Determining Frost Depth in Pavement Systems Using a Mult-Segment Time Domain Reflectometry Probe

TRB Session: Effects of Moisture and Temperature on Pavement Systems

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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 that are currently used to set spring and winter load limits.

Keywords: frozen soil, frost, dielectric, diode, time domain reflectometry, TDR

INTRODUCTION

In cold regions freeze-thaw cycling, and springtime 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 has been well documented (1,2). As well, TDR has 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). According to Hayhoe *et al* (12) 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 evaluate a TDR probe that has the potential to improve frost depth measurements below the pavement. And to subsequently use the TDR frost depth measurements to validate the air temperature degree-day based model currently used to predict frost depth in regions where winter and spring load limits are used.

This paper presents the results from a laboratory study in which frost depth is measured using a multi-segment TDR probe.

BACKGROUND

Current Methods

Methods currently used to estimate frost penetration are limited in a variety of ways. 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 (13).

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, constructed of gypsum, have been used to estimate frost depth below pavements. To date the results are inconclusive, and there is concern that the gypsum in the block will deteriorate with time; thus making them unattractive for long-term use (14). Independent temperature data is also useful and may be required during data interpretation.

Time Domain Reflectometry Method

Environmental Sensors Inc. 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_1 - T_2 or Δt. Using the Δt, the dielectric (Ka) of the soil medium can be calculated from the following equation.

{ EMBED Equation.3 } { EMBED Equation.3 }

[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.

LABORATORY CALIBRATION

Base Material

The base aggregate 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 the state of Minnesota. Target moisture content and dry density for this material were 8.5% and 21.0 kN/m^3, respectively.

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 (Fig. 1). 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 freezing, was wound in between the PVC rings. Two copper-constantan thermocouples were inserted into the core (Fig 2a), and the core was filled with *Quickcrete* (Fig. 2b). 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.

The 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 (Fig. 3a). 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. 3b). 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.

MP Probe

The multi-segment MP probe used in this study was a four-segment *Type K* probe (Fig. 4). 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 Ka during the freezing and thawing cycle.

RESULTS and DISCUSSION

When water freezes a significant decrease in the dielectric of the bulk soil occurs resulting in an abrupt decrease in the propagation time measured by the MP probe. From previous studies we would expect to see a dramatic decrease in the Ka at or below 0 °C, assuming little or no freezing temperature depression.

Figures 5 and 6 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.

Another 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 phase change from liquid to ice.

Secondary is the question of frost depth resolution that can be measured by the MP probe. The resolution 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 (Fig. 4). 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. 7). 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 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.

Studies conducted by Davis (8) suggest that analysis of the raw waveform may be a better way of detecting the freezing front; rather than calculating the Ka from the 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 locating the depth of the freezing front to the nearest centimeter. This approach is relatively straight forward if manual observation and interpretation of the waveform is used. However, automated interpretation of the waveform and determining inflection points would require developing specialized software.

CONCLUSIONS

The MP 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 MP probe is an instrument that has potential for providing both field estimation of frost depth, and as a means for validating air temperature-based models currently used to determine the timing of winter and spring load limits. Field installation and performance evaluations of several MP probes are planned for the fall, winter, and spring 1999-2000.

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LIST OF FIGURES

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

Table 1 Class 5 Special Gradation.

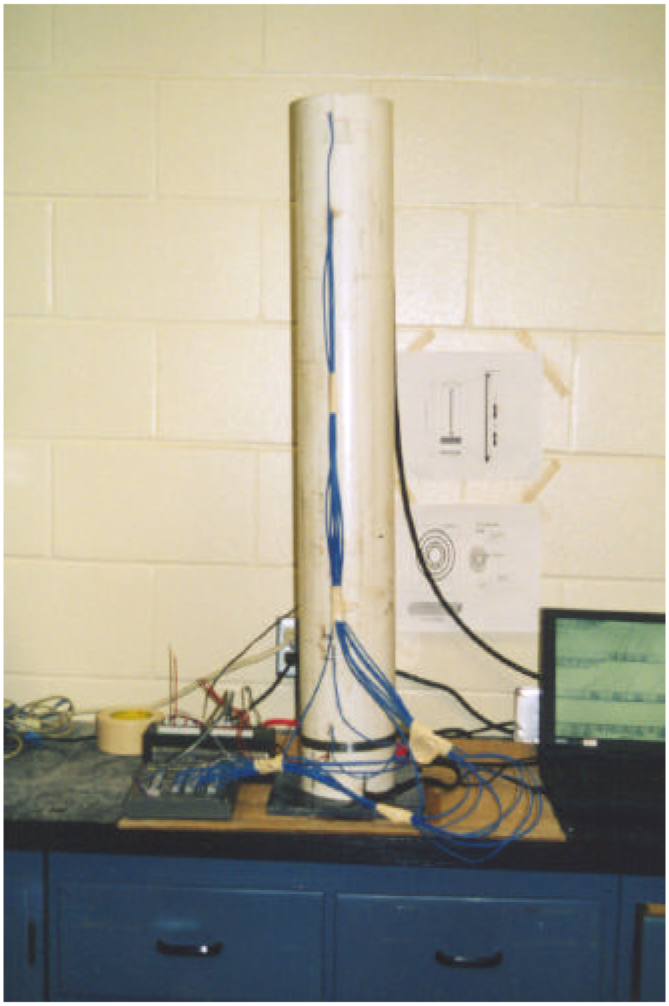
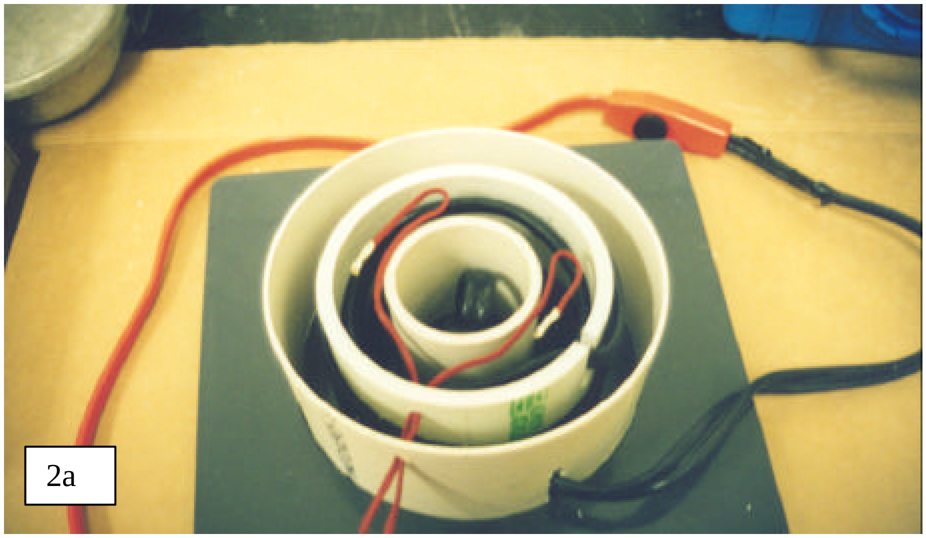


Figure. 1 Soil Column with Multi-Segment TDR probe and thermocouples installed.



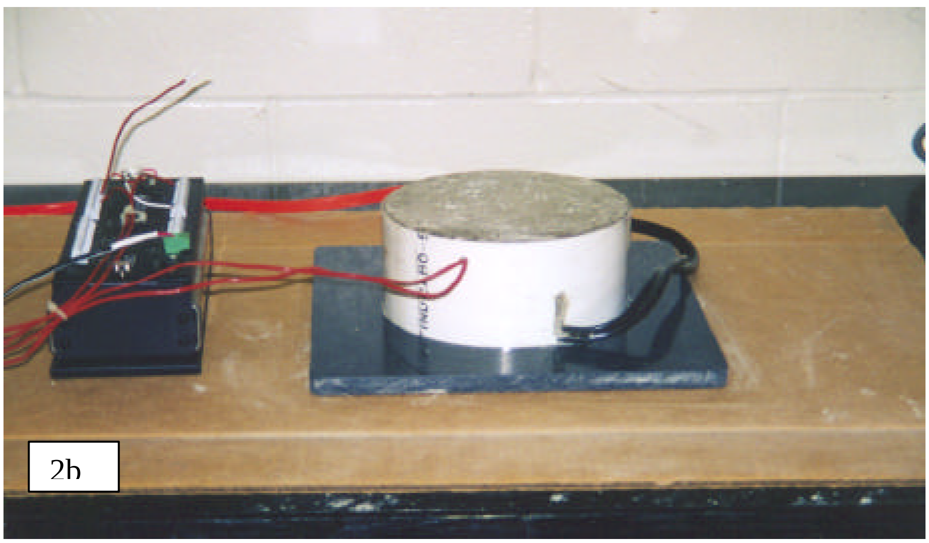


Figure 2 (a) PVC heater core with heating tape and thermocouples. Temperature measurements were taken by a Campbell Scientific Inc. CR10 datalogger. (b) Heater core filled with *Quickcrete* and CR10 datalogger.

Figure 3 (a) Moisture Point probe and thermocouple installation. Two thermocouples were installed along the length of each segment. (b) R13 fiberglass insulation was packed between the soil column and the cardboard form. The insulation was used to confine the freezing to the surface of the soil column.

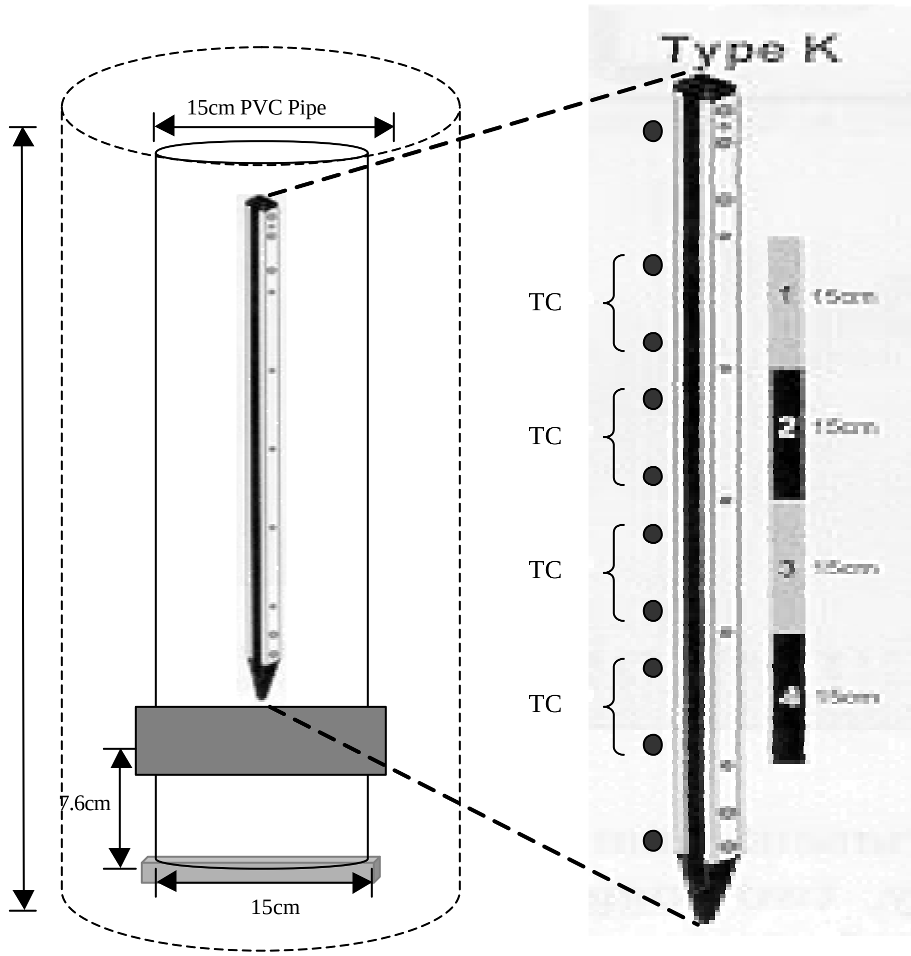


Figure. 4 Pictured is the Type K Moisture Point probe. The Moisture Point probe is a multi-segment TDR probe with four segments each 15 cm in length. TC = Thermocouple locations in reference to the TDR segments.

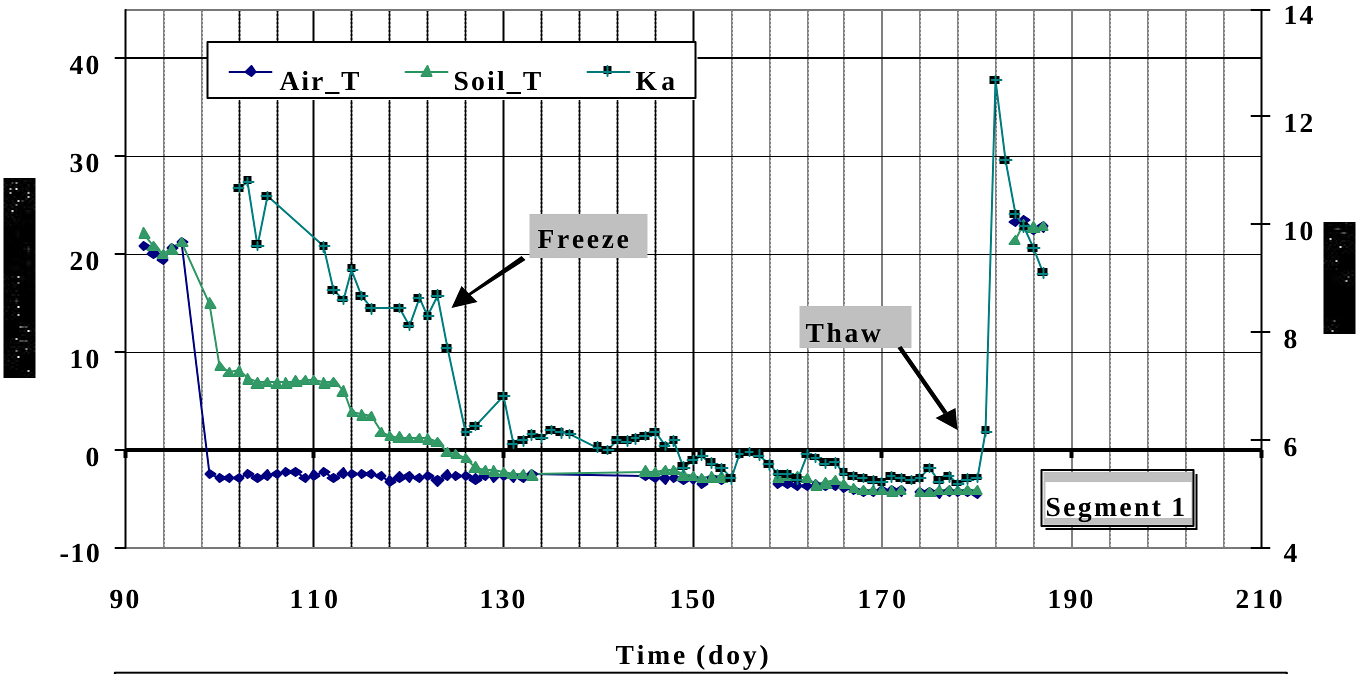


Figure 5 Temperature and Ka vs Time for TDR segment 1 (0-15cm). The Soil_T is the average temperature of the two thermocouples located at the top and bottom of the segment. Segment 1 went through a step-wise freezing cycle. Periodically a layer of insulation was removed and the temperature was allowed to stablize. This can be seen between day 98 and 114. A rapid thaw gives a more distinct change in the Ka.

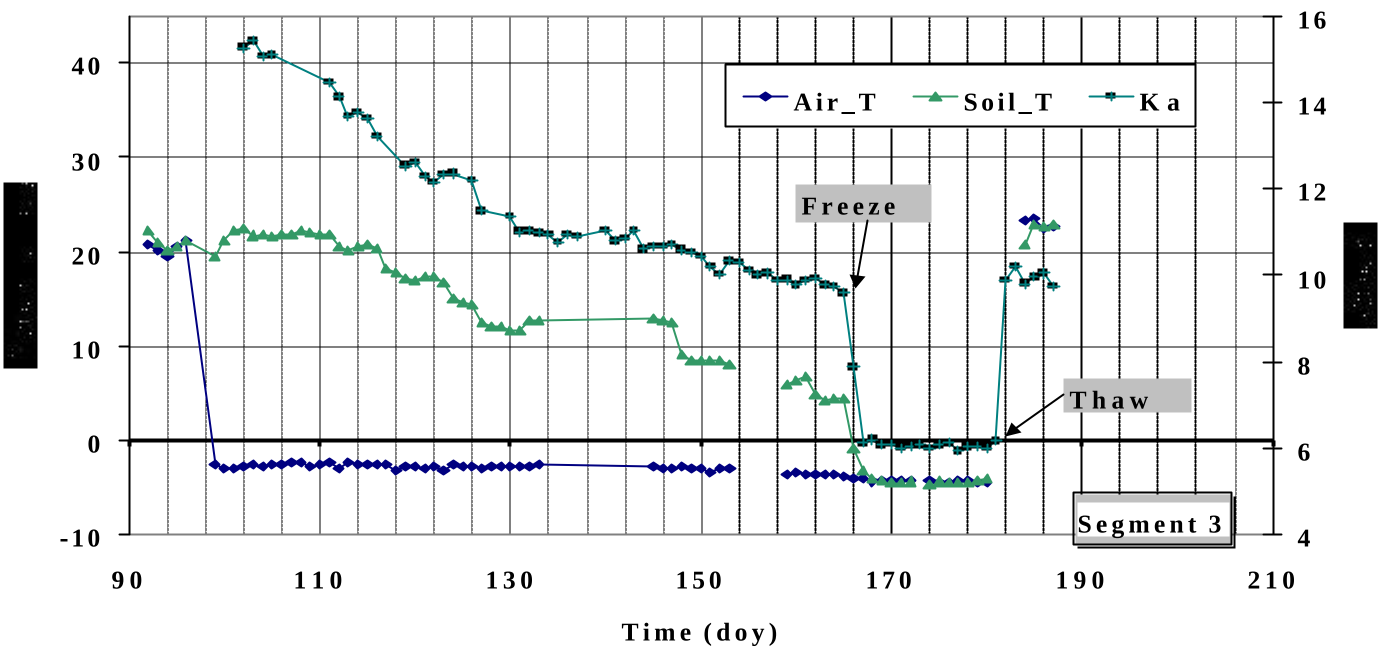


Figure 6 Temperature and Ka vs Time for TDR segment 3 (30-45cm). The Soil_T is the average temperature of the two thermocouples located at the top and bottom of the segment. Segment 3 went through a rapid freeze-thaw cycle on day 165 and day 181 respectively.

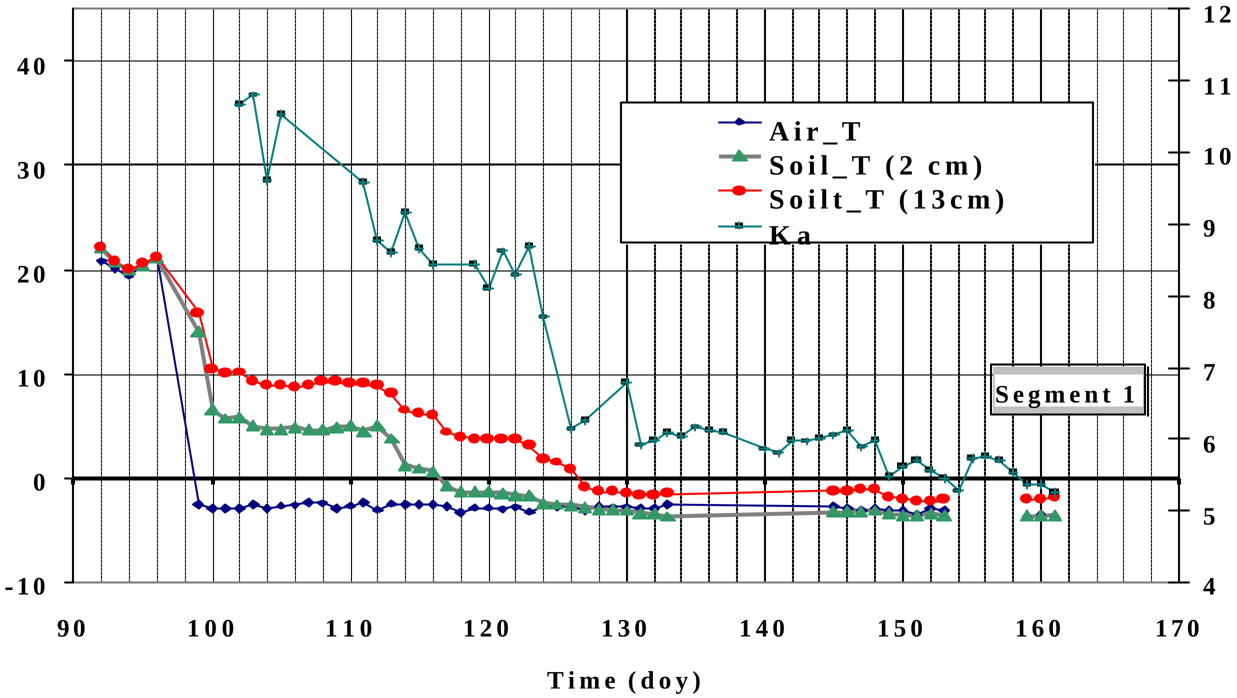


Figure 7 A change in the Ka is evident only after Soil_T (13cm) has dropped below 0 °C. Freezing may be occuring in the upper part of the segment , although it is difficult to detect.

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