Minimally Invasive Technologies For Measurement Of Water in Pavement Systems

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Abstract
In recent years, there has been increasing interest worldwide in the potential pavement life cycle cost and environmental impacts of the interaction of asphalt pavements with water. Trapped water in the aggregate may result in debonding of the bitumen from the stone over time and subsequent deterioration. Intrusion of water into the asphalt (such as into longitudinal joints or cracks) may lead to accelerated deterioration and failure due to freeze/thaw cycles. On the environmental side, water movement through the pavement and subgrade has raised issues of salts and pollutants leaching from the pavement into the groundwater. International conferences and workshops (such as Water in Pavements 2005-2007) underscore the increasing awareness and concern over the effects of the interaction of water with pavements and the environment. Recent research resulting from initiatives, such as COST351, has dramatically increased the awareness and understanding of these important issues (Dawson 2007). Recent research has also shown that knowledge of the water content of the asphalt itself is important in the design and curing of recycled pavement systems, such as Cold in Place Recycling (CIPR) and the emerging emulsion based binders such as Warm Mix Asphalt (WMA). Lagging behind the theoretical research is the development of instrumentation that can validate the research and determine the conditions in the field as related to the presence of water on, in, below, and around pavement systems.

1. Introduction
In this paper we describe two new measurement technologies that have the potential to advance the practical understanding of the interaction of water with pavement systems. We first review the current state of the art in water measurement, identifying the advancements required to provide the needed measurements. We then describe the new technologies that, when used together, can provide a comprehensive near surface assessment of water in the pavement layers as well as the unbound layers below. Measurement of water content alone is not sufficient to understand the dynamics of the pavement system as water mobility must also be considered. To understand mobility, information about the strength, density, and soil type of the unbound layers must be known. Measurement technologies currently used to measure water in pavement systems, such as Ground Penetrating Radar (GPR) and Time Domain Reflectometry (TDR), cannot determine the desired soil parameters that are required for a full picture of water movement.

The new technologies to be described in this paper, which are suitable for portable use in the field, are derived from well established soil characterization sensing approaches. The configuration of the systems under development will be described and preliminary data
presented from testing currently in progress. The first technology employs a minimally invasive penetration to determine the soil type, strength, and water content of unbound layers to a depth of one meter. The second technology, which employs electromagnetic sensing, provides for measurement of water content in and under asphalt pavement itself. Additionally, the technology can be used for quality control to measure pavement density and moisture content. The new technologies complement the research into the interaction of water with pavement systems and provide a means to gain new insights in the fields of prognostics, diagnostics, and design validation.

There are many aspects to the interaction of water with pavement systems. Water may be present by design, as in Warm Mix Asphalt, from deterioration, as in cracked longitudinal joints, or from ground water in proximity to the pavement. The water may be fixed or mobile, moving with the seasons and weather conditions.

In the environmental interaction, water can originate from rain, runoff from higher elevation, and ground water intrusion from soil layers below the pavement. Water can act as a transport media via surface runoff and infiltration through the pavement. There are several sources of potential contaminants that can be carried away from the pavement system by water: vehicle corrosion products, fluid leaks, heavy metals from catalytic converter and tire wear, polish, windshield cleaning agents, salt used during the winter, heavy metals from aggregates and pavement additives (such as slag, crushed building materials, or ash), zinc from road sign hardware deterioration, and herbicides used to control roadside vegetation. The transport of pollutants is controlled by several chemical processes such as adsorption/desorption, dissolution, and exchange reactions. Salt resulting from winter road maintenance can influence these reactions. The water may then transport the pollutants into the ground water system that may then have an effect on fish and humans that use the water for consumption (VTPI 2006). The effect of salt is important in climate regions where salt is placed on the roads during the winter months.

To illustrate the importance of measurement of water present in pavement by design, the example of Cold In-Place Recycling (CIPR) will be used. In CIPR, as practiced in the U.S., 7.5-10 cm of the existing asphalt pavement is milled, mixed with asphalt emulsion, paved and compacted into a new intermediate pavement course. The rehabilitation is usually completed by placing a 4 cm Hot Mix Asphalt (HMA) surface course over the recycled pavement. The economic and environmental benefits of the CIPR process are well established. There are several challenges related to the water content of CIPR emulsions that, if addressed, would make the process even more acceptable. In many U.S. states, after rehabilitation of a highway using CIPR, the contractor must wait a period of 7-10 days until the pavement has achieved final strength. While direct strength measurements with devices such as the Portable Falling Weight Deflectometer are possible, these devices are expensive and cumbersome to use. There is suggestion that measurement of the in-situ water level during the curing period may also provide an indication of the state of cure (Lee 2007). If measurement of the in-situ water were possible, the need to wait a fixed period of time could be obviated. This would permit placing the final HMA overlay earlier and precluding possible traffic induced damage to the CIPR layer. Currently, no reliable quality control density measurements are possible on CIPR due to the fragile nature of CIPR cores and the fact that nuclear gauges cannot be used without an as-placed calibration of the CIPR mix. For the same reasons, contractors cannot use nuclear gauges or available non-nuclear gauges to evaluate process improvements related to on-site mix control and rolling strategy. Finally, the in-situ water content of the pavement that is being recycled has an influence on the water content of the emulsion that should optimally be used (Santagata 2007). The ability to measure the water content prior to beginning the CIPR process will permit finer control of the mix design process with resultant improvement in quality. The design water content of the Warm Mix and foamed asphalt processes has also been shown to influence the ultimate strength and should therefore be closely controlled.
Finally, pavement stability is highly dependent on the degree of saturation of unbound layers below the pavement. Excessive water content in the pavement base, sub-base, and subgrade soils can cause early distress and lead to a structural or functional failure of pavement due to high water pressures that can develop in saturated soils when subjected to dynamic loading. Subsurface water can freeze, expand, and exert forces of considerable magnitude on a pavement. To minimize premature pavement distress, it is imperative to provide adequate drainage to allow infiltrated water to drain out from the base and sub-base. In order to remove the water from the different layers of the pavement system, the current trend is to build subsurface drainage into the system (Rabab’ah 2007). Water damage in an asphalt mixture can be defined as the loss of strength, stiffness and durability due to the presence of water leading to adhesive failure at the binder-aggregate interface and/or cohesive failure within the binder or binder-filler mastic (Gordon 2007).

2. Measurement Needs

Measurement of water in the asphalt pavement takes many forms depending on the application. For design and construction, especially for recycled processes and warm mix or foamed emulsions, where water is present by design, a precise quantitative measurement of gravimetric water content is required. For assessment of water intrusion into the pavement, or detection of water just below the pavement layer, all that may be necessary is to detect the presence and possibly the relative amount of water.

Measurement of water in the unbound layers ideally would take the form of estimation of the degree of saturation. Assessment of the strength, moisture level, and soil type may permit assessment of the degree of saturation or the change in saturation following a rainfall, for example. The measurement should be either non-invasive, such as GPR, or minimally invasive and must be made to a depth of a least one meter to ascertain the degree of saturation of the layers below the asphalt.

Traditional guidelines for drainage system design were based upon saturated conditions. A more realistic approach would assume partially saturated flow. Partially saturated flow is governed by soil characteristics not easily measured, especially with existing means. Large Cone Penetrometers (CPTs) can be used but they are not practical due to cost of surveys and more invasive nature of soundings due to large diameter penetrometers. Portable Dynamic Cone Penetrometers (DCP) can be used to estimate soil strength, but must be used with other sensors, such as GPR and coring, to provide a complete picture.

Applications involving prognostic or diagnostic identification of water in or below pavement can benefit from measurements that can cover a large area quickly and non-invasively. After identification of a possible problem area, minimally invasive near surface penetrations could be conducted to provide detailed information about the subsurface.

3. Science Background

Current Measurement Technologies

Ground Penetrating Radar uses electromagnetic waves in the microwave band to assess the wave propagation velocity in dielectric materials, such as asphalt and soil. The propagation velocity is related to the dielectric properties of the material which are in turn related to density, water content, and salinity. The frequency of the radiation determines both the penetration depth into the medium and the spatial resolution of measurement. Radiation is emitted into the soil by an antenna disposed on or above the surface. At microwave
frequencies, the incident radiation is scattered by dielectric discontinuities in the medium. An antenna above the surface detects the amplitude and travel time of the scattered radiation. The primary uses of GPR are determination of layer thicknesses, location of construction changes, areas of high water, voids, reinforcement and other discrete objects. A primary weakness of GPR is the inability to quantify the exact dielectric constant (and hence the water content or density) without knowing the thickness and volumetric profile of the layers. Also, if the medium is uniform, without distinct scattering centers, the return signal will be very weak. Highly conductive soils, such as clays, significantly limit the penetration of microwaves. Therefore, to perform a complete assessment of unbound layers, other methods, such as the falling weight deflectometer (FWD), CPT, and coring must be employed. The primary advantage of GPR is the ability to gather large amounts of data quickly and non-intrusively over a large area. On the downside, equipment is expensive and results are difficult to interpret.

**Time Domain Reflectometry** is a related technology that employs radiation in the high radio frequency region of the electromagnetic spectrum. The method forms the soil under test into a transmission line generally by driving conductive stakes into the soil. In one commercial product, stakes can be up to 20 cm in length. The method, which measures the density and water content of the material, is suitable for use only on unbound layers not covered by pavement. Without a-priori calibration, the method is influenced by the soil type and gradation.

**Penetrometer Technology**

The current practice in site characterization (where depths to 15 meters and beyond may be assessed) involves use of the Cone Penetration Test (CPT) method (ASTM D3441). In CPT testing, the cone is advanced into the soil at a constant rate of ~2 cm/sec. Due to the large forces required for CPT operation, the units are vehicle mounted to provide the requisite reaction mass. For this reason, the constant push method of advancing the cone is not appropriate for a portable field device. However, most of the research and practice relative to sensing soil strength, type, and water content in a penetrometer configuration has been accomplished on CPT style devices. CPT devices consist of an instrumented sensing head that contains sensors to measure cone resistance, sleeve resistance, and in the CPTu configuration, pore pressure. For the CPT configuration, it has been shown in the literature that the ratio of sleeve friction to cone resistance is correlated to soil type (Robertson 1990). The undrained shear strength (C_u), as calculated from the cone resistance, can be corrected for soil type and pore pressure (Fellenius 2000).

The only approach practical for portable use in the field is a variation on the standard DCP (ASTM D6951). In its most basic form, the DCP consists of a rod fitted with a conical tip that is driven into the soil by energy provided by a slide hammer (Webster 1992). The hammer is dropped a fixed distance onto an anvil attached to the rod, thereby transferring the kinetic energy to the conic tip. If the force is great enough, the soil fails in shear and the tip advances. The penetration of the rod into the soil as a result of the imparted energy is related to the strength of the soil. As the hammer mass and drop height are known, the kinetic energy is known. For coarse materials, the dynamic cone resistance \( q_d \) can be related to the test conditions and instrument geometry according to the commonly used Dutch formula (Cassan 1998).

\[
q_d = \left( \frac{1}{A} \right) \left( \frac{KE}{X} \right) * \left( \frac{M}{M + P} \right)
\]
where $A$ is the cross-sectional area of the cone, $KE$ is the imparted kinetic energy, $X$ is the incremental penetration (usually referred to as the DCP index (DCPI) and stated in mm/blow), $M$ is the mass of the hammer and $P$ is the mass of the penetrometer. The penetration $X$ is a function also of the angle of the cone. Cone angles of 60° and 90° are typically used.

There are several assumptions that are incorporated in Cassan’s formula that can influence the result under certain conditions; strain rate effects are not considered, the angle of the cone is not considered, and the energy coupling efficiency is assumed to be independent of soil conditions.

Many researchers (Webster 1992, Livneh 1987) have correlated the DCP index with an established measurement of soil strength, (CBR). The general equation is

$$\log(CBR) = K_1 - K_2(\log(DCPI))$$

where the $K_1$ and $K_2$ are constants that, for the simple penetrometer described, are dependent on soil type and moisture level. CBR can range from >100 for crushed coarse soils to <1 for fine grained materials containing high organic and water content.

It is well known that the relationship between the penetration per blow and soil strength is influenced by soil type and moisture. In ASTM D6951, for example, three calibration equations are provided for use on coarse materials, CL, and CH clays.

**Electrical Impedance Spectroscopy (EIS)**

The macroscopic interaction of electromagnetic fields with materials is described by Maxwell’s equations. Solution of Maxwell’s equations requires knowledge of three constitutive properties of the material: the magnetic permeability, the dielectric permittivity, and the electrical conductivity. In general, these parameters are dependent upon material composition, temperature, and the frequency of the applied field. As the permeability of typical soils is nearly that of free space, the soil electromagnetic response is determined by the dielectric properties. The heterogeneity of soil combined with significant interfacial electromagnetic effects between the highly polar water molecules and the soil solids surface results in a complex electrical response for which detailed phenomenological theories do not exist. There are three primary polarization effects in soil: bound water polarization, double layer polarization, and the Maxwell-Wagner (M-W) effect. The Maxwell-Wagner effect is the most important phenomenon that affects the low radio frequency dielectric spectrum of soils. The Maxwell-Wagner effect is a macroscopic phenomenon that depends on the differences in dielectric properties of the soil constituents. It is a result of the distribution of conducting and non-conducting areas in the soil matrix. This interfacial effect is dominant at frequencies less than ~30 MHz (Hilhorst 1998).

TransTech research has shown that typical well-graded sandy soils suitable for engineering fill exhibit a single M-W relaxation in the 1-10 MHz range (Gamache 2004). Above this frequency range, the dielectric response is empirically described by mixing equations in which the matrix bulk dielectric constant is proportional to the sum of the products of the volume fractions and dielectric constants of the constituents (Birchak 1974). At frequencies below the M-W relaxation, the apparent permittivity may rise more than an order of magnitude.
magnitude from its value in the mixing region (Gamache 2004). The conductivity is also dispersive, falling with frequency.

A qualitative representation of the dielectric properties of moist soil is presented in Figure 1. The dielectric spectrum can be roughly divided into two parts with the dividing frequency at about 20-50 MHz. The higher frequencies are dominated by the bound and free water relaxations and the lower frequencies are dominated by the Maxwell-Wagner effect. Research has shown that the details of the manifestation of the M-W effect into the impedance spectrum of soil provides a unique signature that can be used to separate the density and moisture contributions to the measured complex permittivity (Gamache 2004). This research has identified features in the M-W portion of the spectrum that can be used in conjunction with a parametric inversion method to calculate dry density and gravimetric water content of compacted soil (Gamache 2007).

4. Description of the New Measurement Approaches

Rapid Soil Characterization System

The first technology to be described, referred to as the Rapid Soil Characterization System (RapSochs), provides for characterization of unbound layers to a depth of one meter. While the primary objective of the technologies presented is to increase understanding of the interaction of water and pavement systems, understanding of the soil properties that relate to water retention and transport is also required. The RapSochs is an extension of well established CPT and DCP technologies that brings together measurement of soil strength, water content, and soil classification. Automation of the DCP drop hammer approach (ASTM D6951) provides the requisite ease of use, portability and cost effectiveness. Incorporation of an extended and miniaturized version of the CPT sensing strategy provides the required measurement capability. The sensing approach combines cone resistance and sleeve friction sensing from proven piezocone (CPT/CPTu) technology with additional new sensing technologies. The cone resistance and sleeve friction data are used to develop soil strength and soil type. Moisture measurement is provided by a TransTech developed EIS sensor. The RapSochs system is comprised of a penetrometer whose configuration (cone area, hammer mass, and drop height) is similar to the standard DCP specified in ASTM D6951. Strain gauges and a friction sleeve are arranged in the standard CPT subtraction cone configuration. An accelerometer is placed in contact with the tip to record the dynamic response to the hammer impact.
The EIS moisture sensor consists of an electrode to inject electromagnetic radiation in the frequency range from 0.5 – 30 MHz into the soil. A second electrode, spaced approximately 2.5 inches axially from the transmitter, senses the resultant signal that has been modified by the dielectric properties of the soil. The EIS approach, developed by TransTech as an alternative to nuclear density gauges, is currently used in an instrument that measures the density and water content of engineering soils (Soil Density Gauge (SDG)).

Laboratory testing has been conducted on a number of soils and conditions at Northeastern University. Data showing the correlation of soil strength measured with the RapSochs compared with a standard DCP is shown in Figure 3. Several advantages of the new technology are apparent in the Figure. In a standard DCP, no confinement is provided at the surface, and the penetrations are all made with a fixed drop height. The result is that, depending on the material, results in the first 100-150 mm are generally not accurate.
RapSochs is designed to provide a uniform equivalent overburden of ~100 mm. In addition, the drop height is adaptively controlled to provide a penetration per blow in the range 12.5-25 mm/blow. In the figure, the DCP measurements are not stable until ~120 mm, while the new approach provides useful data at 20 mm. The RapSochs system is designed to measure soil strength in the range from 1-100 on the CBR scale.

Moisture measurement performance is shown in Figure 4. Five samples of an SW material were prepared at nominal moisture levels of 2%, 3%, 4%, 5%, and saturated (13.2%) gravimetric. The figure shows resolution and tracking at the dry end of the scale as well as performance under saturated conditions.

Preparation of soil samples with uniform strength and moisture large enough to perform multiple non-interfering penetrations is difficult. Due to water mobility and the side effects of the method used to compact the material, samples prepared in closed containers were found to exhibit stiffness and moisture increase with depth. This can be seen in Figure 5. The sample was 0.6 m in diameter by 0.9 m deep, prepared in ~0.1 m layers. The moisture content was changed at several points, resulting in the cyclic pattern shown. Of note is the fineness of the spatial resolution due to the adaptive control of the drop height. The structure in the data is much less evident in the DCP and could be interpreted as spatial noise. The additional data points can be used to increase the accuracy of the measurements.

Asphalt Density and Moisture Sensor

Figure 6 shows the EIS soil density and moisture gauge. In this instrument, the transmit and sense electrodes are configured in a planar arrangement. The sensor can be configured for measurements from the surface, or non-contact measurements in which the sensor can be mounted on a vehicle to survey large areas quickly. The measurement depth is determined by the physical size of the sense elements, the electric field strength, the standoff from the surface, the soil conductivity, and the excitation frequency. The instrument was developed to measure the density and water content of engineering soils used for roadbeds, foundations.
embankments, and retaining walls. In this current research, the SDG is evaluated for measurement of the water content of asphalt in applications such as CIPR and WMA and detection of water in and below all types of asphalt.

Research was conducted to determine the detectability of water in two pavement scenarios that relate to pavement degradation. In the first experiment, a cracked longitudinal joint was simulated in the lab using two 30 cm x 30 cm x 10 cm asphalt blocks brought together along one edge. A scan was made across the joint with data points taken every 6 mm for a total of 32 cm centered on the joint using an EIS Soil Density Gauge with a standoff of 6 mm. Readings were taken with joint dry and with water in the joint held using an absorbent medium. Figure 7 shows the percent difference between the wet and dry readings, clearly demonstrating the detectability. The EIS technology is fast enough to facilitate rapid scans taken with vehicle mounted instruments, similar to currently used GPR.

![Figure 7: Detection of Water in Longitudinal Joint](image)

A second experiment was conducted to determine the ability to detect a saturated condition below a pavement layer using the EIS technology. The instrument used was designed to make quantitative measurements to a depth of 10-15 cm in soil. It will detect dielectric discontinuities, such as a layer of water, to much greater depth. The experiment consisted of placing a 60 cm x 30 cm x 10 cm slab of asphalt in a large container on standoffs to create a volume of air below the slab. A 30 cm linear scan was taken comprised of 25 data points. Data was taken with air and 50 cm deep layer of tap water below the slab. The mean relative permittivity of the dry sample was 1.0403 while the sample with water below the slab showed a relative permittivity of 1.1374, a change of 9.3%. The standard deviation of each data set was 0.027, so the result is significant at the 95% confidence level.

<table>
<thead>
<tr>
<th>Table 1. Curing of CIPR Mat Over One Week Timeframe</th>
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<tr>
<td>Data Location</td>
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<tr>
<td>----------------------------</td>
</tr>
<tr>
<td>Paved 9/21 Location A</td>
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<tr>
<td>Paved 9/21 Location B</td>
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<tr>
<td>Paved 9/15 Location A</td>
</tr>
<tr>
<td>Paved 9/15 Location B</td>
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</table>

To establish the feasibility of measurement of water in pavement by design, the EIS gauge was used to measure the relative water content on a CIPR job during the curing time (7 days in New York State). As the pavement cures, the water content falls and the strength increases. Dependent upon the temperature and precipitation during the cure time, the CIPR
layer may be ready for paving in as little as 2-3 days. Table 1 shows data taken on two finished lanes paved one week apart, showing consistently lower relative moisture level on the older mat. No rain was recorded during the period that could influence the observed change.

For CIPR and other processes in which the existing pavement is recycled (RAP), the in-situ water content of the RAP at the time of construction is important in determining the water content to be used in the emulsion. To assess the ability to determine the pre-construction in-situ water content, data was taken using the EIS sensor in the pavement prior to milling on two CIPR jobs in New York State. The same equipment and crew was used on Johnson Rd. as was used on Benmont Avenue. Data was taken at three locations separated by two meters longitudinally in the center of the paving lane. Data was taken prior to and throughout the paving and rolling operation. The Johnson Road job provided the opportunity to assess the affect of bulk water content by comparison with the Benmont Avenue data. As shown in Table 2, the relative moisture is higher for Johnson Road where heavy rain occurred the day prior to paving. Also note that lane B, which evidenced a much greater degree of alligator cracking prior to paving, showed a higher bulk moisture reading than lane A, indicating possible higher rain retention.

<table>
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<th>Table 2. RAP Bulk Moisture Sensitivity</th>
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<tr>
<td>Job/Lane</td>
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<tr>
<td>Benmont Ave. lane A</td>
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<tr>
<td>Benmont Ave. lane B</td>
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<tr>
<td>Johnson Rd. lane A</td>
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<tr>
<td>Johnson Rd. lane B</td>
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The results of the laboratory testing of the EIS Soil Density Gauge on soils used for construction are presented in Tables 3 and 4. The agreement between the two non-contacting SDGs calculation of moisture and oven dry moisture results (ASTM D2216) were assessed. The results show excellent agreement with the established standards.

<table>
<thead>
<tr>
<th>Table 3. Moisture Agreement Between ASTM D2216 and SDG</th>
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<tr>
<td>Avg. D2216 (% grav)</td>
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<td>---------------------</td>
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<tr>
<td>5.06</td>
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<td>6.43</td>
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<tr>
<td>Avg. STD</td>
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<tr>
<td>Avg. Diff</td>
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5. Further Research

The data available for both the SDG and RapSochs technologies to date has been developed from testing on a limited set of mainly coarse grained materials. In the future, this base of data will be extended to include clays and testing in which moisture levels are controlled.

The SDG was developed for application to quality control of construction materials and is calibrated in the laboratory on samples representative of the major USCS classifications. In the field, the calibration will be adjusted to the in-situ material by entry of job specific test data, such as gradation information and Proctor Test (ASTM D1557) results. For the new field applications posed in this paper, a priori calibration is not practical. In absence of calibration, the moisture level measured will be influenced by density and to a lesser degree salinity and temperature. For the RapSochs configuration, where soil strength and soil type are measured in addition to moisture, research will be conducted to assess the feasibility of using the soil type and strength information to produce more accurate moisture readings.

Additional testing has been initiated to verify the capability of the SDG to make the accurate quantitative measurements required to measure the water content in emulsions containing water and other additives not present in traditional HMA.

“As our understanding of and concern for water resources increase, it is becoming evident that in many contexts, hydrologic processes and components need to be modeled together as an integrated system (Winter 1998). With currently available computing power, it is now feasible to analyze and predict hydrologic systems through integrated modeling.” (Chui 2007) Man-made structures, e.g. pavement systems, can effect dramatic impacts on our hydrologic systems. Deeper understanding may result if they are considered together in modeling and in data analysis. As the models becomes more complex, it becomes even more important to have actual data, such as could be provided by the new technologies described herein, for model validation.

6. Conclusions

We have described practical, portable, easy to use, cost effective technologies that have the potential to facilitate prognostic, diagnostic, and characterization measurements of pavement layers and the unbound layers below and near the pavement system. Preliminary results indicate that the required soil geotechnical parameters necessary to characterize water movement can be extracted from dynamic penetration data.

The advantages of the SDG technology are 1), the potential to rapidly scan large areas in a vehicle mounted configuration and 2), the ability to simultaneously determine moisture and density in a single measurement. Advantages of the RapSochs technology are field portability and minimally invasive measurement (compared to CPT).

7. Acknowledgements

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