Center for Transportation Infrastructure Systems

Continuous Moisture Measurement during Pavement Foundation Construction

Technical Memorandum 2

Task 2: Documentation of Current State of Knowledge

by

Hector Cruz
Mark Baker
Isaac Zuniga
Soheil Nazarian

Conducted for

National Road Research Alliance

July 2021

Center for Transportation Infrastructure Systems
The University of Texas at El Paso
El Paso, TX 79968
(915) 747-6925

Documentation of Current State of Knowledge

Introduction

An ideal foundation layer for long-life concrete pavements should (1) provide uniform support, (2) be neither too soft nor too stiff, (3) provide adequate drainage, (4) not suffer from irreversible plastic deformation, and (5) make use of sustainable methods and materials (White et al., 2021).

Moisture content is a major property of geomaterials that should be monitored during and after the construction of unbound pavement layers. Failing to estimate the moisture content accurately and promptly during construction may negatively impact the proper quality control/quality assurance (QC/QA) of compacted geomaterials. Excessive amounts of water during the life of pavement in different unbound layers of the pavement structure can contribute to the development of early distress and can lead to structural or functional failure of the pavement. Water-related damage can cause one or more of the following forms of deterioration: reduction of subgrade and base and subbase strength/stiffness, differential swelling in expansive subgrade soils, frost heave and reduction of strength/stiffness during frost melt and move of fine particles into the base or subbase coarse materials resulting in a reduction of the hydraulic conductivity (Liang et al., 2016). The interest in measuring the water content in pavement structures increased during the 1980s when several researchers studied this topic. The Strategic Highway Research Program (SHRP) conducted a study to try to clarify how the variations in moisture content influenced the pavement structures (Svensson, 1997). Since then, numerous methods and techniques have been proposed to measure moisture content in the soil. Traditional moisture measurement approaches, such as physical sampling or installing sensors like time domain reflectometry (TDR) probes, provide only spot measures, which are impractical when large-scale investigations need to be performed. Currently, industry professionals are working toward developing a new approach to measure soil water content in real-time over a continuous area.

An idealized pavement cross-section is shown in Figure 1. A desirable pavement section should be placed on top of a uniform pavement foundation that should extend past the driving lane. To ensure a unifrom pavement structure, it should be placed on top of a uniform embankment, when applicable. A review of the literature on this topic is provided next.

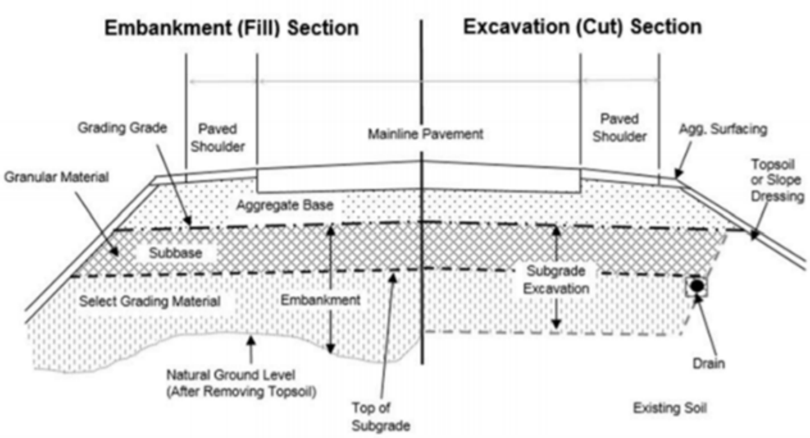

Figure 1. An ideal Pavement Section
(from [http://www.dot.state.mn.us/materials/pvmtdesign/manual.html)](http://www.dot.state.mn.us/materials/pvmtdesign/manual.html)

Measuring Methods

Numerous techniques for determining a reliable moisture content measurement of the soil have been proposed throughout the years. The different methods can be classified based on the approach and measuring principles applied into direct and indirect categories (Svensson, 1997). The direct method (i.e., gravimetric method) consists of extracting a soil sample from a location to be investigated. The soil sample is weighed before and after drying at a temperature of 105°C (220°F). This method is considered the "gold standard" for measuring moisture content.

Indirect methods are based on the use of a radiation source or a probe placed in or on the geomaterial for the measurement of a parameter strongly related to moisture content. The main advantages of these methods are that they are faster, and typically nondestructive since the soil is only disturbed during installation (Evett et al., 2008). None of these methods measure the water content directly, but they each measure a parameter that is reliably correlated with the water content in the soil. The major limitation for some of the moisture content devices as related to this project is that they only provide spot measurements, not spatially continuous measurements. Some examples of these methods and their measurement principles are summarized in Table 1, with the two most common are explained below.

Table 1. Indirect Tests.

Method	Measurement Principle	Explanation
Nuclear Density Gauge	Back-scattered or transmitted gamma-ray count-rate	A high-energy source releases gamma rays (i.e., Co60) that interact with the geomaterial. A gamma detector counts the returned gamma rays at energies related to Compton Scattering, which is strongly related to electron density, and closely related to material density.
Nuclear Moisture Gauge	Thermalized neutron count-rate	A neutron source releases high-energy neutrons, and a neutron detector counts neutrons with dominantly thermalized to lower energy by repeated collision with hydrogen nuclei in water. count-rates are secondarily influenced by neutron capture by some elements.
Nuclear Magnetic Resonance (NMR)	Detection of the weak magnetic moment	When a radio frequency is induced, an atom absorbs a certain amount of energy to move to another stable position within the magnetic field. Once a mixture of soil and water is placed in the NMR analyzer and a radio frequency is induced, a voltage will be applied in the surrounding coil. The applied voltage corresponds to the number of atoms that have absorbed energy and that voltage is directly proportional to the water in the sample (Svensson, 1997).
Capacitance meters	Oscillating circuit to measure changes in frequency	A capacitor uses two insulated electrodes, with the soil being the largest contribution to the dielectric constant. The equipment and the soil form the measuring circuit. The probe detects and measures the change in frequency which is dominated by the water content in the soil. (Svensson, 1997).
Ground Penetrating Radar (GPR)	Short pulses of electromagnetic through the soil	Aside from other functions, GPR can also be used for determining water content in the soil. Differences in transmission time and amplitude of the reflected pulse can also be related to changes in permittivity (dielectric constant). After obtaining the changes in permittivity, the water content of the soil can be calculated (Svensson, 1997).

Table 2. Indirect Tests, cont.

Method	Measurement Principle	Explanation
Thermal Sensors	Heat conductivity or heat capacity of the soil	A pulse of heat is produced and the consequent rise or drop in temperature of adjacent soil is measured over time. Since soil is a poor conductor of heat, and water a good one, the amount of heat or heat transmission relates to the volumetric water content (Evett et al., 2008).
Conductivity Sensors (1)	Electrical conductivity of a porous medium in contact with the soil	An alternating voltage is injected between two electrodes in a porous material exchanging moisture with the soil. The amount of current is a measure of the conductivity and amount of water between the electrodes in the porous material. Instead of calculating volumetric water content, these sensors are used for the estimation of soil water tension (Evett et al., 2008). Conductivity sensors include granular matrix sensors and gypsum blocks.
Conductivity Sensors (2)	Voltage measured at two electrodes from current injected at two other electrodes	Low-frequency alternating current is injected between two electrodes, while a voltage is measured at two electrodes with no current flow. Electrode geometry is used to convert the measured voltage/current ratio to apparent resistivity, while electrode separation controls the measurement volume.
Conductivity Sensors (3)	Eddy currents, induced by an alternating magnetic field, increase with conductivity.	A magnetic field induced by one coil over the ground is measured at a second coil. This secondary field responds to geometry, magnetic susceptibility of the soil, and eddy currents induced in a conductive soil, primarily controlled by moisture content. The eddy current is proportional to soil conductivity and frequency.
Resistance measurements	Resistance between two electrodes	Moisture levels in the soil are measured in terms of their electrical resistance which vary at different moisture contents. As the moisture content increases, the electrical resistance of the soil decreases, and conductance increases. The resistance could vary between several hundred kΩ when wet and more than several hundred MΩ when dry (Saïd, 2007).
Tensiometer measurements	Measurement of a pressure differential in the soil	The basic component of the tensiometer is a porous membrane constituting the interface between the water-filled pressure sensor and the soil. The generated negative pressure within the tube can be measured with a vacuum gauge. These are mainly used for the estimation of water tension (Evett, 2008). However, the water content can be obtained if the relation between matric potential and soil water content is known (Svensson, 1997).

The nuclear density gauge (NDG, Figure 2) allows the measurement of density and estimation of the water content of compacted geomaterials in different fashions (Viyanant et al., 2004). ASTM D6938-17a describes the standard test methods for in-place density and water content of soil and soil-aggregate by nuclear methods. The gauge is calibrated to read moisture mass per unit volume of soil or soil aggregate. Volumetric water content can then be obtained by dividing the water mass per unit volume and multiplying it by 100. Direct transmission and backscatter are other used methods for the nuclear gauge to measure density and water content respectively.

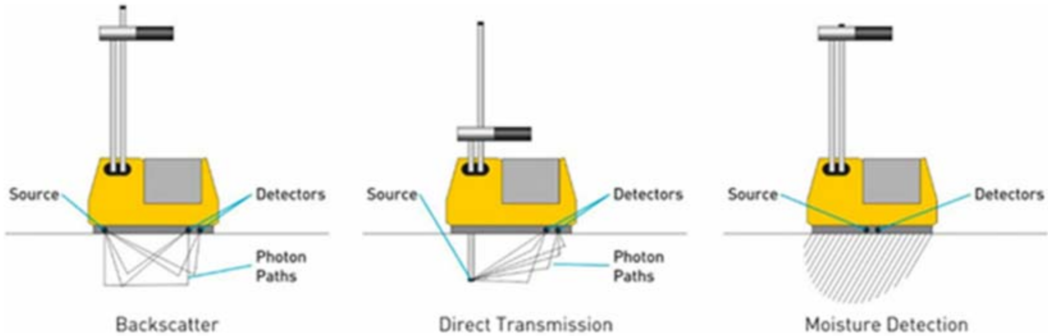

Figure 2. Positioning of a Nuclear Gauge for Three Different Methods (UTEST, 2016).

The neutron moisture measurement determines the water mass per volume by the thermalizing or slowing of fast neutrons that collide with hydrogen atoms in the soil. The neutron source and the thermal neutron detector are both located at the surface and are capable of recording and converting the slow neutron count-rate to a value estimating the water content per volume unit in the soil. With the regulatory requirements of using nuclear sources, other techniques are preferred to measure moisture content on base and subgrades. (Sebesta et al., 2013). The thermal neutron count rate can also be influenced by thermal neutron capture, with iron (Fe) being the most common modifier.

The Time Domain Reflectometry (TDR, Figure 3) method has been extensively used to measure soil water content and electrical conductivity (Jones et al., 2002). TDR operates by sending an electromagnetic pulse to the probe through a coaxial cable and measuring the reflection from the probe end. The time to reflection responds to cable length, the early reflection amplitude is dominated by permittivity (dielectric constant), and later reflection characteristics are dominated by electrical conductivity. The reflection amplitude is dominated by the dielectric constant of the soil around the probe; the permittivity (dielectric constant) is 1 for air, 2-9 for common dry soil particles, and about 81 for water. Since changes in the TDR measured dielectric constant is strongly related to change in water content of soils, it becomes relatively simple to determine the amount of moisture in the soil (Yu and Yu, 2009) for silicate soils. Soils with carbonates, gypsum, and clays have higher dry permittivity and require local calibration for mineral variations.

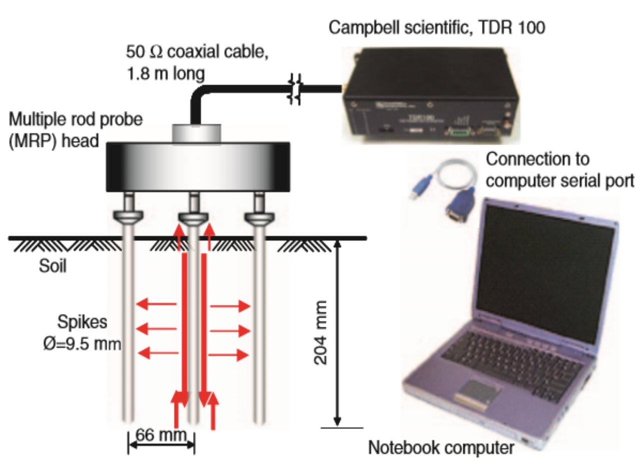

Figure 3. Schema of a Typical TDR System (Yu and Yu, 2009)

Sotelo (2012) evaluated the ability of several different devices to measure moisture content and dry density of various compacted geomaterials. The experimental research consisted of the testing of different geomaterials. The SDG 200, Purdue TDR, and the Decagon 10 HS were evaluated by fabricating more than a dozen small-scale specimens. The Speedy Moisture Tester and DOT600 Roadbed Water Content Meter were also considered using individual soil samples. Overall, TDR was slightly more accurate in determining the moisture content and dry density of the materials tested compared to the SDG 200. The Speedy Moisture Tester was the most accurate in determining the moisture content.

Sebesta et al. (2013) surveyed potential technologies for rapid moisture content measurements on the different layers of the pavement structure. They chose three non-nuclear tests, NDG for comparison purposes, and the oven-dry gravimetric water content for the reference values. The last stage consisted of the evaluation of the new devices including the Electrical Density Gauge (EDG), the DOT 600, and a moisture analyzer. The data collected from several construction projects were used to evaluate the bias, precision, and sensitivity of each device. They scored the devices based on bias, precision, sensitivity, turnaround time, and suitability for testing loose and compacted geomaterials.

Evaluation of Technologies Determining Moisture Content over Time

Bogena et al. (2007) evaluated an ECH_2O probe (model EC-5, low-capacitance sensor by Decagon Devices Inc.) using laboratory and field experiments. They also compared the permittivity and soil water content measurements using TDR and EC-5 sensors. They installed four EC-5 sensors in the field along with two permanently installed TDR probes connected to a data logger. The TDR measurements were performed using a Campbell Scientific TDR100 cable tester system and a sensor reading-permittivity (SRP) model was used to calculate the permittivity measured with the EC-5 sensor. The researchers estimated the soil moisture content based on an equation proposed by Robinson et al. (2003). Figure 4 presents the soil water content measured with the TDR and mean values and standard deviations of all EC-5 sensors for seven months. The results suggested that the EC-5 sensor readings should be adjusted using the corresponding temperature and conductivity correction functions.

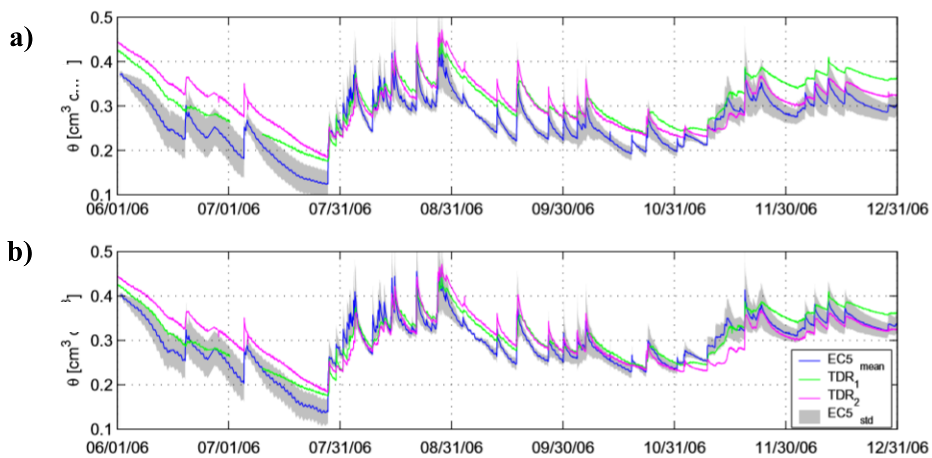

Figure 4. Measured VWC (a) using TDR and EC-5 sensors and (b) using TDR and corrected EC-5 measurements (Bogena et al., 2007)

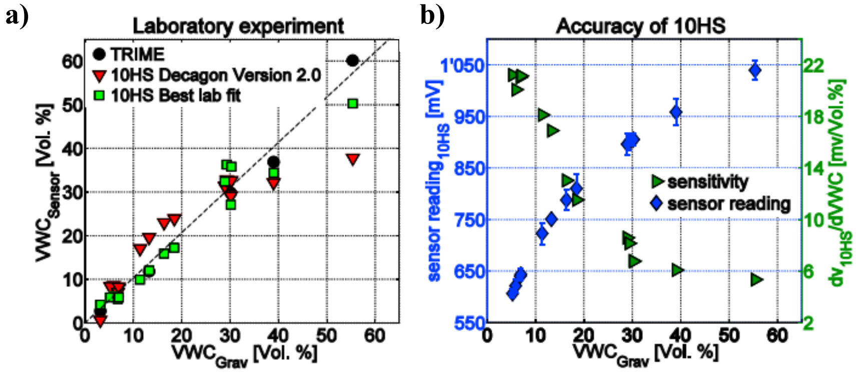

Figure 5. a) Results of Laboratory Measurements with TRIME (TDR) and 10HS (capacitance) Sensors as a function of VWC of the Gravimetric Samples and b) Accuracy of 10HS Sensors (Mittelbach et al., 2011)

Mittelbach et al. (2011) evaluated a different capacitance probe (10HS) to measure the volumetric water content (VWC) in the laboratory and the field. The VWC measurements using 10HS sensors were compared with the corresponding measurements from the gravimetric samples and two TDR sensors (TRIME-EZ and TRIME-IT, IMKO GmbH, Germany). The purpose of the laboratory measurements was to identify the difference in VWC between the 10HS and the TRIME sensors using gravimetric sample measurements as a reference. Figure 5a shows the results of the VWC measured in the lab. For the 10HS sensor, two calibartation functions are displayed (Decagon Version 2.0 and best lab fit). From the results, the TDR measurements were closer to the reference VWC. By contrast, the Decagon Version 2.0 calibration function presented erroneous measurements, especially above 30-40% moisture contents. The best lab fit was able to improve the reading, allowing it to be more reliable. Figure 5b presents the measurement accuracy of sensor reading, showing the variability within the 10HS sensor type (blue) and the dv/dVMC of the 10HS sensor (green). The sensor sensitivity with respect to the dv/dVWC (mV/Vol.%) showed a strong decrease with increasing VWC. The decreasing senstitivity is attributed to the principle of capacitance sensors, by which the capacitor charges slower at high VWC.

For the field measurements, the evaluation of the 10HS sensors took place at the sites of Oensigen (OEN) and Payerne (PAY), Switzerland. At both sites, the soil moisture content was measured with 10HS and TRIME IT/EZ over 13 months. Precipitation and air temperature, along with the absolute soil moisture (soil moisture integrated in millimeters over the measured soil column) are presented for both sites in Figure 6. Using the best field fit significantly improved (with the exception of the last few months) the derived absolute soil moisture content, almost replicating TDR measurements. They determined that the variations between the different 10HS sensors were relatively small. Also, they highlighted that the 10HS sensor required site-specific calibration functions and was most appropriate for low VWC levels. They concluded that the most appropriate setup for accurate soil moisture networks consisted of the parallel capacitance and TDR measurements, using the proper calibration of the 10HS sensors.

Hansen and Nieber (2013) investigated the proficiency of DOT600 (moisture content), WP4C dewpoint potentiometer (matric suction), the Button Heat Pulse Sensor (BHPS) (temperature rise vs. moisture content), and an exudation pressure test device at accurately predicting moisture contents of three subgrade soils (loam, silt, silty/clay) commonly used in Minnesota roadway construction projects.

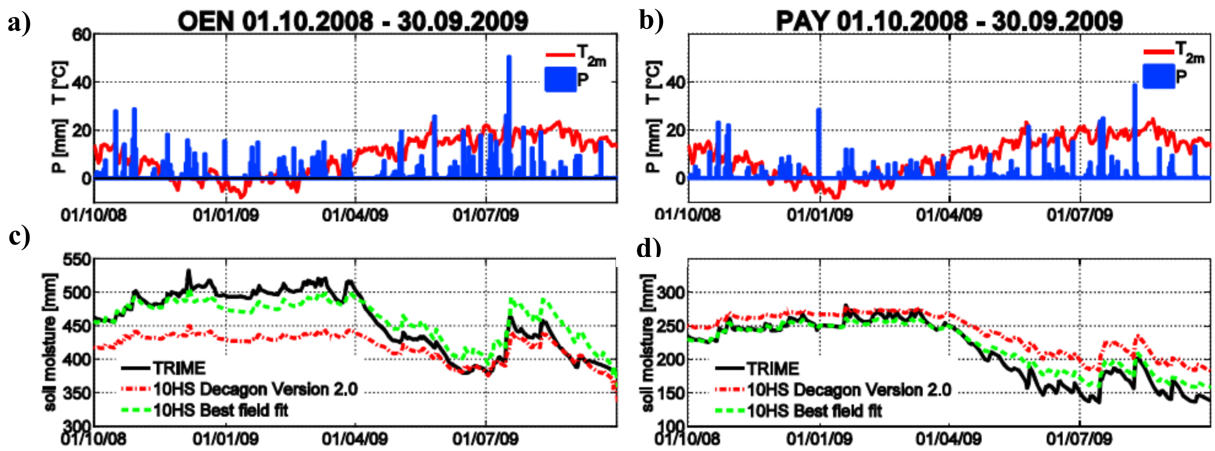

Figure 6. Precipitation and Temperature Measurements for a) OEN and b) PAY, and Absolute Soil Moisture (mm) for c) OEN and d) PAY (Mittelbach et al., 2011)

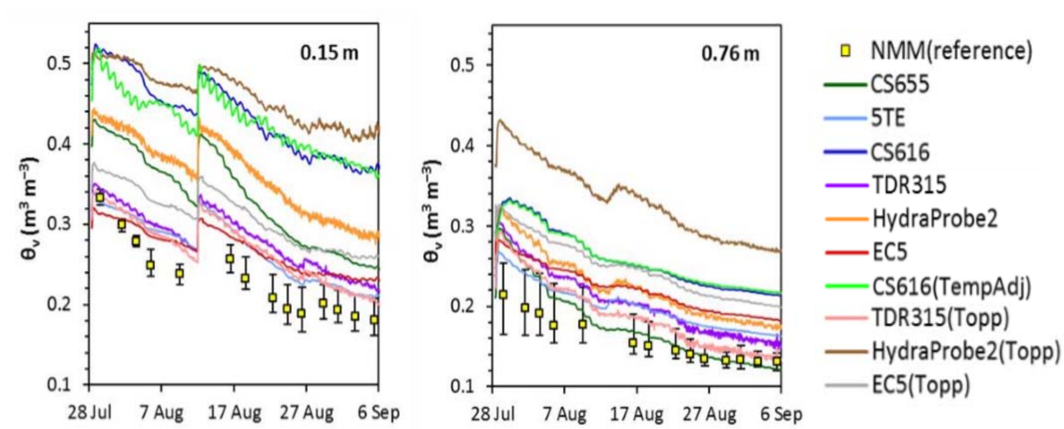

Figure 7. Measurements of VWC at Two Distinct Depths with Single-Sensor Probes as compared with the field-calibrated NMM (Singh, 2017)

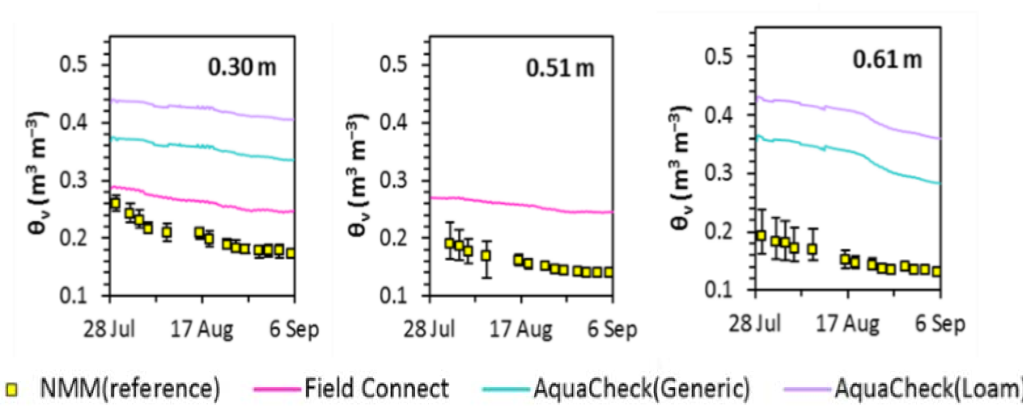

Figure 8. Measurements of VWC at Three Distinct Depths using Multi-Sensor Probes as compared with Field-Calibrated NMM (Singh, 2017)

Singh (2017) analyzed the field performance of eight electromagnetic (EM) sensors (TDR315, CS655, HydraProbe2, 5ET, EC5, CS616, Field Connect, and AquaCheck) in a loam. The specific objectives of that study were to evaluate EM sensors for VWC and compare the factory calibration against their custom calibration approaches for VWC. The field-calibrated neutron moisture meter (NMM) was used as the reference for VWC following Bell et al. (1987). In addition to the default factory calibrations for the EM sensors, the Topp calibration equation (Topp et al., 1980) was considered for TDR315, HydraProbe2, and EC5.

The variation between sensor-reported and reference VWC over time observed in this study is displayed for single-sensor probes in Figure 7 and multi-sensor probes in Figure 8. These plots demonstrated that all evaluated sensors, using either the factory calibrations or the incorporated alternative calibrations, followed the general trend. However, they all overestimated VWC relative to the reference. Using Topp's calibration equation instead of the factory calibration improved the performance of TDR315 but not HydraProbe2 or EC5.

Shaikh et al. (2018) developed a simple laboratory setup to evaluate all six sensors of a profile probe (PP) simultaneously for a particular soil type and compaction state. The PP measurements (based on the principle of TDR and capacitance method) were performed for six soils intended to be used in a multilayer cover system (MLCS). Figure 9 shows the developed experimental setup for the performance evaluation of the PP. This evaluation was achieved by comparing the measured and computed (theoretical) VWC, if the comparison was poor, recalibration was performed. The first results showed a deviation between the measured and computed VWC in the six soil types. Therefore, some calibration constants were used to recalculate the measured VWC from the known values of voltage and the square root of dielectric constant, the results of the recalculated measurements were favorable, as presented in Figure 10.

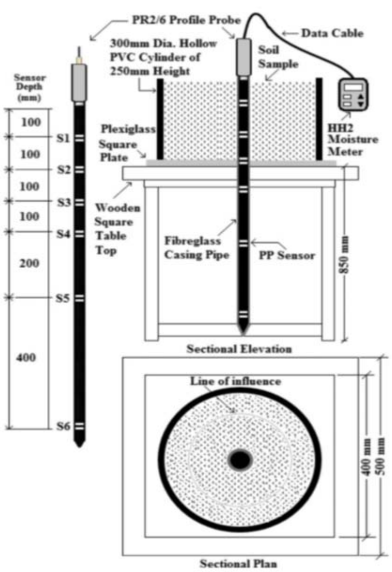

Figure 9. Laboratory Setup for Calibration of PP Sensors (Shaikh et al., 2018)

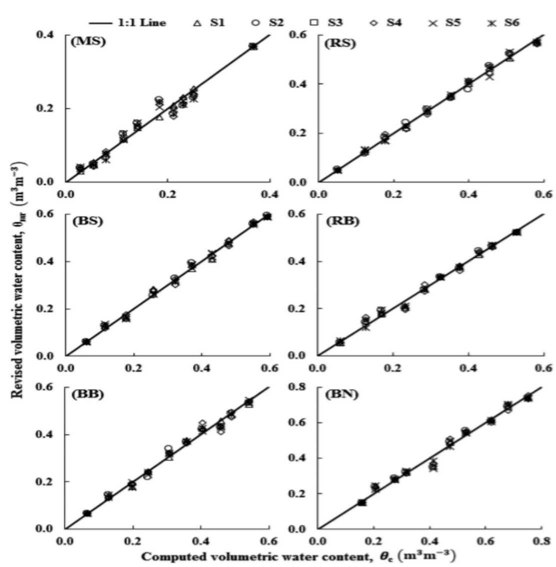

Figure 10. Comparison between Measured (using PP) and Computed VWC (Shaikh et al., 2018)

Figure 11 presents a better visualization of the comparison of different sensor readings before and after calibration for the same compaction state of two soils, denominated RS (medium plastic red soil) and RB (mixed soil with bentonite). Without applying the calibration functions, different sensors gave different measured VWC for the same VWC at a particular compaction state. However, after performing appropriate sensor- and soil-specific calibrations, both the computed and measured VWC matched well and all the sensors displayed similar values. They indicated that the PP moisture measurements were not quite accurate, and they advocated the use of their proposed laboratory procedure for accurate VWC (from ±6 to ±1% using calibration functions) before implementing the PP for field monitoring programs. They concluded that soil water content could be continuously measured by using a multi-channel GPR system.

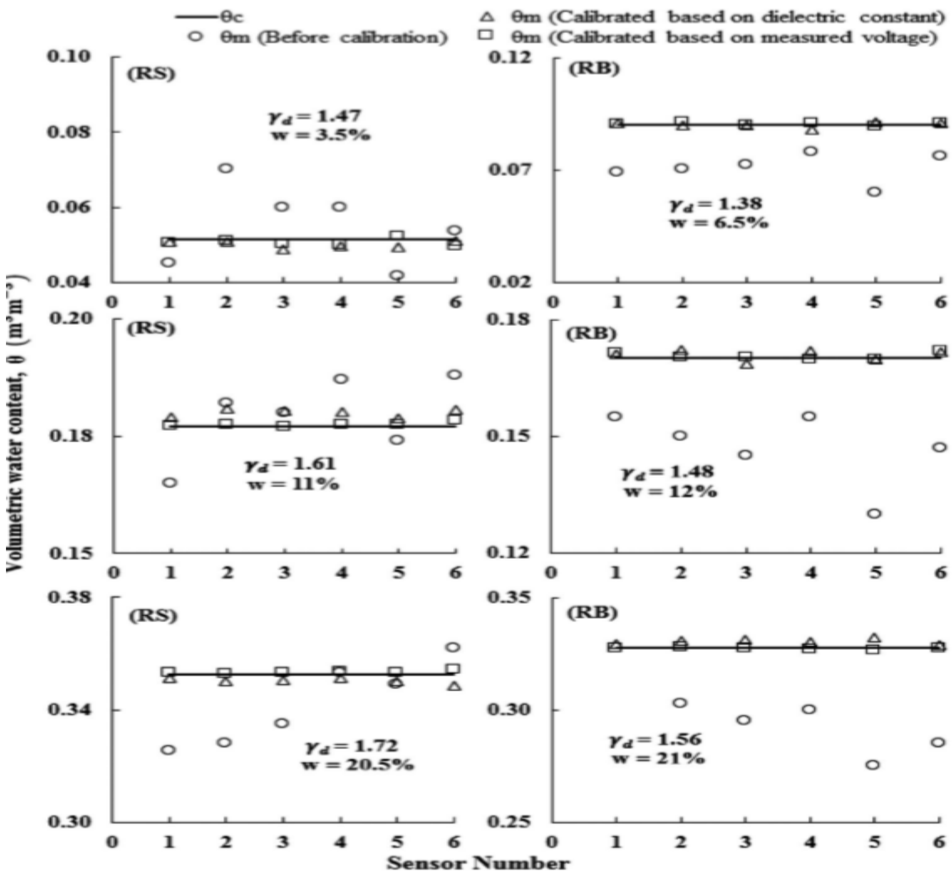

Figure 11. PP measurements before and after calibration at three various compaction states in RS and RB (Shaikh et al., 2018)

Using GPR for Continuous Moisture Content Measurements Over Large Distances

The principle of the GPR consists of transmitting short pulses of electromagnetic energy that are emitted from an antenna into the road structure and reflected back to a receiver antenna (Figure 12). The transmission time and amplitude of the reflected pulse can be related to the location and nature of dielectric discontinuities in the material (Maser and Scullion, 1992, Svensson, 1997). Due to its direct relationship, the moisture content can also be calculated by recording the changes in permittivity (dielectric constant). For highway investigations, the equipment is typically mounted on a van so that data collection can be carried out at a speed close to traffic (Figure 13). GPR antennas are designed for either “air-coupled” or “ground coupled” operations. For the air-coupled mode, the antennas are located about 250 mm above the surface for operation at highway speeds. Ground coupled antennas rest on the ground surface for better signal.

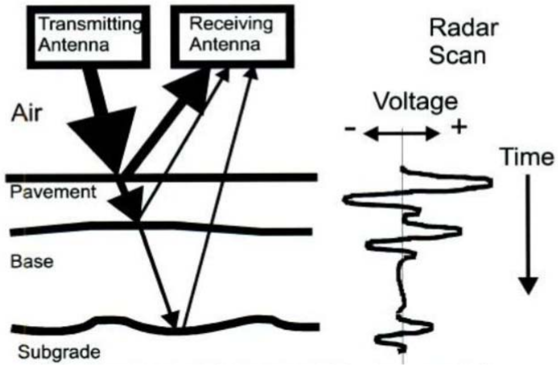

Figure 12. Transmission and Reflections from Interfaces in a Pavement Section

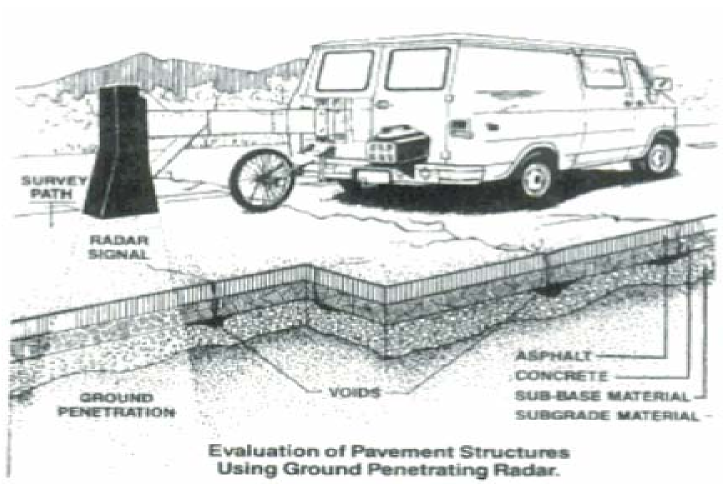

Figure 13. Illustrated example of van-mounted GPR system (Morey, 1998)

The use of GPR for the continuous measurements of soil moisture content on the different layers of a pavement structure has been investigated for a few decades. Maser and Scullion (1992) successfully created a moisture profile obtained from the radar data using a van-mounted horn antenna system. Emilsson et al. (2002) demonstrated the possibility of measuring moisture content continuously in roadbeds using a multi-channel GPR. Their analysis was based on a typical midpoint method using an antenna setup as demonstrated in Figure 14a. The antenna separation in the array varied between 0.15 m to 4 m with three different antenna arrays using frequencies of 250, 500, and 800 MHz. The results presented in this report were based on 500 MHz data. A photo of the 500 HMz antenna array is shown in Figure 14b. They were able to collect data at a speed of around 20-40 km/h and calculate volumetric soil water content at the site. Figure 15 displays the results.

Gerhards et al. (2008) presented a new approach also using a multichannel GPR that allowed measuring simultaneously the depth of a reflector and the average volumetric water content above the reflector with an operational effort only marginally higher than that for traditional measurement. They used a GPR multichannel unit MC4 (manufactured by Malå GeoScience, Sweden) with a 250-MHz antenna system. For a simple analysis, they used a straightforward evaluation procedure that consisted of using two travel times (t_2 and t_3) with a common midpoint (CMP) reflector from different antenna separations (Figure 16).

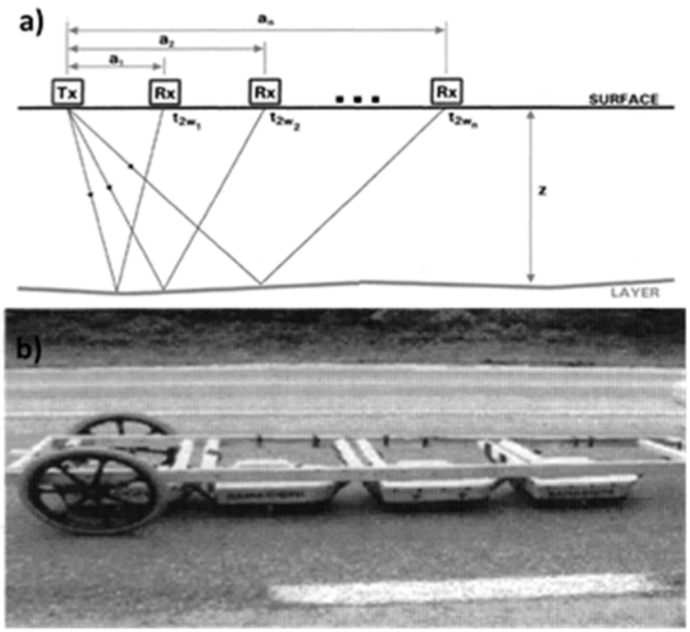

Figure 14. a) Antenna Setup for Velocity Determination and b) 500MHz Antenna Array (Emilsson et al., 2002)

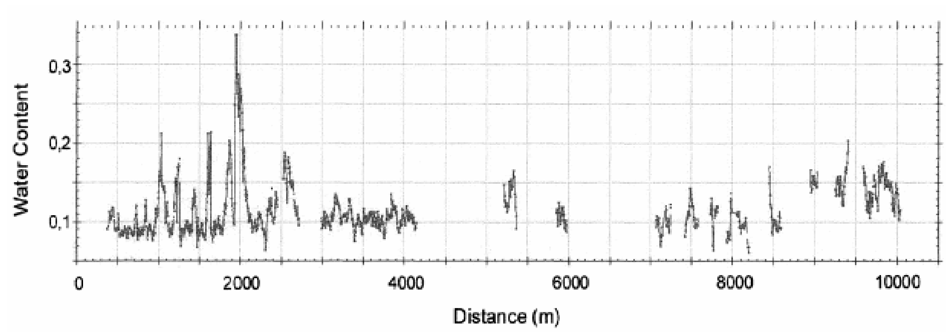

Figure 15. Calculated Soil Moisture Content (Emilsson et al., 2002)

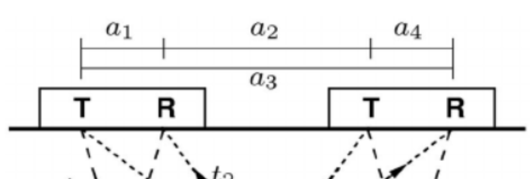

Figure 16. Antenna Setup for Multichannel Measurement (Gerhards et al., 2008)

However, the two-point evalutation does not use all the available information, because for each measurement point, four rays and three antenna separations are available. For this reason, a multipoint evaluation using different numbers of channels (a_1=a_4=0.36 m, a_2=1.76 m, a_3=2.38 m) was performed to obtain the reflector depth and average water content (Figure 17). The gray dashed line corresponds to the multipoint evaluation Channels 1 and 2 and the black dashed line to the evaluation using all channels. They concluded that the application of GPR demonstrated in their study allowed reflector depth and average water content to be obtained simultaneously and had a high potential of quantifying subsurface structure.

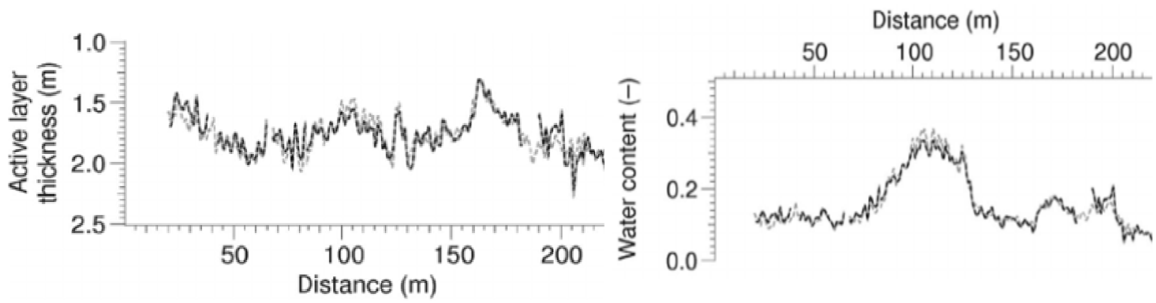

Figure 17. Calculated Reflector Depth (Layer Thickness) and Average Water Content, using Different Number of Channels (Gerhards et al, 2008)

Wollschläger et al. (2010) applied multi-channel GPR at a permafrost site to infer spatial variations in thaw depth and average volumetric water content of the active layer. Their measurements were performed following a modified version of the process followed by Gerhards et al. (2008). Their multi-channel GPR system allowed them to collect data from nine transmitter-receiver combinations, also referred to as "channels." When moving while using the CMP technique, they were able to effectively estimate relative dielectric permittivity, reflector depth, and average soil moisture content for each position along the radargram. They also implemented an inverse evaluation procedure for higher accuracy.

Measurements were conducted on an area approximately 85 m long by 60 m wide with surface and soil textural properties that ranged from medium- to coarse-textured to fine-textured soils, as well as the bed of a gravel road. Figure 18 illustrates the topographically corrected reflected depth, relative dielectric permittivity, and average volumetric soil moisture content of the unfrozen active layer acquired from the multi-channel analysis; red: raw data, dark blue: data averaged using a linearly weighted running mean filter over a 2 m distance, light blue: uncertainty limits for averaged soil moisture contents. Contour plots of the thickness of thawed layer, averaged moisture content and total soil moisture content of the active layer are shown in Figure 19. The total soil moisture content of the active layer can be calculated by multiplying the measured thaw depth and the average soil moisture content. This is an important measure in the permafrost research as it provides direct information about how much water is stored in the active layer. The study demonstrated that the multi-channel GPR technique covered the intermediate scales between the traditional point measurements and space-based remote sensing.

Muller (2017) demonstrated a semiautomatic approach using multi-offset ground penetrating radar (GPR) to achieve quantitative estimates of moisture content and layer depth predictions continuously at traffic speeds for unbound granular (UBG) pavements. The initial application of his techniques focused on the investigation of layer depth and moisture content at large projectlevel scales to assess layer depth as part of pavement rehabilitation investigations and identify the severity of suspected pavement damage due to excessive moisture in the multilayer structure. A second-generation 3D Noise-Modulated (NM-GPR) equipment developed by Reeves (2010) was used for moisture content measurements (Figure 20). That equipment could collect a series of adjacent partly overlapping ground-coupled multi-offset measurements.

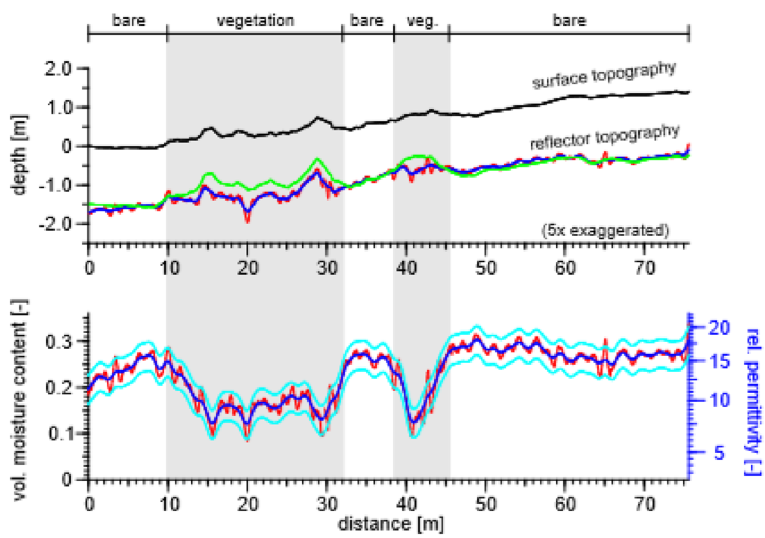

Figure 18. Surface Topography, Reflector Depth, Relative Dielectric Permittivity and Average Volumetric Soil Moisture Content (Wollschläger et al., 2010)

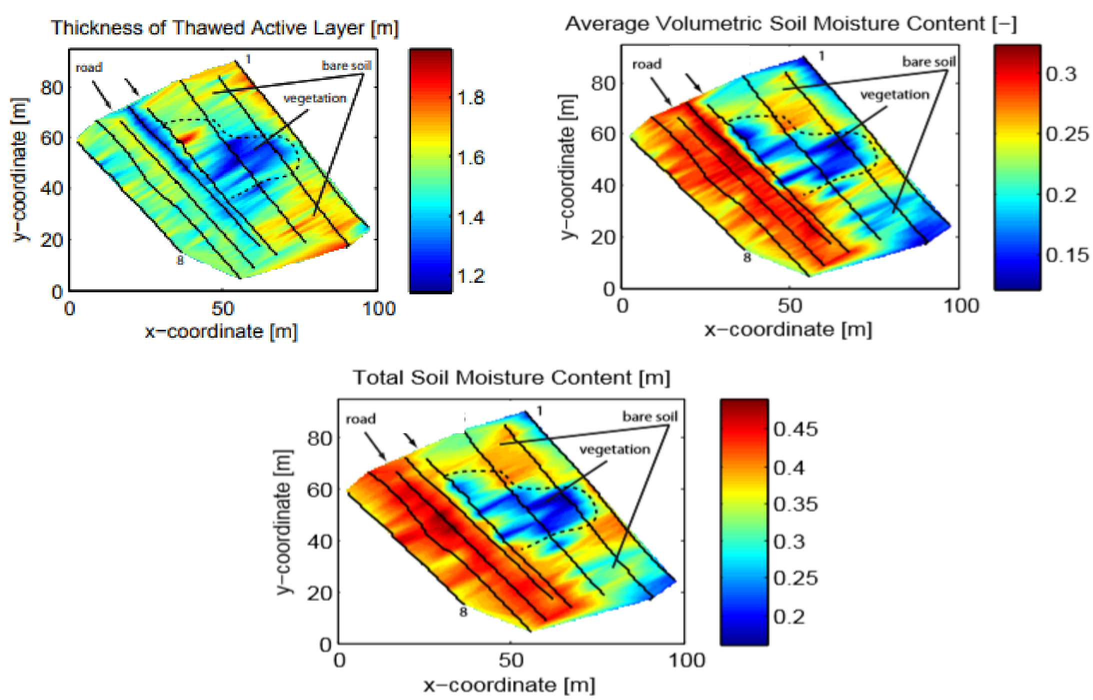

Figure 19. Thickness of Thawed Active Layer, Average Soil Moisture Content and Total Soil Moisture calculated for the thawed active layer within the measurement area (Wollschläger et al., 2010)

Figure 20. Second Generation NM-GPR System incorporating a Traffic-Speed 3D Ground-Coupled Antenna Array (Muller, 2017)

In addition to the NM-GPR, a Traffic Speed Deflectometer (TSD) was used to determine the corresponding deflection profile of the road surface. The TSD is a mobile device that uses a combination of Doppler-vibrometers and complementary sensors to measure the velocity of the deflecting surface at fixed offsets ahead of the load rear wheel (Ferne et al., 2009, Baltzer et al., 2010, Kelley and Moffat, 2011).

The equipment was configured to collect four adjacent wide-angle reflection and refraction (WARR) gathers quasi-continuously while traveling along the road. A modified free-space (MFS) permittivity characterization approach was developed to calibrate the petrophysical relations for UBG pavement materials to establish field moisture predictions. A ray-path modeling-semblance (RM-S1) approach was also used to best match all near-transmitter receivers across the array width.

Site Visit 1 occurred in June 2015, where NM-GPR measurements were obtained. TDR and impulse GPR measurements were collected the next day and the site bitumen sealed two days later. Site Visit 2, which was conducted in May 2016, consisted of the collection of NM-GPR, impulse GPR, and TDR measurements as well as several physical samples along the length of the site. Eight samples (S1 to S8) were excavated during Site Visit 2 to determine the constructed depth of pavement layers and collect material to determine the moisture content of that location. S1 to S4 were collected in 100 mm increments within the pavement and an additional sample was collected in the subgrade. The other four samples (S4 to S8) were obtained from the second portion of the site and the material was sampled within individual layers and in the subgrade. Figure 21 presents the measured response on one of the 32 NM-GPR channels during Site Visits 1 and 2 as well as the impulse measurement collected during Site Visit 2 for comparison. The approximate positions of sample locations S1 to S8 are also indicated.

Figure 22 displays a screenshot of the RM-S1 analysis for the measured multi-offset response (Figure 22a), the optimized ray-path model determined for the location tested (Figure 22b), and an image demonstrating the calculated layer depth, dipping angle, relative permittivity, and predicted volumetric moisture content (Figure 22c). Volumetric content predictions for the locations already analyzed along the road are illustrated in Figure 22d. The RM-S approach was intended to provide an easier and more efficient analysis of multi-offset GPR data collected continuously along the road using 3D GPR equipment. The corresponding volumetric moisture contents calculated using the petrophysical relation that they had developed previously are presented in Figure 23. They concluded that overall, there was a good correlation between the RM-S1 volumetric moisture content predictions and the physical sampling values. Other results demonstrated that TDR and common-offset GPR showed a similar trend compared to RM-S, however, they also reported consistently lower permittivity results. It is important to emphasize that the use of different sensor configurations (common midpoint, multiple arrays, common offset, etc.,) is to improve the ability to detect the layer interfaces and estimate the layer depths. The more accurate the depth predictions are the more accurate the estimation of the permittivity will be.

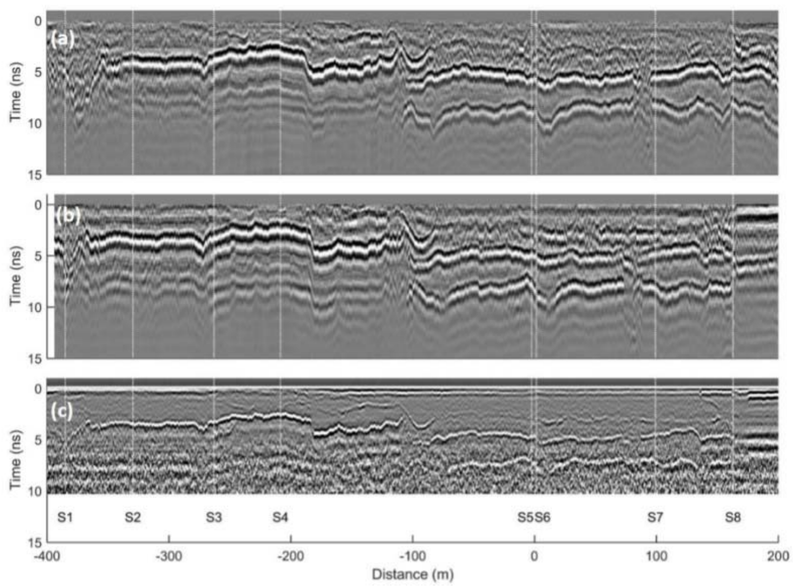

Figure 21. GPR Scans along Test Site for (a) Site Visit 1 using NM-GPR and for Site Visit 2 using (b) NM-GPR and (c) Impulse GPR (Muller, 2017)

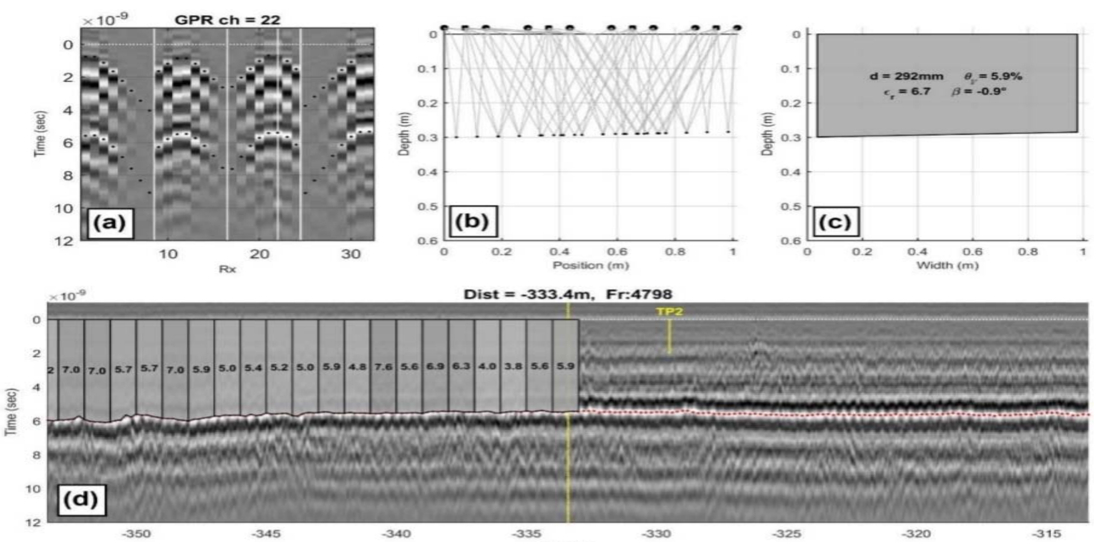

Figure 22. A Screenshot during Multi-Offset Analysis using RM-S1 Approach Showing (a) Measured WARR Response with Airwave and Optimized Ray-Path Travel Time Predictions Overlaid (black dots); (b) Calculated Ray-Path Geometries; (c) Calculated Layer Depth (d), Volumetric Moisture Content (Muller, 2017)

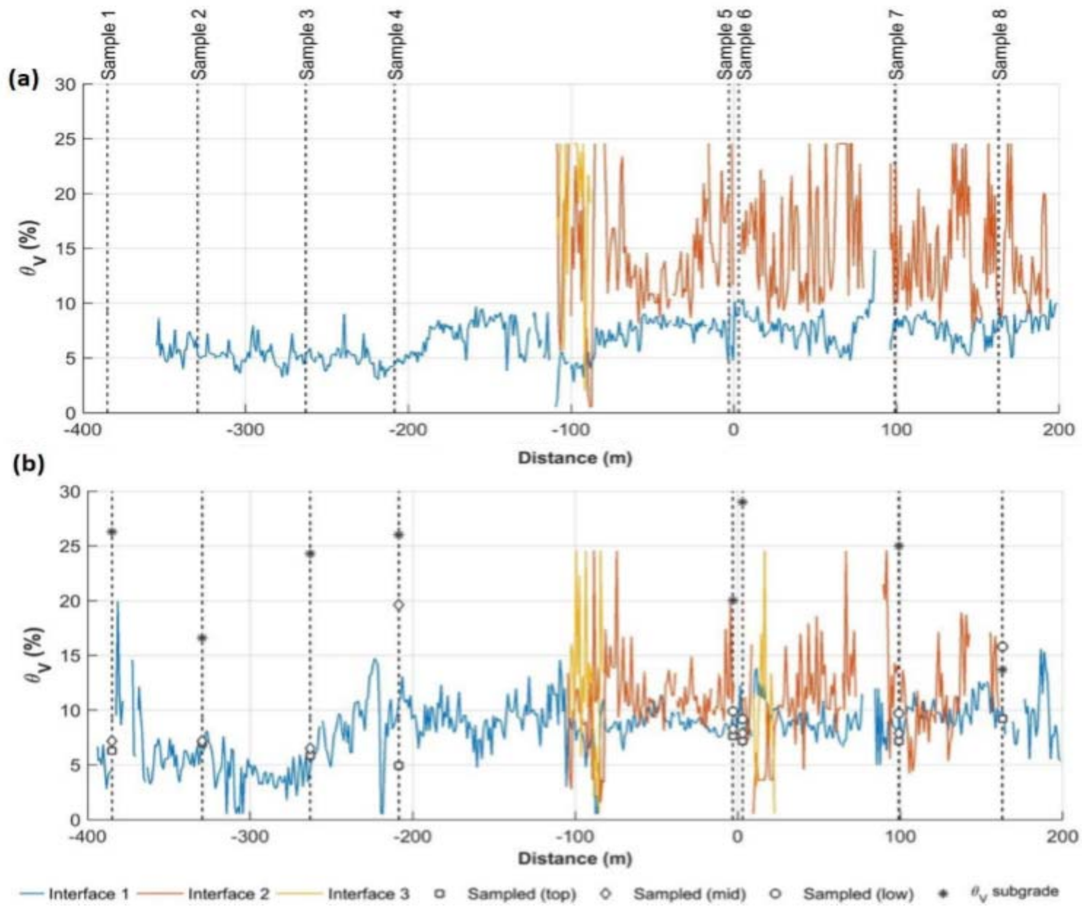

Figure 23. Volumetric Moisture Content Predictions from Permittivity Results during (a) Site Visit 1 and (b) Site Visit 2 (Muller, 2017)

From this study, Muller concluded that predictions using this approach matched well with the physical measurements of layer depth and moisture content of pavement layers. Permittivity predictions also followed similar trends over time compared to embedded TDR sensors and common-offset GPR measurements of buried reflectors but with slightly lower permittivity values. One limitation discussed in that study was that even though data could be obtained at traffic speeds, layers needed to be identified and tracked most likely based on spot assessments at intervals along the road. Also, it was highlighted that that approach could only be used down to the lowest coherent interface, which was typically the subgrade. For that reason, embedded TDR or other sensors would still be required to monitor subgrade moisture.

White (2019) conducted a study with the main goal of optimizing the placement cost of pavements using material compaction energy and moisture content. Their objective was to improve the quality by (1) achieving the minimum critical engineering parameter values over the entire site (2) limit variability of critical engineering parameter values over the entire site (3) restrict spatial areas of non-compliance (4) control moisture contents to ensure post-placement volumetric stability. They demonstrated the variability in QC/QA testing methods for determining water content (Figure 24). This revealed that 79% of the total measurements did not comply with their specified moisture control limits. The propriety-validated intelligent compaction (VIC) technology developed by Ingios Geotechnics, Inc. was used to aid in the construction process and quality assessment. Using intelligent compaction, quality assessment criteria were developed to reveal areas of non-compliance (Figure 25a). Moisture was measured based on its relation to the density of the material as shown in Figure 25b. Moisture was added or removed until reaching the desired density.

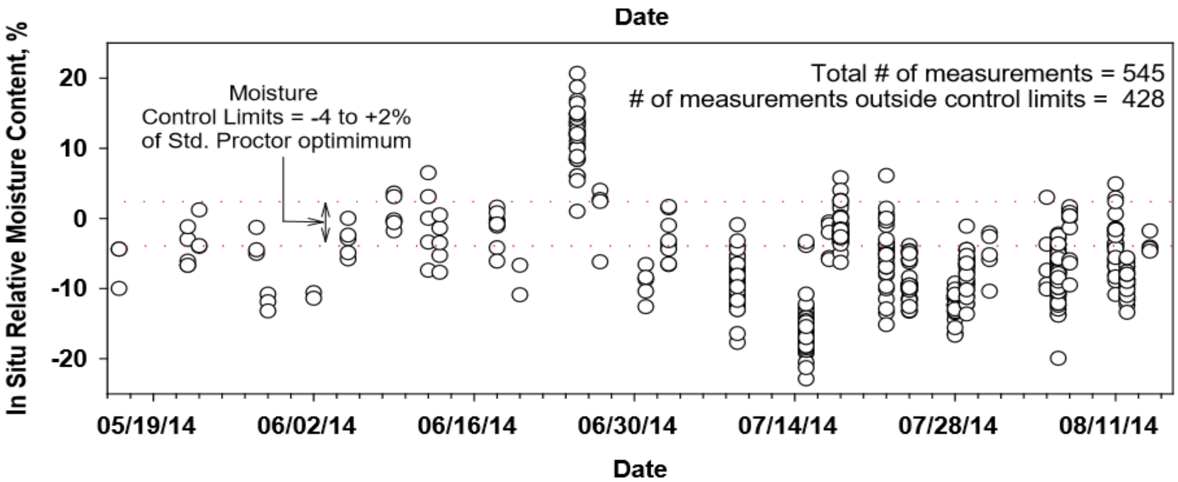

Figure 24. Moisture content measurement variability (White, 2019)

Quality Assessment Criteria	Requirement Meet?	Action Requirement
(1) 90% of IC-MVs ≥ 0.80*IC-TV	NO. 79%	Recompact areas of low IC-MV and remap area.
(2) Standard deviation of the IC-MV ≤ 0.35*IC-TV	YES. 18.9 <20.1	None required
(3) ICM-MV proof mapping area has no contiguous, isolated areas that larger than 80ft²	NO. one isolated area as noted	Reduce moisture content by scarifying and drying. Will be re-compacted and IC-MV map generated.
(4) w% ≥ the hydro-collapse values	YES	None required

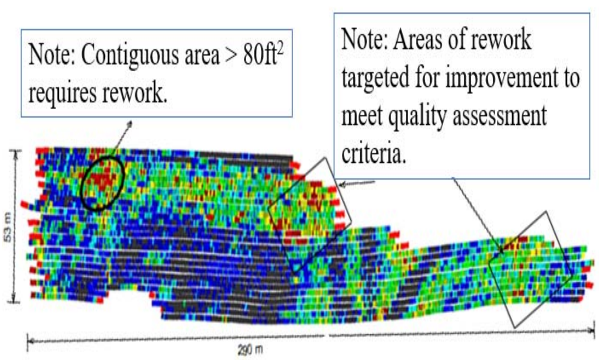

Figure 25. a) Quality Assessment Criteria and b) Intelligent Compaction Map (White, 2019)

Genc et al. (2019) suggested predicting the frost depth and the number of freeze-thaw cycles under a given roadway based on continually updated weather and soil data. Their work intended to create a solution to reduce the development of heaving, dips, cracks, potholes, and unpleasing traveling created by freeze-thaw cycles. Computational modeling was implemented for this study using soil moisture, soil matric suction, and temperature parameters for the analysis. The selected test section was instrumented with an array of soil moisture, matric potential, and temperature sensors installed in 5 boreholes at eight depths (Figure 26). Different sensors were evaluated to select the most convenient one to obtain the measurements for the moisture in the soil. After a comprehensive search of commercially available products, they decided to use the GS1 sensor by Meter Environment. For measuring the matric potential of the soil, the Decagon Devices MPS-6 sensor was selected because of its calibration method and accuracy. The selected test section was also equipped with a weather station to measure air temperatures. Figure 27 shows the sensors and weather stations used in this project. After the installation and data collection process was completed, a remote connection was initiated with the datalogger and the stored data were downloaded. In the end, continuous measurements for moisture content, matric potential, and temperature were obtained. Figure 28 presents an example of the collected data for continuous moisture measurements for the sensors located at 1 ft of depth for the 5 boreholes in this section

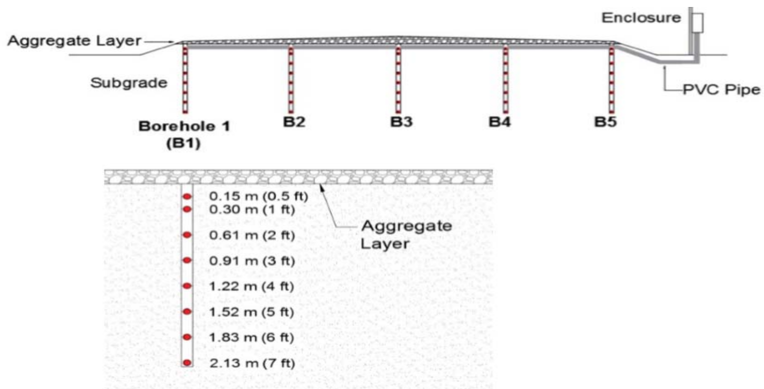

Figure 26. Cross-Sectional View of Roadway and one Boreholes (Genc et al., 2019)

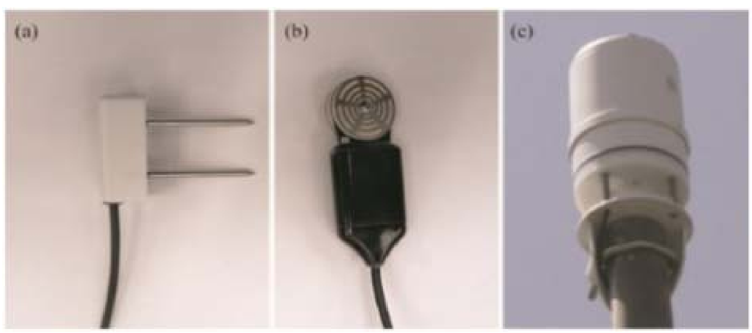

Figure 27. a) GS1 b) MPS-6 c) Weather Station (Genc et al., 2019)

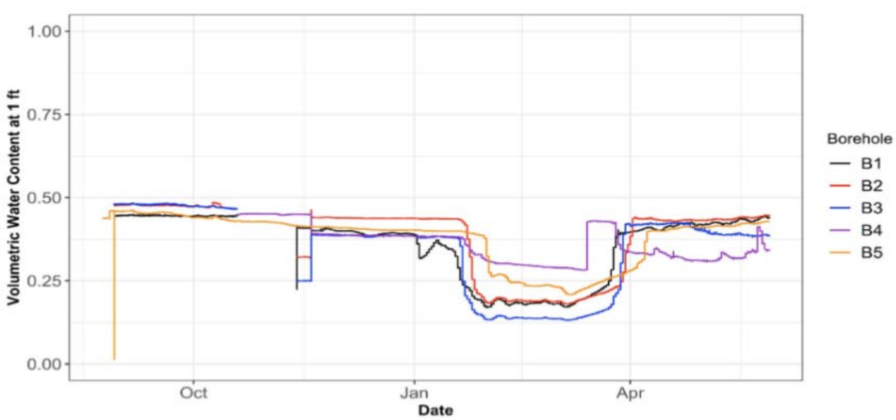

Figure 28. Continuous Moisture Measurement (Genc et al., 2019)

Campbell (2019) discussed some innovations that are changing the way moisture is being measured in geomaterials. The main objective of that study was to deploy a moisture and temperature system to produce the necessary data for a model to predict road weight restrictions. Moisture measurements were obtained using three sensors placed at 6 in., 18 in., and 30 in. An all-in-one weather station was also positioned at the site for temperature measurements. Continuous moisture measurements were developed for 14 days at a depth of 6 in. for different selected sites (Figure 29).

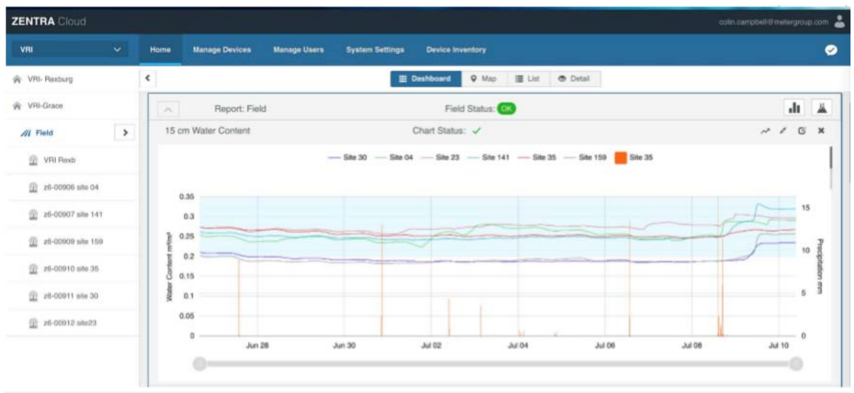

Figure 29. Example of a Continuous Moisture Measurement (Campbell, 2019)

Grabe and Mahutka (2005), through modeling and field measurements, demonstrated that the spatial variation of soil stiffness and pavement roughness exhibited the same statistical characteristics. They determined that the evenness of the pavement was a function of the spatial variation of soil stiffness, in addition to the number of vehicle passes and their load characteristics. They concluded that the long-term quality of the pavement depended on the variability of foundation layers' stiffness.

Brand et al. (2013) contains an excellent historical overview of the studies related to the consequences of the nonuniform foundations on the performance of pavements, especially rigid pavements. They also reported on several case studies to demonstrate the impact of nonuniform pavement foundations. They concluded that "certain nonuniform support of concrete slabs can produce much higher tensile stresses than a uniform support condition, particularly when considering different loading positions and curling conditions, soft support along the pavement edge, and preexisting cracks."

White et al. (2016) conducted an extensive study on the uniformity of earthwork in Iowa and the effectiveness of their existing specifications in providing a uniform final product. One of their conclusions was that the variability of the moisture content significantly contributed to the lack of uniformity of the pavement foundation layer. They recommended the following three options to improve the uniformity:

1. Enhance the current moisture and moisture-density specifications
2. Develop Alternative DCP/LWD-based (strength/stiffness-based) QC/QA specifications
3. Incorporate intelligent compaction (IC) measurements into QC/QA specifications.

Qouting from a comprehensive study performed by White el al. (2021), the following key challenges in terms of uniformity of foundation in general and moisture content in particular:

- Substantial spatial variability (nonuniformity) exists in newly constructed pavement foundations for the range of materials tested.
- If the subgrade layer is nonuniform, the overlying aggregate base layer will be nonuniform.
- Limited geotechnical testing (covering less than 1% of a given work area) is used to accept the engineering support values of pavement foundations, resulting in low reliability.
- Limited technology is available to help earthwork and paving contractors improve the field control of pavement foundation layers during construction.
- Most methods for quality inspection testing do not qualify as direct mechanistic measurements.

References

- Baltzer, S., Pratt, D., Weligamage, J., Adamsen, J., and Hildebrand, G. (2010). "Continuous bearing capacity profile of 18,000 km Australian road network in 5 months." In *24th ARRB* Conference, Melbourne, Australia.
- Bell, J.P., Dean, T.J., and Hodnett, G.C. (1987). "Soil moisture measurement by an improved capacitance technique, Part II. Field techniques, evaluation and calibration." J. of Hydrology 93 (1-2): 79-90
- Bogena, H. R., Huisman, J. A., Oberdörster, C., & Vereecken, H. 2007. "Evaluation of a low-cost soil water content sensor for wireless network applications." *Journal of Hydrology*, *344*(1-2), 32-42.
- Brand, A.S., Roesler, J.R., Chavan, H.L., and Evangelista F. (2013). "Effects of a nonuniform subgrade support on the responses of concrete pavement." Report No. ICT-13-027, University of Illinois at Urbana-Champaign, 142 p.
- Campbell, C. (2019). "Improving the Outcomes of Geomaterial Field Monitoring Campaigns" Transportation Research Board, Washington, D.C.
- Cole, S., & Buis, A. "NASA soil moisture radar ends operations, mission science continues." *SMAP. URL: https://smap. jpl. nasa. gov/news/1247/nasa-soil-moisture-radarends-operations-mission-science-continues/(visited on 09/08/2017)*.
- Emilsson, J., Englund, P., and Friborg, J., (2002). "Simple method for estimation of water content of roadbeds using multi-offset GPR." In Ninth International Conference on Ground Penetrating Radar (Vol. 4758, pp. 422-426). International Society for Optics and Photonics.
- Entekhabi, D., Yueh, S., O'Neill, P. E., Kellogg, K. H., Allen, A., Bindlish, R., and Das, N. (2014). "SMAP handbook–soil moisture active passive: Mapping soil moisture and freeze/thaw from space."
- Evett, S. R., Heng, L. K., Moutonnet, P., and Nguyen, M. L. (2008). "Field estimation of soil water content: A practical guide to methods, instrumentation, and sensor technology." IAEA: Vienna.
- Ferne, B. W., Langdale, P., Round, N., and Fairclough, R. (2009). "Development of a calibration procedure for the UK highways agency traffic-speed deflectometer." Transportation research record, *2093*(1), 111-117.
- Genc, D., Ashlock, J. C., Cetin, B., and Kremer, P. (2019). "Development and pilot installation of a scalable environmental sensor monitoring system for freeze-thaw monitoring under granular-surfaced roadways." Transportation Research Record, 0361198119854076.
- Gerhards, H., Wollschläger, U., Yu, Q., Schiwek, P., Pan, X., & Roth, K. (2008). Continuous and simultaneous measurement of reflector depth and average soil-water content with multi-channel ground-penetrating radar. Geophysics, 73(4), J15-J23.
- Grabe, J., and Mahutka, K.-P. (2005). "Long-term evenness of pavements with respect to soil deformations." Proceedings Seventh International Conference on the Bearing Capacity of Roads, Railways and Airfields.
- Hansen, B.J. and Nieber, J.L. (2013). "Performance-based measurement of optimum moisture for soil compaction." Report MN/RC 2013-28, University of Minnesota, 53 p.
- Jones, S. B., Wraith, J. M., a."nd Or, D. 2002. "Time domain reflectometry measurement principles and applications." Hydrological processes, *16*(1), 141-153.

- Kelley, J., and Moffat, M., 2011. "Review of the Traffic Speed Deflectometer-Final Project Report." *ARRB* Group, Melbourne, Australia, Austroads Report AT1613.
- Kurtz, L. 2019. "How to measure moisture content". Wikihow. URL: https://www.wikihow.com/Measure-Soil-Moisture
- Liang, R. Y., Al-Akhras, K., and Rabab'ah, S. 2006. Field monitoring of moisture variations under flexible pavement. Transportation research record, *1967*(1), 160-172.
- Maser, K. R. and Scullion, T., (1992). "Automated pavement subsurface profiling using radar: case studies of four experimental field sites."
- McNairn, H., Jackson, T. J., Powers, J., Bélair, S., Berg, A., Bullock, P., ... and Pacheco, A. 2016. "Experimental plan SMAP validation experiment 2016 in Manitoba, Canada (SMAPVEX16-MB)."
- Mittelbach, H., Casini, F., Lehner, I., Teuling, A. J., and Seneviratne, S. I. (2011). "Soil moisture monitoring for climate research: Evaluation of a low-cost sensor in the framework of the Swiss Soil Moisture Experiment (SwissSMEX) campaign." *Journal of Geophysical Research: Atmospheres*, *116*(D5).
- Muller, W., (2017). "Characterizing moisture within unbound granular pavements using multi-offset Ground Penetrating Radar."
- Robinson, D.A., Jones, S.B., Wraith, J.M., Or, D., and Friedman, S.P. (2003). "A review of advances in dielectric and electrical conductivity measurement in soils using time domain reflectometry." Vadose Zone J. 2, 444–475
- Saïd, M. N. A. (2007). "Measurement methods of moisture in building envelopes–a literature review." International Journal of Architectural Heritage, 1(3), 293-310.
- Sebesta, S., Taylor, R., and Lee, S. I., 2013. 0-6676: "Rapid field detection of moisture content for base and subgrade: (No. 0-6676)." Texas. Dept. of Transportation. Research and Technology Implementation Office.
- Shaikh, J., Yamsani, S. K., Sekharan, S., and Rakesh, R. R. (2018). "Performance Evaluation of Profile Probe for Continuous Monitoring of Volumetric Water Content in Multilayered Cover System." *Journal of Environmental Engineering*, *144*(9), 04018078.
- Singh, J. (2017). "Performance Assessment of Electromagnetic Soil Water Sensors in Different Soil Textural, Temperature, and Salinity Conditions."
- Sotelo, M. J., (2012). "Evaluation of non-nuclear devices in measuring moisture content and density of soils."
- Svensson, J. (1997). "Moisture content in road pavements: state of the art and development of a simple moisture measurement equipment." Swedish National Road and Transport Research Institute., VTI Meddelande 809A.
- Topp, G.C., Davis, J., and Annan, A.P. (1980). "Electromagnetic determination of soil water content: Measurements in coaxial transmission lines." Water Resources Research 16(3): 574-582
- University of Sherbrooke (2012). "SMAP Validation Experiment (SMAPVEX12)."
- UTEST. 2016. "RoadReader nuclear density gauges".
- Viyanant, C., Rathje, E. M., and Rauch, A. F. (2004). "Compaction control of crushed concrete and recycled asphalt pavement using nuclear gauge." In Geotechnical Engineering for Transportation Projects (pp. 958-966).

- White, D.J., Li S., and Vennapusa P. (2016). "Embankment Quality and Assessment of Moisture Control Implementation," Report IHRB Project TR-677, Center for Earthworks Engineering Research, Iowa State University, 225 p.
- White, D.J. (2019). "Optimizing Placement Cost using Material Specific Compaction Energy and Moisture Content" Transportation Research Board presentation, Washington, D.C.
- White, D.J., Vennapusa P., and Cetin B. (2021). "Improving the foundation layers for concrete pavements: lessons learned and a framework for mechanistic assessment of pavement foundations" Report 09-352, Iowa State University, 141 pp.
- Wollschläger, U., Gerhards, H., Yu, Q., and Roth, K. (2010). "Multi-channel ground-penetrating radar to explore spatial variations in thaw depth and moisture content in active layer of a permafrost site." The Cryosphere, *4*(3), 269.
- Yu, X., and Yu, X. (2009). "Time domain reflectometry automatic bridge scour measurement system: principles and potentials." Structural Health Monitoring, *8*(6), 463-476.
- Yueh, S., O'Neill, P. E., Butler, R., Osornia, L. M., Hu, W., Hanna, M., Ballard, C., and Mizukami, M., Mission Description SMAP. URL: https://smap.jpl.nasa.gov/news/1247/ nasa-soil-moisture-radar-ends-operations-mission-science-continues/*(visited on 09/08/2017)*.