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Effect of Pavement Design Features on the Volumetric Moisture Content of Subgrade Soils

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Abstract

The effect of pavement design features on the volumetric moisture content (VMC) of subgrade soils was studied through the analysis of Time Domain Reflectometry (TDR) data obtained at the Ohio SHRP Test Road. All subgrade TDR readings showed a characteristic annual sinusoidal variation in Volumetric Moisture Content (VMC), reaching a peak during the month of August and a valley during the month of February. This is indicative of a lag that occurs between the normally high precipitation in the spring and the high subgrade moisture that occurs in August. VMC time series may be fitted with a sinusoidal function by regression of data for each sensor, including VMC as the dependent variable and the day of the year (in the Julian calendar) as the independent variable.

Pavement type (AC or PCC) did not appear to have any appreciable effect on the VMC of the subgrade. It was also found that the VMC did not always increase with depth and, typically, the average and mean VMC for each TDR sensor was found to increase and decrease in an oscillatory manner within a very narrow range with depth. VMC data obtained from the Ohio Test Road showed, in most cases, a slight reduction in moisture close to the subgrade surface when longitudinal drains were present.

Key words: Subgrade moisture content, time domain reflectometry, rigid pavements, flexible pavements, test roads

Introduction

State and federal agencies have provided significant funding over the last few decades to improve the performance of multi-layered hot mix asphalt (HMA) and Portland cement concrete (PCC) pavements, and to determine how performance is affected by various parameters associated with mechanistic design. These initiatives have resulted in the establishment of working “field laboratories” to obtain long term response and performance data where traffic and environmental conditions are closely monitored. One such installation was the Ohio SHRP Test Road, a three-mile long facility constructed on U.S. 23 about 16 km (10 miles) north of

Delaware, Ohio. Instrumentation was installed at this site to monitor environmental conditions, traffic loading and dynamic pavement response in several HMA and PCC pavement sections.

Researchers and practitioners have developed various designs and appurtenances to improve pavement performance for several decades. Subgrade stiffness has been established as one critical factor which directly affects pavement response and, ultimately, the development of distress contributing to decreased pavement serviceability. The influence of moisture content, or degree of saturation, on the stiffness of fine-grained subgrade soils has been well established in both laboratory and field studies. The stiffness of coarse-grained soils, however, is not greatly affected by moisture contents below saturation, since the total stress equals the effective stress and the stiffness relates directly to the interaction between individual soil particles. The Ohio SHRP Test Road contains a fairly consistent fine-grained subgrade soil, thus providing an opportunity to observe how different pavement designs affect subgrade moisture at one site.

Specifically, this paper summarizes the effects of HMA and PCC pavements, longitudinal edge drains and dense-graded aggregate base (DGAB) on subgrade moisture.

Background

The Ohio SHRP Test Road originally contained a total of forty HMA and PCC pavement sections in the following four experiments (Sargand, 1994[1]):

SPS-1: Strategic Study of Structural Factors for Flexible Pavements
SPS-2: Strategic Study of Structural Factors for Rigid Pavements
SPS-8: Study of Environmental Effects in the Absence of Heavy Traffic
SPS-9: Asphalt Program Field Verification Studies

Eighteen of the forty sections contained instrumentation to monitor temperature, moisture content and frost depth within the pavement profile, and data has been collected at most of these instrumented sections since 1996. Subgrade moisture was monitored with probes containing a series of ten time domain reflectometry (TDR) gauges installed at depths up to about 1.83 m (6 ft.) below the top of the DGAB or subgrade. The TDR is an electromagnetic sensor used for spatial location (RADAR) and volumetric water content determination. It operates by emitting an electromagnetic wave and by sensing changes in the medium as the wave is reflected back and received by the source. Spatial characteristics and the reflected waveform can then be used to determine distance and moisture content. The use of TDRs for measuring moisture has the following advantages: they are fast and involve a simple analysis, the relationship between dielectric constant (K_a) and volumetric moisture content (VMC) is non-hysteretic and does not drift (Suwansawat, et al. 1999[2]), the cost is reasonable, the equipment is reliable, they can be monitored remotely, and they are nondestructive once the probes have been embedded at the desired location.

To calculate VMC, the dielectric constant (K_a) is first evaluated from the apparent length L_a. After eliminating non-significant losses generated in the signal propagation (Roth et al., 1990[3]), the dielectric constant is calculated by the equation:

$$K_a = \left[\frac{L_a}{(L)(V_p)} \right]^2 \tag{1}$$

Where: L= Length of probe in meters; (0.203 m for FHWA probes).
V_p= Ratio of actual propagation velocity to the speed of light; usually taken as 0.99 (Rada et al. 1995[4]).

The apparent length is commonly determined by either the method of tangents or the method of peaks. Once the dielectric constant is calculated from the apparent length, the VMC can be determined through the polynomial equation:

$$VMC = a_0 + a_1K_a + a_2K_a^2 + a_3 K_a^3 \tag{2}$$

Where, a_0, a_1, a_2 and a_3 are coefficients proposed by FHWA[5] for various soil types (Table 1).

Table 1. Volumetric Moisture Model Parameter Estimates[5]

Model Name	a_0	a_1	a_2	a_3
Coarse - K_a model	-5.7875	3.41763	-.13117	0.00231
Fine - K_a model	0.4756	2.75634	-0.061667	0.000476
All Soil - K_a model	-0.8120	2.38682	-0.04427	0.000292

ERES Consultants, Inc. (2002) through a contract with the FHWA[5], developed the Windows-based computer program MOISTER to evaluate VMC manually or automatically, giving the user the choice of selecting either the method of tangents or the method of peaks to determine apparent length. MOISTER uses TDR traces and supporting documentation from input databases created in MS-ACCESS (version ’97) to generate dielectric constants and volumetric moisture content tables that can be easily exported to any data display computer program.

Data Processing and Analysis

TDR traces obtained between mid 1996 and December 2002 on the Ohio SHRP Test Road were processed using MOISTER and the automatic method of tangents. In total, 11450 records were processed, corresponding to 1145 data collection events at the 18 environmental sites. The ACCESS moisture table generated by MOISTER required additional reorganization to sort records by increasing date and sensor order. To achieve this, a BASIC program was written to transpose and organize all VMC data in columns corresponding to each of the ten sensors installed at individual seasonal monitoring stations from earlier to most recent order of data acquisition.

To facilitate the comparison of the effects of pavement type (HMA or PCC), longitudinal edge drains, and/or dense graded aggregate base (DGAB) on subgrade moisture, pavement sections were paired into groups of two. The groups contained instrumented sections located either across from or adjacent to each other in an effort to minimize variations in soil type, water table elevation and surface topography. Table 2 shows how test sections were combined for study, including: group number, section identification, pavement type, presence of longitudinal edge drains and presence of DGAB.

Table 2. Pavement Section Comparison Matrix

GROUP	SECTION NO.	PAVEMENT TYPE	DRAINS	DGAB
Sections across from each other				
1	N (390104)	HMA	No	No
	E (390205)	PCC	No	No
2	L (390904)	HMA	Yes	Yes
	C (390212)	PCC	Yes	Yes
3	R (390110)	HMA	Yes	No
	J (390263)	PCC	Yes	Yes
Sections adjacent to each other				
4	B (390204)	PCC	No	Yes
	C (390212)	PCC	Yes	Yes
5	H (390203)	PCC	No	Yes
	G (390211)	PCC	Yes	Yes
6	I (390208)	PCC	No	No
	H (390203)	PCC	No	Yes
7	L (390904)	HMA	Yes	Yes
	M (390112)	HMA	Yes	No

Data for each pavement section were statistically analyzed to calculate the average and median VMC for each TDR throughout the monitoring period. Results of the analysis include:

1. Seasonal Variation of Volumetric Moisture Content

A typical VMC time series for the ten TDRs installed in Section B (390204) at the Ohio SHRP Test Road is shown in Figure 1. These sensors, identified as S1 to S10, were located from a depth of approximately 50 mm (2 in.) below the top of the DGAB to a depth of approximately 1.6 m (5.25 ft.) below the top of the subgrade. Sensor S1, which indicated a substantially lower moisture content than the remaining nine sensors, was placed within the DGAB. All subgrade sensors showed a characteristic annual sinusoidal variation in VMC, reaching a peak during the month of August and a valley during the month of February. It is thus possible to fit the VMC test data with a sinusoidal function of the form:

$$VMC = b_0 + b_1 * \sin\left[\frac{2\pi t}{365.25} + b_2\right] \quad (3)$$

Where: VMC = Volumetric moisture content in %

t = Day of the year in the Julian calendar, varying from 1 to 365 or 366.

A regression analysis of data for TDR S5 shown in Figure 1 yielded the following coefficients for Equation 3 and a Coefficient of Determination (R^2) = 0.88:

b_0 = 39.35, b_1 = -2.503 and b_2 = -131.07

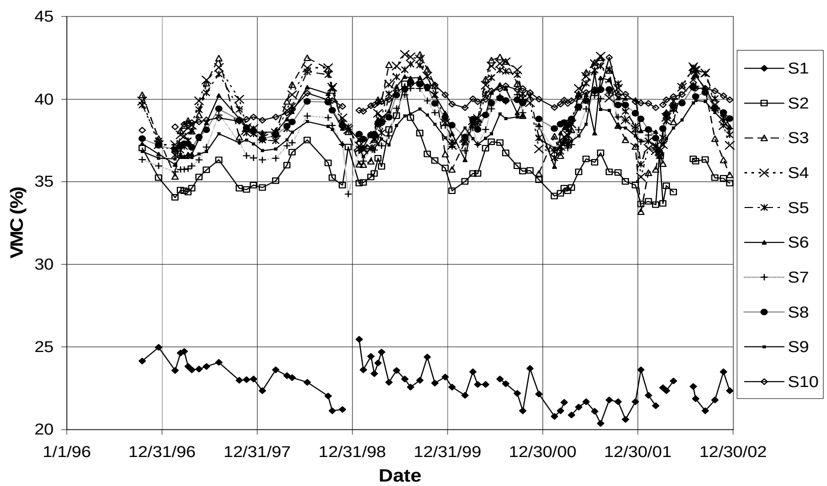

Figure 1. VMC Time Series for Section 390204.

When the coefficients were applied to Equation 3, the maximum VMC occurred on Day 223 (August 11) and the minimum VMC occurred on Day 41 (February 10). Similar results were obtained with the remaining sensors plotted in Figure 1. The timing of maximum and minimum VMCs indicates that a lag exists between the normally high levels of precipitation in the spring and the high subgrade moisture measured in August. This is in substantial agreement with the results of research reported by Figueroa (2004)[6], where consistent relationships were found to exist between one-week or one-month accumulated precipitation and the degree of saturation in the subgrade. A lag time of 80 to 85 days was typical before the degree of subgrade saturation was affected by significant precipitation events. Time series plots for moisture did not show consistent trends of higher VMC with depth in all sections. Average and mean VMCs were found to increase and decrease in an oscillatory manner within a very narrow range at given depths within the subgrade. At times and coinciding with the winter months, the VMC measured by the top few TDRs was significantly lower than normal, suggesting that frost had reached these sensors; thus these points were excluded from the analysis.

Preliminary TDR measurements during subgrade construction in 1995 and after construction of the base and pavement layers in 1996 indicated that soil moisture increased substantially after placement of the base and pavement layers until an oscillatory steady-state condition was reached, as shown in Figure 1. As an example, the VMC time series for Section 390203 showed increases of 2 to 12% after placement of the pavement. This early increase in VMC may have been caused by moisture migrating laterally back into the subgrade after construction and/or the pavement acting as a barrier to moisture evaporation. Moisture could also have followed the TDR cables to the sensor, although the regular seasonal cycles would tend to discount this possibility.

2. Effect of Pavement Type on Subgrade VMC

Pavement type (HMA or PCC) does not appear to have an appreciable effect on the VMC of the subgrade. This is evident by comparing how the average and median VMC of HMA and PCC sections located across from each other in Groups 1, 2 and 3 (Figures 2, 3 and 4, respectively) follow one another closely over time. The presence of a DGAB layer in Sections 390904, 390212 and 390263 is easily detected by the reduced VMC measured by sensor S1. VMC points in Section 390110 (Figure 4) have been shifted one position to the right to more closely match sensor positions with respect to the top of the subgrade in Section 390263. Thus, the depth of TDR S1 in Section 390110 is closer to that of TDR S2 in Section 390263, and so on, as indicated by the horizontal axis labels.

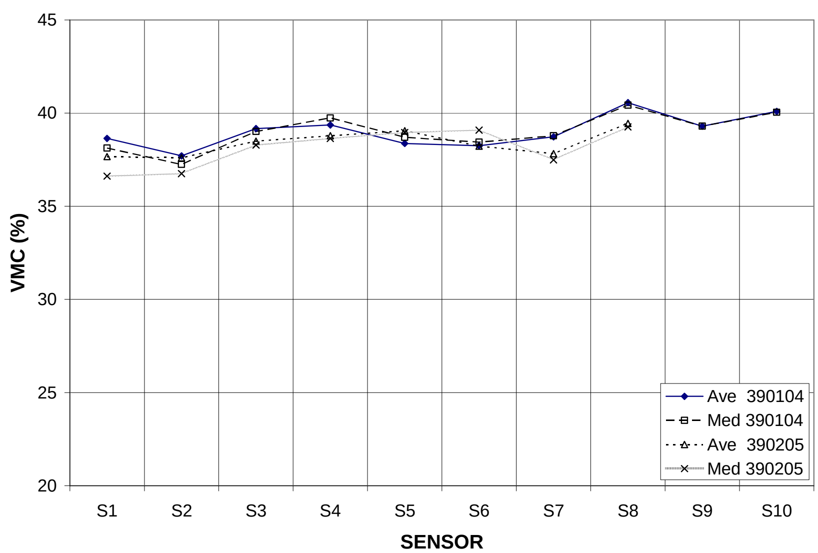

Figure 2. Average and Median VMC in Sections 390104 & 390205.

3. Effect of Longitudinal Drains on Subgrade VMC

Longitudinal edge drains have traditionally been specified to remove excess moisture that enters pavement structures by:

a. Permeating from the surface through porous layers or seeping through joints and cracks.
b. Lateral seepage.

c. Rising water table.
d. Capillary action or interconnected water films.
e. Movement of vapor by temperature gradients and air void space.

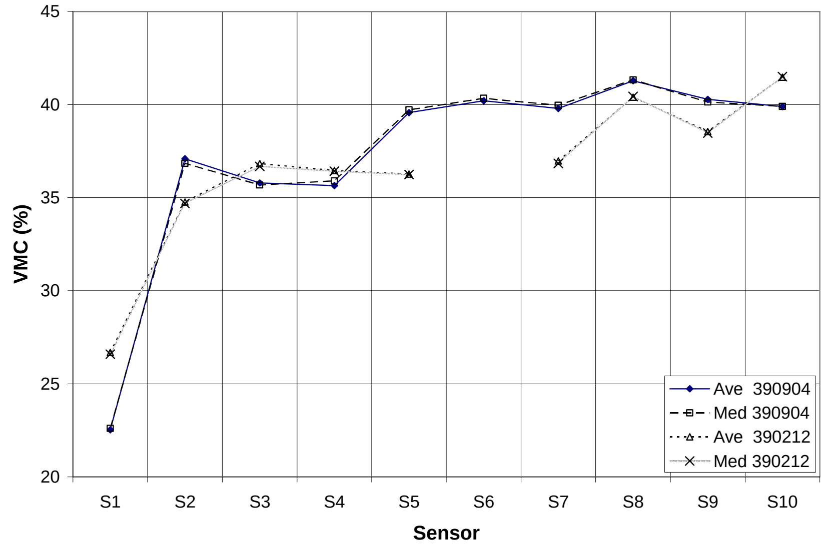

Figure 3. Average and Median VMC in Sections 390904 & 390212.

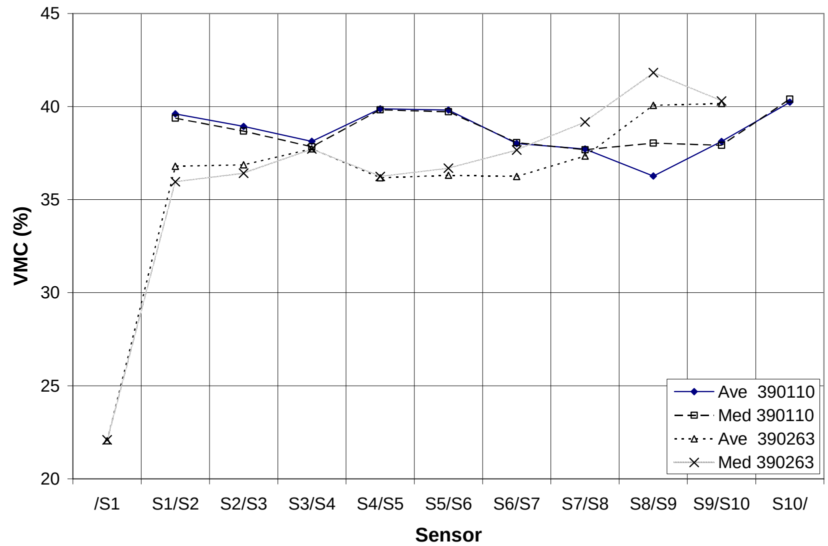

Figure 4. Average and Median VMC in Sections 390110 & 390263.

VMC data obtained from the Ohio SHRP Test Road shows, in most cases, a slight reduction in moisture close to the subgrade surface when longitudinal drains (placed at a depth of 50.8 cm or 20 in) present. Figures 5 and 6 indicate an average reduction of about 2% in VMC measured by the upper sensors in sections comprising Groups 4 and 5 in Table 2. Both of these groups include sections constructed with a DGAB.

Referring back to Figures 2 (sections without drains) and 3 (sections with drains), the latter also shows a slight reduction in VMC measured by the top four sensors. This effect may be influenced, however, by the presence of a DGAB layer in Sections 390904 and 390212, as depicted in Figure 3. The VMC below the bottom of the edge drains was similar in sections with or without drains.

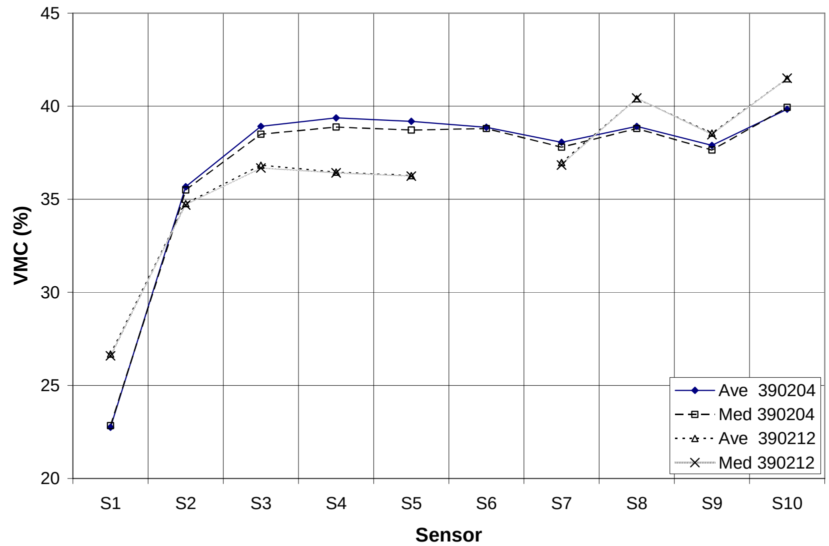

Figure 5. Average and Median VMC (Sections 390204 & 390212).

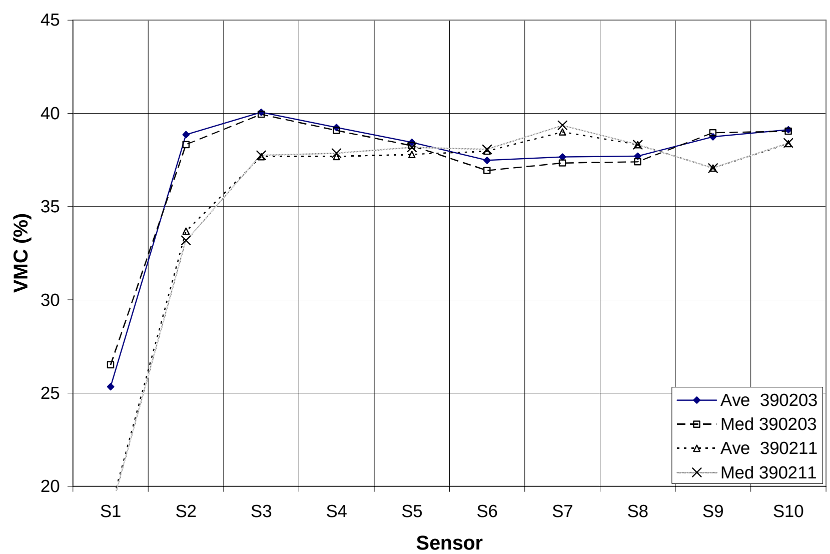

Figure 6. Average and Median VMC (Sections 390203 & 390211).

4. Effect of Dense Graded Aggregate Base on Subgrade VMC

The influence of a DGAB layer on VMC of the subgrade was examined through the comparison of sections in Groups 6 (sections without drains) and 7 (sections with drains) from Table 2, as shown in Figures 7 and 8, respectively. VMC data points for Section 390208 in Figure 7 and for

Section 390112 in Figure 8 have been shifted one position to the right to more closely match the sensor locations with respect to the top of the subgrade with those in Sections 390203 and 380904, respectively.

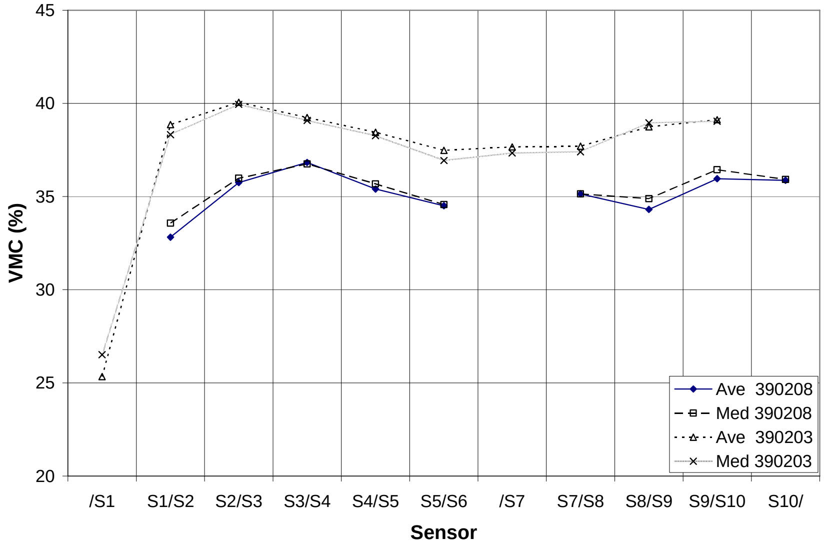

Figure 7. Average and Median VMC (Sections 390208 & 390203).

Even though these figures show that sections with DGAB tended to have a higher VMC within the subgrade when other factors were removed from the comparison, further examination of the data collected indicated that sections exhibiting higher VMC, as an average, also had higher moisture contents at the beginning of the monitoring period. Thus, this anomaly can not be attributed to the presence of the DGAB layer but to localized variations in soil type and the existing moisture regime within the sections.

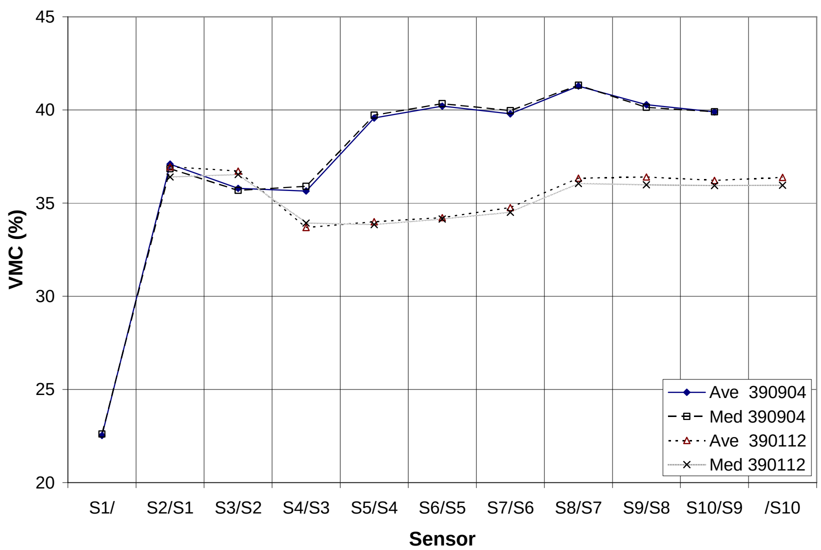

Figure 8. Average and Median VMC (Sections 390904 & 390112).

Summary and Conclusions

The effects of pavement design features on the volumetric moisture content (VMC) of subgrade soils were studied through the analysis of Time Domain Reflectometry (TDR) data obtained at the Ohio SHRP Test Road. All subgrade TDRs showed a characteristic annual sinusoidal variation in VMC, reaching a peak during the month of August and a valley during the month of February. This is indicative of a lag that occurs between the normally high precipitation in the spring and the high subgrade moisture that occurs in August. VMC time series may be fitted with a sinusoidal function by regression of data for each sensor, including VMC as the dependent variable and the day of the year (in the Julian calendar) as the independent variable. A high coefficient of determination ($R^2 = 0.88$) for this regression indicates that the selected peaks for maximum and minimum VMC are quite reliable.

Pavement type (HMA or PCC) did not appear to have any appreciable effect on the VMC of the subgrade. It was also found that the VMC did not always increase with depth and, typically, the average and mean VMC for each sensor were found to increase and decrease in an oscillatory manner within a very narrow range with depth.

VMC data obtained from the Ohio SHRP Test Road showed, in most cases, a slight reduction in moisture close to the subgrade surface when longitudinal drains were present. Average reduction in the VMC was on the order of 2%.

Pavement sections containing a DGAB layer exhibited higher VMCs through the subgrade when other factors were removed from the comparison. Further examination of the available data indicated that sections containing a DGAB layer also had higher subgrade VMC at the start of the monitoring period. Thus, the higher moisture content cannot be attributed to the presence of the DGAB but to localized variations in soil type and the moisture regime within the section. Additional research and monitoring is needed to elucidate the influence of a DGAB layer in the overall subgrade moisture content.

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Biographical Information

J. Ludwig Figueroa is a Professor of Civil Engineering at Ohio University. He joined the department in the fall of 2005 after being awarded the C. Paul Stocker Visiting Professorship between 2004-2005. Dr. Figueroa received his Ph.D. and M.S. degrees in Transportation Materials and Geotechnical Engineering from the University of Illinois at Urbana-Champaign, and his B.S. degree in Civil Engineering from the University of the Andes in Bogota, Colombia. Dr. Figueroa is also an Emeritus Professor from the Department of Civil Engineering at Case Western Reserve University where he retired in 2004. Dr. Figueroa's research interests include Pavement Evaluation, Pavement Analysis and Design and the Effects of Traffic Loads and the Environment on Pavement Performance. Dr. Figueroa has also developed the fundamentals of an energy-based method to evaluate the liquefaction susceptibility of soils deposits which has been verified through centrifuge and torsional shear testing and the analysis of case histories. Dr. Figueroa also participated in the evaluation of liquefied sites that developed during the 1994 Northridge Earthquake in California. He has also developed piezoelectric-based devices for the measurement of dynamic soil properties.

Shad M. Sargand is currently the Russ Professor of Civil Engineering at Ohio University. He is also Associate Director of the Ohio Research Institute for Transportation and the Environment at Ohio University. Dr. Sargand obtained his Ph.D. degree from Virginia Polytechnic Institute and State University and was a Fulbright Scholarship student while earning his undergraduate degree in civil engineering at the University of Nebraska. Dr. Sargand has been a member of the Ohio University faculty since 1981. In recent years, he has been involved in several grant-supported research projects including the unique instrumentation developed for the national test road on U.S. 23 near Delaware, Ohio, sponsored by the Ohio Department of Transportation and the Federal Highway Administration. Dr. Sargand - a nationally recognized expert on pavements, culverts and pipes, bridges, and other highway structures - is obtaining extensive data on the effects of loading and the environment on pavement performance.