Seasonal Load Restrictions on Low Volume Highways:

Pavement Strength Estimation

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Abstract

In Ontario, low volume roads comprise about 20% (3,715 center line kilometers) of the total provincial highway network. These roads are subjected to infrequent but intensive traffic loading as well as a high number of freeze-thaw cycles. During the thaw periods, the water released by the subsurface materials is trapped beneath the pavement resulting in weakening of the base, sub-base and sub-grade materials causing premature deterioration of the pavement. As a result, seasonal load restrictions (SLRs) are applied during the spring thaw to low volume highways which are not structurally designed to carry heavy loads during saturated periods. Currently, methods used to apply SLRs are based on visual observation, field testing, prescheduled dates, and empirical models. If the application and removal dates used for SLRs effectively coincide with the load-carrying ability of the pavements, pavement damage, pavement maintenance costs and economic losses to industries will be minimized. There is a need to develop a rational, quantitative procedure to determine the best time to apply SLRs based on measured or predicted frost conditions and pavement response. As a consequence, a primary objective of this research is to develop models that can be used to estimate the pavement strength as a function of frost/thaw depths, characteristics of pavement structures and other variables. For this purpose, the first step is to explore the application of thermal numerical modelling to estimate frost/thaw depths based on variables related to climate, pavement, base, sub-base and sub-grade conditions. Once these models are developed and calibrated, the second step would be to relate the frost/thaw depths to pavement strength. This research also uses the Mechanistic Empirical Pavement Design Guide (ME-PDG) software to evaluate the pavement performance in terms of rutting, cracking, and surface roughness considering SLRs during the design life of the pavement and to observe changes in these values when simulated SLRs are included in the ME-PDG modelling. The focus of this paper is on the second step as well as the ME-PDG results. Information such as pavement type and thickness, soil characteristics, traffic loading, and other available material properties for the selected sites were collected. Additionally, deflection data from the pavement have been collected using a portable light weight deflectometer (LWD). The work of this research is in progress and this paper presents preliminary results obtained up to date.

Introduction

About 20% of provincial roadways in Ontario are classified as low volume roads. These roads are subjected to infrequent but intensive loading from the trucking industries that use them to access remote locations. In most cases, low volume roads are constructed with thinner pavement layers and do not possess the stiffness and strength of more frequently used roads. In addition, these roads are subjected to annual freeze-thaw cycles which can drastically change the properties of the roadway, either strengthening them during freezing periods or weakening them during thawing periods.

Frost action is the process in which "a combination of frost heave during a downward advance of the freezing front followed by a loss of strength during the spring thaw" (Andersland and

Ladanyi, 2004) occurs. The heaving process is a complex process in which ice nucleation and growth results in ice bands being formed within the subsurface. The presence of the ice bands results in subsurface expansion. Flexible pavements such as those found on most low volume roads can tolerate slight expansive or contractive forces with minimal pavement damage. The stiffness and bearing capacity of the pavement structure will typically increase during freezing periods.

During spring thaw periods, melt water from the thawing base, sub-base and sub-grade materials becomes trapped between the overlaying pavement structure and the underlying frozen soil. This increase in water decreases the strength of the base, subsurface layers and in turn reduces the material's ability to support the overlying pavement structure (Van Deusen, 1998). Consequently numerous jurisdictions throughout North America implement SLRs to minimize pavement damage and pavement rehabilitation costs. Van Deusen (1998) indicates that there is a dramatic decrease in aggregate base stiffness at approximately the time that the thawing front passes through the base layer. Furthermore, Andersland and Ladanyi (2004) suggest that SLRs should commence when the thaw front has passed through the bases and end when the pavement system is completely thawed. Therefore, Ideally placed SLRs would commence when thawing of the base begins and be in place until frost has completely left the subsurface, thus restoring natural drainage conditions. Numerous approaches have been used to predict when SLRs should be implemented. This project focuses on the prediction of frost and thaw trends with a thermal numerical model as well as correlations between the frost depth and the pavement structure strength measurements obtained with a Light Weight Deflectometer (LWD). In addition, correlations between LWD measurements and Falling Weight Deflectometer (FWD) measurements are explored to assess the ability of the LWD to accurately represent pavement stiffness. Furthermore, ME-PDG software is being used to determine pavement performance changes (i.e. rutting, cracking, and surface roughness) when simulated SLRs are implemented during the pavement's design.

Approaches to Spring Load Restriction Implementation

Numerous SLR implementation and removal approaches are used by different jurisdictions throughout Canada and the United States (US). Methods such as the use of field testing (Alberta), empirical model methods (Minnesota, US), prescheduled dates (e.g. Newfoundland), or in many cases a combination of these methods in conjunction with visual observations from experienced personnel (e.g. Ontario) are currently in place. It is imperative that the SLRs are placed and removed at the appropriate times to ensure that economic losses are kept to a minimum. These losses could be in the form of overly conservative restriction periods which result in economic hardships to the trucking industries, or if SLRs are placed too late or are removed too soon losses would incur repairing or replacing low volume highways that experience full traffic loads when in a thaw weakened state.

Field testing methods conducted with the use of a FWD provides an accurate measurement of pavement strength and stiffness. These tests, however, require large equipment and are quite costly to conduct. A further drawback to the use of field testing for SLR implementation is the need for a 3 to 5 day lag time that is required to notify the trucking industry of the impending restrictions, which in turn provides them time to modify loads or select alternate trucking routes.

In regard to empirical model methods, they were developed in an attempt to utilize recorded air temperatures and a 3 to 5 day weather forecast to predict freezing and thawing front behavior. Through this approach it would be possible to predict when the thawing of the pavement structure would begin and the SLR notice could be given prior to the weakening of the road, thus avoiding the 3 to 5 day lag time. An issue that is inherent in current empirically based models is the reliance on site specific conditions such as pavement base, sub-base, and sub-grade materials, water content, and solar radiation, amongst others. This makes it difficult to use an empirically based model that represents the potentially heterogeneous conditions present in a given section of highway.

The use of prescheduled dates allows the trucking industry to manage their schedules well in advance of the SLR implementation. This method, however, is the most susceptible to both over conservatism and incorrect placement dates. The unpredictability of climate on a year-to-year basis makes it difficult to effectively determine when thawing will commence. This results in either SLR implementation when it is not required or when it is too late and damage has already happened during the initial thawing period.

Many jurisdictions currently use visual observation methods to determine when pavement distress is occurring thus triggering the implementation of SLRs. Visual observation techniques require the observation of symptoms of subsurface weakening, such as the presence of melt water on the pavement surface, or increases in pavement deformations. This method typically misses the implementation of SLRs during the initial thaw weakening state as the observations recorded are a result of subsurface thawing. This method also requires a 3 to 5 day lag period. The visual observation method is often used in conjunction with a predetermined SLR time length due to the inability of this approach to assess the depth or amount of frost present within the subsurface.

Thermal Modelling

The use of a thermal numerical model provides an alternative method of estimating freezing and thawing front depths. TEMP/W, a finite element software program available from GEO-SLOPE International Ltd., was utilized for this project. In applying TEMP/W, the pavement base, sub-base and sub-grade materials are discretized using a mesh and are assigned specific thermal properties (thermal conductivity, frozen and unfrozen volumetric heat capacity, and latent heat of water) and material properties (volumetric water content and unfrozen water content). Thermal boundary and initial conditions are then applied to the model and the zero-degree isotherm movements through the subsurface are monitored, as the model transient analysis progresses at specified time intervals.

Numerous upper and lower boundary condition input options are available for use in TEMP/W. For the top boundary condition (i.e. pavement surface), various methods were assessed to most accurately predict the frost and thaw behaviors of the pavement structure. The upper boundary condition options examined include the use of climatic data input and various forms of modified air temperature functions. For the lower boundary condition (i.e. base of the pavement structure), the use of a constant temperature at specified depth and use of temperatures measured at the base of the pavement structure were examined.

The climatic data input option in the software allows for the inclusion of various climatic data on a daily basis including: maximum and minimum air temperature, maximum and minimum relative humidity, wind speed, precipitation amount and precipitation event duration. Options are also available to input net radiation, evapo-transpiration, or location latitude to include the amount and subsequent effects of solar radiation.

For upper boundary conditions modified air temperature functions are used to estimate pavement surface temperatures from measured air temperatures. One method involves modifying air temperatures by a modification function or “n-factor” to account for the effects that climate factors and ground surface conditions have on ground surface temperatures. Following Andersland and Ladanyi (2004), when temperature data are above 0°C, an n-factor of one or greater is applied, depending on the surface material. When the temperatures are below 0°C, an n-factor of one or less is applied to the air temperatures, thereby increasing the temperature. This method proves effective when temperatures are well above, or well below 0°C, however has little effect on temperatures close to 0°C because n-factor modification of these temperatures will result in no significant changes.

Another modification approach utilized was the addition of a floating reference temperature to air temperatures. This approach increases air temperatures by a predefined value which has been established through historical correlations of air and surface temperatures. Reference temperatures are increased through the thawing period to account for the increasing intensity of solar radiation.

Through an examination of the bottom boundary conditions it was observed that the use of temperatures measured at the base of the pavement structure as a function of time provided more reasonable results than did the constant temperature at depth approach, therefore all subsequent modelling was conducted using the measured temperature with time approach.

<u>Mechanistic Empirical Pavement Design Guide (ME-PDG)</u>

The Mechanistic-Empirical Pavement Design Guide (ME-PDG) was developed by the American Association of State Highway and Transportation Officials (AASHTO) Joint Task Force on Pavement (JTFP) under National Cooperative Highway Research Program Projects 1-37 and 1-37A (Baiz, et.al., (2007)). For this research ME-PDG was used to evaluate the changes in the physical condition of the road (i.e. fatigue cracking, rutting and the International Roughness Index (IRI)) when SLRs were implemented and when they were not. ME-PDG software can be downloaded from the internet and is currently setup for review and evaluation purposes only.

There are 3 levels of ME-PDG analysis available. Level 1 ME-PDG analysis is the most comprehensive but requires values determined through field and laboratory test to be input into the program before successful analysis can be completed. Level 2 analysis is less comprehensive than level 1, but can be successfully conducted using estimated data or data from company databases. Level 3 analysis is the least comprehensive of the levels but can be conducted using ME-PDG default database values and far less information is required to complete the analysis. At the time of this research only level 3 was available for analysis.

ME-PDG requires user input values such as pavement structure, pavement materials, Annual Average Daily Truck Traffic (AADTT) and international roughness index (IRI). The ME-PDG software allows for the updating of material properties so as to encompass current and future pavement material developments (Al-Mahdawe et. al. 2009). The software also requires that performance parameters be defined, which if surpassed by the model values would indicate pavement failure and subsequent rehabilitation. If these values are not modified ME-PDG utilizes default performance parameters (Table 1).

Light Weight Deflectometer

Pavement deflection and elastic modulus are indicative measures of pavement strength. A LWD provides a cost effective and time efficient alternative testing apparatus compared to a FWD and a Benkelman Beam Rebound (BBR). The LWD is a portable device that can easily be moved from location to location in order to test in situ pavement deflections and elastic moduli.

The LWD used for this project was the Dynatest 3031 (Figure 1) available from Dynatest International. With this model a preselected drop weight of 10kg, 15kg, or 20kg is dropped down a guide shaft from a specified drop height (approximately 800mm) on to a stack of buffer pads. Below the buffer pads is a velocity transducer (geophone) which measures the pavement deflections that result from the application of the force. Additional geophones can be placed at selected distances from the centre geophone to record the effects of the applied force off centre. Three different loading plates of 150mm, 200mm, and 300mm diameter can be used with this system, which when used in conjunction with the 20kg drop weight can produce up to 15KN peak loads (Dynatest, 2006). Values obtained from the geophone are transmitted via Bluetooth technology to a Personal Digital Assistant (PDA) or a laptop computer where further analysis can be done through the LWDmod software that accompanies the LWD.

The LWDmod program allows for the collected data to be analyzed and assured. Erroneous drops as well as the first drop at any new location can be removed in LWDmod in order to achieve the most accurate data grouping. After the data are assured further analysis and graphs can be created either with the LWDmod software or through exporting the data to Excel. This analysis can indicate deflection, surface modulus and an approximated composite modulus of the pavement structure at the test locations.

Study Sites

For this research, sites on Highways 527, 569, 66 and 624 are currently being studied in Northern Ontario in order to examine correlations between frost depth, FWD measurements and LWD measurements. The two focus sites for this project are on Highways 527 and 569.

The Highway 527 location is in Northwestern Ontario approximately 0.5km north of Highway 811. This section of highway is classified as a low volume road and undergoes freezing and thawing patterns typical to Northern climates. Thermistor sensors are installed from depths of 5cm to 255cm below the pavement surface to record temperatures and determine freezing and thawing fronts as they progressed into the subsurface. Instrumentation is also located on site to record air temperatures and relative humidity.

LWD procedures for the Highway 527 site involved testing on a weekly basis for five weeks during the fall freezing period (beginning October 24, 2008) and for ten weeks (beginning March 9, 2009) during the spring thaw period. Thirty LWD drop locations were established at the test site. Fifteen were located in the northbound lane and fifteen in the southbound lane. At each location, the 20kg weight was dropped six times from the maximum drop height (approximately 800mm) onto the 300mm diameter bearing plate. The first drop at each location was not used in the analysis as this drop is used to help seat the LWD and results of this drop are typically erroneous. Additional geophones were not used in the testing as the values obtained from them did not add significantly to the analysis and interpretation of the data.

Highway 569 is located in Northeastern Ontario approximately 3km east of Highway 11 and is instrumented in the same manner as Highway 527. LWD testing at this location was conducted by the Ministry of Transportation of Ontario (MTO) in conjunction with the University of Waterloo. LWD and FWD tests were conducted side-by-side by the MTO and Waterloo and a correlation of these values was examined in this research.

TEMP/W Frost Depth Comparison

Simulated frost depths using TEMP/W were compared with measured frost depths for the Highway 569 location. Various upper and lower thermal boundary conditions were assessed to most accurately predict subsurface freezing and thawing behavior. Chapin et.al. (2009) indicates that initial modelling indicates that a function of modified air temperature with time results in the best prediction of actual freezing and thawing behavior. It was discovered that the use of the temperature measurements at the lowest thermistor (i.e. at a depth of 255cm) provided more accurate results than the use of a specified constant temperature at depth approach. Further research is being conducted to effectively capture the effects that solar radiation has on the surface temperatures and to encompass these effects in an appropriate upper boundary condition. Research is also being conducted into the influence that various thermal and material properties has on the model.

LWD/Frost Depth Correlations

In situ pavement structure conditions such as surface modulus vary greatly with the amount of frost present within the subsurface and with the depths of the freezing and thawing fronts. Changes in the pavement structure at Highway 527 during the fall freezing period of 2008 and the spring thaw periods of 2008 and 2009 were measured using a LWD. Thermistor data were also collected during this time from which frost and thaw depths were interpreted. The surface modulus values obtained from the LWD for both the north and south bound lanes were compared with frost and thaw depths obtained from the thermistors (Figure 2). It can be observed from these data that increases in the thaw depth will in general decrease the surface modulus values. This observation is supported by the increase in average surface modulus values during the April 12th, 2008 refreeze period. The difference between the north and south bound lanes could be attributed to the pooling of surface water as well as to the observed increase of pavement damage in the southbound lane as compared to the northbound lane. Figure 2 also indicates that the surface modulus values remained low after frost had been completely removed from the subsurface, which may indicate poor drainage conditions.

Figure 3 illustrates the effect of frost penetration on surface modulus values during the fall freezing period of 2008 at the Highway 527 site. It can be observed that an increase in frost depth and the subsequent amount of frost directly corresponds to an increase in the surface modulus. It should be noted that LWD testing conducted after November 21st, 2008 resulted in no measureable pavement deflections, indicating a pavement stiffness that was higher than the sensitivity of the device.

Testing and data collection at the Highway 527 site are currently being conducted through the 2009 spring thaw period. This data will be examined and included in further research. Other comparison methods also currently being pursued include an examination of the pavement structure composite moduli and deflection values versus frost depth.

LWD/FWD Correlations

Much research has been conducted in an effort to correlate LWD measured values with FWD measured values. When examining the modulus values, research suggests that LWD composite modulus values should be modified by a specified factor to obtain corresponding FWD composite modulus values. This modification factor is to account for the smaller drop weights and variances in the testing procedures. Research by Steinert et. al (2005) found that when pavement layers are thin a comparison of composite modulus values indicated that a LWD=1.33FWD correlation provides the highest coefficient of determination (R^2) values (0.87). They also found that when pavement layers are thick a LWD=0.75FWD correlation results gives the best R^2 value (0.56) under these conditions. Steinert et.al (2005) found that “in general terms, correlation coefficients tended to increase as pavement thickness decreased”. In addition to this, the LWDmod software requires the input of estimated seed values to calculate the composite modulus. This estimation reduces the accuracy of the calculated composite modulus values. Due to this, this research examined the surface deflection and corresponding surface modulus determined with the LWD.

Based on side-by-side LWD/FWD testing conducted at northeastern Ontario Highway 569, 66 and 624 sites during the spring thaw period of 2008 it can be observed (Figure 4) that LWD surface modulus = 0.38 FWD composite modulus (Al-Mahdawe et. al. 2009). FWD composite modulus values were plotted against factored LWD surface modulus values (Figure 4) and through an examination of the coefficient of determination (R^2) it can be seen that the data correspondence relatively well (0.75). It can also be observed that data variations become higher with higher modulus values, similar to results indicated by previous research.

Steinert et. al , (2005) indicate that when surface modulus values exceed 4000 MPa correlation irregularities begin to appear.   When excluding data that have surface modulus values greater than 3500MPa (Figure 5), it can be seen that although the R^2 value is essentially the same and the number of outliers has been reduced. Larger data sets may reinforce that excluding surface modulus values above 3500 MPa provide a better statistical fit and therefore further research is being conducted into this matter. Research also continues to determine the most accurate LWD modification factor as well as to define the upper and lower measurement limits of the LWD.

ME-PDG Analysis

Preliminary ME-PDG analysis utilized level 3 as the data required to perform levels 1 and 2 analysis were not available. An AADTT value of 33 was input to represent the truck traffic present at the Highway 527 site. The ME-PDG database values were used for all other traffic data except when SLRs were implemented in which case axel load default values were modified accordingly. Climate data required for analysis were obtained from the closest available and compatible weather stations (Table 2) which are located in the northern United States. Figure 6 illustrates the pavement structure and materials that were used in the ME-PDG analyzes.

ME-PDG analysis conducted using level 3 does not allow the reduction of pavement material properties, such as elastic modulus, during the pavement's spring thaw weakened state. Furthermore, SLR conditions are simulated through the modification of the default axel loads. Additionally, the weather stations providing the data used are located at a significant distance from the Highway 527 site as no Canadian weather stations could be used. Due to these reasons the preliminary ME-PDG analysis results were inconclusive and further research is being conducted into the use of levels 1 and 2 to obtain representative analysis conditions. Further research will also include a sensitivity analysis to establish the effects that varying pavement thicknesses and pavement structures have on results, as well as an examination of results when Canadian climate data are used.

Use of Research in SLR Implementation

Effective estimation of pavement strength is an important part of SLR implementation and removal. Through examination of in-situ freezing and thawing conditions it is possible to calibrate a thermal numerical model, such as TEMP/W, to predict the effects that air temperatures have on subsurface behavior. Relationships between pavement structure strength and stiffness and frost depth can be developed using LWD test results. Once the pavement strength is estimated to fall below a predetermined threshold value using the developed correlations of LWD results with frost depths, SLR notice can be given to the trucking industry. Similarly, SLRs could be lifted when predetermined threshold values are reached. Reliable correlation of LWD values with the FWD values will provide confidence in the ability of the LWD to assess pavement structure conditions. ME-PDG can be used to estimate the pavement surface life and predict when pavement rehabilitation needs to occur.

Summary

The following is a summary of the preliminary results of this research as well as a guideline for further research objectives.

- Preliminary investigation suggests that an FWD composite modulus modification factor of 0.38 will provide values that correspond well to LWD surface modulus measurements taken in side-by-side tests in northern Ontario during the spring thaw, pavement weakened period. LWD surface modulus measurements can also be used to roughly approximate freezing and thawing patterns. These correlations however are in their early stage and continued analysis of data from all northern Ontario selected test sites to further define LWD/frost depth and LWD/FWD correlations is currently being conducted.
- In general, the LWD can be used to approximate thawing front depths during spring thaw periods (Figure 2). Preliminary results also indicate that the LWD can provide an indication about the depth of a freezing front and subsequent frost penetration during freezing periods (Figure 3). However, large increases in pavement stiffness due to the presence of frost result in the inability to measure deflection values with the LWD. Further research is currently being conducted to accurately define both the upper and lower measurement bounds of the LWD.
- Preliminary ME-PDG level 3 analyzes cannot be used to represent the effects of pavement spring thaw weakening. Furthermore, the ME-PDG analyses were conducted using data from weather station within the United States and modified axel loads to represent SLR conditions. This resulted in inconclusive results. Further examination of ME-PDG analysis using levels 1 and 2 should be examined to determine their effectiveness in representing in situ conditions. The use of climate data obtained from Canadian weather stations as well as a sensitivity analysis examining increased truck traffic are also being examined,
- Initial TEMP/W modelling results indicate the use of measured temperatures from the deepest pavement structure thermistor results in more accurate results than the use of a constant temperature at a constant depth approach. Solar energy increases greatly influences the impact of the upper boundary condition on the thermal model. Research

into various methods of effectively representing the solar increases is currently being conducted including the use of an n-factor and reference temperatures.

<u>References</u>

Al-Mahdawe, A., Pflug, M., Boudens, N., Sukkau, T., Hill, D. (2009), *Use of the Lightweight Deflectometer to Assess Pavement Layer Mechanical Properties for Implementation of Spring Load Restrictions on Low Volume Roads*, Bachelor of Engineering Degree Project Report, Civil Engineering Department, Lakehead University, Thunder Bay, Ontario

Andersland, O., Ladanyi, B. (2004), Frozen Ground Engineering, The American Society of Civil Engineers and Wiley and Sons, Inc.

Baiz, S., Tighe, S., Mills, B., Haas, C.T., Huen, K., (2007), *Using Road Weather Information Systems (RWIS) to control Load Restrictions on Gravel and Surface-Treated Highways*, Ontario Ministry of Transportation

Chapin, J., Pernia, J., Kjartanson, B. (2009), *An Approach to Applying Spring Thaw Load Restrictions for Low Volume Roads Based on Thermal Numerical Modelling*, ASCE Cold Regions Conference, (in print)

Dynatest International A/S. (2006), "Dynatest 3031 LWD Light Weight Deflectometer Owner's Manual": Issue: 120606.

Sayers, M. W. (1995), *On the Calculation of International Roughness Index from Longitudinal Road Profile*. Transportation Research Record, Transportation Research Board (TRB), Washington, DC, No 1501, pp 1-12.

Sharpe, Gary W., P.E. (2004), *Distribution of the Recommended Mechanistic-Empirical Pavement Design Guide.* American Association of State Highway and Transportation Officials, Committee Correspondence, Memorandum June 23, 2004

Steinert, B.C., Humphrey, D.N., Kestler, M.A. (2005), *Portable Falling Weight Deflectometer Study*, New England Transportation Consortium, Report No. NETCR52

Van Deusen, D. (1998), *Improved Spring Load Restriction Guidelines Using Mechanistic Analysis*, Cold Regions Impact of Civil Works, Ninth International Conference on Cold Regions Engineering, pp 188-199

Table 1: ME-PDG performance parameter default values (Al-Mahdawe et. al. 2009)

Parameter	Parameter Limit
Terminal IRI (in/mile)	172
Longitudinal Cracking (ft/mile)	2000
Alligator Cracking (%)	25
Thermal Fracture (ft/mile)	1000
Permanent Deformation (in)	0.75
Reliability (%)	90

Table 2: Weather stations used in ME-PDG analysis (Al-Mahdawe et. al. 2009)

Weather Station	State	Distance From Test Site (km)
Falls International Airport	Minnesota	303.4
John F. Kennedy Memorial Airport	Wisconsin	322.7
Chisholm-Hibbing Airport	Minnesota	329.8
Duluth International Airport	Minnesota	341.0
Baudette International Airport	Minnesota	386.1

Figure 1: Dynatest 3130 LWD (Dynatest, 2006)

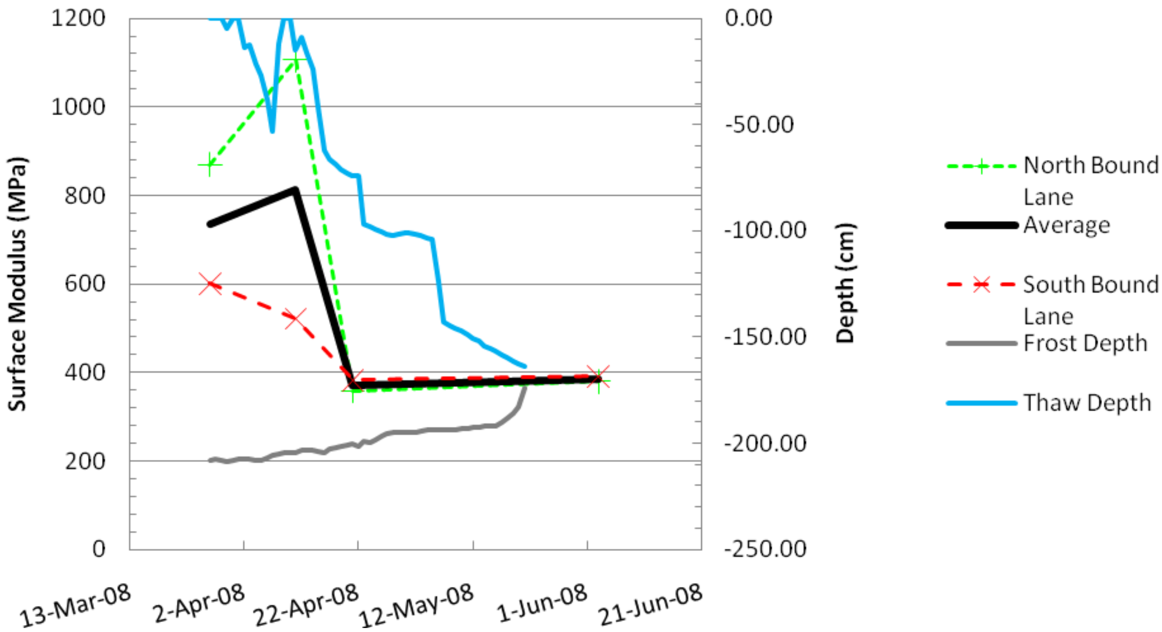

Figure 2: Surface modulus versus frost depth during spring 2008 at the Highway 527 site(Al-Mahdawe et. al. 2009)

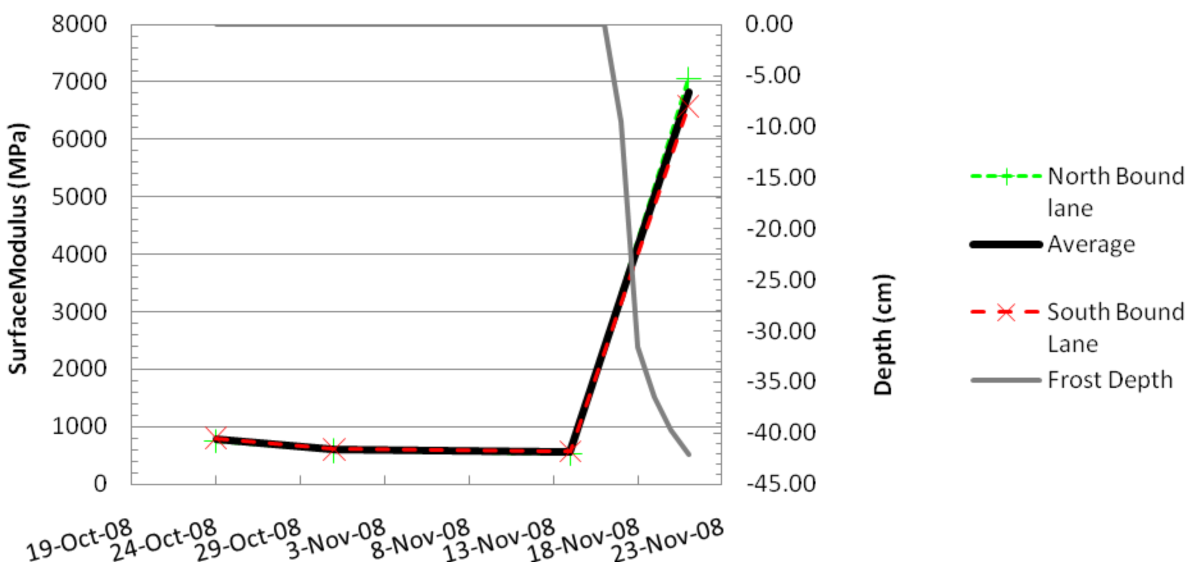

Figure 3: Surface modulus versus frost depth during fall 2008 at the Highway 527 site (Al-Mahdawe et. al. 2009)

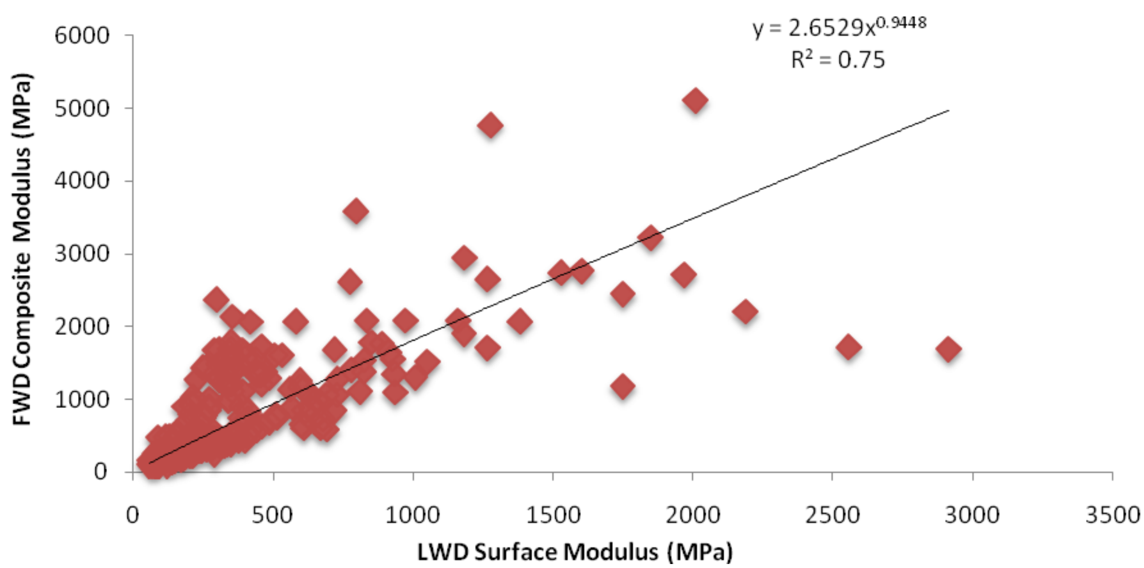

Figure 4: LWD/FWD surface modulus comparison of all northeastern Ontario data (Al-Mahdawe et. al. 2009)

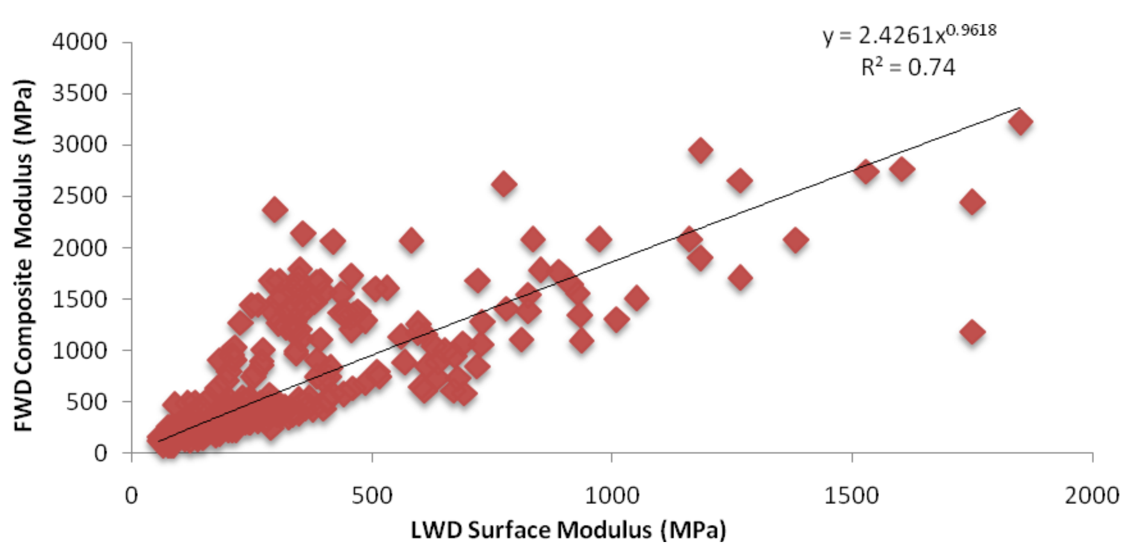

Figure 5: LWD/FWD surface modulus comparison of all Northeastern Ontario data excluding values >3500 (Al-Mahdawe et. al. 2009)

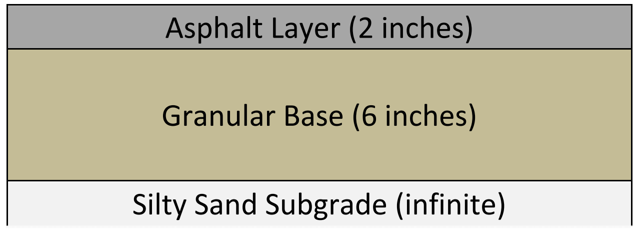

Figure 6: Typical Low Volume Road Pavement Structure used in ME-PDG analysis (Al-Mahdawe et. al. 2009)