Determining Frost Depth in Pavement Systems  
Using a Multi-Segment Time Domain Reflectometry Probe  
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ABSTRACT  
Determining frost depth below the pavement is important for timely implementation of winter and spring load limits. Unfortunately, existing instruments such as resistivity probes, frost tubes and moisture blocks are limited both in terms of data acquisition (automated and continuous measurements) and data interpretation. Consequently a delay between data collection, interpretation, and dissemination of information occurs. A laboratory study was conducted by the Minnesota Department of Transportation investigating the use of the Moisture Point probe as an instrument for locating the depth to the freezing front. The Moisture Point probe combines Time Domain Reflectometry with remote diode switching to provide a profile of the aggregate base and subgrade dielectric properties. From this the frost depth can be estimated. The Moisture Point probe works well in locating the frost depth and improves the ability to successfully implement spring and winter load limits. This method also provides the opportunity to validate air temperature-based models currently used to determine when to begin spring and winter load limits. Integrating the Moisture Point probe into the R/WIS communication architecture could significantly improve pavement life in Minnesota by providing additional critical data in a timely and convenient format.
INTRODUCTION

In cold regions freeze-thaw cycling, and spring-thaw weakening contribute to loss of load bearing capacity and subsequent pavement failure. Determining frost depth below the pavement becomes important for timely implementation of winter and spring load limits. Unfortunately, instruments currently being used to measure frost depth (resistivity probes, frost tubes, and moisture blocks) are limited in terms of ease of data collection and analysis methods. As a result a delay in the collection and dissemination of information, critical for determining pavement conditions, occurs. The Minnesota Department of Transportation (Mn/DOT) is conducting research on the use of Time Domain Reflectometry (TDR) for determining frost depth in aggregate base and subgrade materials.

The use of TDR for measuring soil volumetric moisture content is well documented (1,2). TDR has also been used in a wide variety of geotechnical applications (3). Recent pavement research indicates that TDR methodologies are successful when used for determining base and subgrade moisture conditions (4,5,6,7). TDR methods allow detection of liquid water content in soils because the dielectric constant of liquid water is much higher than that of other bulk soil constituents.

TDR technology has also been examined for use in frozen soils (8,9) for determining the frozen-unfrozen interface and the liquid water content of the frozen soil. Baker et al, (8) determined that the dielectric constant could be used to distinguish between frozen and unfrozen soil water. The dielectric constant of ice is less than that of liquid water, 3 and 80 respectively. Therefore, the change in dielectric constant due to ice formation results in an electrical discontinuity that can be easily detected in the TDR waveform. This provides the means for distinguishing between frozen and unfrozen soil (10,11,12). According to Hayhoe et al (13) the liquid water content based methods, under thawing conditions, are less limited in their range of application than temperature-based methods for determining frost depth.

The objectives of this study are to 1) evaluate a multi-segment TDR probe for improved frost depth measurements below the pavement and 2) implement field testing at designated Road and Weather Information System (R/WIS) sites around Minnesota. This paper presents the results from a laboratory study in which frost depth is measured using a multi-segment TDR probe and describes the field implementation.

BACKGROUND

Methods currently used to estimate frost penetration are limited in a variety of ways. Table 1 provides a summary of current methods for measuring frost depth within the pavement structure. Frost tubes (plastic fluorescein dye tubes) undergo a color change as a result of freezing. Frost tubes readings are taken manually, can be subjective, and often result in slow dissemination of critical information (14). Resistivity probes utilize the resistance change between frozen and unfrozen soil to determine the depth of frost penetration. Data analysis can be subjective and may require the use of thermocouple data in conjunction with probe data to determine frost depth. Data is usually collected manually, but in some cases has been automated. Recently moisture blocks, another type of electrical resistance sensor, have been used to estimate frost depth below pavements. Data from the moisture block sensors is analyzed by monitoring the measured resistance in the soil as it increases above normal summer values when the water freezes. This is typically an order of magnitude larger. Since this analysis is somewhat subjective, thermocouples are usually installed next to the moisture block so that temperature data can be used to
verify frozen conditions. To date the results are inconclusive, with additional concern as to the long-term stability of the gypsum core. (14).

<table>
<thead>
<tr>
<th></th>
<th>Frost Tube</th>
<th>Resistivity Probe</th>
<th>Moisture Block</th>
<th>Thermocouple</th>
<th>TDR Probe</th>
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<tbody>
<tr>
<td>Data Collection</td>
<td>Manual</td>
<td>Primarily Manual</td>
<td>Automated</td>
<td>Automated</td>
<td>Automated</td>
</tr>
<tr>
<td>Data Interpretation</td>
<td>Subjective</td>
<td>Subjective, requiring temperature data.</td>
<td>Subjective, requiring temperature data.</td>
<td>No accounting for freezing point depression</td>
<td>Potential for developing algorithm for automated analysis.</td>
</tr>
<tr>
<td>Installation</td>
<td>Labor intensive. Soil disturbance is extensive.</td>
<td>Labor intensive. Soil disturbance is extensive.</td>
<td>Labor intensive. Soil disturbance is extensive.</td>
<td>Not labor intensive. Minimal disturbance to soil.</td>
<td></td>
</tr>
</tbody>
</table>

Table 1: Comparison of methods currently used for measuring frost depth within pavement system.

Time Domain Reflectometry (TDR) Method

*Environmental Sensors Inc.* (ESI) manufactures the TDR Moisture Point (MP) probe. The MP probe is a multi-segment TDR probe with switching diodes between TDR segments. When installed vertically, the MP probe provides a segmented profile of the soil dielectric properties and therefore, the frost depth. The electronic switching diodes allow separation of vertically oriented waveguides by causing a short at the segment boundaries. As an electromagnetic pulse is fed into the center of the probe, remote diode shorting causes an amplification of the reflections at the start and end of each segment. The MP system measures the propagation time, or rather the time it takes the electromagnetic pulse to travel twice the length (round trip) of the segment. \( T_1 \) is the time at which the measurement system sends the pulse, \( T_2 \) is the time the reflected signal returns to the measurement system. The propagation time of the signal as it travels the length of each probe segment is then, \( T_2 - T_1 \) or \( \Delta t \). Using the \( \Delta t \), the dielectric (\( K_a \)) of the soil medium can be calculated from the following equation.

\[
K_a = \left( \frac{\Delta t \cdot c}{2L} \right)^2 \tag{1}
\]

Where \( c \) is the speed of light, 30 (cm/nsec), and \( L \) is the length (cm) of the segment.

The MP probe construction and use of remote shorting diodes makes this instrument attractive for measuring the downward movement of frost as it penetrates the aggregate base and subgrade below the pavement.

Road and Weather Information System (R/WIS)

R/WIS is an extension of the 1987 Strategic Highway Research Program (SHRP). It is one of many products resulting from that research. Mn/DOT, among other states, is a participant in the Aurora Program (15). The Aurora Consortium initiatives emphasize technological advancement and improved Road and Weather Information Systems in order to more effectively deal with winter road conditions. While the primary focus of the initiatives have been on winter maintenance operations, Mn/DOT is attempting to evaluate and extend the use of R/WIS technology to spring and winter load studies. The focus of R/WIS is the efficient and effective integration and dissemination of road and weather information across the state of Minnesota. The R/WIS system is comprised of a network of weather stations that monitor road and weather conditions and subsequently feed data back to a central database.
for dissemination to the maintenance personnel at the state and local level. A primary goal of R/WIS implementation in Minnesota is the development of a system that is able to accommodate various types of instruments. In particular, a portion of the project is dedicated to testing the system’s communication architecture. Studies conducted by Mn/DOT's Road Research Section investigating new methods for determining frost depth, as well as looking for improved data transfer protocols, were well suited for testing the R/WIS communication protocol. Mn/DOT pavement research in combination with the R/WIS initiatives allows us to meet the needs for initial testing of the R/WIS communication system in addition to field testing of various instruments for measuring frost depth within pavement structures.

LABORATORY CALIBRATION

Base Material
The aggregate base selected for this study was a Class 5 Special (Cl. 5 Sp.) (Table 1). This aggregate is the most commonly used base material on low volume and load restricted roads in Minnesota. Target moisture content and dry density for this material were 8.5% and 21.0 kN/m$^3$, respectively.

<table>
<thead>
<tr>
<th>Sieve #</th>
<th>Opening Size (mm)</th>
<th>Actual Percent Passing</th>
<th>Class 5 Special Specification</th>
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<tr>
<td>1</td>
<td>25.4</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>3/4</td>
<td>18.85</td>
<td>96.1</td>
<td>90-100</td>
</tr>
<tr>
<td>3/8</td>
<td>9.50</td>
<td>75.6</td>
<td>70-85</td>
</tr>
<tr>
<td>4</td>
<td>4.70</td>
<td>59.6</td>
<td>55-70</td>
</tr>
<tr>
<td>10</td>
<td>2.00</td>
<td>43.1</td>
<td>35-55</td>
</tr>
<tr>
<td>20</td>
<td>0.850</td>
<td>26.1</td>
<td>------</td>
</tr>
<tr>
<td>40</td>
<td>0.425</td>
<td>13.6</td>
<td>15-30</td>
</tr>
<tr>
<td>60</td>
<td>0.250</td>
<td>6.66</td>
<td>------</td>
</tr>
<tr>
<td>140</td>
<td>0.107</td>
<td>2.60</td>
<td>------</td>
</tr>
<tr>
<td>200</td>
<td>0.075</td>
<td>1.92</td>
<td>5-10</td>
</tr>
</tbody>
</table>

Table 2: Class 5 Special Gradation.

MP Probe
The multi-segment MP probe used in this study was a four-segment Type K probe (Fig. 1). Each segment is 15 cm in length. The probe is constructed of two stainless steel rails separated by an epoxy and high-density plastic material. The boundaries of the segments are defined by switching diodes, at the start and end of each segment. A personal computer was used to automatically collect probe scans every 3 hours. The output collected during the probe scan included the raw waveforms and the travel time for each of the four segments. The travel time was used to calculate the $K_a$ during the freezing and thawing cycle.
Figure 1: Pictured is the Type K Moisture Point probe. The Moisture Point probe is a multi-segment TDR probe with four segments each 15 cm in length. TC = Thermocouple locations in reference to the TDR segments.

Test Setup
A polyvinyl chloride (PVC) pipe, 15 cm diameter x 91 cm long, was used to construct a soil column in which the MP probe was installed. A heater core was constructed of a 15 cm diameter x 7.6 cm long PVC pipe. Inside the 15 cm diameter outer ring were concentric inner rings of smaller diameter PVC pipe. A heating tape, more commonly used to keep water pipes from

Figure 2: PVC heater core with heating tape and thermocouples. Temperature measurements were taken by a Campbell Scientific Inc. CR10 datalogger
freezing, was wound in between the PVC rings. Two copper-constantan thermocouples were inserted into the core (Fig 2), and the core was filled with Quickcrete. The heater core provided a base for the soil column as well as a means for maintaining a temperature gradient through the soil column. A metal pipe clamp attached the soil column to the heater core and silicon caulk prevented moisture from escaping through the joint. Soil was packed in 5 cm lifts, first packing 5 cm of Cl. 5 Sp. at the bottom of the column before installing the MP probe and thermocouples. Thermocouples were installed at 5 cm from the top of the heater core, and then at intervals such that two thermocouples were associated with each of the four segments. One thermocouple located at the beginning of the segment and the other at the end of the segment. After the sensors were installed and the soil was packed into the column, a cardboard sleeve 30 cm diameter x 107 cm long was placed around the outside of the soil column and heater core. Unfaced fiberglass R13 insulation was cut into 18 cm lengths, folded in half and packed between the cardboard sleeve and PVC column (Fig. 3). Moist paper towels and plastic covered the top of the column to eliminate evaporation from the surface. The set-up was left undisturbed for three days to achieve moisture equilibrium, after which the column was placed in a walk-in freezer. During the freezing cycle insulation was removed one layer at a time to both induce frost penetration from the upper surface and to induce step-wise freezing.

RESULTS AND DISCUSSION

Laboratory

When water freezes a significant decrease in the dielectric of the bulk soil occurs resulting in an abrupt decrease in the propagation time and thus a dramatic decrease in the Ka at or below 0 °C. Assuming little or no freezing temperature depression is occurring. Figures 4 and 5 show the change in the Ka for TDR segments 1 (0-15 cm) and 3 (30-45 cm), during a freeze-thaw cycle. In this study there was a measured decrease in the Ka near 0 °C, although the decrease in the Ka of segment 1 was less dramatic than that of segment 3. This is attributable to the rate at which the soil freezes. Segment 1 went through step-wise freezing, whereas segment 3 went through rapid freezing. This suggests that the rate at which
the soil freezes will affect how easily the change in the Ka can be detected. Likewise, the step-wise freezing reduced the maximum change in the Ka around 0 °C. This needs to be considered if an algorithm for automated frost depth measurements is developed.

**Figure 4:** Temperature and Ka vs Time for TDR segment 1 (0-15cm). The Soil_T is the average temperature of the two thermocouples located at the top and bottom of the segment. Segment 1 went through a step-wise freezing cycle. Periodically a layer of insulation was removed and the temperature was allowed to stabilize. This can be seen between day 98 and 114. A rapid thaw gives a more distinct change in the Ka.

An additional factor to consider is the initial Ka at which the soil begins to freeze. The Ka is a function of the water content and therefore the maximum change in Ka during the phase change depends on the initial water content. If the water content is high, there will be a relatively large decrease in the Ka as the phase change occurs. This is due simply to the initial volume of water available to go through the phase change. If the initial water content is low then the Ka will also be low. As the soil freezes the change in Ka in a low water content soil will be much less than in a soil near saturation. Therefore, initial water contents in the soil will affect the ability to detect the change from liquid to ice. The resolution of the Type K MP probe is limited to the length of each probe segment, in this case 15 cm, because the MP measurement is an integrated value over the length of the segment. This was verified by positioning thermocouples near the top and bottom of each segment (Figure 1). The abrupt decrease in the Ka is only apparent when the temperature of the bottom thermocouple indicates frozen conditions, i.e. the soil along the entire segment is frozen (Fig. 6). For example, on day 117 the thermocouple at the top of the TDR segment drops below 0 °C. The Ka gradually decreases for the next several days, indicating that the freezing front is moving.
Figure 5: Temperature and Ka vs Time for TDR segment 3 (30-45cm). The Soil_T is the average temperature of the two thermocouples located at the top and bottom of the segment. Segment 3 went through a rapid freeze-thaw cycle on day 165 and day 181 respectively.

down the first segment. On day 126 there is a dramatic decrease in Ka coinciding with the bottom thermocouple dropping below 0 °C. In addition to the TDR and thermocouple measurements the soil was mechanically probed, by drilling into the column with an electric drill, to determine the frost depth. This verified the estimated depth based on the TDR and thermocouple measurements.

Figure 6: A change in the Ka is evident only after Soil_T (13cm) has dropped below 0 °C. Freezing may be occurring in the upper part of the segment, although it is difficult to detect.
Studies conducted by Davis (8) suggest that analysis of the raw waveform may be a better way of detecting the freezing front; rather than using the Ka calculated from propagation time. However, this would require feeding the signal into the top of the probe. A top fed signal would travel the entire length of the probe and the remote switching diodes would provide inflections at known points along that length. This method would possibly provide a means of monitoring the freezing front as it migrates along the length of each segment. This approach is relatively straightforward if manual observation and interpretation of the waveform is used. However, for real-time and continuous monitoring automated interpretation of the waveform is desirable.

Field Testing at Remote Sites

Five remote sites (Figure 7) were selected for testing field measurements of the frost depth below the pavement. Two of the sites were R/WIS sites (Effe and Jacobson). Two of the remote sites were "stand alone" solar powered sites (Marshall and Rochester) (16). And one site was located at Mn/Road.

Road and Weather Information System (R/WIS) sites

Field installations consisted of coring the pavement (Figure 8a) approximately 18 inches from the shoulder. Cable connections at the probe were waterproofed with epoxy filled shrink tubing. A slide hammer and pilot rod were used to drive a pilot hole through the base and subgrade layers. The slide hammer was then used to drive the MP probe into the same pilot hole, stopping when the top of the probe was level with the bottom of the pavement layer (Figure 8b). Cables were directed through saw cuts in the surface of the pavement to a PVC conduit located at the shoulder. Backer rod was placed in the saw cut to prevent abrasions and/or breaks in cables. Epoxy was used to fill the saw cuts, cold patch was used to replace pavement core. MP communication cables were run through the conduit to the R/WIS remote processing unit (RPU) installed adjacent to the roadway. Housed in the RPU is the MP-017, intended for integration into environmental monitoring systems. Data is collected from the MP probe every 10 minutes, and loaded to an internet ftp site on a daily basis. Mn/DOT automatically downloads the data from the ftp site and into an existing database.
Figure 8a and b: A drill press was used to core the pavement. The MP probe installation with wires directed towards PVC conduit via kerf cut.

CONCLUSIONS

The multi-segment TDR probe shows promise as an instrument for measuring the frost depth within pavement systems. Measured changes in the dielectric of the aggregate material, during a freeze-thaw cycle gave a good indication of the frost depth. Rapid freezing and thawing, as well as high initial moisture content, produce a distinct and measurable change in the dielectric. Whereas, slow rates of freezing and low initial water contents can make data interpretation difficult. These factors should be considered as automated interpretation techniques are developed. The benefits of integrating the MP probe into the R/WIS system architecture, in conjunction with successful field implementation hold promise that could be realized statewide. By accurately determining the frost depth and effectively disseminating the information to maintenance personnel and decision makers we can reduce the damage to the pavement structure due to increased winter loads and spring-thaw weakening. By reducing the damage during these critical periods we stand to significantly reduce maintenance costs.
References

12. Roberson, R. L. and Siekmeier, J., 2000, Using a Multisegment Time Domain Reflectometry Probe to
System Hardware

A Toshiba Satellite laptop computer controlled the measurement system. PC Procomm Rapid Remote allowed communication with the home base via a modem. This allowed the user to download the data or change any of the sensor parameters. Frost measurements were taken by running a Procomm script file supplied by FSI. The power for the computer and probe would come from two deep cycle marine batteries. The batteries would be continually charged during the daylight hours by solar panels. The computer and a set of electronic boards, MP-017 (Figure 1.), which require a constant 12 volts, controlled the probe. A regulator was used to ensure the 12 volt constant voltage.

Design

The design of a remote monitoring system powered by solar power begins with the measurement of its power requirements. To measure the power requirements a regulated DC power source was needed. The voltage was set at 12 volts and the current was monitored to determine the power requirements of the system. Next the pieces of the system were measured individually to determine their power requirements and hopefully find a way to reduce them. It was found that the largest current draw by an order of magnitude was the computer, specifically the LED screen. To reduce the current draw to the computer the display settings were set such that the screen would turn off after one minute of inactivity. During screen shutoff the system operates normally. This proved to lower the power requirement of the computer by roughly 40%.

Next the system was setup just as if it were operating in the field except the power would be supplied by the DC power source in order to measure the total current requirement of the system. The voltage was set at 12 volts and the current of the system was measured. The measurements were taken during the different activities of the system such as during measurements, during modem calls, and during inactivity. This proved to give the necessary information needed to determine the solar panel size and battery amp-hour life. The power information gathered was sent to Innovative Power Systems and shown in Table 1.
Innovative Power Systems (IPS) is a Minneapolis based company specializing in power supply with photovoltaics. IPS took the power requirement numbers to design a system that would operate continually throughout the winter months in Minnesota. The design was based on 3 hours of daylight at least once every three days. These numbers were determined from a software package at IPS for determining solar panel performance and battery life. The design included two 80-watt PV panels and two maintenance-free, sealed, valve regulated lead acid (VRLA) batteries to ensure adequate power regeneration through the winter months. The minimum state of charge of the batteries should not be less than 70% of the maximum charge based on IPS’s calculations. These calculations are shown in the Appendix.

<table>
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<th>Amps</th>
<th>Hrs / Day</th>
<th>Amp-Hrs</th>
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<td>Computer / Electronics</td>
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19.47

Figure 2. Trenching for Electronic Cables.

Figure 3. Probe Installation with Trench cut into the Pavement
After the trench was cut into the pavement, a rod was slide hammered into the area where the probe would be installed (Figure 4). The rod was the same shape and size as the probe ensuring the probe could be easily installed into the same hole using the slide hammer (Figure 3).

![Figure 4. Creating a Hole for the Probe using a Rod and Slide Hammer](image)

After the probe was almost completely driven into the hole the electronic cables were attached to the probe as shown in Figure 3. The probe was then driven until the top of the probe was level with the bottom of the pavement. The cables were run out through the trench to the enclosure. The trench and hole were filled in with soil and/or cold patch to ensure no damage would occur from traffic. The electronics and computer were installed in an enclosure and connected to the electronic boards that are power by the two batteries. The enclosure with the completed wiring is shown in Figure 5.

![Boards, or](image)

The system takes measurements once every three hours. The data is stored on the computer until it is downloaded to the lab with the modem and a program called Rapid Remote.
ACKNOWLEDGEMENTS
The authors would like to acknowledge the following for their contribution to the study. The Local Road Research Board, The Office of Materials and Road Research Concrete Lab, Machine Shop, and Chad Millner.
Figure 1 Five State-wide Moisture Point probe installations. Two are installed and monitored by the R/WIS RPU.