The Effect of Seasonal Variations on the Resilient Modulus of Unbound Materials

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Paper prepared for presentation
at the Pavements Session
on
Accelerated Pavement Testing, Pavements Session

of the 2005 Annual Conference of the
Transportation Association of Canada
Calgary, Alberta

ABSTRACT

Pavement design continues to advance from empirical towards mechanistic methodologies. A project to develop guidelines for the implementation of the new mechanistic-empirical pavement design guide (ME PDG) for Canadian conditions has been advanced through the Pavements and the Soils and Materials Standing Committees of the Transportation Association of Canada (TAC). This project will identify the needs for the calibration and validation of the M-E Pavement Design Guide for conditions typical for Canada.

Material characterization for input into the ME PDG will be a principle component of data collection activities. More specifically, the major material characteristics associated with unbound materials will quantify stress state and in-situ moisture conditions. Typically, the moduli of coarse-grained materials will increase with the confining stress, while cohesive materials may have a reduction in moduli. Further, the moduli will generally decrease with increases in-situ moisture contents as can be expected with seasonal climatic variation. A study has been undertaken to examine how subgrade material characterization can be better quantified, especially given that seasonal variations in the Canadian climate have a huge impact on test results.

The recently constructed Centre for Pavement and Transportation Technology (CPATT) test track, located at the University of Waterloo provides a readily accessible, safe, and relatively uniform location for determining the seasonal variations of M_r in the unbound layers. The road consists of five different asphalt mix test sections, each approximately 140 m in length constructed over dense graded granular base and a predominantly clay subgrade. In the Fall of 2003, CPATT in collaboration with ARA began a non-destructive deflection testing program to complete pavement load/deflection testing and data analysis of the test track at regular intervals. The primary objective of this work is to compile a database of seasonal variations to the M_r of the unbound layers, which could subsequently be used in the ME PDG calibration. This paper outlines the testing program used to collect the pavement load/deflection data and presents the test results collected to-date.

INTRODUCTION

Pavement performance modelling is an important element in the proper management of pavement infrastructure. It incorporates various factors such as material properties, traffic loads, and climate, plus construction and maintenance schedules to develop performance prediction and life-cycle costs such that the most effective pavement designs can be based on both the technical and economic merits of the project [1].

This paper describes a brief background on the pavement material properties required for use in the Mechanistic-Empirical Pavement Design Guide (ME PDG). Mechanistic-empirical design methods combine theory-based design such as calculated stresses, strains or deflections with empirical methods in which a measured response is related to structural thickness.

The overall purpose of the paper is to identify subgrade and foundation values that could be used for pavement performance prediction. The approach is based on a study which involves the evaluation of deflection using a Falling Weight Deflectometer over various seasons at a controlled test site. The project is a joint research partnership between Applied Research Associates, Inc. (ARA) and the Centre for Pavement and Transportation Technology (CPATT) located at the University of Waterloo. The objective of the paper is to present the methodology of the study and provide preliminary results of the seasonal variation in resilient modulus (M_r) based on deflection testing.

Background

The Mechanistic Empirical Pavement Design Guide (ME PDG), which is a product of the NCHRP Project 1-37A, Development of the 2002 Guide for Design of New and Rehabilitated Pavement Structures, will result in a big change in the way that most agencies in North America design pavements. The project was established to utilize existing mechanistic-based models and databases reflecting current state of the art pavement design procedures. It was developed to address new and rehabilitation design issues and to provide equitable design basics for all pavement issues.

The procedure incorporates impacts related to the environment and aging of materials in a biweekly, monthly manner throughout the pavement design life. Traffic variations over time (i.e. hourly, monthly and annually) were also incorporated. The model was calibrated using Long Term Pavement Performance (LTPP) field data from across the United States. Theoretical distress models (e.g. fatigue cracking, rutting, thermal cracking, joint faulting, slab cracking and punchouts) were formulated and calibrated against observed field data. The process was completed many times to achieve final distress models. Following this, design reliability was incorporated into the procedure. This utilizes statistical principles which compare observed and predicted distress [2].

Currently a pooled fund study, under the Transportation Association of Canada (TAC) is underway to assess how this guide could be calibrated for Canadian conditions. The initial

Phase 1, which involves the development of a road map for a Canadian Calibration us nearly complete at the time of the writing of this paper. Following this analysis, it is expected that a Phase 2 will involve the calibration of this guide for Canadian conditions.

Pavement Material Characterization

The material parameters needed for the ME PDG process may be classified in one of the three major groups [2, 3]:

- Pavement response model material inputs.
- Material-related pavement distress criteria.
- Other material properties.

The pavement response model material inputs relate to the moduli and Poisson's ratio used to characterize layer behaviour within the specific model. Bound materials generally display a linear or nearly linear stress-strain relationship. Unbound materials display stress-dependent properties. Granular materials generally are "stress hardening" and show an increase in modulus with an increase in stress. Fine-grained soils generally are "stress softening" and display a modulus decrease with increased stress. Modulus-stress state relations have been developed for granular materials and for fine-grained soils. In practice, assumed Poisson's ratio values are acceptable for routine mechanistic-empirical pavement design based on isotropic elastic structural analysis models [2].

Material parameters associated with pavement distress criteria normally are linked to some measure of material strength (shear strength, compressive strength, modulus of rupture) or to some manifestation of the actual distress effect (repeated load permanent deformation, fatigue failure of PCC materials).

The basic input data set for characterizing the subgrade or foundation is the same for the design of both flexible and rigid pavements. If sufficient data are unavailable for characterizing the foundation, the pavement designer may use the default values provided in this Guide.

A variety of subgrade, or foundation, characterization alternatives exist, including:

- Laboratory testing of undisturbed or reconstituted field samples recovered from the subsurface exploration process.
- Non-destructive testing of existing pavements found to have similar subgrade materials.
- Reliance on an agency's experience with the subgrade type

All of these alternatives are covered in the Guide; however, laboratory testing and non-destructive deflection testing (NDT) are recommended as the primary characterization methods.

Layered resilient modulus (specifically, resilient modulus or approximations of the modulus of elasticity or Young's modulus) is the property recommended for pavement design and analysis.

Three basic methods can be used to obtain the resilient modulus of each structural layer in the pavement:

- Laboratory repeated load resilient modulus tests.
- Analysis or backcalculation of NDT data.
- Correlations with other physical properties of the materials.

For all new designs, particularly for critical projects, repeated load resilient modulus tests are needed to evaluate the effects of changes in moisture on the resilient modulus of a particular soil. The latest version of AASHTO TP-46, *Resilient Modulus of Unbound Granular Base/Subbase Materials and Subgrade Soils*, should be used for measuring the resilient modulus of a soil in the laboratory. For rehabilitation designs, however, the use of backcalculated elastic modulus to characterize the existing structure and foundation is suggested as it provides data on the response characteristics of the in situ soils and conditions. ASTM D4694 (*Deflections with a Falling Weight Type Impulse Load Device*) and D4695 (*Guide for General Pavement Deflection Measurements*) are standards that can be used for measuring the deflection basins along an existing roadway. ASTM D5858 (*Guide for Calculating In Situ Equivalent Elastic Moduli of Pavement Materials Using Layered Elastic Theory*) is a standard that can be followed for backcalculating layer elastic modulus from deflection basin data. Both laboratory and NDT procedures can be used to produce the resilient modulus of the foundation soils needed for design [2, 3].

In preparation for the release of the ME PDG, agencies are urged to compile databases of regional conditions (climatic, construction material, subgrade, etc.) to calibrate the ME PDG for local conditions. One of the material characteristic input parameters is the resilient modulus (M_r) of unbound materials. This would include non-stabilized aggregate base and sub-base (including recycled crushed asphalt and concrete pavement) as well as subgrade soils.

For the ME PDG, the major material characteristics associated with unbound materials are the stress state and in-situ moisture conditions. Typically, the moduli of coarse-grained materials will increase with the confining stress, while cohesive materials may have a reduction in moduli. Further, the moduli will generally decrease with increases in-situ moisture contents.

For use in the ME PDG, designers will have the option of inputting a representative value for M_r and allowing the Enhanced Climate Integration Model (ECIM) to seasonally adjust the value (to account for the effects of freeze-thaw, etc). Alternatively, the designer may input monthly M_r values representative of the specific location.

Importance of Climate in Mechanistic-Empirical Design

In a pavement structure, moisture and temperature are the two environmentally driven variables that can significantly affect the pavement layer and subgrade properties and, hence, its load carrying capacity. Some of the effects of environment on pavement materials are listed below:

- At freezing temperatures, water in soil freezes and its resilient modulus could rise to values 20 to 120 times higher than the value of the modulus before freezing. Above freezing temperatures, unbound materials are not affected by temperature fluctuations.
- The freezing process may be accompanied by the formation of ice lenses that create zones of greatly reduced strength in the pavement when thawing occurs.
- All other conditions being equal, the higher the moisture content the lower the modulus of unbound materials; however, moisture has two separate effects:
    - First, it can affect the state of stress, through suction or pore water pressure. Coarse grained and fine-grained materials can exhibit more than a fivefold increase in modulus due to the soils drying out. The moduli of cohesive soils are affected by clay-water-electrolyte interaction, which are fairly complex.
    - Second, it can affect the structure of the soil through destruction of the cementation between soil particles.

The distresses considered in the Guide are affected by the environmental factors to some degree. Therefore, diurnal and seasonal fluctuations in the moisture and temperature profiles in the pavement structure brought about by changes in ground water table, precipitation/infiltration, freeze-thaw cycles, and other external factors are modeled in a very comprehensive manner in this mechanistic-empirical design procedure [4].

Scope and Objectives

Since the Fall of 2002, Applied Research Associates, Inc., has completed seasonal Falling Weight Deflectometer (FWD) testing at the University of Waterloo, Centre for Pavement and Transportation Technology (CPATT) test track. A database of seasonal variations to the M_r of the unbound layers continues to be collected. The scope of this paper is two-fold. The paper presents the FWD analysis completed to-date, and presents the results of this analysis with suggested seasonal adjustment factors.

CPATT Field Site

The test track facilities were developed as part of the University of Waterloo's research initiatives with the Centre for Pavement and Transportation Technology (CPATT). The CPATT test track involved the construction of a 709 m roadway in the southeast corner of the Regional Municipality of Waterloo waste management facility. Identified in Figure 1, the test track was constructed in June of 2002. The road consists of five different test sections of asphalt, each approximately 140 m in length. The test road was constructed with a common Granular 'A' base and HL 4 binder course throughout. As seen in Figure 2, a HL 3 control mix was used for the surface course at both ends of the roadway. The three middle sections included Superpave, Stone Mastic Asphalt (SMA), and Polymer Modified HL 3 Asphalt (PMA) surface mixes.

The subgrade soils were predominately clayey. Drainage existed prior to the construction of the test track. It consisted of corrugated steel pipe culverts located underneath the road bed with drainage directed easterly into a ditch which runs parallel to the test track towards a storm water management facility [5].

Local Weather Conditions

Located in southern Ontario, the Waterloo area has experienced a relatively mild climate, as compared to regions further north. Statistical information obtained from the Weather Network, indicate that monthly mean temperatures for this area have typically varied from – 10 ^{o}C to 26 ^{o}C. Precipitation records at the Waterloo Wellington Airport, indicate that rain fall in the Spring to Summer months typically varies from 64 to 93 mm, while in the late fall to winter months, snow accumulation ranges from 13 to 41 cm. The weather statistics for the Waterloo Wellington Airport have been provided in Table 1. The values presented in this table represent the mean value of each meteorological parameter for each month of the year. The sampling period for this data covers from 1961 to 1990 [6].

FWD Testing Program

The FWD testing was completed using a Dynatest 8002 Falling Weight Deflectometer. Testing was performed along the test track at 20 m intervals, in both directions. Testing was completed in each of the five pavement test sections, with test points scattered between directions. At each test location, a series of four load applications were applied to the pavement surface. The first application was a "seating" load to ensure the FWD load plate is firmly resting on the pavement surface. The next three loads were approximately 40, 55, and 70 kN.

The sensor configuration was established to permit the use of closed form mathematical solutions to determine the pavement layer properties in accordance with the *1993 AASHTO Guide for Design of Pavement Structures*. Calibration of the FWD equipment has been completed regularly during the testing program at various American FWD Calibration Centres.

The intent of this testing program was to complete FWD testing on a monthly basis throughout the year. During the Spring thaw period, the intent was to increase the frequency of testing to assess the strength reduction profile. Unfortunately during the summer and fall of 2004, regular testing of the facility was interrupted due to on-going activities at the testing facility.

ANALYSIS OF DATA

Deflection testing is an important tool for determining various pavement properties as described below [2,3]:

- Asphalt concrete pavements.
    - Elastic modulus of each of the structural layers (at non-distressed locations).

    - Structural adequacy (at non-distressed locations).
- Concrete pavements.
    - Concrete modulus and subgrade modulus of reaction (center of slab).
    - Load transfer across joints (across transverse joints in wheelpath).
    - Void detection (at corners).
    - Structural adequacy (at non-distressed location).

One of the more common methods for analysis of deflection data is to backcalculate the elastic properties for each layer in the pavement structure and foundation. Backcalculation programs provide the elastic layer modulus typically used for pavement evaluation and rehabilitation design. At present, interpretation of deflection basin test results usually is performed with static linear analyses, and there are numerous computer programs that can be used to calculate these elastic modulus values (Young's modulus) [2,3].

There are three basic approaches to backcalculating layered elastic moduli of pavement structures: 1) the equivalent thickness method, 2) the optimization method, and 3) the iterative method. Within the past couple of decades, there have been extensive efforts devoted to improve backcalculation of elastic-layer modulus by reducing the absolute error or Root Mean Squared (RMS) error to values as small as possible. These improvements have spawned standardization procedures and guidelines to characterization of the pavement structural layers [2,3].

Most backcalculation programs are limited by the number and thickness of the layer used to define the pavement structure. They are also limited by assuming that the behaviour of pavement layer materials under loading is linear elastic defined using Young's modulus.

For this analysis, the assumed pavement thickness data was based on the construction report from the CPATT test track [5]. These values were used to estimate the stiffness (strength) of the pavement at each of the test locations. Pavement layer stiffness backcalculation used a computer-based model to estimate layer elastic modulus values, given the layer thickness and FWD data. The FWD data provided the magnitude and contact area of the load and the output from the FWD deflection sensors.

Several analysis methodologies were used to analyze the FWD deflection data. These methods employed in this research are based on standard best practice.

Maximum Normalized Deflection

The maximum deflection (D_0), measured in the centre of the load plate, is a good indicator of overall pavement strength. The deflection at this location is a function of the pavement layer stiffness, as well as the support capacity of the subgrade. With deflection being a function of load, and because of slight variations in measured load at each test point, a linear extrapolation of the measured deflection is made to adjust deflections at all test locations to a "standard" load level of 40 kN and temperature of 21^{o}C.

In Figure 3, the normalized deflections have been plotted versus time. The results of the normalized deflections found seasonal variability of D_0 to range from a low of 428 μm in the winter months (very stiff), and a high of 1,096 μm during the spring thaw (relatively soft).

To determine the amount of variability with the normalized deflections, spring adjustment factors consistent with deflection overlay methodologies were calculated. By comparing the pavement deflections in the traditional spring thaw period (early April), with deflections obtained throughout the remaining seasons, spring factors of the FWD deflections data can be determined. A summary of the results for mean maximum deflection, with the calculated spring adjustment factors, is presented in Table 2.

Backcalculation of Pavement Layer Moduli (AASHTO Methodology)

The pavement deflections measured with the FWD at specific distances from the load plate were used to determine the structural properties of the pavement and subgrade through a process known as backcalculation. Backcalculation uses analytical pavement response models to predict deflections based on a set of given layer thickness and moduli. With pavement thickness held constant, the response models identify the set of subgrade and pavement layer moduli that produce deflections that are very similar to those measured in the field.

The procedure as outlined in the *AASHTO 1993 Guide for Design of Pavement Structures*, Part III, Chapter 5, was used to determine the properties of the as-constructed pavements. The resultant data includes the insitu subgrade elastic modulus (E_s), which is reduced by 3 to determine the AASHTO laboratory modulus value (M_r) that is typically used in the AASHTO design equations.

Figure 4 illustrates the seasonal variability of M_r in the subgrade soils. The mean results for the subgrade moduli have been sorted monthly and plotted. The resilient modulus of the subgrade layer was found to vary from 13.7 MPa, in thaw-weakening conditions, to 50.7, in winter conditions. The data shows that winter strength gain can be as high as 88 percent of the effective M_r with a strength reduction as low as 49 percent. In the comparison of strength adjustment, and effective M_r of 27 MPa was used to represent the underlying clayey material. The effective M_r used in our comparison was based on recommendations included in Table 4.1 of the *Adaptation and Verification of the AASHTO Pavement Design Guide for Ontario Conditions*. Future test results will be used to confirm, or adjust the effective M_r.

CONCLUSIONS

The intent of this research program is to complete monthly FWD testing on the CPATT test track, with increased testing frequency during periods of thaw-weakening. The FWD testing thus far has been sporadic and has missed the Summer months because of clay hauls required for the waste management facility. It is our intent to continue with the testing program and to continue monitoring the subgrade strengths through the 2005 summer and fall seasons.

The results of the testing completed to-date, indicate that the subgrade strengths follows the expected trends. The M_r of the subgrade soils is at its highest value (stiffest) in the winter months, followed by a period of Spring weakening were the subgrade is at its weakest (lowest value). In the summer and fall months, the M_r of the subgrade soils are expected to reach a steady state as the Spring moisture dissipates.

With each set of testing completed at the facility, the database continues to grow. The database collected through this program will provide valuable information to the performance of the test track, and quantify the relative damage a pavement is subjected to during each season.

The University of Waterloo has bulk samples of the unbound materials used in the test road construction. Material characterization tests have been will be completed as part of a subsequent study. The FWD backcalculated M_r database will be compared with the laboratory M_r values to establish appropriate correlations.

5.0 REFERENCES

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TABLES

Table 1. Weather Statistics for the Waterloo Wellington Airport, Ontario.

Months	J	F	M	A	M	J	J	A	S	O	N	D
Temperature, °C												
Maximum	-2	-2	3	11	19	23	26	25	20	13	6	0
Minimum	-10	-10	-5	0	6	11	14	13	9	3	0	-7
Mean	-6	-6	-1	6	13	17	20	19	14	8	3	-3
Precipitation												
Rain (mm)	20	27	49	64	76	80	90	93	90	70	72	43
Snow (cm)	40	33	22	8	0	0	0	0	0	1	13	41
Total (mm)	54	56	73	73	76	80	90	93	90	70	83	79
Snow Cover (cm)	16	14	1	0	0	0	0	0	0	0	1	9

Table 2. Summary of Normalized Deflections

Test Date	Surface Temperature		Normalized Deflections (µm)					AVERAGE	Spring Adjustment Factor*
			HL 3-1	PMA	SMA	Superpave	HL 3-2		
November 1, 2003	10 °C	Mean	664	729	747	786	744	**734**	**1.49**
		St. Dev.	55	113	147	85	59	92	
May 21, 2004	10 °C	Mean	760	820	785	989	917	**854**	**1.28**
		St. Dev.	108	157	226	163	155	162	
September 28, 2004	17 °C	Mean	435	472	501	557	501	**493**	**2.22**
		St. Dev.	42	59	103	73	62	68	
November 4, 2004	5 °C	Mean	499	518	514	602	559	**538**	**2.04**
		St. Dev.	45	65	68	88	43	62	
December 1, 2004	2 °C	Mean	544	545	535	648	575	**570**	**1.92**
		St. Dev.	61	68	89	98	58	75	
February 9, 2005	-2 °C	Mean	422	380	441	511	383	**428**	**2.56**
		St. Dev.	103	105	123	83	96	102	
March 15, 2005	2 °C	Mean	408	417	506	525	420	**455**	**2.41**
		St. Dev.	214	278	229	211	210	228	
April 1, 2005	10 °C	Mean	984	984	1056	1327	1128	**1096**	**1.00**
		St. Dev.	196	212	259	290	177	227	
April 14, 2005	10 °C	Mean	702	692	781	920	814	**782**	**1.40**
		St. Dev.	97	108	137	166	85	119	

* - Asphalt Institute MS-17 Spring Adjustment Factor

Table 3. Summary of Resilient Modulus

Test Date	Surface Temperature		Resilient Modulus (MPa)					Average	Variation from Effective M_r *
			HL3-1	PMA	SMA	Superpave	HL3-2		
November 1, 2003	10 °C	Mean	24	22	21	20	21	**21.8**	**-19 %**
		St. Dev.	2.1	3.2	3.0	2.7	1.6	2.5	
May 21, 2004	10 °C	Mean	22	21	21	17	18	**19.6**	**-27 %**
		St. Dev.	3.2	4.0	4.3	2.7	3.3	3.5	
September 28, 2004	17 °C	Mean	39	36	33	29	33	**33.9**	**26 %**
		St. Dev.	4.1	5.5	6.2	3.9	4.3	4.8	
November 4, 2004	5 °C	Mean	30	29	28	24	26	**27.6**	**2 %**
		St. Dev.	3.2	4.4	3.1	4.4	2.6	3.5	
December 1, 2004	2 °C	Mean	26	26	25	22	23	**24.5**	**-9 %**
		St. Dev.	3	5	4	4	3	3.6	
February 9, 2005	-2 °C	Mean	43	48	37	33	48	**41.6**	**54 %**
		St. Dev.	12	13	10	5	19	12.0	
March 15, 2005	2 °C	Mean	55	64	42	38	55	**50.7**	**88 %**
		St. Dev.	29	45	17	17	29	27.3	
April 1, 2005	10 °C	Mean	15	15	13	11	13	**13.7**	**-49 %**
		St. Dev.	3	4	2	2	2	2.8	
April 14, 2005	10 °C	Mean	21	21	19	16	17	**18.9**	**-30 %**
		St. Dev.	3	4	2	3	2	2.7	

* - A M_r of 27 MPa was assumed to be the effective M_r

FIGURES

Figure 1: Regional Municipality of Waterloo waste management facility

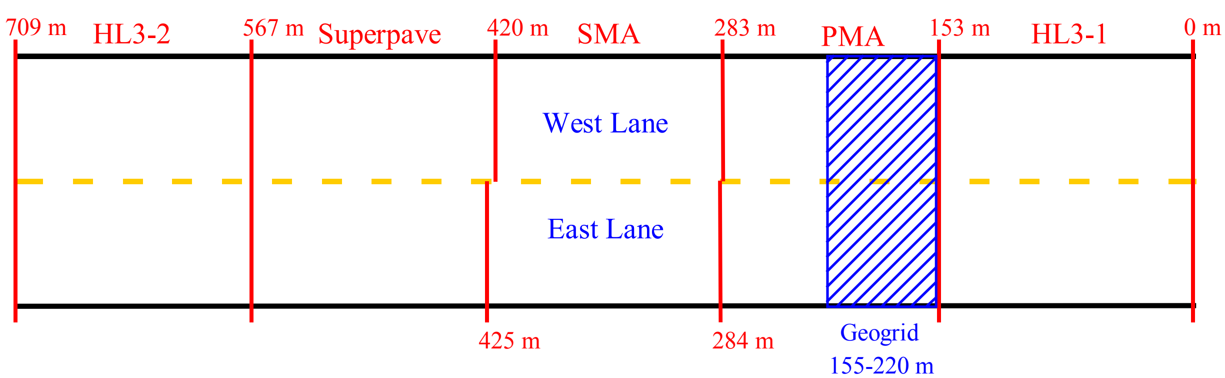

Figure 2: Sectional layout of test track

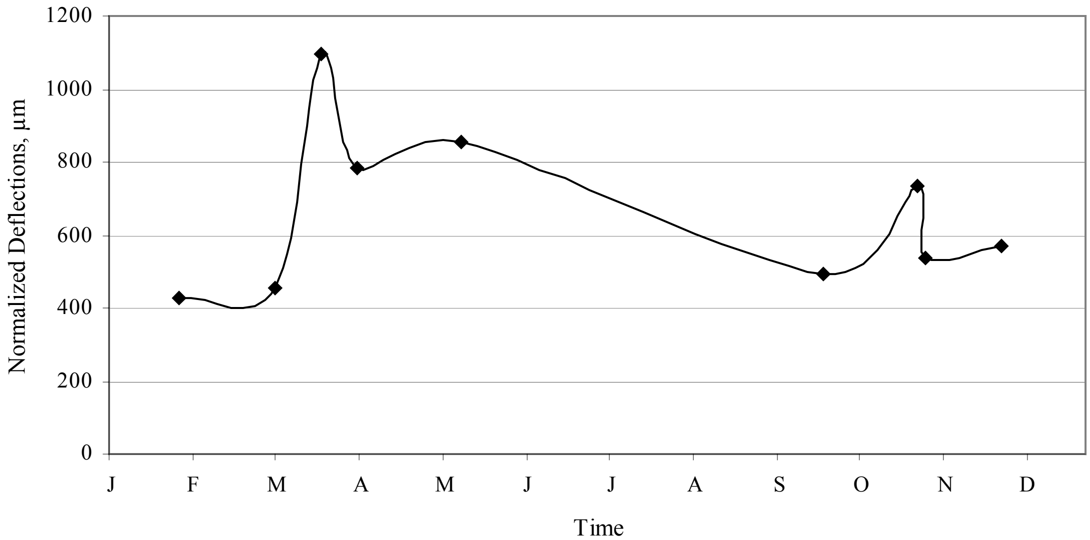

Figure 3. Variations in Normalized Deflections with Seasonal Effects

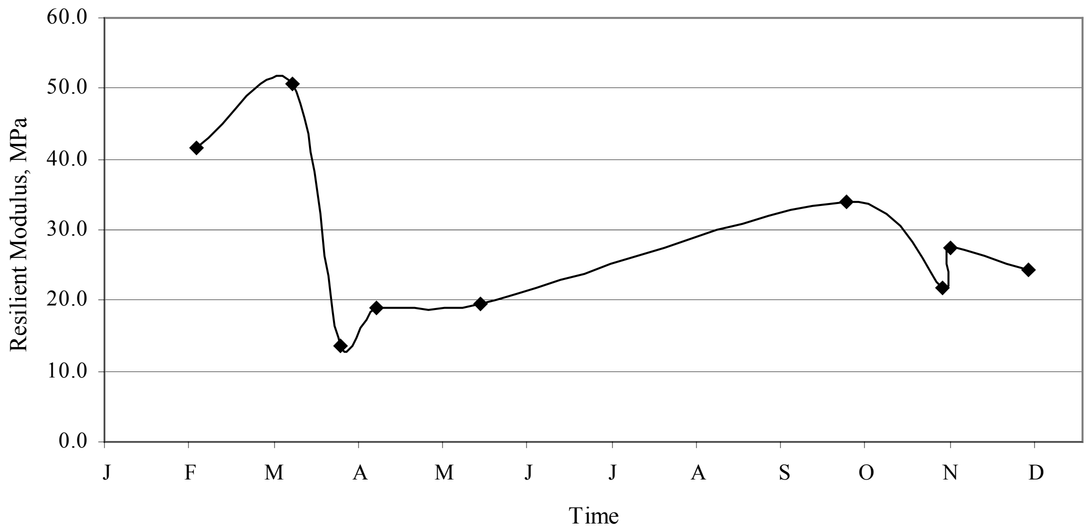

Figure 4. Subgrade Resilient Modulus Variations with Seasonal Effects