Estimating Base Layers and Subgrade Modulii for ME Pavement Design in Manitoba

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ABSTRACT

The assessment of the structural adequacy of an existing pavement scheduled for rehabilitation is an important aspect of pavement rehabilitation design. Non-destructive testing (NDT) has been widely used to determine the design inputs for existing pavement layers in rehabilitation design. The Falling Weight Deflectometer (FWD) is used by different agencies for the non-destructive evaluation of existing pavement layers and subgrade properties. In addition, the deflection basin from the FWD can be applied to select an appropriate rehabilitation strategy. The backcalculated elastic properties of each layer in the pavement and the subgrade from the FWD testing are required for Level 1 and 2 inputs in rehabilitation design when using the AASHTOWare Pavement ME Design program.

This paper focuses on the backcalculation of pavement layers and subgrade modulii using various methods. The backcalculated resilient modulii (M_R) of the base and subgrade from these procedures are compared with modulii from the forward calculation method. This forward calculation method was developed under the Federal Highway Administration's project for reviewing Long-Term Pavement Performance (LTPP) backcalculation data. The calculated modulii are also compared to the laboratory determined resilient modulus for similar materials. The highway sections used in the study are the same test sections proposed to be used to calibrate the Pavement ME distress models in Manitoba. The selected modulii of the pavement layers and subgrade will be used as inputs in the calibration process.

INTRODUCTION

With the recent release of the AASHTOWare Pavement ME design program, the calibration and implementation efforts of Pavement ME design by many highway agencies, the need to accurately characterize the many parameters of existing pavement for design and rehabilitation has increased. Since 1999, Manitoba Infrastructure and Transportation (MIT) have invested in the mechanistic characterization of pavement materials that includes dynamic modulus testing of different bituminous mixes and resilient modulus testing for typical subgrade and granular base materials with varying fines and moisture contents. MIT has also been collecting deflection data using FWD for its network and project level surveys.

The FWD applies a dynamic load onto the pavement surface to simulate traffic loads. The surface deflections at various distances from the load center are recorded by geophone sensors. The MIT's FWD testing program uses 9 sensors placed at 0, 200, 300, 450, 600, 900, 1200, 1500, and 1800 mm from the center of the load plate. For this study, all deflection measurements were taken in the outer wheel path.

The FWD data used in this study were obtained from test sections that are well distributed throughout the Province of Manitoba to capture the various types of subgrade, base materials and asphalt mixes used in Manitoba. Table I lists the location of the test sections, thicknesses of the asphalt and individual base layers, soil classification and description of the subgrade from soil survey and laboratory tests.

Table I: Location of test sections, pavement structure and subgrade type used in estimating subgrade and base moduli.

Pavement Sections		Pavement Structure								Subgrade Type (From Soil Survey)	
No.	Control Section	AC Layer		Base 1		Base 2		Base 3		AASHTO Classifi-cation	Soil Description
		Yr. Built	T, mm	Type	T, mm	Type	T, mm	Type	T, mm		
1	02007070	2001	145	RD MX	50	GR “A”	228			A-4 (1)	SILT, with gravel
2	02007070	2001	145	RD MX	50	GR “A”	225			A-4 (1)	SILT, with gravel
3	02008050	2001	110	RD MX	25	GR “A”	76			A-4 (3)	SILT, sandy,
4	02008090	2004	144	RD MX	250					A-7-6 (20)	CLAY, high plastic
5	02009100	2000	125	GR “A”	188	GR “C”	150	CR RCK	300	A-7-6 (19)	CLAY, high plastic
6	02009100	2000	125	GR “A”	188	GR “C”	150	CR RCK	300	A-7-6 (19)	CLAY, high plastic
7	03003100	2004	211	GR “A”	100	RD MX	76	GR “A”	75	A-6 (7)	CLAY, firm, sandy
8	03003100	2004	201	GR “A”	100	RD MX	76	GR “A”	75	A-6 (7)	CLAY, firm, sandy
9	03003110	2003	175	RD MX	30	GR “A”	150	GR “C”	75	A-6 (5)	CLAY, sandy
10	03003110	2003	166	RD MX	48	GR “A”	150	GR “C”	75	A-6 (5)	CLAY, some silt
11	03003120	2000	117	RD MX	109	GR “A”	164			A-6 (6)	CLAY, sandy
12	03003120	2000	108	RD MX	117	GR “A”	175			A-6 (6)	CLAY, sandy
13	03021070	2000	260	GR “A”	75	GR “C”	100			A-6 (9)	CLAY, sandy
14	03021070	2000	260	GR “A”	75	GR “C”	100			A-6 (9)	CLAY, sandy
15	03025020	2003	167	RD MX	150	GR “A”	75			A-7-6 (11)	CLAY, firm
16	03110010	2000	175	GR “A”	100	GR “C”	150			A-2-4 (0)	SAND, some silt
17	03110010	2000	175	GR “A”	100	GR “C”	150			A-2-4 (0)	SAND, some silt
18	03250010	2000	130	GR “A”	200	GR “C”	50			A-6 (5)	CLAY, sandy
19	03250010	2000	130	GR “A”	200	GR “C”	50			A-6 (5)	CLAY, sandy
20	04005200	2001	168	RD MX	41	GR “A”	175			A-7-6 (20)	CLAY
21	04005200	2001	173	RG MX	36	GR “A”	175			A-7-6 (20)	CLAY,
22	04020040	2004	135	GR “A”	275					A-7-6 (13)	CLAY, high plastic
23	04020040	2004	135	GR “A”	275					A-7-6 (13)	CLAY, high plastic
24	04068020	2000	143	GR “A”	164					A-6 (8)	CLAY, low plastic
25	04068020	2000	149	GR “A”	162					A-6 (8)	CLAY, low plastic
26	04083130	2003	122	GR “A”	200	GR “C”	150			A-2-4	Sand, some silt,
27	04083130	2003	125	GR “A”	200	GR “C”	150			A-2-4	Sand, some silt,

T = thickness

GR “A”/”C” = Granular “A”/”C” base

RD MX = Road Mix

CR RCK = Crushed Rock

Objectives and Scope

The objectives of the study are:

a) Identify the backcalculation method that will provide reasonably accurate resilient modulus of the base and subgrade for use in Pavement ME design for flexible pavement rehabilitation.
b) Investigate the accuracy of calculated resilient modulus of the base layers and subgrade from static linear analysis using: (a) Boussinesq-Odemark model (ELMOD software); (b) Boussinesq model (AASHTO 1993 procedure); (c) Hogg model; and (d) Dorman and Metcalf model. The Hogg model and Dorman and Metcalf model are forward calculation methods used to screen the back calculated resilient modulii in the FHWA's LTPP database.
c) Provide any modifications to the existing guidelines in the use of backcalculated resilient modulus of the base and the subgrade in Pavement ME design. These guidelines include the use of factors to convert field modulus to laboratory modulus.
d) Investigate the use of the combined modulus of the base layers for Pavement ME design.

FORWARD VERSUS BACKCALCULATION METHODS

Backcalculation is an analysis method used to convert measured pavement deflections from FWD into layer moduli. It is an iterative process that uses forward calculation in the intermediate steps. In this study, the interpretation of the deflection basin will be performed with static analysis due to the absence of a standardized procedure for using dynamic analysis. The forward calculation method calculates the surface course and subgrade modulus independently by using different sensors. The base course modulus is derived by matching the total central deflection with the calculated surface course and subgrade modulus. The base course modulus then becomes the least reliable modulus among the three. The inputs for forward calculations are: material properties, layer thicknesses, and applied load. The inputs for backcalculation are measured deflections, applied load, and layer thicknesses.

In backcalculation, optimization technique is used to minimize the difference between the calculated and measured sensor readings and deflection basins. ASTM D5858 recommends that the goodness of fit between the calculated and measured deflections basins or Root Mean Square (RMS) Error of 1 to 2% be achieved. The RMS Error that has been widely used for acceptance varies from 1 to 3%. The percent error per sensor or absolute (ABS) error is 1 to 2 %.

The Root Mean Square Percent Error (RMSE) is calculated from:

$$RMSE = 100\left(\frac{1}{n}\sum_{i=1}^{n}\left(\frac{d_{c_i}-d_{m_i}}{d_{m_i}}\right)^2\right)^{0.5} \qquad \text{- Equation 1}$$

The Absolute Error (ABS) is calculated from:

$$ABS\ (\%) = \frac{1}{n_d}\sum_{i=1}^{n}\left|\frac{d_{ci}-d_{mi}}{d_{mi}}\right| * 100 \qquad \text{- Equation 2}$$

Where: n = Number of sensors used to measure basin
d_{mi} = Measured deflection at point i
d_{ci} = Calculated at point i

The Odemark-Boussinesq Method (ELMOD Software)

ELMOD is an acronym for Evaluation of Layer Moduli and Overlay Design. It is a program developed by Dynatest that can be used for a 5-layer system. It considers the depth to bedrock and non-linear behaviour of the subgrade in the analysis. Using the Odemark Model, the pavement layers are transformed to a semi-infinite half space following the Method of Equivalent Thickness (MET). For the stiffness to remain the same, the following expression must remain constant: $\frac{\frac{b\,x\,h^3}{12}x\,E}{1-v^2}$. The Method of Equivalent Thickness (MET) equation to convert the equivalent thickness of each layer is $h_e = h_1\sqrt[3]{\frac{E_1}{E_2}x\frac{1-v_2^2}{1-v_1^2}}$. After converting all layers to their equivalent thickness, the vertical displacement/deflection per layer is then calculated using Boussinesq's Equation:

$$d_z = \frac{(1+v)\sigma_o a}{E}\left[\frac{1}{\sqrt{1+[{}^{Z}/_{a}]^2}} + (1-2v)\left[\sqrt{1+[{}^{Z}/_{a}]^2} - \frac{z}{a}\right]\right] \quad \text{- Equation 3}$$

Where:

d_z = Displacement
v = Poisson's ratio
σ_o = Stress applied on the pavement
a = Radius of plate
E = Elastic modulus of the layer
z = Depth from the surface

The Boussinesq Model (AASHTO Method)

The AASHTO methodology computes the resilient modulus of the subgrade based on Boussinesq's equation (AASHTO 1993). Boussinesq developed a closed-form equation for a semi-infinite, linear elastic median half-space based on a point load. The AASHTO-based M_R is computed using the following simplified equation:

$$M_R = C * \left[\frac{P(1-\mu^2)}{\pi d_r r}\right] \quad \text{- Equation 4}$$

Where: M_R = Resilient Modulus
C = Correction Factor
P = Plate load (lb)
μ = Poisson's ratio
dr = Deflection measured at r distance from the plate
r = Distance from the load

The Poisson's ratio is recommended to fall within the range of 0.30 to 0.50 (AASHTO, 1993). A Poisson's ratio of 0.40 was used in the calculation of the subgrade resilient modulus. The correction factor is applied to adjust the backcalculated resilient modulus to those obtained from laboratory testing. The Manual for MEPDG recommends a value of 0.33 for all subgrade soils. The AASHTO 1993 design manual recommends using the last sensor deflection for calculating the resilient modulus of the subgrade. In this study, the sensor at 1200 mm is used.

The Hogg Model (Forward Calculation Method)

The Hogg model simplifies the typical multilayered elastic system to an equivalent two-layer model consisting of a thin plate on an elastic foundation. It uses the deflection at the center of the load and one of the offset deflections. The Hogg model considers variations in pavement thickness and the ratio of the pavement stiffness to subgrade stiffness. The equation used to calculate the Hogg subgrade modulus is:

$$E_o = \frac{(1+\mu_o)(3-4\mu_o)}{2(1-\mu_o)}\left[\frac{S_o}{S}\right]\left[\frac{p}{\Delta_o l}\right] \qquad \text{- Equation 5}$$

Hogg showed that the offset distance to the point where the deflection is approximately one-half of that under the center of the load plate was effective in removing biases in the estimation. To calculate this offset distance where deflection is half of center deflection, the equation below is used:

$$r_{50} = \frac{\left[\frac{1}{\alpha}\right]^{1/\beta} - B}{\left[\frac{1}{\alpha}\left(\frac{\Delta_o}{\Delta_r}\right)\right]^{1/\beta} - B} \qquad \text{- Equation 6}$$

The characteristic length of the deflection basin is calculated from:

$$\left[\frac{S_o}{S}\right] = 1 - \overline{m}\left[\frac{a}{l} - 0.2\right] \qquad \text{- Equation 7}$$

$$if\ \frac{a}{l} < 0.2, then\ \frac{S_o}{S} = 1.0$$

Where:

E_o = Subgrade modulus
μ_o = Poisson's ratio for subgrade
S_o = Theoretical point load stiffness
S = Pavement stiffness = p/Δ_o (area loading)
P = Applied load
Δ_o = Deflection at the center of load plate
Δ_r = Deflection at offset distance r
R = Distance from center of load plate
R_{50} = Offset distance where Δ_r/Δ_o = 0.5

l = Characteristic length
h = Thickness of the subgrade
I = Influence factor
α = Curve fitting coefficient
β = Curve fitting coefficient
B = Curve fitting coefficient
y_o = Characteristic length coefficient
$\overline{m}$ = Stiffness ratio coefficient

Compared to any backcalculation approach, the Hogg model of forward calculation gives less variability in resilient modulus between test points. The Hogg model is effective and very easy to use when deriving relatively accurate subgrade modulus.

Dorman and Metcalf (Forward Calculation Method for Intermediate Layers)

The modulus relationship developed by Dorman and Metcalf between two adjacent layers of unbound materials can be used to forward calculate the modulus of the intermediate base layer using Hogg subgrade modulus. The intermediate modulus is calculated using the Equation:

$$E_{Base} = 0.2 * h_2^{0.45} * S_{Sub} \quad \text{- Equation 8}$$

Where: E_{Base} = Dorman and Metcalf base modulus, MPa
h_2 = Thickness of the intermediate base layer, mm
S_{sub} = Subgrade modulus, MPa

Sensitivity of the Subgrade to Repeated Stress

Deflection measurements from FWD can be used to evaluate the sensitivity of the pavement and subgrade materials to repeated loadings. This is done by comparing the trend of the load versus the estimated modulus of the material. The subgrade and base materials undergo either strain softening or strain hardening during the cycle of FWD loadings. The strain softening in fine-grained soil such as clay and silty clay can be due to the contraction of the soil as the load is repeatedly applied. It then generates negative pore pressure as it dilates. The strain hardening of granular soils such as sandy or gravelly soil can be due to the particles locking up into a denser arrangement during the cycle of loading. This feature can be used to verify the type of material in-situ and the effects of loads on the performance of the materials.

A similar procedure can be used to determine the stress sensitivity of the base and AC pavement to repeated stress. Figures 1a and 1b show the stress sensitivity of the subgrade at various test locations. It is expected that the base materials will exhibit strain hardening during the cycle of loading.

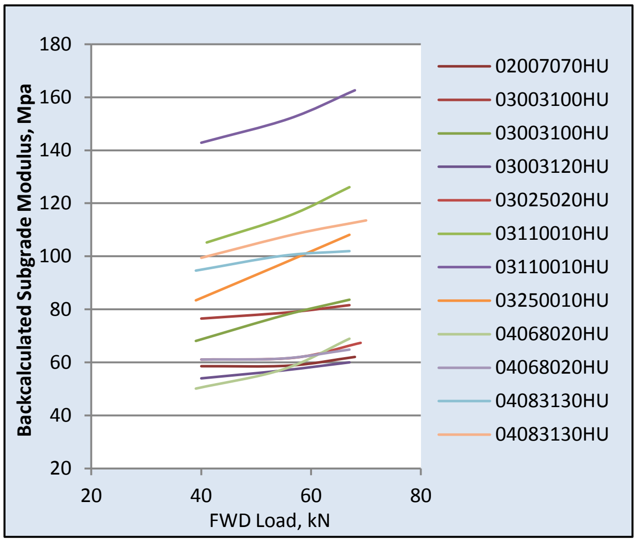

Figure I-A: Strain hardening of the subgrade soil indicating presence of coarse aggregates in the soil.

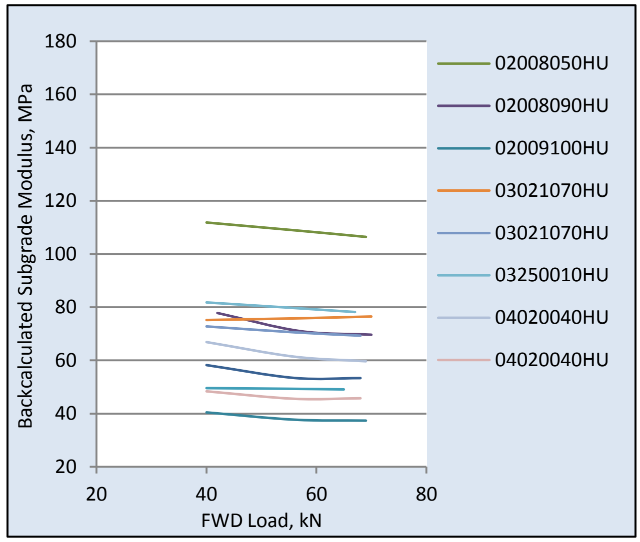

Figure I-B: Strain softening of subgrade soil indicating clayey and silty soil.

ANALYSIS AND DISCUSSION

Backcalculation of the Subgrade Modulus

Six test sections with known subgrade type, gradation and moisture content were used in the analyses. The laboratory resilient modulus of each section was estimated using the values provided in Table II. The Least Square Method and Standard Error of Estimate (SEE) were used to assess which of the models investigated gives a subgrade resilient modulus that best fits with the laboratory resilient modulus. Figure II shows that the resilient modulus estimated from the Hogg model provide the best fit with the laboratory resilient modulus while the Boussinesq and Odemark-Boussinesq models overestimates the resilient modulus of the subgrade.

Table II: Laboratory determined resilient modulus of typical subgrade in Manitoba based on varying moisture contents.

SOIL TYPE	AASHTO Classification	Moisture Content, %	Resilient Modulus, MPa
Silty Sand	A-2-4 (GI=0)	7.7, 9.5, 12.4, 14	58.4, 51.9, 49.7, 39.5
Sandy Silt	A-4 (GI=4)	8.5, 10.9, 12.6, 14.9	66.6, 62.8, 67.5, 56.9
Sandy Clay	A-6 (GI=7)	12.4, 13.6, 15.4, 16.9	101.9, 63.2, 32.3, 15.4
Sandy Clay	A-6 (GI=8)	10.6, 12.5, 14.0, 15.2	105.4, 73.1, 43.5, 20.9
High Plastic Clay	A-7-6 (GI=17)	18.8, 20.4, 23.0, 23.8	108.0, 78.7, 42.1, 34.8
High Plastic Clay	A-7-6 (GI=20)	28.0, 28.3, 31.2, 32.6	63.9, 62.4, 39.7, 31.5

The Manual for MEPDG provides recommended values for C Factor to reduce the backcalculated resilient modulus of the subgrade and base layers to their equivalent laboratory resilient modulus before they can be used in Pavement ME Design. For the subgrade, the recommended C Factor is 0.33. This factor was only applied to the calculated modulus using the Boussinesq and the Boussinesq-Odemark models. Figure III shows that the recommended MEPDG C-Factor of 0.33 underestimates the resilient modulus of the subgrade when compared to laboratory resilient modulus. To reduce the error of estimate, simple iterations were made to determine the C Factor that will give the least square error and Standard Error of Estimate (SEE) of the backcalculated resilient modulii from each model. The C Factors that produced the least error of estimates are 0.69 for the Boussinesq model and 0.75 for the Boussinesq-Odemark model.

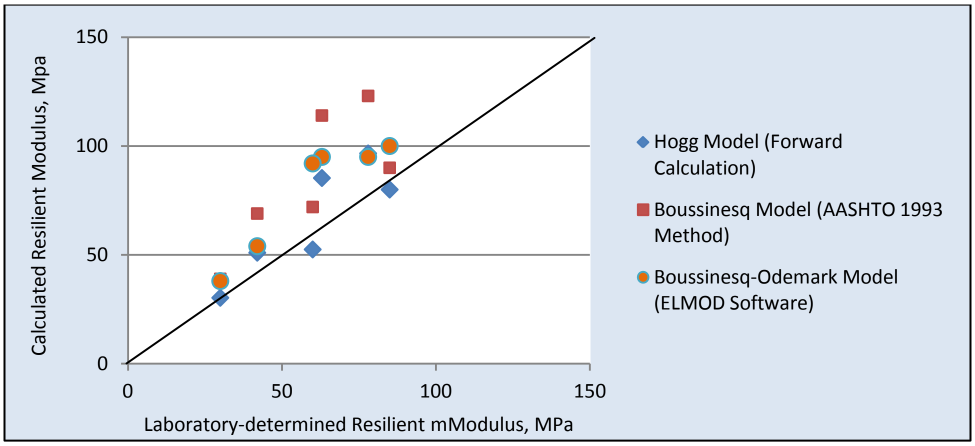

Figure II: Graphical illustration of the laboratory resilient modulus versus calculated resilient modulus of the six test sections using different models.

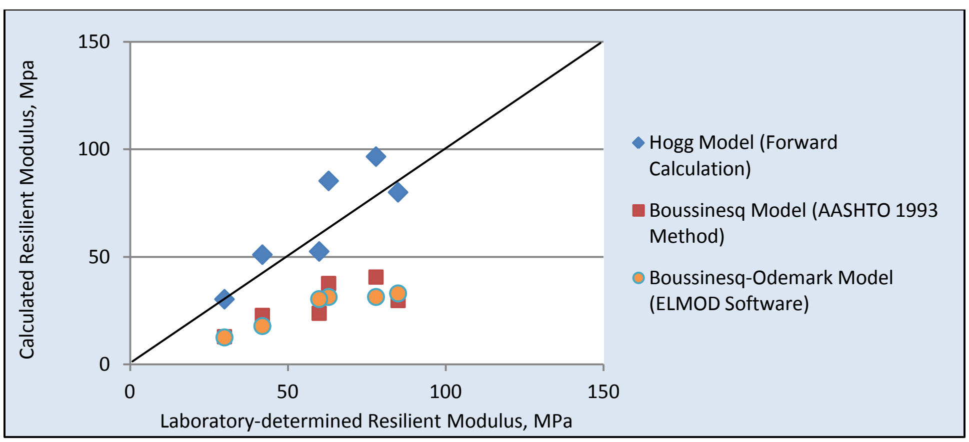

Figure III: Graphical illustration of the laboratory resilient modulus versus the adjusted resilient modulus using MEPDG recommended C Factor of 0.33.

Table III provides the SEE using the MEPDG recommended C Factor of 0.33 and the C Factors determined from this study (MIT). The subgrade resilient modulus calculated from ELMOD gives the lowest SEE after a C factor of 0.75 was applied to the back-calculated resilient modulus. Finally, Figure IV shows the graphical comparison between the laboratory resilient modulus versus the resilient modulus adjusted using the appropriate C Factors as determined in this analysis.

Table III: Statistics for Unadjusted and Adjusted Resilient Modulus of the Subgrade Using Boussinesq, Boussinesq-Odemark and Hogg Models.

Analysis Method	Boussinesq Model (AASHTO 1993)		Boussinesq-Odemark Model (ELMOD)		Hogg Model (Forward Calculation)
Parameter	MEPDG	MIT	MEPDG	MIT	Unadjusted
C Factor	0.33	0.69	0.33	0.75	-
Least Square	7078	964	7650	299	1005.59
SEE	42.07	15.5	43.73	8.65	15.86

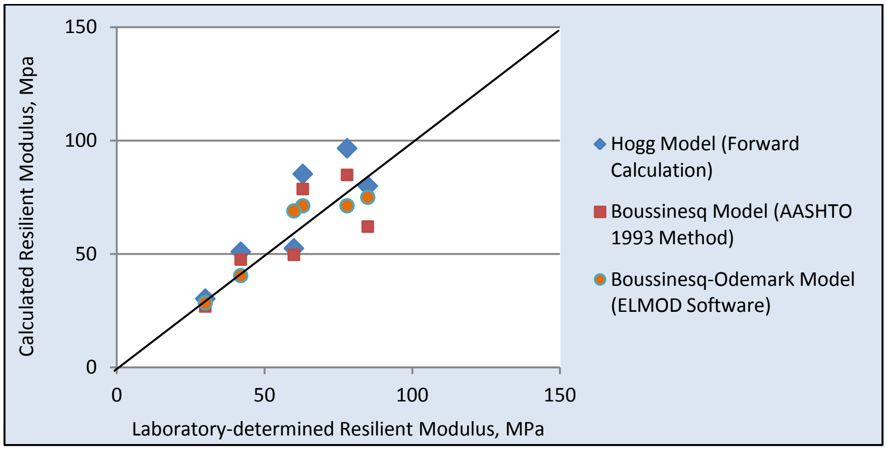

Figure IV: Graphical illustration of the laboratory determined resilient modulus versus adjusted resilient modulus of the subgrade using the C Factors that produce the least Standard Error of Estimate (SEE).

Effect of Subgrade Modulus in Pavement ME Design

To assess the sensitivity of the predicted distresses to changes in subgrade modulus, several runs of the Pavement ME software were done using the maximum and minimum values of laboratory resilient modulus of the subgrade. Refer to Table II. The subgrade material properties such as gradation and plasticity index as determined from soil survey and the typical maximum moisture content and dry density for a similar subgrade material from the Department's material database were used as inputs for analysis. In the analysis, the pavement structure and properties, weather and traffic data were kept constant. Tables IV-A and IV-B show the results of the analysis. In this table, if a range of numbers is given, it indicates an increased predicted distress due to lower resilient modulus of the subgrade. A single number indicates no change in the predicted distress.

For all subgrade types, the predicted terminal IRI varies from 1.88 to 1.94 m/km for a 10-year design and 2.36 to 2.54 m/km for a 20-year design. Based on these results, it appears that the predicted terminal IRI is not sensitive to the subgrade type and resilient modulus. Similar results were observed with the predicted total permanent deformation or total rutting. The difference in the results for all subgrade types and resilient modulii is 0.33 mm for a 10-year design life and 0.83 mm for a 20-year design life and the maximum predicted total rutting in all cases is only 10 percent of the target total rutting after 20 years. The difference in the predicted rutting or permanent deformation can be considered insignificant.

The predicted AC bottom-up fatigue cracking remained at 1.17% for the 10-year design and 1.45% for the 20-year design for all subgrade types investigated. This indicates that the AC bottom-up fatigue cracking is insensitive to the subgrade type and modulus. The predicted total cracking (reflective and alligator) also shows insensitivity to the subgrade stiffness with only a 0.04% difference in prediction for a 10-year design and 0.22% for a 20-year design.

For the 10-year design, the subgrade consisting of silty sand and sandy clay induced the highest AC thermal cracking of 568.68 m/km while sandy silt resulted to lowest thermal cracking of 555.56 m/km. It appears that AC thermal cracking is slightly affected by subgrade type but insensitive to resilient modulus of the subgrade in a 10-year design life. The predicted AC thermal cracking for a 20-year design remained at 608.57 m/km for all types.

The predicted AC top-down cracking showed to have the highest sensitivity to subgrade type and stiffness. Sandy clay subgrade showed the highest sensitivity to changes in resilient modulus compared to other types. Subgrade consisting of silty sand and sandy silt appeared to be the least affected by the change in resilient modulus.

Table IV-A. MEPDG predicted distresses using maximum and minimum values of laboratory-determined subgrade resilient modulus using 10-year design life.

SOIL TYPE	Terminal IRI (m/km)	Total Permanent Deformation (mm)	Total Cracking (Reflective +Alligator) (%)	AC Thermal Cracking (m/km)	AC Bottom-up fatigue cracking (%)	AC top-down fatigue cracking (m/km)
Silty Sand	1.88	1.04-1.14	50.01-49.99	568.68	1.17	165.16-170.58
Sandy Silt	1.89	1.05-1.10	50.01-50.00	555.56	1.17	182.39-184.52
Sandy Clay	1.92-1.93	1.10-1.45	50.00-50.03	567.13	1.17	76.14-183.1
Sandy Clay	1.92	1.10-1.19	50.00-50.02	568.68	1.17	106.57-182.39
High Plastic Clay	1.93-1.94	1.02-1.11	50.00-50.01	567.52	1.17	154.89-181.69
High Plastic Clay	1.94	1.01-1.06	50.01	564.81	1.17	142.31-185.21

Table IV-B. MEPDG predicted distresses using maximum and minimum values of laboratory-determined subgrade resilient modulus using 20-year design life.

SOIL TYPE	Terminal IRI (m/km)	Total Permanent Deformation (mm)	Total Cracking (Reflective +Alligator) (%)	AC Thermal Cracking (m/km)	AC Bottom-up fatigue cracking (%)	AC top-down fatigue cracking (m/km)
Silty Sand	2.36	1.84-1.95	50.19-50.08	608.57	1.45	326.97-402.43
Sandy Silt	2.42	1.82-1.85	50.16-50.11	608.57	1.45	387.23-401.19
Sandy Clay	2.48-2.50	1.85-2.65	50.11-50.33	608.57	1.45	215.95-386.16
Sandy Clay	2.49	1.85-2.17	50.11-50.27	608.57	1.45	289.22-384.01
High Plastic Clay	2.52-2.53	1.80-1.85	50.11-50.20	608.57	1.45	371.70-382.53
High Plastic Clay	2.53-2.54	1.78-1.83	50.15-50.22	608.57	1.45	353.35-402.17

Backcalculation of the Base Layer Modulus

The ELMOD software was used to backcalculate the resilient modulus of the base. The calculated resilient modulus of the subgrade using AASHTO 1993 method was used as a seed modulus for the subgrade. Several iterations were made before reasonable resilient modulus values were obtained. The backcalculated resilient modulii of the base with RMS less than 3% that give reasonable resilient modulus values for the material were selected. These modulii were then averaged and used for further analysis.

The laboratory resilient modulus for the base of the test sections investigated was estimated from the results of the laboratory testing done on various base materials. The aggregate type, fines and moisture contents of the existing base material in the test sections are used to estimate the resilient modulus of the base from laboratory results. The overall results show that the backcalculated resilient modulus of the base is consistently higher than the laboratory determined resilient modulus (See Figure V). The Standard Error of Estimate (SEE) for unadjusted modulus of the base using ELMOD is 182.5. The MEPDG Manual of Practice recommends reducing the backcalculated resilient modulus of the base by a factor equal to 0.62 for base layers below the AC layer. Using this factor, the SEE was reduced to 51.5. The plots of the adjusted backcalculated base resilient modulus compared to unadjusted resilient modulus are shown in Figure V.

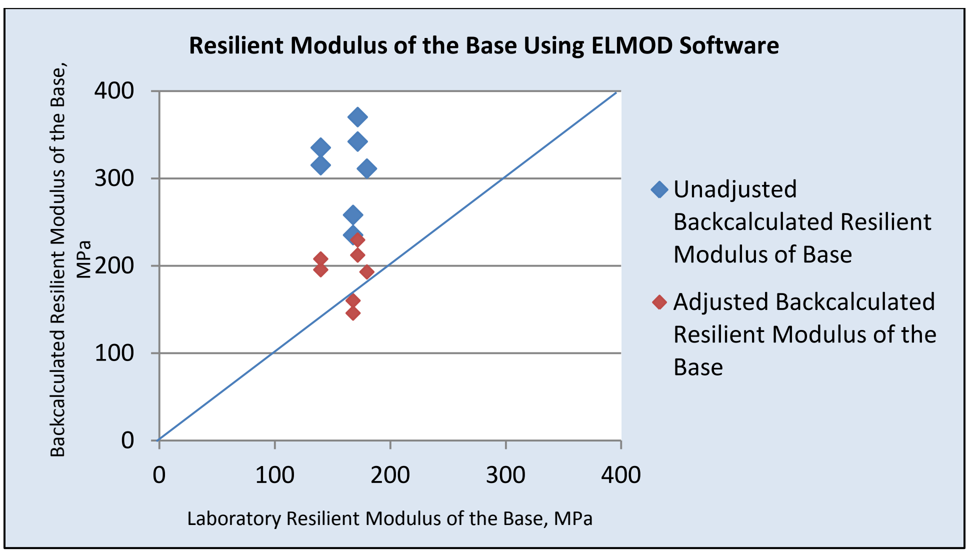

Figure V: Graphical comparison of adjusted and unadjusted backcalculated versus laboratory determined resilient modulus of the base estimated from similar materials.

Combined Modulus of the Base

Some of the challenges in backcalculating the individual base modulus are the variability of field conditions such as thickness of the different layers of the base, the presence of sandwich and stabilized layers, and the insufficient laboratory test data of resilient modulus of base layer materials used. To address these issues, a simplified and practical method is developed to assess the structural condition of base with layers consisting of variable materials. This method combines all the different layers in the base into one layer and backcalculating the effective resilient modulus of the base. This effective resilient modulus represents the combined resilient modulus of the base. The combined resilient modulii of the base for test sections identified for this analysis were backcalculated using the ELMOD software and verified using the Dorman and Metcalf forward calculation equation. The comparison is presented in Figure VI.

In Figure VI, a good correlation between back and forward calculated combined modulii for typical base layers consisting of Granular A over Granular C is observed. For pavement sections with road mix over granular base, including sandwich construction, the base modulus from forward calculation method provides unreasonably low values. Road mix is a base material stabilized with emulsified asphalt. It appears that the forward calculation method used in the study is insensitive to the presence of bound layers in the base. The backcalculated combined resilient modulus of the base using the ELMOD software consistently gives higher values for both sandwich construction and base layers topped with road mix. This indicates that ELMOD takes into account the presence of stiff layers in the base. The results of the backcalculated combined modulus of the base using ELMOD were then used to investigate the possibility of using combined modulus in Pavement ME analysis.

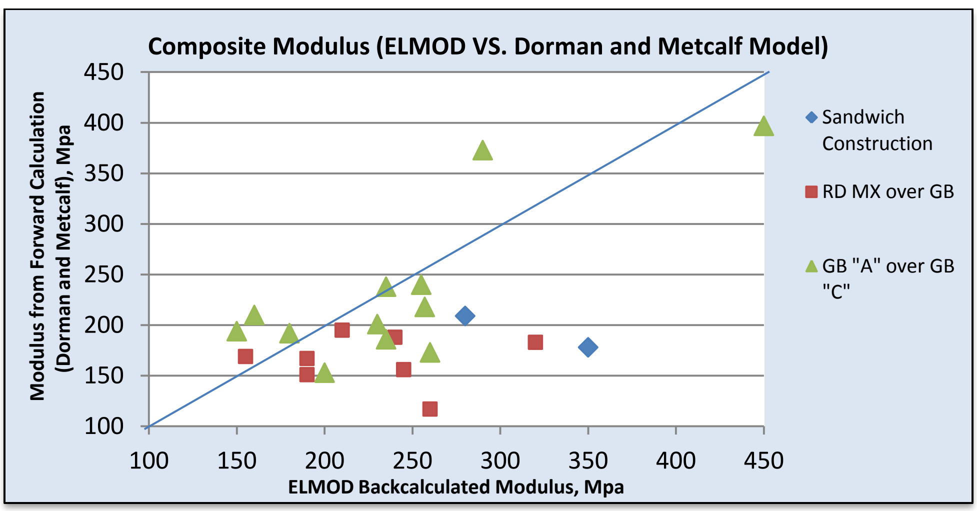

Figure VI: Back versus forward calculated combined resilient modulus of the base layer.

Several runs using Pavement ME Design software were carried out to compare the predicted distresses using combined modulus of the base versus individual moduli of the base layers. For the combined resilient modulus, the material properties of the top layer of the base were used in the analysis. In Table V-A, Columns (i) and (ii) are typical pavement structures consisting of AC layer underlain by Granular “A” and Granular “C”. The results presented in Table V-A show that there is no significant difference in the predicted terminal IRI and total cracking for all cases. The rutting of the subgrade remained at 0.01 mm for all cases. Although the rutting of the base resulting from factored combined modulus is significantly higher compared to the predicted rutting of the total of individual base layers, the difference in the predicted total rutting is insignificant for all cases.

Table V-B gives the predicted distresses for a pavement with base layer consisting of granular "A" and granular "C" over crush rock (Column iii). The base layer sits on the top of a soft high plastic clay subgrade. The results show small variations in the predicted terminal IRI and total cracking. The subgrade rutting remained at 0.01 mm for all cases. The factored combined modulus gives the highest base and total rutting/deformation. The rutting at the asphalt concrete is affected by the variability of the base layer modulii. In Table V-B, Section (iv) represents a sandwich construction. In this case, the predicted terminal IRI and rutting did not show any significant difference among all cases. Although Pavement ME provide predicted top-down and bottom-up cracking where individual layers were used, it gave predicted total cracking as zero (0.0) for both factored and unfactored backcalculated modulus. Also, the predicted total rutting/deformation do not consider the rutting at the base and subgrade layers.

Table V-A: Pavement ME predicted pavement and subgrade distresses using combined and individual layer moduli of the base layer.

Pavement Distress	**i. AC, Gran A, Gran C**				**ii. AC, Gran A, Gran C**			
	A	b	C	d	a	B	c	d
Terminal IRI	2.54	2.54	2.51	2.51	2.6	2.57	2.59	2.57
Total Cracking	50.03	50.03	50.03	50	50.17	50.1	50.16	50.1
Rutting AC only	2.11	2.17	2.14	2.18	2.06	2.06	2.04	2.04
Rutting Subgrade	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
Rutting Base	0.21	0.06	0.09	0.01	2.02	1.01	1.81	1.01
Total Rutting	2.33	2.24	2.24	2.2	4.09	3.08	3.86	3.06

Table V-B: Pavement ME predicted pavement and subgrade distresses using combined and individual layer modulus of the base layer.

Pavement Distress	**iii. AC, Gran A, Gran C, Cr Rck**				**iv. AC, Gran A, RD MX, Gran A**			
	a	b	C	d	a	B	c	d
Terminal IRI	2.77	2.69	2.71	2.67	2.55	2.55	2.52	2.52
Total Cracking	50.56	50.33	50.45	50.31	50	50.02	0.00	0.00
Rutting AC only	3.14	3.04	3.04	2.98	3.1	3.03	2.67	2.63
Rutting Subgrade	0.01	0.01	0.01	0.01	0.01	0.01	0	0
Rutting Base	7.14	4.4	5.22	3.94	0.01	0.05	0	0
Total Rutting	10.29	7.45	8.27	6.93	3.12	3.09	2.67	2.63

Where:

a = Pavement ME prediction using adjusted backcalculated combined resilient modulus of the base layers

b = Pavement ME prediction using unadjusted backcalculated combined resilient modulus of the base layers

c = Pavement ME prediction using adjusted backcalculated resilient modulus of individual layers of the base

d = Pavement ME prediction using unadjusted backcalculated resilient modulus of the individual layers of the base

Seasonal Variation of Resilient Modulus of the Base and Subgrade

The Pavement ME design software gives an option to input the monthly resilient modulus of the subgrade soil. For MIT to be able to use this option, the seasonal variation of the resilient modulus was included in the study. From 2011 to 2013, pavement deflections were measured in 8 different test sites in different seasons of the year using FWD. The FWD tests were done in the summer, fall, start and end of winter and spring seasons. These data were used originally to determine the start and end dates of the winter weight premium and spring restrictions in Manitoba. The same data were used in this study to evaluate the changes in the resilient modulus of the subgrade for Pavement ME design. Due to the large number of data requirement for this analysis, the resilient modulus of the subgrade was calculated using AASHTO 1993 method. The results are plotted in Figures VII-A and VII-B.

The seasonal trend of the backcalculated resilient modulus of the subgrade was compared to the maximum compressive strain on top of the subgrade. In estimating the maximum compressive strain on top of the base and subgrade, a mechanistic relationship between FWD deflections and layer conditions was used. These equations are independent from backcalculated modulii of the base and the subgrade.

The prediction models for critical strains for pavements with unbound aggregate base are: tensile strain at the bottom of asphalt pavement (ε_{ac}), critical strain at the top of the base (ε_{abc}), and critical strain at the top of the subgrade (ε_{sg}). In this study, these critical strains were calculated using the regression equations developed in the study on relationships between FWD deflections and asphalt pavement layer condition indicators by Xu, B. Et.al 2002. These relationships incorporate the complicated dynamic effect of FWD loading and nonlinear behaviour of unbound materials. These equations are:

$$\log(\epsilon_{ac}) = 0.5492 * \log(SCI) + 0.3850 * \log(BDI) + 0.7812 * \log(H_{ac}) - 0.0424 * H_{ac} + 1.3426 \quad \text{- Eq. 9}$$

$$\log(\epsilon_{abc}) = 0.6227 * \log(SCI) + 0.1235 * \log(BDI) + 0.4604 * \log(H_{ac}) - 0.0473 * H_{ac} + 2.2344 \quad \text{- Eq. 10}$$

$$\log(\epsilon_{sg}) = 0.5321 * \log(BDI) + 0.3496 * \log(BCI) - 0.1395 * \log(H_{ac}) - 0.0144 * H_{abc} + 2.3622 \quad \text{- Eq. 11}$$

Where:

ϵ_{ac} = Tensile strain at the bottom of AC

ϵ_{abc} = Compressive strain on top of the base layer

ϵ_{sg} = Compressive strain on of the subgrade

SCI = Surface Curvature Index, calculated from equation: $SCI = D_0 - D_{300}$

BDI = Base Damage Index, calculated from equation: $BDI = D_{300} - D_{600}$

H_{ac} = thickness of asphalt pavement
H_{abc} = thickness of the base layer

With the exception of the test section on PTH 11, the rest of the test sections in Zones 1 and 2 showed an increase in subgrade modulus in early November to twice as much as the summer value. At the start of spring, the test sites showed abrupt decrease in backcalculated resilient modulus. Again, with the exception of the test section on PTH 11, the rest of the test sections exhibited an increase of the subgrade modulus equivalent to summer values at the end of May. The subgrade modulus of the test sections on PTH 11 remained at its lowest until early June. The increase in the resilient modulus of the subgrade during the winter varies per site. This could be attributed to the differences in moisture content of the subgrade soil.

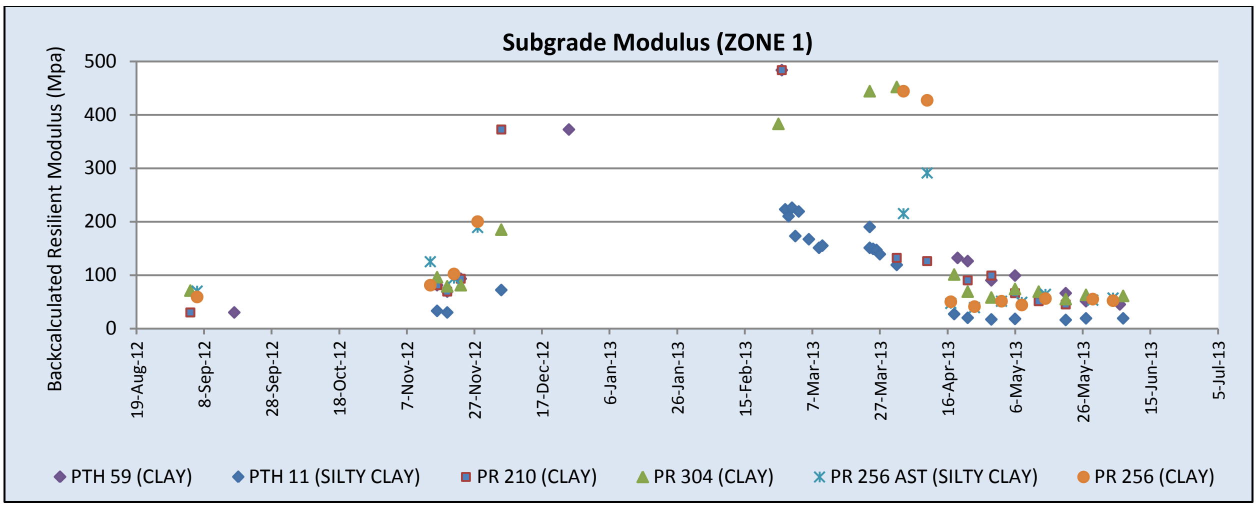

Figure VII-A: Seasonal variation of backcalculated subgrade resilient modulus in Zone 1 (Southern Manitoba).

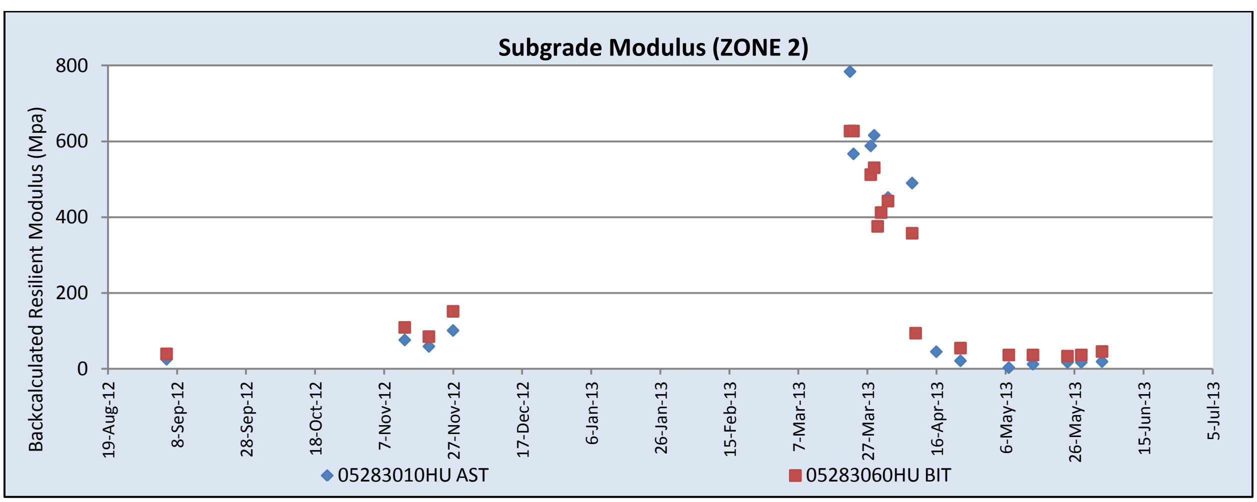

Figure VII-B: Seasonal variation of backcalculated subgrade resilient modulus in Zone 2 (Northern Manitoba).

The compressive strains on the top of the subgrade calculated from the regression equation (Eq. 11) are shown in Figure VII-A for Zone 1 and Figure VII-B for Zone 2. The subgrade on PTH 59 overlain with thick pavement is unaffected by the thawing season. Although there is a decrease in the resilient modulus of the subgrade on PTH 59, the calculated strain remained equivalent to its summer value.

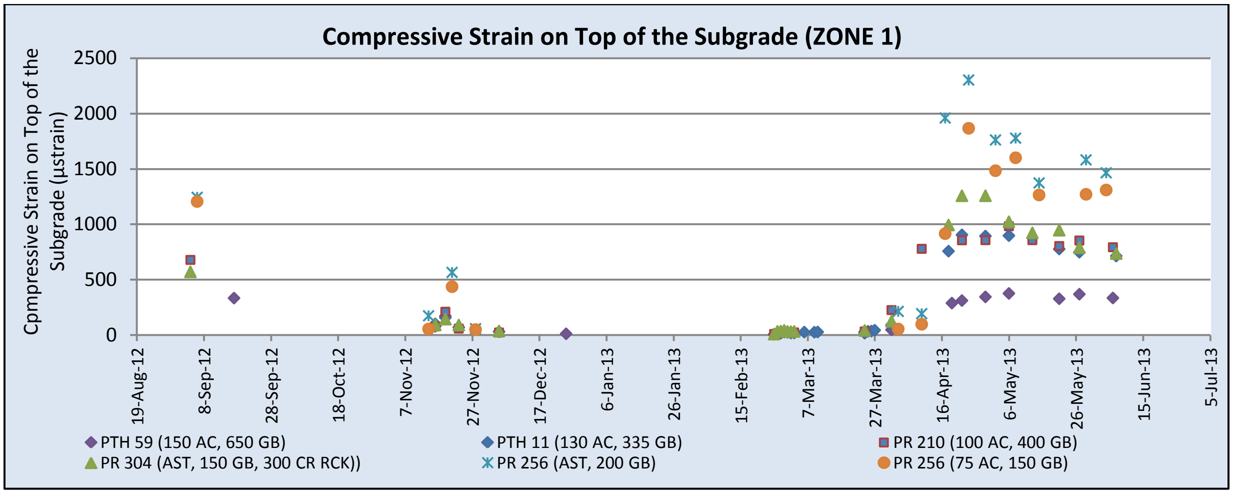

Figure VIII-A: Estimated seasonal variation of compressive strain on top of the subgrade for Zone 1 (Southern Manitoba).

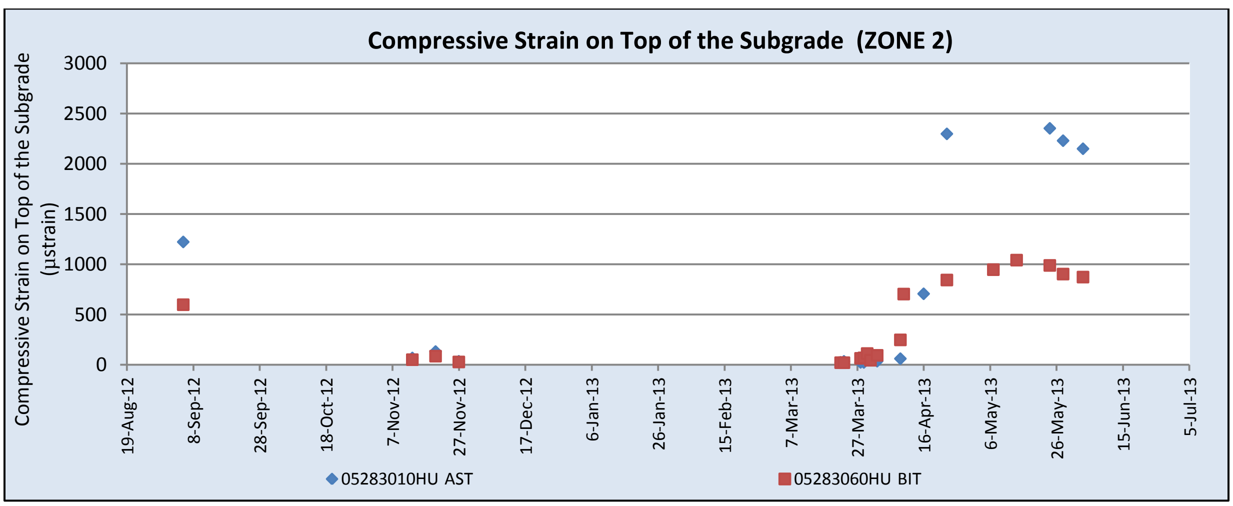

Figure VIII-B: Estimated seasonal variation of compressive strength on top of the subgrade in Zone 2 (Northern Manitoba).

Thinner pavement structures, such as on PR 256, shows abrupt increase in strain in the early spring (See Figure VIII-A). A similar trend was observed from Figures VII-A and VII-B where an abrupt decrease in resilient modulus of the subgrade was noted. The test sections experience between a 25 to 50 percent increase in strain during the spring. The strain decreased to almost zero strain during the winter season. The decrease in strain was observed to start in late fall. Strain started to increase in early April. Thinner pavement structures, such as PR 256 and PR 304 produced higher strains at the start of spring compared to other thicker pavement structures such as PTH 11 and PR 210. Similar observations were made for compressive strains developed on top of the subgrade in Zone 2 (Northern Manitoba). See Figure VIII-B.

The freezing of the base layer during the winter increases its modulus. Due to time constraints, large set of data to be analyzed and the rigorous iterations required to backcalculate the base modulus using the ELMOD software, the seasonal variation of backcalculated resilient modulus of the base could not be presented in this paper. Instead, the regression equation developed by Xu, B. et. al, presented earlier in this report was used to calculate the strain and analyze the behaviour of the base layer due to changes in temperature.

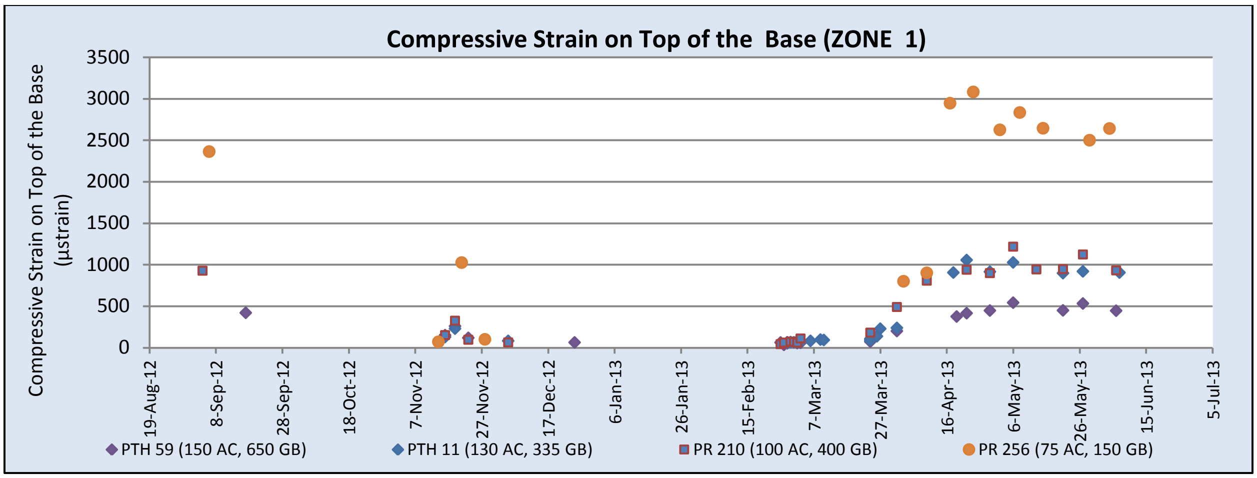

Figure IX-A: Calculated strain on top of the base in Zone 1 (Southern Manitoba).

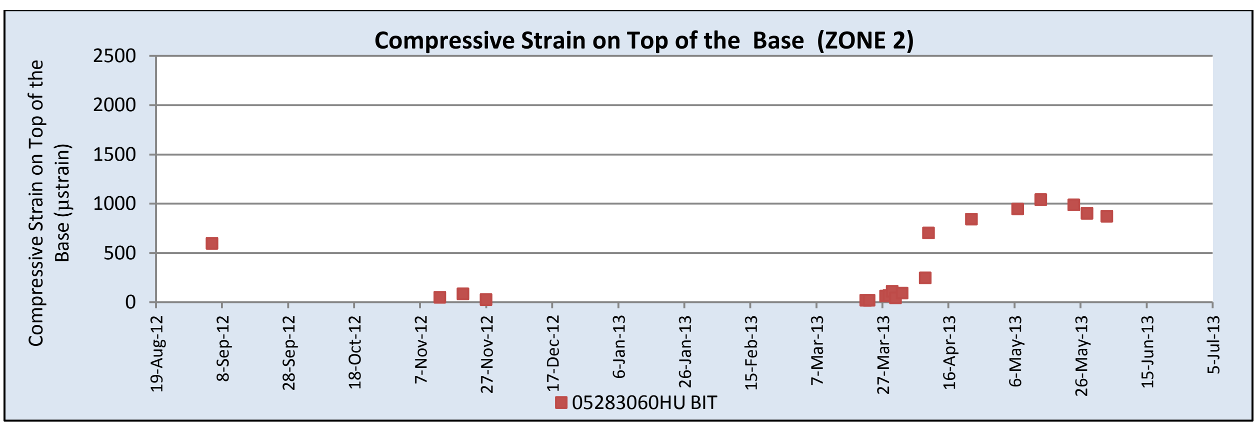

Figure IX-B: Calculated compressive strain on top of the base in Zone 2 (Northern Manitoba).

Figures IX-A and IX-B show that the compressive strain on top of the base reduces in the late fall compared to summer values which could be attributed to increasing stiffness of the asphalt pavement as the temperature drops. The increased stiffness of the asphalt reduces the stress applied and consequently reduces the strain on top of the base. Additional reduction in strain is expected as the asphalt pavement and the base layer start to freeze. In the spring, thin pavements such as PR 256 exhibit the highest increase in strain at the top of the base. Pavements with 100 mm and 130 mm thick AC showed a slight increase in strain in the spring while thick pavements such as PTH 59 showed insignificant increase in the strain in the spring compared to summer value.

Summary of Findings and Recommendations

1. The stress sensitivity analysis of the subgrade may be used to identify change in the *in-situ* material type. This information can be used to determine the required number of boreholes and laboratory testing during the soil survey. This can result in considerable savings to the department where the frequency/extent of change in soil type is less than the standard sampling protocol.
2. The backcalculated layer modulus using ELMOD may vary widely from one load drop to another, or from one location to another. Good judgment should be used when using the backcalculated modulii. The backcalculated layer modulii of the base and subgrade using ELMOD are found to be within the range of values determined from laboratory triaxial tests.
3. There is a close agreement between the laboratory-determined modulus of the subgrade and the modulus calculated using the Hogg model. The comparison of the subgrade modulii between the laboratory resilient modulus and AASHTO 1993 method showed close agreement when a C Factor of 0.69 is used instead of 0.33 in the AASHTO method. The AASHTO 1993 method can be used to estimate a reasonably accurate subgrade resilient modulus when mass calculations are being performed. The recommended backcalculation using the ELMOD software provides a better estimate of the subgrade modulus compared to AASHTO 1993 when a C Factor of 0.75 is used. ELMOD should be used when more accuracy is desired.
4. The modulus of the subgrade could potentially increase by as much as twice the summer value during the months of November and December as the subgrade starts to freeze and in March before the subgrade starts to thaw. The increase in subgrade modulus during the winter season from January to February can be greater than five (5) times the summer value. Due to the thawing of the subgrade in the spring, the backcalculated modulus may decrease by as much as 50% of the summer value between the months of April and July. The modulus does not change significantly from August to October. The trend of the calculated compressive strain at the top of the subgrade also supports this finding.
5. For HMA overlay, the subgrade type and resilient modulus showed very little influence in the predicted rutting, IRI and total fatigue cracking.
6. For pavements with base layers constructed with an A-Base over C-Base, the backcalculated combined modulus of the base using ELMOD can be used in pavement analysis using Pavement ME Design with negligible difference in the predicted total rutting, IRI and total fatigue cracking compared to inputs for individual base layers. Additional case studies are required for a 3-layer base system where crushed rocks are underlain by the C-Base layer. Initial results suggest that the estimated combined layer modulus of a 3-layer base system without applying applying the MEPDG recommended C Factor can be used in the current Pavement ME distress models with minor difference

in the predicted distresses. For sandwich construction, Pavement ME does not provide or gives erroneous prediction for total cracking when individual layer modulus is used.

7. The seasonal trend of the calculated compressive strain at the top of the base is similar to the trend of the calculated strain for the subgrade. Further analysis is required to determine the seasonal variation in the base modulus backcalculations using the ELMOD software.

References:

1. AASHTO Guide for Design of Pavement Structure. AASHTO, 1996.
2. B. Xu, S.R. Ranjithan, and Y.S. Kim. New Relationships Between the Falling Weight Deflectometer Deflections and Asphalt Pavement Layer Indicators. In Transportation Research Record 1806, TRB, Washington D.C. 2002.
3. Soliman, H., Shalaby, A. Evaluation of Subgrade Resilient Modulus for Typical Soils in Manitoba. March 2012.