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FIELD MONITORING SYSTEM FOR SUCTION AND TEMPERATURE PROFILES UNDER PAVEMENTS

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Abstract: The purpose of this paper is to describe the development of and typical results from a new field monitoring system to evaluate changes in matric suction and temperature profiles in subgrade soil layers beneath constructed pavement systems over an extended period of time. This monitoring system involves the placement of sensors capable of inferring the volumetric water content and temperature of soils into a borehole in the shoulder of an existing pavement. High permeability silica flour is used to backfill the borehole around the sensors, so that changes in matric suction with depth in the subgrade can be inferred through the soil-water retention curve of the silica flour. The monitoring results from a pavement site in Arkansas with low permeability clay subgrade are compared with predictions from the Enhanced Integrated Climatic Model (EICM). The measured and predicted temperature distributions match well, but the EICM did not capture the fluctuations in matric suction inferred from the monitoring system. This can be attributed to the fact that the monitoring system captured the 2-dimensional water flow near the pavement shoulder, but also to the possibility that the EICM may not have adequately represented the water flow process through the asphalt and base course layers. Profiles of matric suction and temperature obtained using the monitoring system provide real-time, site-specific feedback on interactions between the atmosphere and pavement systems. Comparison of results from multiple pavement sites with clay subgrades across Arkansas demonstrates the variability in matric suction and temperature changes in different climatic settings.

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INTRODUCTION

Climatic interaction can have a significant impact on the performance of pavements, especially in states such as Arkansas where the subgrade often consists of poorly-draining, fine-grained soils. It is often desirable for engineers to monitor this climatic interaction within the pavement soil layers in order to either identify mechanisms of long-term distress in the pavement, to validate or calibrate design predictions for an upcoming pavement design in the region, or to refine pavement drainage system designs. Accordingly, this study is focused on a new approach to monitor temperature and matric suction distributions with depth in the subgrade beneath existing pavements. Field monitoring of water content and temperature in pavements is not a simple exercise due to the need to place sensors into the subgrade layer without causing significant disturbance to the pavement. Approaches that have been used in the past include placement of instruments into pavements during construction (Ovik et al. 1999), excavation of pits within the pavement (Liang et al. 2007), and excavation of trenches through the subgrade during resurfacing (Gupta et al. 2008). Although valuable information has been obtained from these studies, they involve re-compaction of the subgrade around the sensors, which may lead to hydraulic properties which are not representative of the undisturbed subgrade at other locations along the length of the roadway. The approach proposed in this study is to place sensors within a borehole drilled through the asphalt and base into the subgrade, and then to backfill the borehole layers of silica flour which are hydraulically isolated around each sensor with granular bentonite layers. This paper describes the details of how this approach can be used to infer the matric suction and temperature at different depths in the subgrade, and shows results from installations of this monitoring approach throughout Arkansas. The monitoring results are compared with predictions from the Enhanced Integrated Climatic Model (EICM), a numerical tool currently used to evaluate interaction between the atmosphere and a pavement system, in order to emphasize the need for site-specific monitoring of matric suction and temperature under pavements.

BACKGROUND

The results of the EICM are key inputs for long-term pavement design according to the Mechanical-Empirical Pavement Design Guide (ME-PDG) (National Research Council 2004). It is well established in geotechnical engineering that changes in matric suction in soils lead to changes in effective stress and mechanical properties (e.g., Lu and Likos 2006). The EICM has a long history, and incorporates a statistical model of published weather databases, a hydraulic model for gravity drainage of water from soil, a surface heat transfer model, and a one-dimensional diffusion model for coupled temperature and water flow including soil freezing and frost heave (Liu and Lytton 1985; Liang and Lytton 1989; Dempsey et al. 1985; Guymon et al. 1986). Individual models for each of these phenomena were integrated into the ICM by Lytton et al. (1993) which was refined to form the EICM by Larson and Dempsey (1997). The version of EICM evaluated in this study is Version 3.2 implemented in 2006 by Gregg Larson and Barry Dempsey of Applied Research Associates of Champagne, IL (Larson and Dempsey 2006). The main outputs of the EICM are the climatic conditions at a road location (surface temperature and precipitation), drainage behavior of the aggregate base from initially saturated conditions, changes in pore water pressure and internal temperature distributions due to weather fluctuations, and the likelihood of freeze-thaw conditions. This information has been found to be useful for sizing of drainage and hydraulic barrier systems in design, and has been correlated with the resilient moduli of the different pavement layers.

Calibration and validation of the EICM for states such as Arkansas is critical because of its unique topographical, geological, and geographical settings. Arkansas has several microclimates, a large spatial variation in subgrade soils, and a range in roadway geometries used in design for rural and urban applications. Without validation, use of the EICM for pavement design in Arkansas may either lead to over-design, resulting in high construction costs, or under-design, resulting in premature pavement failure. This was the main motivation behind a recent research project (TRC-0902) performed for the Arkansas State Highway and Transportation Department (AHTD) involving development of a new field monitoring approach to calibrate EICM predictions. Independent validation of the EICM has been attempted in several states departments of transportation in the U.S. including New Jersey (Ahmed et al. 2005), Idaho (Bayomy and Salem 2005), Ohio (Liang 2006; Quintero 2007), and Minnesota (Bjorn et al. 2007; Birgisson et al. 2007). In general, these studies had good success in predicting the variations in temperature with depth beneath the pavement. The model had varying success in predicting measured suction profiles. Birgisson et al. (2007) found that the model matched the water content (or suction) of the base material when it was wet, but under-predicted the water content when it was dry. Bayomy and Salem (2005) and Quintero (2007) observed that the EICM often predicted a negligible change in water content of the subgrade except near the interface with the base course, even though field measurements indicated some fluctuations over time. Zapata and Houston (2008) performed a careful evaluation of the EICM for different settings throughout the country, and observed an improvement in performance when site-specific soil properties were used in the EICM analysis. Although some of the differences between the EICM predictions and field monitoring systems can be attributed to the field monitoring systems used in these studies, the flow process of rainfall through the asphalt and base course layers are complex phenomena to capture in a numerical model.

FIELD TEST SITES IN ARKANSAS

Arkansas is a suitable setting to evaluate the new field monitoring system because there are six distinct regions in the state having different topographic, climatic, and geographic settings, shown in Figure 1. In general terms, the Ozark plateau is relatively dry due to its elevation with freezing temperatures through most of the winter, the Arkansas river valley is more temperate due to the effects of the river and lower elevation, the Mississippi embayment is relatively humid with warmer temperatures throughout the year, Northeast Arkansas has weather patterns affected by the contrast in elevation from the embayment due to Crowley's ridge, the west gulf coastal plain is relatively humid with temperatures similar to Louisiana, and the Ouachita mountains have a blend in climate between the Ozarks and the west gulf coastal plain. Seven pavement locations in each of these regions were selected as field test sites, also shown in the map in Figure 1. The pavement locations were selected to have the same surface treatment (i.e., asphalt concrete), similar geometries (i.e., embankment slopes, drainage ditch shape), previous performance (i.e., lack of cracking or rutting), and topographical settings (i.e., a flat section of road). A summary of the pavement geometry and climate characteristics for the sites is shown in Table 1. Weather data measured at weather stations within 10 miles of each site was collected from a publically-available online database (wunderground.com). This paper focuses primarily on the installation and interpretation results from the installation at Murfreesboro, AR, although a comparison of selected results from the other sites is also included.

FIELD MONITORING PROGRAM

The approach used in this study consists of inserting dielectric/temperature sensors into boreholes formed by pushing a Shelby tube into a core hole through the asphalt and base course layers. Because it is impossible to backfill a borehole with the soil obtained from the borehole (especially in the case of high plasticity clays), an alternative backfill material was required. Silica flour was selected as the backfill because it has a high hydraulic conductivity when unsaturated, and it can be poured easily in dry conditions into the borehole. Silica flour is essentially crushed rock with 100% fines content, and can be obtained from most pottery supply stores. Another advantage of using silica flour is that the calibration of sensors does not need to be performed for each site soil, only for the silica flour. The sensors used in this project were EC-TM® dielectric sensors, obtained from Decagon Devices of Pullman, WA, which are capable of simultaneously measuring temperature and inferring the volumetric water content. The volumetric water content is inferred by measuring the charge time of a capacitor circuit formed between the sensor and the soil. The charge time is directly proportional to the amount of water in the soil. The dielectric sensors can infer the volumetric water content of soils with an accuracy of approximately ±0.03 m^3/m^3, which is sufficient to evaluate flow processes in soils. The dielectric sensors are robust enough for deployment in field applications, and the corresponding datalogger has relatively long battery life and storage capacity (2-3 years).

Before implementation in the field, the sensors were calibrated in the laboratory in silica flour. The calibration setup is shown in Figure 2(a). A dielectric sensor was placed vertically in a graduated cylinder, and the silica flour was placed in dry conditions around the sensor and tamped into place to reach a dry density of 1330 kg/m^3. Water was then allowed to seep into the bottom of the cylinder under a low gradient, and the weight of the cylinder was tracked with time. The average volumetric water content of the soil layer was then correlated with the sensor reading, as shown in Figure 2(b). Negligible volume change occurred in the silica flour during this process. The nonlinear relationship between the average volumetric water content value and the sensor reading is due non-uniformity in water content along the length of the sensor during the upward flow of water. The calibration equation for the sensor was defined by fitting a straight line through the data.

A schematic of the typical monitoring system installed at each of the sites in Table 1 is shown in Figure 3. The goal of this monitoring system was to evaluate the fluctuations of matric suction and temperature in the subgrade under the water and heat flow boundary conditions representative of pavements. Water flow into the subgrade is affected by the asphalt layer, which has comparatively low permeability (unless cracked), as well as by the base course layer, which may transmit water laterally before it is able to enter the subgrade. Heat flow into the subgrade is also affected by the asphalt, which has low albedo and absorbs a greater amount of heat than soil, as well as by the base course layer, which may provide an insulating effect. Although the monitoring system could have been installed anywhere through the cross-section of the pavement, the monitoring systems in this study were all installed through the pavement in the shoulder of the road to avoid closing the road during installation. The subgrade near the shoulder of the pavement is where the greatest fluctuations in matric suction are expected, as water and heat flow may be affected by flow of water into or out of the exposed subgrade in the drainage ditch of the roadway. Although a monitoring station in the pavement shoulder is not ideal for calibration of the EICM, which considers 1-dimensional vertical water and heat flow in the subgrade under the center of the pavement, this choice of location is better than in the drainage ditch of the pavement where there is no asphalt on the surface. Further, measurements from the pavement shoulder provide useful calibration data for flow analyses with other 2-dimensional programs.

A challenge in developing the monitoring system was to ensure that the dielectric sensors infer the matric suction at a desired depth. For example, if the borehole had been backfilled with only silica flour, water flowing through the base course layer would preferentially fill the borehole, bypassing the subgrade. After a sensor has been lowered to a desired depth in the borehole, the hole is backfilled with silica flour to a depth slightly above the sensor and tamped into place with a rod. Next, a 50 to 100 mm-thick layer of granular bentonite is placed in the hole atop the silica flour. The layer of bentonite will hydrate by absorbing water from the surrounding soil, forming a low-permeability seal between the pockets of silica flour surrounding each dielectric sensor. Additional sensors are then placed into the borehole in a similar manner until reaching the top of the subgrade, as shown in Figure 3. The discrete pockets of silica flour at different depths will reach hydraulic equilibrium with the subgrade soil surrounding the borehole at each of the depths. The bentonite layers prevent water entering the silica flour at one depth from passing preferentially to the other layers.

Pictures from installations in Arkansas are shown in Figure 4. The first step in the installation is to create a 10.16 cm core through the asphalt layer. This core is used to determine the as-built thickness of the asphalt layer. The next step is to auger through the base course layer and the top of the subgrade, as shown in Figure 4(a). After subgrade soil is observed on the auger, the hole is cleaned and the as-built depth of the base course layer is measured. Two thin-walled, 91.44 cm-long Shelby tube are then pushed into the subgrade in sequence to obtain intact samples of subgrade soil up to a depth of nearly 2 m from the pavement surface, which also form a smooth hole in the subgrade after extraction. The intact Shelby tube samples of soil from each site were transported to the laboratory for geotechnical characterization. The next step of the installation is to use an asphalt saw to cut a channel in the asphalt to the edge of the shoulder as shown in Figure 4(b). The completed channel is shown in Figure 4(c). Dielectric sensors are placed into the borehole as described in the previous paragraph as shown in Figure 4(d). The dielectric sensor cables are fed through a flexible electrical conduit for protection, which was passed through the channel in the asphalt. The voids around the cables in the base course layer are backfilled with bentonite to prevent lateral flow from the base course into the borehole. Cold mix asphalt was used to patch the hole and channel in the asphalt, as shown in Figure 4(e). The conduit was buried in the subgrade soil and was attached to a metal box attached to a street sign or metal post, as shown in Figure 4(f). The metal box was found to provide good protection of the datalogger from water, traffic, animals, and mowers.

A novel aspect of the monitoring system is the analysis used to infer the matric suction at different depths in the subgrade. The dielectric sensors infer the volumetric water content of the silica flour, not that of the surrounding soil. Although the soil at the interface with the silica flour may have significantly different water content, the matric suction at the interface is continuous. This means that the dielectric sensors are used to infer the matric suction in the soil by way of measuring the water content of the silica flour. The soil-water retention curve (SWRC) for the silica flour is shown in Figure 5 along with that of a typical clay soil. The SWRC of the silica flour was obtained using a hanging column test according to ASTM D6836. This pair of SWRCs can be used to explain the concept of suction measurement using the dielectric sensors. For instance, if the dielectric sensor indicates that the volumetric water content of the silica flour is 0.20 m^3/m^3, a value of matric suction equal to 150 kPa can be estimated using the SWRC of the silica flour. Because the suction must be continuous at the interface between the silica flour and surrounding soil, the matric suction within the soil at this depth must also be 150 kPa. The SWRC for the clay soil can be used to estimate that the volumetric water content of the soil is 0.29 m^3/m^3 for a matric suction of 150 kPa. One reason for selecting silica flour as the backfill is that it has relatively high permeability when unsaturated, which means that water will be readily transmitted from the subgrade soil to the silica flour around the dielectric sensors. Further, the thermal conductivity of silica flour is similar to that of soils, so the temperature measurements from the dielectric sensors can be assumed to represent the temperature in the subgrade.

An example of the calibrated volumetric water content data obtained from one of the sensors is shown in Figure 6(a). The dielectric sensor readings show that the silica flour initially required several weeks to equilibrate with the suction within the surrounding subgrade because it was initially dry. The volumetric water content at each time increment was converted to matric suction using the approach described in the previous paragraph, as shown in Figure 6(b). The results in this figure indicate that conditions were generally wet at the site, except during the summer of 2010, when the suction in the subgrade reached high values due to dry weather conditions.

TYPICAL FIELD MONITORING RESULTS

The values of matric suction and temperature inferred from the dielectric sensors for the site near Murfreesboro are presented in Figure 7. The matric suction values inferred from the sensors at different depths below the pavement surface shown in Figure 7(a) follow reasonable fluctuations representative of wetting and subsequent drying due to climate interaction after December 2009. Representative suction profiles at different times are shown in Figure 7(b). The suction profiles obtained at the wetting and driest times of the year can be used to establish an envelope of typical suction values for a site, which is important for design. Water was often observed in the drainage ditch at the site during data collection, which indicates that the water table is relatively close to the pavement (within 2 meters of the pavement surface). For most of the monitoring period, the magnitude of suction inferred from the dielectric sensors was approximately 50 kPa, which corresponds to nearly saturated conditions. During the summer of

2010 the suction increased up to 3000 kPa, indicating a potentially substantial decrease in water content during a dry period at the site. An increasing trend in suction with height is consistent with drying from the soil surface. The temperatures in Figure 7(c) generally follow the same trend as the air temperature, which will be discussed later in the paper. The temperature profiles shown in Figure 7(d) indicate that the soil nearer the pavement surface is affected more by fluctuations in the temperature of the pavement surface (which may be greater than the air temperature).

Although it is not possible to show the matric suction and temperature data from all 7 sites in this paper, the measured time series of matric suction and temperature obtained from the sensor closest to the pavement surface at six of the seven sites is shown in Figures 8(a) and 8(b), respectively. The data from Marked Tree is not shown because monitoring was stopped shortly after monitoring was started at the other six sites. The data in Figure 8(a) indicates that the matric suction near the base course at each site follows different trends depending on the site-specific boundary conditions, but during the wet season the subgrade typically approaches a suction of approximately 50 kPa. The data in Figure 8(b) indicates that the temperature in the upper portion of the subgrade near the pavement surface does not vary significantly from site to site in trend, but the magnitude of temperature can vary by as much as 20 °C.

COMPARISON WITH EICM PREDICTIONS

The EICM was used to predict the matric suction and temperature profiles at the Murfreesboro, AR site using Level 3 inputs for the subgrade soil properties and weather data, and Level 1 inputs for the asphalt and base layers. Specimens from the Shelby tubes were used to perform characterization tests on the subgrade soil, which classifies as CH according to the unified soil classification scheme (USCS) or as an AASHTO A-7-5 soil. The compacted aggregate base course was assumed to be an AASHTO A-3 soil. The thicknesses of the asphalt and base layers were set to be the same as those measured in the field. The SWRC of the subgrade soil was evaluated using the axis translation technique according to ASTM D6836, and the Fredlund and Xing (1994) SWRC model was fitted to the data. Graphs of the SWRCs for the base and subgrade used in the analysis are presented in Figure 9(a). The saturated hydraulic conductivity of a sample of clay extruded from the upper Shelby tube was measured using a flexible wall permeameter. The hydraulic conductivity functions (HCFs) were predicted using the Mualem (1976) capillary tube model which incorporates the parameters of the Fredlund and Xing (1994) SWRC model. The predicted HCFs are shown in Figure 9(b). The geotechnical index properties and hydraulic properties (the hydraulic conductivity and SWRC parameters) for the subgrade clay are summarized in Table 2. The thermal conductivity of the soil in the Shelby tube was measured using the KD2Pro thermal needle obtained from Decagon Devices of Pullman, WA.

The weather conditions from a weather station approximately 10 miles from Murfreesboro, AR were used in the EICM analysis. The air temperature is presented in Figure 10(a), while the precipitation is presented in Figure 10(b). Because EICM requires hourly inputs, the hourly temperature and precipitation data from a nearby weather station were obtained from the Weather Underground database. The water table was set at a depth of 2 meters from the top of the asphalt layer, based on site observations. The temperature was assumed to equal the mean annual air temperature at a depth of 10 meters below the asphalt surface, which is a common assumption in the design of ground-source heat pumps for locations that do not have a significant upward geothermal gradient (Brandl 2006). The EICM analysis was performed from January 1st 2010 to December 31st, 2010. For the EICM analyses, the initial water content in the subgrade was set to correspond to the water content inferred from the suction measured by the sensors on January 1st (0.324 m^3/m^3). The initial temperature profile used in the analysis was defined as the average annual air temperature.

The predicted suction profiles for the period of modeling are shown in Figure 11(a). This figure indicates that there were slight changes in suction near the top of the subgrade. However, there were no major fluctuations in suction during the summer and fall of 2010, as exhibited in the suction profiles inferred from the field monitoring system shown in Figure 7(b). This may be attributed to the permeability of the intact clay obtained from the laboratory test (which may be lower than the bulk soil mass in the field due to fissures or plant roots). Another reason for this difference may the approach by which the EICM applied infiltration and evaporation boundary conditions to the top of the subgrade. These boundary conditions are not explicitly described in the EICM manual, but are based on empirical relationships from pavements tests rather than on fundamental mechanisms.

Overall, the EICM was found not to provide an acceptable long-term prediction of the suction profiles in the subgrade layer. This observation was consistent with the other sites in Arkansas summarized in Table 1 (McCartney et al. 2010) and previous studies from the literature. Although the EICM has an advantage over other climate interaction models for soils in that it considers the impact of the asphalt and base course on infiltration of water, further refinement may be needed to better capture matric suction trends in clay subgrades. It is important to note that similar analyses were performed for the site with Level 2 soil property inputs, and the results did not change significantly. Because several months were required to obtain the soil-specific parameters in Table 2, a significant advantage was not gained in measuring the hydraulic properties of low permeability soils. This may not be the case in more sites with more permeable subgrade soils.

The predicted temperature profiles for the subgrade at Murfreesboro, AR are shown in Figure 11(b). The temperature results correspond much more closely with the measured temperatures shown in Figure 7(d). The model generally predicted lower temperatures than in the field (6 to 28 °C in the model compared to 3 to 36 °C in the field), possibly due to a greater insulation effect of the asphalt and base course at the site. Overall, a pavement design based on the EICM predictions of temperature is likely to provide adequate design results.

CONCLUSIONS

The experiences gained through the development of a novel field monitoring system and implementation at different locations throughout Arkansas indicates that reasonable profiles of matric suction and temperature could be obtained without significantly disturbing the existing pavement system. The monitoring approach was found to provide real-time, site-specific feedback on interactions between the atmosphere and pavement systems. Comparison of results from multiple pavement sites with clay subgrades across Arkansas indicates the importance of considering local climate conditions on the fluctuations in matric suction and temperature over time. The fluctuations in these variables may be useful in interpreting changes in the mechanical performance of the pavement system. In addition to identifying mechanisms of distress in pavement, the field monitoring results may also be useful to calibrate and refine predictions of water and heat flow through layered pavement systems. Comparisons between the field monitoring data and predictions from the EICM indicate that the model may still require further improvement to capture suction variations in low permeability soils. However, the EICM was found to provide an adequate prediction of the fluctuations in temperature within the subgrade compared to the field measurements. The consideration of the infiltration and evaporation boundary conditions applied to the subgrade surface in the EICM is one topic which should be further investigated to improve the prediction of water flow in low permeability soils.

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FIGURE CAPTIONS

Table 1. Pavement geometry and climate setting data for monitoring sites in Arkansas

Table 2. Geotechnical properties for the soil samples obtained from Murfreesboro

Fig. 1. Regions of Arkansas with distinct climate settings showing locations of sites for pavement monitoring in Arkansas

Fig. 2. Calibration of water content sensors in silica flour: (a) Setup; (b) Definition of calibration equation from transient inflow data

Fig. 3. Schematic of the field installation setup

Fig. 4. Field monitoring system installation pictures: (a) Augering through base course; (b) Cutting channel through asphalt; (c) Final channel in asphalt running to the edge of the shoulder; (d) Installation of sensors and backfilling with silica flour; (e) Cold-mix patch covering the borehole and channel in the asphalt; (f) Datalogger box attached to metal post in shoulder

Fig. 5. SWRCs of silica flour and a typical clay subgrade showing the concept of estimating the suction and volumetric water content of the clay subgrade

Fig. 6. Example of conversion of results from a dielectric sensor embedded in silica flour: (a) Inferred volumetric water content of the silica flour; (b) Converted suction values for the subgrade clay

Fig. 7. Results from field measurements at Murfreesboro: (a) Suction time histories for different depths; (b) Selected suction profiles; (c) Temperature time histories for different depths; (d) Selected temperature profiles

Fig. 8. Comparison of measurements in the subgrade at different sites around Arkansas (note: measurement locations are the closest to the bottom of the base course layers at each site): (a) Matric suction; (b) Temperature

Fig. 9. Soil hydraulic properties used in EICM analysis: (a) SWRCs; and (b) Hydraulic conductivity functions

Fig. 10. Climate conditions used in the EICM analysis: (a) Temperature; (b) Precipitation

Fig. 11. Predictions from EICM for Murfreesboro over the course of a year: (a) Matric suction profiles; (b) Temperature profiles

Table 1. Pavement geometry and climate setting data for monitoring sites in Arkansas

Site	Region	Asphalt thickness (mm)	Base thickness (mm)	Temperature (°C)			Relative humidity (%)			Mean daily precipitation (mm)
				Max.	Mean	Min.	Max.	Mean	Min.	
Greenland	Ozark Mountains	88.9	177.8	20.1	14.0	7.9	91.7	71.4	46.8	3.01
Plumerville	Arkansas River Valley	76.2	177.8	22.1	15.7	9.4	92.8	71.8	45.4	3.28
Malvern	Central Arkansas	50.8	177.8	22.7	17.1	11.3	86.7	66.2	45.2	3.71
Murfreesboro	Ouachita Moutains	82.6	304.8	23.5	16.8	10.1	93.7	70.2	46.0	2.80
Camden	West Gulf Coastal Plain	152.4	355.6	21.8	16.2	10.4	98.0	77.7	52.5	0.70
Lake Village	Mississippi Embayment	114.3	343	23.3	17.6	11.7	89.9	69.9	48.0	3.22
Marked Tree	Northeast Arkansas	60.0	220.0	21.2	15.7	10.1	89.1	69.2	48.3	3.53

Table 2. Geotechnical properties for the soil samples obtained from Murfreesboro

Soil property		Value	Units
Thermal conductivity		2.131	W/(m·°C)
Hydraulic conductivity of saturated soil		2.23×10^{-11}	m/s
Fredlund and Xing (1994) SWRC parameters	θ_s	0.38	m^3/m^3
	θ_r	0.00	m^3/m^3
	a_{FX}	350	kPa
	n_{FX}	1.50	
	m_{FX}	0.40	

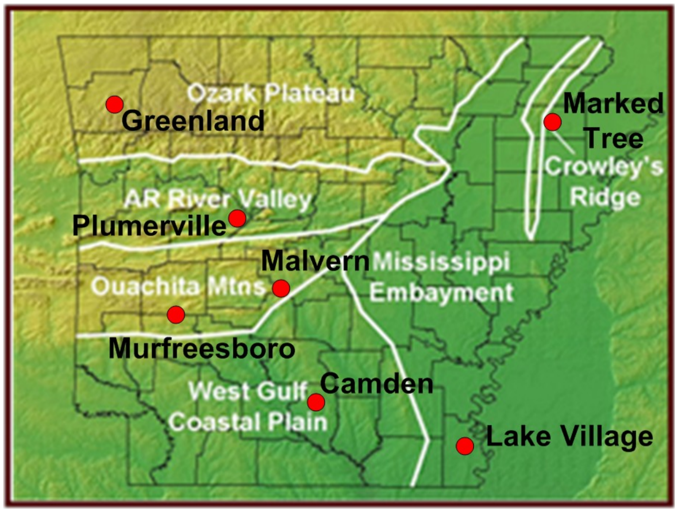

Fig. 1. Regions of Arkansas with distinct climate settings showing locations of sites for pavement monitoring in Arkansas

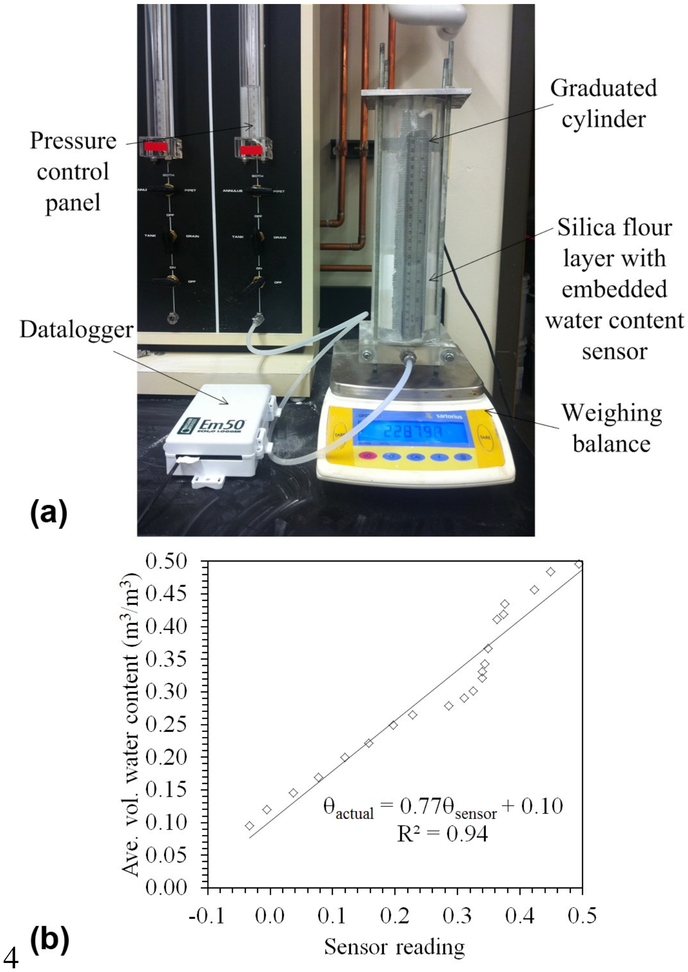

Fig. 2. Calibration of water content sensors in silica flour: (a) Setup; (b) Definition of calibration equation from transient inflow data

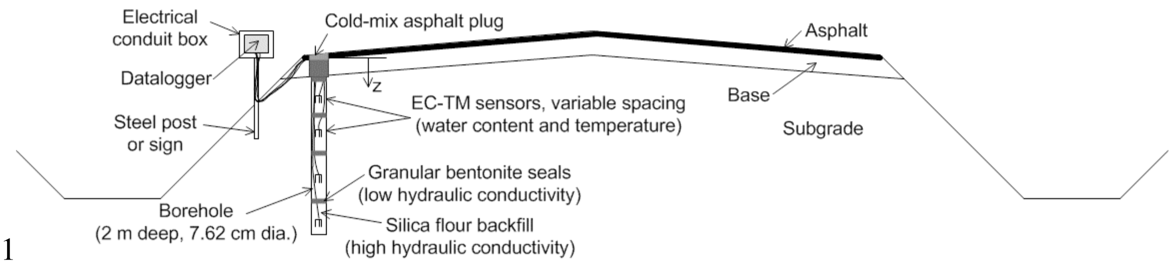

Fig. 3. Schematic of the field installation setup

Fig. 4. Field monitoring system installation pictures: (a) Augering through base course; (b) Cutting channel through asphalt; (c) Final channel in asphalt running to the edge of the shoulder; (d) Installation of sensors and backfilling with silica flour; (e) Cold-mix patch covering the borehole and channel in the asphalt; (f) Datalogger box attached to metal post in shoulder

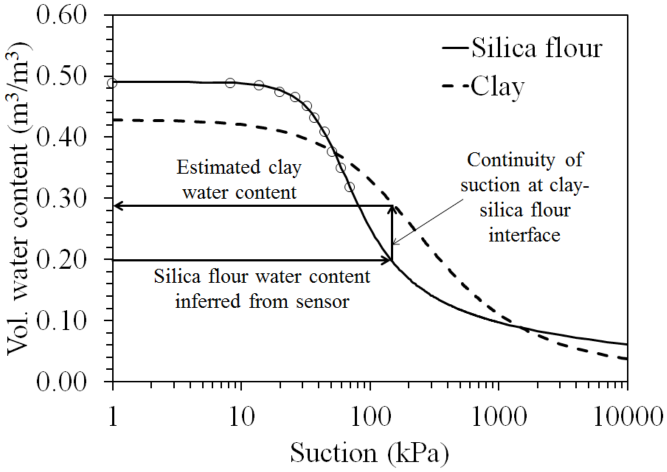

Fig. 5. SWRCs of silica flour and a typical clay subgrade showing the concept of estimating the suction and volumetric water content of the clay subgrade

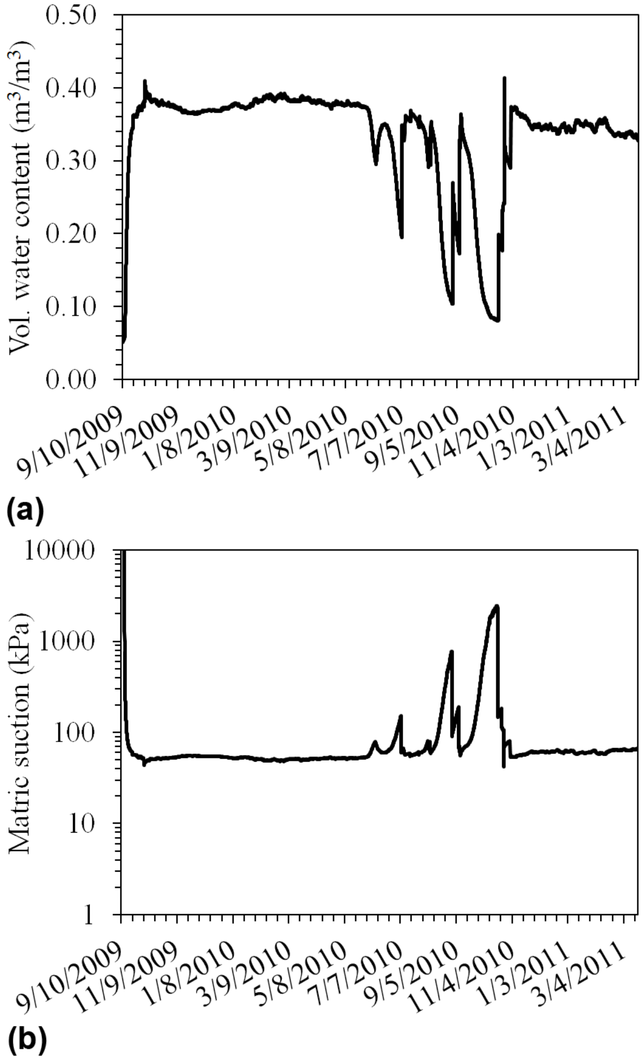

Fig. 6. Example of conversion of results from a dielectric sensor embedded in silica flour: (a) Inferred volumetric water content of the silica flour; (b) Converted suction values for the subgrade clay

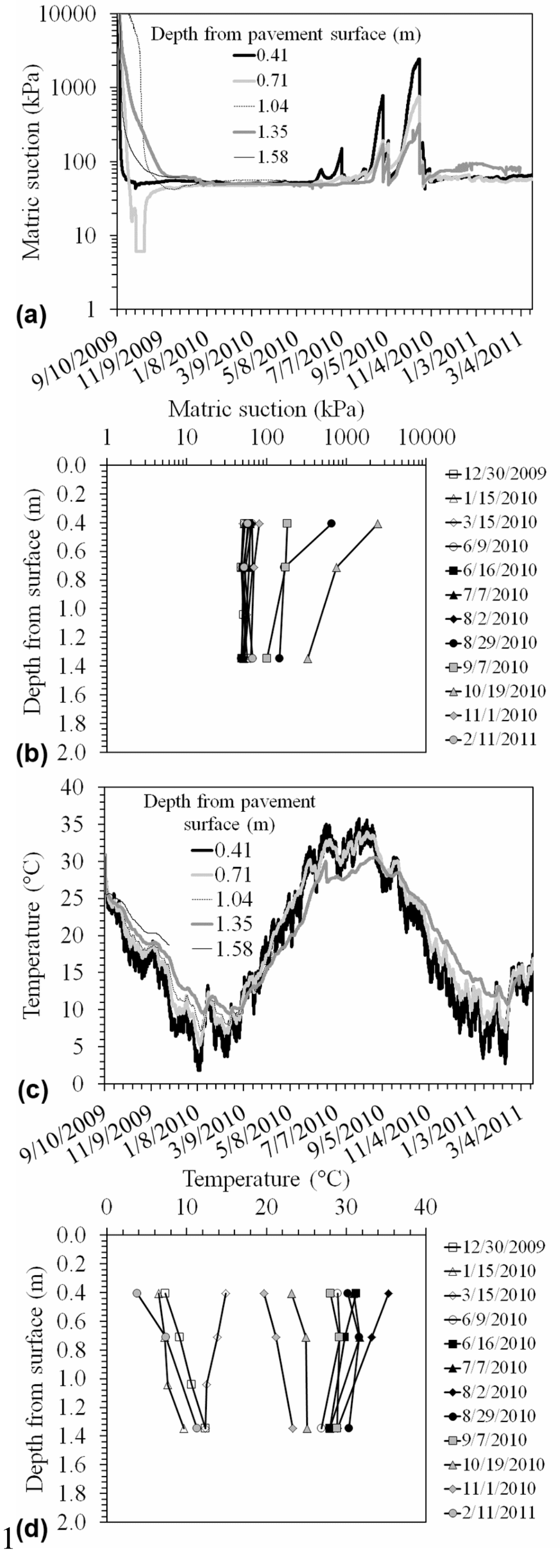

Fig. 7. Results from field measurements at Murfreesboro: (a) Suction time histories for different depths; (b) Selected suction profiles; (c) Temperature time histories for different depths; (d) Selected temperature profiles

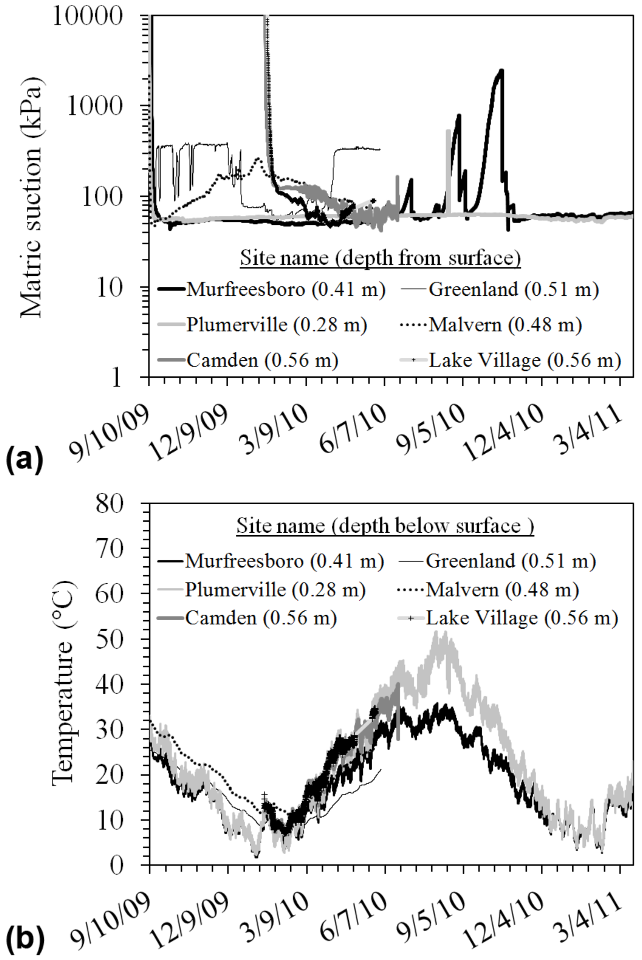

Fig. 8. Comparison of measurements in the subgrade at different sites around Arkansas (note: measurement locations are the closest to the bottom of the base course layers at each site): (a) Matric suction; (b) Temperature

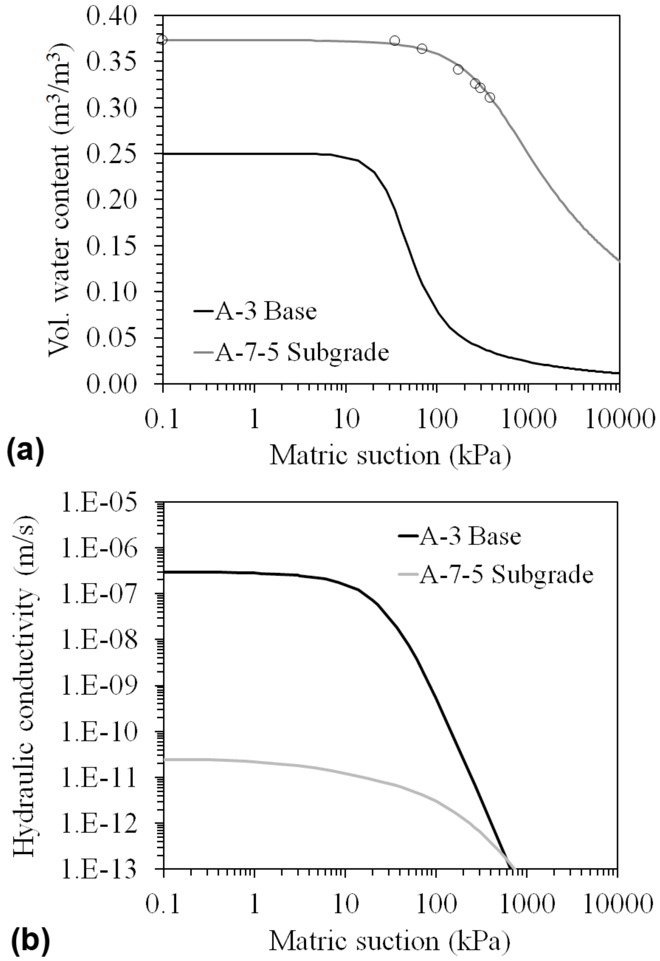

Fig. 9. Soil hydraulic properties used in EICM analysis: (a) SWRCs; and (b) Hydraulic conductivity functions

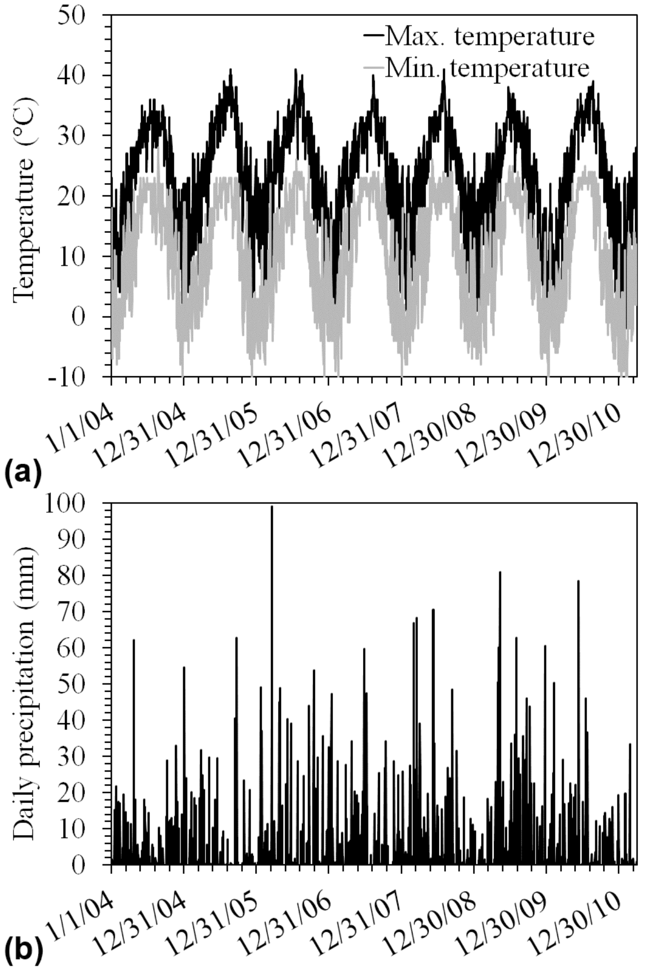

Fig. 10. Historic climate conditions at Murfreesboro used in the EICM analysis: (a) Temperature; (b) Precipitation

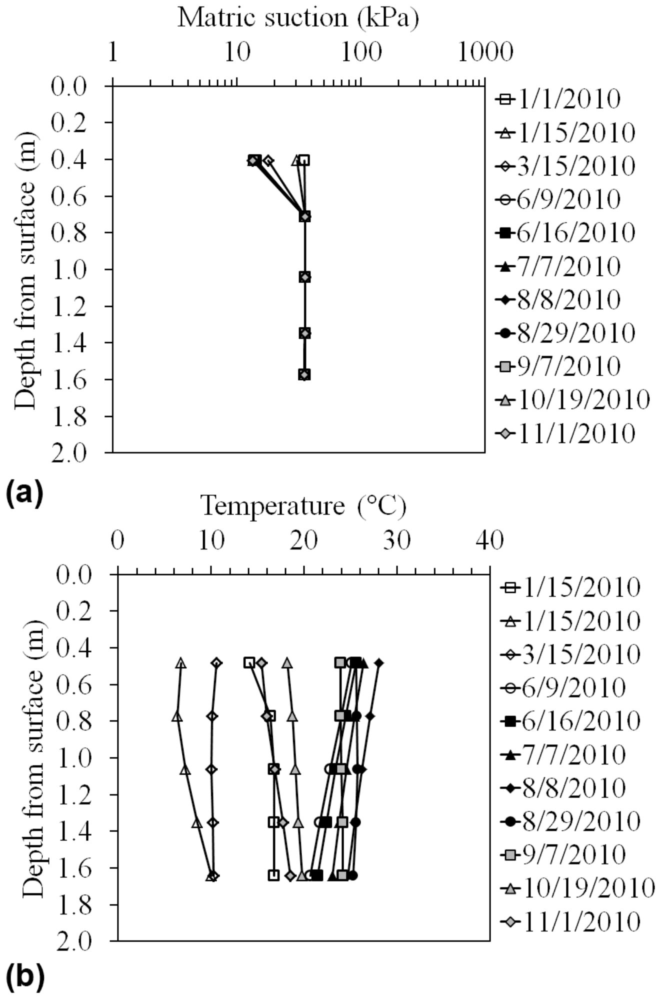

Fig. 11. Predictions from EICM for Murfreesboro over the course of a year: (a) Matric suction profiles; (b) Temperature profiles