CORRELATION STUDY WITH THE LIGHT WEIGHT DEFLECTOMETER IN SOUTH AFRICA

E. Horak*, J. Maina, D. Guiamba*** and A. Hartman******

*Visiting professor to Built Environment, CSIR from University of Pretoria, Pretoria
Email: ehorak@csir.co.za
**Built Environment, CSIR, P.O. Box 395, Pretoria, 0001, South Africa
*** Technical Manager, PDNA, Maputo, Mozambique,
***Managing Director, Geostrada Laboratory Services, Africon consulting Engineers, Pretoria, South Africa

ABSTRACT

The Light Falling Weight Deflectometer (LWD) has recently become available in South Africa as a portable, light weight, user friendly version of the well established Falling Weight Deflectometer (FWD). This device uses very similar technology to the FWD device to most closely simulate the loading rate and area of a single moving wheel. However, with its reduced maximum applied force and load pulse duration, the LWD has a shallower depth of influence than that of the FWD. It is, therefore, ideal for single layer structural evaluation during construction to provide better engineering parameters for quality assurance and quality control (QA/QC) of constructed granular layers and lightly cemented layers than merely conventional density measurements only. Various correlations with other non-destructive structural evaluation devices have been done elsewhere in the world indicating the potential of the LWD as a tool to assist in decision-making related to structural integrity of individual road pavement layers for a wide range of materials. Limited correlation studies between the FWD and LWD in SA have also confirmed this observation. This paper presents findings from a study on correlation between the LWD and FWD test results for sand treated with emulsion (STE) on an experimental construction site in Mozambique.

1. INTRODUCTION

Since its introduction to SA in the mid 1980s (Coetzee et al, 1989 and Horak et al, 1989), falling weight deflectometer (FWD) has become a invaluable non-destructive measuring tool used for structural evaluation of road and airport pavements. A considerable effort worldwide has gone into the development of back-calculation software to determine elastic moduli of road pavement layers from the measured deflection bowls (Horak, 1988). Furthermore, the FWD has also been used to investigate the application of various deflection bowl parameters, as defined in Table 1, in semi-empirical mechanistic relationships for pavement structural evaluations (Horak, 1987). Through the initial work on back-analysis procedures and semi-empirical mechanistic procedures, other researchers (Rohde and van Wijk,, 1996, Joubert, 1993; Horak, 1988, Maree and Jooste, 1999; Maree and Bellekens, 1991 and Horak et al, 1992) have greatly enhanced the use of deflection bowl analysis in the SA mechanistic design procedure.

Table 1 Deflection Bowl Parameters (Horak et al, 1989)

Parameter	**Formula**	**Structural indicator**
1 .Maximum deflection	D_o or Y_o as measured	D_o gives an indication of all structural layers with about 70% contribution by the subgrade
2. Radius of Curvature (RoC)	$RoC= (200)^2/[2D_o (D_o/D_{200})-1]$	RoC gives an indication of the structural condition of the surfacing and base condition
3.Base Layer Index (BLI)	$BLI=D_o-D_{300}$	BLI gives an indication of primarily the base layer structural condition
4.Middle Layer Index (MLI)	$MLI=D_{300}-D_{600}$	MLI gives an indication of the subbase and probably selected layer structural condition
5. Lower Layer Index (LLI)	$LLI=D_{600}-D_{900}$	LLI gives an indication of the lower structural layers like the selected and the subgrade layers
6.Spreadability, S	$S=\{[(D_o +D_1 +D_2+D_3)/5]100\}/D_0$ Where D1, D2, D3 spaced at 300mm	Supposed to reflect the structural response of the whole pavement structure, but with weak correlations
7. Area, A	$A=6[1+2(D_1/D_o) +2(D_2/D_0) + D_3/D_o]$	The same as above
8.Shape factors	$F_1=(D_o-D_2)/D_1$ $F_2=(D_1-D_3)/D_2$	The F2 shape factor seemed to give better correlations with subgrade moduli while F1 gave weak correlations
9. Slope of Deflection	$SD= \tan^{-1}(D_o-D_{600})/600$	Weak correlations observed

The introduction of the light falling weight (LWD) in South Africa (Horak and Khumalo, 2006) led to the question about its correlations with the FWD, as well as other useful instruments normally used in pavement and material evaluations. The LWD is a portable scaled down version of the FWD, which can be operated by one person. A known weight (10kg, 15kg or 20kg) is dropped by a release mechanism at various drop heights to impose various contact pressures through a calibrated system of rubber buffers to the loading plate and simulate a moving single wheel load on pavement surface. The LWD device measures both the force and the deflections with a velocity transducer. The centre deflection is measured and two more readings further away from the load centre can be measured with additional geophones (normally spaced at 300mm). The LWD automatically measures and records the deflection bowl and has software which estimates an elastic stiffness calculated similar to the one used to calculate the surface modulus (Hoffmann et al, 2003 and Ullidtz, 1987) of a layered medium assuming a constant loading on an elastic half-space with uniform Poisson's ratio.

Horak and Khumalo (2006) facilitated the introduction of the first LWD in SA by reporting a pilot correlation study between the FWD and the LWD. This initial study was of limited scope, but helped to verify the extensive development and testing that was done overseas. The pilot correlation study focussed on the possible use of the deflection bowl parameters from LWD tests in a similar fashion to that used and developed for the FWD in benchmark analyses procedures described by Horak and Emery (2006) and Horak (2007 and 2008). Calculation of the surface modulus is standard output generated by both the FWD and the LWD. The moduli values determined from the FWD and LWD test results were correlated as well as the relevant deflection bowl parameters.

The lighter weight and shallower depth of influence of the LWD have indicated from the start that this device may be a particularly valuable tool in the evaluation of road pavement layers during construction. In 2005 and 2006, the first LWD was used intensively, on a road construction site in Mozambique, where sand treated with emulsion (STE) was constructed on Berea red type sand sub-base and subgrade (van Wijk and Carvahlo, 2002 and Hartman et al, 2005). The LWD test results from this site were then correlated with other non-destructive measuring instruments. In the following section, correlations between the FWD and the LWD results are reported.

2. CORRELATIONS BETWEEN FWD AND LWD

2.1 Background to previous correlation studies

A number of correlation studies have been done in the past to determine the relationship between the FWD and the LWD. Because these studies were done on a variety of material types and pavement structures, there is some variance in their correlation. For example Livenh and Goldberg (2001) suggested that the LWD stiffness moduli are about 0.3 to 0.4 times the conventional FWD surface moduli.

Fleming et al. (2000) also conducted field tests to correlate moduli determined with three main types of LWD available on the market with that of the FWD. Their results showed that the resilient surface modulus, determined with the FWD (EFWD) correlated well with moduli obtained from the LWD. However, they found that the correlation coefficients are LWD instrument specific and should first be established before use with confidence. Fleming (2001) reported that a number of factors influence the measured stiffness of the LWD including differences in mass, transducer type and software analysis (which records the maximum deflection as that at the time of the peak force).

Nazzal (2003) found that the best model to predict the FWD back-calculated resilient surface moduli, E_{FWD} (in MPa) from the LWD surface modulus, E_{LWD} (in MPa) is:

$E_{FWD} = 0.97 * E_{LWD}$, with $R^2 = 0.94$, significance level < 99.9% and standard error = 3.31

Nazzal (2003) found that his correlations agreed well with those of Fleming (2000) for a variety of material types. According to Rahimzadeh (2004) the relationship between FWD and LWD was found to be material type and thickness dependent. The FWD is regarded as the most appropriate device for setting the standard, because not only is the loading most representative of real traffic loading, but it can also be used for assessment of all pavement layers as construction proceeds. Either the FWD or the LWD can be used for measurement of stiffness as long as the same plate rigidity factor is assumed ($\pi/2$ for a flexible plate). If the LWD default setting (rigid plate, rigidity factor of 2) is assumed, then a correction factor must be applied, such that $E_{LWD} = 1.273\ E_{FWD}$.

It is also interesting to note that Ping et al (2002) correlated triaxial tests with FWD tests on subgrade materials. They referred to the fact that "*AASHTO Design Guide (AASHTO, 1986 and 1993) found that FWD back-calculated moduli are approximately two to three times higher than the laboratory" (triaxial) determined moduli for subgrades*" (mostly clayey material). In their own study they found that the elastic modulus determined with back-calculation methods (E_{FWD}) has a good correlation with triaxial resilient modulus (M_R);

$E_{FWD} = 1.6539\ M_R$ with $R^2 = 0.3$.

This implies that elastic modulus determined with an LWD (E_{LWD}) could in fact be approximately three times higher than laboratory determined triaxial value and is clearly material type and quality dependent.

2.2 Correlation studies on Sand Treated with Emulsion (STE)

The first LWD in SA was used to perform extensive correlation tests with a number of non-destructive measuring technologies on experimental sections of STE in Mozambique (Hartman et al, 2005). Various thickness of STE (75mm and 100mm) were constructed by labour intensive and machine intensive techniques to emulate the good performance of hot sand asphalt constructed in Mozambique prior to 1970s.

The test set-up of the LWD can be changed by varying the diameter of the loading plate (200mm or 300mm), drop weight (10kg to 20kg) as well as the drop height. In this correlation study the loading plate diameter, drop height and drop weight were maintained at 200mm, 850mm 10kg, respectively. This resulted in an average contact pressure of 313kPa. The standard FWD set up was used to produce 566kPa contact pressure (drop height 850mm, 300mm diameter loading plate with 40kN drop weight). In Table 1 the deflection bowl parameters normally associated with measured FWD deflection bowls are summarised with an indication of structural strength.

The best correlations between the LWD and FWD parameters using regression analysis for the test results obtained from the STE sections are shown in Table 2 . The functions varied from power, linear and logarithmic to see which type gives the best fit based on the best regression correlation value of R^2. A benchmark RAG system, similar to the one mentioned in the introduction, was used to rate the regressions correlations. The red colour was used for R^2 values 0 to 0.5, amber for R^2 values 0.51 to 0.8 and green R^2 values 0.81 to 1.

Table 2 Correlation results between LWD and FWD on STE pavement

Parameters		Regression Equation	R^2	Best fit type
LWD	FWD			
D0	Ymax	$y = 0.3617x^{0.9831}$	0.62	Power
	BLI	$y = 1.6178x^{0.8236}$	0.61	Power
	MLI	$y = 2.4502x^{0.8889}$	0.57	Power
	LLI	$y = 10.198x^{0.7359}$	0.31	Power
D300	Ymax	$y = 0.1586x^{0.9281}$	0.82	Power
	BLI	$y = 1.1044x^{0.6839}$	0.62	Power
	MLI	$y = 0.6674x^{0.9169}$	0.90	Power
	LLI	$y = 1.1297x + 1.963$	0.85	Linear
D600	Ymax	$y = 0.2353x^{0.7421}$	0.67	Power
	BLI	$y = 1.3779x^{0.5086}$	0.44	Power
	MLI	$y = 0.9111x^{0.6901}$	0.65	Power
	LLI	$y = 0.8732x^{0.8742}$	0.82	Power
RoC	Ymax	$y = -351.1\mathrm{Ln}(x) + 2373.4$	0.51	Logarithmic
	BLI	$y = -305.86\mathrm{Ln}(x) + 1904.4$	0.54	Logarithmic
	MLI	$y = -303.97\mathrm{Ln}(x) + 1626.2$	0.43	Logarithmic
	LLI	$y = -190.01\mathrm{Ln}(x) + 904.54$	0.13	Logarithmic
BLI	Ymax	$y = 0.1645x1.045$	0.46	Power
	BLI	$y = 0.609x^{0.9258}$	0.51	Power
	MLI	$y = 1.4986x^{0.9078}$	0.39	Power
	LLI	$y = 10.176x^{0.6305}$	0.15	Power
MLI	Ymax	$y = 0.0269x^{1.1092}$	0.77	Power
	BLI	$y = 0.221x^{0.8555}$	0.64	Power
	MLI	$y = 0.1266x^{1.1316}$	0.90	Power
	LLI	$y = 0.3735x^{1.1301}$	0.71	Power
SD	Ymax	$y = 0.0004x^{1.0184}$	0.56	Power
	BLI	$y = 0.0017x^{0.8747}$	0.58	Power
	MLI	$y = 0.003x^{0.9149}$	0.51	Power
	LLI	$y = 0.0159x^{0.7022}$	0.24	Power
F1	Ymax	$y = 1.3338x^{0.1138}$	0.01	Power
	BLI	$y = 0.8259x^{0.2114}$	0.05	Power
	MLI	$y = -0.0032x + 3.2909$	0.01	Linear
	LLI	$y = -0.0262x + 4.1189$	0.08	Linear

The LWD has geophones only up to 600mm from the centre point of loading and, therefore, deflection bowl parameters calculated from LWD measurements are restricted to those shown in Table 2. It is important to note that deflection at the centre of the loading plate (D_0) does not have good correlation for LWD and the FWD. This is clearly due to the difference in contact pressure and the shallow depth of influence of the lighter LWD weight and low drop height of the LWD.

It is also significant that the deflection at 300mm (D_{300}) of the LWD has the best correlations with the FWD set of deflection bowl parameters. It is also significant that MLI (LWD) also had better correlations with the same parameter determined with the FWD. This was also found by Horak and Khumalo (2006) on a light granular base pavement.

As shown previously by Horak and Khumalo (2006), there were also weak correlations between the LWD and the FWD determined RoC and BLI on this STE pavement structure. The deflection bowl parameters F1 and SD (see in Table 1) have very poor correlations as shown in Table 2. The results shown reflect the 10kg LWD setup as specified earlier, the R^2 improves as we move from 10kg to 20kg LWD setup although the results follow the same trend here described.

3. CORRELATIONS BETWEEN CIT, RCCD AND LWD ON STE PAVEMENTS

One of the envisaged applications of the LWD is for compaction control. This potential was reported by Horak and Khumalo (2006). For that reason, correlations with other non-destructive testing equipment have also been investigated by other researchers elsewhere. The equipment investigated include the Dynamic Cone Penetrometer (DCP), the Clegg Impact Tester (CIT) and the PLT (Thompson et al, 2008). This work focussed on the development and use of roller-integrated continuous compaction control and intelligent compaction control. It was found that subgrade stability measurements from these in situ testing devices followed the roller measured stiffness accurately. A correlation study by Siddiki et al. (2008) concentrated on using the DCP as the main evaluation tool for problematic compaction control of bottom ash embankment construction. It was found that initial criterion developed for this specific material was very good for the quality control with the DCP.

In the construction monitoring of the STE in Mozambique, CIT and Rapid Construction Control Device (RCCD) measurements were performed, which enabled the evaluation of these non destructive testing devices as potential construction evaluation tools. The CIT consists of a drop weight instrumented with an accelerometer in a confined thin-walled metallic cylinder acting as guide tube. The basic principle that governs the functionality of the CIT is that the deceleration of a dropped body is directly related to the stiffness and shear resistance offered by the dropped mass strikes (Guthrie and Rees, 2008). The accelerometer mounted on the CIT weight measures the peak deceleration of the weight as it strikes the aggregate surface. A Clegg Impact Value (CIV) is measured where one CIV is equivalent to 10 times the gravitational acceleration. Four successive drops of the hammer at the same location constitute one test, and normally completed within 30 seconds. This test is included in the American Society of Testing Materials (ASTM) D5874, Standard Test Method for Determination of the Clegg Impact Value (CIV) of Soils (Guthrie and Rees, 2008). The light CIT using either a 2.5lb or 5lb weight dropped through 12inches were used on the STE experimental section.

The RCCD is a scaled down version of the DCP. The penetration energy of the cone shaped point is a calibrated air gun spring which is loaded by pulling it into position. Three successive shots are then fired into a measuring hole to give an average penetration value. The RCCD has already been correlated with the CBR and DCP tests (de Beer et al 1994). The fact that much shallower penetrations are obtained with the RCCD than with the DCP means that this instrument is ideal for layer compaction control. It is easier to work with than the DCP and one operator can do a set of readings within 30 seconds.

In Table 3, the correlations established between the CIT and the RCCD with the FWD bowl parameters are shown for the specific STE material. As in the case with the correlation between FWD and LWD done before, the same colour code for the regression coefficients (R^2) was used. It is clear that there were no good correlations between the CIV and FWD and also RCCD penetration and the FWD. In general the CIV had better correlation coefficients than that of the RCCD. This is to be expected as the CIV relies also on a dropped weight for measurements. The RCCD measures the in situ shear resistance characteristics while the LWD and CIV measure elastic properties of materials. The fact that there is emulsion in the STE material influences also the RCCD value and, therefore, this lack of good correlation should be viewed as non-indicative of other granular materials.

Table 3 Correlation results between CIT, RCCD and FWD on STE pavements

Parameters		Regression Equation	R^2	Best fit type
Devices	FWD			
CIV	Ymax	$y = 58.744e^{-0.0007x}$	0.47	Exponential
	BLI	$y = 55.666e^{-0.001x}$	0.53	Exponential
	MLI	$y = -8.8662Ln(x) + 83.392$	0.26	Logarithmic
	LLI	$y = 75.889x^{-0.1631}$	0.12	Power
RCCD	Ymax	$y = 11.45e^{0.0003x}$	0.07	Exponential
	BLI	$y = 12.015e^{0.0003x}$	0.05	Exponential
	MLI	$y = 9.9987x^{0.0584}$	0.02	Power
	LLI	$y = 7.4113x^{0.1519}$	0.11	Power

Note: The table above reflects the comparison study between CIT and RCCD with FWD bowling parameters.

4. CONCLUSIONS AND RECOMMENDATIONS

The LWD has a shallow depth of influence due to the lighter weight being dropped by hand as compared to the FWD. The LWD clearly has the potential to be used as a construction control device of granular and soil layers. Previous studies showed that there are good correlations between elastic moduli determined with the LWD and the FWD. Correlations between laboratory's determined resilient moduli and elastic moduli determined with the FWD have also been established in the past. However, it is clear that such correlations are material type and pavement structure dependent.

Previous limited studies with the LWD have shown that surface elastic moduli determined with the LWD have material specific correlations with that of surface elastic moduli determined with the well known FWD. That study also showed that the use of deflection bowl parameters determined with the LWD for benchmarking or relative comparison also has potential for construction control purposes. Therefore, the study on STE focused on correlations between the LWD deflection bowl parameters with that of the FWD, the penetration rate of the RCCD, or DCP and the CIV values of the CIT. These are all non destructive measuring technologies which can clearly enhance the normal density focused layer construction control.

The good correlations established for the STE between the FWD and the LWD deflection bowl parameters showed that benchmarking with the deflection bowl parameters would be possible for such material types in future. The study between LWD deflection bowl parameters and the CIT or RCCD did not produce good correlations. It is, therefore, suggested that the LWD always be used in combination with density measurements or RCCD and the CIT.

5. ACKNOWLEDGEMENTS

Mr Pedro Carvalho of ANE is acknowledged for his championing the use of the sand treated with emulsion in Mozambique and for his facilitating role ions and monitoring the experimental sections.

6. REFERENCES

[1] Chen DH, Wang JN and Bilyen J. 2001. ***Application of the DCP in the Evaluation of Base and Subgrade Layers***. 80th Annual Meeting of the Transportation Research Board, January 2001, Washington, D.C.

[2] Coetzee NF, van Wijk AJ and Maree JH (1989) ***Impact Deflection Measurements.*** Proceedings of the Fifth Conference on Aspahlt Pavements in Southern Africa. Swaziland, 1989

[3] Committee of State Road Authorities (CSRA) *(1996**) Guidelines for rehabilitation design of flexible pavements.*** Technical Recommendations for Highways 12 (TRH 12), Department of Transport (DoT), Pretoria.

[4] Fleming PR 2001. ***Field Measurement of Stiffness Modulus For Pavement Foundations*** Transportation Research Board 1755, Submitted to the 2001 Annual Meeting of the Transportation Research Board For Presentation and Publication. Washington, D.C.

[5] Gurp C, Groenendijk J and Beuving E. 2000. ***Experience With Various Types of Foundation Tests*** Proceedings of the Fifth International Conference on Unbound Aggregate In Roads, Nottingham, United Kingdom.

[6] Guthrie WS and Reese GB. 2008. ***Use of the Heavy Clegg Impact Soil Tester to Assess Rutting Susceptability of Cement –Treated Material under Early Trafficking.*** Paper presented at TRB 2008 Annual Meeting, Washington, January 2008

[7] Hartman AM, Van Wijk A, Carvalho P, Horak E. 2005. ***Emulsion Treated Sand for Low Volume Roads in Mozambique – the STE Research Section****.* T2 Kwa-Zulu Natal Conference, Oct. 2005. Pietermaritzburg, South Africa.

[8] Hoffman O, Guzina BB and Drescher A. 2003. ***Enhancements and Verification Tests For Portable Deflectometers***, Final Report 2003-10. Minnesota Department of Transportation, St-Paul, MN.

[9] Horak E (1987) ***The use of surface deflection basin measurements in the mechanistic analysis of flexible pavements.*** Proceedings of the Fifth International Confenernce on the Structural design of Asphalt Pavements. Ann Arbor, Michigan, USA, 1987.

[10] Horak E and Khumalo T (2006) ***Deflection bowl parameters correlation of a light and standard falling weight deflectometer.*** Southern African Road Federation (SARF) combined international Conference with The International Road federation (IRF), September, Durban, South Africa.

[11] Horak E (1988). ***Aspects of Deflection Basin Parameters used in a Mechanistic Rehabilitation Design Procedure for Flexible Pavements in South Africa.*** PhD thesis, Department of Civil Engineering at the University of Pretoria, Pretoria, South Africa.

[12] Horak E (2007) ***The use of Surface Moduli as determined with the Falling Weight Deflectometer.*** Paper accepted for presentation at the Southern Africa Tranpsortation Conference (SATC), Pretoria, July 2007

[13] Horak E and Emery S (2006***) Falling Weight Deflectometer Bowl Parameters as analysis tool for pavement structural evaluations***. 22nd Australian Road research Board (ARRB) International Conference. October 2006, Brisbane, Australia.

[14] Horak E, Maree JH and van Wijk AJ (1989) ***Procedures for using Impulse Deflectometer (IDM) measurements in the structural evaluation of pavements.*** Proceedings of the Annual Transportation Convention Vol 5A, Pretoria, South Africa.

[15] Joubert PB (1995) ***Structural Classification of pavements through the use of FWD deflection basin parameters.*** Proceedings of the Annual Transportation Convention, Pretoria, South Africa.

[16] Lacante, S.C. 1992. ***Comparative Study of Deflection Basins Measured on Road Structures With Various Non-Destructive Measuring Devices**.* Thesis for MTech. Technikon of Pretoria, Pretoria, South Africa.

[17] Livneh, M, Goldberg Y (2001). ***Quality Assessment During Road Formation and Foundation Construction: Use of Falling-Weight Deflectometer And Light Drop Weight;*** Transportation Research Record 1755, Submitted to the 2001 Annual Meeting of the Transportation Research Board For Presentation and publication, Pp 69-77.

[18] Maree JH and Bellekens RJL (1991) ***The effect of asphalt overlays on the resilient deflection bowl response of typical pavement structures.*** Research report RP 90/102 for the Department of Transport. Chief Directorate National Roads, Pretoria , South Africa.

[19] Maree JH and Jooste F (1999) ***Structural Classification of Pavements through the use of IDM Deflection Basin Paramaters***, RDAC Report PR 91/325. Department of Transport, Pretoria, South Africa.

[20] Ping WV, Yang Z and Gao Z (2002) ***Field and Laboratory Determination of Granular Subgrade Moduli.*** Journal of Performance of Constructed Facilities. November 2002.

[21] Rahimzadeh B, Jones M and Thom N. (2004). ***Performance Testing of Unbound Materials Within the Pavement Foundation***, 6th International Symposium on Pavement Unbound-UNBAR6, Nottingham, 6-8 July 2004

[22] Rohde GT and Van Wijk AJ. 1996. ***A Mechanistic Procedure To Determine Basin Parameter Criteria**.* Southern African Transportation Conference, Pretoria, South Africa.

[23] Siddiki NZ, Khan A, Kim DK and Cole T. 2008. ***Use of In Situ Tests in Compaction Control of a Bottom Ash Embankment.*** Paper presented at TRB 2008 Annual Meeting, Washington, January 2008

[24] Thompson MJ, White DJ, Geiselman H and Siemeier J. 2008. ***Variable Feedback Control Intelligent Compaction to Evaluate Subgrade and Granular Pavement Layers- Field Study at Minnesota US 14.*** Paper presented at TRB 2008 Annual Meeting, Washington, January 2008

[25] Van Wijk I and Carvalho P. 2002, ***Innovative Use of Sands in Pavement Layers: Experience in Mozambique.*** 2nd World Engineering Congress, Sarawak, Malaysia, 22-25 July 2002