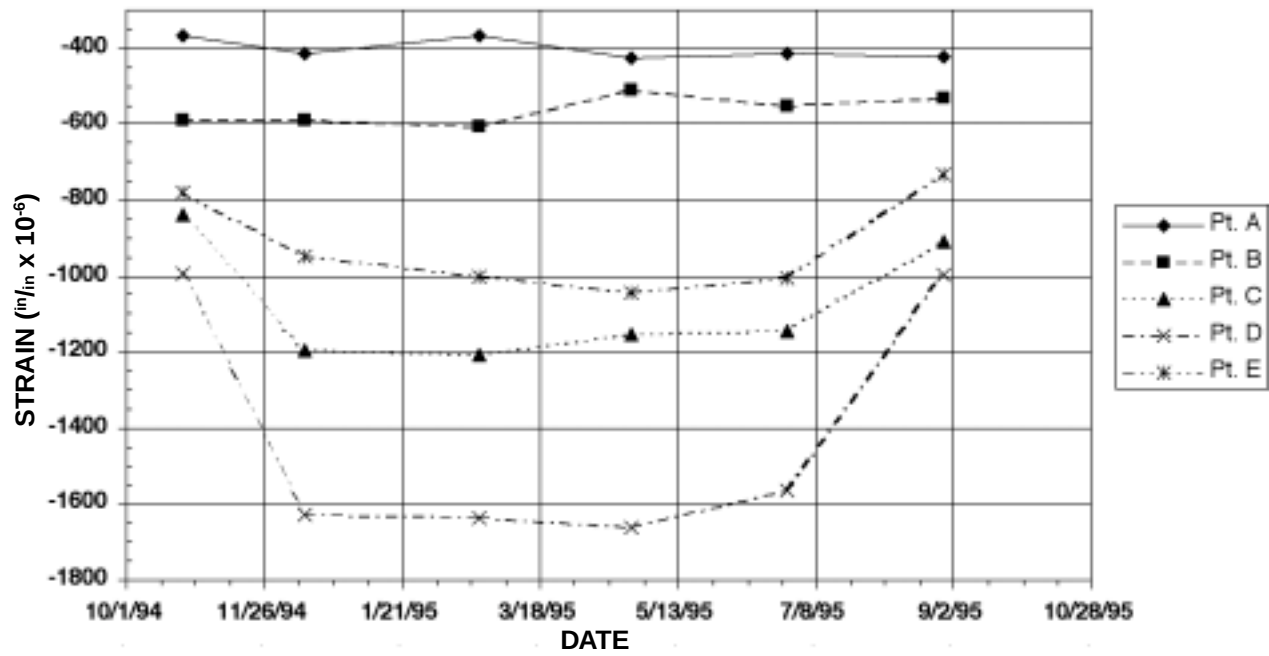
Figure 26—Seasonal variation in area parameter.



a) Subgrade Modulus: Willamette—Site 1.

b) Subgrade Modulus: Willamette—Site 2.

Figure 27—EVERCALC determined seasonal change in subgrade modulus. Legend refers to the five individual FWD



a) Vertical Subgrade Strain: Willamette—Site 1.

b) Vertical Subgrade Strain: Willamette—Site 2.

Figure 28—EVERCALC determined seasonal change in subgrade compressive strain. Legend refers to individual FWD impact points.

Subgrade Strain

Subgrade vertical compressive strain is an important parameter in predicting the amount of pavement rutting. The subgrade strain was determined during the EVERCALC backcalculation process. As seen in figure 28, the strain at a given testing location was fairly constant through the year. There was a general trend of increasing strain in the wet season and decreasing strain in the dry season, but only a slight trend. The variation in strain (and thus, rutting potential) among the five test spots within a test site exceeded the seasonal variation at any given test spot. This suggests that for these sites, the natural variability of site conditions is more important than seasonal variations in determining pavement structural needs.

Conclusions from Willamette Test Site

1. No short-term dramatic changes in site properties were observed, only relatively gradual, annual variations in moisture content, area parameter, and modulus.
2. TDR (and to a lesser degree RF) probes performed well in tracking seasonal changes in moisture contents.
3. Road management load restrictions based on seasonal variation in subgrade moisture (short of “dry-season-only haul”) are probably not feasible for this sort of environment (i.e., wet/dry). No short-term period of susceptibility to high intensity damage was observed.

Ochoco Field Sites Location and General Layout

The two Ochoco National Forest test sites were located on the Ochoco Ranger District, Forest Service Road No. 22 at mileposts 0.1 and 0.4 (figures 29 and 30). Forest Road 22 is a double-lane paved road with road grades less than 2 percent. Site 1 was located at an elevation of 4,020 feet in a generally shaded area while site 2 was at an elevation of 4,140 feet in a more open area. The average annual precipitation in the vicinity of the sites is 14 to 30 inches, depending on elevation. Design freezing indices for the area

(average of three coldest winters in the last 30 years) range from 500 to 750 degree-days F, depending on elevation. The area's mean freezing index for 30 years of records range from 100 to 250 degree-days F. Freezing index is a measure of the severity of a winter climate. It is calculated by summing the daily difference between the daily average temperature (sum of the daily high and low divided by two) and 32 °F for days when the daily average temperature is less than 32 °F. For example, if the daily low was 10 °F and the daily high was 40 °F, then the daily average temperature would be 25 °F and the freezing index for that day would be 7 degree-days F. The daily freezing indices are summed over a winter to determine a locations freezing index for a particular winter. Freezing indices measured at sites 1 and 2 were 501 and 355 degree-days F, respectively, for the winter of 1994/1995.



Figure 29—Ochoco National Forest—Site 1 during the January 25, 1995 FWD testing.



Figure 30—Ochoco National Forest—Site 2 during FWD testing. Paint marks indicate instrumentation locations and FWD test points.

Each test site had five FWD test location points, spaced 20 feet apart located between the wheel paths. Instrumentation points for TDR, RF, and two thermistor strings were located between the FWD test location points as shown on figures 31 and 32. The TDR and RF probes were all installed horizontally, either into the sidewall of the augured holes or compacted within the backfill.

Site Surfacing Structure and Material Properties

The pavement structure at site 1 consisted of 3 inches of asphalt concrete over 15 inches of a 1-inch-minus, dense graded, crushed aggregate overlying a clayey-sand to silty-sand subgrade soil. The pavement structure at site 2 consisted of 4.25 inches of asphalt concrete over 12 to 18 inches of a 1-inch-minus, dense graded, crushed aggregate overlying a clayey sand subgrade soil.

A subsurface investigation was performed at each site for the purpose of determining the depth to a material change or “hard layer” used in the backcalculation analysis and for monitoring groundwater fluctuations. Three drive probes were inserted at each site to depths ranging from 8 to 12 feet at site 1 and 9 to 12 feet at site 2. Standpipes were placed in the holes for water level monitoring.

TDR, RF, and Thermistor Instrumentation

The TDR probes, RF probes, and thermistor strings were installed in 10-, 6-, and 4-inch-diameter augured holes, respectively. Soil and aggregate was saved from specific depths of the excavation and reused as backfill at corresponding depths. In some instances, extra material was necessary to backfill the hole. The subgrade TDR and RF probes were all pushed into the sides of the augured holes while probes within the base course were compacted into backfilled aggregate. All installed probes were rotated approximately 45 degrees from the probe installed immediately below.

TDR probes at the 34-inch depth at site 1 and the 38-inch depth at site 2 failed to operate following

installation, probably caused by damage during the installation process. The RF probe at the 21-inch depth at site 2 also initially failed to operate, but began producing readings in March 1995.

The thermistor strings were installed with 13 thermistors located between the top of the asphalt concrete, at a depth of 64 inches, and the 14th thermistor located to monitor air temperatures.

Data Collection and FWD Testing Program

Data was collected from temperature (thermistor) and weather conditions, moisture content (TDR and RF), and groundwater from September 30, 1994 to August 30, 1995. Readings were obtained at least once per month during the summer and increased to approximately weekly during the winter. Readings were collected manually when site visits were made. One thermistor string at each site was monitored with an automated data acquisition unit throughout the duration of the project.

FWD data was obtained throughout the year for the purpose of determining material layer strengths and seasonal strength variations. Data was obtained approximately monthly during the summer and biweekly during the winter. At five times in the winter, FWD data was collected on 2 or 3 consecutive days.

Analysis and Results

Temperature

Temperature was monitored two to four times per hour at each site from October 30, 1994 through September 30, 1995 by means of the Handar data acquisition units. The data was used to produce the frost profiles displayed in figure 33. Typically, frost penetration occurred at rates of approximately 2 to 3 inches per day. Typical rates of both bottom-up and top-down thawing were 1 to 2 inches per day. These roughly equal bottom-up and top-down thaw rates contrast with the colder climate test sites in Montana and New Hampshire, where bottom-up thaw rates were only 10 to 20 percent of the top-down rate.

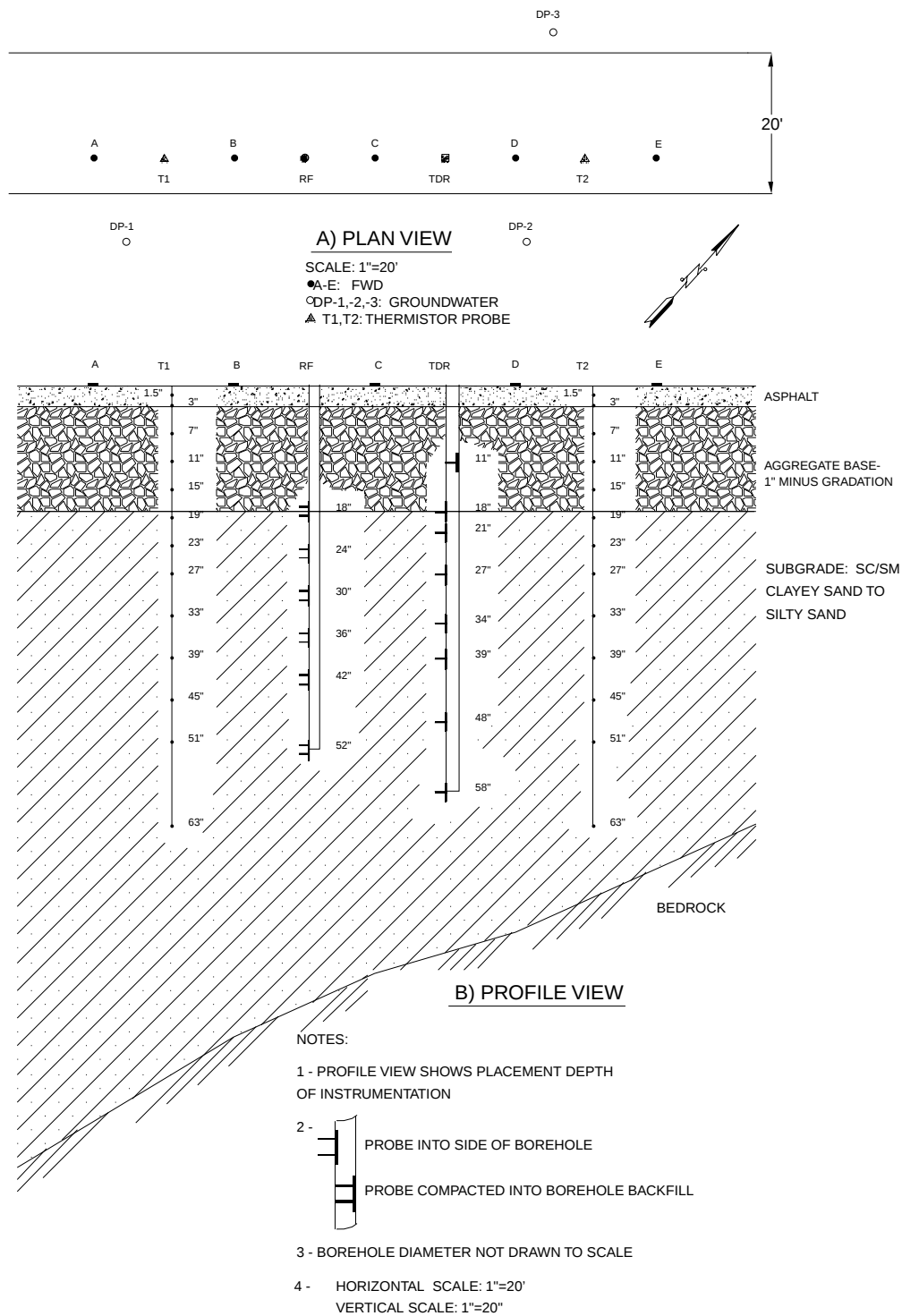


Figure 31—Instrument Layout: Ochoco National Forest—Site 1.

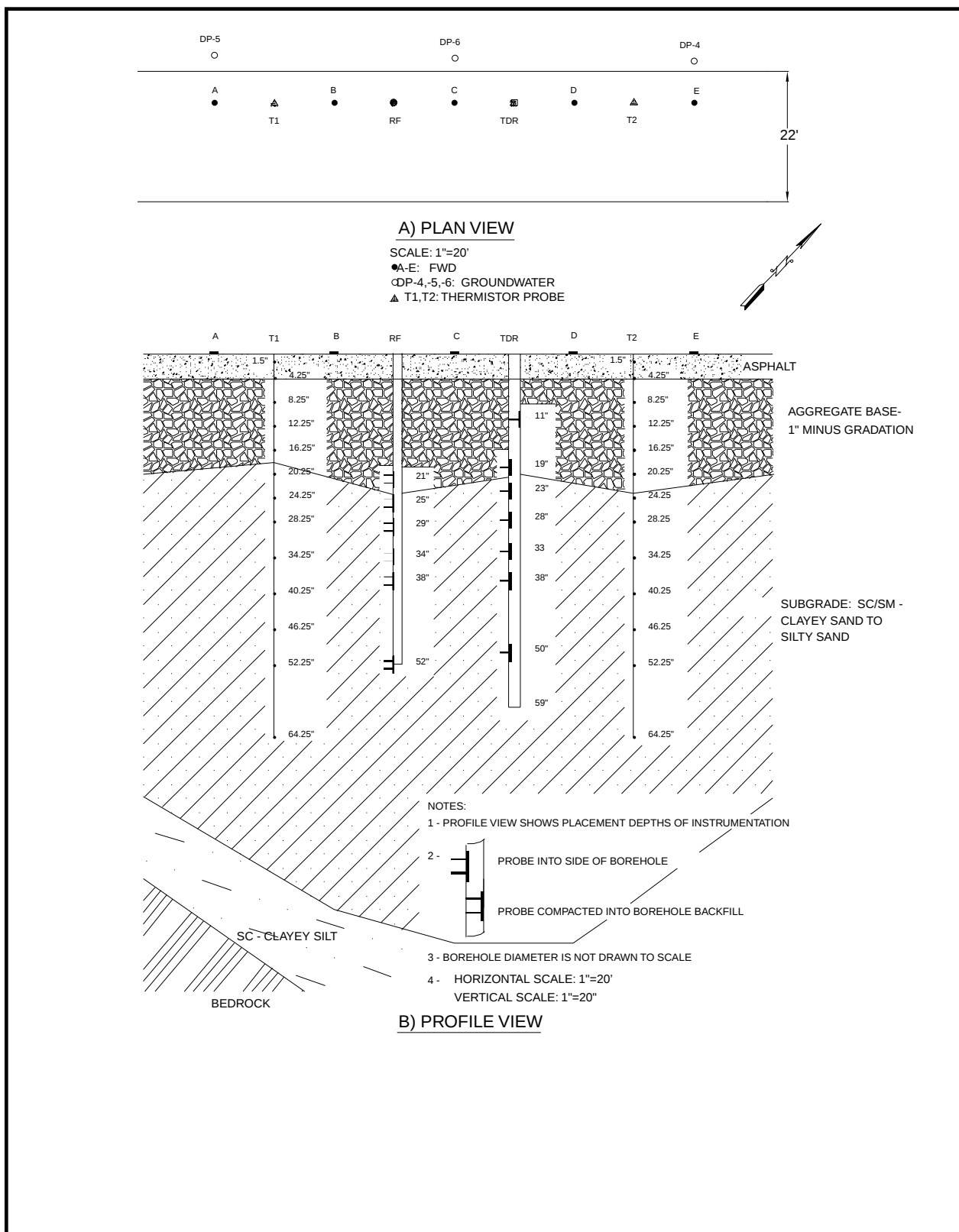
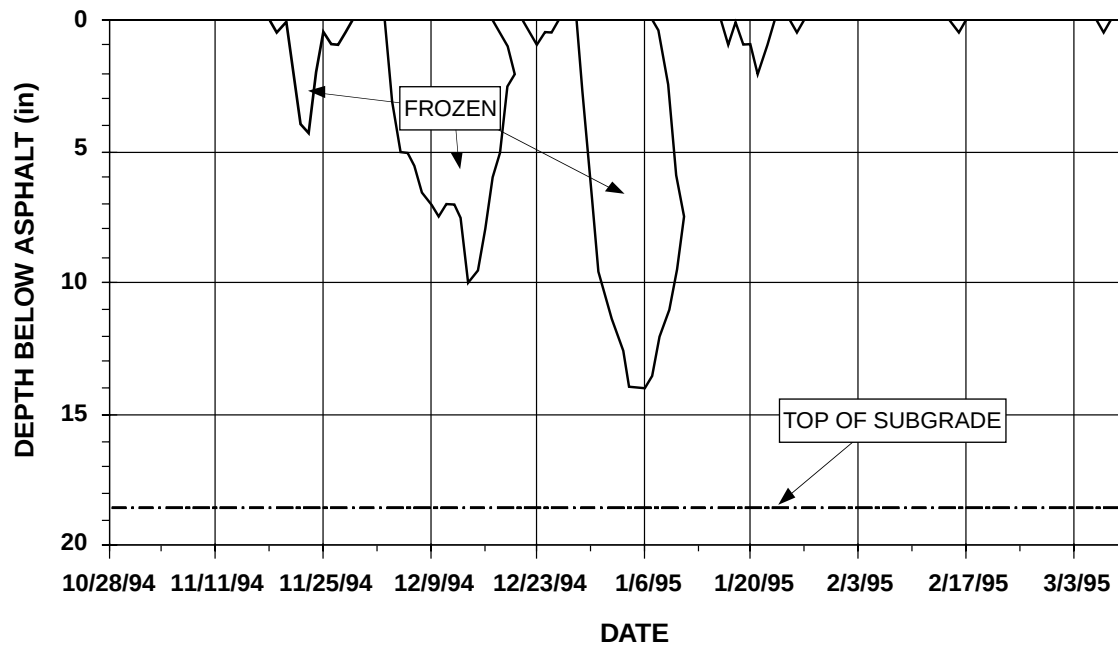
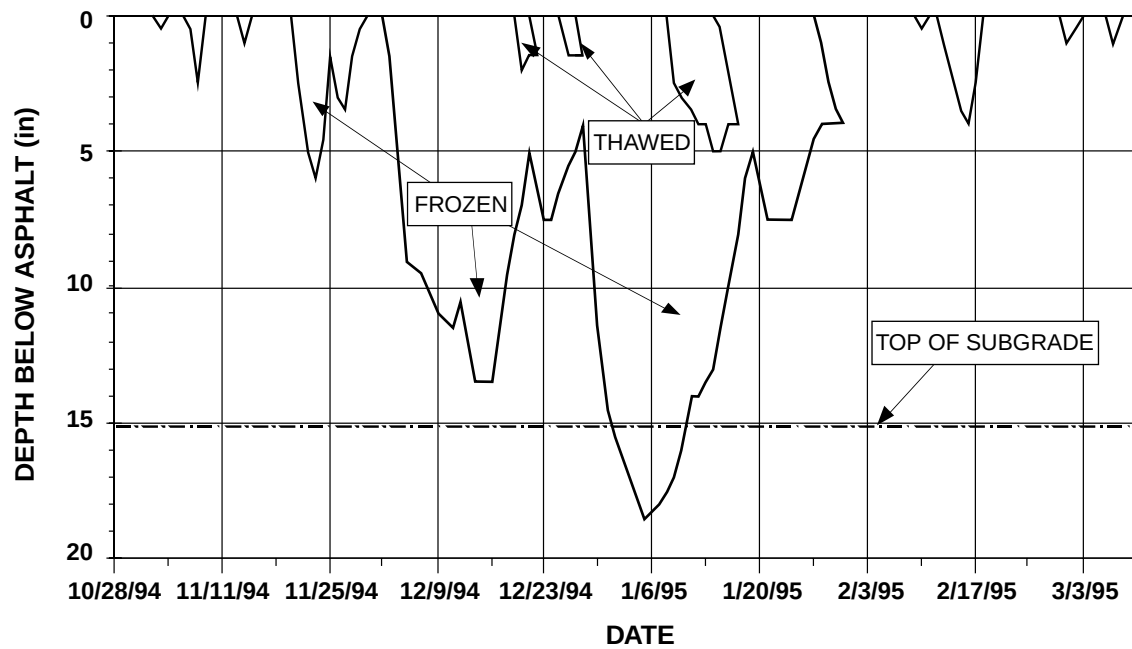


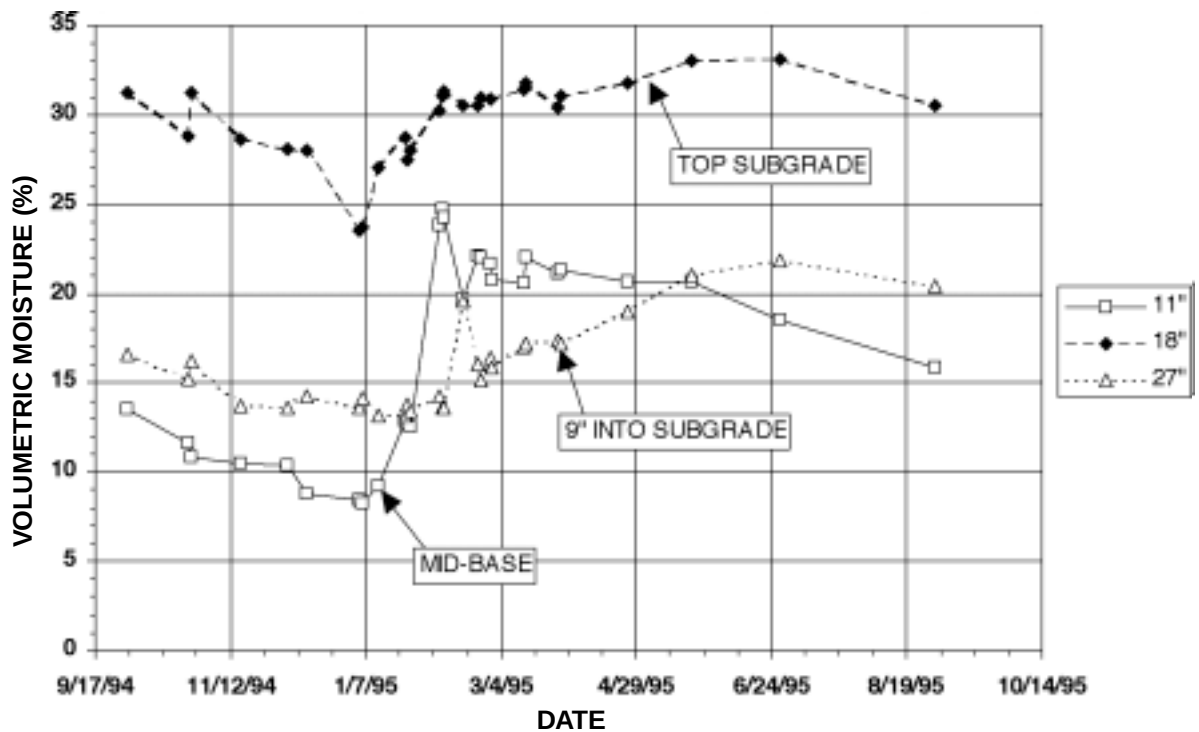
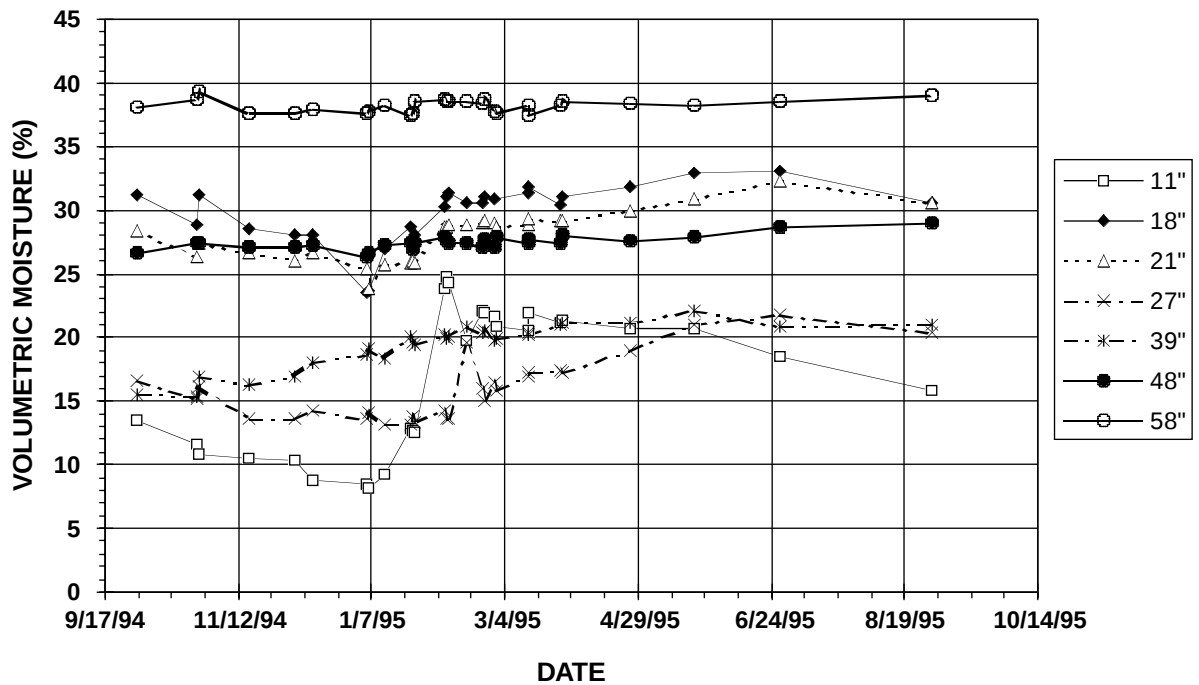
Figure 32—Instrument Layout: Ochoco National Forest—Site 2.



a) Frost Profile: Ochoco—Site 1

b) Frost Profile: Ochoco—Site 2

Figure 33—Seasonal frost depth profiles. Note that most of the thawing occurred from bottom up at these sites. There are also shallow frost penetrations and multiple freeze/thaw events.



a) TDR Volumetric Moistures: Ochoco—Site 1

b) Selected TDR Volumetric Moistures: Ochoco—Site 1

Figure 34—TDR measured moisture contents. Note the moisture spikes in base and upper subgrade during early February thaw.

Also reflecting the less severe winter conditions in eastern Oregon were three complete freeze-thaw cycles (freezing 4 inches or greater below the asphalt concrete) observed at each site. The maximum freezing depths at sites 1 and 2 were 14 and 18 inches, respectively. Partial thawing followed by refreezing occurred on three separate occasions during December and January at site 1. During these time intervals, as well as at the end of the major freezing period, water was trapped above the ice. At site 2, water was trapped above the ice for only short periods of time during the end of the major freezing period. At both sites, for the most part, thawing occurred from the bottom up.

TDR and RF

The volumetric moisture content fluctuations for each site are shown in TDR and RF figures 34 through 37. In general, most probe locations show only moderate moisture fluctuations in that they were below the freezing depth. In addition, the moisture variation decreases with increasing depth. The TDR probes at 11 and 18 inches at site 1, the RF probe at 18 inches at site 1, and the TDR probe at 11 inches at site 2 are within the freeze-thaw zone. These probes clearly show the decrease in volumetric moisture when frozen (actually reflecting the low dielectric constant of ice) and a subsequent increase in moisture after thaw.

Groundwater

Groundwater levels were monitored in the three open standpipes installed at each site (figure 38). At site 1, the groundwater did not fluctuate significantly throughout the year, but was only 2 feet from the ground surface on the north end of the site. At site 2, the groundwater levels fluctuated by approximately 4 feet in each well. The increase in water levels at site 2 corresponded closely to the rapid melting of the frost profile at site 2 after January 6, 1995. This may be a consequence to site 2 being a much sunnier site than site 1.

Area Parameter

The area parameter, a convenient index of overall pavement stiffness, was calculated for the Ochoco sites in a similar manner to the Willamette sites.

As seen in figure 39, the area parameter increased markedly from the fall value of 18 square inches per inch to a peak value of 29 square inches per inch corresponding to the date of the maximum frost penetration. After the thaw, the value dropped to 14 to 16 square inches per inch then gradually increased back to the fall value of 18 square inches per inch.

It is interesting to note that the two sites have similar area parameter values with the exception of the FWD tests performed during the third week of January. From the frost profiles, it can be seen that site 1 was still frozen approximately 8 inches below the asphalt, while site 2 had little or no frost. This difference is clearly reflected in the calculated area parameters.

Layer Moduli

The layer moduli values were backcalculated for each FWD testing point from the deflection data using EVERCALC. The pavement structure was modeled as a four-layer system when no ice was present and a five-layer system with ice present. With no ice present, layer 1 was the asphalt concrete, layer 2, the aggregate base course, layer 3, the subgrade to the "hard layer," and layer 4, the hard layer. When ice was present, layer 2 was the thickness of frozen aggregate (and top of subgrade when frozen), layer 3, the unfrozen aggregate, layer 4, the subgrade to the "hard layer," and layer 5, the hard layer.

As shown in figures 40 and 41, above 32 °F, the relationship between backcalculated asphalt concrete modulus and temperature is fairly flat at approximately 500 and 700 ksi for sites 1 and 2 respectively. Below 32 °F, at site 2 the modulus increased above 1,000 ksi for some test locations and over 900 ksi for some locations at site 1. The backcalculated subgrade modulus values for both sites show moduli values in the fall of 13 ksi, a decreased modulus value of 10 ksi through most of the winter, with a "spike" of 27 ksi at site 1 in January. The spike value for site 1 occurred when freezing penetrated 2 inches into the subgrade. Backcalculated base modulus values for both sites were 24 to 33 ksi during the fall, decreasing in the spring to 12 to 17 ksi. Results during the winter on several test dates at both sites indicated base modulus values exceeding 100 ksi when frozen.

Subgrade Strain

Both vertical compressive strain at the top of the subgrade and tensile strain at the bottom of the asphalt concrete were calculated from the deflection data for each testing date using EVERCALC and EVERSTRESS. EVERSTRESS is a companion WSDOT PC computer program to EVERCALC and can be used to calculate stresses, strains, and deflections throughout a pavement structure (WSDOT 1995b). Subgrade vertical compressive strain is an important parameter in predicting pavement rutting. Asphalt tensile strain is likewise an important parameter in predicting fatigue cracking (WSDOT 1995).

As shown in figure 42 for site 1, the subgrade strain in the fall was -500×10^{-6} inches per inch (the negative indicating compression). The strain decreased to zero strain on January 7, 1995 when freezing penetrated through the aggregate base and 2 inches into the subgrade. After the thaw, the strain increased to approximately -650×10^{-6} inches per inch and gradually decreased back near the fall value of -500×10^{-6} inches per inch. A similar trend, shown in figure 43, occurred at site 2.

Damage Factors

Relative damage factors were computed for both subgrade rutting and asphalt cracking. The relative damage factors are defined as the amount of heavy traffic the pavement could support at a reference time (in this case, the initial fall test point) divided by the amount of heavy traffic the pavement could support at any other given time. Table 1 presents the equations for rutting and asphalt fatigue cracking used in this study and as used by WSDOT in their EVERPAVE software (EVERPAVE is WSDOT's asphalt pavement overlay PC computer design program). Rutting failure is described in the EVERPAVE manual (WSDOT 1995b) as a 0.75-inch-deep rut. No definition of asphalt fatigue failure is provided in the EVERPAVE manual, but similar equations to the one presented define failure as cracking occurring over 10 percent of the wheel path area (FHWA 1994).

Table 1—Damage Factor Equations.

Rutting:

Damage Factor = N_{rf}/N_{ri} , where

N_{ri} is the loads to failure (rutting) at any time, i

N_{rf} is the loads to failure (rutting) at the reference time (fall), and $N_r = a \times e_v^b$, where

N_r = loads to failure,

$a = 1.077 \times 10^{18}$,

e_v = vertical subgrade compressive strain (in/in $\times 10^{-6}$), and

$b = -4.4843$

Fatigue (AC cracking):

Damage Factor = N_{fi}/N_{ff} , where

N_{fi} is the loads to failure (fatigue) at any time, i

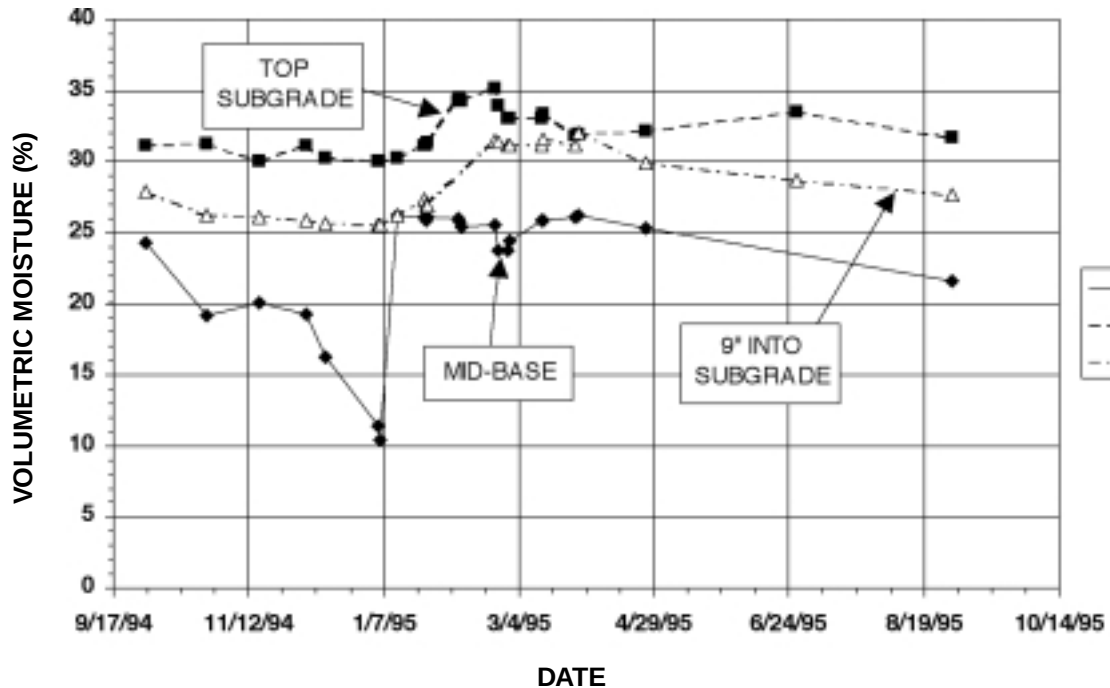
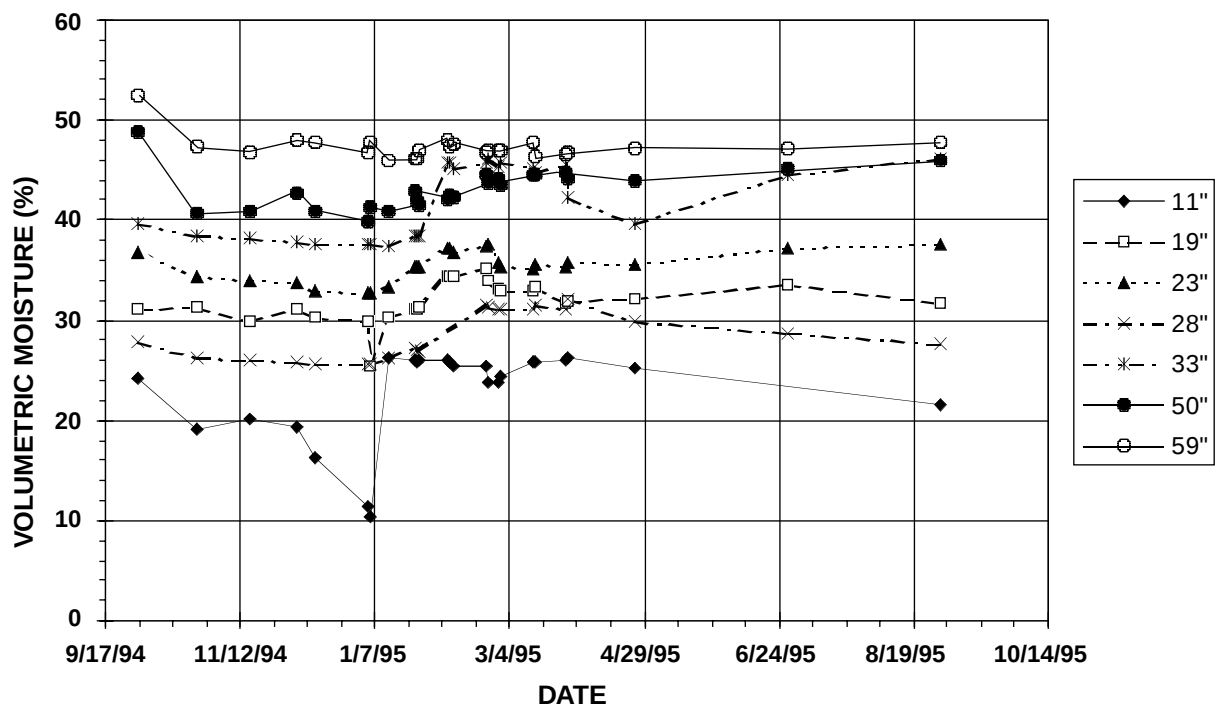
N_{ff} is the loads to failure (fatigue) at the reference time (fall), and

$\log N_r = 14.82 - 3.291 \log(e_t) - 0.854 \log(E_{ac})$, where

N_r = loads to failure,

e_t = tensile strain at the bottom of the asphalt (in/in $\times 10^{-6}$)

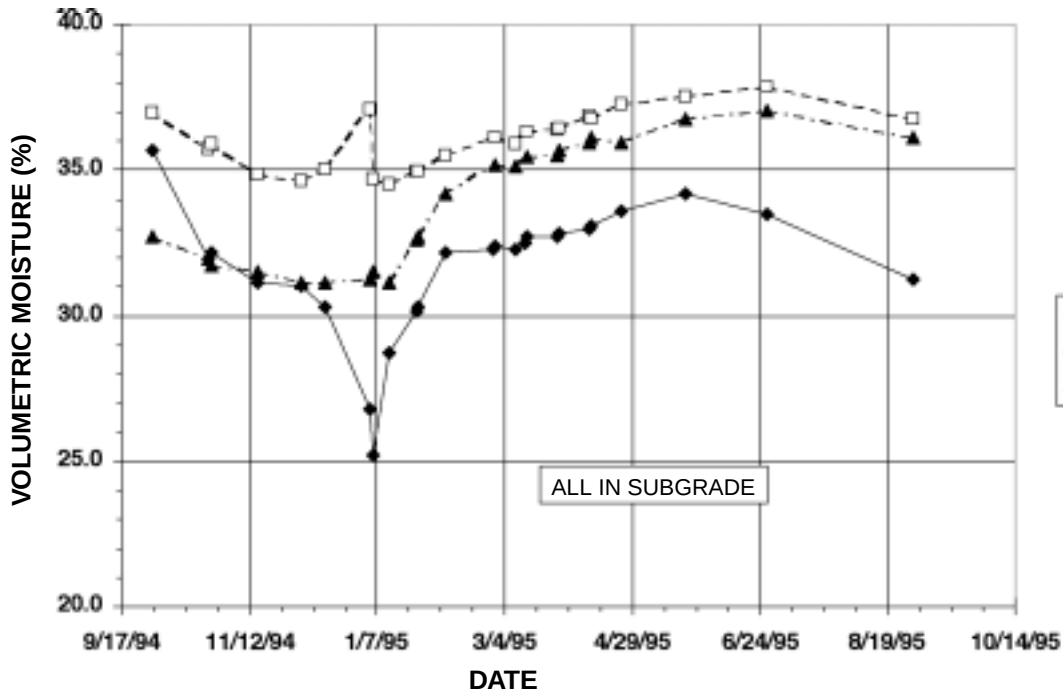
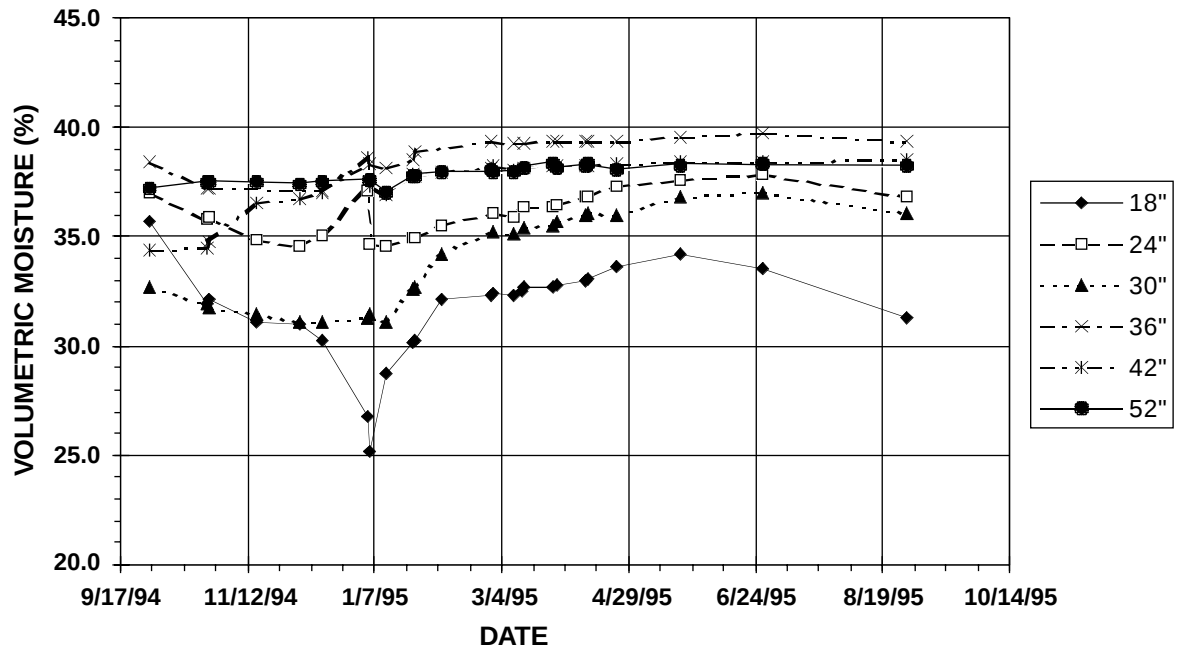
E_{ac} = stiffness of asphalt (ksi)



a) TDR Volumetric Moistures: Ochoco—Site 2

b) Selected TDR Volumetric Moistures: Ochoco—Site 2

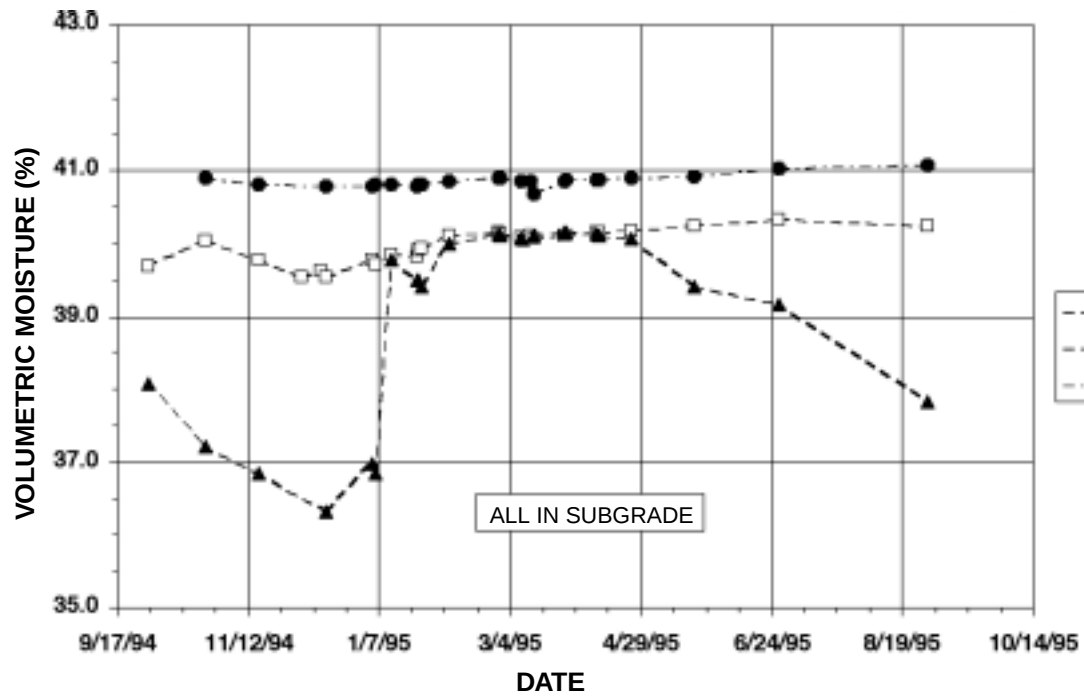
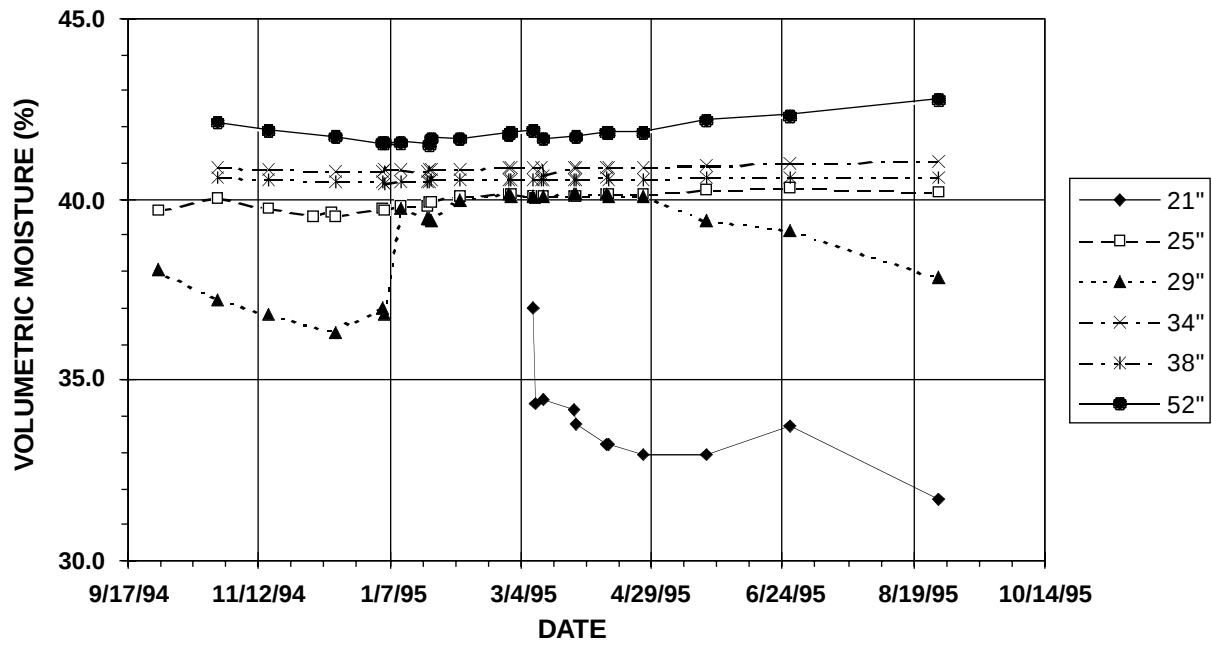
Figure 35—TDR measured moisture contents. Note the sharp drop of the mid-base sensor indicating freezing conditions in early January.



a) RF Volumetric Moisture: Ochoco—Site 1

b) Selected RF Volumetric Moistures: Ochoco—Site 1

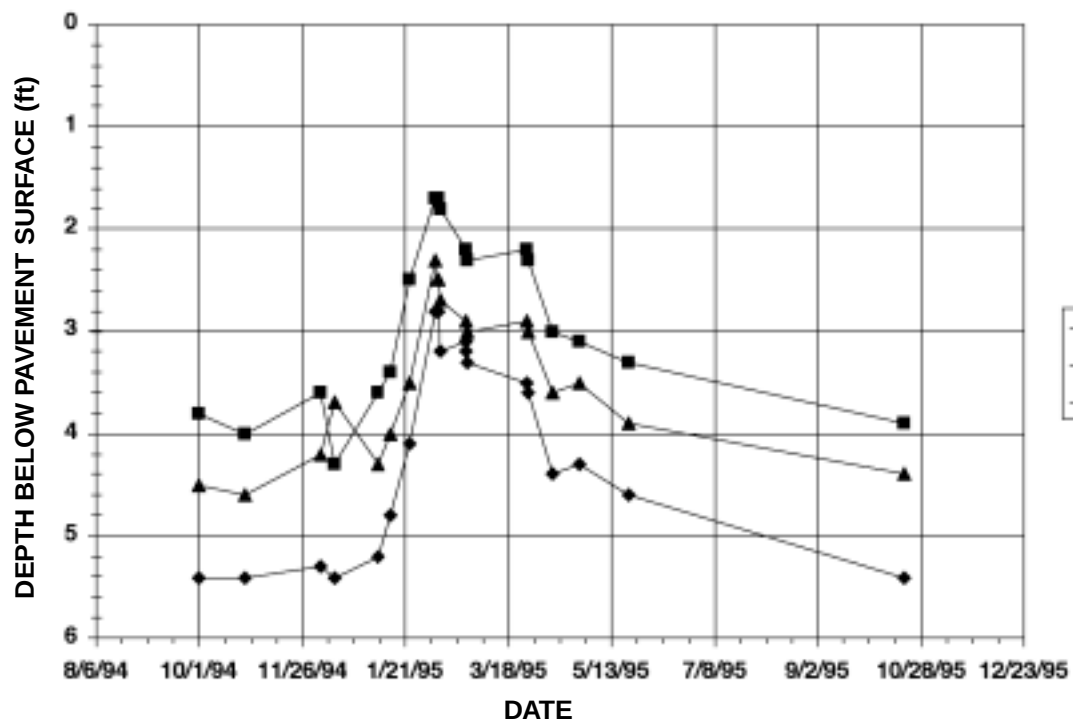
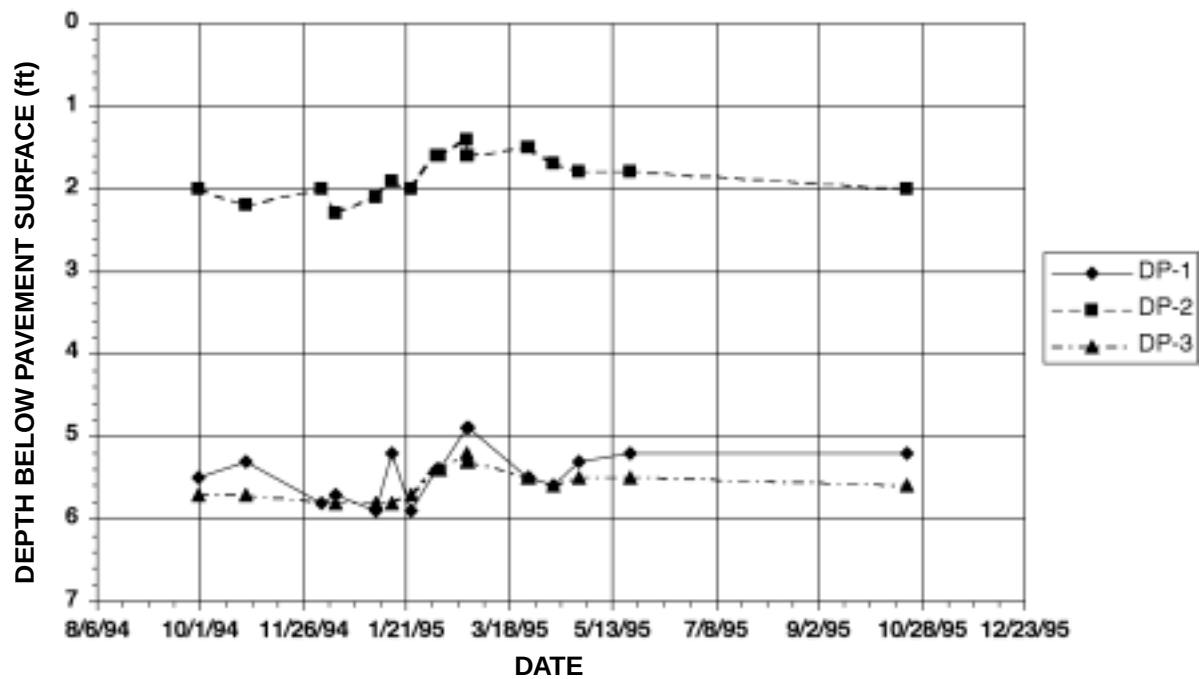
Figure 36—RF measured moistures. Note the sharp drop of the sensor at an 18 inch depth indicating the approaching freezing front in early January.



a) RF Volumetric Moisture: Ochoco—Site 2

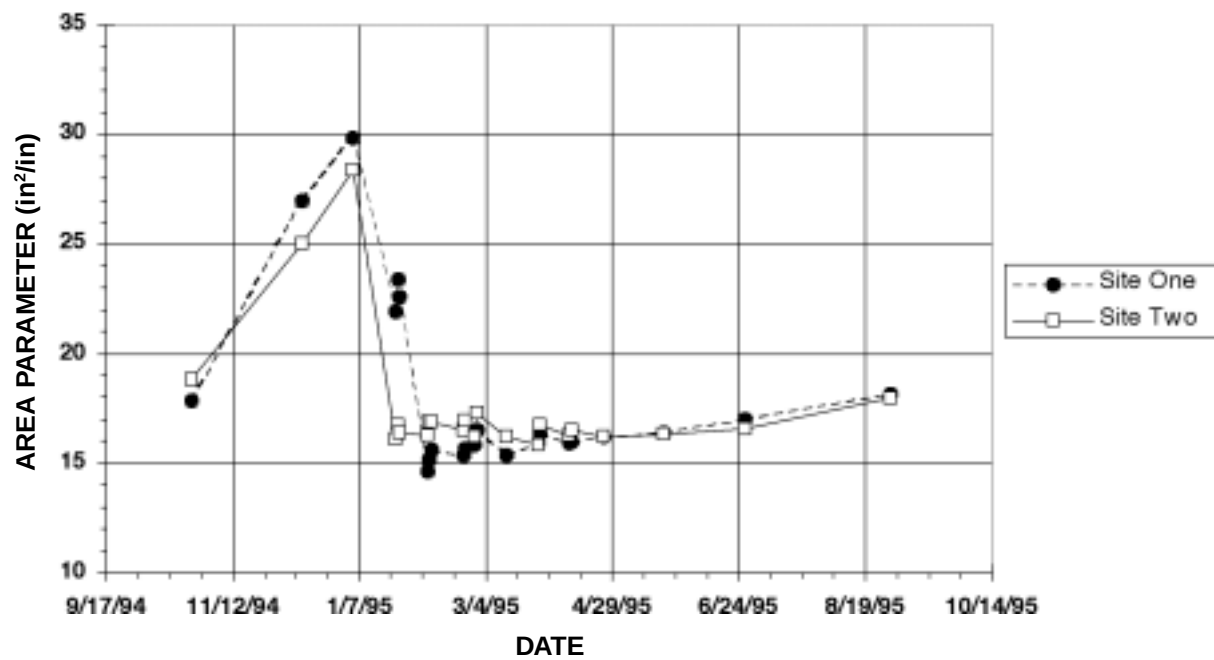
b) Selected RF Volumetric Moistures: Ochoco—Site 2

Figure 37—RF measured moistures. All sensors are located below frost penetrated depth.



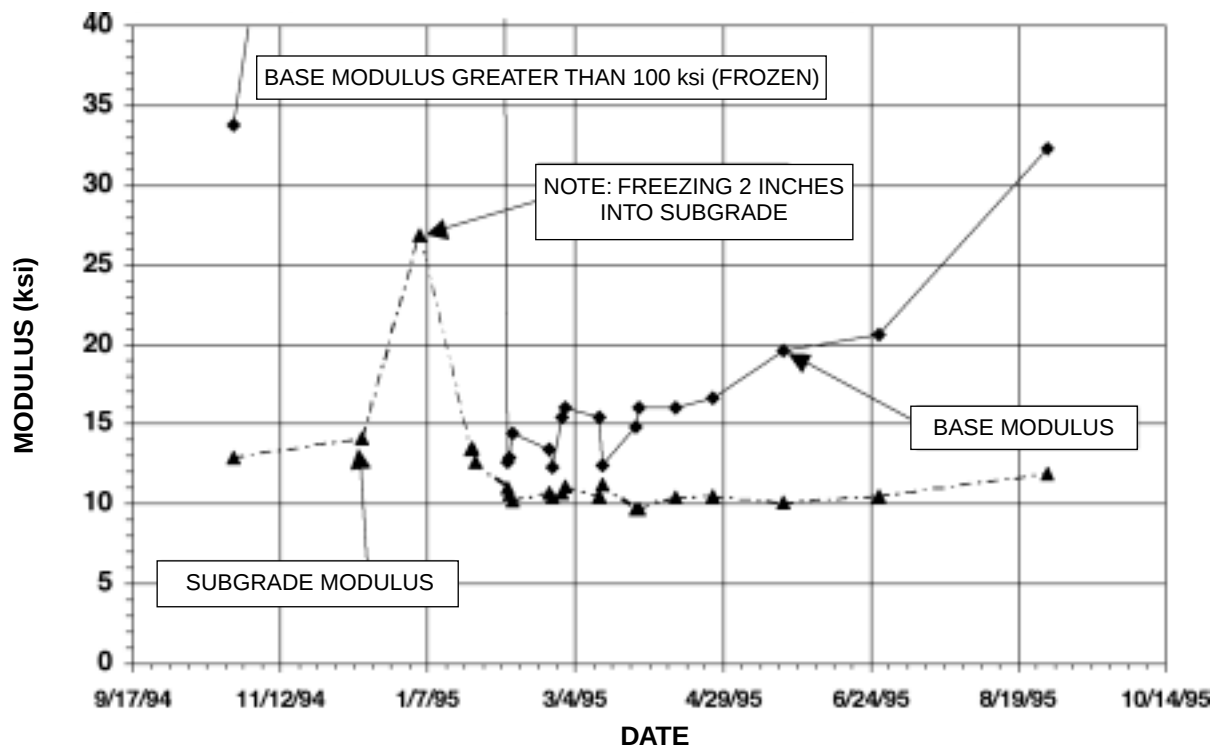
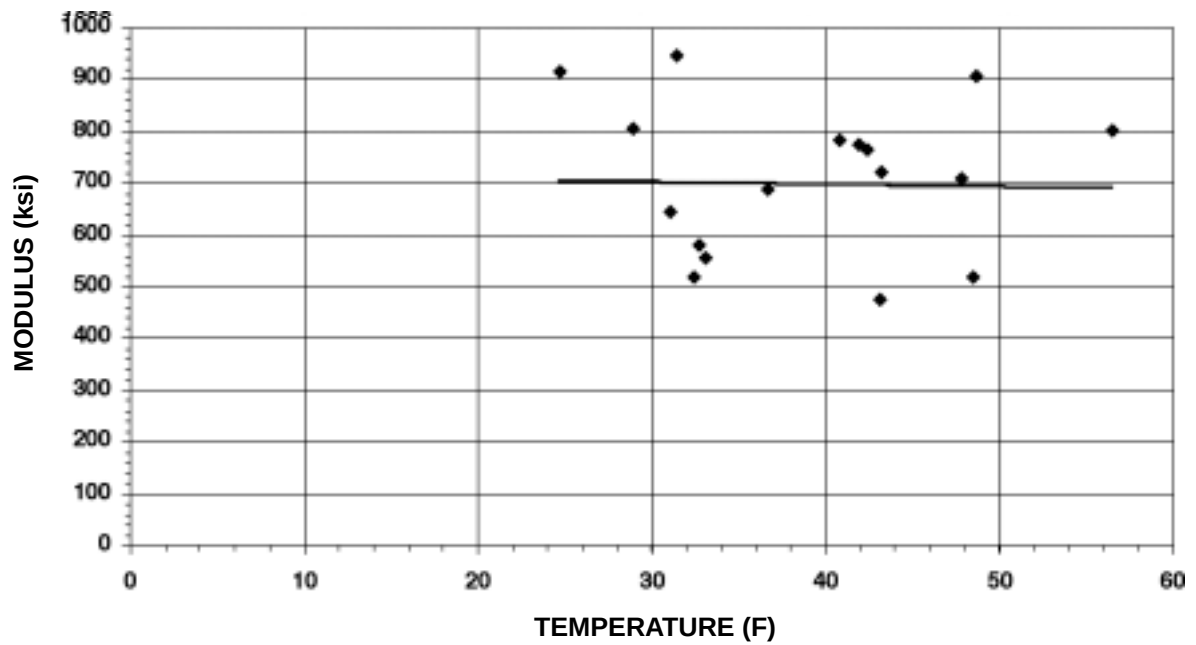
- a) Groundwater Depth: Ochoco—Site 1
- b) Groundwater Depth: Ochoco—Site 2

Figure 38—Seasonal groundwater depths.



Area Parameter (D0-D36): Ochoco—Sites 1 and 2

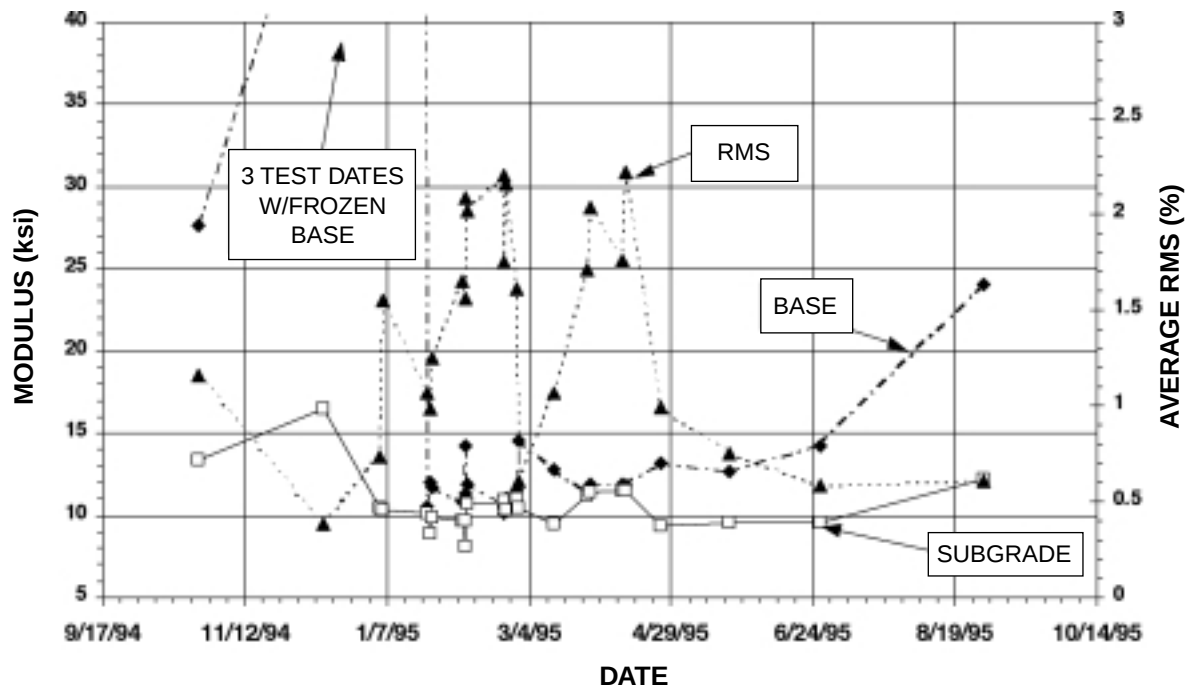
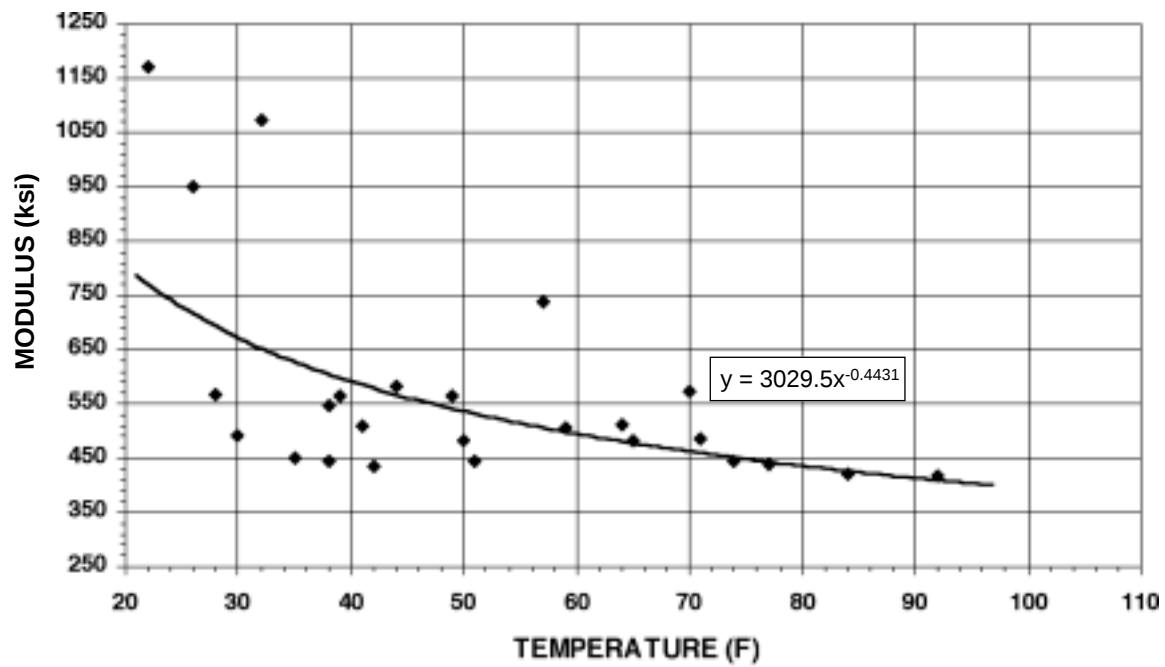
Figure 39—Seasonal change in area parameter. Note the sharp increase in December and early January as freezing occurs.



a) Backcalculated AC Moduli: Ochoco—Site 1

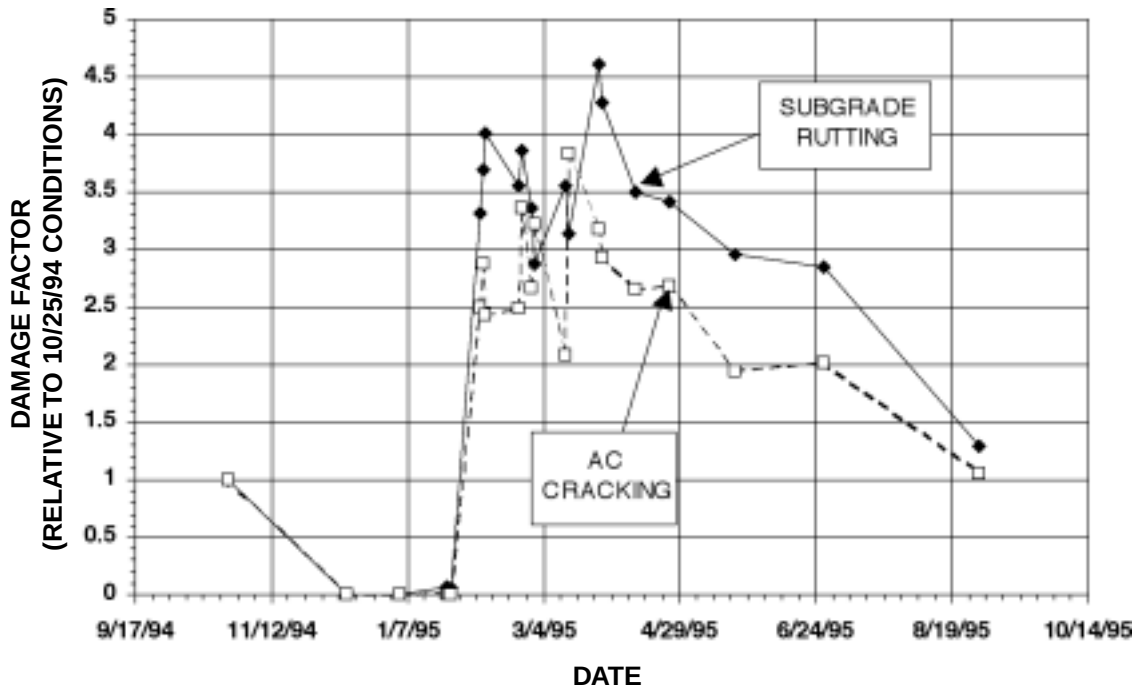
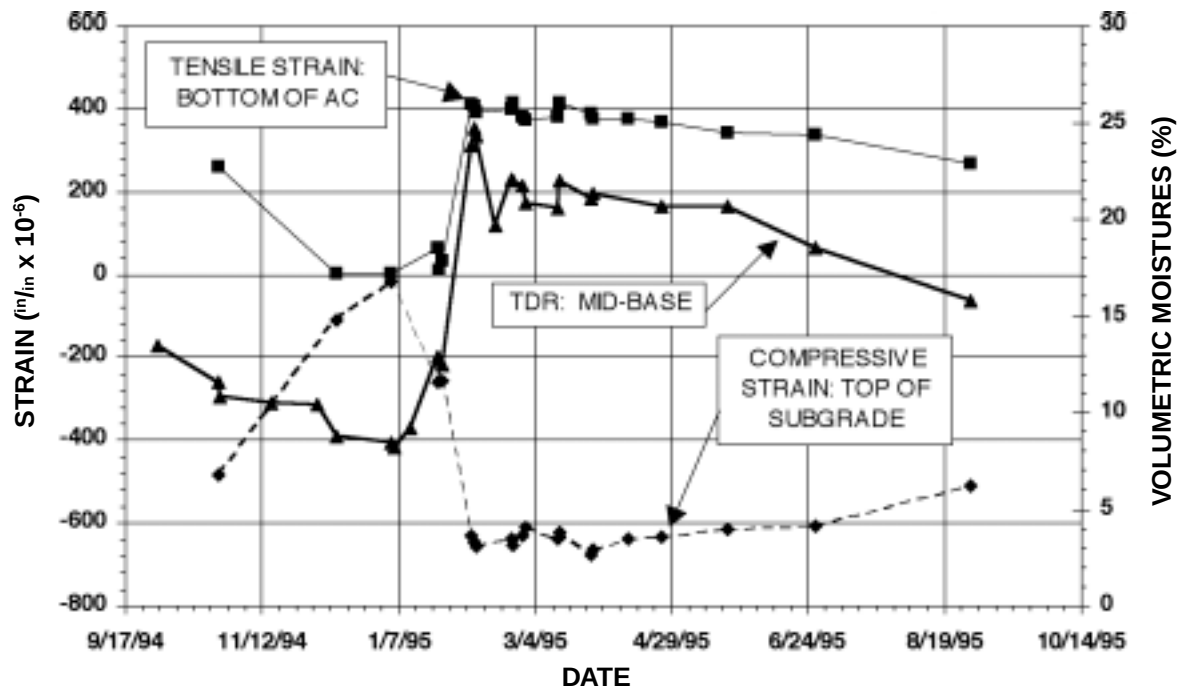
b) Base and Subgrade Modulus: Ochoco—Site 1

Figure 40—EVERCALC backcalculated moduli.



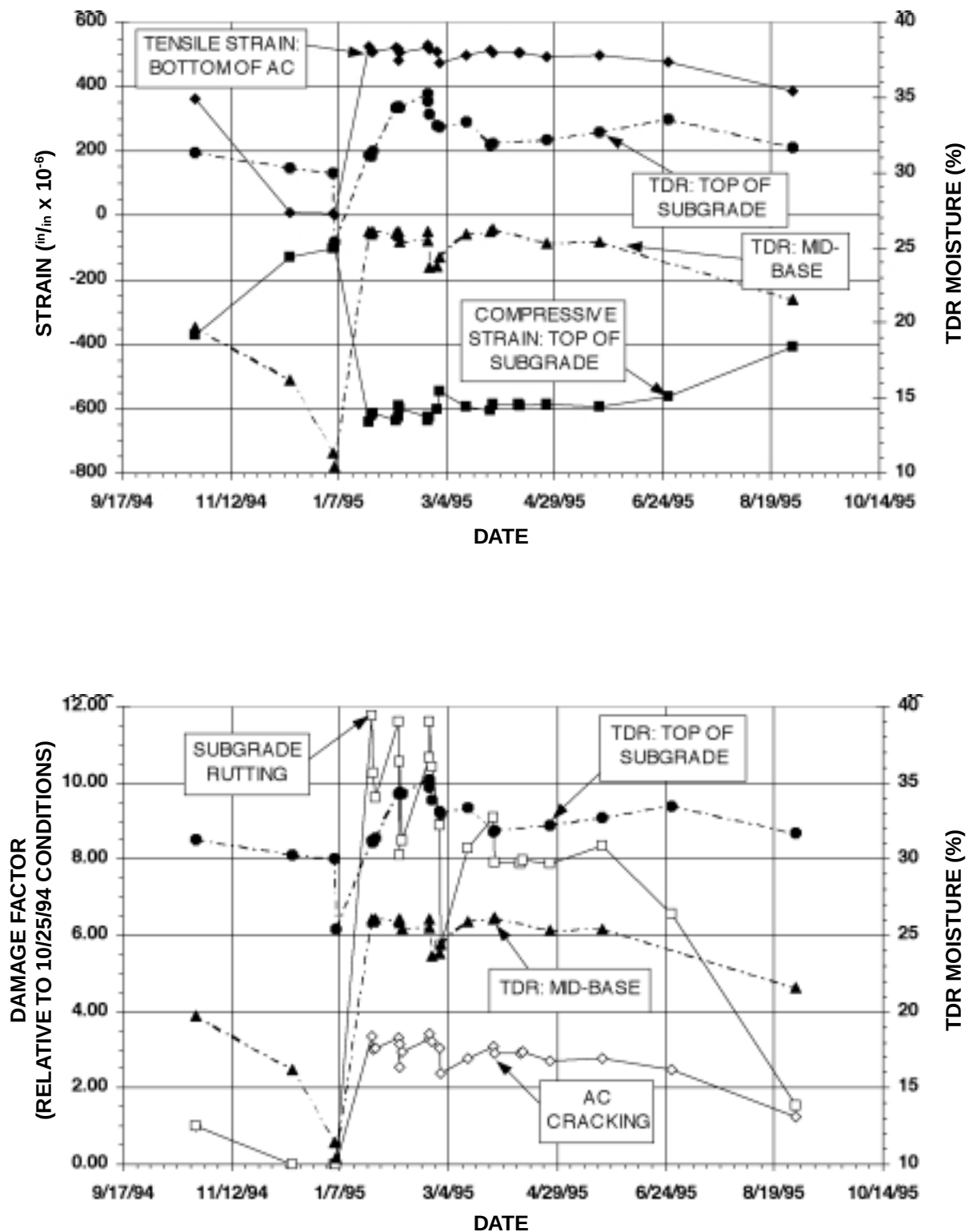
- a) AC M(r) vs. Temperature: Ochoco—Site 2
- b) Moduli and Backcalculated RMS Values: Ochoco—Site 2

Figure 41—EVERCALC backcalculated moduli.



- Critical Strains at 55F and TDR Moisture at Mid-Base: Ochoco—Site 1
- Damage Factors: Ochoco—Site 1

Figure 42—Critical pavement strains and damage factors. Note the near zero damage potential during frozen conditions of December and January.



a) Critical Strains [at 55F AC M(r) Field Curve] vs. TDR Moisture: Ochoco—Site 2

b) Damage Factors vs. TDR Moisture: Ochoco—Site 2

Figure 43—Critical pavement strains and damage factors compared with selected TDR moistures.

As was shown in figure 42 for site 1, the damage factor for rutting is 1.0 for the reference initial fall test point. (Note the first three data points in figures 42b and 43b are the same for rutting and AC cracking.) The damage factor approached zero for approximately 5 weeks when the freezing profile penetrated the base course and into the subgrade, increased to a maximum value of 4.7 in April, then decreased back to near 1 in August. A similar relationship is presented in figure 43 for site 2 that had a maximum damage factor for rutting of 11.8.

For site 1, the damage factor for asphalt fatigue cracking is 1.0 for the reference initial fall test point. The damage factor decreased to 0.0 during maximum freezing, increased to a maximum value of 3.9 in March, then decreases to 1.0 in August. Again, site 2 followed a similar trend and had a maximum value for fatigue cracking of 3.4. Maximum damage factor values for subgrade rutting were greater than those for asphalt cracking at both sites. The damage factor for rutting was much greater than the damage factor for AC cracking at site 2, but that was not the case at site 1. This is probably because the asphalt thickness is greater at site 2. The figures also show damage factor variations are reflective of changes in the TDR measured moisture at selected probes within the base and upper subgrade. In particular, the site 2 TDR probe at the top of the subgrade measured peak values during February, at a time when the damage factors were also at their maximums.

Conclusions from Ochoco Sites

1. Freeze-thaw conditions existed at these sites from November through March. The conditions were cyclic and included periods of both partial and total midwinter thaw. Maximum frost penetrations were relatively shallow ranging from 14 to 18 inches below the asphalt.
2. Due to the relatively shallow frost depths and apparently high residual ground heat from the previous summer, rates of thawing from the bottom up were high relative to other sites within this study. Consequently, most thawing on the Ochoco sites occurred from the bottom up, allowing for vertical drainage as thawing progressed. Only during isolated cases, lasting for less than a week at a time, did top-down thawing occur, impeding vertical drainage.
3. Due to the highly cyclic nature of freezing and thawing at the Ochoco sites, FWD testing only captured the concluding portion of the strength loss occurring after thawing of the most severe freeze-thaw cycle (18 inches maximum freezing depth). The maximum relative damage factor calculated was 4 to 5 times the fall conditions for cracking and approximately 11 times fall conditions for subgrade rutting. The recovery to a damage factor of 2 required approximately 3 to 4 months. This is probably due to the fine-grained nature of the soil and the associated drainage properties.
4. Maximum damage factors for subgrade rutting were greater than those for asphalt fatigue cracking at both sites implying that, for these relatively "thick" pavement structures, increased rates of rutting may be the most likely consequence of heavy vehicle use during the late winter/early spring.
5. It appears that the relatively modest increases in damage factors at these sites are only partly explained by seasonal freezing-thawing conditions. Only very brief, subdued "spikes" in post-thaw moisture contents were observed, and then only from probes within the aggregate base or upper subgrade. Elevated moisture contents (and groundwater levels) persisted for months beyond thawing. It seems likely these increased moisture contents and the associated increase in damage factors, are more likely related to snow melt and spring runoff than direct effects of thaw-weakening.
6. Critical periods of thaw weakening monitored at the Ochoco sites appear to have been very brief due to the relatively mild winter conditions. Use of thermistors and TDR (or RF) equipment allows monitoring of the timing, duration, and indirectly, the severity of these sporadic conditions and could be used to limit vehicle use accordingly. The longer periods of sustained elevated moisture contents observed are probably better handled as a pavement design issue. The observations obtained at these sites

would be helpful in determining seasonal adjustment factors for use in current mechanistic type design programs.

7. TDR (and to a lesser degree RF) probes did a good job of tracking seasonal moisture changes.

Kootenai Field Sites

Location and Climate

The Kootenai National Forest is located in the northwest corner of Montana, bordering both Canada and Idaho. The two field test sites on the forest were located on the Canoe Gulch Ranger District, approximately 15 miles north of Libby, MT at mileposts 12.4 and 17.0 along Forest Service Road No. 6800 (Pipe Creek Road, figures 44 and 45). Pipe Creek Road (in the vicinity of the test sites) is typical of many “low-volume,” asphalt surfaced FS roads; road widths vary from 18 to 20 feet, cut/fill and shallow turnpike construction were used, grades vary from 2 to 5 percent, with a “composite” asphalt surfacing consisting of a series of paving and maintenance activities over a period of more than 25 years. The test site locations were intentionally selected to provide relatively uniform aspect and shading characteristics throughout the site lengths.



Figure 44—Kootenai National Forest—Site 1 during instrumentation installation.



Figure 45—Kootenai National Forest—Site 2.

Climate in this part of Montana, approximately 100 miles west of the Continental Divide, is affected by both modified maritime and continental influences. Maritime influences generally dominate in the winter and result in rain or snow when warm Pacific air masses are cooled as its passes through the mountain ranges. Continental influences generally dominate in the summer with low-pressure areas from the hot southerly interior causing convection type showers and occasional cloud bursts. Winters are neither as wet nor as warm as the Pacific coastal area, but are generally less severe than areas to the east of the Continental Divide. The mean daily July temperature in Libby (nearest long-term weather station) is 67 °F with an extreme maximum of 109 °F. January is the coldest month with a mean daily temperature of 23 °F and an extreme low of -46 °F. Extremely low temperatures are not common however, and temperatures of 0 °F are reached on only 12 days in an average year (figure 46).



Figure 46—Kootenai National Forest Site 2 on March 14, 1996 near beginning of subsurface thawing. Note the water is “bleeding” up through the pavement.

Elevations of the test sites were 2,800 and 3,100 feet at sites 1 and 2, respectively. Libby's elevation is approximately 2,100 feet with an average annual precipitation of 18 inches. Precipitation varies widely in the forest, ranging from 14 inches to over 100 inches at higher elevations, approximately 70 percent of the total falling as snow. Due to their higher elevations, both sites would be expected to have colder temperatures and more precipitation than Libby. Design freezing indices (average of three coldest winters in the last 30 years) range from 1,000 to 1,500 degree-days F, depending on elevation. The areas mean freezing index for 30 years of records range from 500 to 1,000 degree-days F. Freezing indices for sites 1 and 2 were 1,056 and 1,114 degree-days F, respectively, for the winter of 1995/1996.

Instrumentation Layout and Site Description

Plan and profile views of the test site layout are shown in figures 47 and 48. Each site was 80 feet in length. The five FWD test points (A–E), spaced 20 feet apart, were painted on the asphalt surface at each site to facilitate repeat testing at the same locations. The FWD testing schedule was selected to focus on the critical thaw-weakening period, with additional tests conducted during 1995 through 1996 to provide late summer/early fall reference values and other typical seasonal values.

Two thermistor probes, each containing 12 thermistors, were installed in boreholes at opposite ends of each site to monitor subsurface temperatures to a depth of approximately 65 inches. Additional thermistors monitored the asphalt pavement and air temperatures. At each site, eight TDR and six RF probes were installed in 10-inch and 6-inch-diameter auger holes, respectively, to monitor subsurface moisture contents to depths of 50 to 60 inches. Due to the coarse, rocky nature of the subgrade soils, all TDR probes were compacted into the borehole backfill. Backfill material was conserved from the augering process and supplemented, where necessary, with similar on-site material. Ten of the 12 RF probes at the two sites were inserted horizontally into the sides of the boreholes, using modified pry bars and wooden blocks to provide leverage. The remaining two RF probes (at site 1) were placed vertically. All TDR and RF probes functioned normally following installation with the exception of RF probe No. 5 at site 1, which was apparently damaged during the installation process.

Two open-well standpipes consisting of geotextile wrapped, slotted, 1-inch-diameter PVC pipe were installed in boreholes at opposite ends of each site to monitor groundwater elevation changes. The boreholes were drilled to approximately 20 feet in depth at both sites through silty, sandy gravels containing cobbles and small boulders (GM). No bedrock was encountered. Groundwater was encountered during installation of the standpipes at site 1; however, none was observed at site 2. Native materials consisted of glacial till and glacial outwash deposits, some of which had been reworked through alluvial processes to produce the large terraces traversed by present day Pipe Creek Road.

Surfacing materials at the sites are variable both in quality and thickness. Site 1 was a build-up of asphalt surfaces (chipseals, cold mix, patches) varying from 2.5 to 3.5 inches in total thickness, overlying, in most cases, a weaker (“crumbly”) asphalt coated layer from 1.25 to 2.00 inches in thickness. This weaker asphalt layer, in turn, overlays a 0.5-inch-thick BST (bituminous surface treatment). Sporadically, a 1.25- to 2.00-inch-thick layer of 1/2-inch-minus, fine, sandy aggregate was found sandwiched above the oldest BST.

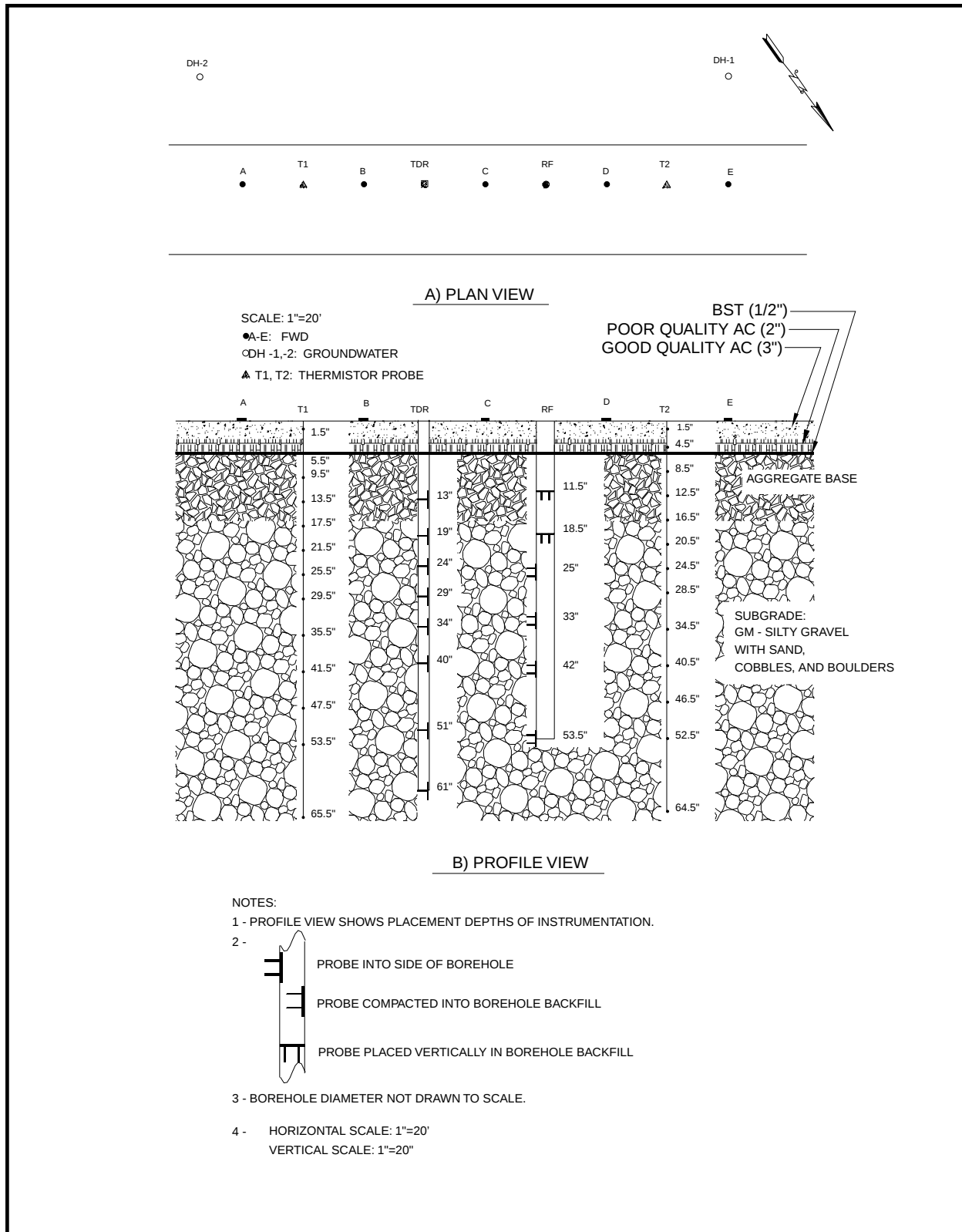


Figure 47—Instrument Layout: Kootenia National Forest—Site 1.

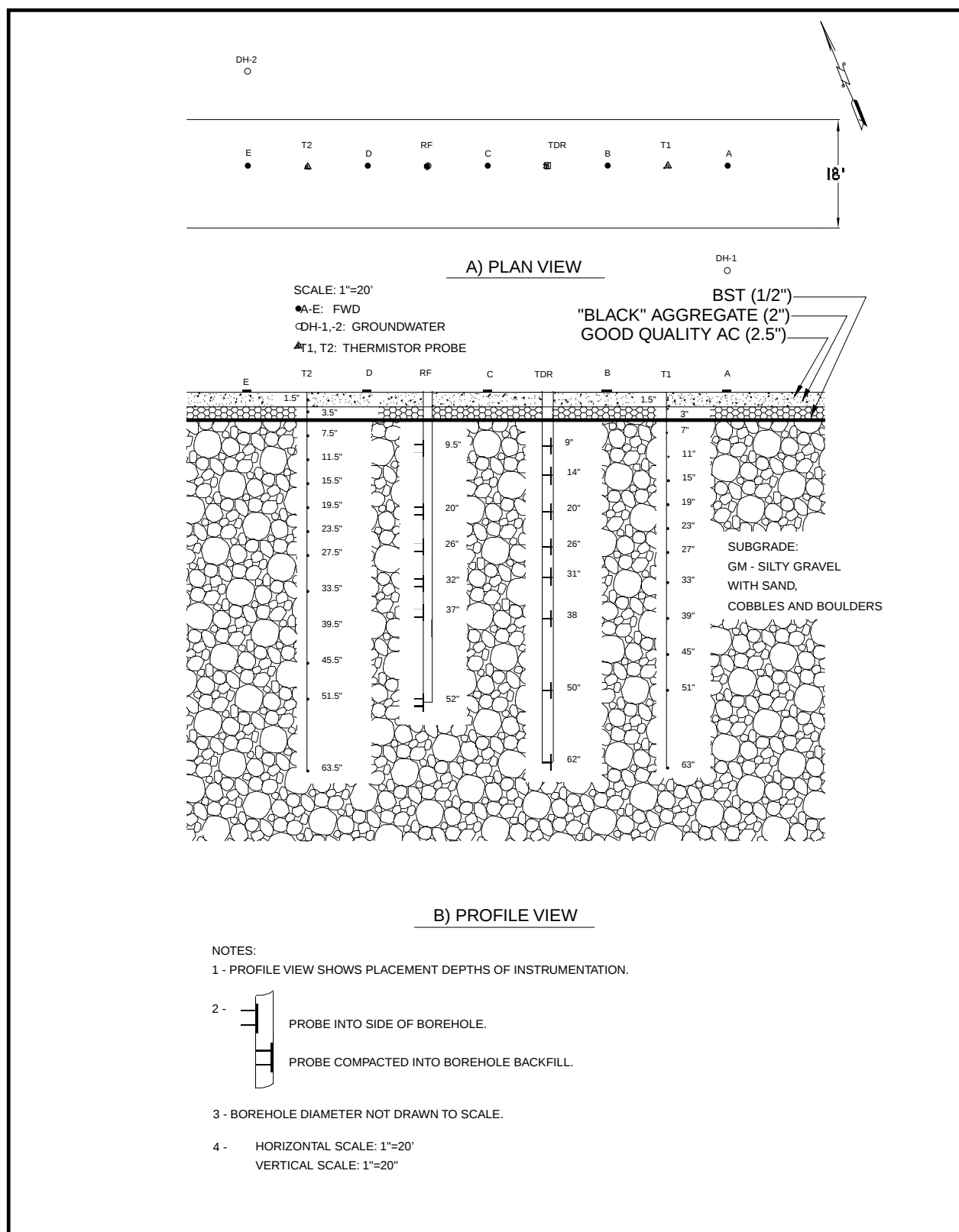


Figure 48—Instrument Layout: Kootenia National Forest—Site 2.

Underlying the asphalt layers was a “pit-run” base course, 10 to 12 inches in thickness, which was field classified as a GP-GM gravel with small cobbles. The subgrade at site 1 was a silty-gravel (GM) with cobbles and boulders, approximately 65 percent gravel, 20 percent sand, and 15 percent nonplastic fines. For moduli backcalculation purposes, all degraded asphalt layers, below the uppermost 2.5 to 3.5 inch thickness, were combined with the underlying base course thickness.

Site 2 had a surface layer of intact asphalt from 2.25 to 3.00 inches in thickness overlying a 2.0- to 2.5-inch-thick layer of asphalt-coated, fine aggregate that was no longer a cohesive material. Sporadically, underlying this fine aggregate, was a 1/2-inch thick BST, similar to that found at site 1. No discernible difference could be seen between the material underlying the lowest BST and deeper subgrade materials. For this reason, it is believed that no distinct base course exists at site 2. As with site 1, during moduli backcalculations, all degraded asphalt layers under the uppermost asphalt surface were combined into the underlying granular material layer (i.e., subgrade in the case of site 2).

Data Collection and FWD Testing Program

Data collection consisted of temperatures (thermistors), moisture contents (TDR and RF), groundwater, and site conditions (i.e., sunny, cloudy, raining, dry, snowing, etc.) from September 23, 1995 to September 27, 1996. Readings were obtained at least monthly during the summer, fall, and early winter, increasing to daily during the 6-week thaw period that occurred between mid-March and early May. Readings were collected manually during all site visits. One thermistor probe at each site was connected to an automated data collection device. Temperature readings from the thermistors in this probe were taken either two or four times each hour, depending on the depth of the individual thermistor; the more frequent readings were taken on the upper thermistors.

FWD data was collected throughout the year to determine material layer strength variations. A total of 33 FWD testing events occurred during the study period. Two of these were performed during October 1995 to establish reference conditions. The remainder occurred between March 18 and May 8, 1996 to monitor the progressive change in material strengths throughout and immediately following spring-thaw. Testing generally occurred, alternately, in the midmorning and midafternoon on consecutive days to observe the effect of differences in asphalt temperature on the backcalculated strengths.

Asphalt Coring

On May 9 and 10, 1996, following completion of the FWD testing, a total of 10 asphalt cores from each of the sites were obtained for laboratory modulus testing (figure 49). Two cores were taken at each FWD test spot: one directly from the painted FWD impact point and another approximately 1 to 1.5 feet from the test spot, along the line of the deflection measuring sensors. The cores were tested at temperatures of 35, 55, and 80 °F in an environmental chamber at the Willamette Laboratory.



Figure 49a—Drilling AC pavement cores for laboratory modulus testing. Kootenai National Forest—Site 2.

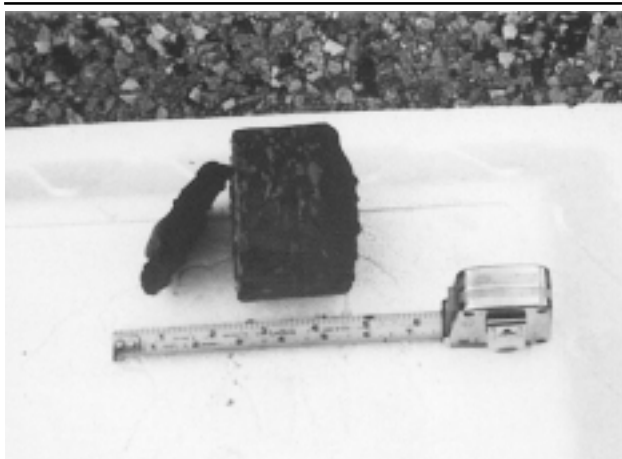


Figure 49b—Typical AC pavement core from Kootenai National Forest sites. Note the thin, older BST surface found below thicker AC.

Analysis and Results

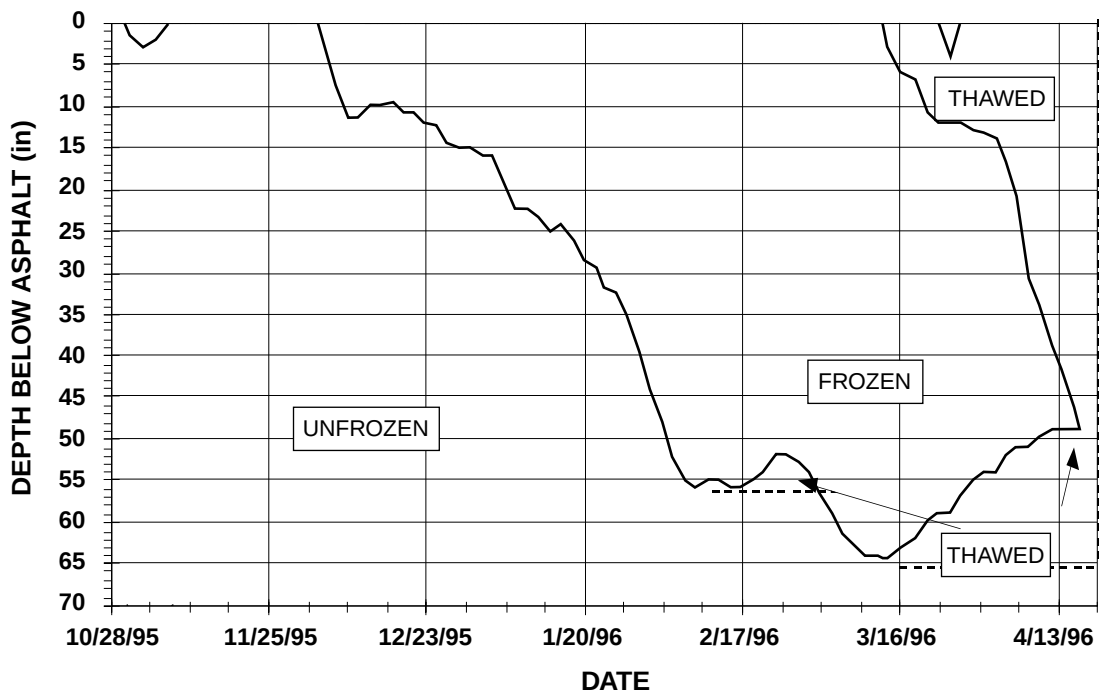
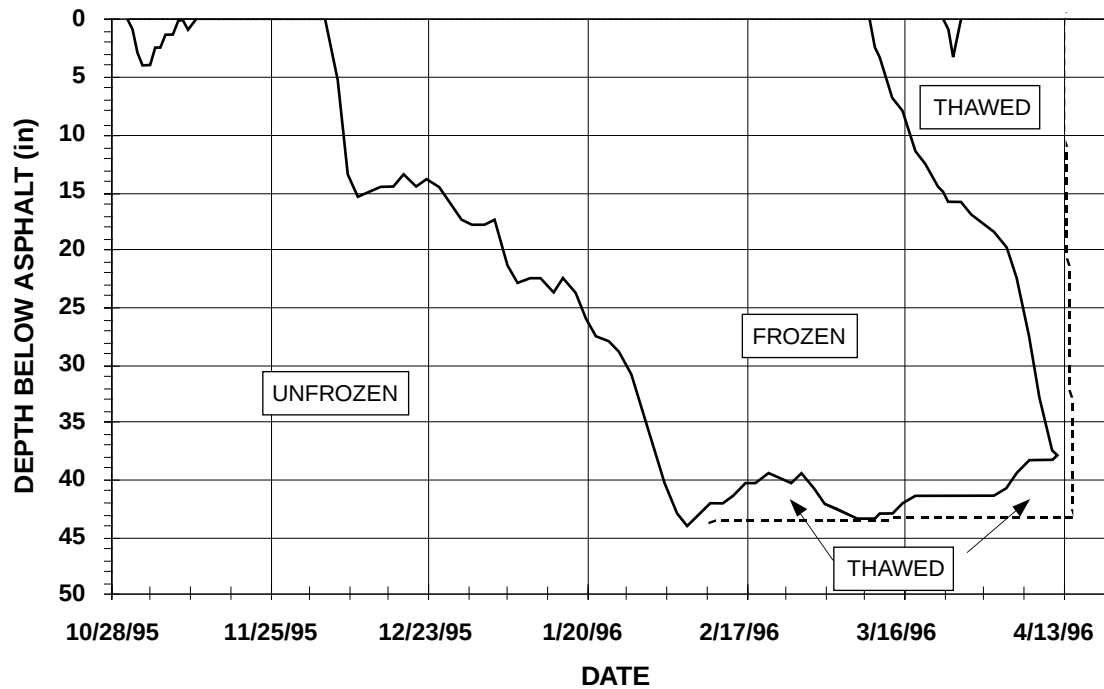
Temperature

Frost profiles depicting the timing, extent, and duration of freezing and thawing at the test sites were constructed using the temperature data collected. As seen in the plots shown in figure 50, a single major freezing and thawing event dominates winters in this part of the country (contrasting with the multiple, relatively minor events observed at the Ochoco National Forest sites). Two minor periods of freezing and thawing did occur: one in early November and another in the later part of March; however, the overall pattern is clearly one of massive progressive freezing, followed in the spring by nearly continuous thawing, predominately from the top down. Again, this predominately top-down thawing and associated impeded vertical drainage contrasts sharply with the results from the Ochoco sites. Typical rates of freezing in early December at the Kootenai sites were approximately 2.0 to 2.5 inches per day. Rates of thawing during the later part of March and early April were approximately 1.5 to 2.5 inches per day from the top down and approximately 0.2 to 0.5 inches per day from the bottom up. In addition, approximately 80 percent of the thawing at these sites occurred from the top down, with total thawing occurring over a period of about 5 weeks.

TDR and RF

TDR and RF volumetric moisture content fluctuations for each site are shown in figures 51 through 53. The monitored changes are more dramatic than those observed at the Willamette or Ochoco sites. Both Kootenai sites and both types of instrumentation show the same general pattern of relatively stable values until freezing occurs in early December. After freezing, the values sharply drop to reflect the lowered dielectric constant of the frozen soil. Interestingly, the deepest sensors (both TDR and RF) at site 1, which did not freeze, show increased moisture contents as freezing progresses, possibly due to groundwater being drawn toward the freezing front as a result of increases in capillary tension of the soil moisture. With the initiation of thawing in early March, both TDR and RF sensors recorded a large, sharp increase in moisture contents to levels well above those observed immediately prior to freezing. This suggests that moisture may have been added to the structures during the freezing process; it may also, in part, be a result of surface infiltration of moisture from adjacent melting snow-banks. Since both vertical and horizontal drainage is impeded by frozen ground, distinctive peaks formed during the thawing process. It can be seen that the peaks of individual sensors occur sequentially as thawing progressed in depth. As thawing progressed, an equally rapid sequential decrease in moisture contents was observed until a few days following complete thawing, at which point the slope of the moisture content recovery curve significantly flattens. This suggests that the moisture trapped above the ground ice, at least for coarse-grained soils, such as those found at these sites, drains rapidly following thaw. A secondary, much less rapid “drying” phase follows the initial “drainage” phase, with moisture contents eventually returning to levels approximating those observed the previous fall.

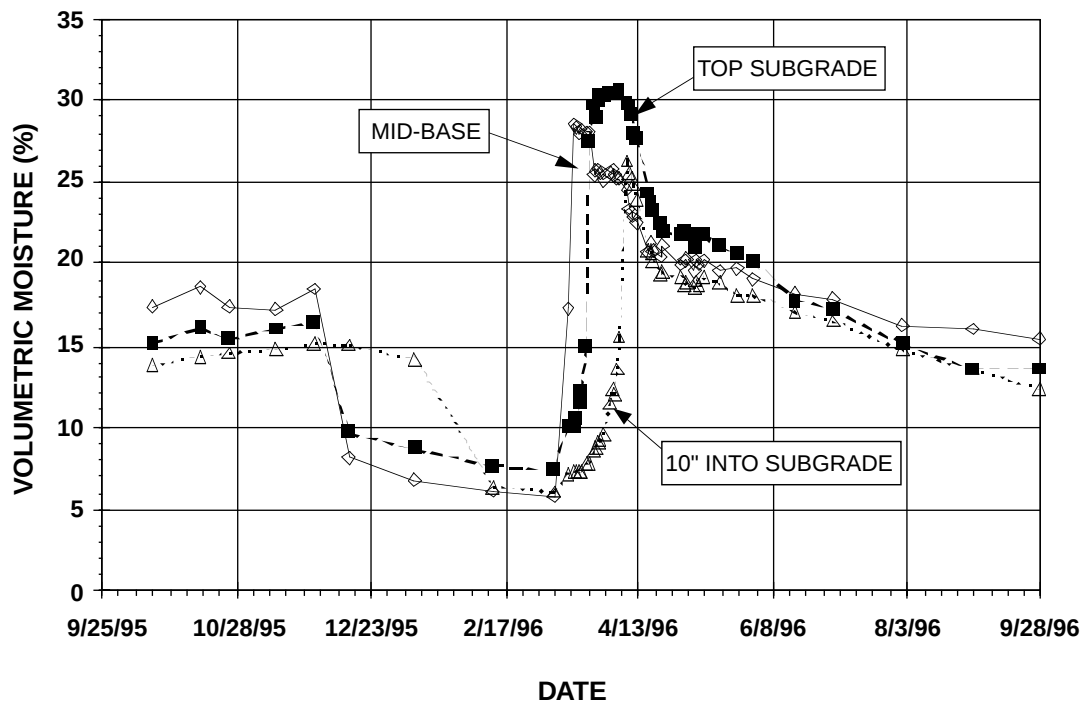
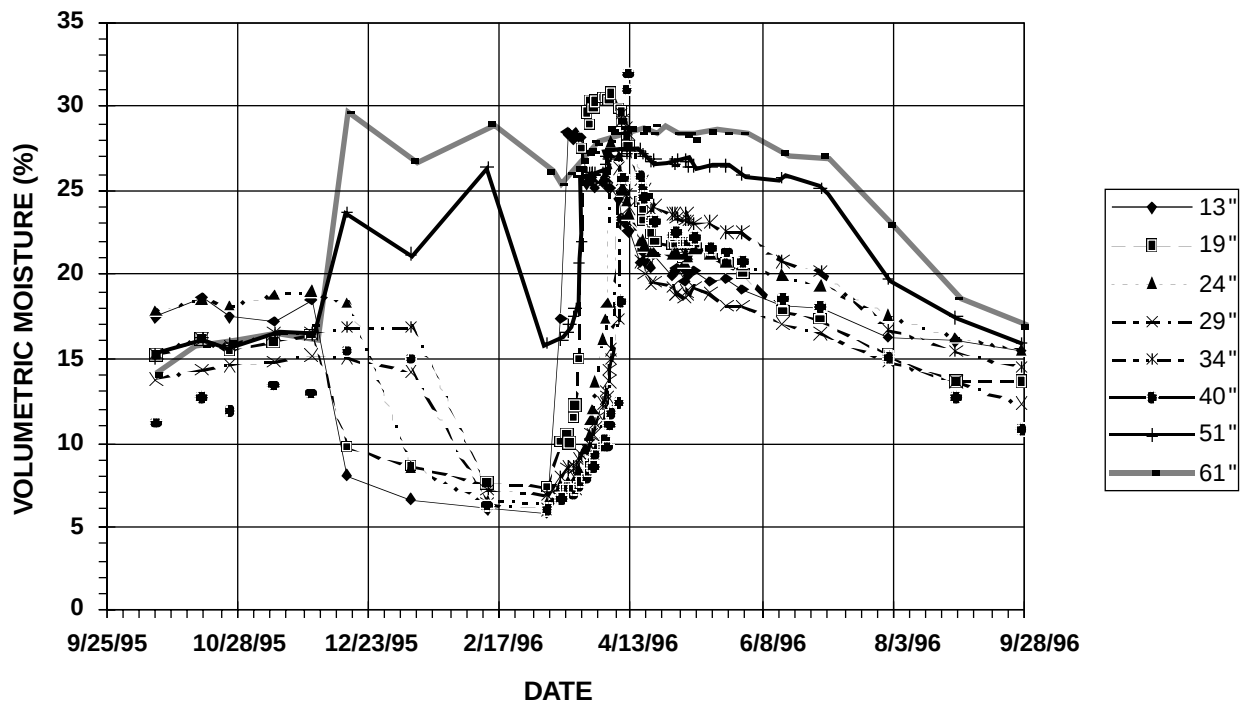
Interestingly, as previously mentioned, groundwater was not encountered in the 20 foot deep monitoring holes of site 2; yet, even in these very coarse-grained soils, a moisture peak upon thawing, similar to that observed at site 1, is apparent. There are two possible sources for this moisture peak: it is the result of moisture desiccated from underlying unsaturated soils, or it could be a result of surface infiltration from adjacent melting snow banks on the road shoulders.



a) Frost Profile: Kootenai—Site 1

b) Frost Profile: Kootenai—Site 2

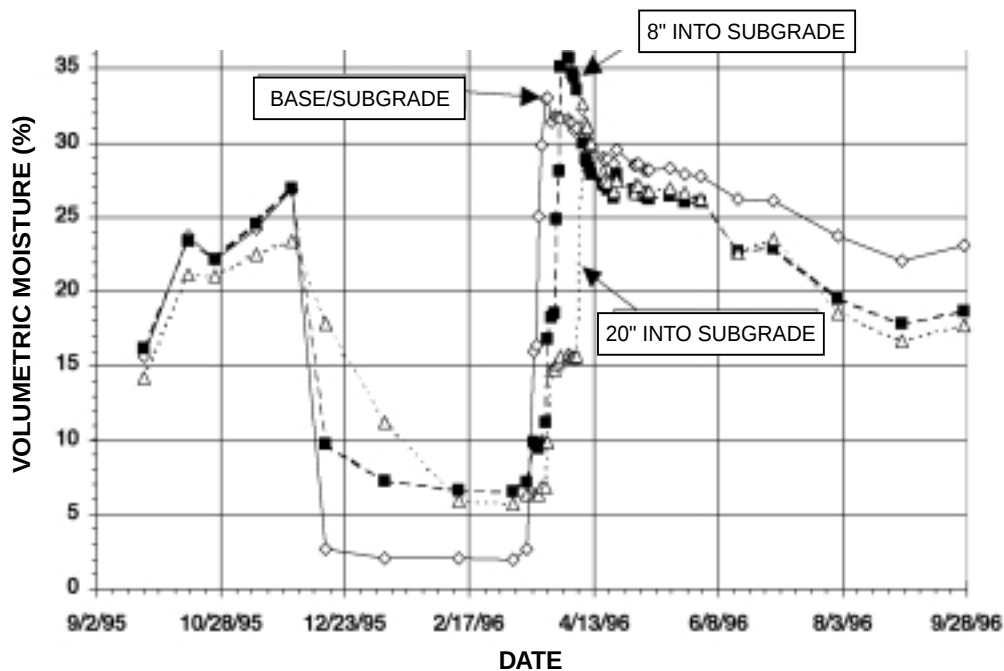
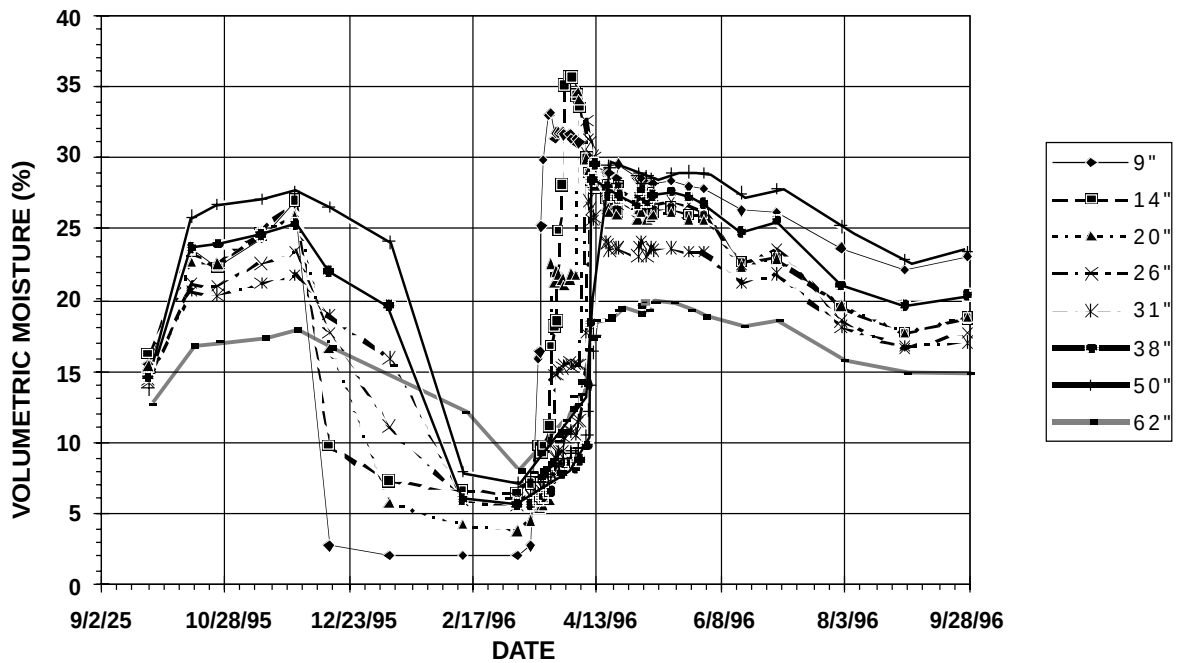
Figure 50—Seasonal frost profiles. Note the majority of thawing occurred from top down at these sites.



a) TDR Volumetric Moistures: Kootenai—Site 1

b) Selected TDR Volumetric Moistures: Kootenai—Site 1

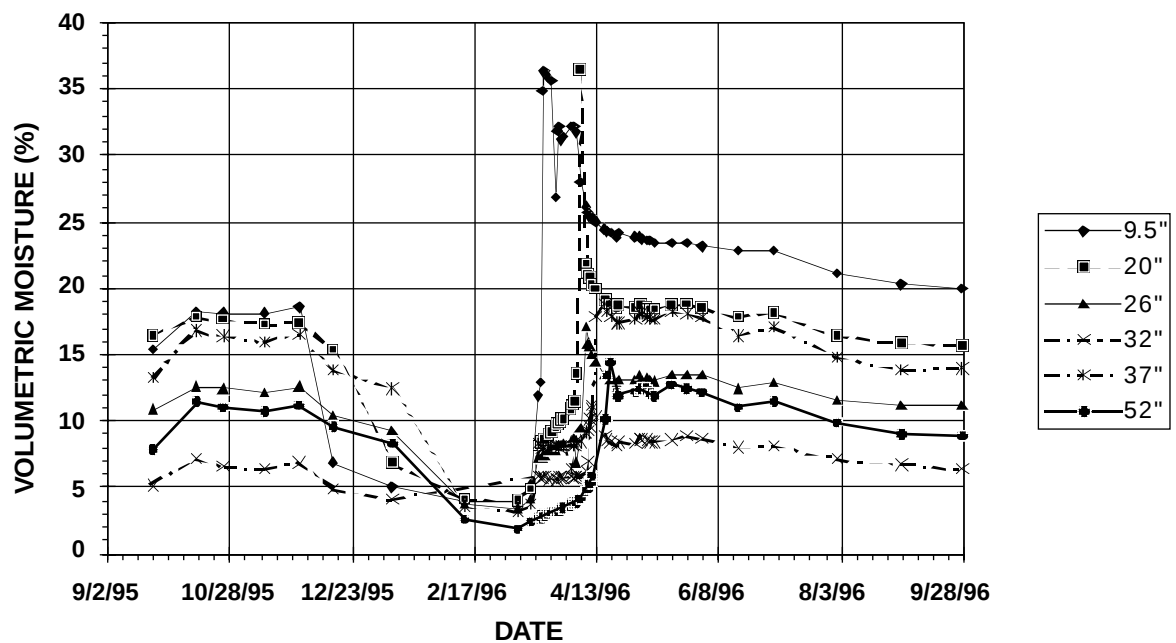
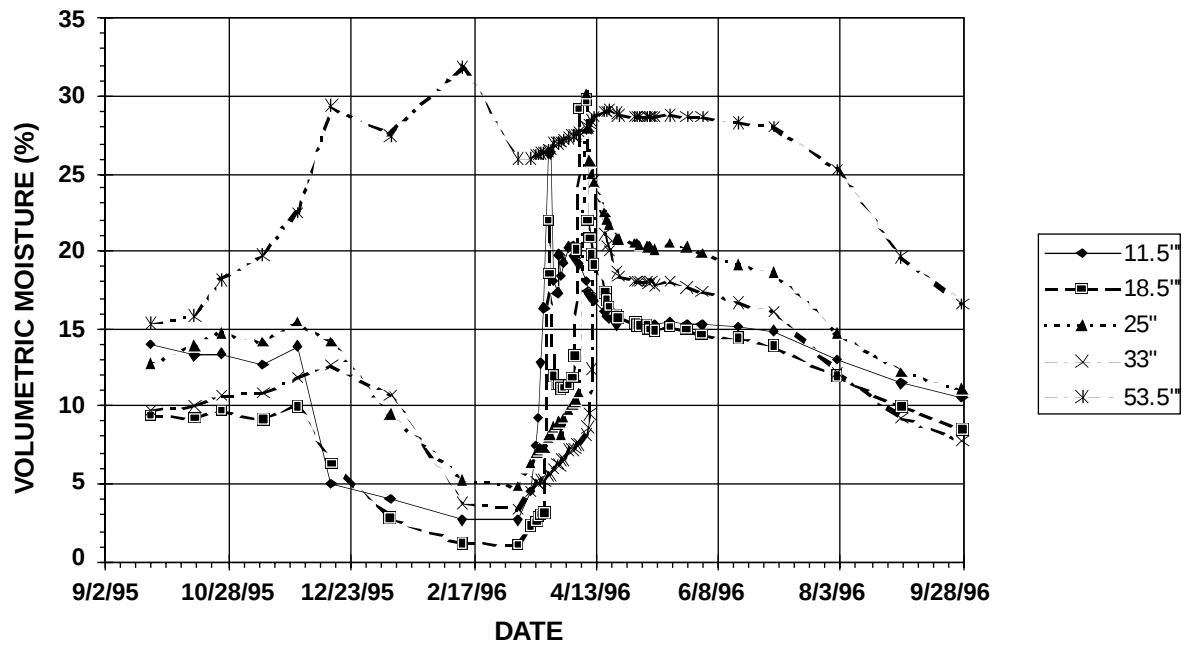
Figure 51—TDR measured moisture contents. Note the pronounced peaks during thaw. Sensors at 51 and 61 inches were below depth of frost penetration.



a) TDR Volumetric Moisture: Kootenai—Site 2

b) Selected TDR Volumetric Moistures: Kootenai—Site 2

Figure 52—TDR measured moisture contents. Note the pronounced peaks during thaw. All sensors were within frost penetration depth.



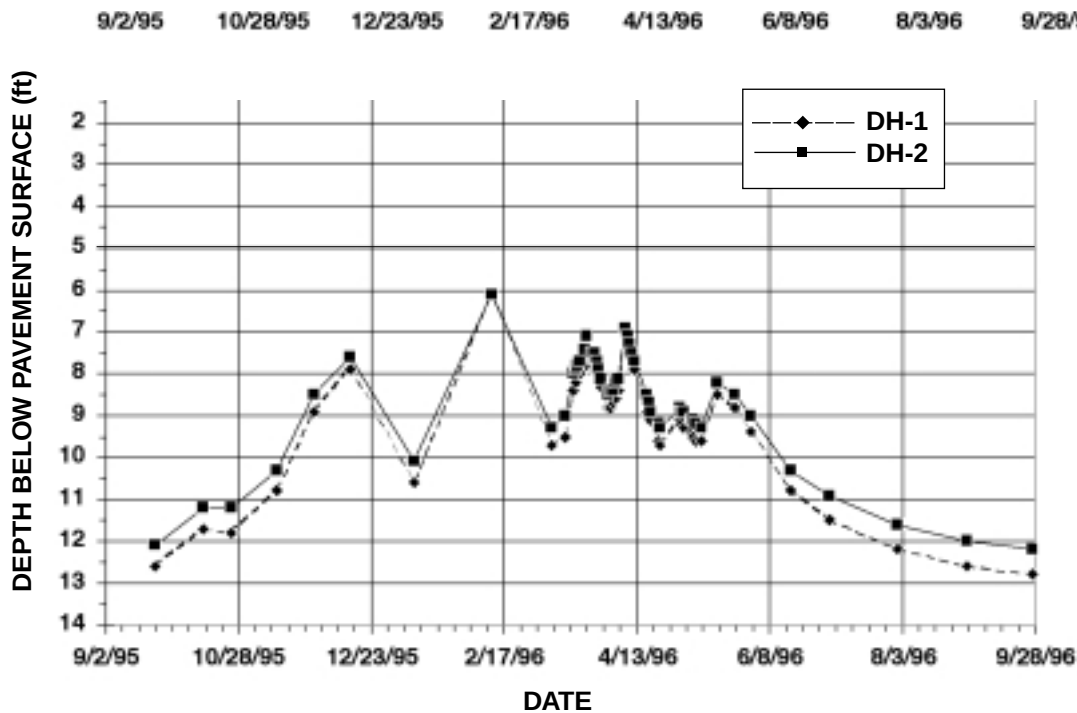
a) RF Volumetric Moistures: Kootenai—Site 1

b) RF Volumetric Moistures: Kootenai—Site 2

Figure 53—RF measured moisture contents moisture contents. Similar pronounced peaks were observed by TDRs during thaw. Sensor at 53.5 inch depth (site 1) was below depth of frost penetration.

Groundwater

Figure 54 shows groundwater measurements obtained from site 1. As mentioned above, groundwater was not observed within the 20-foot depth of the observation wells at site 2. Both observation wells at site 1 indicated similar groundwater depths and rates of change. In general, groundwater depths at site 1 were 12 to 13 feet below the pavement surface during the late summer and early fall. The highest measured groundwater levels, approximately 6 feet below the pavement, occurred in mid-February when ground-freezing was near its maximum and prior to any thawing. Levels varied from 7 to 9 feet below the pavement surface during the period of thaw, gradually decreasing to the previous fall levels.

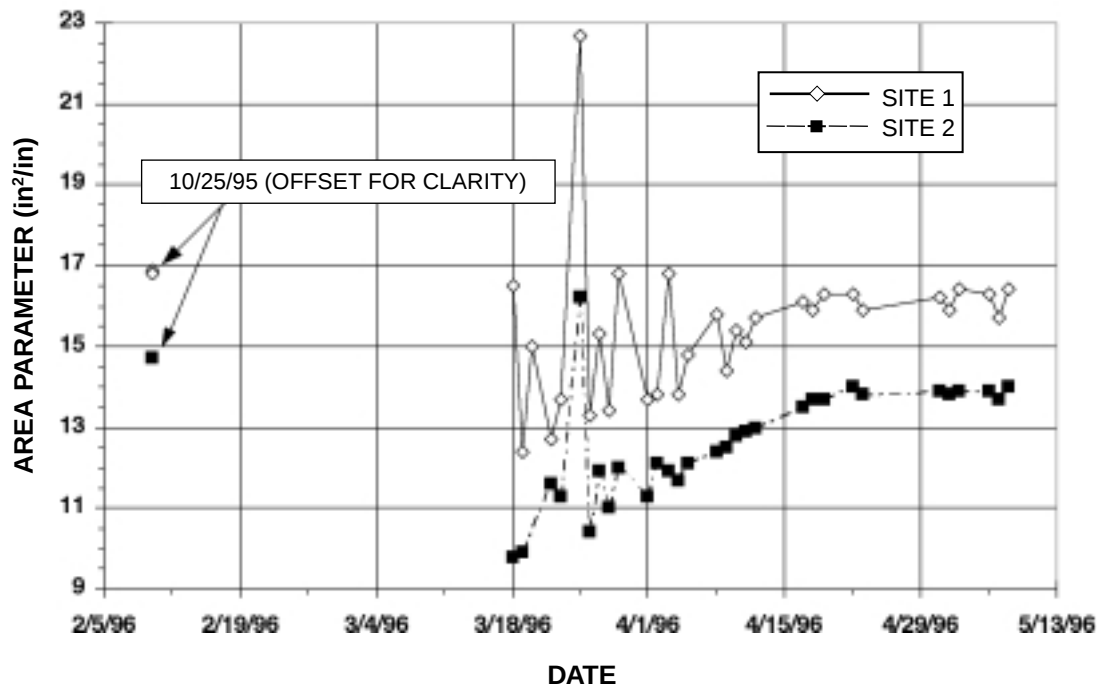


Groundwater Depth: Kootenai—Site 1

Figure 54—Seasonal groundwater depths.

Area Parameter

Area parameters were calculated for the Kootenai sites in a manner similar to the Willamette and Ochoco sites. The resulting values are shown in figure 55. Values indicated that, unlike the Ochoco sites, there is a significant difference in overall stiffness between sites 1 and 2, with site 2 being weaker. This is reasonable given the thinner asphalt surface, lack of base course, and weaker subgrade. In addition, it is apparent that both Kootenai sites are less stiff throughout the year than sites on the Ochoco National Forest. Again, this is reasonable given the superior asphalt quality, greater asphalt thickness, and graded, crushed base that exist at the Ochoco sites. The Kootenai sites had fall reference value area parameters of approximately 15.5 and 12.5 square inches per inch for sites 1 and 2, respectively. Values were somewhat erratic during the thawing process, cycling, roughly, with changes in asphalt temperature (due to sequential testing alternately performed in midmorning and midafternoon). A sharp peak was observed on March 25, 1996, following 3 days of continuously subfreezing temperatures. Thermistor data indicates several inches of refreezing below the asphalt occurred during this period of time. Beginning approximately April 3, 1996, with 12 to 18 inches of thaw below the asphalt, a period of less erratic strength recovery occurred. By April 18, 1996, within a week following complete thawing, relatively stable values were achieved, only slightly below values of the previous fall.



Area Parameter (D0-D36): Kootenai—Sites 1 and 2

Figure 55—Seasonal change in area parameters. Note the sharp spike on March 15, 1996 coincides with a period of partial refreezing of base materials.

Layer Moduli

Layer moduli values were backcalculated for each FWD testing point from the load and deflection data using EVERCALC. During backcalculations, sites 1 and 2 were modeled somewhat differently. When no ground ice was present, site 1 was modeled as a four layer problem with layer 1 being asphalt, layer 2 being base course, layer 3 being subgrade above the watertable, and layer 4 being subgrade below the watertable. Since the depth to the watertable was always known, EVERCALC was allowed to backcalculate the layer 4 moduli. When ground ice was present, site 1 was modeled as a five-layer problem, layer 1 being asphalt and layer 2 being one half the thawed thickness (until the 14-inch-thick base was completely thawed, at which point layer 2 became the thawed base). Layer 3 was the lower one half of the thawed thickness (until the 14-inch-base was completely thawed, at which point layer 3 became the thawed subgrade). Layer 4 was the frozen subgrade, and layer 5 was the unfrozen subgrade below the ground ice.

When no ground ice was present, site 2 was modeled as a four layer problem with layer 1 being asphalt, layer 2, the upper 18 inches of subgrade, layer 3, a 39-inch-thick subgrade unit, and layer 4, a “hard” layer at approximately 60 inches in depth. EVERCALC was allowed to backcalculate the modulus of layer four. The 60-inch-hard-layer depth was based on preliminary runs that showed this depth produced the lowest RMS errors. Site 2 (with ground ice) was modeled as a four or five layer problem depending on the thaw depth. With less than 14 inches of thaw, layer 1 was the asphalt, layer 2, the thawed subgrade, layer 3, the frozen subgrade, and layer 4, the unfrozen subgrade below the ground ice. With greater than 14 inches of thaw, layer 1 was the asphalt, layer 2, the thawed subgrade thickness minus 6 inches, layer 3, was the lowest 6 inches of thawed subgrade, layer 4, the frozen subgrade, and layer 5, the unfrozen subgrade below the ground ice.

In general, backcalculation RMS errors were less for unfrozen conditions than for frozen conditions, as might be expected. For unfrozen conditions, average RMS values for all FWD tests were 1.0 and 1.2 percent for sites 1 and 2, respectively. For tests where ground ice was present, the overall average values were 1.3 and 1.8 percent, respectively.

Backcalculated moduli for the asphalt layers were compared with moduli obtained from laboratory testing on site cores. Figure 56 shows the results of laboratory testing on cores from sites 1 and 2 along with the temperature/modulus curve for WSDOT B Mix for comparison. The general shape of all three curves is very similar, with the cores from site 1 indicating a somewhat stiffer mix than WSDOT "B", while site 2 cores indicate a softer mix. Figure 57 compares the laboratory core results with backcalculation results for the asphalt layers. Considerable scatter is evident in the backcalculated results, as might be expected when attempting backcalculations with such thin asphalt layers. Each backcalculated value represents the average result for the five FWD test points at each site for a particular testing date. Even with the scatter, it is apparent the backcalculated best-fit curves for the sites are quite similar in slope and considerably flatter than the respective laboratory curves. This may be attributed to the greater lateral confinement that exists in the field compared to the unconfined laboratory tests.

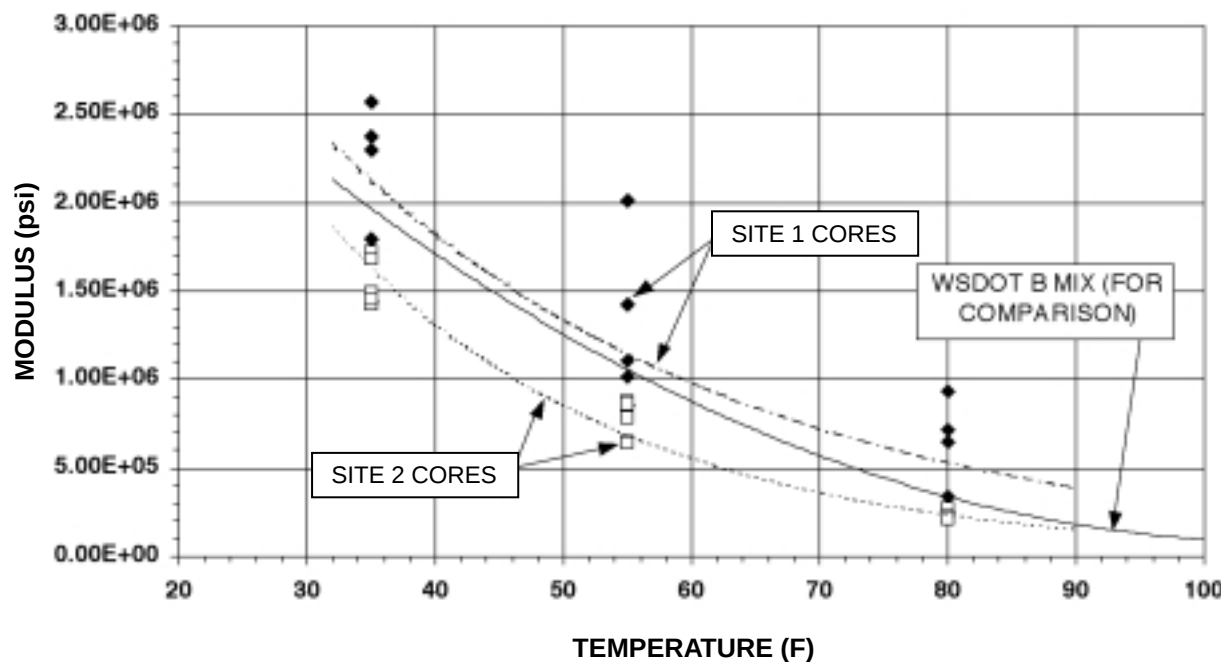


Figure 56—Laboratory modulus tests on site AC cores. WSDOT B mix is shown for comparison.

Seasonal variations in the backcalculated moduli for base and subgrade layers are shown in figures 58 and 59. Also displayed on these figures is the thawed depth on each test date. Reference values from the previous fall are also shown. Both base and subgrade moduli show a trend toward stabilized values, though still reduced from the previous fall values, coinciding with the time all ground ice thaws. Minimum subgrade moduli were calculated to be approximately 4 ksi at both sites 1 and 2. This compares to early fall values of approximately 14 ksi and 21 ksi for sites 1 and 2, respectively. Minimum subgrade moduli occurred with thaw depths of 18 inches. The base course fall value was approximately 26 ksi and was reduced to a minimum of approximately 18 ksi during spring thaw. Several sharp spikes can be seen in the base moduli during the thawing period. From the thermistor data, it is apparent that

several inches of refreezing of the base occurred just prior to the March 25, 1996 tests and this is reflected in the backcalculated values. Although the subsurface temperature data is inconclusive concerning the other base moduli spikes during the later half of March, the monitored air temperatures do suggest that some minor amounts of refreezing may have occurred.

Critical Strains and Damage Factors

Both vertical compressive strain at the top of the subgrade and horizontal tensile strain at the bottom of the asphalt were calculated using EVERSTRESS with the EVERCALC backcalculated moduli values. As explained earlier, these parameters allow estimates to be made of a pavement's ability to withstand rutting of the subgrade and fatigue cracking of the asphalt surfacing. For the strain calculations, a fixed asphalt modulus equal to the value determined for 55 °F from the best-fit curve for backcalculated values (figure 57) was used; this was done to model a typical sunny spring day during thaw and was intended to reduce the scatter in the results that would be introduced by using varying asphalt moduli values.

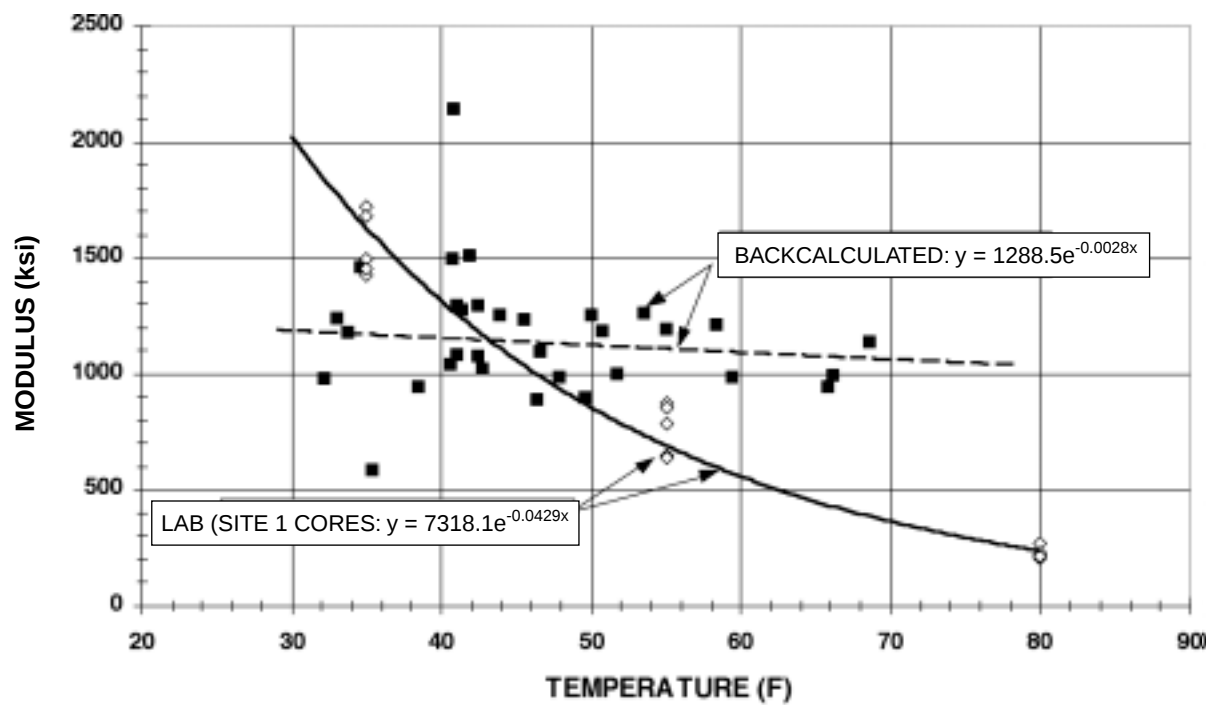
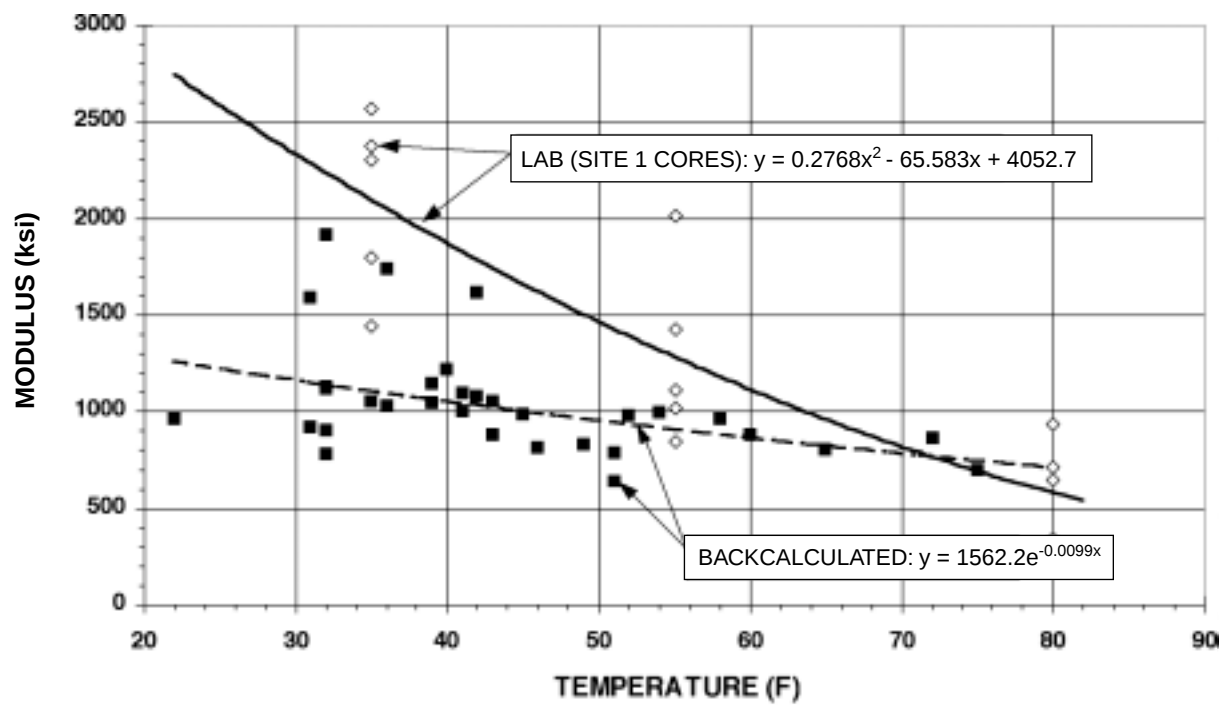
The resulting strains were used to calculate damage factors in a manner similar to that discussed for the Ochoco sites. Figures 60 and 61 show the results of the calculations for Kootenai sites 1 and 2, respectively. Also displayed on these figures are the TDR moisture contents measured at the top of the subgrades and the thaw depth based on thermistor temperature measurements. Moisture contents at the top of the subgrades are shown because moisture changes at this position reflect conditions within the overlying base, as well as the upper subgrade. Changes in moisture content of these uppermost layers is likely to dominate changes in overall pavement strength.

Since site 2 did not have a true base course, the "subgrade" depth was selected 6 inches under the asphalt for strain and damage factor calculations. Both sites reacted similarly with both strains (particularly for subgrade rutting) and damage factors starting out relatively low, increasing significantly as the thawing process progresses and moisture contents increase, and finally

decreasing rapidly as ground thawing is completed and moisture contents decrease. These trends are the same as those observed earlier in the area parameter. Maximum damage factors for rutting of 32 and 45 were calculated for sites 1 and 2, respectively. Maximum damage factors for asphalt fatigue cracking were approximately 2 for both sites. The results suggest, at least for these pavement structures, that during spring thaw, the rutting potential increases more than the potential for fatigue cracking. This may be a consequence of the relatively high strength subgrade soils found at these sites and their ability to provide support for the asphalt surfacing even during thaw-weakened conditions.

Conclusions From Kootenai National Forest Field sites

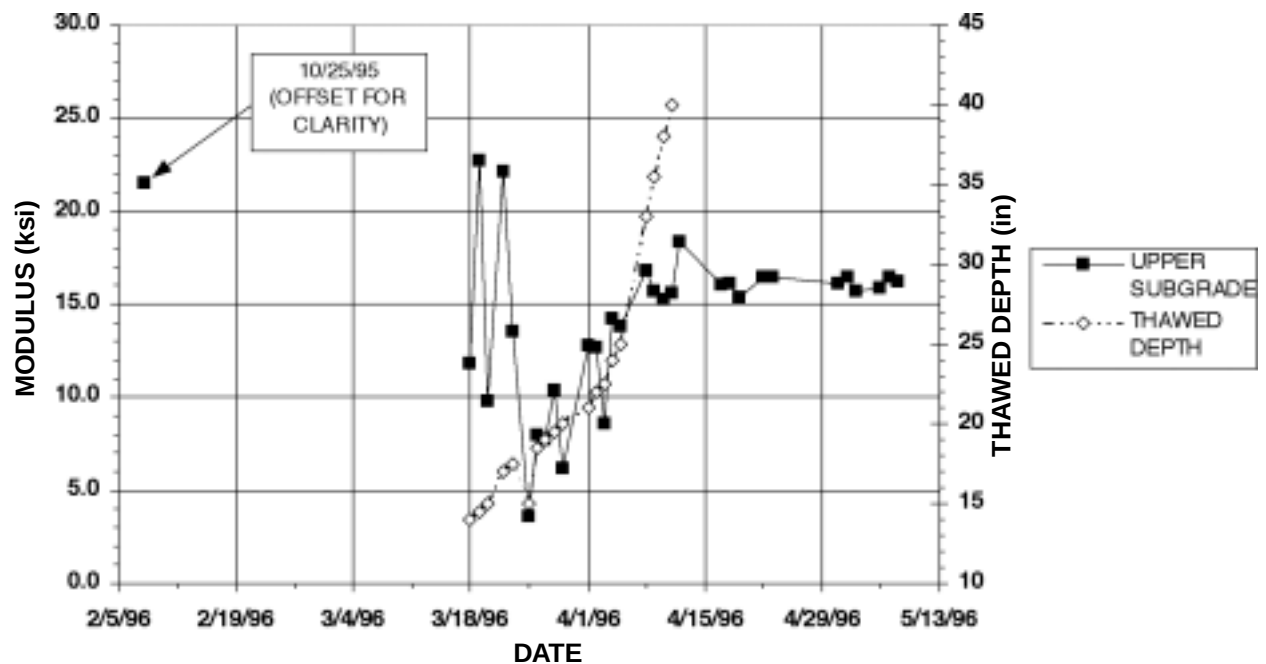
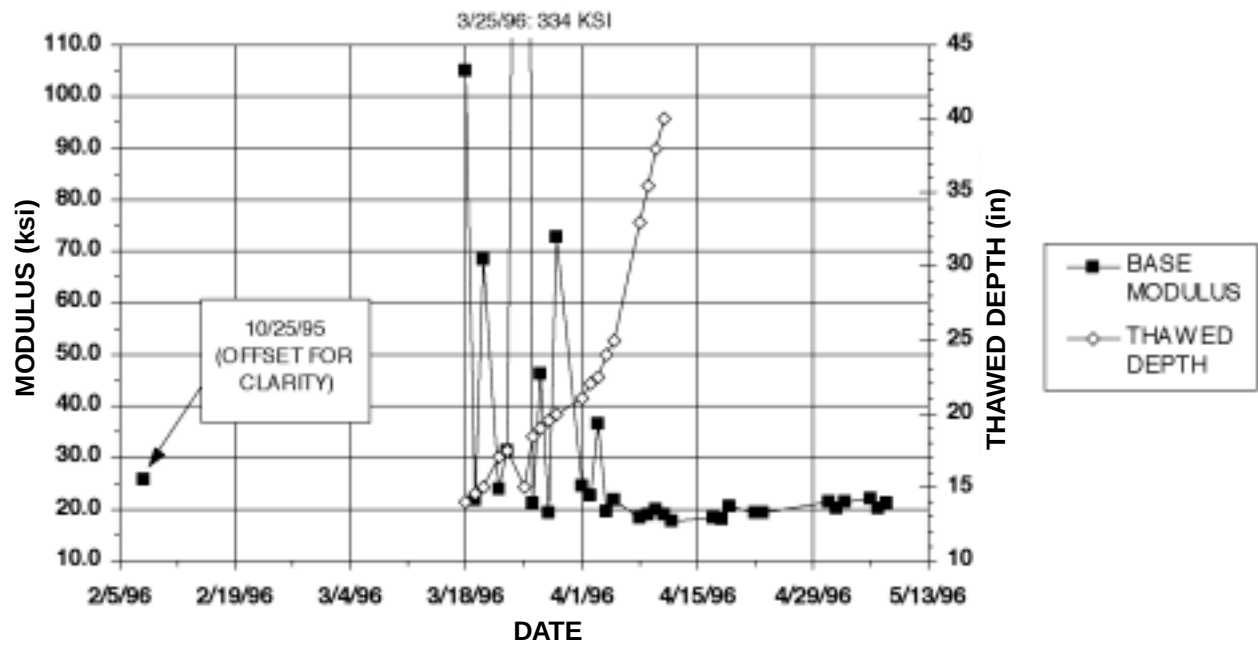
1. A generally single, relatively deep, frost occurred at these sites. The sites were continuously frozen from early December through early March. A single, brief period of frost occurred in early November, but thawed from the bottom up within a week. Another isolated period of refreezing of several inches below the asphalt occurred during the primary thaw in late March, but rethawed within a few days. Maximum frost depths below the asphalt were approximately 43 and 63 inches for sites 1 and 2, respectively. Initial freezing in early December occurred at a rate of approximately 2.0 to 2.5 inches per day.
2. Thawing predominantly occurred from the top downward, in contrast to the Ochoco sites where most thawing was from the bottom upward. Typical rates of thawing from the top downward were 1.0 to 2.5 inches per day while bottom upward rates were typically 0.2 to 0.5 inches per day. Over a period of 5 weeks, between early March and mid-April, 80 percent of total thawing occurred from the top downward.
3. Both TDR and RF devices worked well in monitoring seasonal changes in base and subgrade moisture contents. Both clearly show post-thaw increases in moisture contents above prefreeze conditions. The increased moisture contents may be a result of ice lens growth during freezing, surface water infiltration from



a) Lab vs. Backcalculated AC Moduli: Kootenai—Site 1

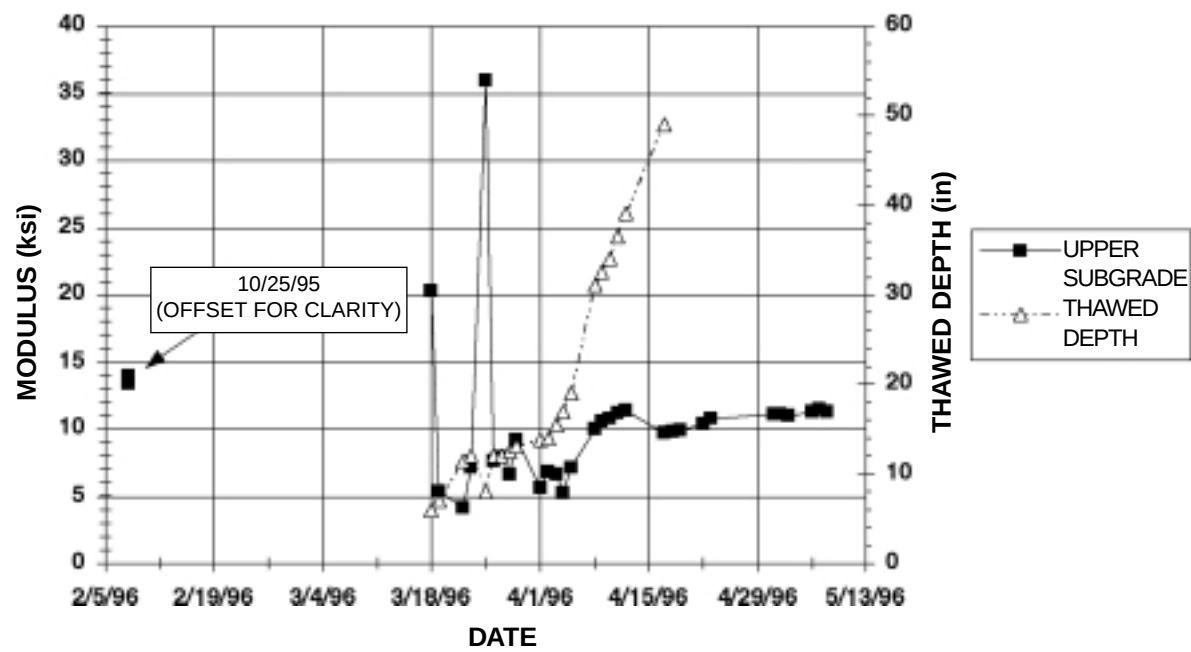
b) Lab vs. Backcalculated AC Moduli: Kootenai—Site 2

Figure 57—EVERCALC backcalculated AC moduli compared to laboratory core test values. Note that backcalculated values indicate less temperature sensitivity.



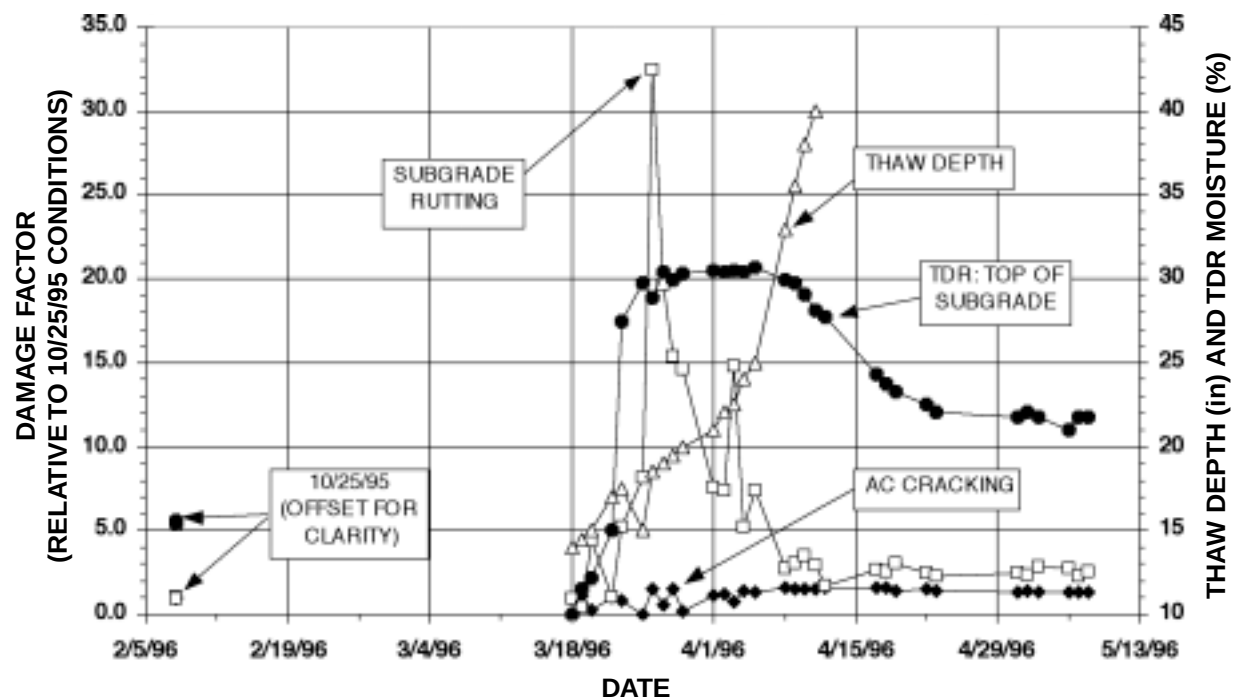
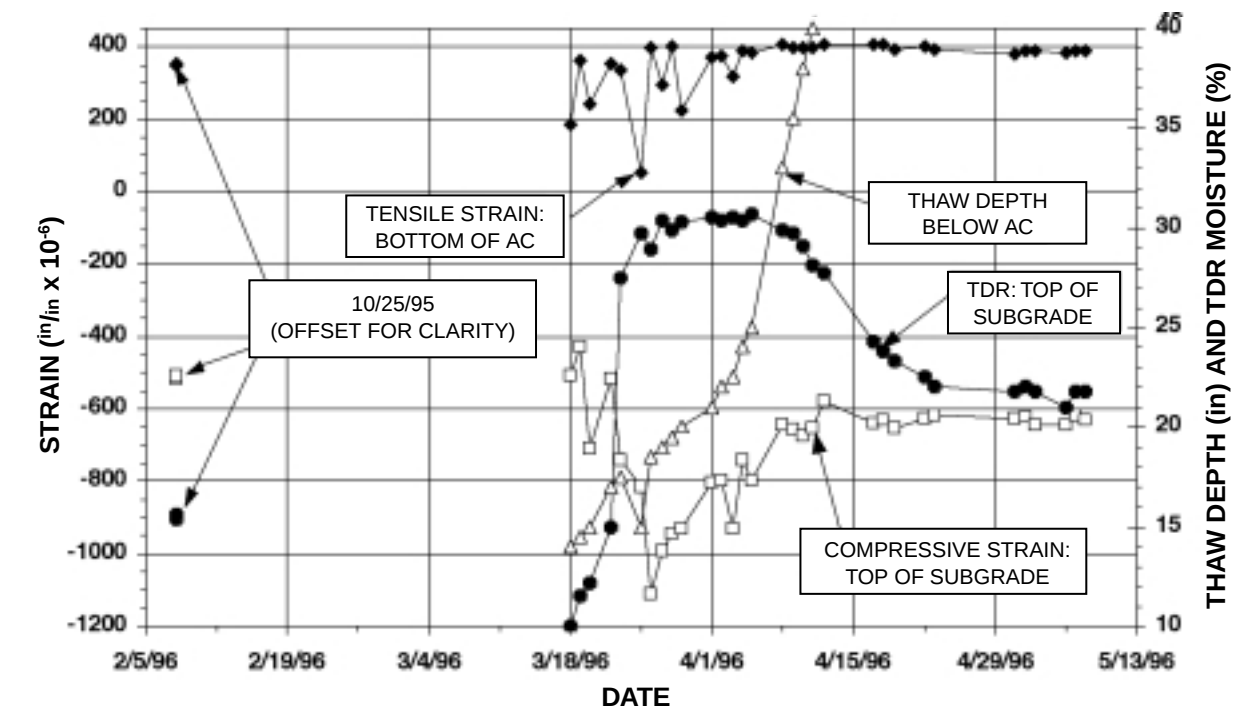
- Base Modulus vs. Thawed Depth Below Asphalt: Kootenai—Site 1
- Subgrade Modulus vs. thawed Depth Below Asphalt: Kootenai—Site 1

Figure 58—EVERCALC backcalculated base and subgrade moduli. Note that values stabilize as thawing concludes.



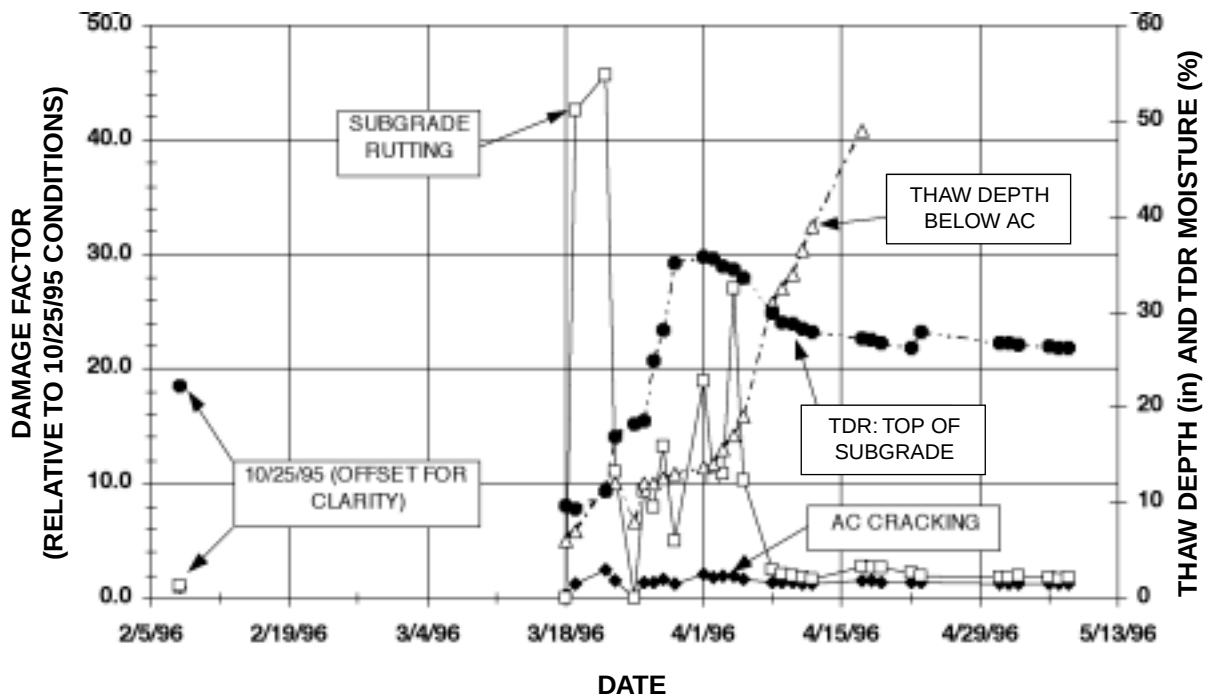
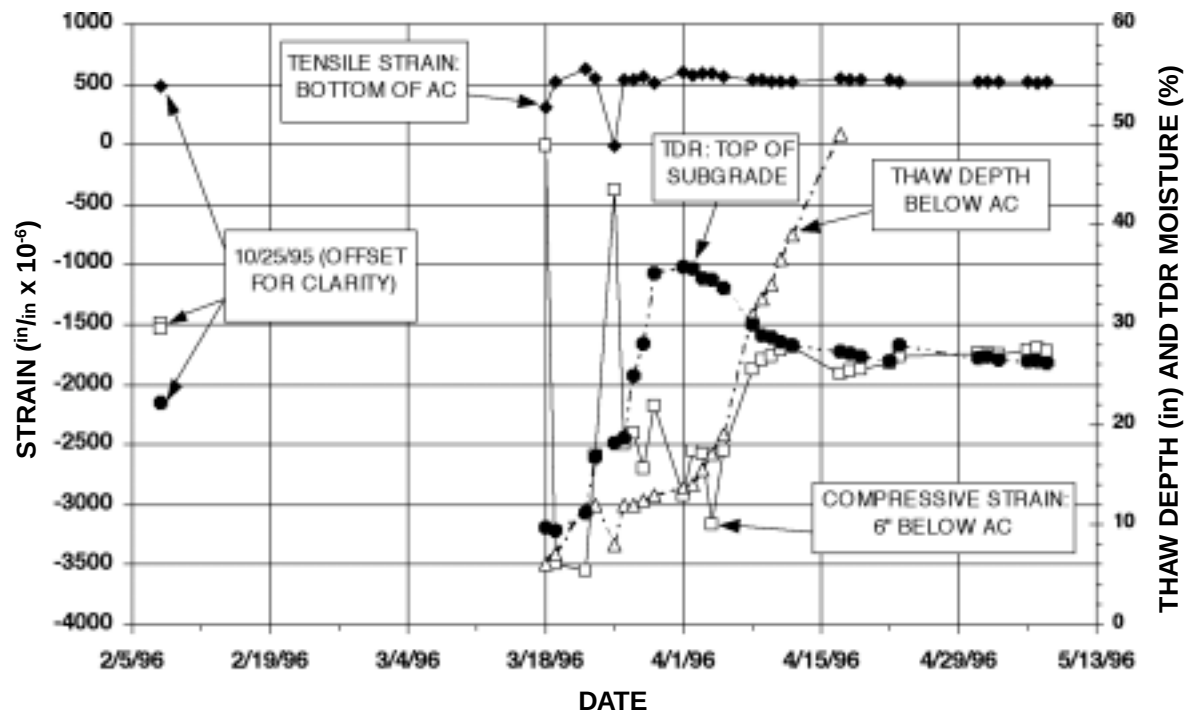
Upper Subgrade Modulus vs. Thawed Depth Below Asphalt: Kootenai—Site 2

Figure 59—EVERCALC backcalculated subgrade modulus. Note the value stabilizes as thawing concludes.



- a) Critical Strains [at 55F AC, Field Curve M(r)] vs. Thaw Depth and TDR Moisture: Kootenai—Site 1
- b) Damage Factors vs. Thaw Depth and TDR Moisture: Kootenai—Site 1

Figure 60—Comparison of changes in critical pavement strains, damage factors, selected TDR moistures and thaw depth.



a) Critical Strains [at 55F AC, Field Curve $M(r)$] vs. Thaw Depth and TDR Moisture: Kootenai—Site 2

b) Damage Factors vs. Thaw Depth and TDR Moisture: Kootenai—Site 2

Figure 61—Comparison of changes in critical pavement strains, damage factors, selected TDR moistures and thaw depth.

adjacent melting snow, or both. In any case, the vertically impeded drainage as a result of the frozen subgrades produced a distinctive, temporary peak in moisture contents that correlated with increases in critical strain levels and damage factors. The distinctive peak, and most of the increased moisture content above fall values, subsided within 1 week following complete thaw. Maximum damage factors of 32 and 45 for rutting and a factor of 2 for asphalt fatigue cracking were calculated for the two sites.

4. Results indicate that environmental monitoring with TDR (or RF) devices in combination with thermistors can provide a viable means of identifying periods of lowered pavement strength during thaw. This information would be helpful in determining the optimal timing and duration of load restrictions. For the soils present at these sites, the critical period of thaw weakening strongly coincided with the period of thawing as identified by the thermistor probes and the period prior to "drainage" as identified by the TDR and RF probes.
5. The relative seasonal moisture contents monitored at these sites provide useful information for estimating seasonal factors for use during mechanistic pavement design.

White Mountain National Forest Test Site

Location and Climate

The White Mountain National Forest project site was located on York Pond Road No. 13, an asphalt surfaced forest road in northern New Hampshire, approximately 10 miles north of Berlin, NH (figure 62). Historically, daily air temperatures, precipitation, and snow depths have been recorded at the New Hampshire State Fish Hatchery, an official weather monitoring site approximately 2 miles west of the project site at an elevation of 1,381 feet above mean sea level (MSL). Mean annual air temperature at the weather station is 42.8 °F, and the design air-freezing index, or average of the coldest 3 years of the last 30 years of record, is 1,848 °F days. The mean and design lengths of the freezing season are 127 and 148 days, respectively. The lowest minimum daily

temperature in January is -35 °F. Conditions are representative of much of the northern United States and of many northern national forests.



Figure 62—White Mountain National Forest site on December 15, 1994. The shed on the side of the road housed the data-logger equipment.

Site Description and Instrumentation Layout

York Pond Road is, for the most part, in extremely poor condition. It is a narrow, winding, asphalt concrete surfaced forest road that exhibits excessive differential frost heaving each spring. Differential heave as great as 8 inches over a horizontal distance of 5 feet is not uncommon. The original road foundation consisted of a sandy-silty subbase with a silty-sandy base course ranging from 0 to 2 feet in thickness. Past road repairs consisted of simply adding more material in localized areas. This repair method contributed toward an already highly variable gradation, moisture content, and subgrade strength.

The worst 1-1/2-mile-long section of York Pond Road was reconstructed through a contract awarded by the FS during the summer of 1994. Construction of three 50-foot long drainage test sections for a research project conducted by CRREL was included in this endeavor. In a cooperative agreement with the USFS, CRREL agreed to install, monitor, and analyze data from a TDR/RF test site located near the drainage test sections.

The two 100-foot USDA FS test sections (York Pond Road stations 34+50 to 35+50 and 32+00 to 33+00) lie immediately to either side of, and serve as control sections for the three drainage test sections. The two USDA FS test sections consist of a 2-inch-thick hot-mix asphalt concrete surface course, a 12-inch-thick layer of crushed aggregate, a 6-inch-thick layer of bank run gravel, and a 1- to 1.5-foot-thick layer of sandy-gravel base from the original road. The subgrade is sandy-silt. Initially, most measurements were recorded manually; however, data-logging systems were installed in the middle of the first winter of monitoring. The site instrumentation layout was similar to the Ochoco and Kootenai sites.

York Pond Road traffic is composed of logging trucks hauling from several timber sales, occasional construction traffic, water trucks associated with a state fish hatchery, a school bus, and automobile traffic. The volume of truck traffic depends primarily on the number of active timber sales and therefore varies from year to year.

Shading, aspect, and road grade are relatively consistent across each site. The primary test section from station 34+50 to 35+50 (fully instrumented and monitored) is generally exposed to the sun with shade cover only a short part of the day. The secondary site, from station 32+00 to 33+00 (in which pavement strength and temperature are monitored, but moisture is not) is primarily shade covered. Future reference to “the test section” refers only to the primary test section from station 34+50 to 35+50. The asphalt along this reconstructed portion of York Pond Road is in good condition, except for one transverse crack that occurred during the first year of monitoring. Groundwater monitoring wells were installed at each side of the test section.

This study reports FWD results collected during the winter and spring of 1997 through 1998. Although additional testing was performed during other years, this data represents the best FWD coverage obtained while moisture probes were operating properly.

Analysis and Results

Subsurface Temperature Regime

Figure 63 shows frost penetration through the later portion of the 1997/1998 winter-spring season. The 32 °F isotherm was determined by interpolating subsurface temperatures recorded by thermistors. Information, such as state of ground and corresponding depths, is necessary to redefine layer thickness of materials of similar moduli for backcalculation during frozen conditions. A period of partial thawing and refreezing, lasting approximately 9 days, occurred during early March.

Similar to the sites on the Kootenai National Forest, these sites experienced primarily top-down thawing in the spring with approximately 80 percent of thawing occurred in this manner. Initially, top-down thaw progressed at 3.5 inches per day through the coarse base/subbase materials. This rate decreased to 1.2 inches per day once the finer grained, wetter subgrade materials were encountered.

Subsurface Moisture Regime

Because TDR devices measure dielectric constant, which is directly proportional to unfrozen water content, freezing and thawing the pavement can also be shown by TDR readings over time. Figure 64 shows the TDR measured moisture contents at the test site. TDR probes at depths of 9.2 and 15.2 inches beneath the pavement surface show relatively low, constant unfrozen water content between early December and early March. On March 9, these probes recorded a spike in moisture content which coincides with a period of partial thaw as measured by the thermistor string (figure 63). The period of partial thaw ended on March 13 with both the thermistors and TDR probes indicating that fully frozen conditions had returned. Thawing began again on March 25 with the TDR probes showing a rapid increase in measured moisture contents peaking during the first week in April. Moisture contents then declined rapidly on April 15, at which point the rate of decrease substantially slows. This transition from a rapid to slower decrease in moisture contents occurs at roughly the same time as the thawing of the last of the ground ice (figure 63). The process of

thawing of the entire pavement structure from the surface downward is shown by the progression of TDR curve peaks.

Although RF probes worked well at other USDA FS test sites, RF probes at this particular site did not function properly, consequently RF moisture content graphs are unavailable. It was noted by CRREL that problems with the RF probes have been experienced at a variety of non-USDA FS monitoring sites. They have observed that probes are typically functional when read manually; however, the failure rate is high when used with an automated data acquisition system. Because the electronics are located in the sensor head and the sensors are then buried, evaluation/assessment of the problem would entail excavation and removal of nonfunctional probes. In contrast to the RF probes, TDR probes used for these monitoring sites contained minimal electronics in the sensor head.

The groundwater table at the test site is shown in figure 65. No significant fluctuations were observed during the spring of 1998. Depth to the water table is typically used to define a stiff layer for backcalculation. Water depth shown in the figure corresponds to depth below the top of the open observation wells to either side of the road, not the pavement surface.

Area Parameter

As with the other test site locations, a normalized area parameter was calculated as an index of pavement stiffness.

For the Berlin data, averages of deflections at each drop height were used. An increase in area parameter followed by a general leveling off is shown in figure 66. The values stabilized during early April when thaw depths were approaching 3 feet and TDR moisture contents were rapidly declining.

Pavement Layer Moduli

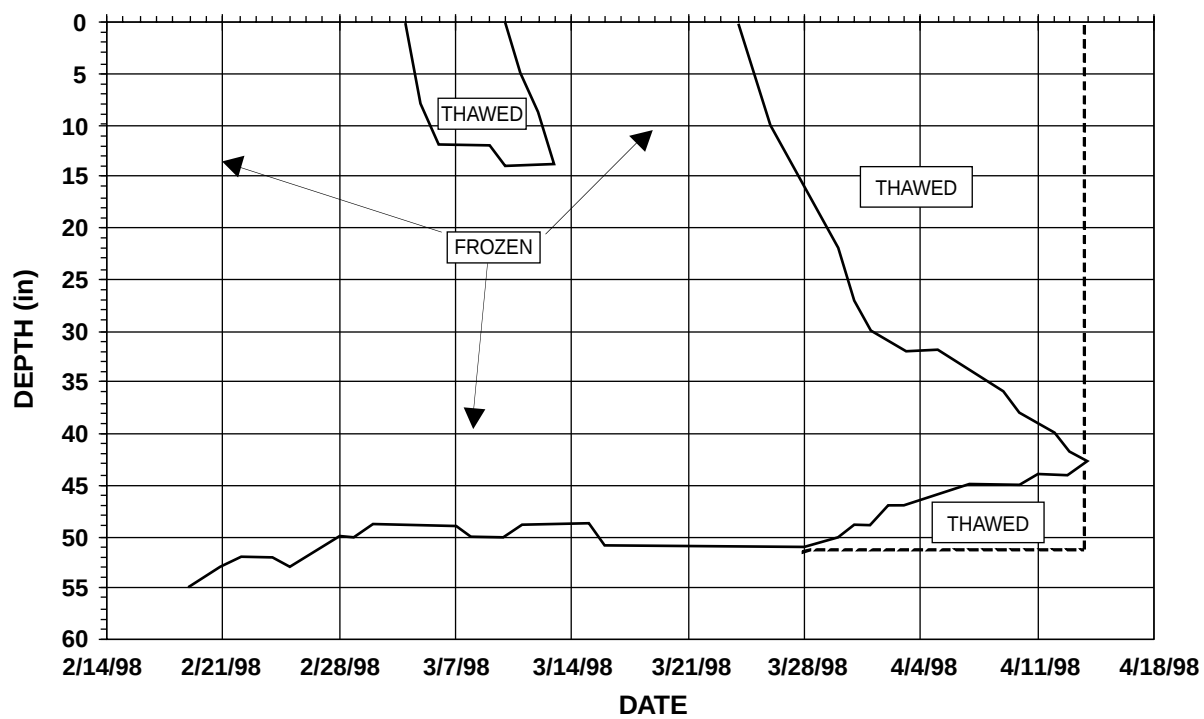
Pavement layer moduli were backcalculated throughout the spring season using the EVERCALC program. Backcalculated base course and subgrade modulus values are shown through the

spring season in figure 67. Note the marked decrease in modulus of the base course as thaw progresses followed by a gradual recovery. In contrast, the subgrade modulus does not show a similar trend in the time during which monitoring took place. The lack of a sudden drop and recovery of the subgrade modulus is unusual since most roads monitored during past research projects have shown a particularly low modulus for a short time during spring thaw. It may be that the subgrade underwent only minor changes in moisture content, as shown by the 36-inch TDR probe in figure 64, resulting in similarly minor changes in subgrade modulus. It is also possible this could be attributed to backcalculation procedure (spring thaw) weaknesses previously mentioned.

Figure 68 shows a comparison of the backcalculated AC modulus on the FWD test dates verses a standard WSDOT B mix. The resulting curves are similar to the backcalculated curve indicating a somewhat stiffer (i.e., less temperature sensitive) mix than the WSDOT B mix.

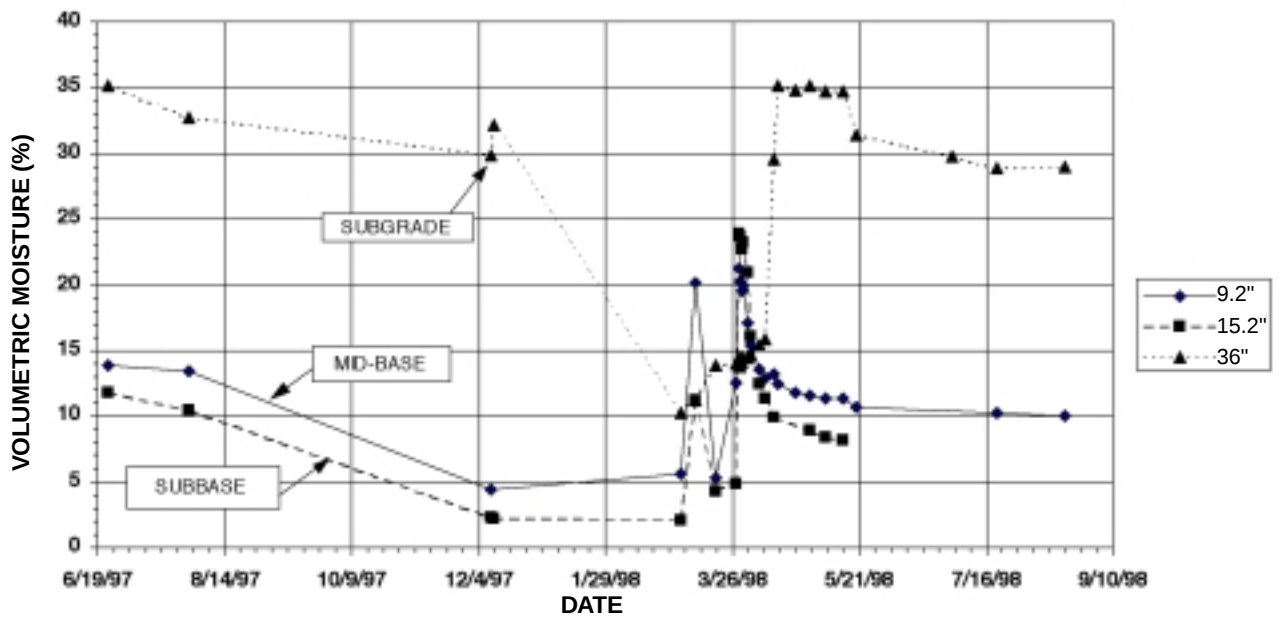
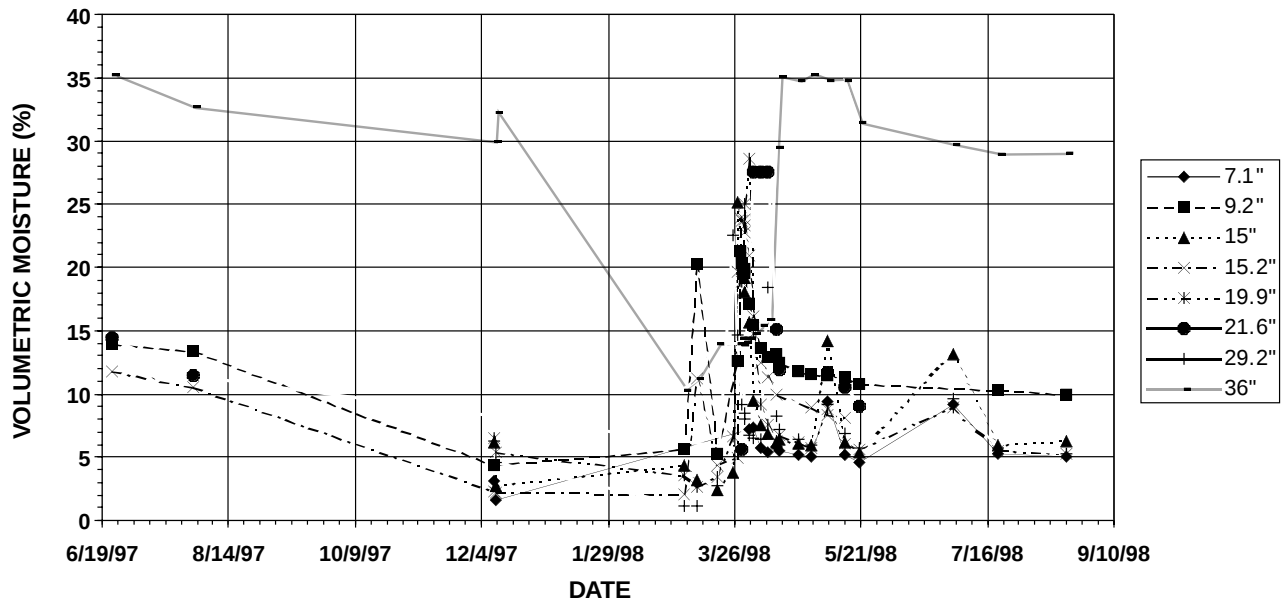
Critical Strains and Associated Damage

Strains at the critical locations were determined using EVERSTRESS. Figure 69 shows a generally increasing horizontal tensile strain at the bottom of the asphalt concrete that somewhat levels out, comparable to strains determined at site 1 on the Kootenai. Vertical compressive strain shows the same trend (with compression and tension simply opposite in sign). Strain peaks somewhat later in the top of the subgrade compared with in the base, as would be expected, as thaw progresses from the surface downward and excess moisture dissipates. Both tensile and compressive strains stabilize at approximately the same time as all ground ice thaws and the rapid decrease in TDR moisture transitions to a more moderate rate of decline.



Frost Profile: White Mountain National Forest Site

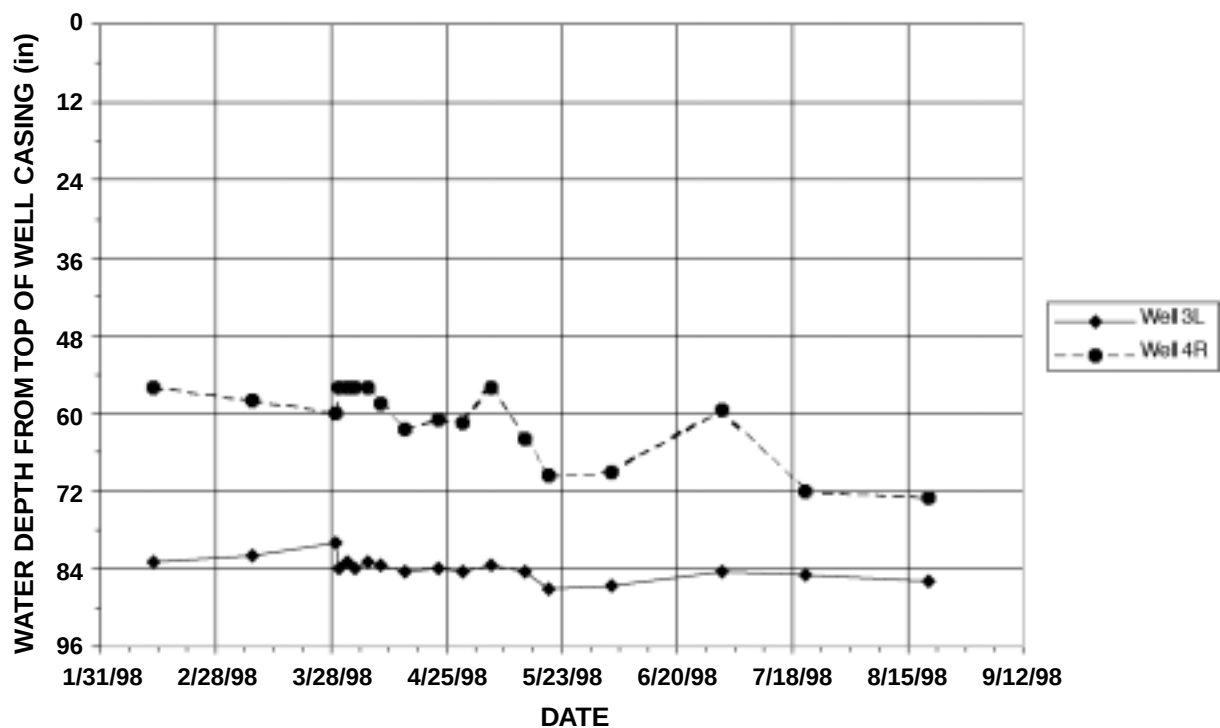
Figure 63—Partial season frost profile. Note that thawing occurred predominately from the top down with a significant partial thaw during early March.



a) TDR Volumetric Moistures: White Mountain National Forest Site

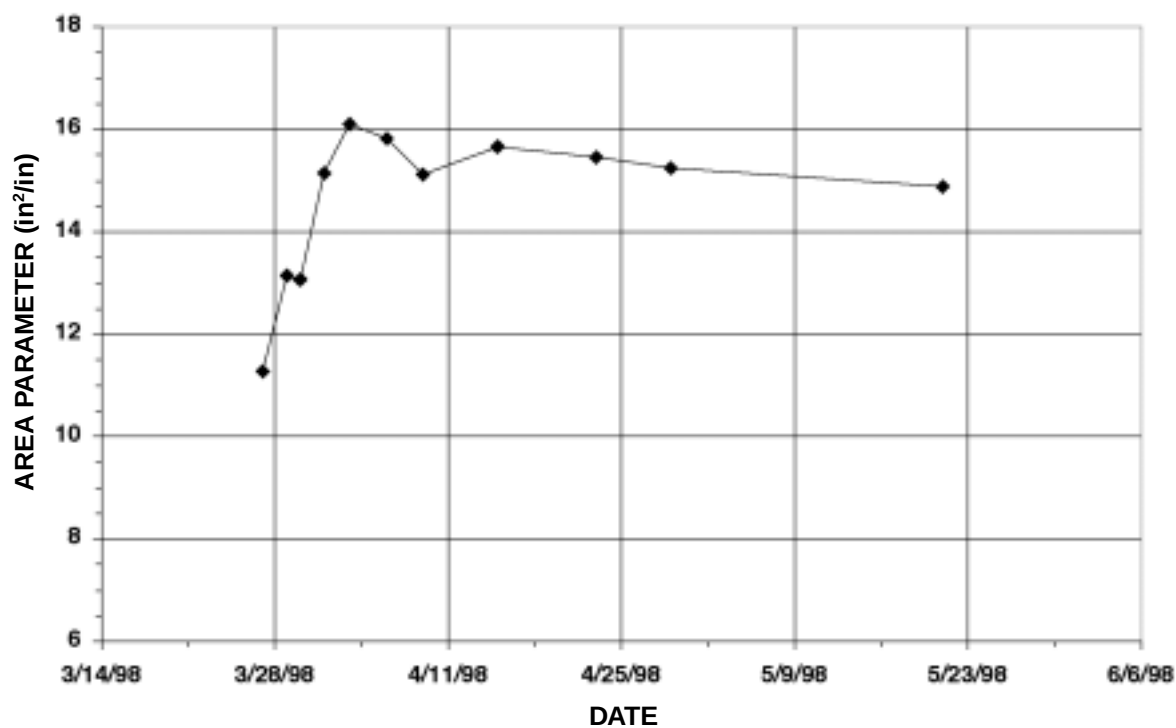
b) Selected TDR Volumetric Moistures: White Mountain National Forest Site

Figure 64—TDR measured moisture contents. Note the drop in values as freezing occurs. The sharp spike on March 9, 1998 at 9.2 and 15.2 inches coincides with period of partial thaw. Peaks during spring thaw are similar to Kootenai sites.



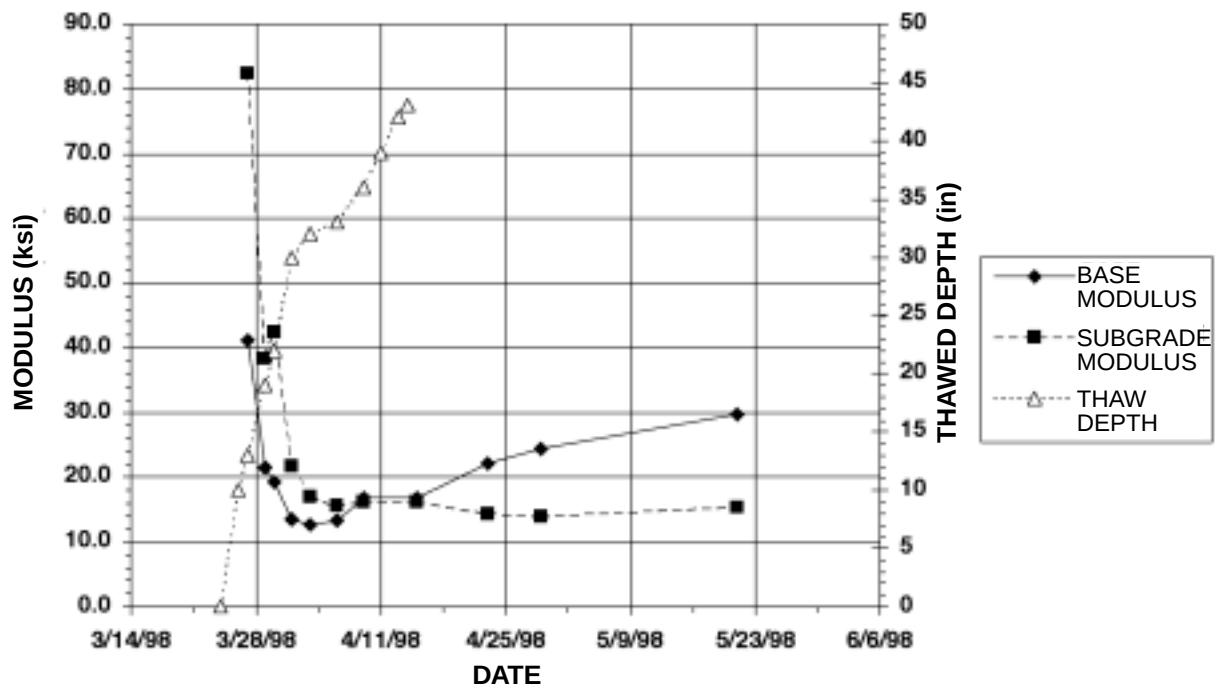
Groundwater Depth: White Mountain Site

Figure 65—White Mountain test site seasonal groundwater depths.



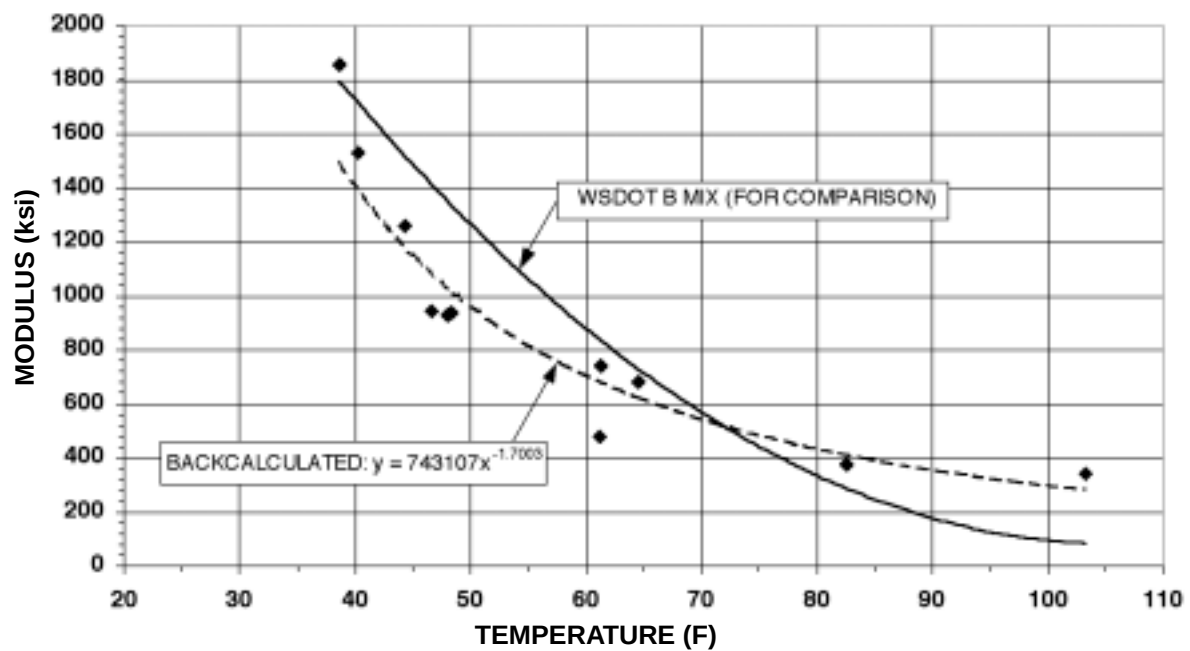
Area Parameter: White Mountain National Forest Site

Figure 66—Seasonal change in area parameter. Note the stabilization of values as thawing concludes.



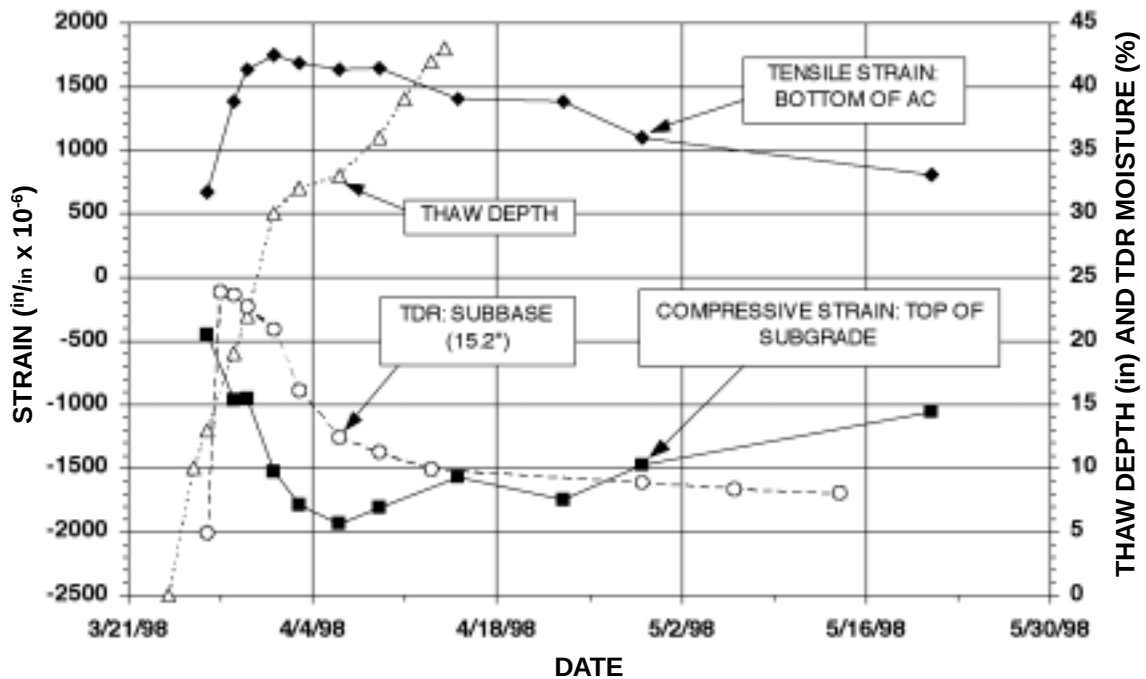
Modulus vs. Thawed Depth: White Mountain Site

Figure 67—EVERCALC backcalculated base and subgrade moduli compared to thaw depth.



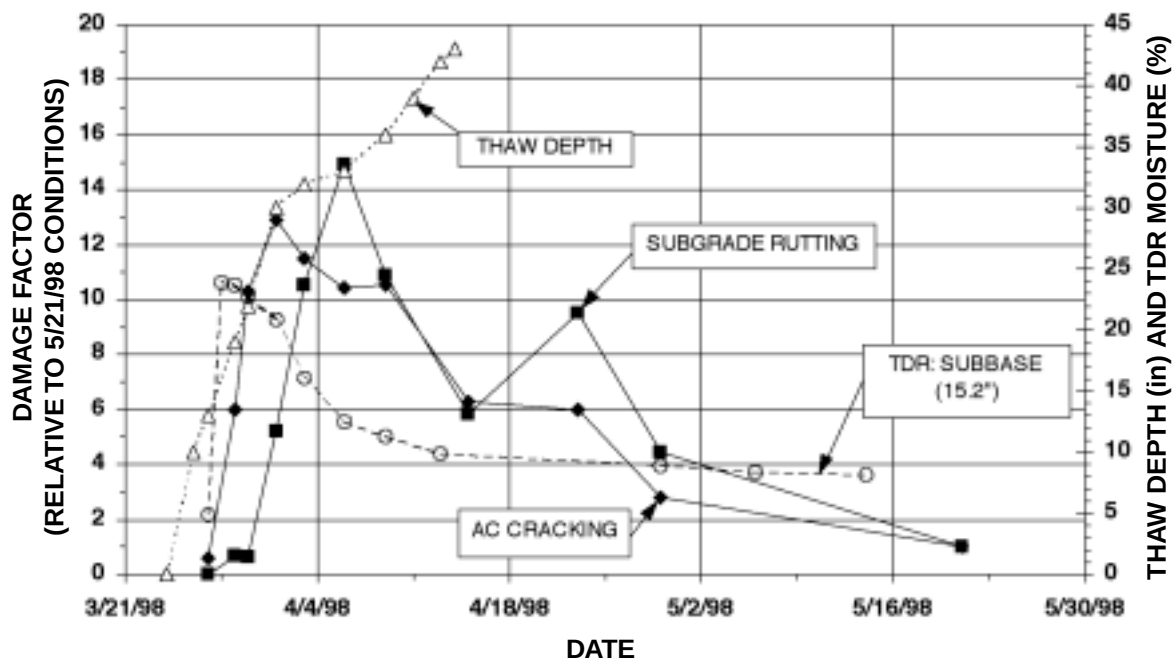
Backcalculated AC Moduli: White Mountain National Forest Site

Figure 68—EVERCALC backcalculated asphalt moduli compared to WSDOT B mix.



Critical Strains (at 55F AC) vs. Thaw Depth and TDR Moisture: white Mountain National Forest Site

Figure 69—Seasonal change in EVERSTRESS determined critical pavement strains compared to TDR moisture (at 15.2 inches) and thaw depth.



Damage Factors vs. Thaw Depth and TDR Moisture: White Mountain National Forest Site

Figure 70—Seasonal change in damage factors compared to TDR moisture (at 15.2 inches) and thaw depth.

Damage Factors as Related to Environmental and Structural Parameters

Figure 70 ties together environmental and structural parameters. As with the other study sites, damage factors (defined as the ratio of the number of loads to reach failure under normal summertime conditions to the number of loads to reach failure under freeze-thaw conditions) were determined for cracking (function of horizontal tensile strain at the bottom of the asphalt) and rutting (as a function of vertical compressive strain at the top of the subgrade). The figure shows damage in relation to thaw depth and moisture content as measured by the TDR at 15.2 inches (subbase). As believed to be the case, but to be evaluated in this study, the highest potential for damage occurs during early April when trapped moisture within the pavement structure is at its peak. This also coincides with subgrade modulus being at its lowest as shown in figure 67.

Conclusions from the White Mountain National Forest Site

1. For this site, moisture content appears to be a good indicator of when load restrictions could be removed; after the moisture has dissipated, damage potential dramatically decreases. However, the authors' recommendations would be to wait a given length of time (1 week) after water content had dropped before allowing traffic to resume. The recovery of base course modulus and the decrease in corresponding damage is a gradual process, not a marked change as with the onset of thaw.
2. Another recommendation is to install multiple TDRs at depths deemed to be critical (near the bottom of the subbase and within the top of the subgrade in this instance).
3. Because of reliability problems experienced with the RF probes at this and other non-USDA FS sites, CRREL would currently recommend TDRs for this and other similar moisture monitoring applications.
4. The observation that moisture content provides a good indicator of when to resume hauling is similar to preliminary conclusions reached when the study was approached slightly differently

without using backcalculation (Kestler et al. 1999). Soil moisture was found to correlate well to deflection basin area (defined slightly differently than in this report), which itself can be correlated to modulus according to the U.S. Army Corps of Engineer's design procedure for pavements in seasonal frost areas (Bigl and Berg 1996).

Overall Summary and Conclusions

To minimize road damage during spring thaw, the USDA FS needs an affordable, reliable, quantitative method for determining when to suspend and commence hauling heavy loads. Using temperatures measured by thermistors has proven to work well for determining when to suspend hauling. This study focused on how to determine when hauling can be resumed.

TDR and RF moisture sensors underwent laboratory testing with several soils at known moisture contents to validate internal moisture correlations, as well as cyclic freeze-thaw testing to examine probe durability. Sensors proved to be durable, accurate, and repeatable under standard and adverse weather conditions. TDR and RF moisture sensors, as well as thermistors probes and groundwater monitoring wells, were installed at seven test sites on four national forests. Seasonal changes in subgrade and base moisture contents, subsurface temperatures, groundwater levels, and pavement stiffness were monitored for approximately 1 year at all test sites. Correlations between these various parameters were observed and reported.

To maximize pavement life and minimize maintenance costs, traffic can be restricted or prohibited during critical periods when high intensity damage tends to occur and be allowed to resume once damage susceptibility is reduced. By using sensors, monitoring a damage-related parameter can provide information that can be used to control this re-establishment of traffic. Therefore, environmental and structural variations during which the major portion of damage actually occurs were evaluated in this study. Because strain is traffic induced, it is not a viable parameter that can be measured. While modulus is independent

of traffic and is a good indicator of when traffic should be allowed, it is tedious to calculate and requires an FWD, which is a costly piece of equipment and none are currently owned by the FS. However, based on the observations discussed, it appears that monitoring subsurface soil moisture using TDR probes can provide an efficient, alternative method for determining when damage susceptibility is reduced and heavy loads can be resumed. Only minimal damage occurs once excess moisture has dissipated. The reduced moisture contents needed to minimize damage will vary according to soil type. However, it was found in this study that the exact moisture content values are unimportant for this particular application, rather, it is the distinctive shape of the moisture recovery curve observed which can be useful.

Principal Overall Conclusions of the Study

1. Both the TDR and RF technologies provided reasonably accurate and reliable volumetric moisture contents under laboratory-controlled conditions with a variety of soil types. This was true for testing under both room temperature and freezing-thawing conditions. The RF probes tended to be slightly more accurate compared with gravimetric determined values. This result is possibly due to the RF's three internal soil moisture correlation curves versus the single curve used by the TDR unit. Laboratory testing showed the TDR and RF probes to be a durable, reliable, and repeatable method for measuring unfrozen water content in soils subject to freeze-thaw cycling. TDR and RF probes can be used to determine frozen versus thawed conditions.
2. The TDR devices proved to be more rugged and reliable than the RF devices during field operations. Changing RF cable connector ends due to continual oxidation of the original aluminum contacts was necessary early in the field tests. Repeated problems were also encountered with the Vitel RF probe reader units which had a tendency to indicate probe failures. Opening the unit and removing a battery, thus "rebooting" the device, would often correct the problem. Because of these and other difficulties, feedback from field operators responsible for collecting data indicated a preference for the TDR units. All RF probes located at the White Mountain National Forest site failed early in the field test portion of the study for unknown reasons.
3. As expected, freezing conditions were most severe at the Kootenai and White Mountain National Forest sites. Maximum frost depths of 4 to 5 feet were observed at these sites. Freezing generally consisted of a single, massive, continuous event with "spring thaw" beginning in mid- to late March. Thawing extended over a period of 3 to 4 weeks, with 80 percent occurred from the top downward.
4. TDR monitored volumetric moistures at the Kootenai and White Mountain National Forest sites responded similarly during thaw. Initially, a dramatic increase in moisture contents to values well above those immediately preceding freezing were observed. These were followed by a similarly rapid peaking and decrease in moisture followed by a much less extreme decline through the spring and summer. This relatively sharp transition of the moisture response curve from a rapid "drainage" phase to a slower "drying" phase was found to roughly coincide with the thawing of all ground ice. Recovery and stabilization of area parameters, moduli, critical strains, and damage factors were also found to coincide with the end of the "drainage" period as indicated by the TDRs.
5. In contrast to Kootenai and White Mountain National Forest sites, the Ochoco test sites exhibited several episodes of relatively mild freezing and thawing. Maximum frost depths ranged from 14 to 18 inches below the asphalt surface. Also contrasting with the more severe sites, approximately 80 percent of the thaw occurred from the bottom upward, thus drainage was less impeded during most thawing events.
6. TDR data obtained from the Ochoco National Forest sites indicate moisture peaks associated with thawing are neither as extreme nor as lengthy as those observed at the Kootenai and White Mountain National Forest sites. However, subdued peaks on selected sensors located within or just below the frost zone were observed. These results suggest the Ochoco

site would experience a similar moisture response curve as that observed on the Kootenai and White Mountain sites if a more severe winter than that of 1994/1995 occurred.

7. Seasonal variations in area parameter, moduli, critical strains, and damage factors were less at the Ochoco National Forest sites than observed at the Kootenai and White Mountain National Forest sites. The less severe effects at the Ochoco National Forest sites was likely the result of less frost penetration into the subgrade, as well as the predominately bottom-upward thawing observed. More severe effects would be expected during a colder winter than the one observed during this study.
8. Though significantly less in severity, damage factors at the Ochoco National Forest sites experienced an extended period of recovery compared to the Kootenai National Forest sites. The finer grained, plastic subgrade soils at the Ochoco National Forest sites appear to extend the period of weakening well beyond the thawing of all ground ice.
9. In contrast to all other study sites, the Willamette National Forest test sites did not experience measurable freezing. Only relatively gradual, long-term (annual) variations in site properties were observed. The variations coincided with the annual wet/dry cycle experienced at the location.
10. The use of field installed TDR (or improved RF) probes and thermistor strings for road management purposes appears best suited for relatively severe winter climates which undergo deep, persistent freezing. Based on the results of this study, the timing and duration of the marked weakening occurring in these climates, due to thawing, can be monitored through the use of these technologies. Less severe freeze-thaw climates, such as those found in the Ochoco National Forest, may also benefit from the use of these technologies, particularly during more severe winters. Little or no benefit is seen from the use of these technologies in wet/dry climates, such as those observed on the Willamette National Forest test site. Such wet/dry climates offer no relatively short-term period of susceptibility to high intensity road damage.

Thus, designing for use that includes the wetter periods appears, in most cases, to be a more appropriate strategy.

11. Though not analyzed in detail for this study, data collected that details the timing, duration, and magnitude of moisture variations in subgrade and base materials provide useful examples of typical values to assist in determining seasonal factors for mechanistic pavement design.

In summary, it is believed that by using thermistors to quantitatively determine the start and progression of thaw and provide data on frost depth, and by using soil moisture sensors to quantitatively determine recovery from a thaw-weakened condition, the optimal balance between reducing road damage and maximizing road use can be achieved. Monitoring these environmental parameters will provide information useful in scheduling both the beginning and the end of load restriction periods.

Future Plans and Recommendations

An implementation guide based on experiences from this study is funded and scheduled for publication in 2001. The guide will provide equipment descriptions, installation guidelines, current costs, and data interpretation guidance based on results from this study.

It is believed that results from this study will aid in the development of guidelines for reopening roads to hauling after the spring thaw, based upon soil moisture dissipation. However, additional monitoring and expansion of the database to validate and develop more comprehensive guidelines for different soil types and environments is highly recommended. Data collected during this study may also be useful for validating various computer models used to predict ground temperatures and moisture contents.

In addition, future studies correlating TDR measured moisture changes with daily precipitation, groundwater fluctuations, and percent subgrade saturation would be of interest.

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