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Estimation of pavement layer moduli of thin-sealed roads for use in pavement management systems

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ABSTRACT

Condition assessment and maintenance of vast road networks is a challenge both technically and financially in many low and middle-income countries (LMICs). It often requires rapid data collection techniques, quick analysis of the data, accurate defect identification, and appropriate allocation of scarce funds. The Falling Weight Deflectometer (FWD) equipment can be used for rapid non-destructive techniques of assessing the condition of road pavement layers. Many road agencies in LMICs are acquiring FWDs and Pavement Management Systems (PMS) for data collection and maintenance planning. The analysis of FWD data requires rigorous back-calculation techniques that cannot be easily integrated into PMS. Surface deflection bowl parameters (DBP) have since been used for classification of pavement conditions. However, DBP do not yield values of layer elastic moduli, that are increasingly being used in rehabilitation design. Moreover, the DBP that are currently in use are applicable to roads with at least 50 mm asphalt concrete surfacing and have not been checked for validity on roads incorporating thin bituminous seals such as chip seal, and cape seal. Thus, a system that rapidly estimates layer elastic moduli from DBP and that can be easily integrated into PMS is required now and in the near future, for LMICs. Defective sections or pavement layers identified through this approach can then undergo more rigorous analysis using FWD specialist back-calculation software. This study developed equations that reliably estimate the layer moduli from DBP of pavements surfaced with thin bituminous seals. This was done through conducting FWD tests on selected road sections, conducting back-calculation using specialist software, and testing which DBP best correlates with the back-calculated elastic moduli. These equations are used to rapidly identify pavement layers and sections that are deteriorating season by season, and hence, target and plan appropriate maintenance interventions.

Keywords: Elastic moduli, FWD, Surface deflection bowl parameters, Thin bituminous seals

1. INTRODUCTION

Most FWD data analysis software give reliable results for few analysis points where specific details of the pavement at each point can be refined, adjusted and reviewed and reanalysed if necessary. The software, however, struggle with analysis of bulk data because it uses average pavement layer thicknesses and not point specific thicknesses. This leads to large errors in computed moduli for individual pavement layers that are not constructed to acceptable thickness tolerances – common in developing countries. A more accurate method of the use of the FWD would therefore be to first use Surface deflection bowl parameters (DBP) to narrow down the road sections or pavement layers that are in pre-critical or critical conditions from bulk data collected (Fuentes et al., 2022). Surface deflection bowl parameters (DBP) are various combinations of the geophone deflections in equations that are used to estimate the strength of various pavement layers. Then after this, undertake a detailed in-depth analysis (more time-consuming) of the identified sections using specialist FWD analysis software is necessary. Additionally, it is perhaps more important to detect road sections whose condition is changing significantly between surveys, so that they can undergo detailed field investigations and samples taken from those sections for detailed laboratory studies. The use of DBP is therefore a good option for narrowing down road sections requiring specific in-depth analysis. However, with use of mechanistic analysis programs, layer elastic moduli are required instead of the DBP. The computation of layer elastic moduli using back-calculation software could be a daunting task if it is to be done on a network basis to an appreciable level of detail. This is more so the case when one considers analysing data collected say for 30,000 km of road network (typical network size for a developing country). This represents over 60000 drop points (1 drop ever 500 m) and 180,000 FWD drops (3 drops per point). Some FWDs are capable of estimating materials moduli as measurements are undertaken in-situ, but firstly, the majority of them require the data to be processed and analysed externally. Secondly, most of the software do not accept inputs of layer thicknesses less than 50 mm for the asphalt layer. This would not be useable for the thin bituminous seals (20-30 mm) described in this paper.

Therefore, correlation equations that convert suitable DBP to reasonable estimates of elastic moduli would therefore solve the issue of analysing a large set of data and obtaining layer elastic moduli at the same time. These equations would be applied to FWD data in a simple MS Excel spreadsheet to quickly identify sections of road or points requiring further in-depth analysis. The MS Excel spreadsheet can be linked to mechanistic analysis equations and programmed to show colour codes for points or sections or pavement layers of sections of concern, those that can benefit from an upgrade, those requiring rehabilitation, and other requirements. The sections, points, or layers identified using the correlation equations in the MS Excel spreadsheet are further analysed in detail with FWD moduli back-calculation software or further investigation is carried out on those sections, points, or layers.

Correlation equations can also be easily integrated into pavement management systems (PMS) to quickly identify sections that require attention either for maintenance, rehabilitation, and further detailed investigation. Once integrated into a PMS, the yearly trend or progression is easily analysed, and any unacceptable rates of progression investigated before critical levels are reached. On the other hand, integrating FWD back-calculation software into PMS would be extremely complex, with the probable need for installation permission/authorization.

2. THE FWD AND ITS ROLE IN NETWORK MANAGEMENT

The aim of this study was to evaluate and develop correlation equations based on FWD surface deflection bowl parameters (DBP) for the estimation of back-calculated moduli for pavements layers with thin bituminous seals 20 - 30 mm thick (not asphalt) on granular pavements incorporating cement-treated bases. The study also sought to develop a simple spreadsheet that can be used for the monitoring of condition changes, year-on-year, of the road sections in the network. The surface deflection bowl parameters (DBP) that were evaluated were the Radius of Curvature (RoC), Base Layer Index (BLI), Middle Layer Index (MLI), and Lower Layer Index (LLI), and the parameters proposed in TRL (1999). These surface deflection bowl parameters (DBP) were developed for evaluation of pavements with asphalt concrete surfacings.

The use of deflection bowl parameters offers a quick and simple way to assess the pavement's structural integrity and performance potential. A major advantage of the parameters is that with minimal computer programming power they can be quickly integrated into pavement management systems without the need for back-calculation. In addition, Horak (2008) also shows criteria to correlate the deflection bowl parameters to the structural condition of the pavement layers. This is a very useful empirical approach to pavement condition assessment.

Thus, pavement condition at network level can be quickly assessed and road sections that are either poor or fair can be easily identified for further investigations. Detailed analysis (back-calculation) of the FWD deflection data for these sections would then be undertaken using specialist FWD analysis software. However, most deflection bowl parameters developed apply to roads with at least a 50 mm thick asphalt surfacing. The majority of the bituminous paved road network in developing countries comprises bituminous surface dressings/ surface treatments (20 - 30 mm thick). For example, in Zambia, out of about 10,000 km of the paved road network, about 6,500 km is surface-dressed with thin bituminous seals RDA (2018). These seals are typically applied on cement-treated road bases (nominal 150 mm thick). which is overlaid on granular sub-bases (nominal 200 mm thick). The cement-treated bases still act as granular material pavements to a large extent since they are treated with only 2%-3% of cement by mass (Department of Transport, 1986).

Regarding the use of SCI, Dehlen (1961) introduced an index to indicate the strength of the asphalt surfacing and bound base – the radius of curvature (RoC) by use of the deflection beam. This is computed using Equation 1:

$$RoC = ((L^2)/(2*D_0*(1-D_{200}/D_0)) \quad (1)$$

Where:

RoC = Radius of curvature;

L = 127 mm in the original Dehlen (1961) curvature metre and 200 mm for the FWD;

D_0 = the deflection at the centre of the applied load; and

D_{200} = the deflection at the 200 mm from the centre of the applied load.

Work in South Africa in the 1980s on the use of the FWD led to the substitution of L with the introduction of the deflection at 200 mm from the centre of the loading plate of the FWD. TRL (1999) recommends three deflection bowl parameters; one as an indication of the condition of the upper pavement layers (surfacing and base) and another as an indication of the subgrade strength. These are:

- D1 as indication of total pavement strength;
- D1-D4 as an indication of the upper pavement layers; and
- D6 as an indication of the subgrade condition.

Where:

D1 = the deflection recorded by the geophone located at the centre of the loading plate.

D4 = the deflection recorded by the geophone located at 900 mm from the centre of the loading plate. For thin asphalt surfacing or seal, D4 is taken as the deflection recorded by the geophone located at 600 mm from the centre of the loading plate.

D6 = the deflection recorded by the geophone located at 1500 mm from the centre of the loading plate.

Kim and Ranjithan (2000) developed other deflection bowl parameters as described below (Equation 2, 3, and 4):

$$SCI = d_0 - d_{300} \quad (2)$$

Where:

SCI = Surface curvature index (SCI). This provides an indication of condition of bound layers – usually the surfacing and base.

d_0 = the deflection at the centre of the applied load.
d_{300} = the deflection at the 300 mm from the centre of the applied load.

$$BDI = d_{300} - d_{600} \tag{3}$$

Where:
BDI = Base Damage Index (BDI). This provides an indication of condition of the middle layer, usually the sub-base.
d_{300} = the deflection at the 300 mm from the centre of the applied load.
d_{600} = the deflection at the 600 mm from the centre of the applied load.

$$BCI = d_{600} - d_{900} \tag{4}$$

Where:
BCI = Base Curvature Index (BCI). This provides an indication of condition of the sub-base or subgrade.
d_{600} = the deflection at the 600 mm from the centre of the applied load.
d_{900} = the deflection at the 900 mm from the centre of the applied load.

Horak (2008) notes that Surface Curvature Index (SCI), Base Damage Index (BDI), and Base Curvature Index (BCI) are now respectively referred to as Base Layer Index (BLI), Middle Layer Index (MLI), and Lower Layer Index (LLI).

Queensland Government (2012) defines a curvature function CF = D_0-D_{200}. Where D_0 is the deflection at the centre of the applied load and D_{200} is the D200 is the deflection at the 200 mm from the centre of the applied load. The CF is used to estimate the likelihood of fatigue cracking in the asphalt layer. For granular pavements with thin bituminous seals, the curvature function indicates the strength of the granular base layer. High values of the CF (e.g., 0.4 mm for results derived using an FWD with a 40 kN loading) may indicate a pavement that is lacking stiffness, a very thin pavement, or a pavement with a cracked asphalt surface. Low values of the CF (e.g., <0.2 mm for results derived using an FWD with a 40 kN loading) indicate a stiff pavement. However, Horak (2008) notes that, owing to the closeness (200 mm) of the geophone to the edge of the loading plate and the associated surface disturbances observed, the RoC (and by inference, CF) is used with less confidence. Horak and Emery (2006) also note that these variabilities have also been observed in other methods of analysis that tended to rely on the deflection value at 200 mm from the centre of the applied load, such as the Australian method where a curvature ratio is calculated based on that value.

3. RESEARCH METHODOLOGY

3.1 Choice of software

BAKFAA (US FAA, 2018), a pavement analysis software (developed by the United States Federal Aviation Authority, Pavement Design and Evaluation Division) was used for the analysis of the pavement layer moduli. This software was chosen because it accepts inputs from various makes/models of FWDs, it can analyse up to 9 pavement layers, and it is free. The software uses various algorithms for mulit-layer elastic theory to compute pavement layer moduli.

Additionally, most FWD analysis software such as MODULUS, ELMOD, EVERCALC, and 2020 version of BAKFAA cannot analyse pavements with less than 50 mm asphalt surfacing. The subject of this study is roads with thin bituminous seals, non-structural seals less than 30 mm thick, laid on granular non-bituminous bases. This pavement configuration is common in developing countries. The condition of such granular road bases and their supporting layers is critical to the performance of the seal and the pavement.

However, Tarefder and Ahmed (2013) showed that EVERCALC software produces modulus values closer to the laboratory resilient modulus of asphalt compared to MODULUS and BAKFAA software.

3.2 Study roads and validation

Three roads of identical pavement construction in northern Zambia were selected for the study. On each road, 2 road sections were studied: thus, providing a total of six sections in Zambia. On each section at least 30 deflection measurement points were tested. Two roads of similar construction in Uganda were used to validate the correlation equations developed in Zambia and check their applicability for use in the 50 kN drop weight. On each of the 2 roads in Uganda, 2 sections were studied: thus providing 4 road sections for validation in Uganda. At least 20 deflection measurement points were used for each section in Uganda.

The pavements of all the study roads comprised double bituminous surface dressing (double chip seal) on 150 mm of cement-treated lateritic gravel base (cement content of 2 – 3% by mass) on 200 mm neat (untreated) lateritic gravel sub-base, on in-situ subgrade. Therefore, the combined thickness of the bituminous seal, base, and subbase for the pavement structures studied is only about 370 mm. All the pavements have been in existence for more than 40 years; however, the bituminous seal was renewed in 2012 (7 years before the study). The roads have each carried an estimated 2 – 3 million equivalent standard axles since construction. A photograph of the test on-going on one of the sections is shown in Figure 1.

On each road, two sections were selected, based on surface defects one that is defect-free and another showing defects such as cracks, ruts or potholes. Each section was 300 m long. The FWDs used both in Zambia and Uganda were adequately (annual calibration by the manufacturers and routine sensor calibration) calibrated before commencing the study. FWD readings were taken every 20 m on both lanes of each road on the outer wheel track. The selected target drop load was 40 kN. The geophone spacings were: 0, 200, 300, 450, 600, 750, 900, 1200, 1500, and 2000 mm from the centre of the loading plate.

For the drop load of 50 kN, data from a similar undertaking in Uganda for a road with similar pavement structure to the study roads in Zambia was used; albeit the pavement had been in existence for about 29 years as opposed to the 40 years for the Zambia roads. The roads studied in Zambia and Uganda were all located in similar climatic regions with mean annual rainfall of about 1200 mm/yr and temperature of 28 °C.

Back-calculation of the layer moduli was then carried out using BAKFAA and the moduli values were then plotted against the various deflection bowls. The best-fit equations were then recorded and compared. About 190 test points were used in the back-calculation. Of these points, only seven did not meet the root mean square deviation criteria for BAKFAA of 5 μm (Santos and Rezende, 2020). These seven points were excluded from the comparisons. The moduli obtained from back-calculation were plotted against trial surface deflection bowl parameters. Correlation equations were then obtained with the use of an MS Excel spreadsheet and the best-fit equations (with highest R^2) were selected and discussed in the following section. The best-fit equations relate the surface deflection bowl parameters (DBP) to the back-calculated moduli that would be obtained if a comprehensive back-calculation is performed. They are therefore a good way of rapidly estimating the back-calculated moduli from a combination of multiple geophone deflections.

Figure 1. FWD testing ongoing on one of the study road sections

4. FINDINGS AND DISCUSSION

4.1 Comparison of surface and base layer deflection bowl parameters

The back-calculated moduli for the base layer were plotted against the RoC, BLI (D_0-D_{300}), D_0-D_{600} and the CF (D_0-D_{200}); all as defined in Equation 5 to Equation 8. The points plotted with high positive and acceptable (i.e., $R^2 \geq 60\%$ or 0.6 as described by Walubita et al. (2022)) correlation coefficient of determination as seen in Figure 2. The best fits were power functions. The R^2 values (see Equation 5 to Equation 8, and Equation 12) were 0.75 for RoC, 0.70 for BLI, 0.52 for D_0-D_{600}, and 0.80 for CF. On the basis of higher R^2 values, the 'Adjusted Bowl Parameters' (parameters defined by the authors in Equation 12) can be analytically considered to be better estimators of layer moduli than the 'Common Bowl Parameters' reported by Horak (2008), Kim and Ranjithan (2000), and (TRL, 1999). It was further observed that road sections in poor condition had mean base moduli less than 400 MPa; this can be adopted as the critical investigatory level whenever road sections show base moduli less than this value.

Much as literature (inferred from Horak, 2008) indicated that using the CF (D_0-D_{200}) is often associated with variabilities, the equations show that this was the best fit of the four deflection bowl parameters. As observed (in Figure 2 top right) for pavements with thin bituminous seals on cement-treated granular bases, the disturbance with the geophone located at 200 mm does not occur. However, the RoC may be preferred as the indicator of choice for network management purposes since it gives a good indicator of the base condition ($R^2 = 0.75$) and additionally, it is a good indicator of crack initiation of bituminous seals. Van Zyl and Jenkins (2019) showed that that a small radius of curvature (RoC) less than 50 m, as calculated from the deflection bowl, will result in rapid fatigue (even with newly constructed seals). This is typically manifested by the initiation of wheel path cracks.

4.2 Comparison of Sub-base Layer Deflection Bowl Parameters

The back-calculated moduli for the sub-base layer were plotted (Figure 3) against the MLI (D_{300}-D_{600}), and Adjusted MLI (D_{200}-D_{600}) - a parameter defined by the authors. In the Adjusted MLI, the deflection from the geophone at 200 mm from the loading plate is used instead of the deflection at 300 mm used in the MLI. TRL (1999) does present any deflection bowl parameters for assessing the sub-base strength. The points plotted with high positive and acceptable coefficient of determination (R^2) as seen in Figure 3. The best fits were again power functions. The R^2 values (see Equation 9 and Equation 13) were 0.83 for MLI and 0.82 Adjusted MLI (Equation 13). The correlation equations are also presented in Equation 9 and Equation 10. Like findings by Fuentes et al. (2022), it was further observed that road sections in poor condition had mean sub-base moduli less than 150 MPa. This can thus be adopted as the critical investigatory level whenever road sections show sub-base moduli less than this value.

The MLI is indeed a good indicator of the sub-base layer moduli. The Adjusted MLI is also equally good and does not suffer much of the variability warned of in literature. On the basis of higher R^2 values, the 'Adjusted Bowl Parameters' are in general better estimators (or equal estimators) of layer moduli than the 'Common Bowl Parameters' reported by Horak (2008), Kim and Ranjithan (2000), and (TRL, 1999).

4.3 Comparison of Subgrade Deflection Bowl Parameters

The back-calculated moduli (from BAKFAA) for the subgrade layer were plotted against the LLI (D_{300}-D_{600}), D_{1500} as recommended by TRL (1999), and D_{600} (a parameter proposed by the authors). The points plotted with high positive and acceptable coefficient of determination (R^2=0.98). The best fits were again power functions. The R^2 values (see Equation 10 and Equation 11) were 0.74 for LLI, 0.88 for D_{1500} and 0.98 for D_{600}. The correlation equations are also presented in Equation 10, Equation 11, and Equation 14.

The D_{600} (proposed by the authors in Equation 14) provides the best indication of the subgrade strength on the basis that it has the highest R^2 value compared to the other parameters. It should be noted that a ratio (0.35-0.75) should usually be applied to back-calculated subgrade moduli to calibrate/reduce it to values similar to laboratory-determined moduli FHWA (2017). On the same basis of the R^2, D_{1500} also provides a very good indication, whilst LLI provides the lowest – albeit reasonable. The plausible explanation given for why D_{600} provides the best correlation for subgrade moduli in this case is that the subgrade depth is shallow. The combined thickness of the bituminous seal, base, and subbase for the pavement structures studied is only about 370 mm. Therefore, the geophone whose deflection best represents the subgrade stiffness should not be far away from the load centre.

Fitted equations (Equation 5 to Equation 14) to obtain elastic moduli using various deflection bowl parameters, and their corresponding coefficients of determination, using 40 KN drop load, are presented below.

- RoC = Radius of curvature;
- E = Elastic moduli of a given layer;
- D_0 = the deflection at the centre of the applied load;
- D_{200} = the deflection at the 200 mm from the centre of the applied load;
- D_{300} = the deflection at the 300 mm from the centre of the applied load;
- D_{600} = the deflection at the 600 mm from the centre of the applied load;
- D_{900} = the deflection at the 600 mm from the centre of the applied load; and
- D_{1500} = the deflection at the 600 mm from the centre of the applied load.

Surface, Curvature function (CF) based on deflections as per Queensland Government (2012)

$$E = 184474*(D_0-D_{200})^{-1.059} \quad (5)$$

R^2=0.80

Surface/Base, Radius of curvature (RoC) based on deflections as per Horak (2008)

$$E = 7.32*RoC-44.378 \quad (6)$$

R^2=0.75

Base, Base layer index (BLI) based on deflections as per TRL (1999)

$$E = 132046*(D_0-D_{600})^{-0.893} \quad (7)$$

R^2=0.52

Base, Base layer index (BLI) based on deflections as per Kim and Ranjithan (2000), Horak (2008)

$$E = 223857*(D_0-D_{300})^{-1.028} \qquad (8)$$

$R^2=0.70$

Sub-base, Middle layer index (MLI) based on deflections as per Kim and Ranjithan (2000), Horak (2008)

$$E = 36608*(D_{300}-D_{600})^{-1.207} \qquad (9)$$

$R^2=0.83$

Subgrade, Lower layer index (LLI) based on deflections as per Kim and Ranjithan (2000), Horak (2008)

$$E = 2346*(D_{600}-D_{900})^{-0.676} \qquad (10)$$

$R^2=0.74$

Subgrade, Lower layer index (LLI) based on deflections as per TRL (1999)

$$E = 5218*(D_{1500})^{-0.914} \qquad (11)$$

$R^2=0.88$

Base moduli based on adjusted bowl parameters (deflections at alternative offsets)

$$E = 184474(D_0-D_{200})^{-1.059} \qquad (12)$$

$R^2=0.80$

Sub-base moduli based on adjusted bowl parameters (deflections at alternative offsets)

$$E = 139857*(D_{200}-D_{600})^{-1.31} \qquad (13)$$

$R^2=0.82$

Subgrade moduli based on adjusted bowl parameters (deflections at alternative offsets)

$$E = 16838*(D_{600})^{-0.969} \qquad (14)$$

$R^2=0.98$

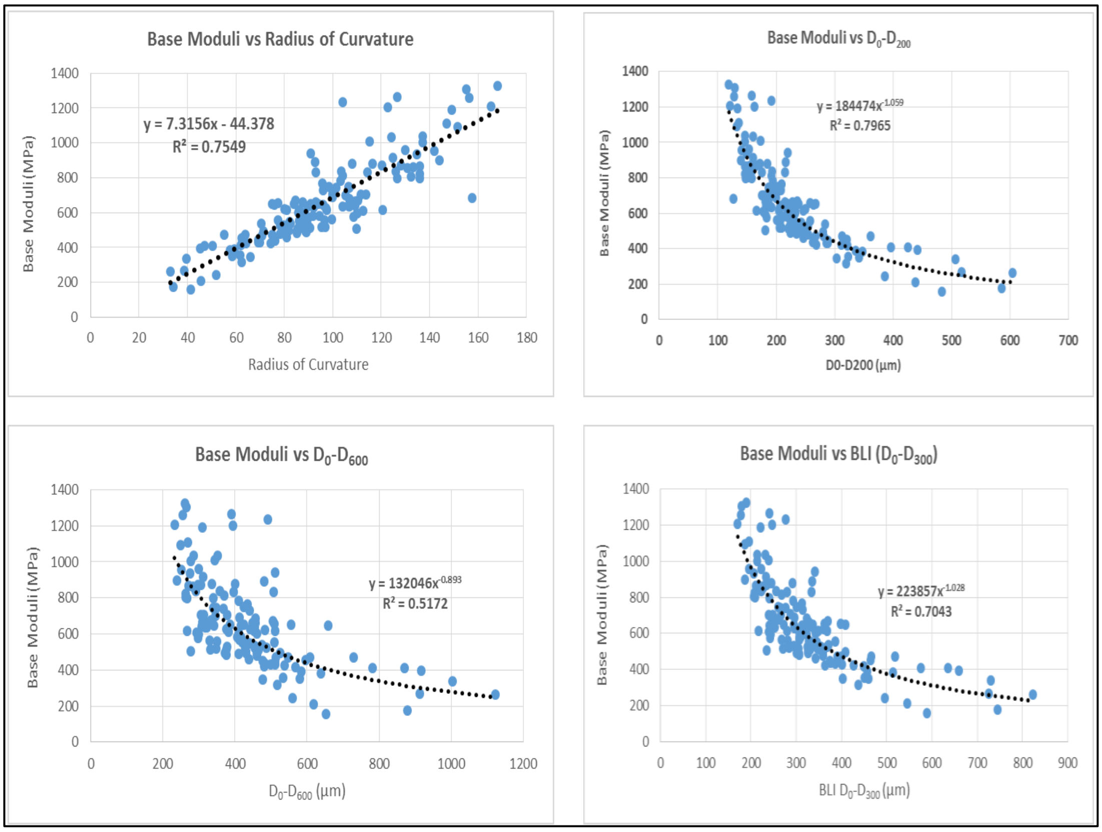

Figure 2. Base layer moduli and deflection bowl parameters

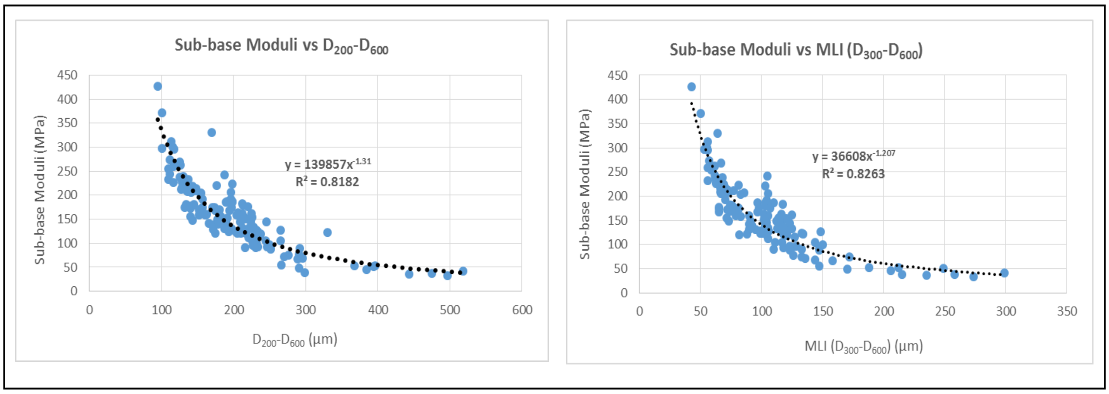

Figure 3. Sub-base layer moduli and deflection bowl parameters

4.4 Comparison and validation with 50 kN drop load

From the Zambia country component of the study, it is evident that the deflection bowl parameter that best represents the base layer moduli is the CF (D_0-D_{200}) at the 40 kN drop load, although the RoC also gives high positive and acceptable correlation. It is also evident that the MLI (D_{300}-D_{600}) or adjusted MLI (D_{200}-D_{600}) provide the best indicator for the sub-base moduli and the D600 the best indicator for the subgrade moduli. The common FWD measurement drop loads in most countries are 40 kN and 50 kN.

A similar approach as undertaken in Zambia was also done in Uganda to validate the surface deflection bowl parameters (DBP) developed from the Zambia component of the study, or failing that, ascertain the most suitable DBP at the 50 kN drop load level.

Fitted equations (Equation 15 to Equation 24) to obtain elastic moduli using various deflection bowl parameters, and their corresponding coefficients of determination, for validation using 50 KN drop load, are presented below. The best fits in this case were the RoC for the base layer, the Adjusted MLI for the subbase (although the MLI also gives high positive and acceptable correlation), and D_{600} for the subgrade.

The best equations for the 50 kN drop load were obtained from the same geophones (hence the same DBP) as that determined for the 40 kN drop load. This validates the methodology used in the study.

In Equation 15 to Equation 24 below, the following terms apply:

- RoC = Radius of curvature;
- E = Elastic moduli of a given layer;
- D_0 = the deflection at the centre of the applied load;
- D_{200} = the deflection at the 200 mm from the centre of the applied load;
- D_{300} = the deflection at the 300 mm from the centre of the applied load;
- D_{600} = the deflection at the 600 mm from the centre of the applied load;
- D_{900} = the deflection at the 600 mm from the centre of the applied load; and
- D_{1500} = the deflection at the 600 mm from the centre of the applied load.

Surface, Curvature function (CF) based on deflections as per Queensland Government (2012)

$$E = 184474(D_0-D_{200})^{-1.059} \quad (15)$$

R^2=0.80

Surface/Base, Radius of curvature (RoC) based on deflections as per Horak (2008)

$$E=0.1381*RoC^2-19.391*RoC+1251 \quad (16)$$

R^2=0.85

Base, Base layer index (BLI) based on deflections as per TRL (1999)

$$E = 45076*(D_0-D_{600})^{-0.685} \quad (17)$$

R^2=0.59

Base, Base layer index (BLI) based on deflections as per Kim and Ranjithan (2000), Horak (2008)

$$E = 132046*(D_0-D_{600})^{-0.893} \quad (18)$$

R^2=0.52

Sub-base, Middle layer index (MLI) based on deflections as per Kim and Ranjithan (2000), Horak (2008)

$$E = 4*10^6*(D_{300}-D_{600})^{-2.109} \quad (19)$$

R^2=0.83

Subgrade, Lower layer index (LLI) based on deflections as per Kim and Ranjithan (2000), Horak (2008)

$$E = 596*(D_{600}-D_{900})^{-0.238} \quad (20)$$

R^2=0.11

Subgrade, Lower layer index (LLI) based on deflections as per TRL (1999)

E=2408*(D1500)-0.624 (21)

R^2=0.68

Base moduli based on adjusted bowl parameters (deflections at alternative offsets)

$$E = 50665*(D_0-D_{200})^{-0.805} \quad (22)$$

R^2=0.77

Sub-base moduli based on adjusted bowl parameters (deflections at alternative offsets)

$$E = 8*10^6*(D_{200}-D_{600})^{-1.922} \quad (23)$$

R^2=0.88

Subgrade moduli based on adjusted bowl parameters (deflections at alternative offsets)

$$E = 13362*(D_{600})^{-0.868} \quad (24)$$

R^2=0.87

5. CONCLUSION AND RECOMMENDATION

The correlation equations base on the surface deflection bowl parameters can estimate, with a very good level of accuracy, the elastic moduli for road pavement layers. Therefore, from a road network management perspective, the equations developed can be used for rapid condition classification of existing road sections, and identification of road sections that need further detailed analysis and investigation. For network level management of roads, the equations can be easily integrated into pavement management systems to classify the road network condition accurately and quickly. Intervention levels can thus be set based on these equations (similar to those contained in Horak (2008)). This helps to keep the road network in an optimal structural condition. Sections or pavement layers identified as critical based on these equations are then subjected to in-depth analysis using the FWD back-calculation software. In the absence of a pavement management system, a simple programmed MS Excel spreadsheet (included as part of this paper) where all the FWD deflection data is pasted from the FWD data files can be used. Subsequent changes in the condition of the sections or pavement layers can then be easily noted and further investigation conducted to apply the right maintenance treatment. These changes can be tracked using the PMS or a simple MS Excel spreadsheet. A second possible application of the equations is in the rapid identification of rod sections whose performance can be improved by the application of an overlay. A last possible application is the rapid identification of which layers require improvement either as a maintenance approach or for heavy rehabilitation purposes.

Regarding the technical aspects, the study has shown that for shallow pavements with thin bituminous seals, the correlation equations based on SCI involving D_{200}-D_{600} is the best curvature index of the base layer strength or condition at 40 kN drop load. A correlation equation ($E = 184474*(D_0\text{-}D_{200})^{-1.059}$ of R^2=0.80) based on this index is the most suitable for use in estimating the base moduli for the 40 kN drop weight.

For the sub-base strength or condition, the MLI (D_{300}-D_{600}), with equation MLI. $E = 36608*(D_{300}\text{-}D_{600})^{-1.207}$ of R^2=0.82, is the best curvature index for the 40 kN drop load, whereas the Adjusted MLI (D200-D600), with equation $E = 8*10^6*(D_{200}\text{-}D_{600})^{-1.922}$ of R^2=0.88, is the best curvature index for the 50 kN drop load. The difference between the correlations for the MLI and the Adjusted MLI is small and therefore either can be used at the two drop load levels. D600 is the best curvature index of the subgrade strength or condition for both 40 kN (with equation $E = 16838*(D_{600})^{-0.969}$ of R^2=0.98) and 50 kN (with equation $E = 13362*(D_{600})^{-0.868}$ of R^2=0.87) drop loads.

The key geophones for use with the new bowl parameters are therefore those located at 0, 200, 300 and 600 mm from the centre of the loading plate. This therefore means that there is scope to carry out similar structural condition assessment of roads with shallow pavements using the Light Weight Deflectometer (LWD) with geophone extensions; LWD geophone extensions are limited to 600 mm. The LWD is significantly cheaper than the FWD. A typical LWD costs about US$30,000 compared to an FWD, US$200,000. An LWD is also simple to operate and thus several more technicians can be incorporated in network surveys to ensure that the full road network is surveyed every year. Both the managerial and technical advantages are key to successful pavement management in low-income countries. A key lesson learnt from this project is that home-grown solutions can be developed through in-house applied research to address challenges faced by various technical institutions of low- and middle-income countries.

Finally, the quality of data used for this study was reliable, given that calibrated FWDs were used by a trained technologist to collect the data. The results and correlation equations are valid since all the coefficients of determination (R^2) of the recommended equations were above 0.60 (60%), which is very good. In fact, the lowest value was 0.80. The results were validated using data from Uganda and the validation equations were also very good, with the lowest R^2 value equal to 0.77. Therefore, the correlation equations are applicable for similar pavements (20-30 mm bituminous seal applied on 150 mm cement-treated road base which is overlaid on 200 mm granular sub-base) in similar environments (tropical climate) using and FWD drop load of either 40 kN or 50 kN. It is recommended that future studies should develop similar equations for different pavement structure combinations, for example, 20-30 mm bituminous seal applied on 150 mm crushed rock road base which is overlaid on 200 mm gravel sub-base. Other thickness combinations should be evaluated.

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