Evaluation of New Technologies for Quality Control/ Quality Assurance (QC/QA) of Subgrade and Unbound Pavement Layer Moduli

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Authors:

Mohammad H. Shafiee, PhD Student

Somayeh Nassiri, PhD

Md. Rokibul H. Khan, MSc Student

Alireza Bayat, PhD, PEng

Department of Civil & Environmental Engineering
University of Alberta

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Executive summary

Nondestructive tests (NDT) are widely used for structural evaluation and characterization of pavement layers' moduli for flexible and rigid pavements. Light weight deflectometer (LWD) is an emerging NDT for in-situ measurement of pavement layers' moduli. LWD tests are based on the same concept as the commonly used falling weight deflectometer (FWD) and measure the pavement surface deflections under a load drop. Compared to the FWD device, LWD is inexpensive, compact, portable and easy-to-use.

This study investigated the application of LWD, with respect to conventional FWD, for subgrade layer characterization. In doing so, a series of LWD tests alongside FWD tests were performed on the finished subgrade surface during the construction of the new access road to the Edmonton Waste Management Center. Both tests were performed along the centerline and the outer wheelpath of the access road. Subgrade modulus was backcalculated using the FWD and LWD deflection data in elastic half-space theory.

The LWD backcalculated modulus did reflect the variation along the roadway at cut and fill sections. Inconsistencies, however, did exist at some test locations along the roadway between the FWD and LWD backcalculated moduli, especially for the tests performed along the centerline. Overall, LWD was found to be a convenient and safe test procedure, which is able to identify non-uniformities along the compacted subgrade. More field tests are required to establish its sensitivity and its correlation with FWD backcalculated moduli and its applicability for construction uniformity control.

1. Introduction

Falling weight deflectometer (FWD) is a non-destructive test (NDT) used for several purposes, such as evaluating the uniformity and quality of construction along the road and backcalculating the pavement layers moduli. The Resilient modulus (Mr) of pavement unbound layers is a design input parameter in the newly developed Mechanistic Empirical Pavement Design Guide (MEPDG). Highway agencies are taking steps towards the MEPDG implementation, making unbound layers mechanistic characterization essential. However, FWD testing is associated with high initial costs. Therefore, the number of FWD equipment owned by highway agencies is limited, resulting in few annual testing opportunities for the highway network. Light weight deflectometer (LWD) is an emerging NDT technology, manufactured to serve similar purposes as the FWD test. LWD has several advantages over FWD, including lower initial costs, lower operational time and cost and simplified testing procedure. However, since the apparatus is relatively new, it is crucial to investigate its validity against conventional FWD test results.

The main objective of this study is to evaluate the applicability of LWD testing for unbound material characterization and construction quality control. One LWD device was purchased in 2012, using the financial support provided by the Centre of Transportation Engineering & Planning (C-TEP). LWD tests were performed on the new access road to Edmonton Waste Management Center (EWMC), part of the University of Alberta's Integrated Road Research Facility (IRRF). First, FWD tests were performed on the finished surface of the subgrade during the construction phase of the access road in summer 2012. FWD tests were performed along the roadway centerline and outer wheelpath. LWD tests were performed immediately after the FWD tests at the same locations.

The report is intended to present a summary of the test results and findings. A Problem statement and a summary of past research studies on subgrade and base/subbase moduli characterization and also the application of LWD for pavement unbound material characterization is provided in Sections 2 and 3, followed by a description of the test sections in Section 4. The LWD and FWD test procedures, and the corresponding data analysis and findings are discussed in Section 5.

2. Problem statement

Alberta Transportation conducts nuclear density (ND) tests to evaluate the quality of compaction of the unbound pavement layers. Density testing using the ND gage is a slow and labor-intensive process, especially when the base materials contain large aggregate size (greater than one inch). There are many safety concerns and much paperwork associated with the operation of a NDG. Further, the presence of certain mineral compounds in the soil can render the density and moisture measurements inaccurate, more so if the ND gage calibration is not performed prior to taking measurements at each construction project. The test is conducted at random spots along the road section, which may not necessarily represent the quality of compaction along the entire road section. Further the NDG test does not provide an estimate of the mechanical properties of the subgrade. Resilient modulus of the subgrade soil is a critical parameter for pavement design. In recent years, the MEPDG has attracted the attention of highway agencies and pavement engineers and researchers. Using the MEPDG for pavement design requires a comprehensive knowledge of the mechanical properties of the materials that make up the pavement structure. Resilient modulus is the parameter used in the MEPDG to characterize the pavement unbound materials.

A practical test procedure, which can be used for construction quality control and provide measurements of the materials' mechanistic properties is a favorable alternative to ND test (Chen et al., 1999). FWD tests can be performed on top of finished subgrade, subbase and base layers for quality and uniformity control and at the same for establishing the design inputs for pavement design. However, as mentioned previously, the FWD equipment is costly and the number of equipment in the province is very limited. LWD is a portable and easy-to-use device and can potentially be used to characterize the unbound layers mechanistic properties and replace the hazardous NDG and expensive and time consuming FWD. This study aims at evaluating the applicability of LWD in testing the subgrade layer moduli.

3. Background

3.1 Pavement unbound layers characterization

As mentioned previously, the MEPDG implementation plan has already started in many provinces and states in North America. One of the key parameters in pavement design using the MEPDG is the subgrade soil M_R. Resilient modulus is defined as the ratio of deviator stress to the recoverable strain as shown in Equation 1.

$$M_R = \frac{\sigma_d}{\varepsilon_r} \qquad \text{Equation 1}$$

Where,

σ_d = Deviator stress (MPa),

ε_r = Recoverable strain (mm/mm).

The 1993 American Association of State Highway and Transportation Officials (AASHTO) Pavement Design Guide recommends using M_R as an input parameter to define the subgrade support. To meet this recommendation, AASHTO laboratory tests T-274-87 "Standard Method of Test for Resilient Modulus of Subgrade Soils” and TP292-92 “Standard Method of Test for Resilient Modulus of Subgrade Soils and Untreated Base/Subbase Materials” and the provisional standard TP46-94 “AASHTO Provisional Method for Determining the Resilient Modulus of Soils and Aggregate Materials” were proposed. The complexity of the laboratory test procedure and the high cost of the test equipment forced highway agencies to explore other test methods for characterizing the unbound layers, especially in-situ field tests. At the same time, correlations were established between the in-situ and laboratory tests results.

One of the in-situ tests developed for characterizing the subgrade soil is the California Bearing Ratio (CBR), developed by the California Department of Transportation before World War II. CBR is basically a penetration test for evaluation of the mechanical strength of the road subgrade and base course. CBR value can be used to predict M_R based using Equation 2. It is noted that the correlation is reasonable for fine grained soils with a soaked CBR of 10 or less (AASHTO 1993).

M_R (MPa) = 10.3(CBR) Equation 2

Dynamic Cone Penetrometer (DCP) introduced in the 1960s for pavement evaluation, is another device that has been employed for characterization of subgrade soils. In fact, DCP is used as a rapid means of assessing the sequence, thickness and in-situ bearing capacity of the unbound layers and underlying subgrade that comprise the pavement structure. Chai et al. (1998) proposed the model presented in Equation 3 to determine the subgrade M_R based on DCP tests.

$M_R = 17.6(\frac{264}{DCP})^{0.64}$ Equation 3

where,

M_R is in MN/m^2 and DCP = blows/300 mm penetration.

NDT evaluation of pavement structures, principally deflection testing, has gained essential popularity for assessing the structural capacity of the pavement. Deflection tests include applying a static, vibratory or impulse load on the pavement surface and measuring the resulting deflections at the surface. Static or slow moving loads are employed in the case of Benkelman Beam, the LaCroix Deflectograph, and the Curviameter, whilst vibratory loads are applied by the Dynaflect, the Road Rater, the Corps of Engineers 16-kip (71-kN) Vibrator, the Federal Highway Administration's Cox Van and Geogauge. In contrast to vibratory loading for Dynaflect, near field impulse loads are applied when using the KUAB and Phoenix FWD. The near field impulse devices are also available in small-scale including the Loadman, German Dynamic Plate Bearing Test (GDP), TRL Foundation Tester (TFT) and Prima 100. "Far field" impulse loads are impact devices, whose primary use is in Spectral Analysis of surface wave method. Wave propagation is used by the Shell Vibrator, which loads the pavement harmonically and sets up standing surface waves, the peaks and nodes of which are found by using moveable sensors (George, 2006). The rolling wheel deflectometer (RWD) measures the response from one-half of an 18-kip single-axle load traveling at normal highway speeds. This technology can measure deflections for approximately 200 to 300 lane-miles per day, which is approximately 10 times the production of traditionally used FWD testing (Diefenderfer, 2010).

Deflection testing has been a standard evaluation procedure used by Alberta Transportation. In the mid 1960's, Alberta Transportation started using Dynaflect to measure pavement deflections. Dynaflect is one of the first steady-state dynamic deflection devices to use two steel loading plates and five velocity transducers for deflection measurement. In 1989, Alberta Transportation began using FWD testing for pavement testing and currently interprets the Dynatest FWD deflections to estimate the structural adequacy of pavement (Alberta Transportation, 1997).

During Dynatest FWD testing, a dynamic load is applied to the pavement surface. The load is provided through dropping a weight from (typically three) different heights to generate different load impulses and impacts on the pavement structure. The pavement deflections are recorded at the surface using an array of geophones (seismometers) or velocity transducers (Shahin, 2005), which are arranged in a line at certain distances from the plate load center (Figure 1). The produced deflection basin generally reflects the response of the pavement under the applied load, which is used to backcalculate each layer's stiffness modulus (Figure 1).

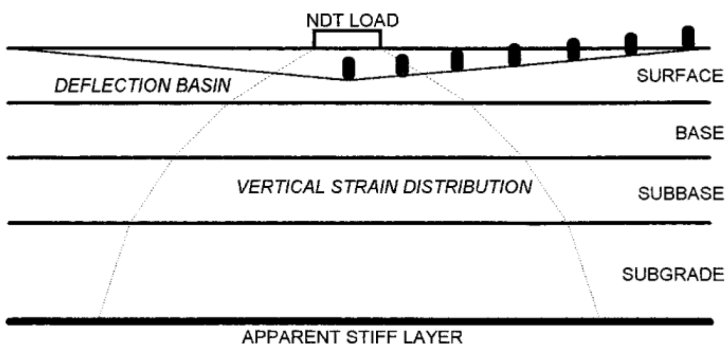

Figure 1-Deflection basin and stress distribution in NDT (ASTM D5858 – 96).

The deflection basin from the FWD testing is used to backcalculate the pavement layers' moduli. The back analysis approaches for determining each layer's stiffness has evolved to include robust computer software programs. Elastic theory analysis and backcalculation iterative tools are considered two well-established approaches for estimating layer stiffness under NDT evaluation (Lytton et al, 1989). The most commonly used regression method for estimating the subgrade M_R is the AASHTO backcalculation method. In this method, the subgrade modulus is backcalculated using the deflection at a sufficiently large distance from the load center based on the elastic layer theory. The subgrade M_R is estimated using Equation 4. The AASHTO 1993

Guide also presents Equation 6 for predicting the effective modulus of the pavement structure (i.e., modulus of all layers above the subgrade).

$$M_R=\left(\frac{0.24P}{d_r r}\right) \text{ and } r\geq 0.7a_e \qquad \text{Equation 4}$$

$$a_e=\sqrt{a^2+\left(D\sqrt[3]{\frac{E_P}{M_R}}\right)^2} \qquad \text{Equation 5}$$

$$d_0=1.5Pa\{\frac{1}{M_R\sqrt{1+\left(\frac{D}{a}\sqrt[3]{\frac{E_P}{M_R}}\right)^2}}+(1-\frac{1}{\sqrt{1+\left(\frac{D}{a}\right)^2}})/E_P\} \qquad \text{Equation 6}$$

where,

M_R= subgrade resilient modulus (MPa),

P= FWD load (N),

d_r= deflection at the sensor located at distance of r (mm),

r= distance from plate center (mm),

a_e = radius of stress bulb at the subgrade-pavement interface (mm),

a= FWD load plate radius (mm),

D= total thickness of pavement layers above subgrade (mm),

d_0= deflection under the load plate (mm),

E_P= effective modulus of all pavement layers above subgrade (MPa).

After finding the initial value for the subgrade modulus, effective modulus of pavement can be determined using deflection recorded under the plate center (d_0) according to Equation 6. The effective modulus of the pavement is calculated by an iterative method to find a_e and satisfy the reasonable distance criteria for parameter r.

The most commonly used method for backcalculation of layers moduli for flexible pavements is the iterative method. Various pavement analysis computer software packages are available that estimate each layer's modulus based on iterative methods. These software packages include, but are not limited to: BISDEF, CHEVDEF, MODULUS, MODCOMP, EVERCALC, PEDMOD, ELMOD and MICHBACK. The programs differ in terms of the internal forward computation model used to calculate the deformations and the error minimization scheme. Two popular forward computation models are the numerical integration methods and the approximation methods. The error minimization is conducted by determining the absolute mean square error or the percent mean square error. Generally, backcalculation initiates from the default or user-defined seed moduli and the user-defined geometry of the pavement structure. Deflections are then calculated using the multi-layer elastic theory. The error relative to the measured deflections is determined to check whether the initial modulus needs to be modified. Figure 2 shows the simplified flow chart for backcalculation in EVERCALC software in which deflections are computed using WESLEA multi-layer elastic program (EVERSERIES, 2005).

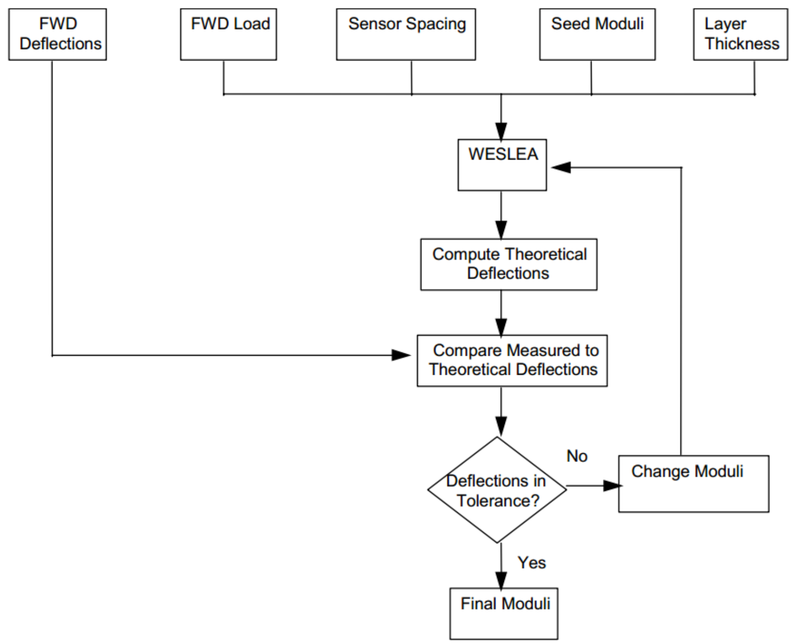

Figure 2-Common analysis approach in EVERCALC backcalculation program (EVERSERIES, 2005).

Whilst numerous studies have attempted FWD measurements on the pavement surface, only a few have targeted FWD tests conducted directly on the subgrade surfaces. In their study of the Minnesota Department of Transportation Road Research Facility (MnROAD), Van Deusen et al. (1994) documented the difficulties associated with analyzing the data from the FWD tests performed directly on top of the subgrade. All deflection data were used to estimate the subgrade M_R based on the homogenous half-space model commonly named as the Boussinesq's theory. Equation 7 depicts the half-space model.

$$E = \frac{\pi(1-\nu^2)\sigma_0 a}{2d_1} \qquad \text{Equation 7}$$

where,

σ_0 = applied pressure (MPa),

a = radius of the loading plate (mm),

d_1 = deflection under plate center (mm) and

ν = Poisson ratio of the subgrade material.

After analyzing for the 40 sections, Subgrade M_R estimated using Equation 7, was found to be varied from 63 to 177 MPa. While subgrade M_R obtained from laboratory varied from as low as 36 MPa to as high as 232 MPa. No specific correlation between the laboratory and deflection-based M_R was reported.

George (2003) conducted a substantial study on using the FWD test for characterizing the subgrade M_R incorporation with the Mississippi Department of Transportation. Ten as-built subgrade sections reflecting typical subgrade soil materials, including both fine and coarse grain soils, were selected and tested with FWD. Shelby tubes were employed to extract undisturbed soil samples those intentionally used for repeated load triaxial tests as mentioned in AASHTO TP46 protocol. Other routine laboratory tests were conducted to determine the physical properties of the samples, and in turn, classify the soil being tested. Elastic moduli, E_1 to E_7, were estimated employing the half-space theory (Equation 7) using FWD seven sensor deflections. Two distinct moduli E_1 and $E_{3\text{-}5}$ (refers to the average modulus of E_2, E_3 and E_5) for all the tests were established. The lesser of the two (E_1 and $E_{3\text{-}5}$) serves as the design resilient modulus. A short-cut procedure for predicting resilient modulus was also recommended, which employs an $E_{3\text{-}5}$ section average for a low moduli range, that is E_1 < 9000 psi (62 MPa), and lesser of E1 and $E_{3\text{-}5}$ for E_1 > 9000 psi (62 MPa). An exclusive program, FWDSUBGRADE, was developed to analyze the FWD deflection data from subgrade tests, extracting first sensor modulus E_1, and average of three offset sensor moduli, E_{3-5}, from which only design resilient modulus is derived. Figure 3 depicts the flow-chart for the FWDSUBGRADE program.

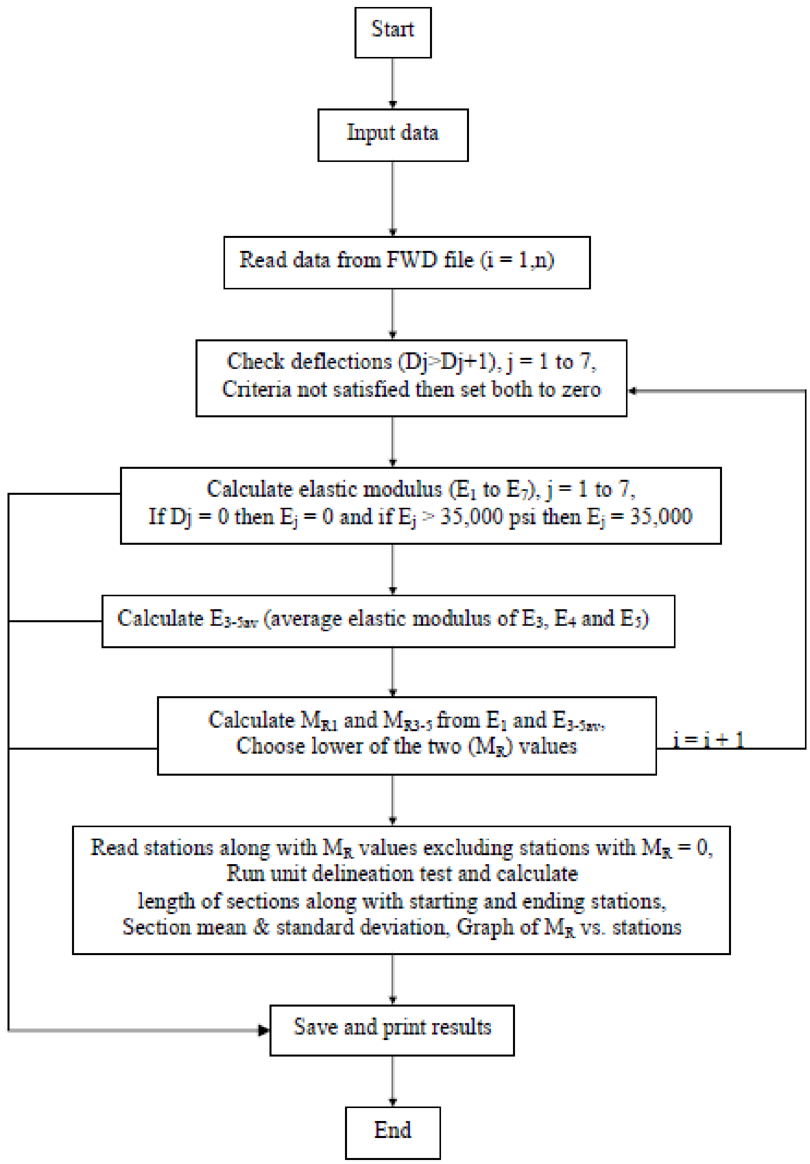

Figure 3-Flow chart of program FWDSUBGRADE (George 2003).

AASHTO 1993 Design Guide permits the use of both laboratory and backcalculated moduli, but discloses that the moduli determined by both procedures are not equal. There may be a number of factors contributing to the mismatch between the laboratory and backcalculated moduli. The Guide, therefore, suggests that the subgrade modulus determined from deflection measurements on the pavement surface, E_{back}, be adjusted by a factor of 0.33. Various values have been established for correcting the backcalculated M_R to the design subgrade modulus. In one study, considering three different pavement sections in North Carolina, both laboratory and backcalculated M_R ware determined. The ratio of laboratory-measured modulus values to the corresponding backcalculated values varied from 0.18 to 2.44 (Ali and Khosla, 1987). Other investigator reported the results of similar tests in Washington State, suggesting a ratio in the range of 0.8 to 1.3 (Newcomb, 1987). However, Von Quintus et al. (1998) reported ratios in the range of 0.1 to 3.5 in a study based on data obtained from the Long Term Pavement Performance (LTPP) database. "Despite several improvements made over the years, researchers have cited several uncertainties as well as limitations associated with the laboratory test procedure (TP46), a list of which follows:

1. The laboratory resilient modulus sample is not completely representative of in-situ conditions because of sample disturbance and differences in aggregate orientation, moisture content, in-situ soil suction and level of compaction (or re-compaction).

2. Inherent equipment flaws make it difficult to simulate the state of stress of the material in-situ.

3. Inherent instrumentation flaws create uncertainty in the measurement of sample displacements.

4. Lack of uniform equipment calibration and verification procedures lead to differences not only between labs but also within a given lab.

5. Laboratory specimens represent the properties of a small quantity of material, and not necessarily the average of the mass of material that responds to a typical truck axle.

6. The time, expense and potential impact associated with a statistically adequate sampling plan as well as testing add up to large expenditure.” (George, K. P., 2003).

Meanwhile a NDT, such as the FWD deflection test is attributed with providing the in-situ modulus, and is also capable of identifying inherent spatial variation. This report explores the viability of LWD, a smaller version of FWD, in estimating subgrade material modulus, a substitute for resilient modulus for pavement design.

3.1.1 Light weight deflectometer (LWD)

Another NDT device, which can be used for pavement structural evaluation, is the LWD also referred to as the Portable Falling Weight Deflectometer (PFWD). LWD is a simple, portable, small and easy-to-use device, which works based on a similar concept as the FWD. Figure 4 shows a schematic illustration of a typical LWD device. For an LWD test, the falling load (weighing 10 kg or more, depending on the model and manufacturer) is dropped on a rigid steel plate placed on a leveled surface of the soil from a fixed height (also based on the model and manufacturer) along the rod and hits the spring-damper. The deflection is measured by an accelerometer sensor located at the plate center and the measurement is stored in a small data acquisition system attached to the LWD.

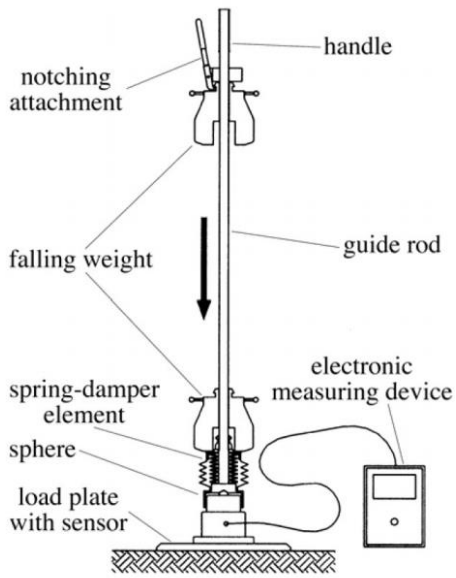

Figure 4-Schematic presentation of various components of a typical LWD device (Adam, C. & Adam, D., 2003).

The LWD test procedure starts with a preload drop on top of a leveled area of the material under testing. The area is leveled prior to testing to attain a direct and complete contact between the plate and the material. Three consecutive test runs (plate drops) are conducted and the average of obtained maximum amplitude of load pulse and the corresponding plate deflection is used for calculation of the modulus of the material under testing. In general the device software integrates the geophone (velocity transducer) signal to determine the maximum (or peak) deflection value. This has two important ramifications, the first being that under test the peak deflection may not occur at the same instant as the peak load (Figure 5), and usually does not, specifically for lower stiffness materials. The second is that the maximum deflection may include an element of permanent/plastic deflection in addition to recoverable/elastic deflection. This depends upon the 'strength' of the materials under test, and the efficacy of the contact between the geophone foot and the material under test (Fleming at el., 2007).

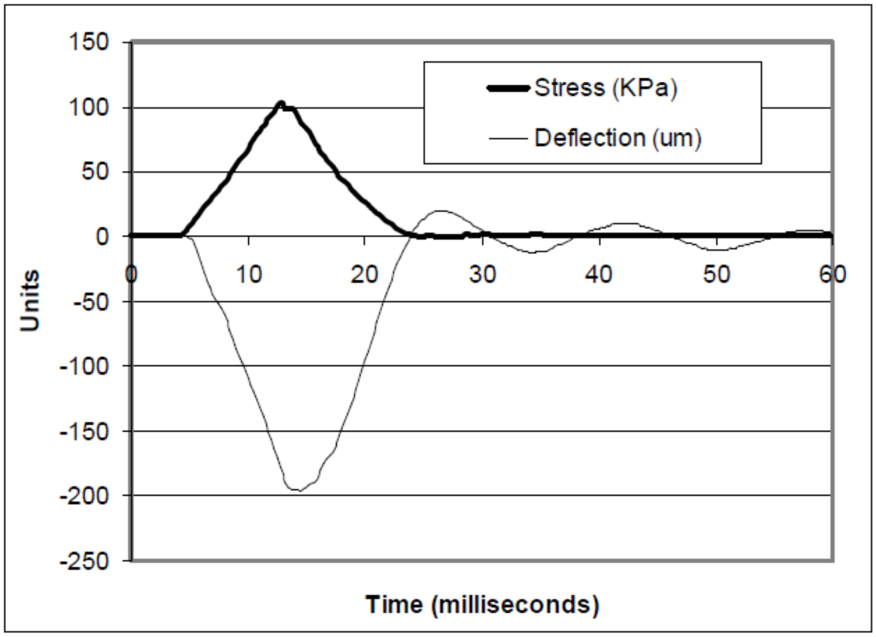

Figure 5-Example of a LWD output from a laboratory test (Fleming at el., 2007).

LWD can be used, as an alternative to the costly and time consuming FWD test, to characterize the in-situ modulus of the soil subgrade, subbase and base materials. Several types of LWD devices have been manufactured and used, which vary in drop height, load weight and instrumentation. Table 1 provides a summary of the characteristics of some common LWD devices from five different manufacturers such as CSM, Zorn, Prima, Loadman and TFT. These devices are different from each other in terms of diameter, mass and style of plate, drop mass and height, type of damper employed, category of plate sensors used, impulse time, maximum load that can be imparted, contact pressure and Poisson's ratio. For each device, plate diameter is not the unique one. Overall, the plate diameter varies from 100 to 300 mm. Drop masses, on the other hand, vary between 10 to 15 kg. Drop heights are observed to be fixed for Zorn and Loadman which are 0.72 and 0.80 m respectively, while for the rest three are variable. Geophone sensors are used in CSM, Prima and TFT devices whilst accelerometers are employed for Zorn and Loadman. Rubber dampers are used for Prima, Loadman and TFT but for CSM and Zorn, urethane and steel spring dampers are employed respectively. Maximum load imparted, also found varying from 1 to 20 kN (Mooney and Miller, 2009).

Table 1-Physical characteristics of typical LWD devices (Mooney and Miller, 2009).

Manufacturer	CSM	Zorn	Prima	Loadman	TFT
Plate style	Solid	Solid	Annulus	Solid	Annulus
Plate diameter(mm)	200,300	150,200,300	100,200,300	130,200,300	100,150,200,300
Plate mass(kg)	6.8,8.3	15	12	6	Variable
Drop mass(kg)	10	10	10,15,20	10	10,15,20
Drop height(m)	Variable	0.72	Variable	0.8	Variable
Damper	Urethane	Steel spring	Rubber	Rubber	Rubber
Force measured	Yes	No	Yes	Yes	Yes
Plate response sensor	Geophone	Accelerometer	Geophone	Accelerometer	Geophone
Impulse time(ms)	15-20	18±2	15-20	25-30	15-25
Max load(KN)	8.8[a]	7.07[a]	1-15[a]	20[a]	1-15[a]
Contact stress	User def.	Uniform	User def.	Rigid	User def.
Poisson's ratio	User def.	0.5	User def.	0.5	User def.

[a] Dependent upon drop height and damper

3.1.2. Previous field studies on LWD and FWD

A number of studies have been conducted using the PFWDs on full pavement structures for routine assessment. Experience with PFWDs in the United States is very limited, but showing an increasing trend. The United Kingdom Highways Agency sponsored extensive investigations for the development and use of a range of PFWDs over the past 15 years. One of the strategic aims has been to establish a specification for the PFWD device to be used as a field amenability tool within a routine based specification for pavement foundation construction. Nonetheless, earlier the introduction of field testing had been restricted by the necessity for reliable in-situ testing methods to measure suitable parameters, yet vigorous enough to withstand the relatively harsh site environment. The LWD has been used comprehensively by different investigators into the evaluation of materials in the field, in the laboratory, on fully constructed in-service (thinly surfaced) roads and more recently on artificial sport surface constructions (Fleming et al., 2007). The FWD, on the other hand, has been in use now for over 20 years, including a certain amount of usage on unbound pavement foundations. It is a tried and trusted tool and is seen by many as a standard alongside which other dynamic plate tests should be judged. By this measure, many authors have reported correlations between the FWD and PFWDs. It is reasonable that the use of PFWDs is more trusted if they show good correlation to the FWD (Fleming et al., 2007). Several researchers worked on developing correlations between FWD and LWD backcalculated modulus. This includes several case studies performed on different types of materials and pavement structures. Fleming et al. (2000) conducted a comprehensive study on LWD (Prima 100) and FWD. They compared the FWD modulus at a site of 450mm granular capping over silty clay with LWD modulus and found that LWD modulus is 0.97 times that of FWD modulus with R- Square (R^2) of 0.6 (based on 25 tests). Further, they established that the developed correlation was very likely to be site, material and device specific. In another study with different soil properties with a 260mm of lime and cement treated clay subgrade, they observed a different correlation. They found modulus obtained from LWD is 1.21 times greater as compared to FWD modulus with R- Square (R^2) equal to 0.77. At another site with a standard granular foundation (225 mm well graded crushed rock over a granular subgrade) for several sections the ratio of LWD and FWD modulus ranged between 0.8 to 1.3 , with R- Square (R^2) value of 0.5 or lower (169 tests). However, this latter site was quite wet and the stiffness values were generally low relative to other sites evaluated.

Nazzal et al. (2004) carried out comparative testing of the FWD and LWD on live construction sites on granular subgrade and at an accelerated load test facility. They also used the LWD Model Prima 100 and finally presented a general relationship as LWD modulus is 1.031 times higher than FWD modulus having a very good regression coefficient R-Square (R^2) of 0.97.

Steirent et al. (2006) considered the potential of the use of LWD (Prima 100) for observing traffic load control associated with spring-thaw seasonal variations. They produced a comparison between the LWD and FWD on a variety of sites at differing times of the year. The relationship between the LWD and FWD was revealed to vary with reducing asphalt thickness. In addition, the goodness of the fit between the LWD and FWD subgrade moduli showed a better correlation (R-Square = 0.87) on thinner asphalt layers with a LWD to FWD modulus ratio of 1.33. But for the thicker asphalt, the ratio dropped down to 0.75 with a reduced R-Square (R^2) of 0.56. Table 2 provides a summary of aforesaid correlation equations developed to relate FWD and LWD moduli in three different studies.

Table 2-Regression analysis between LWD and FWD modulus from different studies.

Equation	**Layer Description**	**R-Square (R^2) Value**	**LWD Model**	**Source**
LWD(MPa) = 0.97FWD(MPa)	450-mm granular capping over silt and clay	0.60	Prima 100	(Fleming et al., 2000)
LWD(MPa) = 1.21FWD(MPa)	260-mm lime-cement treated clay subgrade	0.77	Prima 100	
LWD(MPa) = 0.80 to 1.30FWD(MPa)	225-mm well-graded crush stone granular subgrade	0.50	Prima 100	
LWD (MPa) = 1.03FWD(MPa)	Granular subgrade	0.97	Prima 100	(Nazzal et al., 2004)
LWD(MPa) = 1.33FWD(MPa)	Thin asphalt layer	0.87	Prima 100	(Steirent et al., 2006)
LWD(MPa) = 0.75FWD(MPa)	Thicker asphalt layer	0.56	Prima 100	

The University of Alberta purchased one LWD device manufactured by Zorn. As seen in Table 1, ZFG 3.0 comprises a 10 kg drop weight, which is a 30 cm diameter loading plate, and is released from a 70-cm height. Each drop produces a 7.07 kN dynamic load with a 18 ms duration on top of the material under testing. It is assumed that the material is subjected to 100 kN/m^2 uniformly distributed stress. The test program and the backcalculation results are discussed in the following section.

4. Field Test Program

4.1 Description of the test road

The FWD and LWD tests for this study were performed during the construction of the subgrade of the access road connecting the EWMC to 130 Ave. The road is approximately 500 m long and is a test track, which includes an embankment made of Tire Derived Aggregate (TDA) in the southern sections. Figure 6 shows the location of Integrated Road Research Facility (IRRF) test facility in Edmonton, Alberta. This two-way, two-lane access road, when fully constructed, will consist of a 220 mm Hot Mix Asphalt (HMA) surface layer and a 450 mm Granular Base Course (GBC) on a subgrade.

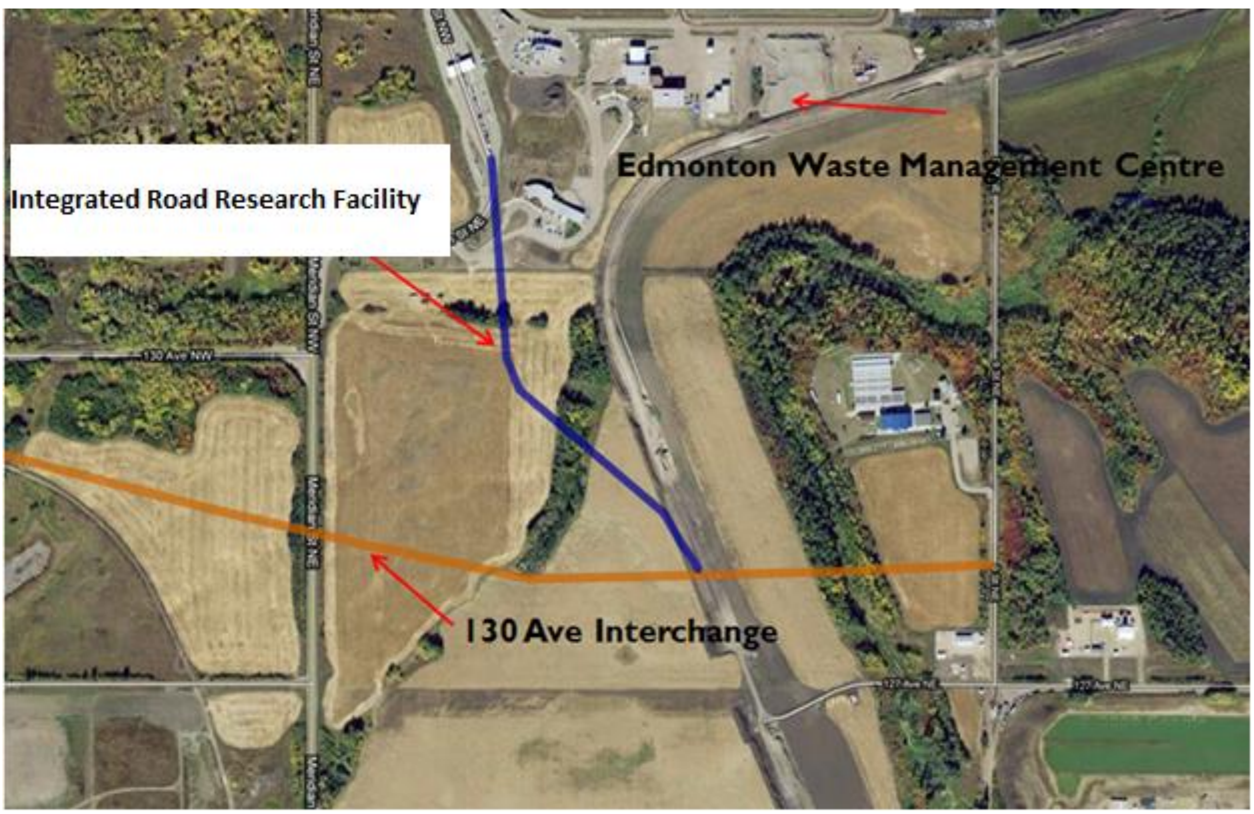

Figure 6-Geographical location of the IRRF's test road.

Figure 7 shows a schematic of the test road, which indicates that the TDA fill test sections are located from Stationing 130 + 080 to Stationing 130 + 140. FWD and LWD tests were carried out along the road from Stationing 130 + 040 through Stationing 130 + 250 on top of the finished subgrade.

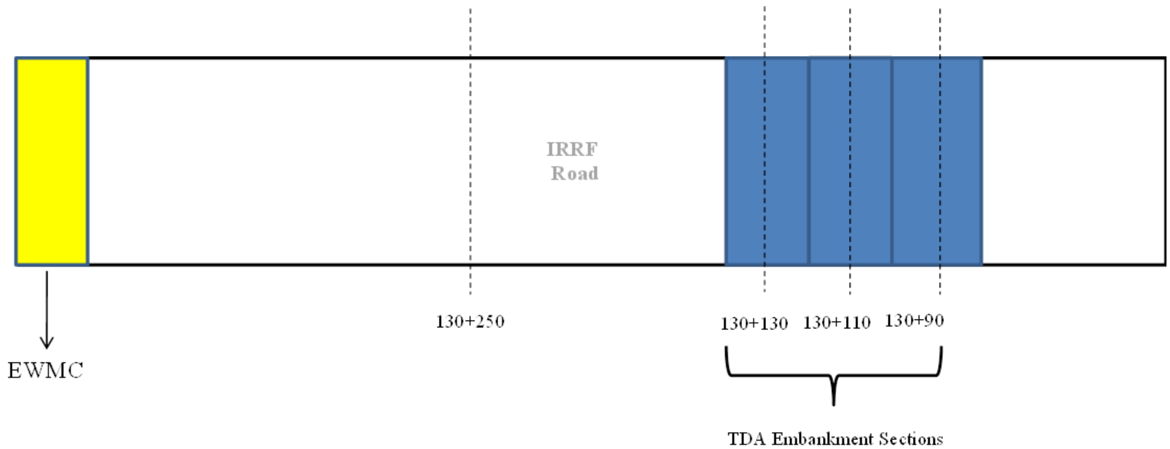

Figure 7-Schematic presentation of the IRRF test sections.

Figure 8 shows the schematic structure of the various sections, which were tested along the road. As shown in Figure 8 (a) the first section (Stationing 130 + 80 through Stationing 130 + 100 in Figure 7) is made of TDA from Passenger and Light Truck Tire (PLTT). This section consists of two layers of PLTT and a 0.5-m native soil layer in between. Each PLTT layer is three meters thick and was wrapped using a non-woven geotextile that separates the PLTT layer from the surrounding soil. One meter of native soil was placed over the top PLTT layer. The cap layer was then topped with 450-mm GBC and 160-mm HMA. PLTT contained TDA particles that were mostly thin and plate-like in shape made from tires with a rim diameter of up to 49.5-cm. PLTT used in this section was produced by Liberty Tire Recycling Canada.

The second section, as shown in Figure 8 (b), is TDA from Off-The-Road (OTR) tires, with a rim diameter of up to 99 cm. OTR is a significant waste in the province of Alberta and the IRRF test road study aims to evaluate the potential for useful applications of scrap OTRs for the first time. The OTR section stretches from Stationing 130 + 100 to Stationing 130 + 120 and has a similar structure configuration as that of the PLTT section.

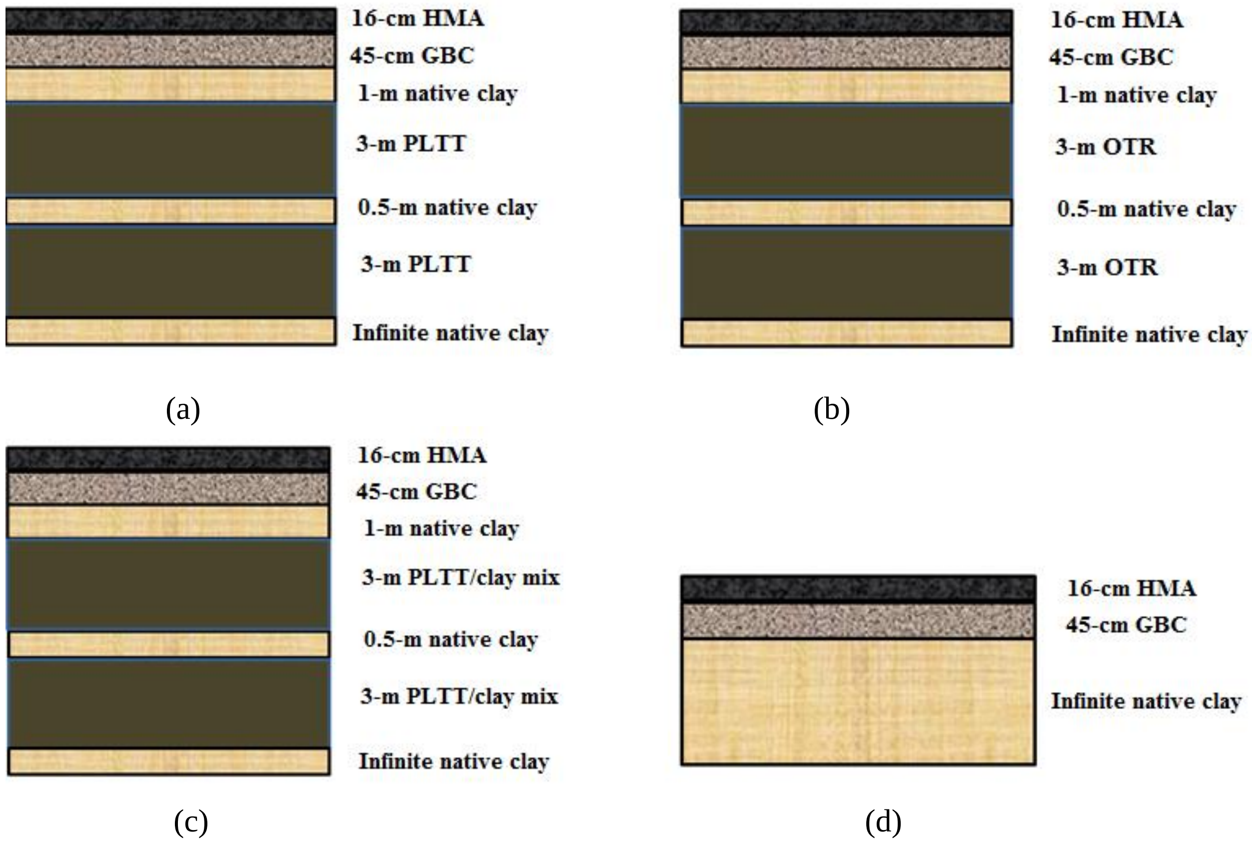

Figure 8-Schematic presentation of the pavement structure for the (a) PLTT section, (b) OTR section, (c) PLTT-soil mixture section and (d) Native soil test section.

Figure 8 (c) shows the cross section of the roadway from Stationing 30 + 120 to Stationing 30 + 140 comprising of two 3-m layers of PLTT-soil mixture with 0.5 m of native soil placed in between. To decrease the compressibility of TDA alone, PLTT was mixed with fine grained soil in this section. PLTT and native soil were mixed at a 50/50 ratio by volume. Again, a one meter native soil, 450 mm of GBC and 160 mm of HMA was placed on top of the PLTT-soil mixture layer. Figure 8 (d) the remaining sections from Stationing 30 + 140 to Stationing 30 + 260, where the pavement consists of native soil layer as the subgrade, 450-mm GBC and 160-mm HMA layer on the surface.

4.2 Subgrade soil characterization and field tests

During the excavation for the test embankment, samples were taken from the subgrade soil. Gradation tests in accordance with ASTM C-136-06 showed that the soil is uniformly graded sand, with 34 percent of the particles passing sieve No. 200. The soil was characterized as Clayey Sand (SC) according to the Unified Soil Classification System (USCS), with liquid and plastic limits of 25 and 16 percent, respectively. The maximum density and optimum moisture content for the subgrade soil were determined as 18 kN/m^3 and 16.5 percent, respectively in the laboratory following the ASTM D 698-07 test procedure.

FWD and LWD tests were conducted on July 11th, 2012 from Stationing 30 + 35 to Stationing 130 + 255 on top of the 1-m soil cover in the eastbound lane. The drops were performed at 5-m intervals along the TDA fill sections and 10-m intervals at central sections with normal subgrade along both the outer wheel path and the centerline. The Dynatest FWD device was used to apply four drops resulting in target load magnitudes of 5.8, 8.1, 10.0 and 12.4 KN on a 300-mm diameter load plate. The deflections were measured by seven geophones located at 1200, 900, 600, 450, 300, 200 and zero mm from the center of the load plate (Figure 9 (a)). LWD tests were also carried out at the same locations after FWD applications using the LWD-ZFG 3.0 device (Figure 9 (b)).

(a) (b)

Figure 9- (a) FWD; and (b) LWD testing on the finished subgrade at the IRRF's test road facility.

5 Analysis of tests data

5.1 Backcalculation of subgrade modulus

As described previously, to investigate the load bearing capacity of the subgrade of the IRRF test sections, FWD tests were conducted at predetermined locations in the eastbound lane along the outer wheel path and the centerline. FWD testing was performed at 10-m intervals on top of the finished subgrade before construction of the base layer. The deflections from the FWD tests on top of the subgrade were used herein to backcalculate the subgrade modulus along the test road. Prior to backcalculation, the FWD deflections were normalized to the corresponding target load according to ASTM D5858-96, the Standard Guide for Calculating In-Situ Equivalent Elastic Moduli of Pavement Materials Using Layered Elastic Theory. To do so, the drops where the load varied by 5 percent or more from the target load, the actual deflections were normalized. Thus, the actual deflections were multiplied by the target-load-to-actual-load ratio to obtain the normalized deflections. The normalized deflections under the plate load were used in Equation 7, to backcalculate the subgrade modulus, where ν was defined as 0.35 for the subgrade soil, according to the recommendations found in the Mechanistic Empirical Pavement Design Guide documentation for this type of soil (ARA Inc. ERES Consultants Division 2004). The backcalculated modulus for the four drops at each location along the centerline and the outer wheel path are presented in Figures 10 and 11, respectively.

According to Figure 10, the backcalculated subgrade modulus along the outer wheelpath is relatively consistent with average values of 60, 53, 49 and 47 for drops 1 through 4, respectively. Subgrade modulus shows an abrupt increase to 86 MPa at Stationing 130 + 145. This point is the end of the fill sections and the start of the normal existing ground. Beyond the transition point at Stationing 130 + 150, the modulus tapers gradually to a minimum value of 47 MPa at Stationing 130 + 190. Another sudden increase is evident at Stationing 130 + 220. A possible explanation for the variation is the change in the natural soil profile at this station, as the last segment lies on the back slope of the underlying soil.

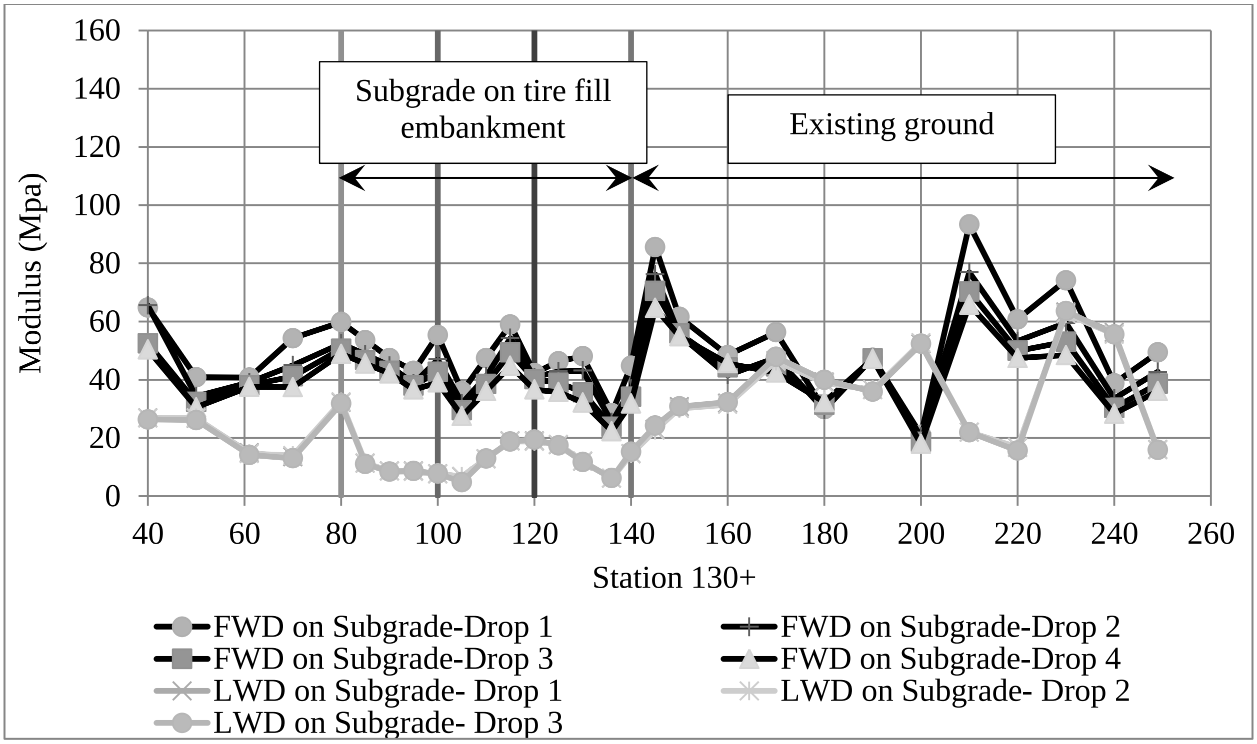

Figure 10-Variation of backcalculated subgrade modulus along the outer wheel path on top of the subgrade.

Figure 11 presents the FWD backcalculated Moduli along the centerline. The average modulus along the roadway is 70, 61, 58 and 54 MPa for Drops 1 through 4, respectively. These average values are consistently higher than those obtained for the tests performed in the outer wheel path, as discussed previously. The backcalculated modulus drops from the start point (Stationing 130 + 40) from a maximum of 107 MPa to a minimum of 28 MPa at Stationing 130 + 55 and then picks up to a maximum value of 74 MPa. The reason for the variability in the first 40 m of the test section is not clear (no variation is evident in Figure 8 for the same section). The modulus significantly drops at the edge of the tire fill embankment (Stationing 130 + 80) and remains as low as 32 MPa over the fill sections. Backcalculated modulus starts to increase at the end of the fill sections at Stationing 130 + 140 and continues to ascend until Stationing 130 + 170. A sudden drop is seen at Stationing 175, which may be due to several reasons such as localized moisture. A sudden drop is noted at Stationing 130 + 190, where as discussed previously the terrain changes. Based on this discussion one can conclude that significant variability existed in the uniformity and quality of compaction of the subgrade along the centerline. It is evident that special care is required during compaction, especially at the transition zones from fill to normal ground or cut sections.

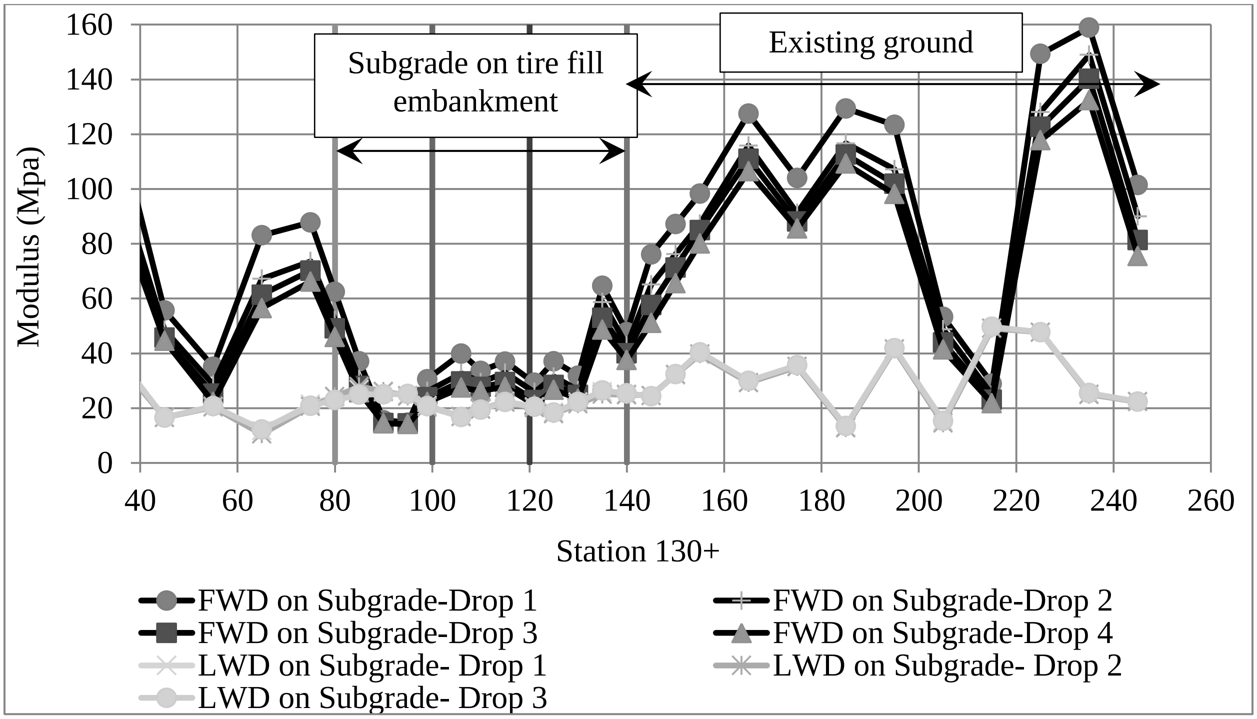

Figure 11-Variation of backcalculated subgrade modulus along the centerline on top of the subgrade.

As described previously, LWD tests were performed on top of the finished subgrade at the same locations, where the FWD tests were performed (at 10-m intervals) along the centerline and the outer wheel path. Each LWD test began with a seating drop and was followed by another three consecutive drops at each location. The subgrade modulus for each drop was backcalculated using Equations 7. Note that the stress level for all the drops were defined as 0.1 MPa (for a 10 kg load dropped on a 300-mm diameter plate) since no load measuring device is available for the ZFG 3.0.

LWD backcalculated moduli for three drops at each location are superimposed on Figures 10 and 11 for the tests along the outer wheel path and centerline, respectively. Based on Figure 10, the LWD and FWD backcalculated moduli agree relatively well, especially for the sections with normal ground. Also, LWD backcalculated moduli shows a drop for the tire fill sections with respect to the sections on normal ground. For the tests performed along the centerline (Figure 11) the backcalculated moduli from FWD and LWD tests agree for the tire fill sections. However, the LWD modulus remains consistently lower than the FWD modulus for other sections. Further, the extensive variability in the subgrade modulus reflected in the FWD results is not seen in the LWD results along the centerline.

A correlation study was conducted to investigate the relationship between the FWD and LWD backcalculated modulus for the subgrade layer. The correlation between the LWD and FWD modulus corresponding to Drops 1 and 2, where load levels are compatible with those for the LWD test was investigated. The test results for the sections with normal subgrade from Stationing 130 + 40 to 130 + 80 and Stationing 130 + 140 to 130 + 250 along the centerline and outer wheel path was used in Figure 12. FWD and LWD correlation was performed for the above-mentioned stationing to exclude the effect of tire embankment on the linear function. As seen in the figure a strong linear correlation was not able to be established between the FWD and LWD backcalculated moduli for the test road. The differences between the backcalculated moduli from FWD and LWD tests can have resulted from inherent differences between the test equipment, including the equipment weight, loading rate and so forth. More field tests on a verity of subgrade soil material can help expand the LWD-FWD deflection database and potentially establish a correlation between the two tests.

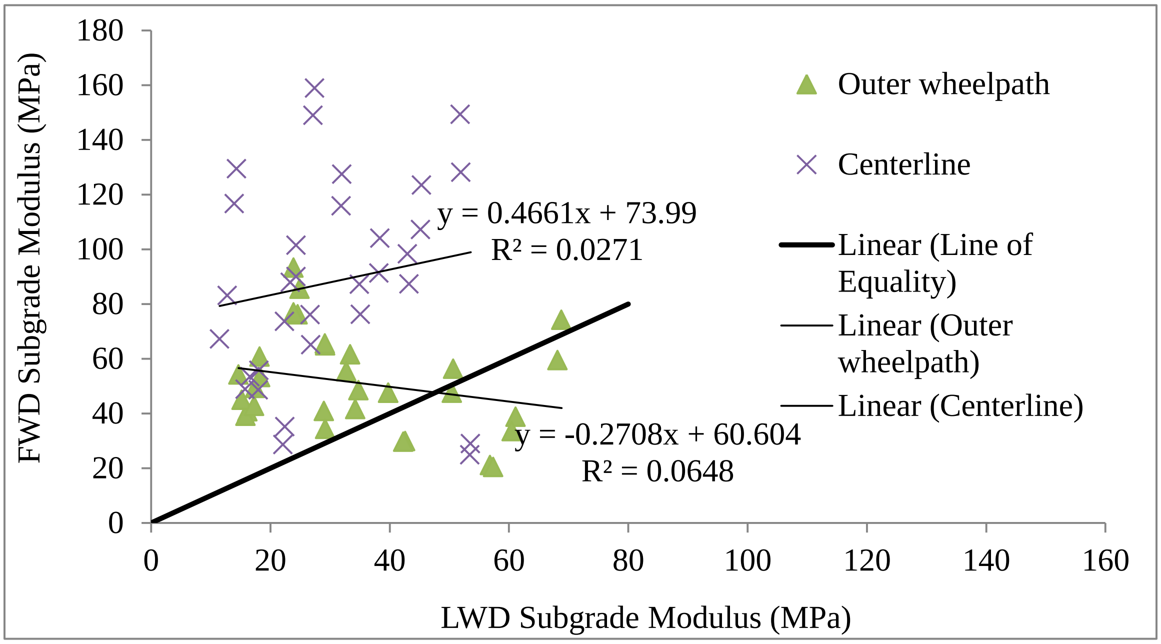

Figure 12-Correlation between the FWD and LWD backcalculated subgrade soil modulus.

6 Summary and conclusions

Light weight deflectometer (LWD), a rather new nondestructive test device for pavement layers material characterization was evaluated in this study. FWD tests were also performed along the LWD tests and were used as a benchmark to evaluate the LWD test results. The tests were performed during the construction of the new access road to the Edmonton Waste Management Center (EWMC) in summer 2012. FWD tests were performed on top of finished subgrade along the Centerline and the outer Wheelpath.

It was found that the FWD test performed on the subgrade can be very sensitive to many variables along the road. Some of the influential factors can be change in the terrain slope, fill versus normal ground or cut and moist versus dry zones. FWD testing appears to be a good tool for in-situ uniformity testing of subgrade construction. The FWD test results showed that special care needs to be taken during compaction at transition zones between cut and fill sections and also where the ground topography varies.

LWD test results showed sensitivity to fills versus normal ground and can be used to evaluate the uniformity of subgrade along the road section. More LWD tests need to be performed on a variety of road sections with varying topography and soil type to establish the correlation between the FWD and LWD backcalculated moduli to be used in pavement design across the province.

The efforts presented in this report will continue to focus on analyzing the deflection data collected during the FWD and LWD tests performed on top of the finished granular base layer for the same test site. Future analysis will focus on evaluation of applicability of LWD in characterizing pavement unbound layers' moduli.

7 References

AASHTO Guide for Design of Pavement Structures 1993. AASHTO, Washington, D.C., 1993.

Adam, C., and D., Adam, (2003). "Modelling of the Dynamic Load Plate Test with the Light Falling Weight Device," *Asian Journal of Civil Engineering (Building and Housing)*, Vol. 4, No. 2-4, pp. 73-89.

Alberta Transportation and Utilities. (1997). "Pavement Design Manual", Edmonton, AB.

Ali, N.A., and Khosla, N.P. (1987). "Determination of Layer Moduli Using a Falling Weight Deflectometer," In *Transportation Research Record 1117*, Transportation Research Board, National Research Council, Washington, D.C., 1987, pp. 1-10.

ARA, Inc., ERES Consultants Division. "Guide for Mechanistic-Empirical Design of New and Rehabilitated Pavements Structures," National Cooperative Highway Research Program (NCHRP), Transportation Research Board, National Research Council, Champaign, IL, March 2004.

ASTM C 136-06 (2006). "Standard Test Methods for Sieve Analysis of Fine and Coarse Aggregates," ASTM International, West Conshohocken, PA.

ASTM D5858-96 (2008). "Standard Guide for Calculating In-Situ Equivalent Elastic Moduli of Pavement Materials Using Layered Elastic Theory," ASTM International, West Conshohocken, PA.

ASTM D 698-07 (2007). "Standard Test Methods for Laboratory Compaction Characteristics of Soil Using Standard Effort," ASTM West Conshohocken, PA.

Chai, G., and Roslie, N., (1998). "The Structural Response and Behavior Prediction of Subgrade Soils using Falling Weight Deflectometer in Pavement Construction," 3rd International Conference on Road and Airfield Pavement Technology.

Chen, D.H., Wu, W., He, R., Bilyeu, J., and M., Arrelano. (1999). "Evaluation of in-situ Resilient Modulus Testing Techniques," *Geotechnical Special Publication* (ASCE), Vol. 86, pp. 1-11.

Diefenderfer, B.K., (2010). "Investigation of the Rolling Wheel Deflectometer as a Network-Level Pavement Structural Evaluation Tool," *Final Report*, Virginia Transportation Research Council.

EVERSERIES USER'S GUIDE-Pavement Analysis Computer Software and Case Studies (2005). Washington State Department of Transportation, Olympia, WA.

Fleming, P.R., Frost, M.W. and Rogers, C.D.F. (2000). "A Comparison of Devices for Measuring Stiffness In-situ," *Unbound Aggregates in Road Construction*, In Dawson, A.R. (ed.) Unbound Aggregates in Road Construction: Proceedings of the Fifth International Symposium on Unbound Aggregates in Roads, Nottingham, UK, pp. 193-200.

Fleming, P.R., Frost, M.W., and Lambert, J. P. (2007). "Review of Lightweight Deflectometer for Routine in-situ Assessment of Pavement Material Stiffness," In *Transportation Research Record*, No. 2004(1)*: Journal of Transportation Research Board*, National Research Council, Washington, D.C., pp. 80-87

George, K. P. (2003). "Falling Weight Deflectometer for Estimating Subgrade Resilient Moduli," *Final Report*, Submitted to Mississippi Department of Transportation, University of Mississippi.

George, K. P. (2006). "Portable FWD (PRIMA 100) for In-situ Subgrade Evaluation," *Final Report*, Submitted to Mississippi Department of Transportation, University of Mississippi.

Highways Agency Design Guidance for Road Pavement Foundations. (2009). Interim Advice Note 73, Draft HD 25, Highway Agency, London.

Lytton, R.L. (1989). "Backcalculation of Pavement Layer Properties," *Nondestructive Testing of Pavements and Backcalculation of Moduli, ASTM STP 1026*, A. J. Bush III and G. Y. Baladi, Eds., American Society for Testing and Materials, Philadelphia, pp. 7-38.

Mooney, M.A., and Miller, P.K. (2009). "Analysis of Lightweight Deflectometer Test based on in-situ Stress and Strain Response," *Journal of Geotechnical and Geoenvironmental Engineering*, Vol. 135, No. 2, pp. 199-208.

Nazzal, M., Abu-Farsakh, M., Alshibli, K., and L., Mohammad. (2004). "Evaluating the Potential Use of a Portable LFWD for Characterizing Pavement Layers and Subgrades," *Geotechncial Engineering for Transportation Projects: Proceedings of Geo-Trans 2004*, Los Angeles, CA.

Newcomb, D.E. (1987). "Comparison of Field and Laboratory Estimated Resilient Moduli of Pavement Materials", Asphalt Paving Technology, *Association of Asphalt PavingTechnologists*, Vol. 56, pp. 91-106.

Shahin, M.Y. (2005). "Pavement management for airports, roads, and parking lots," *Springer Science and Business Media, LLC*, New York, NY.

Steinert, B.C., Humphrey, D.N., and M.A., Kestler. (2006). "Portable Falling Weight Deflectometers for Tracking Seasonal Stiffness Variations in Asphalt Surfaced Roads," *85th Transportation Research Board annual meeting*, Compendium of papers CD-ROM, Washington, D.C.

Von Quintus, H.L., and Killingsworth, B.M. (1998). "Comparison of Laboratory and In-Situ Determined Elastic Moduli," *76th Transportation Research Board annual meeting,* Compendium of papers CD-ROM, Washington, D.C.