Technical Paper

ISSN 1997-1400 Int. J. Pavement Res. Technol. 6(1):45-51

Evaluation of MEPDG Seasonal Adjustment Factors for the Unbound Layers' Moduli Using Field Moisture and Temperature Data

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Abstract: This study focuses on identifying the effects of seasonal variations in the environmental conditions on the unbound layers' moduli for a pavement structure located in Southern Ontario. Using field instrumentation and data collection, volumetric moisture content and temperature were measured throughout the pavement at the Centre for Pavement and Transportation Technology test section. Falling weight deflectometer (FWD) tests were performed at 20-m intervals in six different months. Seasonal trends in the unbound layers' temperature and moisture measurements were identified and analyzed. Three distinct periods of frozen, recovering and fully recovered, were found to characterize seasonal variations in the moisture content. The field data was used to evaluate the Enhanced-Integrated Climatic Model (EICM)'s predictions for the environmental conditions on road unbound layers' moduli. The difference between the EICM predictions and the moisture measurements in the unbound layers was found to be as high as 70 and 30 percent in the subbase and subgrade layers in some periods. The EICM overestimation for the volumetric moisture content (VMC) in the subbase resulted in a 50 percent underestimation in the modulus predicted by the Mechanistic-Empirical Pavement Design Guide (MEPDG) for this layer during the recovering period. It was also found that the FWD back calculated subgrade moduli in different seasons, excluding the freezing season, fits the MEPDG-predicted subgrade moduli at depth 910 mm with a R-squared of 80 percent.

Key words*: Modulus; Moisture; Seasonal variation; Subgrade; Temperature.*

Introduction

Changes in the pavement moisture content influence the unbound layers' moduli and consequently the overall load-carrying capacity of the pavement. The presence of moisture, brought about by either precipitation, changes in the ground water table or freeze-thaw cycles, can significantly compromise the stiffness of the base/subbase and subgrade. The temperature profile throughout the pavement dictates the time when the moisture in the unbound layers freezes. The freezing period is followed by the spring-thaw, during which the unbound layers experience a substantial reduction in stiffness. This behavior of the unbound layers and its effect on pavement performance provides enough motivation for monitoring the environmental conditions in the pavements that are constructed in cold climate regions.

When using the 1993 American Association of State Highway and Transportation Officials' (AASHTO) Design Guide, seasonal variations in the subgrade is considered in the design for regions with extended sub-freezing temperatures. Under winter-freeze conditions, typical values of approximately 140 to 345 MPa are advised for the subgrade resilient modulus (MR). For the spring-thaw period, MR is recommended to be considered as 20 to 30 percent of summer/fall MR. Besides the adjustments in the subgrade modulus, the year needs to be broken down into time intervals of either 12 full months or 24 half months, during which different subgrade moduli are effective. The relative damage (u_f) to which the pavement is subjected is estimated empirically during every season, using the corresponding MR. The MR corresponding to the u_f averaged over one year is used in the design as the subgrade effective MR [1]. The characterization of the subgrade in different seasons, especially during the thawing season when the subgrade is the weakest, is a complex task and depends on several factors such as climatic conditions, pavement structure and materials. The Federal Highway Administration (FHWA) survey in 2007 revealed that 70 percent of departments of transportation in the Unites States have plans to implement the new Mechanistic-Empirical Pavement Design Guide (MEPDG) as a substitute for the AASHTO 1993 Design Guide [1]. When using the MEPDG, changes in temperature and moisture content throughout the pavement and also seasonal variations in the unbound layers' moduli are considered in the design procedure. The Enhanced-Integrated Climatic Model (EICM) is a one-dimensional heat transfer and moisture flow model, linked internally to the MEPDG software. The EICM is used to predict the variations in the moisture content in the unbound layers and the temperature profile throughout the pavement section, using the site-specific ambient climatic data and ground water table. Based on the predicted temperature, each year of the pavement design life is divided into three periods of frozen, recovering (thawing) and fully recovered. During the freezing period, a constant stiffness value between 7,000 and 17,500 MPa is assumed for the unbound layers' MR, depending on the layers' properties (percent fines and plasticity). During the other two periods, the user-defined (reference) resilient modulus (M_{Ropt}) is adjusted, based on the predicted moisture content in the unbound layers. Seasonally adjusted MR values are used in the computation of pavement critical responses to loads and consequently damage at different locations of the pavement [3].

This study presents the data from a pavement-monitoring program for a test section located in wet-cold climatic conditions

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Note: Submitted May 21, 2012; Revised August 21, 2012; Accepted August 27, 2012.

with severe annual freeze-thaw cycles. Moisture content and temperature changes in the unbound layers are measured for a flexible pavement located in Southern Ontario, Canada. The field data was first used to evaluate the accuracy of the EICM predictions for moisture content for the test section. Second, the effect of the inaccurate prediction for moisture content on the MEPDG seasonal adjustment factors for the unbound layers' moduli was investigated. The seasonal adjustment factors are also established for the test section, using the falling weight deflectometer (FWD) test data performed in six different months. The seasonal adjustment factors from the MEPDG and the FWD test are compared statistically.

Overview of the Test Section

The Center for Pavement and Transportation Technology (CPATT) test track is a 709-m stretch of a two-lane asphalt road section, located in the Regional Municipality of Waterloo's waste management site in the province of Ontario. The entire test section is comprised of five different sections, each composed of a different binder mixture for the wearing course. The first 153-m stretch of the test section (focus of this study) is composed of the Ontario Provincial Standard Specification (OPSS) 313 Hot-Laid 3 (HL3) Asphalt Concrete (AC) and was instrumented at approximately 123-m in the south bound lane. A schematic layout of the instrumented test section is provided in Fig. 1.

The pavement structure for the instrumented test section includes an approximately 225-mm thick HL3 wearing course, placed over 200-mm of Granular A base layer, which sits on top of a 300-mm of Granular B subbase layer placed over a subgrade layer made of Granular A. The HL3 mixture consists of 40 percent crushed gravel, 45 percent asphalt sand, 15 percent screenings, and 5.3 percent Performance Grade (PG) 58-28 binder. Granular A, as defined in the OPSS 1010 [4], consists of crushed rock composed of hard, uncoated, fractured fragments, reduced from rock formations or boulders of uniform quality. Granular B consists of clean, hard, durable uncoated particles from deposits of gravel or sand.

The test section was instrumented in April of 2004 to measure the variations in temperature and volumetric moisture content (VMC) in the subbase and subgrade layers. A schematic of the pavement profile is presented in Fig. 2. As displayed in the figure, the pavement temperature was measured at four different depths of 250-, 530-, 1135-, and 1735-mm. Type T107B thermistors from Campbell Scientific were utilized for this purpose. The changes in the VMC were measured, using two Type CS616 time domain reflectometer (TDR) probes from Campbell Scientific. The two probes were installed at depths of 585- and 1150-mm, as seen in Fig. 2. The ambient temperature and precipitation data were also available from the weather station at the University of Waterloo, approximately five km from the site for the test section. The data was collected at 5-minute intervals and was recorded using a CR10X datalogging system. More details regarding the instrumentation and data collection can be found in another reference [5].

Seasonal Variations in Pavement Temperature

Temperature data was utilized to characterize the severity of winter in terms of frost penetration depth, and the approximate onset of freezing and thawing in the unbound layers. Fig. 3 shows the pavement temperature measurements at four different depths for one year, between April 2004 and May 2005. The gap in the data seen during March 2005 is because the datalogger was temporarily removed from the site. It is seen in the figure that both daily and seasonal temperature fluctuations decrease with depth throughout the pavement cross section. For instance, the temperature at

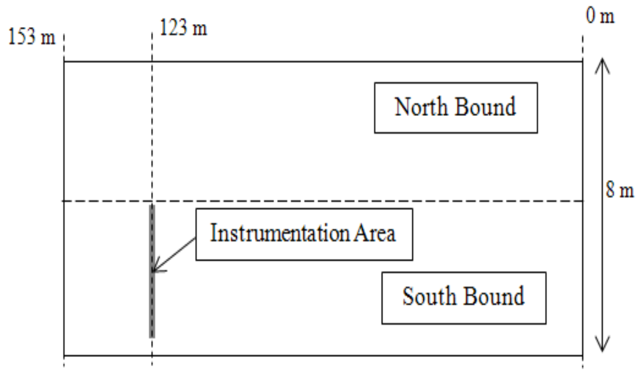


Fig. 1. Schematic Layout of the Instrumented Test Section.

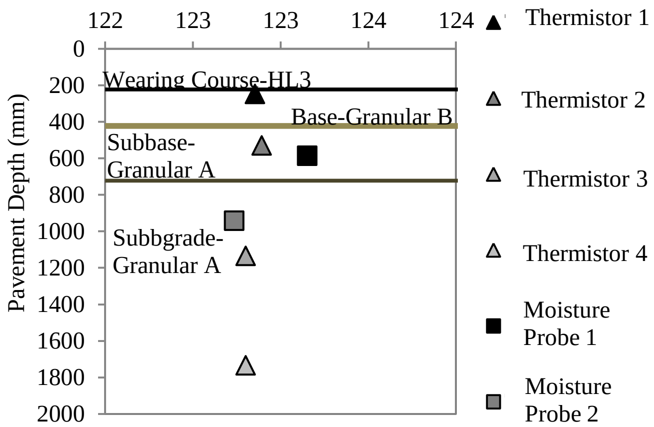


Fig. 2. Schematic of Pavement Profile Illustrating the Sensors' Exact Locations.

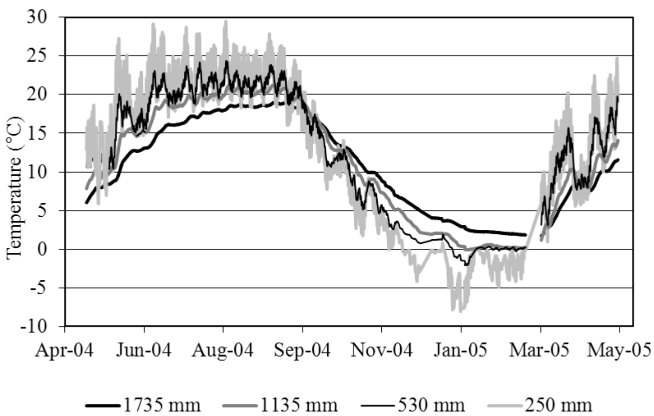


Fig. 3. Temperature Variation at Four Different Depths in the Pavement.

250-mm shows a seasonal variation of 38℃ with daily fluctuations in the order of 10- to 20℃, while at 1735-mm, a seasonal variation of 17℃ with daily fluctuations in the order of 1℃ is observed.

As seen in Fig. 3, at depth 250-mm, freezing conditions prevail from November 2004 to the end of March 2005. The two thermistors located at 530- and 1135-mm indicate that freezing conditions occur during the period between December 2004/January 2005 and the end of March 2005. Lastly, the thermistor located at 1735-mm indicates that no freezing ground conditions occurred over the monitoring period at this depth. From the above discussions one can conclude that freezing depth for the site is between 1135- and 1735-mm. This freezing depth correlates with the findings from the five-year program conducted by the Ontario Ministry of Transportation for measuring frost penetration in different subgrade soils throughout Ontario. Based on this study, frost depth measured between 1970 and 1975 on Highway 7 in Guelph, within 30 km of the CPATT site, ranged between 1.22- and 1.57-m [6].

Seasonal Variations in VMC in Unbound Layers

Fig. 4 presents the VMC measurements at two different depths of 585- and 1150-mm, during the period between April 2004 and January 2006. According to Fig. 4, over the span of two years, the VMC measurements are consistently higher at depth 1150-mm in comparison to the measurements made at depth 585-mm. On the other hand, the trend of behavior seen in the measurements at both depths is very similar. Three distinct trends are noticeable during each year in the VMC measurements at both depths. Period I (April to October): decreasing trend, Period II (October to November/December): increasing trend, and Period III (November/December to March (winter months)): rapid and sudden fluctuations. As seen in the figure, the same three periods are apparent over both years of data collection. During the second year, on the other hand, the VMC at both depths seems to be slightly higher over Periods I and II in comparison to the first year. It is interesting to note that the analysis of long-term data from MnROAD also revealed an annual increase of one to two percent in the VMC measurements in the unbound layers over the first three years after construction [7]. According to the reference, the drift is more apparent during the first year. The authors attributed this to consolidation of the material after one year service.

To explain the different trends seen in the VMC at the two depths in the pavement, precipitation and pavement temperature measurements made at the site for the test section during the monitoring period were used. Fig. 5 presents the VMC measured at both depths over the first year of data collection, together with total monthly rainfall measured at the site for the test section. According to Fig. 5, in Period I, occurring during the spring/summer season, VMC drops from 20 to 10 percent at depth 585-mm and from 25 to 21 percent at depth 1150-mm. Monthly rainfall over this period shows a descending trend from May to July and then from July to August. The month of July included an exceptional heavy rainfall of 41-mm in one day. During Period I, due to the high rate of evaporation occurring at the pavement surface, less water infiltrated into the sublayers. Also, as the base layer continued to dry out during the hot months of summer, its hydraulic conductivity decreases and less water that permeates through the surface actually

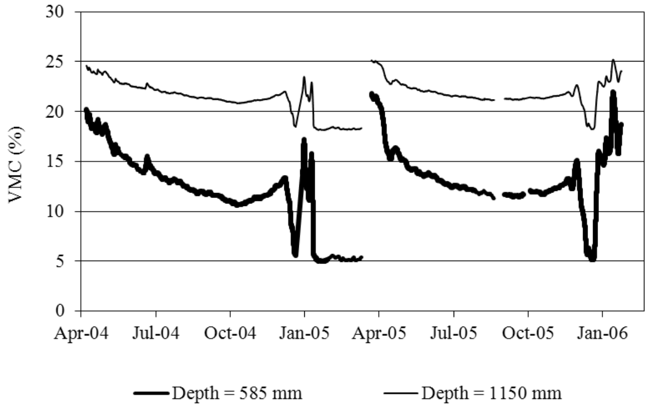


Fig. 4. Seasonal Variations in the VMC Measurements in the Subbase and Subgrade.

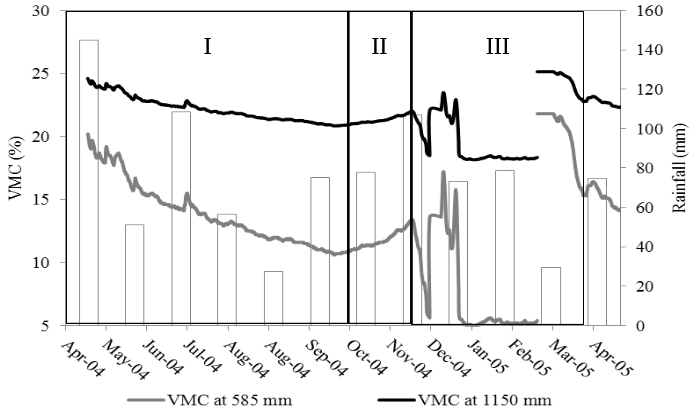


Fig. 5. Total Monthly Rainfall Measured at the Test Site Together with the VMC Measurements in the Subbase and Subgrade.

reaches the subbase and subgrade. Period II occurred from October to December, when the VMC shows an increasing trend. Based on Fig. 5, during this period the VMC increases from approximately 23 to 24 percent at depth 585-mm, and from 11 to 14 percent at depth 1150-mm. A constant growth is observed in Fig. 5 for the monthly rainfall over this period, which agrees with the trend seen in the VMC over this period. The end of Period II and the beginning of Period III represents the onset of freezing in the pavement. This period starts in December 2004 and continues to March 2005. During Period III, the VMC initially decreases rapidly from 24 to 18 percent at depth 585-mm and from 14 to 5 percent at depth 1150-mm. This is followed by sharp fluctuations in the VMC and then by a period during which the VMC remains relatively constant at values of 18 and 5 percent at 585- and 1150-mm, respectively. According to Fig. 5 during Period III, rapid fluctuations are seen in the VMC when temperatures reach sub-zero degrees Celsius in December and January. The VMC remains at the minimum during February and early March, during which the pavement remains frozen (see Fig. 6). The freezing period is followed by a sudden jump in the VMC in late March, when the pavement temperature reaches above zero degrees Celsius. Through laboratory testing of frozen soils, Patterson and Smith (1981) found that since the dielectric constant of ice is similar to that of dry soil, the TDR probes provide minimum measurements during frozen conditions

[8]. The changes observed in the TDR measurements during different seasons can be used to indicate when ground freeze and thaw events occur.

The temperature measurements taken in the subbase and subgrade layers at two depths of 530- and 1135-mm (close to the two depths where the VMC measurements were made) are presented in the form of a monthly average in Fig. 6 together with the VMC measured at both depths over the first year of the data collection period. It is noticed in Fig. 6 that the trends seen in the monthly temperature during different periods agree very well with the trends observed in the VMC measurements. Five different trends are apparent in the temperature and VMC measurements. During the first three months in the spring, temperature at both depths increases consistently. This trend coincides with the sharp decreasing trend seen in the VMC measurements at both depths. Over the next three months, the monthly temperature at both depths remains almost constant, while the VMC at both depths continues to gradually decrease. During Period II in Fig. 6, temperature at both depths drops, while the VMC measurements show a sudden increase. Over Period III on Fig. 5, temperature remains at the freezing point, which coincides with the fluctuations seen in the VMC. Lastly, after Period III, temperature starts to increase, which is reflected by a sudden increase due to thawing followed by a decrease in the VMC.

Evaluation of EICM Predictions for VMC and Temperature

The EICM software, version 3.4, was used to predict the temperature and VMC profiles in the unbound layers for the test section. The input parameters for the wearing course were defined based on the information found in the OPSS for the HL3 mixture. The AASHTO soil classifications A-1-a and A-1-b were used to define the subbase and subgrade materials, respectively. Soil properties such as gradation, density, percent fines and plastic index were kept as the default values in the EICM. The climatic file available in the MEPDG software, containing the hourly data from the weather station located in Buttonville Airport, Ontario was used to provide the climatic inputs for the EICM. This climatic file was selected because it includes 20 years of climatic data; from 1987 to 2007, which covers the monitoring period. Also this station is one of the closest weather stations to the test site, whose data is available for use in the MEPDG (Buttonville Airport is approximately 100 km east of the test track). The depth to the water table was defined as 1.5-m, which is the Level 3 default value in the MEPDG.

The predicted VMC during two years after the construction of the test section is presented in Fig. 7 (a) and (b) for the subbase and subgrade layers, respectively. When using the EICM, the number of allowable nodes for each layer is limited so that a minimum distance of one inch is maintained between the adjacent nodes in each layer. The EICM predictions corresponding to the nodes closest to the depths of the TDR probes in the test section were used for comparisons. The corresponding VMC measurements are also superimposed on Fig. 7 (a) and (b) for comparisons. Based on Fig. 7 (a), the EICM-predicted VMC at mid-subbase maintains a constant value of 18.5 percent during Periods I and II (the pre-freezing periods). As seen in Fig. 7 (a), although this value matches the field measurements in April, it is consistently higher than the VMC

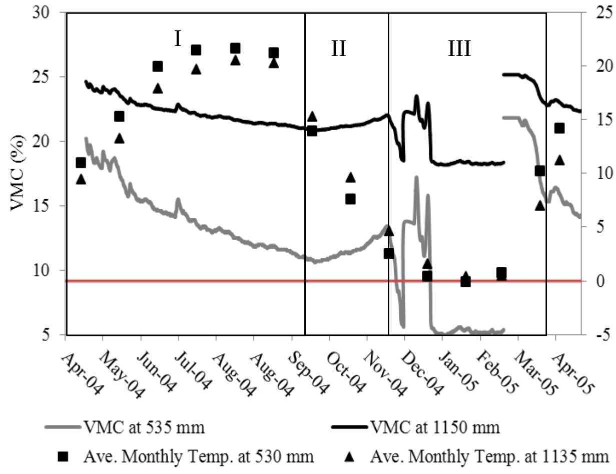
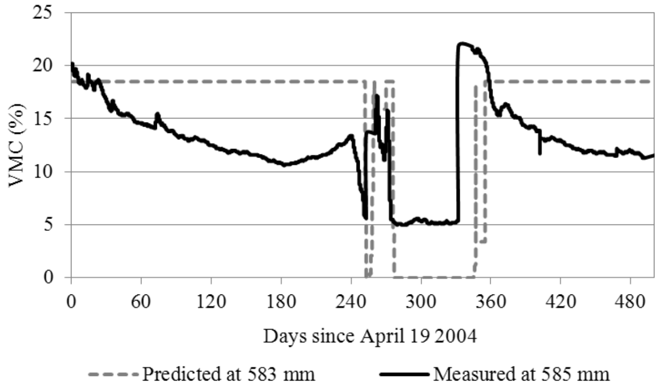
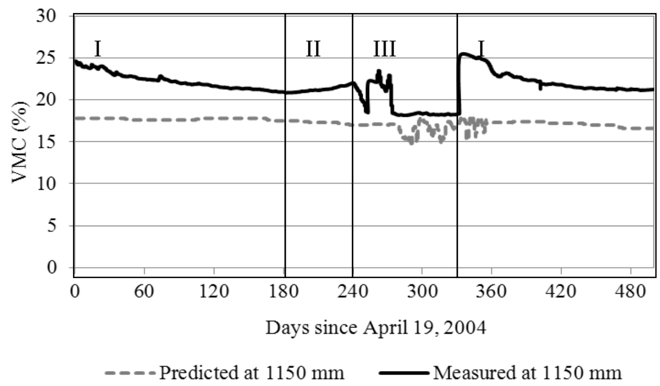


Fig. 6. Pavement Temperature Together with the VMC Measurements in the Subbase and Subgrade.



(a)



(b)

Fig. 7. The EICM-predicted Versus the Field Measurements for the VMC in the (a) Subbase and (b) Subgrade Layers.

measurements between May and December in both years. The maximum difference between the predictions and measurements in the first year is approximately 70 percent and is observed between Day 80 and 180.

According to Fig. 7 (b), for the subgrade layer at depth 1150-mm, the VMC measurements during Periods I and II is consistently higher than the EICM predictions at the same depth. The difference is highest during April and May and decreases during the recovering period. The onset of freezing in the predicted VMC, indicated by

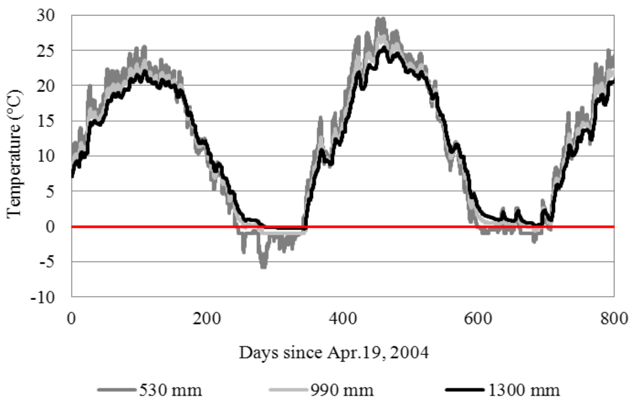


Fig. 8. The EICM-predicted Temperature in the Unbound Layers.

the abrupt fluctuations, coincides with the onset of freezing observed in the field measurements at mid-subbase during both winters. However, for the subgrade layer, the fluctuations in the predicted VMC start approximately 60 days later than the first set of fluctuations in the VMC measurements over the first winter. During the second winter, as opposed to the field measurements, no freezing occurs in the subgrade layer's predicted VMC. The start of thawing in the VMC predictions at mid-subbase shows a delay of approximately 10 days, when compared to the field measurements. At the onset of thawing, the predicted VMC at mid-subbase returns to the exact level prevalent prior to freezing. This behavior does not agree with the observations in the field measurements. A sudden increase is seen in the VMC measurements as thawing initiates. The same behavior is seen for the subgrade layer. It should be noted that the differences observed between the field measurements and the EICM predictions, in terms of the VMC values and onset of freezing and thawing, can partially be due to the difference in the environmental conditions between the test section and the select weather station. It is expected that using the climatic data measurements made at the site for the test section during the monitoring period and also the seasonal measurements of the ground water table help improve the accuracy of the EICM predictions for VMC.

The EICM temperature predictions corresponding to the same depths as that of the TDR probes are presented in Fig. 8. According to Fig. 8, the predicted temperature at mid-subbase reached a maximum of 24℃ over the summer of 2004 and a minimum of -5℃ during the 2004-2005 winter. These values agree with the field measurements at depth 530-mm, presented in Fig. 3. For the subgrade at depth 1300-mm, a maximum of approximately 22℃ is seen over the summer of 2004 and a minimum of 0℃ is observed for the winter of the same year. These values match very well with temperature measurements in the test section at depth 1135-mm.

Seasonal Variations in Unbound Layers' Moduli

Seasonal variations in the VMC of the unbound layers affect the moduli of these layers and consequently the stiffness of the overall pavement structure. Furthermore, during the winter, when temperature in the sublayers falls below zero, the moisture in the unbound layers freezes. This period is followed by a thaw-weakening period. Using the MEPDG for pavement design, seasonal variations in the unbound layers' VMC and consequently moduli is considered, using the EICM. An environmental factor, F_{env}, is estimated, based upon the EICM predictions for the unbound layers' VMC and temperature. F_{env} is used to seasonally adjust the unbound layers' moduli over the three different periods of thawing, fully recovered and freezing during every year throughout the design life. The respective relation is expressed in Eq. (1) [2]:

$$M_R = F_{env} . M_{Ropt} \tag{1}$$

In Eq. (1), M_{Ropt} is the user-defined MR (or the default value in the MEPDG software) for the unbound materials' moduli at the optimum moisture content. F_{env} is a composite factor, which represents the adjusting factor corresponding to each of the three different periods. F_{env} varies for different soil types with different percent fines (P200) and plasticity (PI). A summary of the relations incorporated into the MEPDG for estimating F_{env} for different periods is provided in Table 1.

In order to establish the effect of the differences previously observed in the EICM-predicted VMC especially for the subbase layer, F_{env} was established following two different procedures. In the first procedure, the temperature and VMC measurements in the test section were utilized. In doing so, the temperature measurements were used to establish the three periods of thawing, freezing and recovered for the test section. The VMC measurements at mid-subbase and in the subgrade were exploited to estimate FU and FR for the test section using Eqs. (2) to (6) in Table 1. In the second procedure, the MEPDG-simulation for the test section was conducted, using the same values for the layers' input parameters and climatic file as the ones used in the EICM. The unbound layers' moduli reported in the MEPDG output spreadsheet were then normalized to the fully recovered MR observed in the Month of October to establish F_{env} The comparison of F_{env} established following the two procedures highlights the effect of the EICM's inaccurate predictions for VMC in the unbound layers.

When using the field measurements to establish FU and FR for the test section, the current and optimum degrees of saturation, S and S_{opt}, respectively, need to be established as seen in Eq. (3). These parameters were established for the subbase and subgrade materials, using Eqs. (7) to (9) available in the MEPDG documentation:

$$S = \frac{\theta}{\theta_{sat}} \tag{7}$$

for $P_{200} * PI > 0$:

$$\theta_{opt} = 0.36 + 0.0143(P_{200} * PI)^{0.75} \tag{8}$$

$$S_{opt} = 6.752(P_{200} * PI)^{0.147} + 78 \tag{9}$$

Using the above relations and the default values in the MEPDG for P200 and PI of Granular A and B materials, S_{opt} was estimated at approximately 52- and 58 percent for the subbase and subgrade, respectively. The value of approximately 36 percent was established for θ_{sat} for both layers. FU and FR were estimated at both depths, using the respective VMC measurements. The results are presented in Fig. 9. As described previously, F_{env} established using the seasonal moduli reported in the MEPDG output file for the subbase

Table 1. Relations Incorporated into the MEPDG for Estimating F_{env} in Different Seasons [3].

F_{env}	Relations	
Frozen Period - F_F	$F_F = \frac{M_{R\,frz}}{M_{R\,opt}}$	(2)
Unfrozen / Fully Recovered Period - F_U	$\log F_U = a + \frac{b-a}{1+\exp[\ln\left(-\frac{a}{b}\right)+k_m(S-S_{opt})]}$	(3)
	For Coarse-grained: a = -0.3123; b = 0.3; k_m = 6.8157	
	For fine-grained: a = -0.5934; b = 0.4; k_m = 6.1324	
	S: Predicted Degree of Saturation	
	S_{opt}: Optimum Degree of Saturation	
Recovering Period - F_R	If $\left(S_{equil} - S_{opt}\right) < 0$ $F_R = RF + R_{equil} * RR \times RF$	(4)
	If $\left(S_{equil} - S_{opt}\right) > 0$ $F_R = R_{equil} \times (RF + RR - RR \times RF)$	(5)
	RF: Varies between 0.4 and 0.6	
	$RR = \Delta t / T_R$	(6)
	Δt : Number of Hours Since Thawing Started,	
	T_R : 90 Days for $P_{200} \times PI < 0.1$	
	T_R : 120 Days for $P_{200} \times PI > 10$	
	T_R : 150 Days for $0.1 < P_{200} \times PI < 10$	

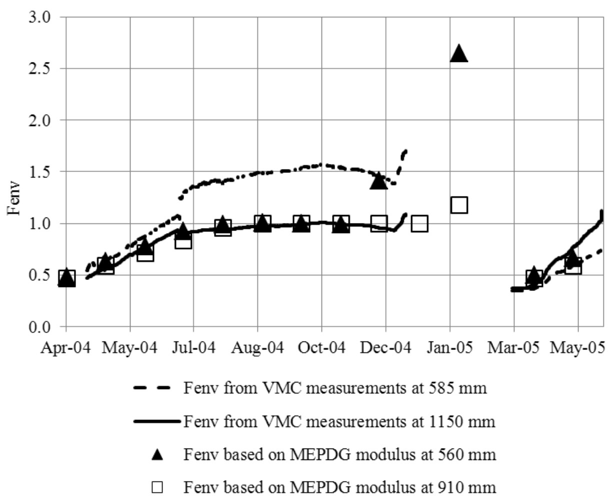


Fig. 9. Predicted F_{env} Using the VMC Measurements Versus F_{env} Based on the MEPDG-predicted Layers' Moduli.

and subgrade, is also superimposed in Fig. 9. It should be noted that the MEPDG-predicted MR is reported in the MEPDG output file at different depths for the unbound layers.

According to Fig. 9, as expected, the F_{env} established using the VMC measurements for the subbase layer is higher in comparison to the F_{env} established for the subgrade, especially during the fully-recovered period. This difference is due to the substantially lower VMC measurements in the subbase layer in comparison to the VMC measurements in the subgrade during this period, according to the field data presented in Fig. 4. Lower VMC in the unbound layer results in a higher modulus for that layer. The F_{env} was established using the layers' moduli from the MEPDG output file. The F_{env} for both the subbase and subgrade layers during thawing and recovered periods were almost the same. It should be noted that F_{env} for the subbase during the month of March was 22, which is beyond the scales presented in Fig. 9 for F_{env} and therefore is not presented in the figure. The comparison of the two F_{env}, one established based on the field data and the other established based upon the MEPDG-predicted moduli, reveals that the EICM inaccurate predictions for the VMC of the subbase layer results in an approximately 50 percent underestimation in the modulus for this layer, during the fully-recovered period.

The FWD tests were also performed along the test section at 20-m intervals for six months: May, September, October, January, March and April of 2004-2005. For every month, the backcalculated subgrade modulus was averaged over the entire test section. The monthly average values were normalized to the backcalculated MR during October to establish F_{env}. These values are presented in Fig. 10, together with the F_{env} established using the subgrade moduli reported in the MEPDG output file at two depths of 560 and 910-mm. Again, the F_{env} for March is excluded from the analysis due to its high value. According to Fig. 10, the F_{env} from the MEPDG at depth 560-mm shows the best match with the F_{env} based on the FWD tests in the month of May with a percent difference of 16 percent. The difference increases to 22 percent in September and reaches its maximum during the freezing period. At depth 910-mm, the percent difference between the predicted and measured F_{env} remains at 22 percent during the thawing and recovering periods in year one. The difference decreases to only 5 percent at the onset of thawing in May 2005. Fig. 11 presents how well the MPEDG-predicted F_{env} agrees with the F_{env} established based on the FWD tests. According to Fig. 11, the F_{env} from the MEPDG (excluding the freezing period) fits the F_{env} from the FWD tests with a coefficient of determination (R-squared) of 50- and 80 percent at depths 560 and 910-mm, respectively. Based on this observation, one can conclude that the MEPDG models' predictions for the subgrade seasonal moduli at depth 910-mm agrees very well with the FWD backcalculated subgrade moduli during the thawing and recovered periods. More field data is required to evaluate the accuracy of the FF used in the MEPDG during the freeing period.

Conclusions

The seasonal trend in the pavement environmental conditions in the unbound layers was analyzed in this study for a test section in southern Ontario. The changes in the VMC measurements in the unbound layers over two years and temperature in the same layers

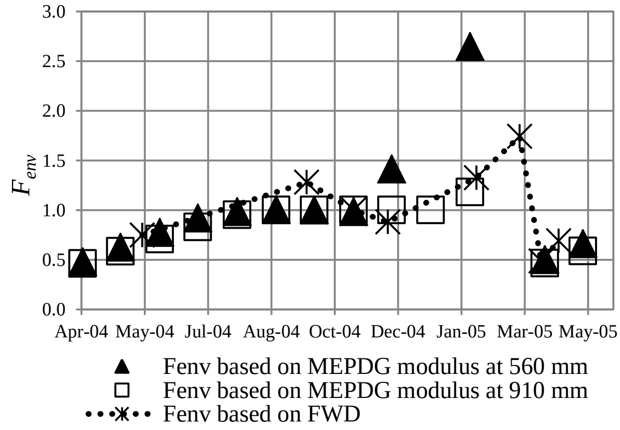


Fig. 10. FWD Backcalculated Subgrade Modulus Versus MEPDG Predictions for Subgrade Modulus at Two Depths.

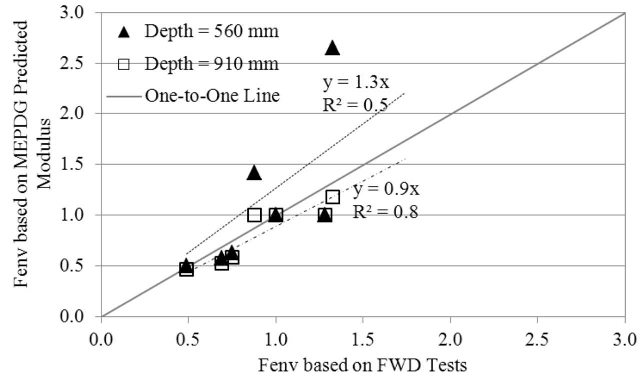


Fig. 11. Statistical Analysis of the MEPDG-predicted versus FWD Backcalculated F_{env}.

available for one year were presented and discussed. Precipitation, air temperature, and FWD test data were also available for the test section over the monitoring period. Based on the pavement temperature data, it was found that during the winter months the pavement froze to a depth of at least 1135-mm. During the freezing period followed by the thawing period, the VMC showed sudden and large fluctuations. It was concluded that the TDR probes can be used to identify the time when the ground freeze-thaw events occur. The analysis of the VMC measurements showed that three distinct periods of frozen, recovering and fully recovered are experienced by the pavements in southern Ontario climate conditions.

The VMC measurements in the subbase and subgrade were used to evaluate the EICM predictions using the default values for ground water table and also the weather data available in the MEPDG. It was found that the EICM is able to identify freezing and thawing periods in the unbound layers. During the recovering period, the EICM predictions showed a maximum difference of 70 and 30 percent from the field measurements in the mid-subbase and subgrade, respectively. These differences reveal that using the weather data available in the MEPDG from the closest weather station to the test site and the default value of 1.5-m for the ground water level, the EICM predictions for VMC are not accurate. The EICM's inaccurate predictions for VMC resulted in approximately 50 percent underestimation in the subbase modulus during the fully recovered period. The FWD backcalculated subgrade moduli agreed very well (with an R-squared of 80 percent) with the MEPDG-predicted subgrade moduli at depth 910-mm during the thawing and recovered periods.

Acknowledgement

The authors would like to thank Dr. Mark Knight and Dr. Ralph Haas for their support during this research study. Thanks are also expressed to the Natural Science and Engineering Research Council of Canada (NSERC) and the Centre for Pavement and Transportation Technology (CPATT) for their financial support. The authors also acknowledge Ken Bowman and Terry Ridgway, technical staff at the University of Waterloo, for their contributions during the instrumentation and data collection. Applied Research Associates Inc. (ARA) is acknowledged for providing the falling weight deflectometer (FWD) test data and backcalculation results. The efforts of Dr. Barry Dempsey from the University of Illinois in providing the latest version of the enhanced-integrated climatic model (EICM) Software are gratefully appreciated.

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