TOWARDS USING THE LIGHT FALLING WEIGHT DEFLECTOMETER AS A CONSTRUCTION CONTROL DEVICE

J.H. HEATHCOTE

TOWARDS USING THE LIGHT FALLING WEIGHT DEFLECTOMETER AS A CONSTRUCTION CONTROL DEVICE

JOHAN HENRY HEATHCOTE

A dissertation submitted in partial fulfilment of the requirements for the degree of

MASTER OF ENGINEERING (TRANSPORTATION ENGINEERING)

In the

FACULTY OF ENGINEERING

UNIVERSITY OF PRETORIA

February 2016

DIE GEBRUIK VAN DIE LIGTE VALLENDE GEWIG DEFLEKTOMETER AS ′n KONSTRUKSIE KONTROLE TOESTEL

JOHAN HENRY HEATHCOTE

′n Verhandeling voorgelê ter gedeeltelike vervulling van die vereistes vir die graad

MAGISTER IN INGENIEURSWESE (VERVOERINGENIEURSWESE)

In die

FAKULTEIT INGENIEURSWESE

UNVERSITEIT VAN PRETORIA

Februarie 2016

UNIVERSITEIT VAN PRETORIA
UNIVERSITY OF PRETORIA
YUNIBESITHI YA PRETORIA

DISSERTATION SUMMARY

TOWARDS USING THE LIGHT FALLING WEIGHT DEFLECTOMETER AS A CONSTRUCTION CONTROL DEVICE

JOHAN HENRY HEATHCOTE

Supervisor: Professor Doctor Wynand J vdM Steyn

Co-Supervisor: Doctor Emile Horak

Department: Civil Engineering

University: University of Pretoria

Degree: Master of Engineering (Transportation Engineering)

The Light Falling Weight Deflectometer (LFWD) is a dynamic non-destructive test developed to estimate the in-situ stiffness modulus of pavement materials. The technology of this device is very similar to that of the Falling Weight Deflectometer (FWD) to most closely simulate the loading rate and area of a single moving wheel. The LFWD is a portable scaled down hand operated version of the mechanical electrical FWD that applies an impulse load from a drop weight impacting a circular plate resting on the surface to impose various contact pressures through a calibrated system of rubber buffers. The LFWD, like the FWD, measures both the force and deflections with a velocity transducer to calculate the stiffness of the particular layer.

Over the past decade the LFWD has experienced increased popularity due to the fact that non-destructive tests can be undertaken to determine aspects of a constructed layer's engineering and physical properties and because it is portable. The LFWD would ideally be used to provide better engineering parameters for the quality assurance and quality control during the construction of granular and lightly cemented layers.

Previous LFWD research consists of correlation studies between different strength characterisation testing equipment of pavement layers, there is however, a lot of variability present in these

correlation relationships. One of the most prominent sources of engendering variability within the LFWD measurements is attributed to inconsistent operation protocol.

This study was undertaken to establish an operation protocol for the Dynatest 3031 LFWD device and to consequently investigate the influence of various parameters on the surface moduli and deflection bowl parameters yielded by the LFWD and to determine a reliable relationship between LFWD stiffness results, deflection bowl parameters and other pavement material parameters. The ensuing intention is to accurately predict the model or monitor the basic material characteristics and enhance standard construction quality control testing in a practical engineering quality control application.

LFWD deflection bowl benchmark analysis in conjunction with the calculated surface modulus values can effectively be used as a first step screening tool in identifying areas or zones of distress in a newly constructed pavement layer. The concept of the well-known Red, Amber, Green (RAG) structural condition rating system have been utilised for the LFWD derived deflection bowl parameters and proposed surface moduli ranges for granular base pavements.

This study confirms that the LFWD can be utilised as a non-destructive quality control testing device in a practical engineering quality control application. In spite of the lack of exactness of the current RAG criteria, it had been experienced that such a high sample density non-destructive test method and benchmarking can help identify areas or spots in a constructed layer which warrants additional conventional testing. Additional research is however necessary to continuously improve and revise the proposed ranges in order to achieve accurate and reliable flexible pavement quality and acceptance control procedures for the LFWD device.

UNIVERSITEIT VAN PRETORIA
UNIVERSITY OF PRETORIA
YUNIBESITHI YA PRETORIA

SAMEVATTING VAN VERHANDELING

DIE GEBRUIK VAN DIE LIGTE VALLENDE GEWIG DEFLEKTOMETER AS ′n KONSTRUKSIE KONTROLE TOESTEL

JOHAN HENRY HEATHCOTE

Promotor: Professor Doktor Wynand J vdM Steyn

Medepromotor: Doktor Emile Horak

Departement: Siviele Ingenieurswese

Universiteit: Universiteit van Pretoria

Graad: Magister in Ingenieurswese (Vervoeringenieurswese)

Die Ligte Vallende Gewig Deflektometer (LVGD) is 'n dinamiese nie-destruktiewe toetsapparaat wat ontwikkel is om die in-situ styfheid modulus van plaveisel materiale te bepaal. Die tegnologie van hierdie toestel is soortgelyk aan dié van die Vallende Gewig Deflektometer (VGD) om die belading en kontakdruk van 'n enkele bewegende wiel akkuraat te simuleer. Die LVGD is 'n draagbare, afgeskaalde handgekontroleerde weergawe van die meganiese elektriese VGD wat 'n impulslas toepas van ‘n vallende gewig op ‘n ronde plaat wat op die oppervlak rus, impakteer om ′n kontakdruk oor te dra op die plaveisel deur 'n gekalibreerde stelsel van rubber buffers. Die LVGD, soos die VGD, meet beide die kontakdruk en defleksies met 'n versnellingsmeter om die styfheid van ‘n bepaalde laag te kan bereken.

Gedurende die afgelope dekade het die LVGD toenemende gewildheid ervaar te danke aan die feit dat draagbare nie-destruktiewe toetse gedoen kan word om aspekte te bepaal van ‘n gekonstrueerde laag se ingenieurs en fisiese eienskappe. Die LVGD sou ideaal gebruik word om beter ingenieurs-parameters vir die kwalitiet konstruksie kontrole beheer te verskaf tydens die konstruksie van klip en gruis-materiaal en ligte gestabiliseerde plaveisellae.

Vorige LVGD navorsing bestaan uit korrelasiestudies tussen verskillende sterkte karakteriserings toetstoerusting van die plaveisellae. Daar is egter baie variasie teenwoordig in hierdie korrelasie verwantskappe. Een van die mees prominente bronne van variasie binne die LVGD meetings word toegeskryf aan teenstrydige operasionele protokol tydens toetsing.

Hierdie studie is onderneem om 'n operasionele protokol te vestig vir die Dynatest 3031 LVGD toestel en om gevolglik die invloed van verskeie parameters op die oppervlakmoduli en defleksiekom parameters wat opgelewer word deur die LVGD te ondersoek. Dit het 'n betroubare verhouding tussen LVGD styfheid resultate, defleksiekom parameters en ander plaveisel materiaal parameters daar gestel. Die daaropvolgende voorneme is om die basiese materiaal eienskappe met behulp van 'n model akkuraat te voorspel of te kan moniteer. en om as eerste orde aanduider toetse gebruik te word met standaard konstruksie kontrole beheertoetsing in 'n praktiese ingenieurswese kontrole beheer omgewing.

LVGD defleksiekom parameters maatstaf of relatiewe ontleding in samewerking met die berekende oppervlakmodulus waardes kan effektief gebruik word as 'n eerste orde keuringsinstrument in die identifisering van gebiede of sones van swakker materiaal kwaliteit in 'n nuut gekonstrueerde plaveisellaag. Die konsep van die bekende relatiewe maatstaf met Rooi, Amber, Groen (RAG) strukturele toestand graderingstelsel is gebruik, en kriteria voorgestel vir die LVGD afgeleide defleksiekom parameters en voorgestelde oppervlakmoduli vir klip en gruis-materiaal of korrelmateriaal kroonlaag plaveisels se strukturele sterkte evaluering.

Hierdie studie bevestig dat die LVGD benut kan word as 'n nie-destruktiewe konstruksiekontrole beheertoetsing apparaat in 'n praktiese konstruksiekontrole beheer omgewing. Ten spyte van die gebrek aan akkuraatheid van die huidige RAG kriteria, is dit ervaar dat so 'n hoë frekwensie toets potensiaal, nie-destruktiewe toets metode kan help om areas of kolle in 'n gekonstrueerde laag te identifiseer wat bykomende konvensionele toetse regverdig. Verdere navorsing is egter noodsaaklik om voortdurend die voorgestelde evalueringskriteria te verbeter en te hersien om akkurate en betroubare buigsame plaveisel kwaliteit en aanvaarding beheer prosedures vir die LVGD toestel daar te stel.

ABSTRACT

Title: Towards using the light falling weight deflectometer as a construction control device

Author: Johan Henry Heathcote

Supervisor: Professor Doctor Wynand J vdM Steyn

Co-Supervisor: Doctor Emile Horak

Department: Civil Engineering

University: University of Pretoria

Degree: Master of Engineering (Transportation Engineering)

The Light Falling Weight Deflectometer (LFWD) is an impact load non-destructive test instrument measuring in-situ effective stiffness of pavement materials. It is a portable hand operated version of the Falling Weight Deflectometer (FWD). The LFWD, like the FWD, measures both the force and deflections with a velocity transducer.

This study was undertaken to establish an operation protocol for the Dynatest 3031 LFWD device. The influence of various parameters on the surface moduli and deflection bowl parameters yielded by the LFWD were investigated. A reliable relationship between LFWD derived stiffness, deflection bowl parameters and other pavement material parameters were determined. The basic material characteristics can be determined non-destructively and enhance standard construction quality control testing in a quality control application.

It was confirmed that the LFWD can be utilised with a structural benchmark approach as well. The Red, Amber, Green (RAG) structural condition rating system criteria used with a high sample density benchmarking can help identify areas or spots in a constructed layer which warrants additional conventional testing. Additional research is however necessary to continuously improve and revise the proposed ranges in order to achieve accurate and reliable flexible pavement quality and acceptance control procedures for the LFWD device.

ACKNOWLEDGEMENT

I wish to express my appreciation to the following organisations and persons who made this dissertation possible:

a) This dissertation is based on the LFWD research conducted by Ndodana Consulting Engineers, Lichenry Construction, the University of Pretoria and the Council for Scientific and Industrial Research (CSIR), Division for Built Environment. The opinions expressed are those of the author and not necessarily represent the policy of the before mentioned.

b) Dr Emile Horak, my co-supervisor, for his continuing support, mentorship and encouragement throughout the duration of my career and this study.

c) Professor Wynand Steyn, my supervisor for his aspiring guidance, patience, on-going support and invaluable advice.

d) My family, friends and Leré for their longstanding love, support and encouragement.

Alle eer aan God my Vader en Redder vir die insig en vermoë om my studies klaar te gemaak het.

~

All glory to God my heavenly Father and Saviour for the insight and ability to complete my studies.

TABLE OF CONTENTS

PAGE

APPENDICES

LIST OF TABLES

PAGE

LIST OF FIGURES

PAGE

1 INTRODUCTION AND BACKGROUND

1.1 INTRODUCTION

The Light Falling Weight Deflectometer (LFWD) is a mobile dynamic non-destructive test device developed to estimate the in-situ stiffness modulus of pavement materials. The technology of this device is very similar to that of the Falling Weight Deflectometer (FWD) to most closely simulate the loading rate and area of a single moving wheel. The LFWD is a portable scaled down hand operated version of the mechanical electrical FWD that applies an impulse load from a drop weight impacting a circular plate resting on the surface to impose various contact pressures through a calibrated system of rubber buffers. The LFWD, like the FWD, measures both the load force and deflections via a velocity transducer to calculate the stiffness of the layered pavement system.

Over the past decade the LFWD has experienced increased popularity due to the fact that non-destructive tests can be undertaken to determine aspects of a constructed layer's engineering and physical properties and because it is portable. The LFWD measures deflection under the point of loading as well as at two offsets normally at 300 mm and 600 mm from the point of loading (Dynatest, 2014).

The FWD deflections are often used in linear elastic layered mathematical models to back-calculate effective elastic moduli of a pavement structure. The lower impulse load and limited offset measurement points make the LFWD not a good instrument for such back-analysis procedures. In short the FWD is ideal to evaluate the whole pavement structure while the LFWD is limited to the layers within 200 mm to 300 mm of the applied load for evaluations, which is typically the base layer.

The LFWD would ideally be used to provide better engineering parameters for the quality assurance and quality control during the construction of granular and lightly cemented layers (Horak et al., 2008). The LFWD has limited depth of influence on a pavement structure, typically limiting the response to the upper 200 mm to 300 mm of the pavement structure (Senseney and Mooney, 2010; Senseney et al., 2015). The need therefore arises to further research the potential of single layer non-destructive structural evaluation in order to establish a reliable relationship between LFWD stiffness results or deflection bowl parameters and other pavement material parameters.

Previous research on the LFWD encompassed essentially correlation studies between different strength characterisation testing equipment of pavement layers, however, there seems to be a lot of variability present in these correlation relationships (Horak et al., 2008; Apeagyei and Hossain, 2010).

1.2 BACKGROUND

Due to the increased popularity of the LWFD, there has been a great drive to further the existing research on the device. The most noticeable advancement of the LFWD research was that conducted by the Department of Transportation in Minnesota in the United States. This research aimed to establish an operation protocol for a specific LFWD model with corresponding methodologies on analysing and interpreting the recorded data. The potential of the LFWD as an ideal construction quality control device due to its ease of operation, mobility and non-destructive test operation was recognised by Flemming et al. (2007).

The LFWD is readily available in South Africa, however, there is currently no South African operation protocol for the LFWD. Different LFWD users operate the equipment and analyse the data differently yielding inconsistent, unreliable and irreproducible test results. It is therefore necessary to establish a South African LFWD operation protocol for South African conditions.

The deflection measurements yielded from the LFWD operation protocol could consequently be used to develop an evaluation model and directly relating it to the pavement layer's compaction using the pavement layer engineering parameters. It is therefore also important to understand the South African material classes, properties and characteristics as they constitute a fundamental part of pavement engineering (De Beer and Maina, 2008; TRH4, 1996; TRH14, 1985).

1.3 PROBLEM DEFINITION

Previous research regarding the LFWD includes mostly correlation studies with other stiffness measuring devices. Correlation studies have been predominantly done between the LFWD, FWD, Dynamic Cone Penetrometer (DCP), Rapid Construction Control Device (RCCD) and the Clegg Impact Tester (CIT). The studies did not produce good correlations between the testing equipment and showed that the stiffness values yielded are extremely sensitive to the material characteristics at the time of testing (Guiamba, 2011). Other research includes identifying testing protocol and data analysis of the LFWD (Edwards and Flemming, 2009; Siekmeier et al., 2009). It has also been established that moisture within the pavement may have a significant effect on the yielded stiffness moduli (Van Aswegen, 2013).

It has been identified in previous research that the LFWD would be best utilised for quality control / quality assurance and structural evaluation of a single layer compacted earthwork and pavement construction. The LFWD makes use of Boussinesq and Odemark homogeneous layer configuration to calculate an approximation or surface modulus value (Siekmeier et al., 2009). However, the variability in material characteristics / parameters at the time of testing causes the stiffness values (surface moduli) to fluctuate, therefore yielding an inaccurate indication of the pavement strength.

The need therefore arises for further research of single layer non-destructive structural evaluation in order to establish a reliable relationship between LFWD stiffness results and other pavement material parameters. This relationship could consequently be utilised to predict the quality and engineering characteristics of different pavement layers in a practical engineering quality control application.

1.4 OBJECTIVES

The objectives of the study are to investigate the influence of various parameters on the surface moduli and deflection bowl parameters yielded by the LFWD and to establish a reliable relationship between LFWD stiffness results, deflection bowl parameters and other pavement material parameters. The ensuing intention is to accurately predict the model or monitor the basic material characteristics and enhance standard construction quality control testing in a practical engineering quality control application.

1.5 SCOPE

The scope essentially focuses on simple deflection bowl parameters and the simplified surface moduli calculated, as correlated with the compaction of the pavement layers.
The scope of the work comprised of the following:

1) Establish a proper protocol for operating the LFWD and for analysing the output data (which can also be used as an operation manual);
2) Relate deflection bowl parameters and surface stiffness results with material parameters such as compaction density;
3) Analyse raw output data in order to formulate a typical benchmark model, and
4) Calibrate and validate the benchmark model in order to yield reasonably accurate deductions in order to predict the pavement layer performance in a practical engineering quality control application.

1.6 CONTRIBUTION TO STATE OF KNOWLEDGE

This research directly contributes to the quality and acceptance control procedures that are utilised on construction sites. By establishing an evaluation model based on the stiffness values which are directly related to the pavement layer's compaction by taking into consideration key parameters such as the moisture content of the material, one could possibly benchmark or compare whether a pavement layer is of at least a certain specified engineering quality. The LFWD derived measurements show good correlations with typical layer and material properties and could therefore be utilised in conjunction with standard current quality control tests such as density. The tests are also non-destructive and not time consuming. Due to mobility of the LFWD a significant amount of test measurements are able to be taken non-destructively ensuring a considerable distribution and sample size.

1.7 RESEARCH PROGRAM

Research was conducted in the following sequence:

1. Establishing a preliminary testing and operation protocol for the LFWD;
2. Field and laboratory testing was carried out on four distinct construction sites for a variety of pavement layers;
3. Data were analysed in order to formulate a typical benchmark model for predicting pavement behaviour under different engineering parameters, and
4. Utilization of field / laboratory data from other sites in order to calibrate the established benchmark model.

1.8 STRUCTURE OF REPORT

The structure of the report is depicted schematically in Figure 1.1 and indicates the main purpose of each chapter.

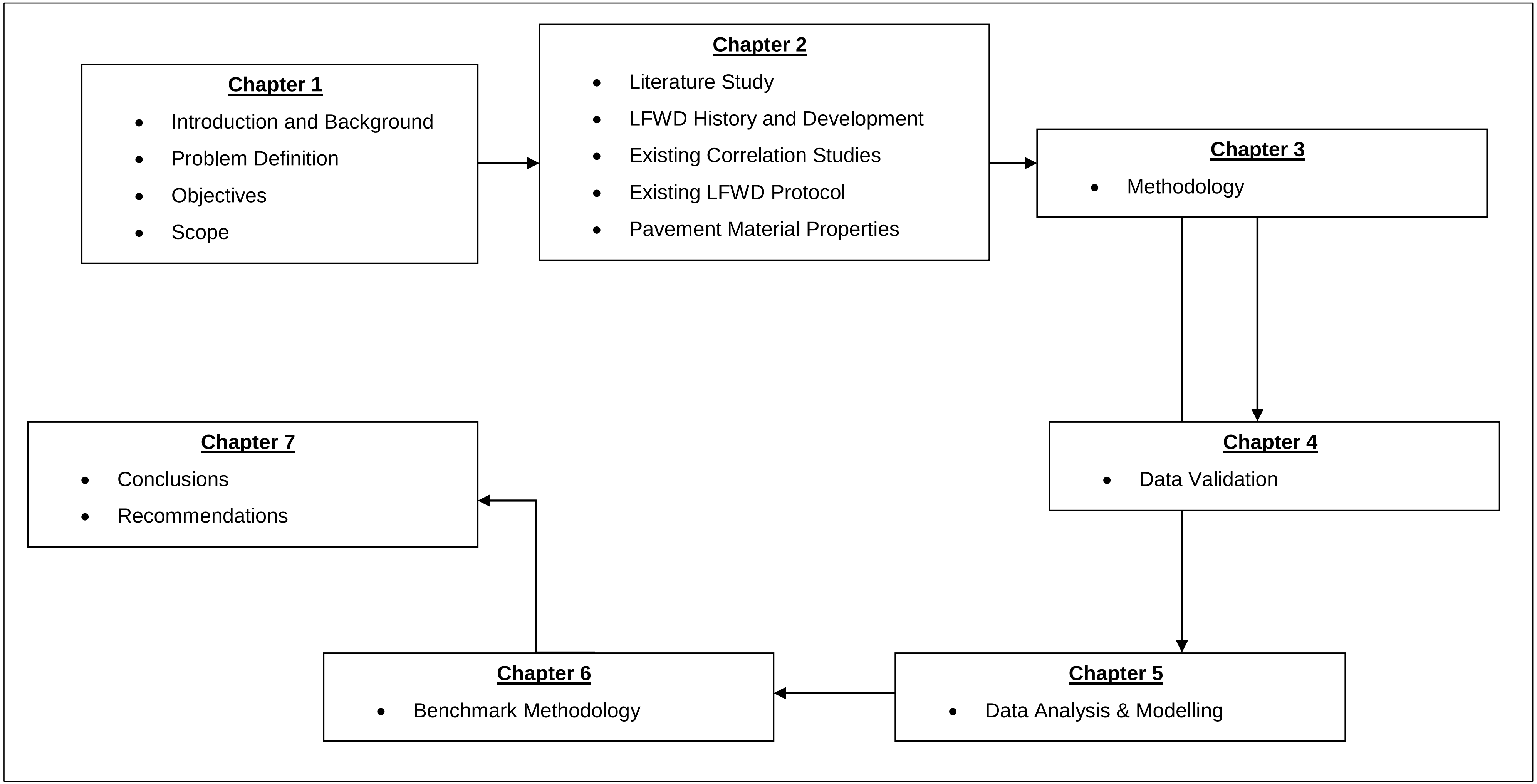

Figure 1.1: Schematic layout of thesis structure.

1.9 REFERENCES

Apeagyei, A.K. and Hossain, M.S. (2010). *'Stiffness-Based Evaluation of Base and Subgrade Quality using Three Portable Devices'*, proceedings of the 89th Transportation Research Board (TRB) Annual Meeting, January 10 -14 2010, Washington. U.S.A.

De Beer, M. and Maina, J. (2008). *'Some Fundamental Definitions of the Elastic Parameters for Homogeneous Isotropic Linear Elastic Materials in Pavement Design and Analysis'*, proceedings of the 27th South African Transport Conference (SATC), July 2008, Pretoria, South Africa.

Dynatest (2014). *'Dynatest 3031 Light Weight Deflectometer (LWD)'*, www.dynatest.com, (5 May 2014).

Edwards, P. and Flemming, P. (2009). *'LWD Good Practice Guide (Draft 9)'*, Pavement Foundation Group (PFG), Minnesota, U.S.A.

Flemming, P.R., Frost, M.W and Lambert, J.P. (2007). *'A Review of the Lightweight Deflectometer (LWD) for Routine In-situ Assessment of Pavement Material Stiffness'*, proceedings of the 86th Transportation Research Board (TRB) Annual Meeting, July 7 -9 2007, Washington.

Guiamba, D.Z. (2011). *'Comparitive study of non-destructive field testing devices on bitumen emulsion stabilised materials'*, MSc. Thesis, University of Pretoria, Pretoria, South Africa.

Horak, E., Maina, J., Guiamba, D. and Hartman, A. (2008). *'Correlation study with the light weight deflectometer in South Africa'*, proceedings of the 27th South African Transport Conference (SATC), July 2008, Pretoria, South Africa.

Senseney, C.T. and Mooney, M.A. (2010). *'Characterization of a two-layer soil system using a lightweight deflectometer with radial sensors'*, proceedings of the 88th Transportation Research Board (TRB) Annual Meeting, January 11 -15 2010, Washington. U.S.A.

Senseney, C.T., Grasmick, J. and Mooney, M.A. (2015). *'Sensitivity of lightweight deflectometer deflections to layer stiffness via finite element analysis'*, Canadian Geotechnical Journal, Vol 52, 2015, pp 961-970

Siekmeier, J., Pinta, C., Merth, S., Jensen, J., Davich, P., Camargo, F. and Beyer, M. (2009). *'Using the Dynamic Cone Penetrometer and Light Weight Deflectometer for Construction Quality Assurance'*, Report no. MN/RC 2009-12, Minnesota Department of Transport, Minnesota, U.S.A.

TRH 4 (1996). *'Draft TRH 4 : Structural design of flexible pavements for interurban and rural roads'*, Department of Transport, Pretoria, South Africa.

TRH 14 (1985). *'TRH 14 : Guidelines for road construction materials'*, Department of Transport, Pretoria, South Africa.

2 LITERATURE STUDY

2.1 INTRODUCTION

The literature study is divided into four sections ranging from the development and history of the LFWD, existing LFWD research, existing operation protocols and the review of literature related to fundamental knowledge regarding pavement material properties.

2.2 LFWD HISTORY AND DEVELOPMENT

2.2.1 Different types and components

There are several types of LFWDs currently available on the market. These LFWDs have different features that cause measurement variances between the devices. Some of these device features may include its physical characteristics, the deflection accelerometer instrument and the algorithm utilised to determine the energy transferred to the ground (Siekmeier et al., 2009). Different types of LFWD devices currently available on the market and their main physical characteristics are summarised in Table 2.1. Figure 2.1 shows a typical schematic of a Dynatest 3031 LFWD device, illustrating the respective components.

Table 2.1: Different LFWD Devices (Lindemann, 2014).

Device	Plate Diameter [mm]	Plate Thickness [mm]	Falling Weight [kg]	Maximum Applied Force [kN]	Load Cell	Total Load Pulse [ms]	Type of Buffers	Deflection Transducer Type
Zorn	100, 150, 200, 300	45*, 28, 20	10, 15	7.07	No	18 ± 2	Steel Spring	Accelerometer (Plate)
Keros / Carl Bro	150, 200,300	20	10, 15, 20	15	Yes	15 to 30	Rubber (conical)	Velocity (Ground)
Dynatest 3031	100, 150, 200**, 300	20	10, 15, 20	15	Yes	15 to 30	Rubber (flat)	Velocity (Ground)
Prima	100, 200, 300	20	10,20	15	Yes	15 to 20	Rubber (conical)	Velocity (Ground)
Loadman	110, 132, 200, 300	Unknown	10	17.6	No	25 to 30	Rubber	Accelerometer (Plate)
ELE	300	Unknown	10	Unknown	No	Unknown	Unknown	Velocity (Plate)

*Uncertain/suspect values

**The standard loading plate diameter for the Dynatest 3031 device is 200 mm

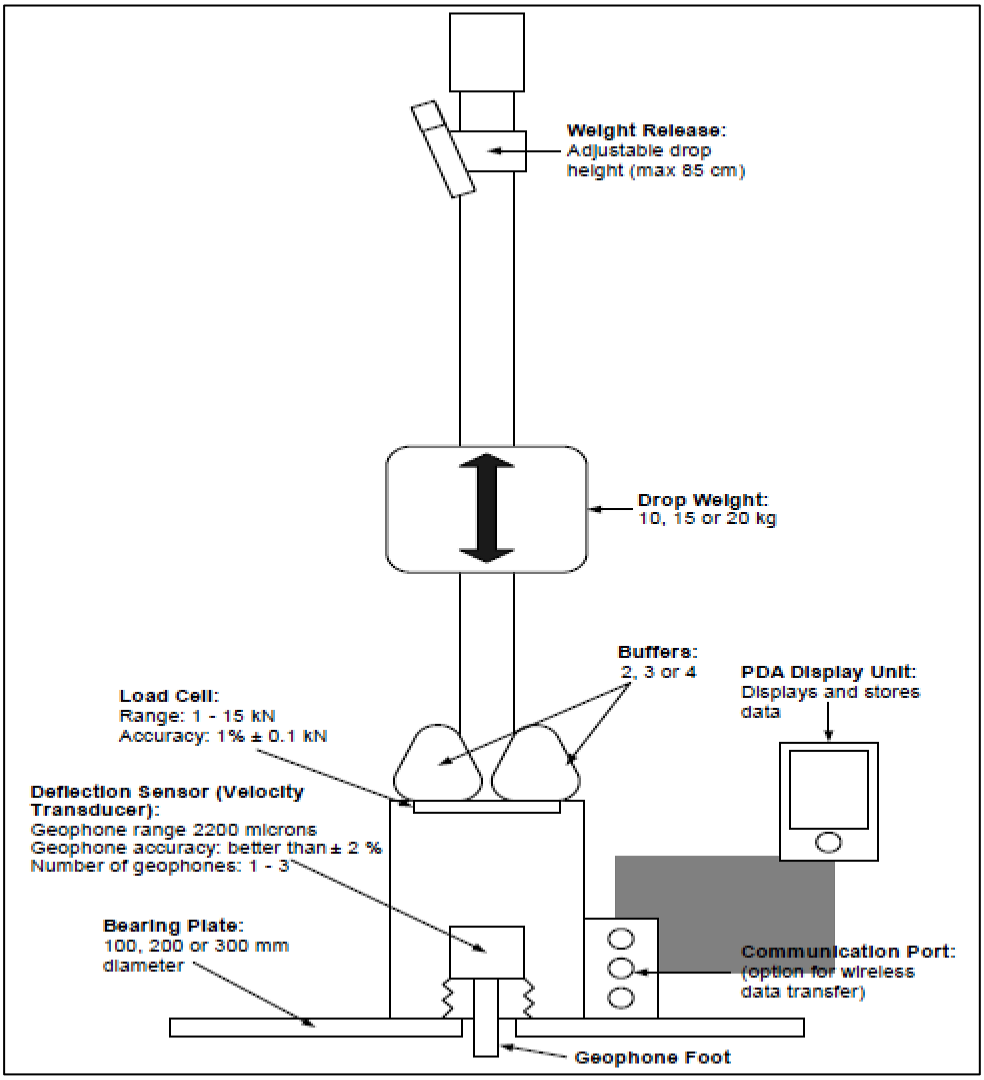

Figure 2.1: Schematic Layout of Typical LFWD (Tan et al., 2014).

Figures 2.2 and 2.3 illustrate the specific LFWD device utilised with its corresponding components. The LFWD has an approximate weight of 26 kg which normally includes a 10 kg falling mass that impacts on the bearing plate via four rubber buffers that consequently produces a load pulse of 15 to 20 milliseconds with a load range of 1 to 15 kN (up to 450 kPa) with its 200 mm diameter loading plate. The 300 mm diameter loading plate yields a load range of up to 200 kPa (Tan et al., 2014). The LFWD has varying drop weights of 10, 15 and 20 kg. All LFWD models have an adjustable drop height up to 900 mm (Mork, 2008). The LFWD can accommodate different soil types and contact pressures by interchanging different loading plates ranging between 100 and 300 mm diameter (Peterson et al., 2007; Apeagyei and Hossain, 2010).

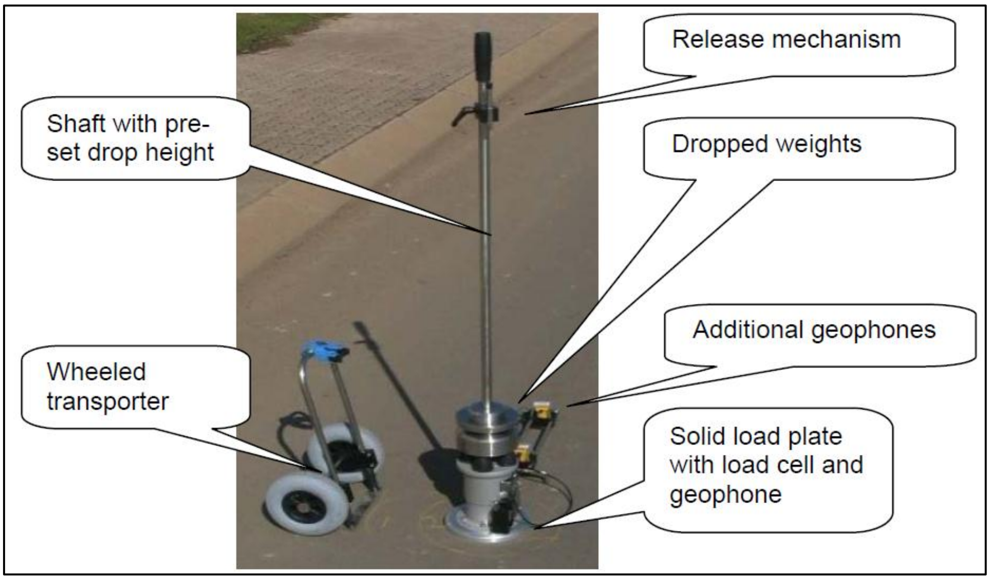

Figure 2.2: Dynatest 3031 Light Falling Weight Device (LFWD) (Horak and Khumalo, 2006).

The LFWD makes use of two types of sensors to measure the impact force (load cell) from the falling mass, and the velocity of the surface (geophone) from which the deflection is determined by integration. The LFWD is also equipped with a 'Personal Digital Assistant' (PDA) device that records the measured deflection and consequently utilises Dynatest software such as 'LWDmod', which is similar to ELMOD for Dynatest FWD, to calculate the in-situ stiffness modulus of pavement layers.

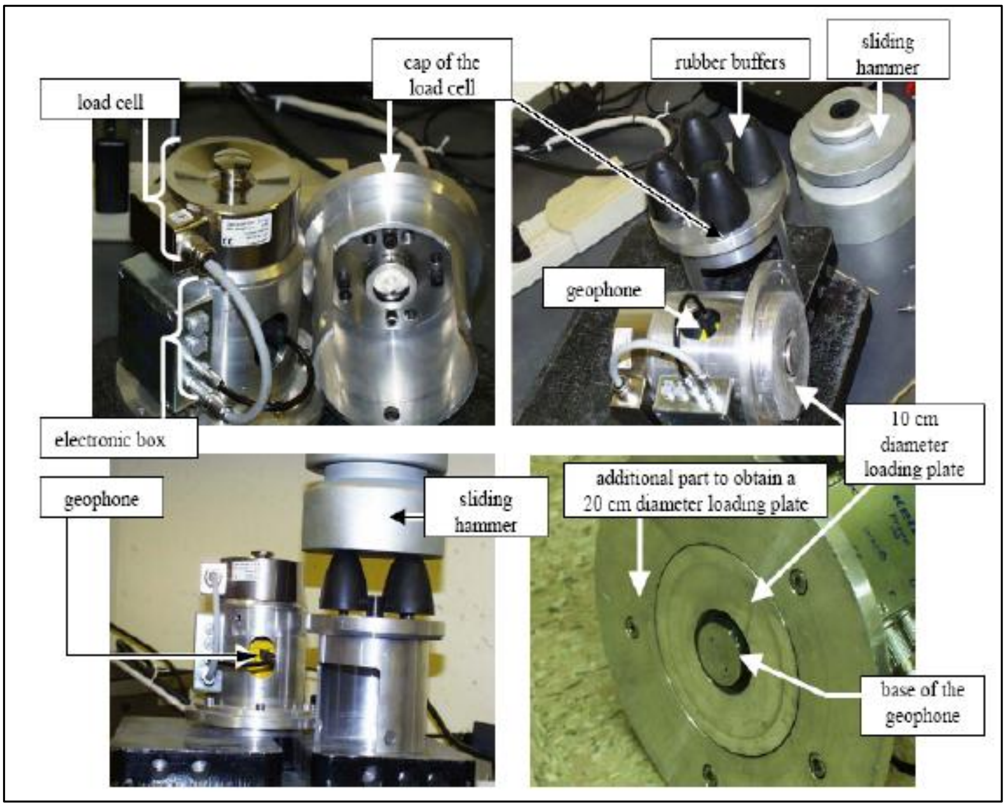

Figure 2.3: Components of the Dynatest 3031 Light Falling Weight Device (LFWD) (Horak and Khumalo, 2006).

2.2.2 Fundamental Surface Modulus Principles

It is of utmost importance to understand and distinguish between the surface modulus and other types of moduli found in soil mechanics. The following sections discuss the fundamental principles of the surface modulus.

2.2.2.1 Boussinesq's equations

In the 1870s Boussinesq derived model evaluations which are applicable in principle to describe motions that are sensibly two-dimensional and which have the form of a perturbation of the one dimensional wave equation. Boussinesq equations could also be used to calculate the stress, strain and displacement conditions in a homogeneous, isotropic, linear elastic semi-infinite space under a point load (Highways Department, 2000). The stress, strain and displacement conditions under a uniform load can be found by integration. At depth z below the centreline of a uniform circular load σ_0 with radius a, the stress, strain, radius of curvature and displacement are given in Equations 2-1 to 2-6.

$$\sigma_z = \sigma_0 \text{ x } \left\{1 - \left[\frac{1}{1+\left(\frac{a}{z}\right)^2}\right]^{\frac{3}{2}}\right\} \qquad \text{Equation 2-1}$$

$$\sigma_r = \sigma_t = \sigma_0 \text{ x } \left\{\frac{1+2\mu}{2} - \frac{1+\mu}{\left(1+\left(\frac{a}{z}\right)^2\right)^{\frac{1}{2}}} + \frac{\frac{1}{2}}{\left(1+\left(\frac{a}{z}\right)^2\right)^{\frac{3}{2}}}\right\} \qquad \text{Equation 2-2}$$

$$\varepsilon_x = (1 + \mu) \text{ x } \left\{\frac{\frac{z}{a}}{\left(1+\left(\frac{z}{a}\right)^2\right)^{\frac{3}{2}}} - (1 - 2\mu)\left\{\frac{\frac{z}{a}}{\left(1+\left(\frac{z}{a}\right)^2\right)^{\frac{1}{2}}} - 1\right\}\right\} \qquad \text{Equation 2-3}$$

$$d_z = (1 + \mu) \text{ x } \sigma_0 \text{ x } \left\{\frac{a}{E} \text{ x } \frac{1}{\left(1+\left(\frac{a}{z}\right)^2\right)^{\frac{1}{2}}} + (1 - 2\mu) \text{ x } \left\{\left(1+\left(\frac{z}{a}\right)^2\right)^{\frac{1}{2}} - \frac{z}{a}\right\}\right\} \qquad \text{Equation 2-4}$$

$$R = E \text{ x } \left\{\frac{\frac{a}{[(1-\mu^2) x\, \sigma 0]}}{1+\left[\frac{\frac{3}{2}}{(1-\mu)}\right] x \frac{z^2}{a}}\right\} \text{ x } \left(1+\left(\frac{z}{a}\right)^2\right)^{\frac{5}{2}} \qquad \text{Equation 2-5}$$

$$\varepsilon_r = \frac{\frac{z}{2}}{R} \qquad \text{Equation 2-6}$$

Where:

σ_z = vertical stress

σ_r = radial stress

σ_t = tangential stress

ε_z = vertical strain

ε_r = horizontal strain

d_z = vertical displacement

R = radius of curvature

μ = Poission ratio

2.2.2.2 Odemark's Method of equivalent thickness

Boussinesq's equations are only applicable to one homogenous layer. In practice, most pavement structures are not homogenous but are layered systems. Odemark developed an approximate method to transform a system consisting of layers with different moduli into an equivalent system where thicknesses of the layer are altered but all layers have the same modulus (Odemark, 1949). This is known as the Method of Equivalent Thickness (Highways Department, 2000). The transformation assumes that the stiffness of the layer remains the same, and is depicted in Equation 2.7.

$$\frac{I \, x \, E}{(1-\mu^2)} \qquad \text{Equation 2-7}$$

Where:

E = Layer Modulus

I = Moment of Inertia

μ = Poisson's ratio

Since I is a function of the cube of the layer thickness, the equivalent thickness transformation for a two layer system can be expressed as per Equations 2-8 and 2-9.

$$h_1 \text{ x } \frac{E1}{(1-\mu 1^2)} = h_e^3 \text{ x } \frac{E2}{(1-\mu 2^2)} \qquad \text{Equation 2-8}$$

OR

$$h_e = h_1 \text{ x } \left[\frac{E1}{E2} \text{ x } \frac{(1-\mu 2^2)}{(1-\mu 1^2)}\right]^{\frac{1}{3}} \qquad \text{Equation 2-9}$$

Where:

h_1 = layer thickness

E_1 = layer modulus

μ_1 = Poisson's ratio

h_e = equivalent layer thickness

E_2 = layer modulus

μ_2 = Poisson's ratio

Since this is an approximate method, an adjustment factor must be applied to obtain a better agreement with elastic theory. The adjustment factor depends on the layer thickness, modular ratios, Poisson's ratios and the number of layers in the pavement structure (Ullidtz et al., 1994). The equivalent thickness equation can therefore be expressed through Equation 2-10.

$$H_c = f \times h_1 \times \left(\frac{E1}{E2}\right)^{\frac{1}{3}}$$ Equation 2-10

Where:

h_1 = layer thickness

E_1 = layer modulus

f = adjustment factor

H_c = equivalent layer thickness

E_2 = layer modulus

To analyse a multi-layer pavement structure with known layer moduli, the layers can be successively transformed into an equivalent system with a homogenous layer modulus equal to the modulus of the semi-infinite subgrade layer by applying Odemark's method. Boussinesq's equations can then be applied to calculate the stress, strain and displacement conditions within the equivalent layered system (Pronk, 1994; Highways Department, 2000).

2.2.2.3 Ullidtz's elaboration of Odemark's Theory

Ulilidtz extended the theory of Odemark by using a more accurate determination of a correction factor, in the equivalent layer thickness calculation of Odemark. Instead of a constant correction factor of 0.9 as in the original Odemark's theory, Ullidtz took into consideration other factors such as the ratio of the layer thickness and the radius of the load (Pronk, 1994; Ullidtz, 1987).

The merit of the elaboration of Odemark's theory by Ullidtz is the fact that he also developed an application of the equivalent layer thickness theory for multi-layer systems for cases in which the moduli of the subgrade and foundation are stress dependent (Horak, 1988; Horak, 2007).

2.2.2.4 Surface Modulus

In any pavement structural evaluation the correct classification and determination of the subgrade strength forms the basis of any analysis and evaluation of the pavement response. The nature of the subgrade moduli can be investigated by determining the surface moduli (Horak, 2007). The surface modulus is the "weighted mean modulus" of the semi-infinite space calculated from the surface deflection using Boussinesq's equations (Ullidtz, 1987). The surface modulus directly under the point of loading at maximum deflection D_0 is calculated as per equation 2-11.

$$E_0(0) = 2 \text{ x } (1-\mu^2) \text{ x } \sigma 0 \text{ x } \frac{a}{d0(0)} \qquad \text{Equation 2-11}$$

The general formula for surface modulus at any point away from the point of maximum deflection is:

$$E_0(r) = \frac{(1-\mu^2) \text{ x } \sigma 0 \text{ x } a^2}{r \text{ x } d0(r)} \qquad \text{Equation 2-12}$$

(valid for r > 2a)

Where:

$E_0(r)$ = surface modulus at distance r

μ = Poisson's ratio of subgrade

σ_0 = uniform stress on the plate

a = radius of the loading plate

r = distance from the centre of the load

$d_0(r)$ = surface deflection at distance r

Ullidtz (1987; 2005) determined that the gradient of the Surface Modulus (SM) further away from the point of maximum deflection (D_0) can be used to identify whether the subgrade has stress softening, stress hardening or purely linear elastic behaviour. The simple slope differential of the surface modulus, or Surface Modulus Differential (SMD) (such as SMD= SM_{600}- SM_{900}), can be used to determine whether the subgrade response is stress stiffening, or stress softening.

This implies that the equivalent or accumulated SM contribution of the pavement structure (SM_{pav}) can be calculated in a number of possible ways. It can be assumed SM_{pav} has the same stiffness as that of the subgrade (e.g. using SM_{300}, SM_{600} or SM_{900}) in the idealised elastic solid half space. It is generally true that subgrade stiffness or effective elastic modulus corresponds best with deflections at 900 mm or further along the deflection bowl (Horak, 1988). Therefore it can be reasoned SM_{pav} is best calculated by SM_{900} = SM_{pav} for this converted ideal elastic half space (Horak et al., 2015).

2.2.3 LFWD's Stiffness Modulus Calculation Review

Different LFWD devices are configured and used differently depending on the model and testing agency. This research was based on the deflection measurements performed using the Dynatest 3031 LFWD device (Dynatest, 2014) as this is the device that is available to the author.

The influence depth of the LFWD is affected by a multitude of factors including the material properties, the drop weight, the drop height, the loading plate diameter and the number of geophones utilised during test measurements (Flemming et al., 2007; Siekmeier et. al, 2009). Flemming and Siekmeier have determined that the depth of influence of the LFWD is approximately 1 to 1.5 times the loading plate diameter. Other researchers (Nazzal, 2003; Abu-Farsakh et al., 2004) established similar influence depth findings.

The surface deflection modulus at the centre of the loading plate may be determined using Equation 2-13 while the surface deflection modulus at a distance from the centre of the load may be determined with Equation 2-14 (Guiamba, 2011).

$$E = \frac{f \times (1-v^2) \times \sigma \times a}{\delta c} \qquad \text{Equation 2-13}$$

$$E = \frac{f \times (1-v^2) \times \sigma \times a^2}{r \times \delta r} \qquad \text{Equation 2-14}$$

Where:

E = Surface Modulus

v = Poisson's ratio (default: 0.5)

σ = Applied stress at surface (kPa)

a = Radius of loading plate (mm)

δ_c = Centre deflection (micron)

f = Factor that depends on the stress distribution

Uniform: f = 2 (default)

Rigid plate: f = π/2

Parabolic, granular: f = 8/3

Parabolic, cohesive: f = 4/3

r Distance from centre of the load (mm)

δ_r Deflection at the distance r from the centre of the load (micron)

The Dynatest LWDmod software uses Odemark's layer transformation approach together with Bousinesq's equations in order to forward-calculate deflections. Odemark's layer transformation's basic assumption is that the layered structure can be transformed into an equivalent uniform, semi-infinite material, whereby Boussinesq's equations can be utilised to calculate deflections. The Odemark-Boussinesq method has two critical assumptions, namely: (1) layer thicknesses should be more than one-half the radius of the loading plate, and (2) moduli should decrease with each descending layer by at least a factor or two (Embacher, 2007; 2008). There are also other assumptions like the value of Poisson's ratio assumed as equal to 0.5. This may have a negligible effect, however it must be stressed that surface moduli thus determined are approximations only.

2.2.4 Variables Affecting Deflection Measurements

There are many test variables that could significantly influence the deflection measurements taken with the LFWD. Such variables could be grouped into two categories, namely, LFWD equipment and pavement layer material variables (Stamp and Mooney, 2013; Tan et al., 2014).

LFWD equipment variables

Different LFWD models and devices yield different configurations and variables. Such equipment variables include the drop weight, drop height, load contact area, rate of loading and the number of geophones (Siekmeier et al., 2009). All of these variables create variation and inconsistency in the deflection measurements and therefore signifies the necessity to create a standardised protocol for a specified LFWD model. Recent indications are that temperature may influence the buffer system and therefore also the load duration of the dropped weight (Flemming et al., 2007; Flemming 2008). LFWD devices should not be used when temperatures fall below 5℃ to ensure that the device's components, particularly the rubber buffers, work as intended (Edwards and Flemming, 2009). While test protocols are important a general calibration protocol for each type of LFWD device is required.

Pavement layer material variables

The stiffness properties of granular pavement layer materials are exceptionally influenced by their moisture content. Pavement layer materials with high moisture contents are known to deform much more easily than those with small moisture contents (Theyse, 2006). The water molecules essentially act as a lubricant that enables the soil grains to slide past each other more easily resulting in pavement layer materials with large moisture contents appearing to have poor stiffness characteristics even after being sufficiently compacted. A fully saturated granular layer may react differently in that excessive pore water pressure may influence the rebound for the layer stiffness (De Beer and Maina, 2008). Also, when the moisture content is very low, some materials exhibit high suction pressures which result in high layer stiffness.

Other pavement layer material variables that could vary deflection measurements include the grading, and therefore grading modulus of the soil. Pavement layer materials composed primarily of gravel and coarse sand usually have larger strength and modulus values than materials with large amounts of fine sand (Yoder and Witczak, 1975).

2.2.5 Quality Control and Assurance Opportunity

The versatility of the LFWD has ensured that the device has enjoyed increased popularity over the past decade as a tool to implement effective quality assurance procedures during construction. The opportunity exists to implement new quality assurance procedures with the LFWD that will improve test precision, increase inspector efficiency and safety, and allow for immediate verification of pavement layer specifications (Flemming et al., 2007).

2.2.6 South African and International Research

South African research pertaining to the LFWD is relatively limited in comparison to that of the international community. The South African complement of the LFWD research predominantly entails correlation studies between different kinds of non-destructive quality control testing methods used in southern Africa (Horak and Khumalo, 2006).

The international community has greatly contributed to the LFWD research complement. The Department of Transportation in Minnesota, United States seems to have taken the lead in this research lately. The contribution consists of standardised testing protocols, correlation studies with various non-destructive testing devices, the effects of varying parameters and testing conditions and establishing target stiffness values when testing soil and pavement layer types. Although much research has already been done on the LFWD, there is still great opportunity to further the collective knowledge on the device (Siddiki, 2012).

2.3 EXISTING RESEARCH

2.3.1 Correlation Studies

There has been extensive LFWD correlation studies and research done in the past ten years. Some of the most prominent correlation studies include that with non-destructive testing tools (NDT) such as the FWD, the DCP, the Static Plate Loading Test (SPLT), the RCCD, the PSPA and the CIST. These non-destructive devices utilise either static or dynamic loading mechanisms (Horak et al., 2008; Guiamba, 2011).

There is consensus among researchers that all relationships between the different testing tools were extremely dependent on the material type and layer thickness. The SPLT and the FWD are regarded as the most appropriate NDT tools in relation to the LFWD (Guiamba, 2011).

Nazzal (2003) completed a correlation study between the SPLT and the LFWD on cement treated soils, lime treated soils and unstabilised fine-grained soils which are expressed in Equation 2-15.

$$E_{(PLT)} = 0.69\ E_{(LFWD)} + 20.9 \qquad \text{Equation 2-15}$$

With a R^2 value of 0.94, significance level < 99.9% and standard error of 29.8.

Nazzal (2003) extended on the research of Flemming et al., (2009) and consequently established a relationship to predict the FWD back-calculated resilient surface moduli from the LFWD surface modulus as illustrated in Equation 2-16.

$$E_{(FWD)} = 0.97\ E_{(LFWD)} \quad \text{for } 12.5\ \text{MPa} < E_{(LFWD)} < 865\ \text{MPa} \qquad \text{Equation 2-16}$$

With a R^2 value of 0.94, significance level < 99.9% and standard error of 33.1.

Horak and Khumalo (2006) conducted a pilot correlation study between deflection bowl parameters measured with the LFWD and the FWD on a granular base pavement road. FWD deflection bowl slope parameters have a well-established track record of application at project level as well as at network level as a pavement structural analysis benchmark method (Zhang et al., 2003; Horak and Emery, 2006; Zhang et al., 2011). The benchmark analysis methodology developed in South Africa makes use of the FWD deflection bowls measured on flexible pavements with simple spreadsheet calculations to derive deflection bowl parameters (Horak and Emery, 2006; Horak, 2008; Horak et al., 2015).

The basic parameters include maximum deflection (YMax), Base Layer Index (BLI), Middle Layer Index (MLI) and Lower Layer Index (LLI). As implied, these basic parameters are associated with different zones with depth in the pavement structure (Horak et al., 2015). Radius of Curvature (RoC) and BLI have been found to correlate well with surfacing and base layers, MLI mostly with the subbase layer and the LLI correlates mostly with selected and subgrade layers (Horak, 2007). Table 2.2 shows the deflection bowl parameters that can be utilised for the LFWD analysis.

Table 2.2: Deflection Bowl Parameters relevant to LFWD.

Deflection Bowl Parameter	Formula	Structural Indicator
Maximum Deflection	D_0 as measured	Gives an indication of all structural layers with as much as 70% contribution by the subgrade when measured with the FWD
Radius of Curvature (RoC)	$\text{RoC} = \frac{L^2}{2D0[\left(\frac{D0}{D300}\right)-1]}$ Where L = 300mm for the LFWD	Gives an indication of the structural condition of the surfacing and base condition (Typically the top 75 mm)
Base Layer Index (BLI)	$\text{BLI} = D_0 - D_{300}$	Gives an indication of primarily the base layer structural condition
Middle Layer Index (MLI)	$\text{MLI} = D_{300} - D_{600}$	Gives an indication of the subbase and probably selected layer structural condition

This simplified FWD based benchmark analysis method also overcomes the need for expert knowledge and associated analysis techniques as the deflection bowl parameters are calculated via simple or standard spreadsheet calculations from the measured deflection bowls (TRH12, 1997; Horak et al., 2015). This benchmark methodology also demonstrated that the inherent knowledge of the whole deflection bowl can be used effectively for structural evaluations in an initial or preliminary analysis stage (Horak et al., 2015). Table 2.3 illustrates the different deflection bowl parameter relationships yielded from the regression analysis done by Horak and Khumalo (2006).

Table 2.3: Deflection Bowl Parameter Relationships from Regression Analysis (Horak and Khumalo, 2006).

Deflection Bowl Parameter	FWD Settings	LFWD Settings	Correlation Formula	Correlation Coefficient (R^2)
Ymax	40 kN	20 kg, 200 mm	$Ymax_{(FWD)} = -127.43 + 2.08\ Ymax_{(LFWD)}$	0.58
MLI	25 kN	20 kg, 200 mm	$MLI_{(FWD)} = 22.63 + 1.58\ MLI_{(LFWD)}$	0.97
BLI	25 kN	20 kg, 200 mm	$BLI_{(FWD)} = 103.1 + 0.3\ BLI_{(LFWD)}$	0.28
RoC	25 kN	20 kg, 200 mm	$RoC_{(FWD)} = 76.2 + 0.55\ RoC_{(LFWD)}$	0.78
SD	40 kN	20 kg, 200 mm	$SD_{(FWD)} = 0.82 + 1.3\ SD_{(LFWD)}$	0.37
F1	25 kN	20 kg, 200 mm	$F1_{(FWD)} = 0.4 + 0.15\ F1_{(LFWD)}$	0.96

2.3.2 Asphalt Joints

Du Terte et al. (2010) investigated whether a non-destructive portable device such as the LFWD would be able to detect whether asphalt joints exhibit any signs of a lower density than the interior portion of the mat.

It was found that the deflection measurements were not only affected by the stiffness of the surface layer but also by the sub-structure of the pavement. It was difficult to identify the quality of the joint which is confined to the wearing course. Although the possibility to determine the asphalt joint quality by means of a LFWD exists, further research is required to estimate the contribution of the sub layers to the deflection measurements.

2.4 EXISTING LFWD PROTOCOL

One of the greatest sources of engendering variability within the measurements is attributed to inconsistent operation protocol. Different institutions utilise different protocols for different models of the LFWD. The first step to create reproducible and reliable measurements is to standardise the operation protocol of the LFWD.

2.4.1 LFWD Good Practice Guide

The LFWD Good Practice Guide was published by the Pavement Foundation Group to address the need for consistency in the implementation of LFWD's into international practice. The guide notes that there are differences in manufacture's specifications that can result in differences in the measured surface modulus when comparing data between the different LWD devices (Edwards and

Flemming, 2009). The guide also states that a calibration procedure, in-house or as recommended by the manufacturer, be implemented for each LFWD device.

The Good Practice Guide has been produced as a decision support tool for the operation of the equipment where it also includes guidance on deciding whether the measurements are acceptable based on the deflection signal response. Figure 2.4 illustrates a flow diagram summarising the variables and decision points involved in the LFWD testing.

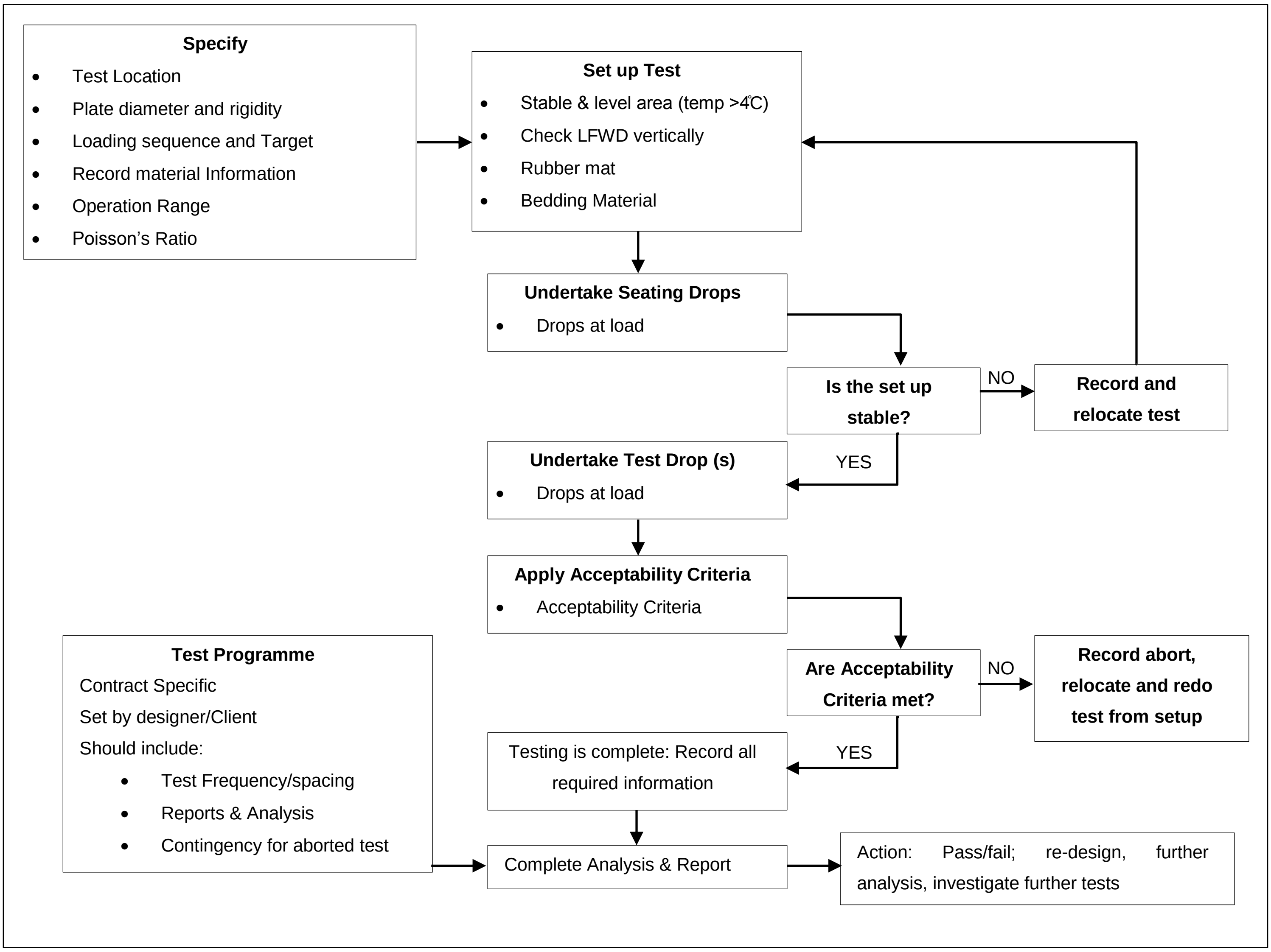

Figure 2.4: Flow diagram for generic LFWD Good Practice Guide (Edwards and Flemming, 2009).

The LFWD Good Practice Guide is seen as a statement of current knowledge that only includes guidance and recommendations for site operations. The guide also affirms that the LFWD operators should have appropriate training and be conversant with the specific LFWD model.

2.4.2 Minnesota Department of Transportation Test Method

The Minnesota Department of Transportation published a LFWD test method specifically for the Zorn (ZFG2000) LFWD model. This test method employs principles from the Good Practice Guide (Section 2.4.1) as well as the standard test method published by the American Society for Testing and Materials (ASTM) (Grading and Base Manual, 2015).

The test method sets out procedures ranging from LFWD configuration, testing constraints, site selection, procedure, maintenance and equipment calibration. It is recommended that the manufacturer's guidance on maintenance and calibration be followed with the appropriate annual certification supplement to the LFWD in-house consistency checks. The LFWD in-house consistency checks are to ensure that the LFWD and measurement system is responding in a repeatable manner on a consistent test surface (Siekmeier et al, 2009).

2.4.3 Challenges Currently Experienced

Due to the fact that the LFWD is still relatively novel technology, there are challenges that need to be overcome for the equipment to become an accepted and reputable quality and acceptance control test procedure during the construction stage.

The biggest challenge with the existing LFWD protocols is to produce reliable and repeatable test measurements. The different LFWD models currently available introduce some variability as no two models will measure the same deflection or surface modulus at the same location. This issue has been partially addressed by the publication of the LFWD (Zorn model) test method by the Minnesota Department of Transportation. The need therefore arises to implement a standardised test and calibration method for each of the LFWD models in order to yield similar reliable and repeatable measurements between the different LFWD models (Edwards and Flemming, 2009).

The availability of the LFWD equipment also poses as a hindrance as the equipment is not readily available to be used on any construction site, not to mention the availability of a preferred LFWD model. This challenge will be mitigated in due time as the LFWD research increases and the test procedure becomes more widely accepted as a reputable quality and acceptance control test procedure (Grading and Base Manual, 2015).

Other challenges include the variable material characteristics of the different pavement layers being tested. Each region and country has their own unique material classification system and conditions. Minnesota Department of Transportation have devised anticipated surface modulus target values for each material class and condition for the ZORN LFWD model. Each region or country with different material classes should ideally also determine anticipated surface modulus target values for the specific LFWD model (Tan et al., 2014).

The opportunity exists to contribute directly to flexible pavement quality and acceptance control procedures that are utilised on construction sites. The tests are non-destructive and not time consuming. Due to mobility of the LFWD a significant amount of test measurements are able to be taken ensuring a considerable distribution and sample size.

2.5 PAVEMENT MATERIAL PROPERTIES

2.5.1 Material Properties

Materials get distinguished from one another by their inherent material properties or characteristics. These material properties constitute a fundamental part of pavement engineering. These characteristics are determined through laboratory tests such as:

- Sieve analysis (grading);
- Atterberg indicator tests;
- Volumetric properties such as Apparent Relative Density (ARD), Bulk Relative Density (BRD) and water absorption;
- Gravimetric properties characterised through Maximum Dry Density (MDD) and Optimum Moisture Content (OMC), and
- California Bearing Ratio (CBR) of the material.

The fundamental characteristics and properties as determined from the tests above are utilised to classify a material into a specific group of which the behaviour and limitations when used in a pavement structure can be deduced (TRH14, 1985; TRH4, 1996).

SANRAL has recently endeavoured to compile and publish a 'Best Practice Guideline' for pavement engineering in the South African roads industry called the South African Pavement Engineering Manual (SAPEM) which covers all aspects of pavement design. It also details information on general materials and testing relating to material types in pavement structures (SAPEM, 2014). These tests as set out in SAPEM will become the South African standard reference for general statements regarding pavements.

2.5.2 Materials Classification

2.5.2.1 Conventional Classification

According to TRH4 (1996) and TRH14 (1985), materials can be classified according to their fundamental behaviour and strength characteristics. Unbound granular material is classified from G1 to G10 according to its fundamental behaviour and strength characteristics.

A G1 quality material is usually obtained from crushing solid unweathered quarried, mine rock or boulders. It is defined as a “graded crushed stone”. G2 and G3 quality material may contain natural fines not derived from crushing the parent rock and are usually obtained by the same process as a G1 quality material. G4, G5 and G6 quality material are defined as “natural gravel or mixture of natural gravel and boulders which may require crushing’. Any of these materials may be modified using additives such as cement, lime, bitumen or polymers in order to enhance certain strength characteristics of the material. G7, G8, G9 and G10 quality material are defined as gravel-soil (TRH14, 1985).

Table 2.4 shows an abbreviated summary of the criteria used to classify unbound granular materials in terms of TRH4 and TRH14, as well as indicating the approximate similar AASHTO classification for the same material.

Table 2.4: Abbreviated summary of Granular Materials as per TRH4 (1996), TRH14 (1985) and AASHTO (1928) classification system.

General Definition	Classification (TRH4 and TRH14)	Abbreviated Specifications	Approximate AASHTO Classifications
Crushed Material	G1	Maximum size 37.5 mm	A-1-a A-1-b A-3
		86 – 88% apparent relative density	
		Soil fines PI < 4	
	G2	Maximum size 37.5 mm	
		100 – 102% Mod AASHTO or 85% bulk relative density	
		Soil fines PI < 6	
	G3	Maximum size 37.5 mm	
		98 – 100% Mod AASHTO	
		Soil fines PI < 6	
Natural Material	G4	Minimum CBR = 80% @ 98% Mod AASHTO	A-2-4 A-2-5 A-2-6 A-4 A-5
		Maximum size 37.5 mm	
		98 – 100% Mod AASHTO	
		Soil fines PI < 6 (PI ≤ 8 for calcrete)	
		Maximum swell 0.2% @ 100% Mod AASHTO	
	G5	Minimum CBR = 45% @ 95% Mod AASHTO	
		Maximum size 63.0 mm or 2/3 of layer thickness	
		Density as prescribed	
		Soil fines PI < 10	
		Maximum swell 0.5% @ 100% Mod AASHTO	
	G6	Minimum CBR = 25% @ 95% Mod AASHTO	
		Maximum size 63.0 mm or 2/3 of layer thickness	
		Density as prescribed	
		Soil fines PI < 12 or 3GM+10	
		Maximum swell 1.5% @ 100% Mod AASHTO	
	G7	Minimum CBR = 15% @ 93% Mod AASHTO	A-2-6 A-2-7 A-6 A-7-5 A-7-6
		Maximum size 2/3 of layer thickness	
		Density as prescribed	
		Soil fines PI < 12 or 3GM+10	
		Maximum swell 1.5% @ 100% Mod AASHTO	

	G8	Minimum CBR = 7% @ 93% Mod AASHTO	
		Maximum size 2/3 of layer thickness	
		Density as prescribed	
		Soil fines PI < 12 or 3GM+10	
		Maximum swell 1.5% @ 100% Mod AASHTO	
	G9	Minimum CBR = 7% @ 93% Mod AASHTO	
		Maximum size 2/3 of layer thickness	
		Density as prescribed	
		Soil fines PI < 12 or 3GM+10	
		Maximum swell 1.5% @ 100% Mod AASHTO	
	G10	Minimum CBR = 3% @Mod AASHTO	
		Maximum size 2/3 of layer thickness	
		Density as prescribed or 90% Mod AASHTO	

2.5.2.2 Design Equivalent Material Classification (DEMAC)

The object of this method is to provide a reliable, rational and consistent indication of the appropriate material class. The method is based on the use of all available information, and uses fuzzy logic and uncertainty theory to assess the certainty that materials belong to a particular class. Although the method was specifically developed for use in the structural design method for pavements that incorporate Bituminous Stabilised Materials (BSMs) the approach can be used in any pavement design context with all common material types, and is especially relevant for rehabilitation design (TG2, 2009).

The material classification system provides for granular and cement stabilised materials adopted for this material classification method are aligned with TRH14 (1985). The TRH14 classification system is regarded as being highly suitable for new construction and rehabilitation design, as the behaviour and performance patterns of each material class is known with some certainty. However, with the design equivalent material classification method, the design equivalent materials class (DEMAC) and will not necessarily meet the specifications for that material class as given in TRH14. However, since materials to which design equivalent classes are assigned have been in service for some time, the raw material would conform to (or exceed) the specifications for the class, as stated in TRH14, in almost all instances (TG2, 2009).

When a DEMAC is assigned to a material, it implies that the material exhibits in situ shear strength, stiffness and flexibility properties similar to those of a newly constructed material of the same class. The outcome of the assessment becomes more reliable as more tests indicators are added to the assessment. This is because each test typically explains only a small part of the material behaviour. More complex tests, like triaxial tests, may evaluate cohesive or frictional elements together, but will do so only for a specific moisture or bitumen. The use of other indicators will still be required to determine how a material will behave if the moisture state or bitumen content varies (TG2, 2009).The system is therefore a holistic assessment, which works best when a comprehensive range of test indicators are used.

The DEMAC system allows the pavement materials of the constructed pavement structure to be evaluated and classed according to their in-situ properties and behaviour, while the TRH14 classification system considers each pavement layer individually and relies on the pass or fails type criteria. The DEMAC system will also benefit by using the LFWD deflections as an additional test indicator.

2.5.3 Resilient Response

2.5.3.1 Basic Definitions

In order to avoid the misunderstanding of terms in the following sections, the basic mechanics and material definitions must be defined. These are as follow:

Elasticity, stress and strain

Elasticity is the physical property of a material by which it returns to its original dimensions during unloading (i.e. the removal of stress) (Gere, 2001). Stress is defined by the force exerted on a specific area, while strain is the ratio of the deformation per unit of the original length at infinitely small scale (Gere, 2001; Dawson, 2009).

Stiffness

Stiffness is the resistance of a body to deformation by an applied force. Elastic modulus is sometimes used as an indication of the stiffness of a material (Gere, 2001).

Resilience

Resilience represents the ability of a material to absorb and release energy within the elastic range of that material (Gere, 2001).

Elastic modulus / Hooke's Law

The Elastic modulus or the modulus of elasticity is described by Hooke's Law. The law describes the elastic modulus through the equation $\sigma = E(\epsilon)$ in which σ is stress, € is strain and E a constant of proportionality known as modulus of elasticity. It defines the linear relationship between applied loads (stress) and resulting elongation (strain). Figure 2.5 to follow illustrates the stress strain relationship dictated by Hooke's Law.

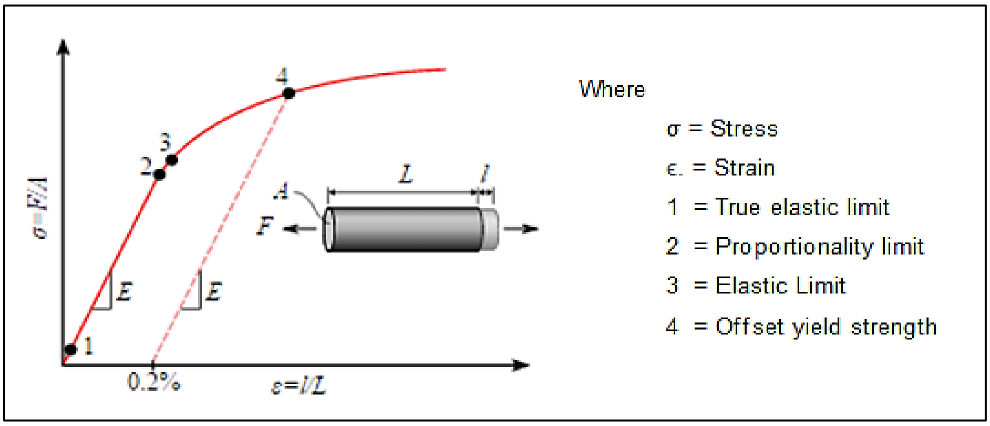

Figure 2.5: Stress strain curve for nonferrous alloys (Gere, 2001).

The strain is directly proportional to stress throughout a materials elastic range, i.e. for stresses below the proportionality limit. Number 3 from Figure 2.5 denotes the elastic limit after which permanent deformation takes place until the material yields at number 4 on the curve. The position of numbers 1 to 4 on the stress strain curve is determined by the curve dimensions with increasing stress (Gere, 2001).

Young's modulus

Several parameters measuring the strength of materials arise from the generalised Hooke's Law such as Young's Modulus, Bulk Modulus (K) and Shear Modulus (G) (De Beer and Maina, 2008). Even though strength does not necessary equal stiffness, in the context of this study, the pavement strength makes reference to the elastic modulus response properties, i.e. stiffness.

Young's Modulus is often incorrectly also termed the elastic modulus or the modulus of elasticity. Young's Modulus describes the response of a material to linear strain (De Beer and Maina, 2008).

The bulk modulus is defined as the increase in pressure required resulting in a given relative decrease in volume. It measures the resistance of a substance to uniform compression (response of a material to uniform pressure) (De Beer and Maina, 2008).

The shear modulus is sometimes referred to as the modulus of rigidity and is defined as the ratio of shear stress to shear strain. In the case of road pavement materials, shear modulus is concerned with the deformation of a solid when it experiences a force parallel to one of its surfaces while its opposite face experiences an opposing force, such as friction (De Beer and Maina, 2008).

Poisson's Ratio

Poisson's ratio is the ratio of lateral strain to axial strain caused by a load parallel to the axis in which axial strain is measured (Yoder and Witczak, 1975; De Beer and Maina, 2008). For a perfectly incompressible material such as rubber, which deforms elastically at small strains, Poisson's ratio is exactly 0.5 (De Beer and Maina, 2008).

2.5.3.2 Resilient Response for Flexible pavement design.

The theory of elasticity in flexible pavement design assumes that all materials in the pavement structure are homogeneous, isotropic and linear elastic. Based on this theory, Poisson's ratio and modulus of elasticity would be required to calculate the stresses, strains and deflections in the pavement layers.

The concept of resilient modulus (M_R) for the characterisation of elastic response of subgrade soils in flexible pavements were first introduced by Seed et al. (1962). The resilient Modulus (M_R) is used to define the elastic stiffness of pavement materials and is defined as the repeatedly applied wheel load stress divided by the recoverable strain determined after shakedown of the material (Anochi-Boateng, 2007). The shakedown theory describes the observed permanent behaviour of unbound material and is not specific in terms of the critical parameter that controls the permanent deformation of the material (Theyse, 2006).

2.5.4 Factors influencing resilient response

Factors that affect the resilient behaviour of pavement material are not only limited to the inherent material properties such as strength of aggregate of unbound materials, but also other factors to a varying degree that include the following:

Effect of Stress

Studies concluded that the most significant factor that affects resilient modulus of pavement materials is the level of stress. The resilient modulus of pavement materials (course to fine grained granular materials) was found to increase considerably with the increase in confining pressure and sum of the principal stresses (Van Aswegen, 2013).

Effect of Density

In general, pavement material responds stiffer and stronger with an increase in density. It was also found that with an increase in fines content, density decreased for well graded aggregate (Hicks and Monismith, 1971). The effect of density seems to be less profound at high stress levels than at lower stress levels (Lekarp et al., 2000).

Effect of grading, fines content and maximum grain size

Research has shown that the stiffness of the materials is dependent, to some degree, on the particle size and its distribution. Hicks and Monismith (1971) reported some reduction in resilient modulus with increasing fines content for well-graded partially or uncrushed material, with little to no effect on well-graded crushed material. Jorenby and Hicks (1986) reported initial increase in stiffness followed by a reduction in stiffness when clayey fines were added to well-graded crushed aggregate due to the increased contacts as pore space is filled, followed by the excess fines displacing the coarse particles, ultimately being the particles on which stiffness relies (Lekarp et al., 2000).

Previous researchers could not conclusively prove the influence of grading and maximum grain size of material when these values are within acceptable specification ranges and it is deemed to have minor influence on the stiffness. Various researchers have found that uniformly graded material yielded only slightly stiffer results than well-graded material (Lekarp et al., 2000).

Effect of moisture content

Moisture content has been found to significantly influence pavement material both in in-situ conditions and laboratory conditions. Numerous researchers have reported that the resilient response of dry and most partially saturated materials is similar, and that as saturation increased, especially past the optimum value, resilient response decreased (Lekarp et al., 2000). Another interpretation is that the moisture content determines the level of lubrication of particles which determines how easily deformation can take place, decreasing the resilient modulus (Lekarp et al., 2000). It was also presented that localised pore suction pressure decrease with increased saturation, leading to lower inter particle contact forces (Lekarp et al., 2000; Van Aswegen, 2013).

2.5.5 Current estimated target values related to pavement material properties

The Minnesota Department of Transportation has generated sets of estimated “target values” simulating the expected ranges of measured deflections of the different pavement layers with respective pavement material properties and classifications. The Minnesota Department of Transportation produced target values for two general groups of unbound materials during pavement construction, namely, granular and fine grained (Grading and Base Manual, 2015).

2.5.5.1 Granular Material Target Values

The grading numbers and moisture contents were used to select the appropriate target values for each compacted granular material. A sieve analysis was used to determine the grading number and an oven dry test was typically performed to determine the moisture content. The Grading Number (GN) is a method utilised by the Minnesota Department of Transportation which represents the sum of the percentages of particles passing each sieve. The GN concept was derived from the Fineness Modulus (FM) equation, which is used in concrete mix design. The GN formula is quite similar in format, although it uses the percentage passing each sieve in the calculation (Oman, 2004). The GN formula is illustrated in the equation to follow:

$$GN_{(\%\ \text{Passing})} = \frac{25mm+19mm+9.5mm+4.75mm+2.0mm+0.425mm+0.075mm}{100} \quad \text{Equation 2-17}$$

If 100% of the material passes each of the sieves listed in the equation above, the GN reaches its maximum value of 7.0 which represents an extremely fine gradation. Conversely, if 0% passes all of the sieves, the GN falls to its lowest value of 0.0 representing tremendous coarse material (Oman, 2004). In order to relate and compare the Minnesota Department of Transportation's LFWD target surface modulus values with the South African target values, it would be a requirement to establish a similar grading number sieve analysis with the South African pavement layers being tested.

Table 2.4 illustrates the estimated Dynatest LFWD target values according to each material's grading number and moisture content. The moduli were calculated using a Poisson's ratio of 0.35 and a plate rigidity of 0.79 (Davich et al., 2006). The Zorn LFWD target values shown in Table 2.5 have these two constants set by the manufacturer with a Poisson's ratio of 0.5 and a plate rigidity of 1.0). The difference between the two LFWDs has a direct effect on the calculated moduli (Grading and Base Manual, 2015).

Table 2.5: Minnesota Department of Transportation LFWD Target values for granular materials (Siekmeier et al., 2009).

Grading Number	Moisture Content	Target LFWD Modulus (Dynatest)	Target LFWD Modulus (Zorn)
GN	%	MPa	MPa
3.1 to 3.5	5 to 7	120	80
	7 to 9	100	67
	9 to 11	75	50
3.6 to 4.0	5 to 7	120	80
	7 to 9	80	53
	9 to 11	63	42
4.1 to 4.5	5 to 7	92	62
	7 to 9	71	47
	9 to 11	57	38
4.6 to 5.0	5 to 7	80	53
	7 to 9	63	42
	9 to 11	52	35
5.1 to 5.5	5 to 7	71	47
	7 to 9	57	38
	9 to 11	48	32
5.6 to 6.0	5 to 7	63	42
	7 to 9	50	33
	9 to 11	43	29

2.5.5.2 Fine Grained Material Target Values

The plastic limit and moisture content were used to determine the LFWD target values when evaluating the compacted condition of the fine grained pavement material. In this case, the plastic limit was used instead of the grading number to classify the soil. For fine grained soils, a sieve analysis and a hydrometer test were deemed not viable. The plastic limit test determines when a soil changes from a plastic to a solid-like consistency and is defined as the moisture content at which the soil begins to crumble when it is rolled into a three millimetre thread. Table 2.6 shows the estimated target LFWD deflection values for fine grained soils (Tan et al., 2014).

Table 2.6: Minnesota Department of Transportation LFWD Target values for fine grained materials (Siekmeier et al., 2009).

Plastic Limit	Estimated Optimum Moisture Content	Field Moisture as % of Optimum Moisture	(ZORN) LFWD Deflection Target at field moisture MIN	(ZORN) LFWD Deflection Target at field moisture MAX
%	%	%	mm	mm
Non-Plastic	10 to 14	70 to 74	0.5	1.1
		75 to 79	0.6	1.2
		80 to 84	0.7	1.3
		85 to 89	0.8	1.4
		90 to 94	1.0	1.6
15 to 19	10 to 14	70 to 74	0.5	1.1
		75 to 79	0.6	1.2
		80 to 84	0.7	1.3
		85 to 89	0.8	1.4
		90 to 94	1.0	1.6
20 to 24	15 to 19	70 to 74	0.8	1.4
		75 to 79	0.9	1.6
		80 to 84	1.0	1.7
		85 to 89	1.2	1.9
		90 to 94	1.4	2.1
25 to 29	20 to 24	70 to 74	1.0	1.7
		75 to 79	1.2	1.9
		80 to 84	1.4	2.1
		85 to 89	1.6	2.3
		90 to 94	1.8	2.6
30 to 34	25 to 29	70 to 74	1.3	2.0
		75 to 79	1.5	2.2
		80 to 84	1.7	2.4
		85 to 89	1.9	2.7
		90 to 94	2.2	3.0

Although the fine grained material target values are representative of the Zorn LFWD model, it still provides an indication of the affect that moisture has on the deflection and consequently the stiffness of the fine grained material.

2.6 SUMMARY

The literature study investigates the development and history of the LFWD, existing correlation and protocol studies and the review of literature related to fundamental knowledge regarding pavement material properties.

There are several types of LFWDs currently available on the market. These LFWDs have different features that cause measurement variances between the devices. Some of these device features may include its physical characteristics, the deflection accelerometer instrument and the algorithm utilised to determine the energy transferred to the ground (Siekmeier et al., 2009). This research was based on the deflection measurements performed using the Dynatest 3031 LFWD device (Dynatest, 2014) as this is the device that is available to the author.

The Dynatest LWDmod software uses Odemark's layer transformation approach together with Boussinesq's equations in order to forward-calculate deflections. Odemark's layer transformation's basic assumption is that the layered structure can be transformed into an equivalent uniform, semi-infinite material, whereby Boussinesq's equations can be utilised to calculate deflections.

There has been extensive LFWD correlation studies and research done in the past ten years. Some of the most prominent correlation studies include that with non-destructive testing tools (NDT) such as the FWD, the DCP, the Static Plate Loading Test (SPLT), the RCCD, the PSPA and the CIST. There is consensus among researchers that all relationships between the different testing tools were extremely dependent on the material type and layer thickness. The SPLT and the FWD is regarded as the most appropriate NDT tool in relation to the LFWD (Guiamba, 2011).

FWD deflection bowl slope parameters have a well-established track record of application at project level as well as at network level as a pavement structural analysis benchmark method (Zhang et al., 2003; Horak and Emery, 2006; Zhang et al., 2011). The benchmark analysis methodology developed in South Africa makes use of the FWD deflection bowls measured on flexible pavements with simple spreadsheet calculations to derive deflection bowl parameters (Horak et al., 2015).

The biggest challenge with the existing LFWD protocols is to produce reliable and repeatable test measurements. The different LFWD models currently available introduce some variability as no two models will measure the same deflection or surface modulus. This issue has been partially addressed by the publication of the LFWD (Zorn model) test method by the Minnesota Department of Transportation. The need therefore arises to implement a standardised test method for each of the LFWD models in order to yield similar reliable and repeatable measurements (Edwards and Flemming, 2009).

The opportunity exists to contribute directly to flexible pavement quality and acceptance control procedures that are utilised on construction sites. The tests are non-destructive and not time consuming. Due to mobility of the LFWD a significant amount of test measurements are able to be taken ensuring a considerable distribution and sample size.

Materials get distinguished from one another by their inherent material properties or characteristics. Some of these material properties constitute a fundamental part of pavement engineering. The fundamental characteristics and properties are utilised to classify a material into a specific group of which the behaviour and limitations when used in a pavement structure can be deduced

(TRH14, 1985) and (TRH4, 1996). Unbound granular material is classified from G1 to G10 according to its fundamental behaviour and strength characteristics (TRH4, 1996, TRH14, 1985).

Factors that affect the resilient behaviour of pavement material are not only limited to the inherent material properties such as strength of aggregate of unbound materials, but also other factors to a varying degree that include the effect of stress, density, grading and moisture content (Lekarp et al., 2000; Van Aswegen, 2013).

The Minnesota Department of Transportation has generated sets of estimated "target values" simulating the expected ranges of measured deflections of the different pavement layer with respective pavement material properties and classifications. The grading numbers and moisture contents were used to select the appropriate target values for each compacted granular material, while the plastic limit and moisture content were used to determine the LFWD target values when evaluating the compacted condition of the fine grained pavement material.

These target values, similar to benchmark methodology, act as a screening tool for evaluation of pavement layers after construction to identify areas of potential structural defects. Such areas and zones identified can then be analysed in more detail via various other means.

2.7 REFERENCES

Abu-Farsakh, M., Alshibli, K., Nazzal, M. and Seyman, E. (2004). *'Assessment of In-situ Test Technology for Construction Control of Base Courses and Embankments*'. Louisiana Transportation Research Centre, Federal Highway Administration.

American Association for Highway Transportation Officials (AASHTO), (1928), M 145 or ASTM D3282, U.S.A.

Anochie-Boateng, J.K. (2007). *'Advance Testing and Characterisation of Transportation Soils and Bituminous Sands'*, PhD dissertation, University of Illinois, Urbana, U.S.A.

Apeagyei, A.K. and Hossain, M.S. (2010). *'Stiffness-Based Evaluation of Base and Subgrade Quality using Three Portable Devices'*, proceedings of the 89th Transportation Research Board (TRB) Annual Meeting, January 10 -14 2010, Washington. U.S.A.

Davich, P., Camargo, F., Larsen, B., Roberson, R. and Siekmeier, J. (2006). *'Validation of DCP and LWD Moisture Specifications for Granular Materials'*, Minnesota Department of Transport, Minnesota, U.S.A.

Dawson, A. (2009). *'Water in Road Structures - Movement, Drainage and Effects'*, Geotechnical, Geological and Earthquake Engineering, Volume 5, Springer Science and Business Media B.V. (Based on WATMOVE study reported as COST Action No. 351).

De Beer, M. and Maina, J. (2008). *'Some Fundamental Definitions of the Elastic Parameters for Homogeneous Isotropic Linear Elastic Materials in Pavement Design and Analysis'*, proceedings of the 27th South African Transport Conference (SATC), July 2008, Pretoria, South Africa.

Du Tertre, A., Cascante, G. and Tighe, S.L. (2010). *'Combining PFWD and Surface wave Measurements for Evaluation of Longitudinal Joints in Asphalt Pavements'*, proceedings of the 89th Transportation Research Board (TRB) Annual Meeting, January 10 -14 2010, Washington. U.S.A.

Dynatest (2014). *'Dynatest 3031 Light Weight Deflectometer (LWD)'*, www.dynatest.com, (5 May 2014).

Edwards, P. and Flemming, P. (2009). *'LWD Good Practice Guide (Draft 9)'*, Pavement Foundation Group (PFG), Minnesota, U.S.A.

Embacher, R.A. (2007). *'Intelligent Compaction and Lightweight Deflectometer Technology Transfer Workshop'*, IC and LWD Workshop, Minnesota Department of Transport, Minnesota, U.S.A.

Embacher, R.A. (2008). *'LWD Fundamentals'*, proceedings of the 12th Annual Minnesota Paving Conference, February 2008, Minnesota, U.S.A.

Flemming, P. (2008). *'Intelligent Compaction and Lightweight Deflectometer Technology Transfer Workshop',* IC and LWD Workshop, Minnesota Department of Transport, Minnesota, U.S.A.

Flemming, P.R., Frost, M.W and Lambert, J.P. (2007). *'A Review of the Lightweight Deflectometer (LWD) for Routine In-situ Assessment of Pavement Material Stiffness'*, proceedings of the 86th Transportation Research Board (TRB) Annual Meeting, July 7 -9 2007, Washington.

Gere, J.M. (2001). *'Mechanics of materials'*, Fifth Edition, Brooks/Cole, U.S.A.

Grading and Base Manual (2015). 'Minnesota Department of Transport : Grading and base manual', Geotechnical Section, Minnesota Department of Transport, Minnesota, U.S.A.

Guiamba, D.Z. (2011). *'Comparitive study of non-destructive field testing devices on bitumen emulsion stabilised materials'*, MSc. Thesis, University of Pretoria, Pretoria, South Africa.

Hicks, R.G. and Monismith, C.L. (1971). *'Factors influencing the resilient properties of granular materials'*, Transportation Research Record 345, Transportation Research Board (TRB), Washington, U.S.A.

Highways Department (2000). *'Guidance notes on backcalculation of layer moduli and estimation of residual life using falling weight deflectometer test data'*, Research and Development Division, Hong Kong, China.

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.

Horak, E. (2007). *'Surface Moduli Determined with the falling weight deflectometer used as a benchmarking tool*, proceedings of the 26th South African Transport Conference (SATC), July 2007, Pretoria, South Africa.

Horak, E. (2008). *'Benchmarking the structural condition of flexible pavements with deflection bowl parameters'*, Journal of the South African Institute of Civil Engineering, Vol. 50, No 2, June, pp 2-9.

Horak, E. and Emery, S. (2006). *'Falling Weight Deflectometer Bowl Parameters as an analysis tool for pavement structural evaluations'*, proceedings of the 22nd Australian Road Research Board (ARRB) International Conference, October 2006, Brisbane, Australia.

Horak, E. and Emery, S. (2009). *'Evaluation of airport pavements with FWD deflection bowl parameter benchmarking methodology'*, 2nd European Airport Pavement Workshop, 13-14 May 2009, Amsterdam, Netherlands.

Horak, E., Emery, S. and Maina, J. (2015). *'Review of FWD benchmark analysis on road and runways'*, proceedings of the 11th South African Conference on Asphalt Pavements (CAPSA), August 2015, Sun City, South Africa.

Horak, E., Hefer, A. and Maina, J. (2015).*'Determining pavement number values for flexible pavements utilising falling weight deflectometer deflection bowl information'*, proceedings of the 34th South African Transport Conference (SATC), July 2015, Pretoria, South Africa.

Horak, E. and Khumalo, T. (2006). *'Deflection bowl parameters correlation of a light and standard falling weight* deflectometer', proceedings of the 4th South African Road Federation (SARF) / International Road Federation (IRF), September 2006, Durban, South Africa.

Horak, E., Maina, J., Guiamba, D. and Hartman, A. (2008). *'Correlation study with the light weight deflectometer in South Africa'*, proceedings of the 27th South African Transport Conference (SATC), July 2008, Pretoria, South Africa.

Jorenby, B. N., and Hicks, R. J. (1986). *'Base Course Contamination Limits'*, Transportation Research Record 1095, TRB, National Research Council, Washington, U.S.A., pp. 86–101.

Lekarp, F., Isacsson, U. and Dawson, A. (2000). *'State of the art I : Resilient response of unbound aggregates'*, Journal of Transportation Engineering, Volume 126, No. 1, January / February, 2000, pp 66-75.

Lindemann, M., 2014. *'Nuclear Vs. Non-nuclear testing and transition development of curves'*, proceedings of the 93rd annual meeting of the Western Association of State Highway and Transportation Officials (WASHTO), New Mexico, U.S.A.

Mork, H. (2008). *'Light Weight Deflectometer, principles and Versatility'*, proceedings at the NVF/BRA Symposium, February 2008, Oslo, Norway.

Nazzal, M. (2003). *'Field Evaluation of - Test Technology QC/QA during Construction of Pavement Layers and Embankments'*, MSc Thesis, Louisiana State University, Louisiana, U.S.A.

Odemark, N., (1949). “Investigations as to the elasticity properties of soils and design of pavements according to the theory of elasticity.” Report No,77, Statens Vaeginstitut, Stockholm, Sweden.

Oman, M. (2004). *‘Advancement of grading and base material testing’*, Minnesota Department of Transportation, Minnesota, U.S.A.

Petersen, J.S., Romanoschi, S.A., Onyango, M. and Hossain, M. (2007). *‘Evaluation of Prima Light FWD as a Quality Control Tool for the Compaction of Fine Grained Soils’*, proceedings of the 86th Transportation Research Board (TRB) Annual Meeting, January 21 -25 2007, Washington. U.S.A.

Pronk, A. (1994). *‘Equivalent Layer Theories: State of the Art Report’*, Dienst Weg en Waterboukunde (DWW), Delft, Netherlands.

SAPEM (2014). *‘South African Design Manual (SAPEM)’*, Second Edition, March 2014, South African National Roads Agency SOC Ltd (SANRAL), Pretoria, South Africa.

Seed, H.C., Chan, C.K. and Lee, C.E. (1962). *‘Resilient characteristics of subgrade soils and their relation to fatigue failures in asphalt pavements’*, proceedings of International Conference on Structural Design of Asphalt Pavements, University of Michigan, U.S.A.

Siddiki, N. (2012). *‘Light Weight Deflectometer’*, Worksop, Office of Geotechnical Services, Indiana Department of Transportation, Indiana, U.S.A.

Siekmeier, J., Pinta, C., Merth, S., Jensen, J., Davich, P., Camargo, F. and Beyer, M. (2009). *‘Using the Dynamic Cone Penetrometer and Light Weight Deflectometer for Construction Quality Assurance’*, Report no. MN/RC 2009-12, Minnesota Department of Transport, Minnesota, U.S.A.

Stamp, D.H. and Mooney, M.A. (2013). *‘Influence of Lightweight Deflectometer Characteristics on Deflection Measurement’*, Geotechnical Testing Journal, Vol. 36, No. 2, 2013, pp. 216–226, doi:10.1520/GTJ20120034. ISSN 0149-6115.

Tan, D., Hill, K. and Khazanovich, L. (2014), *‘Quantifying Moisture Effects in DCP and LWD Tests Using Unsaturated Mechanics’*, Minnesota Department of Transport, Minnesota, U.S.A.

Tan, D.J., Khazanovich, L., Siekmeier, J. and Hill, K.M. (2014). *‘Discrete Element Modelling of the Effect of Moisture and Fine Particles in the Light Weight Deflectometer Test’*, proceedings of the 93rd Transportation Research Board (TRB) Annual Meeting, January 12 -16 2014, Washington. U.S.A.

TG 2 (2009). *'Technical Guideline 2: Bitumen Stabilised Materials'*, Second Edition, May 2009, Asphalt Academy, Pretoria, South Africa.

Theyse, H. (2006). *'The Suction Pressure, Yield Strength and Effective Stress of Partially Saturated Unbound Granular Pavement Layers'*, CSIR Built Environment, Pretoria, South Africa.

TRH 14 (1985). *'TRH 14 : Guidelines for road construction materials'*, Department of Transport, Pretoria, South Africa.

TRH 4 (1996). *'Draft TRH 4 : Structural design of flexible pavements for interurban and rural roads'*, Department of Transport, Pretoria, South Africa.

TRH 12 (1997). *'Draft TRH 12 : Flexible pavement rehabilitation investigation and design'*, Department of Transport, Pretoria, South Africa.

Ullidtz, P. (1987). *'Pavement Analysis'*, Elsevier Science, New York, U.S.A.

Ullidtz, P. (2005). *'Modelling Flexible Pavement response and Performance'*, ISBN 8750208055, Elsevier, New York, 2005.

Ullidtz, P., Krakup, J. and Wahlman, T. (1994). *'Verification of pavement response models'*, Non-destructive testing of pavements and backcalculation of moduli (Second Volume), ASTM STP 1198, American Society for Testing and Materials (ASTM), Philadelphia, U.S.A.

Van Aswegen, E. (2013). *'Effect of Density and Moisture Content on the Resilient Response of Unbound Granular Material'*, PhD dissertation, University of Pretoria, Pretoria, South Africa.

Yoder, E.J. and Witczak, M.K. (1975). *'Principles of Pavement Design'*, Second Edition, John Wiley and Sons.

Zhang, J. (2010). *'Evaluation of Mechanistic based compaction measurements for earthwork QC/QA'*, MSc Thesis, Iowa State University, Iowa, U.S.A.

Zhang, Z., Claros, G., Manual, L. and Damnjavonic, I. (2003). *'Evaluation of the pavement structural condition at network level using falling weight deflectometer (FWD) data'*, Paper presented at 82nd Transportation Research Board (TRB) Annual Meeting, January 12 -16 2003, Washington, U.S.A.

Zhang, Z., Murphy, M.R. and Peddidhotla (2011). '*Implementation study of a structural condition index at the network level'*, proceedings of the 8th International Conference on Managing Pavement Assets (ICMPA), Paper ICPMA145, November 15 – 19 November 2011, Santiago, Chile.

3 METHODOLOGY

3.1 INTRODUCTION

In terms of the problem statement, study objectives and the scope of the study, the intention is to establish a reliable relationship or model to predict or monitor the basic material characteristics of constructed single pavement layers (granular, soil or lightly cemented) in a practical engineering quality control application. This chapter presents the methodology followed for further development and refinement of such a model.

3.2 RESEARCH DESIGN

3.2.1 Problem statement and study objectives

The problem statement of this study is as follows: The influence of material characteristics / parameters of constructed pavement layers on the measured LFWD stiffness.

The objectives of the study are to investigate the influence of various parameters on the surface moduli and deflection bowl parameters yielded by the LFWD and to establish a reliable relationship between LFWD stiffness results, deflection bowl parameters and other pavement material parameters. The ensuing intention is to accurately predict the model or monitor the basic material characteristics and enhance standard construction quality control testing in a practical engineering quality control application.

3.2.2 Process applied to problem statement

The LFWD measurements were conducted with the Dynatest 3031 LFWD device in accordance with a preliminary LFWD operation protocol as described in Chapter 3.3. The recorded deflection measurements from the LFWD are utilised to determine the approximate surface modulus of each layer.

The LFWD test measurements were recorded on a variety of newly constructed pavement layers on four distinct sites, namely, Waterkloof Air Force Base (WAFB), Walvis Bay Airport in Namibia, the R104 near Bronkhorstspruit, and the R23 near Greylingstad. The locality of the test sites are indicated in Figure 3.1. These four different site locations were selected in order to obtain a variety of construction sites with varying test conditions, climatic and material conditions. WAFB site was selected because it was constructed with conventional pavement layers and materials. Walvis Bay Airport site was selected due to the different climatic and material conditions. The R104 was selected because of the variety of unconventional pavement layers constructed. The R23 Greylingstad site was selected to test newly paved asphalt layer in a quality control application.

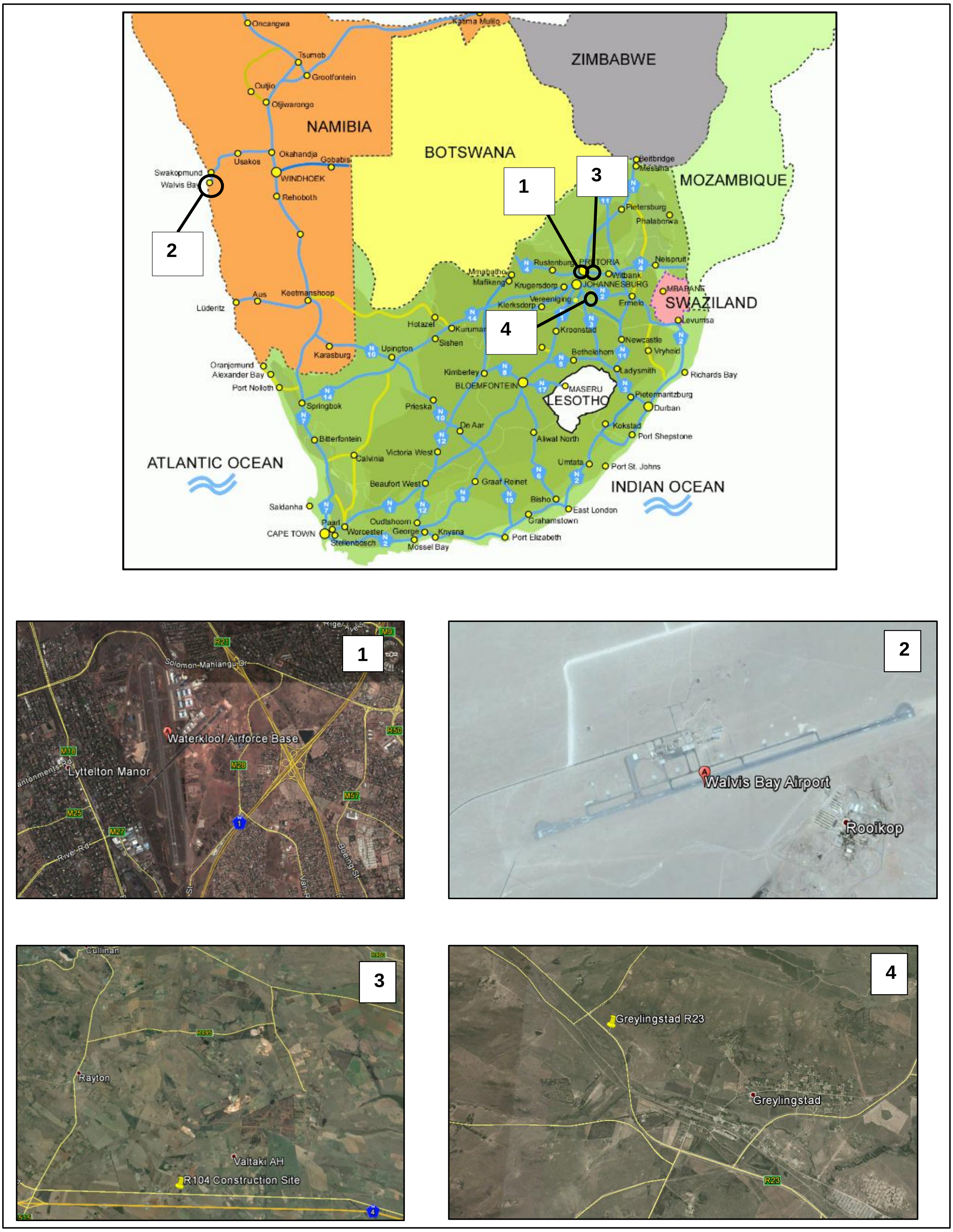

Figure 3.1: Locality Map of Testing Sites.

Laboratory tests were conducted on all of the newly constructed pavement layers on the WAFB site only. These tests included routine laboratory tests (according to TMH1 (1986)).

3.3 METHODOLOGY

3.3.1 Research instruments

This research was based on the deflection measurements performed using the Dynatest 3031 LFWD device. The LFWD operation protocol is discussed in more detail in the following section.

Routine laboratory tests were conducted on the WAFB site's newly constructed pavement layers on the same positions where the LFWD measurements were recorded. Such routine tests included Atterberg indicators, volumetric properties, gravimetric properties, and compaction characteristics to name a few, which are discussed in Section 3.3.2.2.

3.3.1.1 LFWD operation protocol

LFWD devices are configured and used differently depending on the model and testing standards applied (Grading and Base Manual, 2015). The Minnesota Department of Transportation and the American Society for Testing and Materials (ASTM) recently published a national standard for the operation of the LFWD with a load cell. There is currently however, no South African National Standard for the operation and data analysis of the LFWD for South African conditions.

The Dynatest 3031 LFWD operation protocol employed for this study is based on the research done at the Minnesota Department of Transportation and the American Society for Testing and Materials (ASTM).

The LFWD configuration must be consistent for the entire testing phase. The following fundamental configuration was employed for this study:

Diameter of bearing weight: 200 mm (contact pressure of 312 kPa)

Drop weight: 10 kg

Drop height: 850 mm

Positions of the Geophones: Under the point of loading and at 300 mm and 600 mm offsets

The following represents the testing protocol employed during the collection of data for this study:

I. Prior to placing the LFWD on the material to be tested, the surface must first be levelled. Particularly loose or rutted surface material was removed from the surface;
II. Assemble the LFWD and turn it on;
III. Turn on the PDA and load the appropriate program;
IV. Configure the LFWD as above;

V. Lift the weight until it connects with the trigger mechanism;

VI. Release the trigger mechanism while holding the top of the guide rod to prevent the instrument from moving;

VII. Perform three seating drops to ensure that plastic deformation of the surface material does not affect the measurements;

VIII. Repeat steps [V] and [VI] until at least four tests have been performed, and

IX. Move to the next testing location.

The LFWD deflection measurements must be screened by eliminating any clear and obvious test inaccuracies by inspecting the PDA directly subsequent to each drop. Figure 3.2 shows the typical signal responses that an LFWD operator would be expected to see under different circumstances which could be used in identifying obvious inaccuracies. These obvious inaccuracies may be due to additional seating, movement of the LFWD during the drop or an irregular testing surface. Figures 3.3 and 3.4 illustrate the effect that seating drops have on the test measurements.

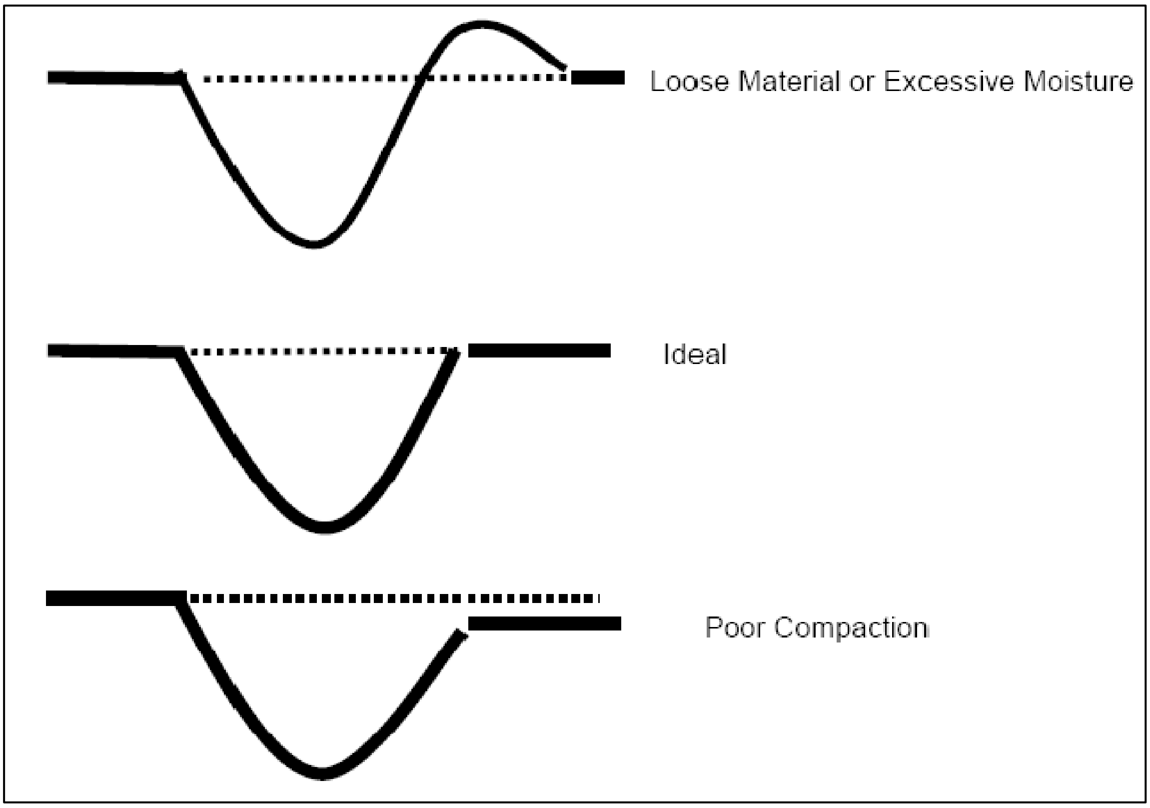

Figure 3.2: Typical LFWD signal responses (Siddiki, 2012).

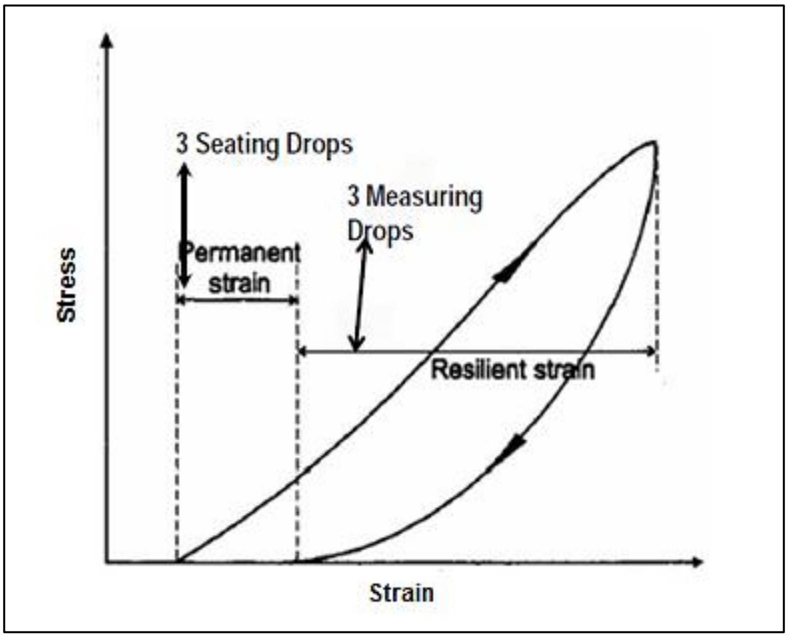

Figure 3.3: Effect of seating drops on deflection measurements (Siddiki, 2012).

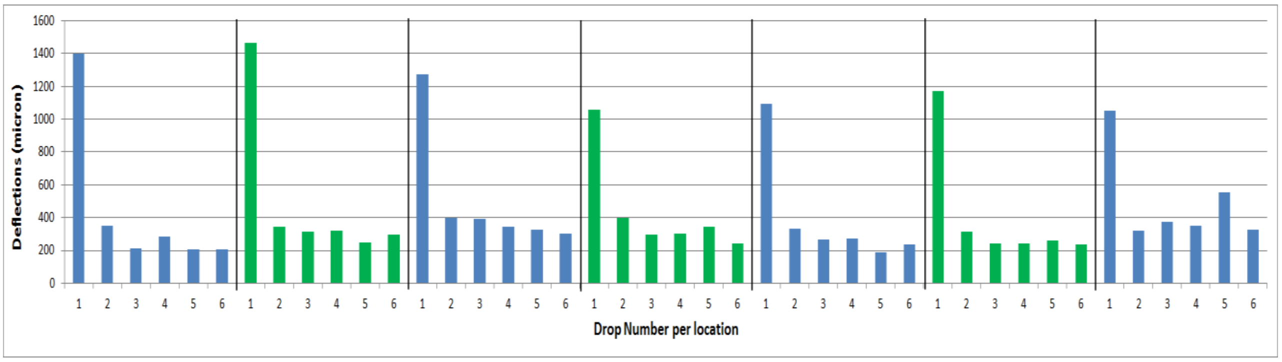

Figure 3.4: Deflection measurements of a G1 Base showing the effect of seating.

If these protocol measures are followed the scatter in results tend to become significantly less. Due to the large inherent variability present within the test measurements, the data have to be statistically screened in order to determine any outliers by utilising Committee of Land Transport Officials (COLTO) Quality Control statistical evaluation techniques (Committee of Land Transport Officials (COLTO), 1998).

Once the outliers have been discarded the data are analysed using statistical evaluation methods. The data are consequently used to do structural and material layer evaluation by various means.

The LFWD device should not be used when temperatures fall below 5°C to ensure that the device's components, particularly the rubber buffers, work as intended. There is no practical upper limit on the temperature. The LFWD must be regularly calibrated to ensure that the device yields accurate and relevant deflection measurements. The Minnesota Department of Transportation recommends calibration to take place on a yearly to two yearly basis depending on the frequency of use (Siekmeier et al., 2009).

Further details of the operation protocol are presented in Appendix A.

3.3.2 Data

The data for this thesis were obtained through LFWD field measurements and laboratory testing. Due to the fact that the stiffness of the supporting layers affects the stiffness of the following layer, it is assumed that all supporting layers satisfy the intended design specifications. Only summaries of data are given where relevant to discussion in Chapters 4 to 6. Complete result sets are contained in the Appendices referred to in the relevant sections.

Continued quality control was done throughout the period of LFWD and laboratory testing to ensure that no errors due to operator error or equipment failure were translated into the data obtained.

The respective sample sizes and number of test locations for the different sites are shown in Table 3.1.

Table 3.1: Sample sizes of LFWD research sites.

DESCRIPTION	WAFB	WALVIS BAY AIRPORT	R104	R23
Number of Points	2 250	600	2 140	672
Locations	450	140	428	112

3.3.2.1 LFWD data screening

The LFWD deflection measurements must be screened by eliminating any clear and obvious test inaccuracies. These clear and obvious inaccuracies as illustrated in the prior section can be detected immediately after the test by inspecting the PDA unit. Outliers can only be identified and eliminated when statistical evaluation methods are applied.

3.3.2.2 Routine testing

Routine laboratory testing was done to describe the pavement layer characteristics of the sampled layers. These tests include:

- Sieve analysis to determine the particle size distribution of the material;
- Atterberg indicator tests to characterise the fine fraction of the material;
- Compaction characteristics;
- Volumetric properties characterised through Apparent Relative Density and Bulk Relative Density (ARD and BRD) and water absorption;

- Gravimetric properties characterised through maximum dry density and optimum moisture content (OMC and MDD) using the Mod AASHTO method, and
- California Bearing Ratio (CBR) of the pavement layer;

3.3.3 Analysis

3.3.3.1 Outlier Identification

Data obtained were analysed using statistical methods. Due to the large inherent variability present within the test measurements, the data had to be statistically screened in order to determine any outliers by utilising Equation 3-1. The value of T_0 was compared to the critical value (T) for each sample size. When the absolute value of T_0 was greater than T, then x_0 was considered to be an outlier and excluded from further analysis (Committee of Land Transport Officials (COLTO), 1998). Further details regarding outlier identification are discussed in Section 4.2.1.

$$T_0 = \frac{X0 - \overline{x}}{Sn} \qquad \text{Equation 3-1}$$

Where:

n = sample size

Sn = sample standard deviation

T_0 = outlier indicator

X_0 = value of the test result differing most from the mean

$\overline{x}$= arithmetic mean

3.3.3.2 Deflection Bowl Parameters and Surface Modulus

The deflection bowl parameters are typically used with the FWD data, however, could also be utilised for the interpretation of LFWD data. The LFWD deflection measurements are consequently utilised to calculate the main deflection bowl parameters as well as the surface modulus of each testing location as discussed in Section 2.2 and 2.3. The depth of influence of the LFWD limits it to structural condition evaluation to a typical single layer between 200 mm and 300 mm with confidence.

3.3.3.3 Viability of Back-calculation of the LFWD Data

Back-calculation is a mechanistic evaluation of pavement surface deflection basins typically generated by the FWD device. Back-calculation uses a measured surface deflection and attempts to match it with a calculated surface deflection generated from an identical pavement structure using assumed layer surface moduli. The assumed layer surface moduli in the calculated model are adjusted until they produce a surface deflection that closely matches the measured one. The combination of assumed layer surface moduli that results in this match is then assumed to be near the actual in situ moduli for the various pavement layers. The back-calculation process is usually iterative and normally done with computer software. It is highly dependent on the accurate layer thickness determination. The latter vary over length and width of normal pavement structures and is acknowledged as a major reason for variability in derived effective elastic moduli.

There are inherent inaccuracies with the back-calculation of the FWD deflection measurements however it is widely accepted and used within the industry. The use of back-calculation of the LFWD is still largely uncharted and would introduce too great unknowns and new variables that will detract the study from achieving its primary objective. The lower impulse load and limited geophone offset measurements restricts the effective depth of the LFWD whereby making it not a good instrument for such back-analysis procedures. Therefore the LFWD data will not be back-analysed and falls out of the scope for this study.

3.3.3.4 Benchmark Methodology

The well-known Red, Amber, Green (RAG) condition rating system, often applied in Pavement Management Systems (PMS) and pavement condition ratings, is utilised in this simplified deflection bowl parameter and surface modulus benchmark evaluation. RAG represents red for severe condition, amber for warning condition and green for sound condition. The criteria for the RAG relative structural condition states are based on a semi-empirical model which provides for accurate benchmark or relative evaluation of pavement structural capability (Horak and Emery, 2006; Horak, 2008; Horak et al., 2015).

These criteria are based on an extension downwards of criteria used with the FWD based on contact pressure versus deflection. The higher contact pressures achievable with variable weight drop versus deflections measured formed the basis of RAG criteria developed for roads and airports (Horak and Khumalo, 2006; Horak, 2008; Horak et al., 2015).

3.3.4 Fundamental considerations as quality assurance instrument

Previous studies (Guiamba, 2011) have concentrated on correlations between various non-destructive evaluation tools and found that the variation in results produced very weak correlations. This is due to a number of reasons. Lack of a consistent operation protocol, seating problems, surface unevenness and normal variation in LFWD results are clearly contributors. This made it difficult to use the LFWD as a quality assurance tool. Another methodology which concentrates on the material properties before it actually reaches the specified density therefore had to be found. It is also not feasible to do back-analysis with the LFWD results due to the limited depth of influence. Therefore the attempt was made to rather use a relative or benchmark methodology at the region of density below specified density, on density and above specified density. In this way the industry norm of using density as a primary quality control tool could then be possibly correlated with LFWD output for the fuller range of densities and not just after specified density was achieved.

The ensuing intention of this study is to accurately predict the model or monitor the basic material characteristics and enhance standard construction quality control testing in a practical engineering quality control application. In order to achieve this goal the LFWD deflection measurements and subsequent output parameters need to be related and compared to a minimum design / performance specification of the pavement layer. Due to the lack of an established South African LFWD operation and analysis protocol, the most reliable measurements are the deflection measurements which can accurately be used to calculate the BLI, the maximum deflection and the surface modulus of the tested pavement layer.

It is important to note that the surface modulus values calculated with FWD data will be different from the surface modulus calculated from the LFWD when tested on the same material layer. Therefore the LFWD surface modulus measurements cannot be directly related to a specified design stiffness of a pavement layer. The relative compaction of specific pavement layers can however be compared to the LFWD surface modulus measurements in order to establish a relationship between the two parameters to ascertain when a specific relative compaction has been achieved to act as an supplementary quality control and assurance tool.

The most effective way to utilise the LFWD measurements at this stage however, is to use it as a benchmarking tool, hence, a first step screening tool in identifying areas or zones of distress in a newly constructed pavement layer.

3.4 LIMITATIONS

The limitations of this study are briefly discussed in this section.

3.4.1 Light Falling Weight Deflectometer

Due to the fact that the LFWD is relatively new to quality and acceptance control testing, there are inherent limitations to the testing equipment and protocol. Limitations that are expected for this study include the following:

LFWD Operation Protocol

Because no South African national standard for the operation and data analysis of the LFWD for South African conditions currently exist, an operation protocol was established using similar industry standards and procedures from different countries and different testing and material conditions. This operation protocol will most probably intermittently yield unexplainable measurements during the course of this study. Therefore, the limitations of the utilised LFWD protocol can only be identified and consequently mitigated as further LFWD test measurements are done.

Behaviour of test measurements on different materials

Different pavement materials will yield different signal responses and deflections. The ambiguity is specifically presented when very stiff pavement layers are tested such as heavily stabilised layers, concrete - and asphalt layers. The deflection measurements will yield surface moduli that will be so high that no useful conclusion can be made from it. Therefore, the recommended practical maximum stiffness value of the Dynatest 3031 LFWD device is 1 000 MPa which relates to a centre deflection value of approximately 35 micron.

3.4.2 Laboratory Testing

There should not be any limitations to the laboratory testing as all of the tests being done are regulated and accredited by the South African National Accreditation System (SANAS). The only error that might arise from the laboratory testing could be attributed to the sampling and transport of the samples, however, duplicated samples have been taken to ensure that the test results are consistent and accurate.

3.4.3 Analysis

Analysis through statistical methods is widely recognised. However, the extent to which obtained results can be used to generalise conclusions is limited, since it is only applied to a limited data set. With more comprehensive data available, the analysis could be more refined and more general conclusions can be drawn. Nonetheless, the data range of materials was sufficient for adequate analysis to reach a conclusion in terms of the problem statement and objectives.

3.4.4 Conclusion

The methodology described in this chapter was used in the remainder of the thesis. Data obtained through the research instruments was analysed according to the methods described. More detail of the analysis will be given in the chapter to follow.

3.5 SUMMARY

This chapter presented the methodology followed in order to establish a reliable relationship or model to predict the behaviour of newly constructed single pavement layers in a practical engineering quality control application.

The LFWD deflection measurements were sourced from four distinct sites, exhibiting different testing conditions, climate and pavement materials.

The LFWD operation protocol employed for the recording of deflection measurements originates from the principles employed and recommended by the Minnesota Department of Transportation, the American Society for Testing and Materials (ASTM) and Edwards and Flemming's "LWD Good Practice Guide" (Edwards and Flemming, 2009).

Other sourced data for this study includes routine laboratory testing results of the newly constructed pavement layers at WAFB.

The recorded LFWD deflection measurements and routine laboratory test results will be subject to a series of data analyses which include outlier identification, deflection bowl parameter and surface modulus calculations, benchmark methodology and statistical analysis.

The limits of this study were briefly discussed and distinguished between the LWFD protocol, behaviour of different pavement materials, the routine laboratory testing and data analyses.

3.6 REFERENCES

Committee of Land Transport Officials (COLTO). (1998). *'Standard Specifications for Road and Bridge Works for State Road Authorities'*, South African Institution of Civil Engineering (SAICE), Halfway House, South Africa.

Edwards, P. and Flemming, P. (2009). *'LWD Good Practice Guide (Draft 9)'*, Pavement Foundation Group (PFG), Minnesota, U.S.A.

Grading and Base Manual (2015). 'Minnesota Department of Transport : Grading and base manual', Geotechnical Section, Minnesota Department of Transport, Minnesota, U.S.A.

Guiamba, D.Z. (2011). *'Comparitive study of non-destructive field testing devices on bitumen emulsion stabilised materials'*, MSc. Thesis, University of Pretoria, Pretoria, South Africa.

Horak, E. (2008). *'Benchmarking the structural condition of flexible pavements with deflection bowl parameters'*, Journal of the South African Institute of Civil Engineering, Vol. 50, No 2, June, pp 2-9.

Horak, E. and Emery, S. (2006). *'Falling Weight Deflectometer Bowl Parameters as an analysis tool for pavement structural evaluations'*, proceedings of the 22nd Australian Road Research Board (ARRB) International Conference, October 2006, Brisbane, Australia.

Horak, E., Emery, S. and Maina, J. (2015). *'Review of FWD benchmark analysis on road and runways'*, proceedings of the 11th South African Conference on Asphalt Pavements (CAPSA), August 2015, Sun City, South Africa.

Horak, E., Hefer, A. and Maina, J. (2015).*'Determining pavement number values for flexible pavements utilising falling weight deflectometer deflection bowl information'*, proceedings of the 34th South African Transport Conference (SATC), July 2015, Pretoria, South Africa.

Horak, E. and Khumalo, T. (2006). *'Deflection bowl parameters correlation of a light and standard falling weight* deflectometer', proceedings of the 4th South African Road Federation (SARF) / International Road Federation (IRF), September 2006, Durban, South Africa.

Siddiki, N. (2012). *'Light Weight Deflectometer'*, Worksop, Office of Geotechnical Services, Indiana Department of Transportation, Indiana, U.S.A.

Siekmeier, J., Pinta, C., Merth, S., Jensen, J., Davich, P., Camargo, F. and Beyer, M. (2009). *'Using the Dynamic Cone Penetrometer and Light Weight Deflectometer for Construction Quality Assurance'*, Report no. MN/RC 2009-12, Minnesota Department of Transport, Minnesota, U.S.A.

TMH 1 (1985). *'Technical Methods Highways 1 : Standard test methods for roadbuilding materials'*, Department of Transport, Pretoria, South Africa.

4 DATA VALIDATION

4.1 INTRODUCTION

In this chapter the LFWD deflection measurements and material test results will be explored and validated in order to establish a model to predict the behaviour of newly constructed pavement layers in a practical engineering quality control setting. Only the LFWD deflection measurements recorded at the WAFB site are presented in this chapter in order to illustrate the typical LFWD data sets. The LFWD deflection measurement analyses from all four sites are presented in Chapters 5 and 6.

4.2 LFWD DEFLECTION MEASUREMENTS

Sections 4.2.1 to 4.2.2 contain summaries of the results obtained. Complete result sets are contained in the Appendices referred to in the relevant sections.

4.2.1 LFWD data set

A typical LFWD data set is represented in Table 4.1. This specific data set extract is measurements taken at WAFB on a G1 crushed stone base. Defl. 1, 2 and 3 denotes deflections under the load plate at 0 mm, 300 mm and 600 mm offsets respectively. E_0 represents the surface modulus calculated from Defl. 1. The first drop at each location was removed from the data set due the seating effect of the LFWD loading plate. Complete result sets are contained in Appendix B.

Table 4.1: Typical LFWD data set.

Location / Point Nr	Drop	Contact Pressure (kPa)	Defl. 1 (Micron)	Defl. 2 (Micron)	Defl. 3 (Micron)	Measured E_0 (MPa)
1 + 40	2	145	443	19	8	86
	3	147	418	20	8	93
	4	145	382	16	6	100
	5	144	401	15	6	95
	6	108	312	10	5	91
Average			**391.20**	**16.00**	**6.60**	**93.00**
Standard Deviation			**49.64**	**3.94**	**1.34**	**5.15**
0 + 380	2	146	400	12	6	96
	3	143	395	12	6	95
	4	145	343	13	5	111
	5	145	328	13	5	116
	6	144	303	13	5	125
Average			**353.80**	**12.60**	**5.40**	**108.60**
Standard Deviation			**42.41**	**0.55**	**0.55**	**12.97**
1 + 200	2	146	380	8	4	102
	3	145	418	8	4	91
	4	147	358	6	4	108
	5	148	393	7	4	99
	6	147	395	6	4	98
Average			**388.80**	**7.00**	**4.00**	**99.60**
Standard Deviation			**21.99**	**1.00**	**0.00**	**6.19**

4.2.1.1 Outlier Identification

The data measurements were analysed and checked for any outliers by using the quality control procedure as prescribed in the Standard Specifications for Road and Bridge Works for State Road Authorities published by the Committee of Land Transport Officials (Committee of Land Transport Officials (COLTO), 1998). Equation 4-1 depicts the suitable outlier identification formula. The value of T_0 was compared to the critical value (T) for each sample size. The critical value T for the respective sample sizes are illustrated in Table 4.2. When the absolute value of T_0 was greater than T, then x_0 was considered to be an outlier and excluded from further analysis (Committee of Land Transport Officials (COLTO), 1998; Van As, 2010).

$$T_0 = \frac{X0-\bar{x}}{Sn} \qquad \text{Equation 4-1}$$

Where:

n = sample size

Sn = sample standard deviation

T_0 = outlier indicator

X_0 = value of the test result differing most from the mean

$\bar{x}$= arithmetic mean

Table 4.2: Critical value (T) for the applicable sample size.

Number of observations (n)	Critical Value (T)
4	1.46
5	1.67
6	1.82
7	1.94
8	2.03
9	2.11
10	2.18

Tables 4.3 and 4.4 show a typical LFWD data set with identified outliers. This specific data set extract represents measurements taken at WAFB on a G1 crushed stone base layer.

Table 4.3: Typical LFWD data set with Outliers.

Location / Point Nr	Drop	Contact Pressure (kPa)	Defl. 1 (Micron)	Defl. 2 (Micron)	Defl. 3 (Micron)	Measured E_0 (MPa)
0 + 860	2	145	408	35	13	93
	3	146	391	35	13	99
	4	146	377	27	8	102
	5	147	378	28	8	103
	6	103	286	20	7	95
Average			**368.00**	**29.00**	**9.80**	**113.00**
Standard Deviation			**47.52**	**6.28**	**2.95**	**19.71**
3 + 280	2	147	310	38	14	125
	3	110	226	29	9	127
	4	147	297	25	4	130
	5	109	315	19	4	91
	6	102	293	18	3	92
Average			**288.20**	**25.80**	**6.8**	**113.00**
Standard Deviation			**35.93**	**8.17**	**4.66**	**19.71**

Table 4.4: Typical LFWD data set outlier identification.

Location / Point Nr	Drop	D1 Outlier check		D2 Outlier check		D3 Outlier check	
		T_0	T = 1.67	T_0	T = 1.67	T_0	T = 1.67
0 + 860	2	0.842	No	0.955	No	1.08	No
	3	0.484	No	0.955	No	1.08	No
	4	0.189	No	-0.318	No	-0.61	No
	5	0.210	No	-0.159	No	-0.61	No
	6	**-1.723**	**Yes**	-0.432	No	-0.95	No
Location / Point Nr	**Drop**	**D1 Outlier check**		**D2 Outlier check**		**D3 Outlier check**	
		T_0	T = 1.67	T_0	T = 1.67	T_0	T = 1.67
3 + 280	2	0.61	No	1.49	No	1.55	No
	3	**-1.73**	**Yes**	0.39	No	0.47	No
	4	0.24	No	-0.10	No	-0.60	No
	5	0.75	No	-0.83	No	-0.60	No
	6	0.13	No	-0.96	No	-0.82	No

The LFWD data measurements identified as outliers are consequently removed and excluded from any further data analysis.

4.2.2 Deflection bowl parameter and surface modulus modelling

The deflection bowl parameters and surface modulus are calculated by using the processed LFWD data measurements. The deflection bowl parameters relevant to the LFWD are the Base Layer Index (BLI), Middle Layer Index (MLI), Maximum deflection and the Radius of Curvature (RoC) which are represented by Equations 4-2 to 4-4 (Horak and Emery, 2006).

$$BLI = D_0 - D_{300} \qquad \text{Equation 4-2}$$

Where:

BLI = Base Layer Index (micron)

D_0= Deflection measured under the point of loading (micron)

D_{300} = Deflection measured at an offset of 300 mm from the point of loading (micron)

$$MLI = D_{300} - D_{600} \qquad \text{Equation 4-3}$$

Where:

MLI = Middle Layer Index measured in micron (micron)

D_{300} = Deflection measured at an offset of 300 mm from the point of loading (micron)

D_{600} = Deflection measured at an offset of 600 mm from the point of loading (micron)

It is important to note that with the lower load application of the LFWD, the depth of influence of the deflection induced by the manually dropped weight is limited. Therefore the reliability of the MLI deflection measurements is suspect (Horak et al., 2015).

$$R_oC = \frac{L^2}{2D0\left[\left(\frac{D0}{D300}\right)-1\right]} \qquad \text{Equation 4-4}$$

Where:

RoC = Radius of Curcature (m)

L = 300 mm for LFWD

D_0= Deflection measured under the point of loading (micron)

D_{300} = Deflection measured at an offset of 300 mm from the point of loading (micron)

The surface modulus at the centre of the loading plate is determined using Equation 4-5 (Ullidtz, 1987; Guiamba, 2011).

$$E = \frac{f \times (1-v^2) \times \sigma \times a}{\delta c} \qquad \text{Equation 4-5}$$

Where:

E = Surface Modulus

v = Poisson's ratio (default: 0.5)

σ = Applied stress at surface (kPa)

a = Radius of loading plate (mm)

δ_c = Centre deflection (micron)

f = Factor that depends on the stress distribution

Uniform: f = 2 (default)

Rigid plate: f = π/2

Parabolic, granular: f = 8/3

Parabolic, cohesive: f = 4/3

Table 4.5 illustrates typical deflection bowl parameters and calculated surface moduli for a granular base. This specific data set depicts results from measurements taken at WAFB on a G1 crushed stone base layer. Complete result sets are contained in Appendix C.

Table 4.5: Typical deflection bowl parameter and calculated surface moduli results.

Location / Point Nr	Surface Modulus (MPa)	BLI (Micron)	MLI (Micron)	RoC (m)	Max Deflection (Micron)
0+540	142.90	218.20	6.40	206.23	256
0+600	106.25	273.80	6.20	164.35	376
0+660	130.32	210.00	4.20	214.29	254
0+10	164.08	174.00	4.00	258.62	215
0+20	125.72	233.80	4.40	192.47	273
0+30	163.83	176.60	5.60	254.81	218
0+40	90.34	334.00	2.80	134.73	428
0+60	141.97	209.00	3.35	215.31	233
0+80	108.04	256.00	2.00	175.78	313
0+100	89.16	290.25	1.00	155.04	355
0+120	135.36	218.40	3.75	206.04	234
0+140	117.76	224.80	2.40	200.18	295
0+160	152.48	197.20	2.60	228.19	250

Figures 4.1 to 4.5 illustrate typical deflection bowl parameters and surface moduli for the G1 crushed stone base layer.

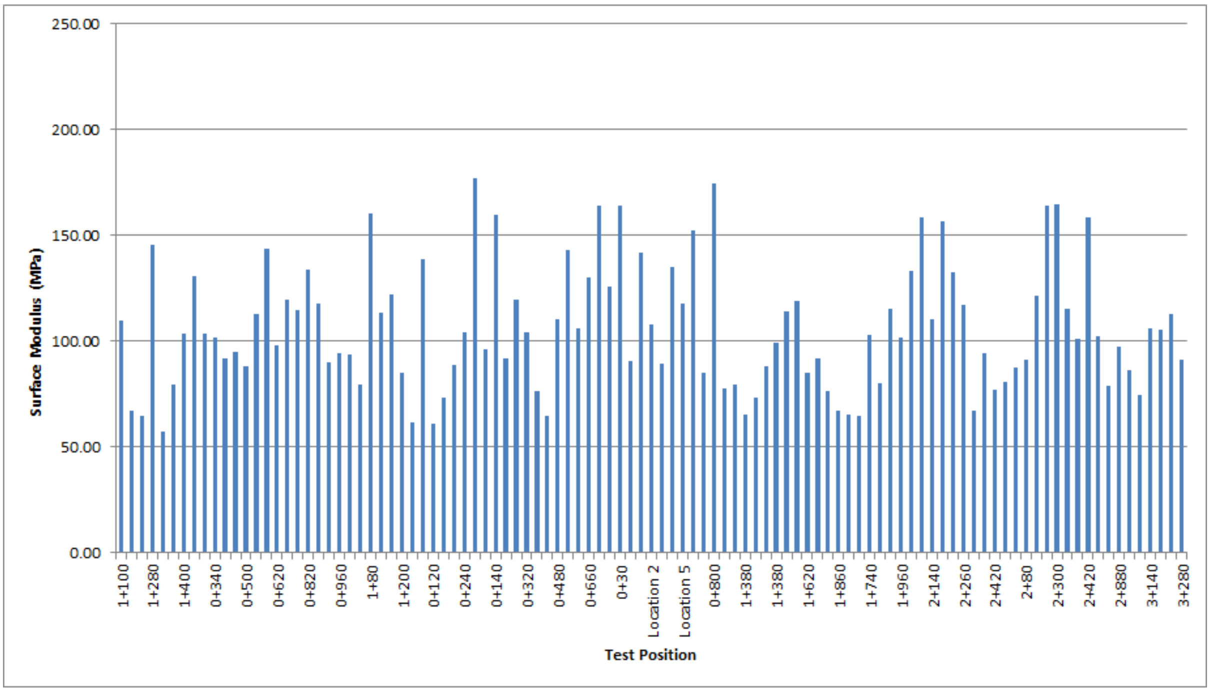

Figure 4.1:Typical Surface Modulus results of G1 base layer.

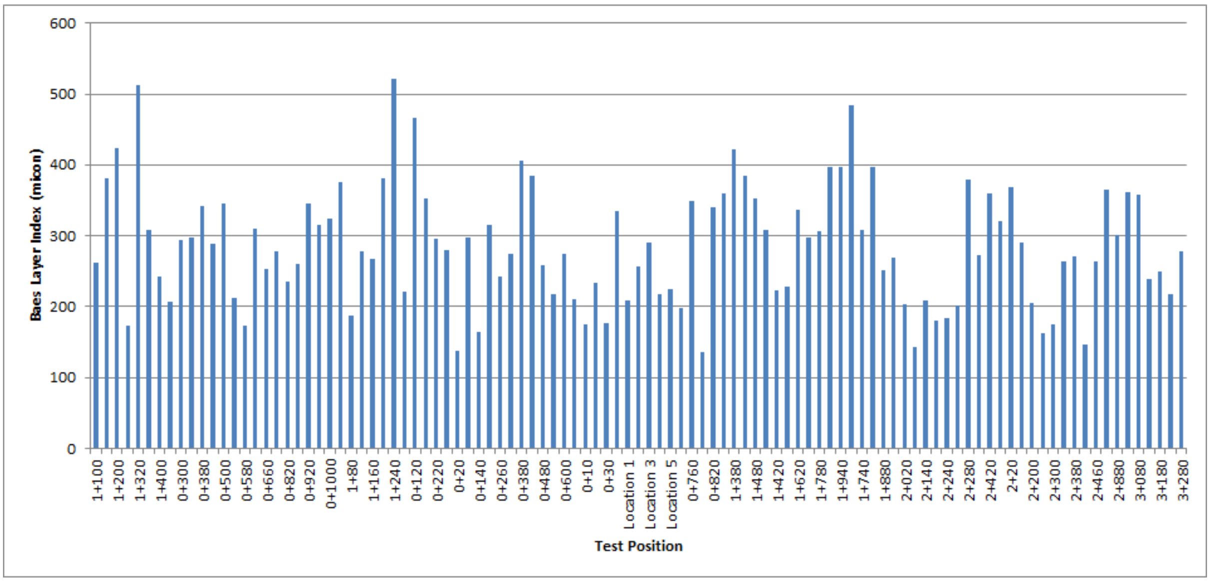

Figure 4.2: Typical BLI results of G1 base layer.

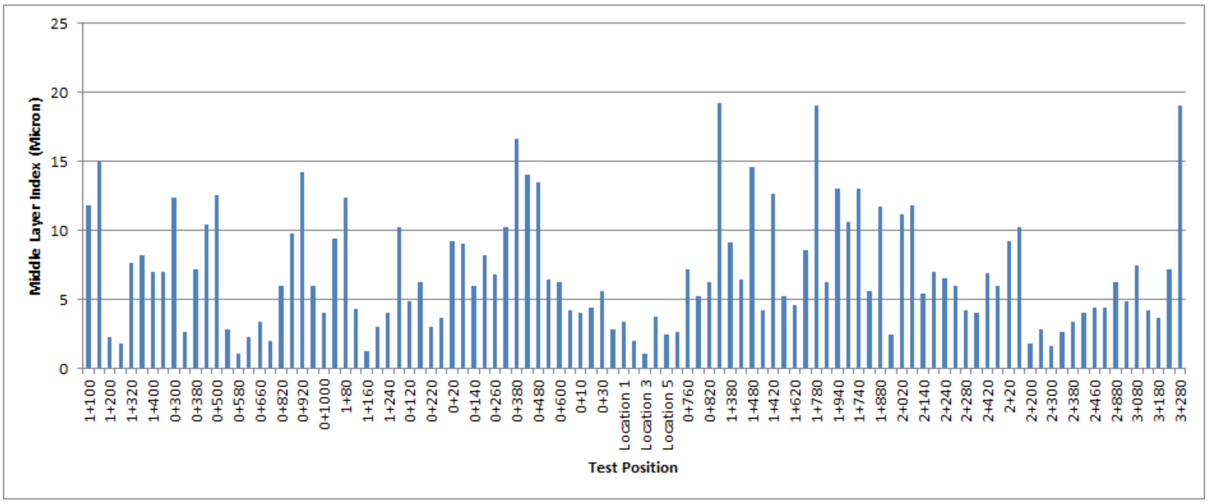

Figure 4.3: Typical MLI results of G1 base layer.

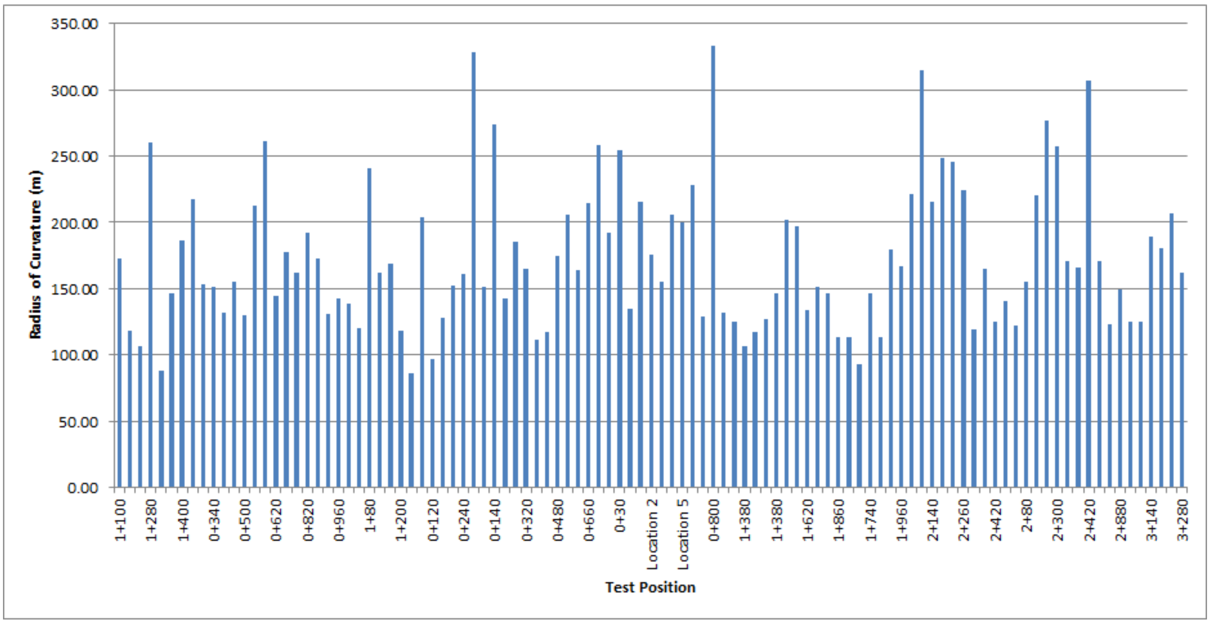

Figure 4.4: Typical RoC results of G1 base layer.

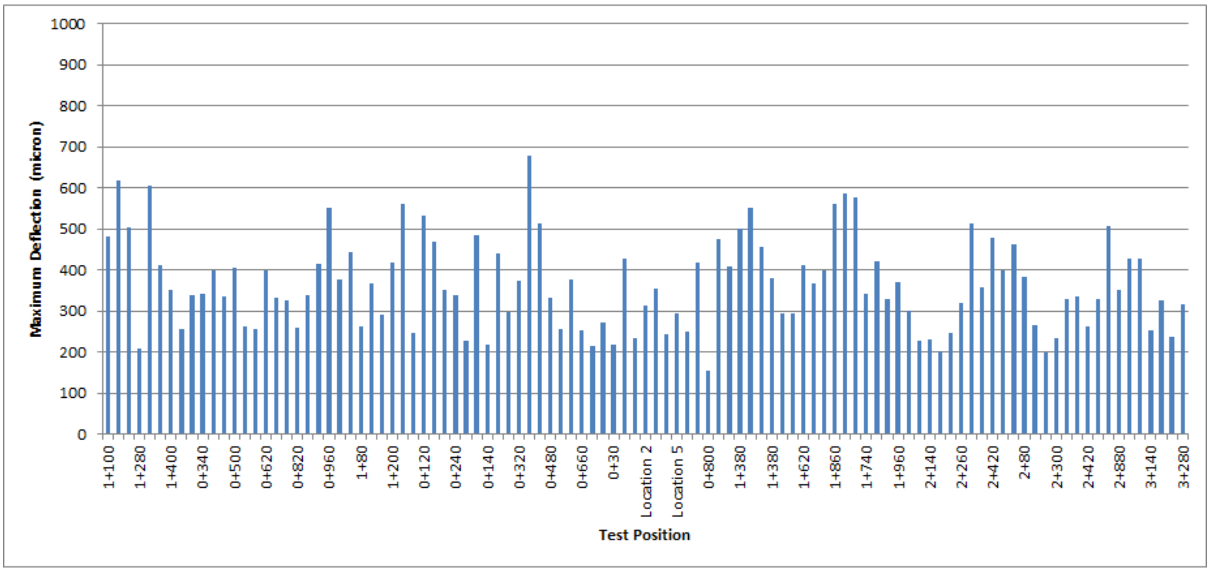

Figure 4.5: Typical maximum deflection results of G1 base layer.

4.3 MATERIAL TEST RESULTS

The material test results obtained for this study are representative of newly constructed pavement layers at WAFB. Complete result sets are contained in Appendix D.

4.3.1 Routine test results

Routine material test results were obtained for the G1 crushed stone base layer, granular sub-base layer, upper-selected layer and for a fill pavement layer. Table 4.6 illustrates typical routine material test results for the G1 crushed stone base obtained at WAFB.

Table 4.6: Typical Routine material test results at WAFB for G1 base layer.

Test Ref.	PI	ARD (kg/m^3)	OMC$_{mod}$ (%)	Compaction %
B002	NP	2811	3.2	87.7
B004	NP	2812	2.3	87.3
B005	NP	2814	2.1	89.0
B006	NP	2806	2.1	87.8
B007	NP	2819	2.3	88.4
B008	NP	2805	1.8	89.0
B009	NP	2823	2.5	88.2
B010	NP	2801	1.5	89.4
B011	NP	2762	2.5	88.1
B012	NP	2802	2.1	88.7
B013	NP	2798	1.7	87.1
B014	NP	2760	2.8	89.4
B016	NP	2779	1.2	88.5
Average	**NP**	**2799.4**	**2.16**	**88.4**
PI	**Plasticity Index**			
ARD	**Apparent Relative Density**			
OMC$_{mod}$	**Mod AASHTHO optimum moisture content**			
Compaction %	**Relative compaction (ARD)**			

Figure 4.6 depicts the typical grading results of the sampled G1 base layer at WAFB. The results appear reasonable and within the expected limits for the type of material tested.

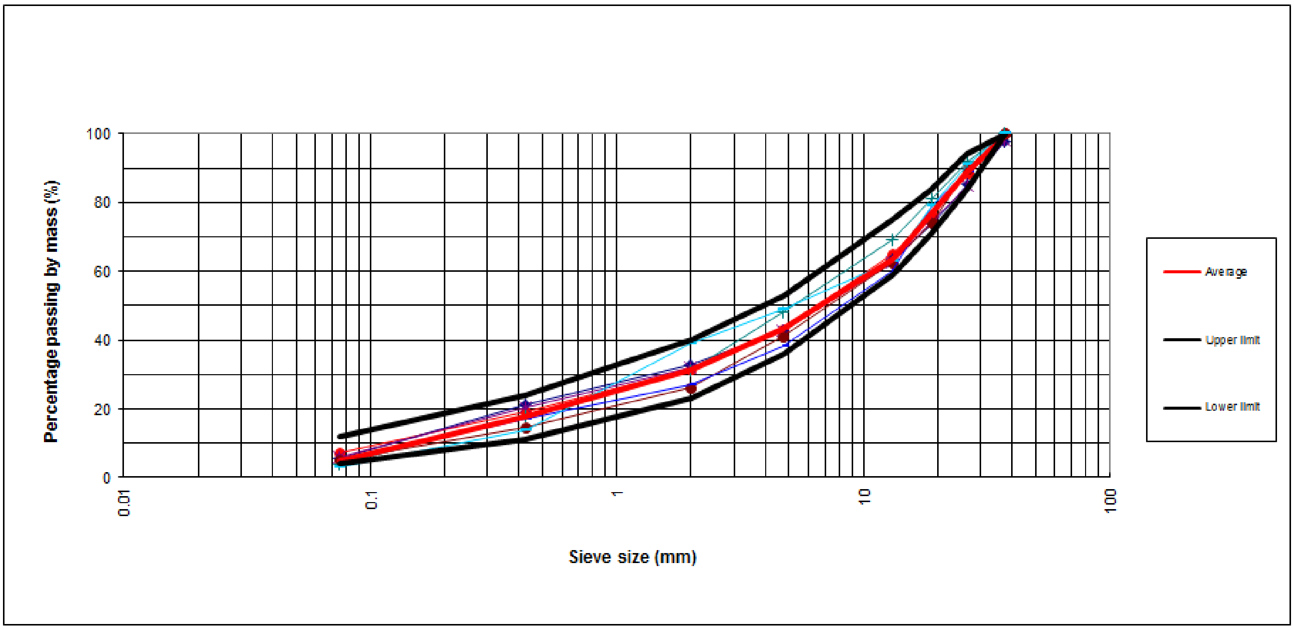

Figure 4.6: Typical Grading of G1 base layer at WAFB.

4.4 SUMMARY

This chapter comprised of investigating and validating the LFWD deflection measurements in order to establish a quality control model to predict the behaviour of newly constructed pavement layers. Only the LFWD deflection measurements recorded at the WAFB site are presented in this chapter in order to illustrate the typical LFWD data sets. The procedure to manage outliers in the LFWD data set was described and illustrated.

The processed LFWD deflection measurements are consequently utilised to calculate the deflection bowl parameters and surface moduli. Typical deflection bowl parameters and surface modulus results were illustrated for a G1 base layer recorded at WAFB.

Typical G1 base layer routine material test results were also depicted for a G1 base layer sampled at WAFB. The Grading analysis for the pavement layer was also illustrated.

These typical data sets shown in this chapter merely illustrated the available LFWD data measurements available for this study as well as the data processing and analysis procedure.

4.5 REFERENCES

Committee of Land Transport Officials (COLTO). (1998). *'Standard Specifications for Road and Bridge Works for State Road Authorities'*, South African Institution of Civil Engineering (SAICE), Halfway House, South Africa.

Guiamba, D.Z. (2011). *'Comparitive study of non-destructive field testing devices on bitumen emulsion stabilised materials'*, MSc. Thesis, University of Pretoria, Pretoria, South Africa.

Horak, E. and Emery, S. (2006). *'Falling Weight Deflectometer Bowl Parameters as an analysis tool for pavement structural evaluations'*, proceedings of the 22nd Australian Road Research Board (ARRB) International Conference, October 2006, Brisbane, Australia.

Horak, E., Emery, S. and Maina, J. (2015). *'Review of FWD benchmark analysis on road and runways'*, proceedings of the 11th South African Conference on Asphalt Pavements (CAPSA), August 2015, Sun City, South Africa.

Ullidtz, P. (1987). *'Pavement Analysis'*, Elsevier Science, New York, U.S.A.

Van As, S. (2010). *'Applied Statistics for Civil Engineers'*, B.Eng Honours course material, University of Pretoria, Pretoria, South Africa.

5 DATA ANALYSIS AND MODELLING

5.1 INTRODUCTION

In this chapter the test results for the different sites are analysed and interpreted. The test results comprise that of LFWD deflection measurements and routine material test results.

5.2 ANALYSIS OF LFWD DEFLECTION MEASUREMENTS

The Dynatest 3031 LFWD device was utilised to collect deflection measurements on four distinct construction sites. Complete results sets are contained in Appendix C and D.

5.2.1 WAFB

LFWD deflection measurements were recorded on four newly constructed pavement layers. These pavement layers consist of a G1 quality crushed stone base, G4 quality granular sub-base, G6 quality granular selected layer and G8/10 quality fill layers. For each of these newly constructed pavement layers, routine material quality control tests were also conducted.

The LFWD deflection measurements were utilised to determine the deflection bowl parameters and surface moduli of each newly constructed pavement layer. The routine quality control material test results, specifically the compaction density, were consequently correlated with the deflection bowl parameters and surface moduli in order to determine whether a relationship exits.

5.2.1.1 G1 Crushed stone base layer

Even though the MLI deflection bowl parameter can be calculated as illustrated in Section 4.3, the shallow depth of influence of the LFWD signifies that the MLI deflection measurements will not yield accurate or reliable information. Therefore, the only deflection bowl parameters that will be calculated further in this study are the BLI and RoC. The surface modulus is also used as a useful indicator of the pavement performance when correlated with the relative compaction of the newly constructed pavement layers.

Figures 5.1 to 5.3 illustrate the relationship between the BLI, RoC and the surface modulus with the relative compaction of the G1 crushed stone base layer.

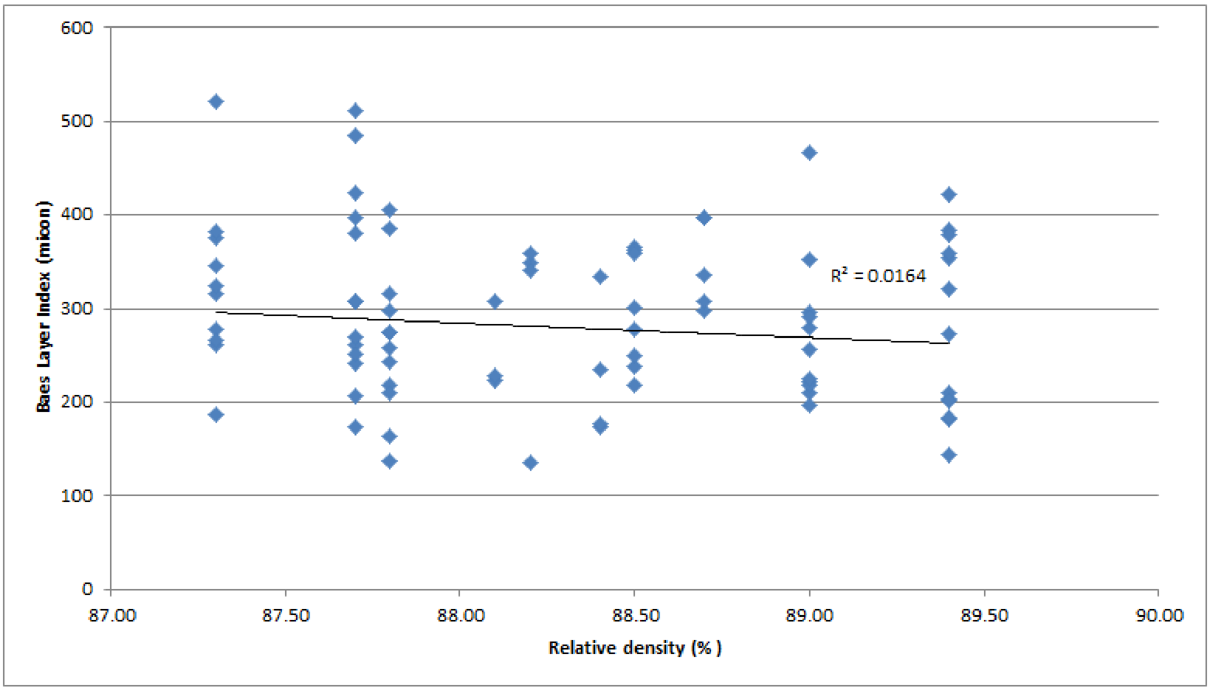

Figure 5.1: BLI vs. relative density of G1 crushed stone base layer.

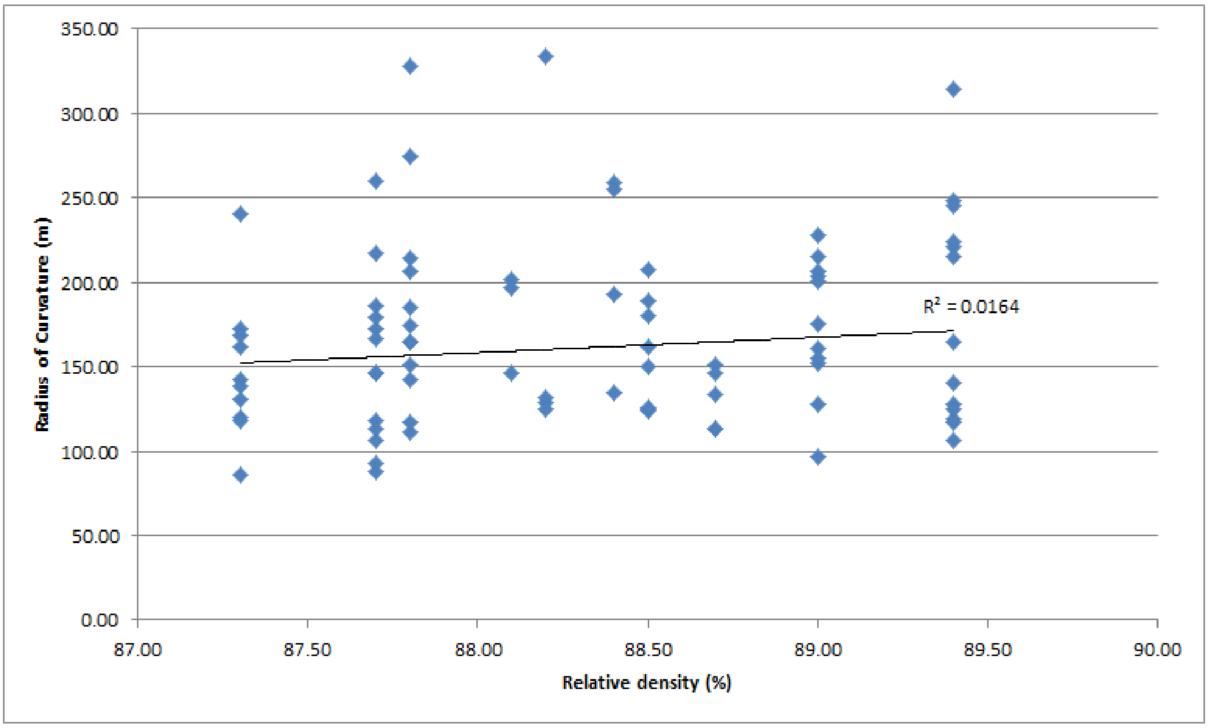

Figure 5.2: RoC vs. relative density of G1 crushed stone base layer.

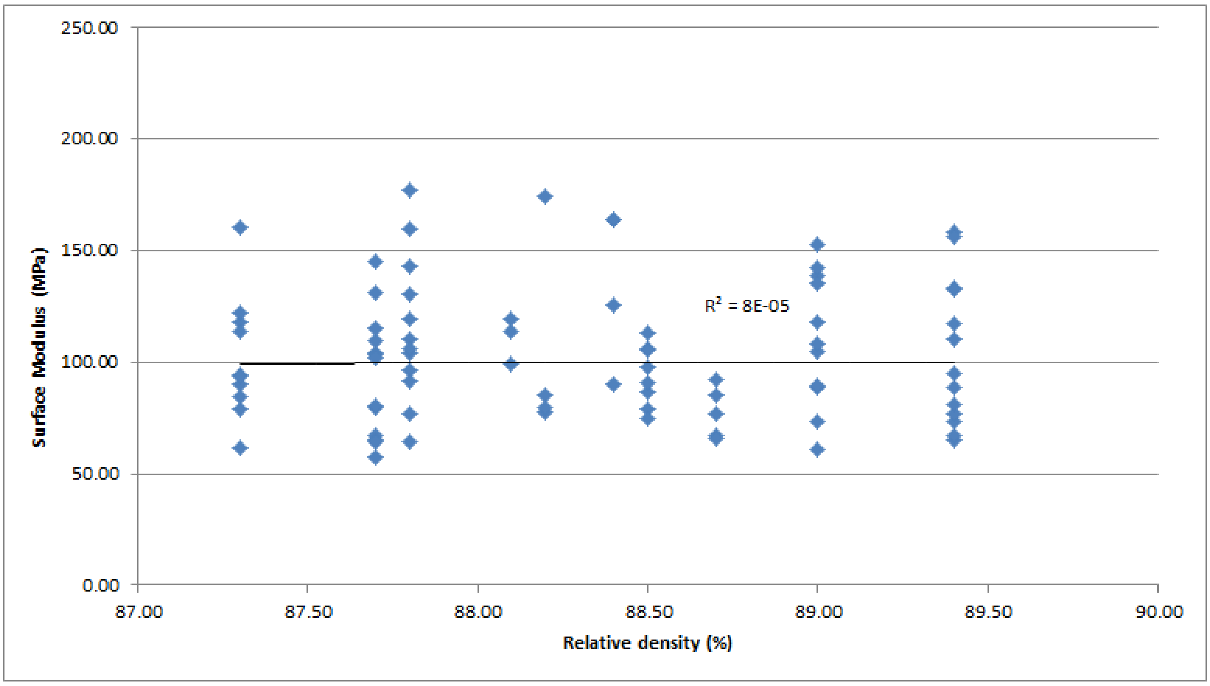

Figure 5.3: Surface Modulus vs. relative density of G1 crushed stone base layer.

The figures above suggest that no substantial relationship can be identified between the BLI, RoC and the surface modulus with the relative compaction of the G1 crushed stone base layer.

The inherent problem with the LFWD and the quality control data set is that only the pavement sections with satisfactory strength and compaction characteristics were sampled and recorded. Therefore the data set only represents one type of pavement state and not for a failing or below strength pavement layer.

In order to create a more accurate model or relationship between the different parameters, it would be necessary to not only sample pavement layer sections that are of satisfactory strength and compaction, but also pavements that are below the specified requirements.

5.2.1.2 Granular layers

The deflection bowl parameters, namely the BLI and RoC, and the surface moduli of the G4 quality granular sub-base, G6 quality granular selected layer and G8/10 quality fill layers were consolidated and correlated with the relative mod AASHTO compaction of the newly constructed pavement layers.

Figures 5.4 to 5.6 present the relationship between the BLI, RoC and the surface modulus with the relative mod AASHTO compaction of the newly constructed granular pavement layers.

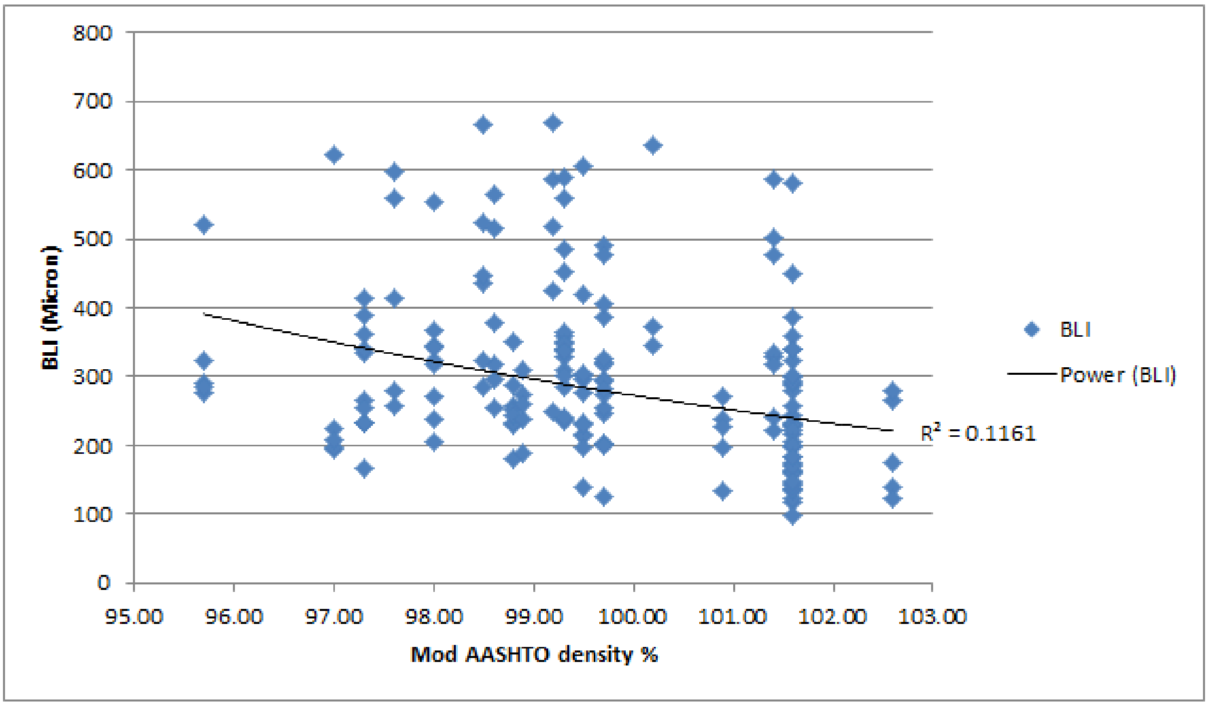

Figure 5.4: BLI vs. relative Mod AASHTO density of granular pavement layers.

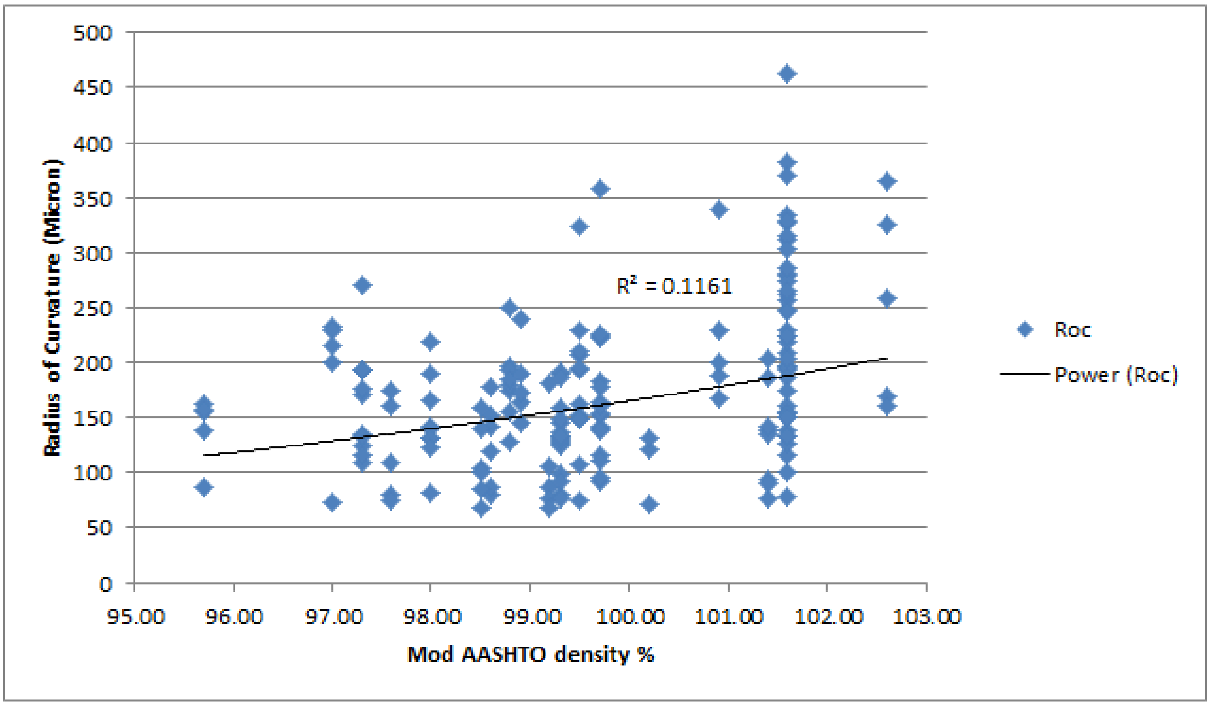

Figure 5.5: RoC vs. relative Mod AASHTO density of granular pavement layers.

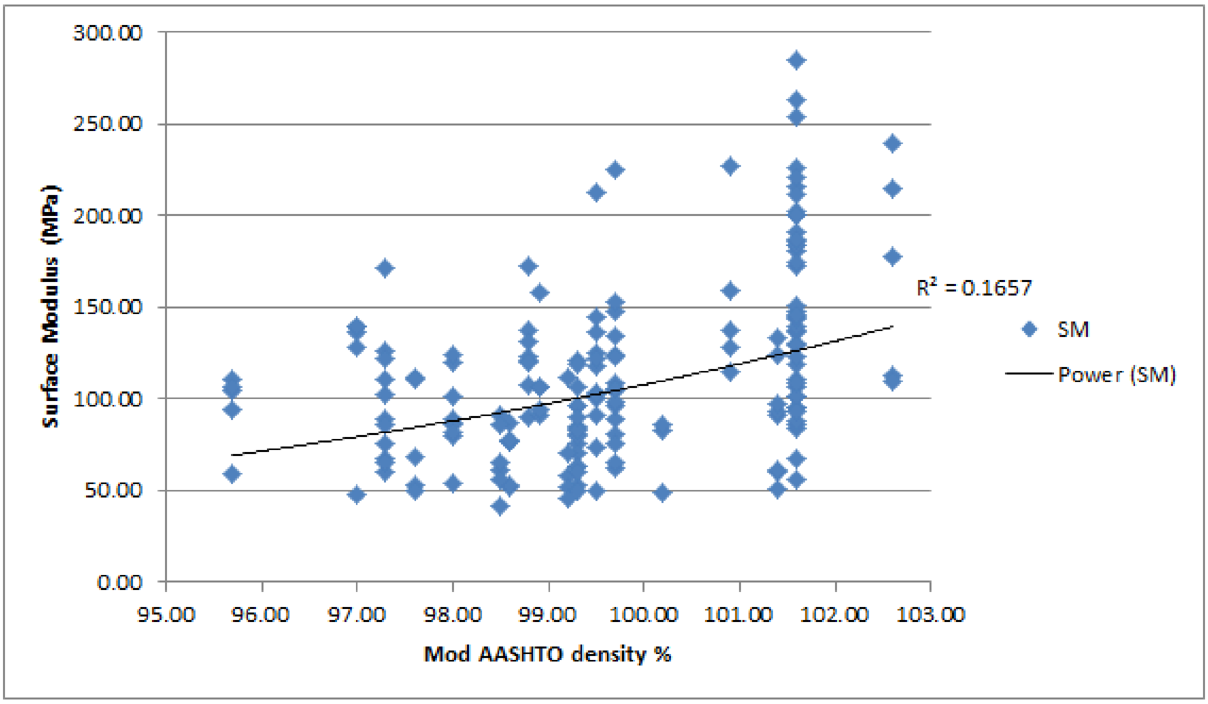

Figure 5.6: Surface modulus vs. relative Mod AASHTO density of granular pavement layers.

The figures above suggest that there is indeed a relationship between the relative Mod AASHTO compaction and the deflection bowl parameters and surface moduli although still statistically weak. The relationship suggests that BLI decreases as the base hardens, and inversely for the RoC and the surface modulus. These relationships are true to actual behaviour as a dense base is bound to show an increase in effective elastic modulus and therefore also an increase in RoC. The larger than ideal spread of the data would suggest that the pavement strength flattens out or plateaus towards higher relative densities.

Similar to that of the G1 crushed stone base, there is a shortfall of 'failing' or below strength pavement results which would aid in producing a more accurate relationship between the different parameters.

Table 5.1 illustrates the expected values of the BLI, RoC and surface modulus for a pavement layer compacted to 95% mod AASHTO when using the relationships established from Figures 5.4 to 5.6. Therefore BLI being lower also correlates with a strong and sound base layer (Horak et al., 2015).

Table 5.1: Expected values of BLI, RoC and surface modulus for granular pavement compacted to 95% mod AASHTO.

BLI (Micron)	RoC(Micron)	Surface Modulus (MPa)
418	100	66

The data represented in Figure 5.4 to 5.6 merely signifies that there exists a relationship between pavement strength and the degree of compaction of the pavement layer. Additional research of the full spectrum of pavement quality control results would be necessary to improve the model.

5.2.1.3 G1 crushed stone base consolidated with the granular layers

In an attempt to create a larger database of deflection bowl parameters and surface moduli and achieve a large spectrum of pavement strength and relative compaction results, the G1 apparent relative densities were converted to relative mod AASHTO densities.

Figure 5.7 illustrates a relationship between the bulk relative density and the relative mod AASHTO compaction density. This relationship was utilised to convert the G1 apparent relative densities into the relative mod AASHTO densities.

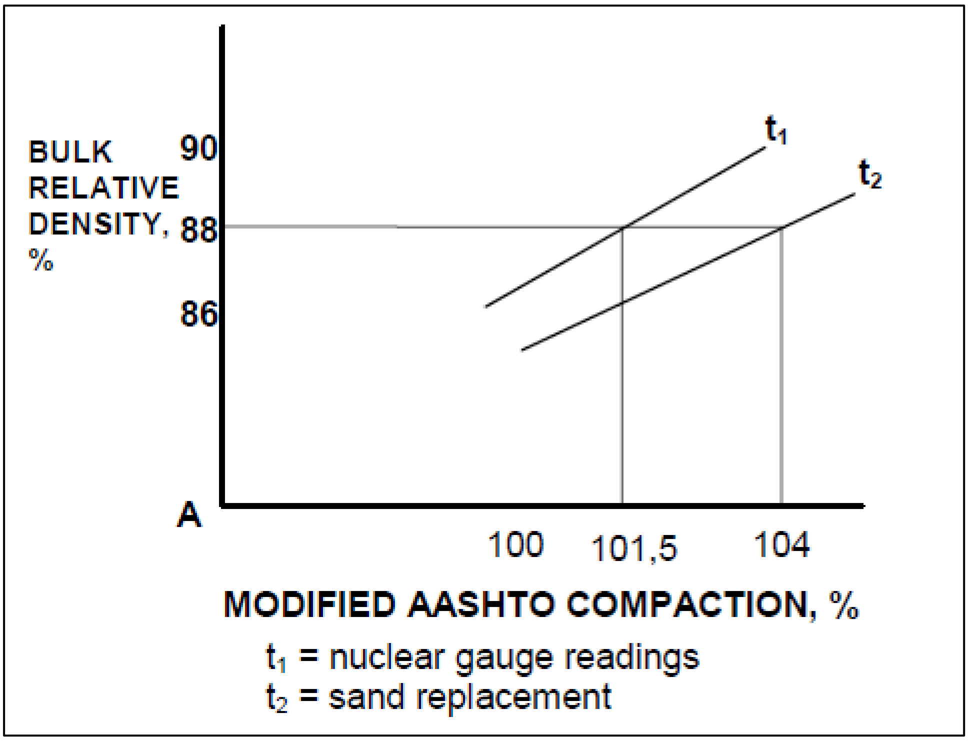

Figure 5.7: Relationship between bulk relative density and modified AASHTO compaction percentage (Department of Transport and Public Works, 2006).

The converted G1 data set was consequently consolidated with the deflection bowl parameters and surface moduli data set of the granular pavement layers. Figures 5.8 to 5.10 present the relationship between the BLI, RoC and the surface modulus with the relative mod AASHTO compaction of the consolidated granular pavement layers.

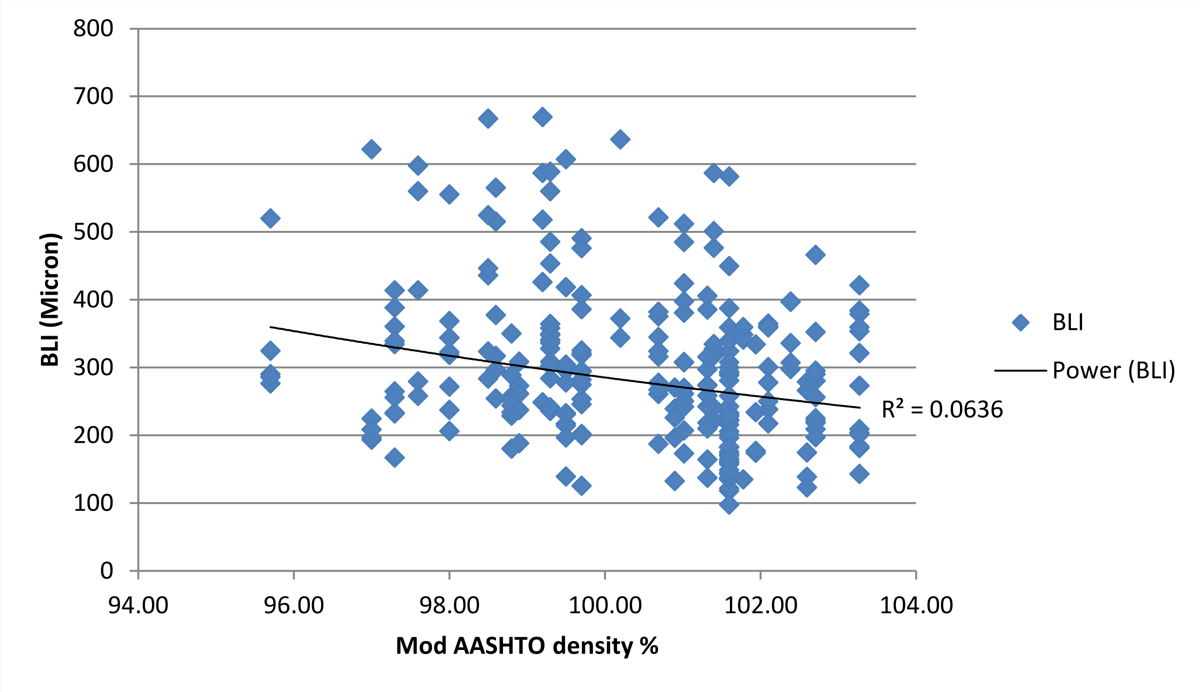

Figure 5.8: BLI vs. relative Mod AASHTO density of consolidated granular pavement layers.

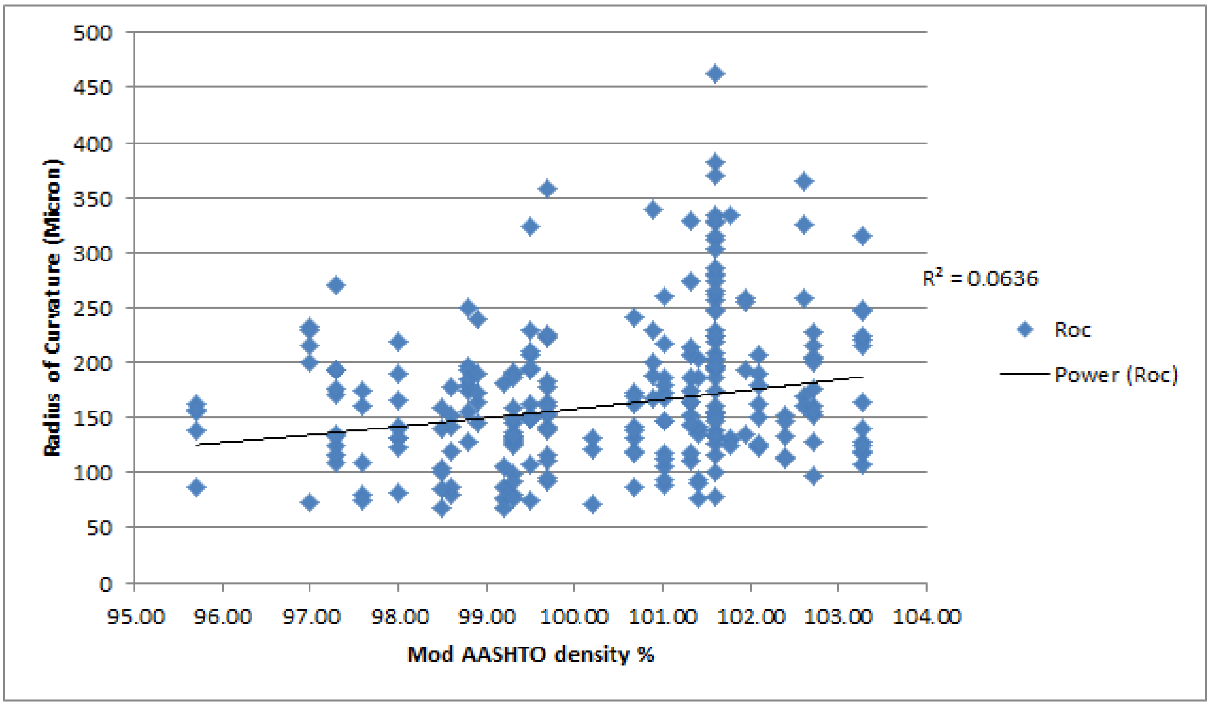

Figure 5.9: RoC vs. relative Mod AASHTO density of consolidated granular pavement layers.

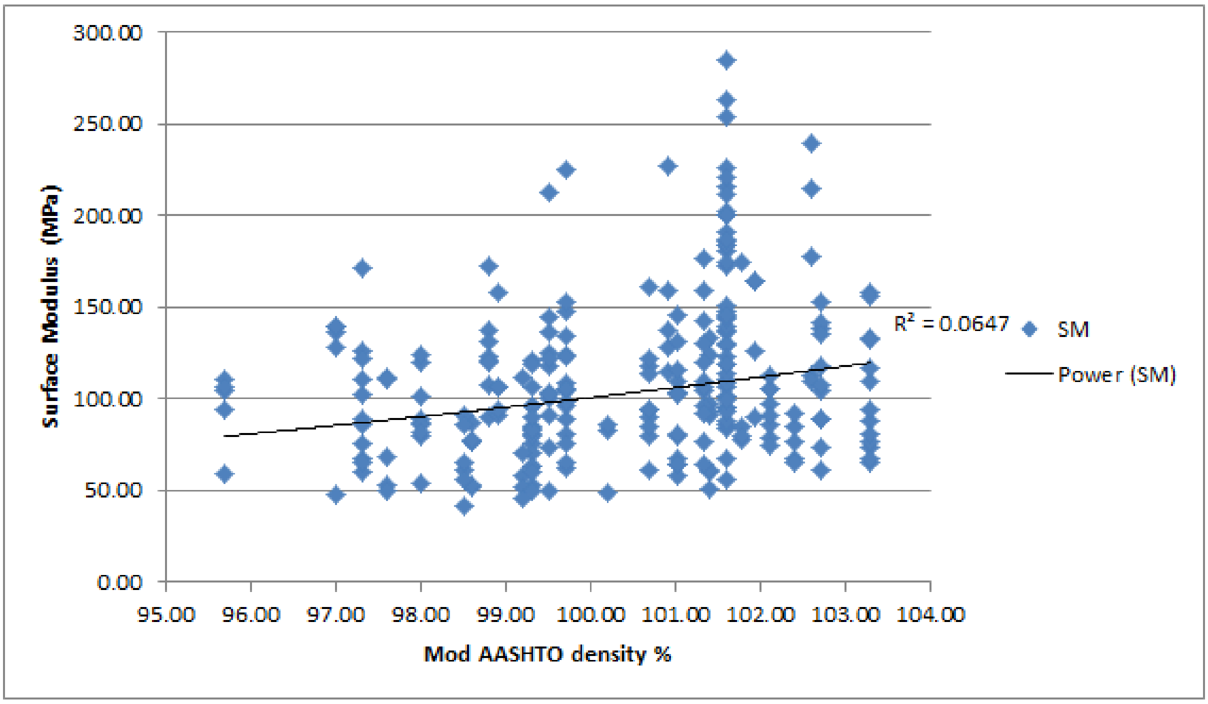

Figure 5.10: Surface modulus vs. relative Mod AASHTO density of consolidated granular pavement layers.

With the addition of the converted G1 data set, the established relationships appear to have weakened due to further spreading of data points towards the higher compaction values. It would again appear that the pavement strength flattens out towards the higher Mod AASHTO densities. This again reinforces the point made in Sections 5.2.1.1 and 5.2.1.2 that a larger data set with ‘failing’ or below strength pavements are required to establish a more accurate model between the pavement strength and the layer’s relative density.

5.2.1.4 Pavement layer strength relationship with relative mod AASHTO density compaction

In order to attain data that represents a pavement layer that is below and with satisfactory strength characteristics, LFWD deflection measurements were deliberately taken on a pavement layer during the construction process. LFWD and density measurements were taken on a continuous basis as the layer was being compacted. Figure 5.11 illustrates the relationship between the normalised pavement layer strength and the relative mod AASHTO densities of a G5 quality material pavement layer. The deflection measurements were normalised in order to establish a comparative platform between the different pavement material layer types.

Figure 5.11 shows a strong correlation between the pavement strength measurements and the relative density of the layer. The pavement layer strength levels off as the layer achieves greater compaction, which is approximately 94% relative mod AASHTO density. This correlation relationship confirms for a specific material class like a G5 in this case, would enable LFWD measurements and calculations such as the surface modulus to indicate with confidence when such a constructed layer may in fact not meet the density requirement. The area depicted in Figure 5.11 that is above 96% relative mod AASHTO density is also representative of the data in Figure 5.10.

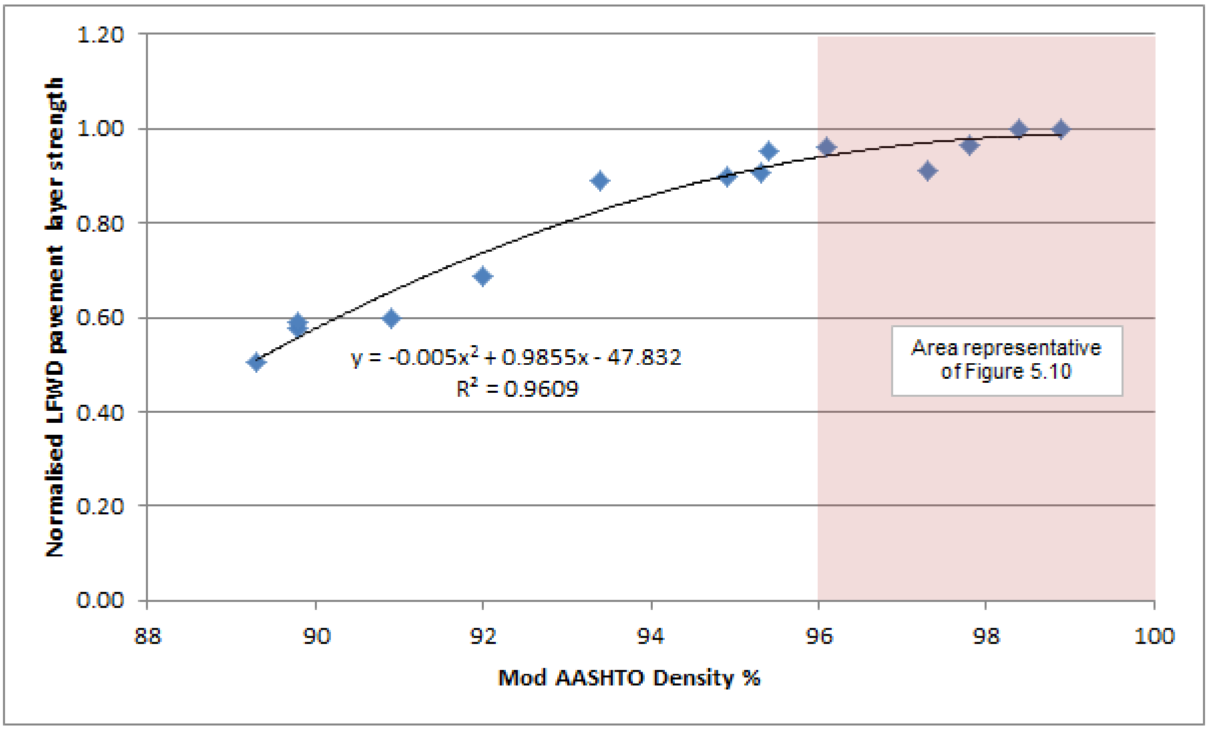

Figure 5.11: Normalised LFWD measured pavement layer strength vs. relative Mod AASHTO density of a granular pavement layer.

Recent studies by Umashankar et al., (2015) confirm that the surface modulus increases with increases in the compacted density of pavement layers. It should however be noted that different pavement materials with different material characteristics will inevitably perform differently.

5.2.1.5 Contribution of underlying pavement layers

It is acknowledged that the underlying pavement layers will make a contribution to the surface modulus determined for the granular layer under construction. This however falls outside the scope of this study and it is therefore recommended that further research be conducted to isolate the contribution of the underlying layers.

5.2.1.6 Minnesota Department of Transportation target value comparison

In an attempt to relate the surface modulus target values established by the Minnesota Department of Transportation with the LFWD deflection measurements sampled at WAFB, grading numbers for each test position at WAFB were calculated and compared with respective established target ranges.

The grading numbers and moisture contents were used to select the appropriate target values for each compacted granular material. The Grading Number (GN) is a method which represents the sum of the percentages of particles passing each sieve (Oman, 2004). The GN formula is illustrated in the equation to follow:

$$GN_{(\% \text{ Passing})} = \frac{25mm+19mm+9.5mm+4.75mm+2.0mm+0.425mm+0.075mm}{100} \quad \text{Equation 5-1}$$

If 100% of the material passes each of the sieves listed in the equation above, the GN reaches its maximum value of 7.0 which represents an extremely fine gradation. Conversely, if 0% passes all of the sieves, the GN falls to its lowest value of 0.0 representing tremendous coarse material (Oman, 2004). Table 5.2 presents the grading number and corresponding surface moduli where a sieve analysis was conducted on the G1 crushed stone base.

Table 5.2: Grading numbers and surface moduli of G1 crushed stone base.

Test Reference	B002	B004	B005	B006	B007	B008	B009	Average
Grading Nr	3.3	3.2	3.2	3.1	3.4	3.2	3.4	**3.3**
Surface Modulus (MPa)	113.9	106.2	101.2	119.5	136.0	124.1	104.2	**115.0**

The target surface modulus value for a granular material with a grading number between 3.1 and 3.5 and moisture content percentage between 5 and 7 % is 120 MPa as established by the Minnesota Department of Transportation. The average surface modulus value yielded from the WAFB data where a sieve analysis was conducted on the G1 crushed stone base was determined to be 115 MPa. The WAFB surface modulus value is relatively close to the established target value from Minnesota Department of Transportation which would indicate that the LFWD data and protocol is relatable between different countries of LFWD testing.

5.2.2 Walvis Bay Airport

LFWD deflection measurements were sampled on Walvis Bay Airport construction site. The LFWD deflections were sampled on a 100 mm thick waterbound macadam (WBM) base layer with thin asphalt surfacing. The LFWD deflection measurements were taken without the two additional geophones, therefore, only maximum deflection and derived surface modulus values could be used during the analysis. Table 5.3 and Figures 5.12 to 5.13 present the maximum deflection and surface modulus of the WBM base layer sampled.

Table 5.3: Average surface deflection and surface modulus of WBM base layer with thin asphalt layer.

Average Maximum Deflection (micron)	Average Surface Modulus (MPa)
190	180

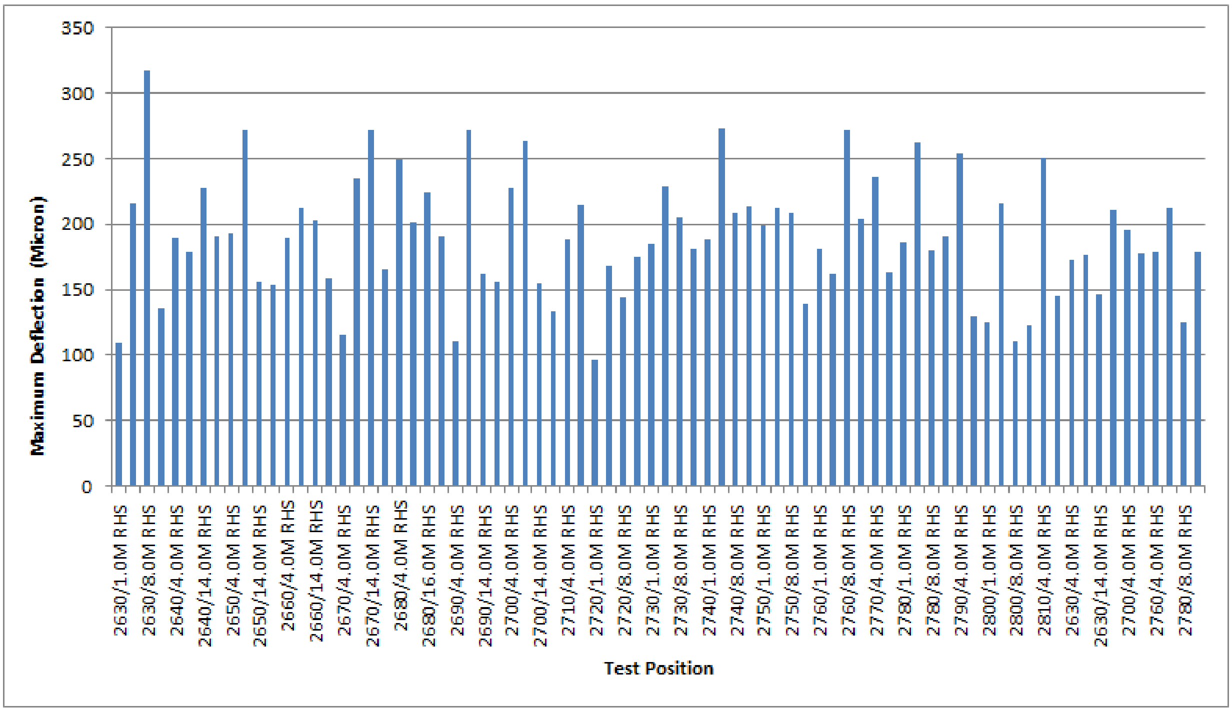

Figure 5.12: Maximum deflection of waterbound macadam base layer with an asphalt surfacing.

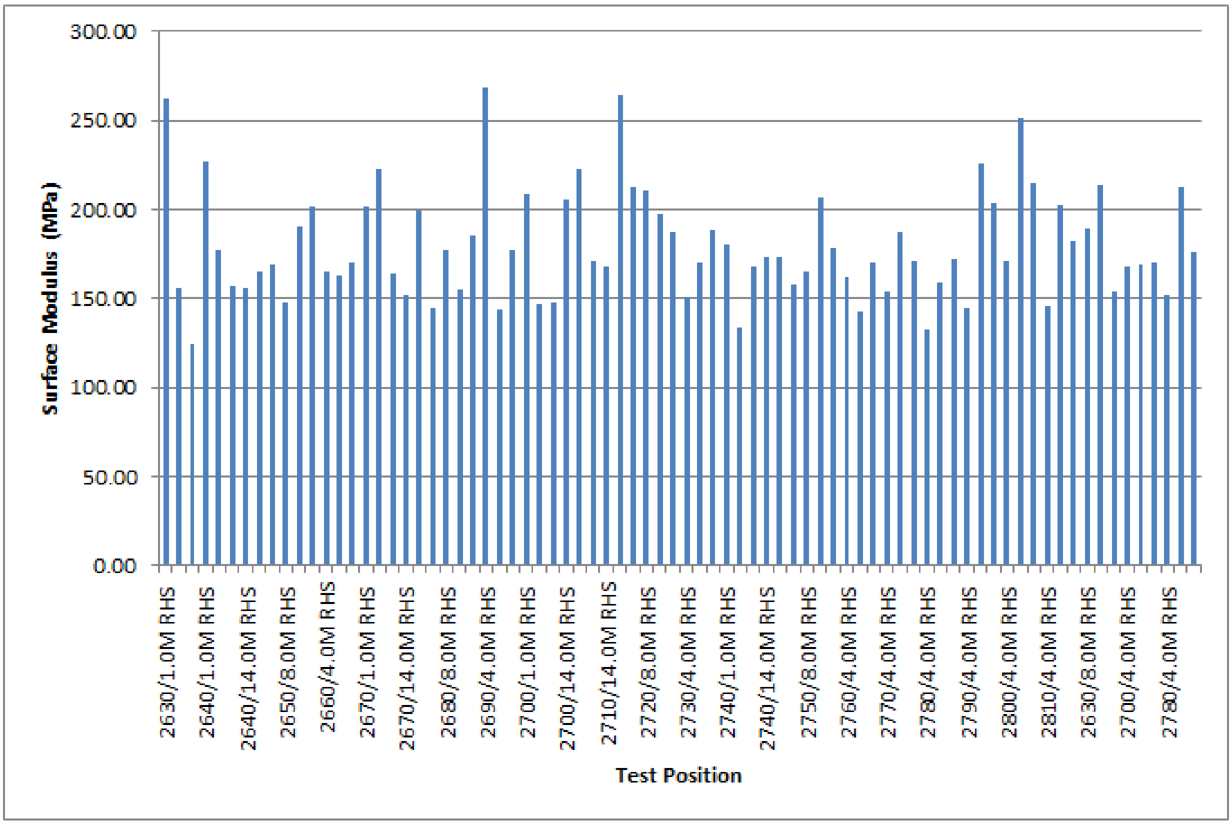

Figure 5.13: Figure 5.1: Surface Modulus of waterbound macadam base layer with an asphalt surfacing.

It was expected that the WBM base layer will exhibit similar pavement strength characteristics as the G1 crushed stone base layer. The difference in the pavement strength between the G1 base layer at WAFB and the WBM can be attributed to the asphalt surfacing on the WBM.

The similar pavement strength characteristics between the two pavements reinforce the motion to use a standardised LFWD protocol and relative benchmarking methodology to add value to construction quality control process.

5.2.3 R104

The R104 near Bronkhorstspruit site was selected to sample LFWD deflection measurements because of the variety of unconventional pavement layers constructed. The pavement layers constructed consisted of a Foam Treated Base (FTB), Emulsion Treated Base (ETB), Cement Treated Base (CTB) and a Bituminous Treated Base (BTB).

LFWD deflections measurements were sampled on each pavement layer type at different times after the layer was constructed. The LFWD deflection measurements were taken without the two additional geophones, therefore, only maximum deflection and derived surface modulus values could be used during the analysis.

5.2.3.1 Foam Treated Base

LFWD deflection measurements were sampled one and three days after the pavement layer has been constructed. Table 5.4 and Figures 5.14 and 5.15 illustrate the relative increase in pavement strength with time.

Table 5.4: Average maximum deflection and surface moduli values for a FTB base layer, one and three days after construction.

Average Maximum Deflection (micron)		Average Surface Modulus (MPa)	
Day 1	Day 3	Day 1	Day 3
415	196	590	1037

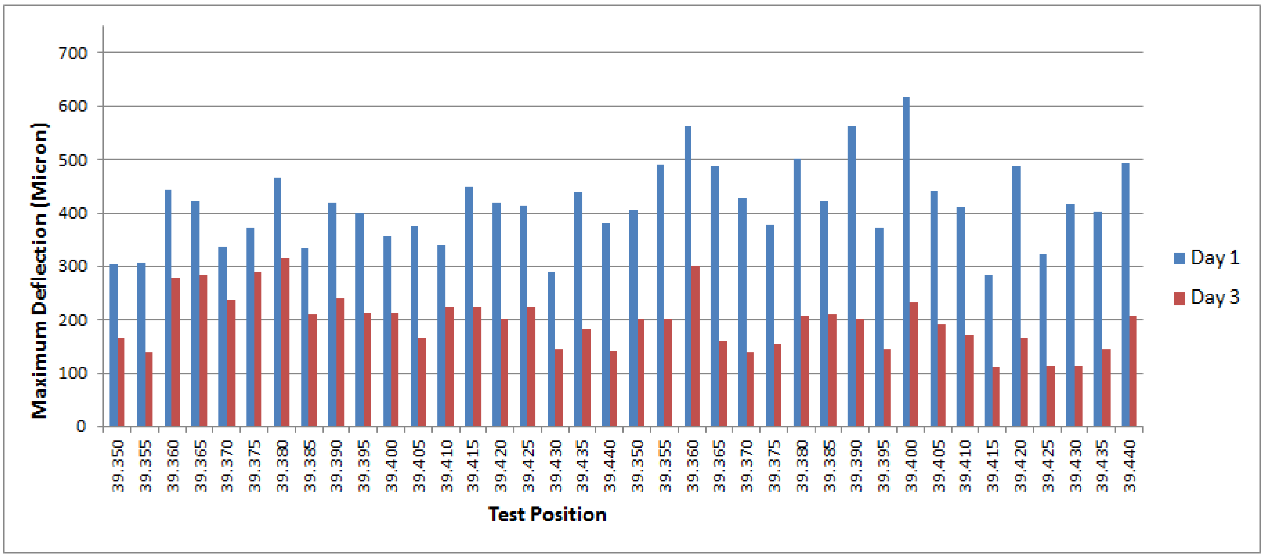

Figure 5.14: Maximum deflection values for a FTB base layer one and three days after construction.

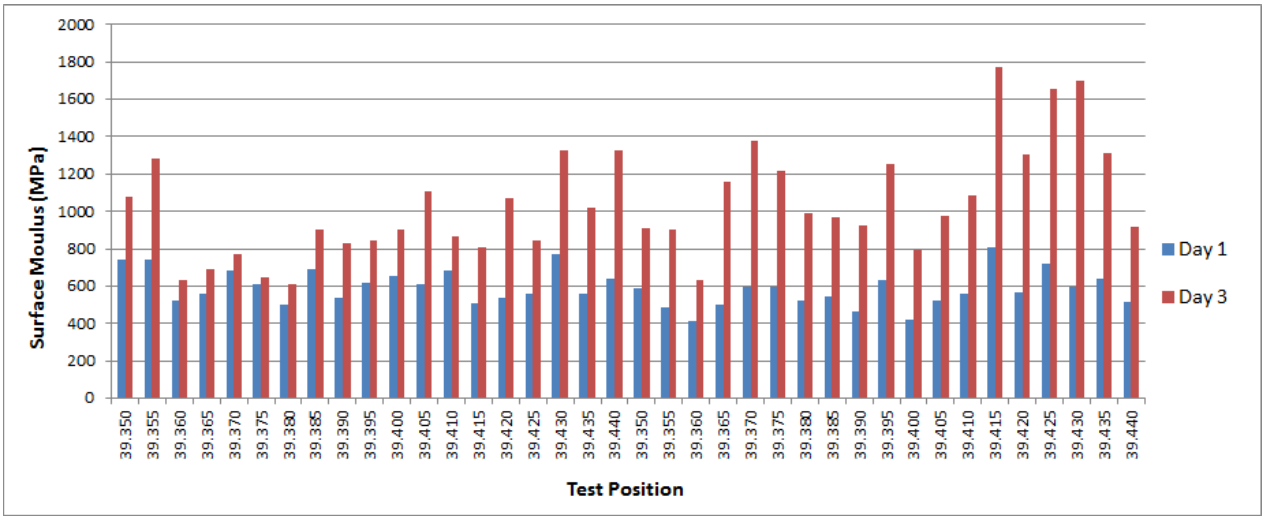

Figure 5.15: Surface modulus values for a FTB base layer, one and three days after construction.

The time series data clearly indicate that the FTB pavement strength has increased relatively between the respective times of measurement.

5.2.3.2 Emulsion Treated Base

LFWD deflection measurements were sampled one, five, seven and seventeen days after the pavement layer has been constructed. Table 5.5 and Figures 5.16 and 5.17 illustrate the relative increase in pavement strength with time. Deflection measurements were recorded at later stages after the layer has been constructed in order to demonstrate the initial curing improvement of the layer, therefore fewer deflection measurements were sampled.

Table 5.5: Average maximum deflection and surface moduli values for a ETB base layer, one, five, seven and seventeen days after construction.

Average Maximum Deflection (micron)				Average Surface Modulus (MPa)			
Day 1	Day 5	Day 7	Day 17	Day 1	Day 5	Day 7	Day 17
466	303	181	176	242	339	1209	1361

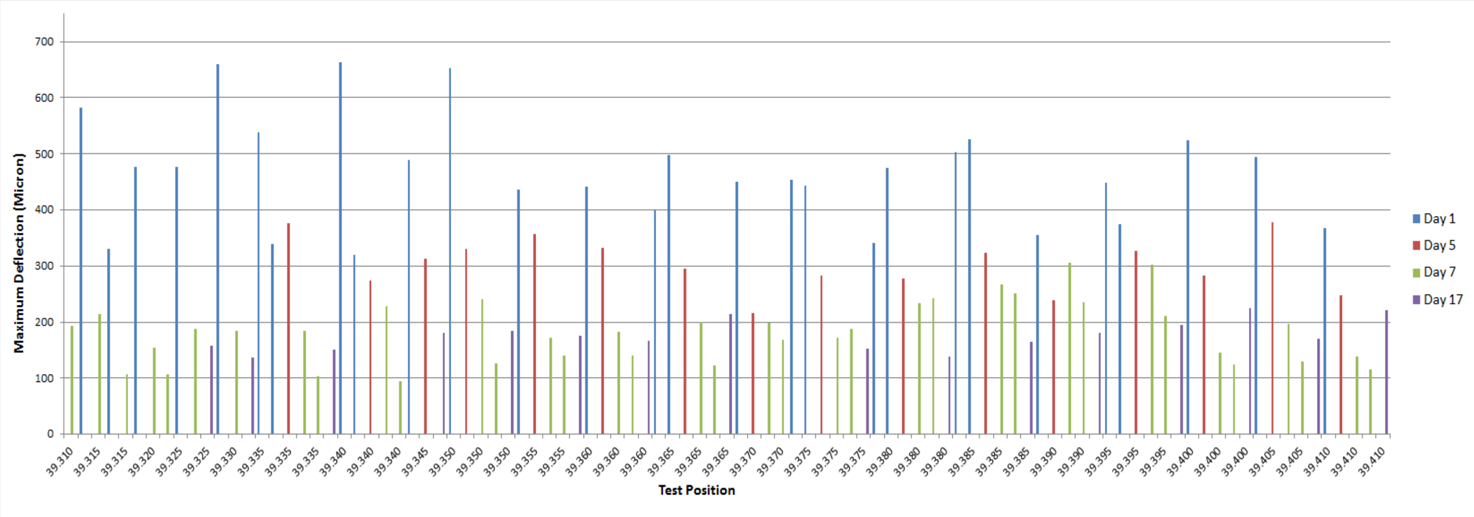

Figure 5.16: Maximum deflection values for an ETB base layer one, five, seven and seventeen days after construction.

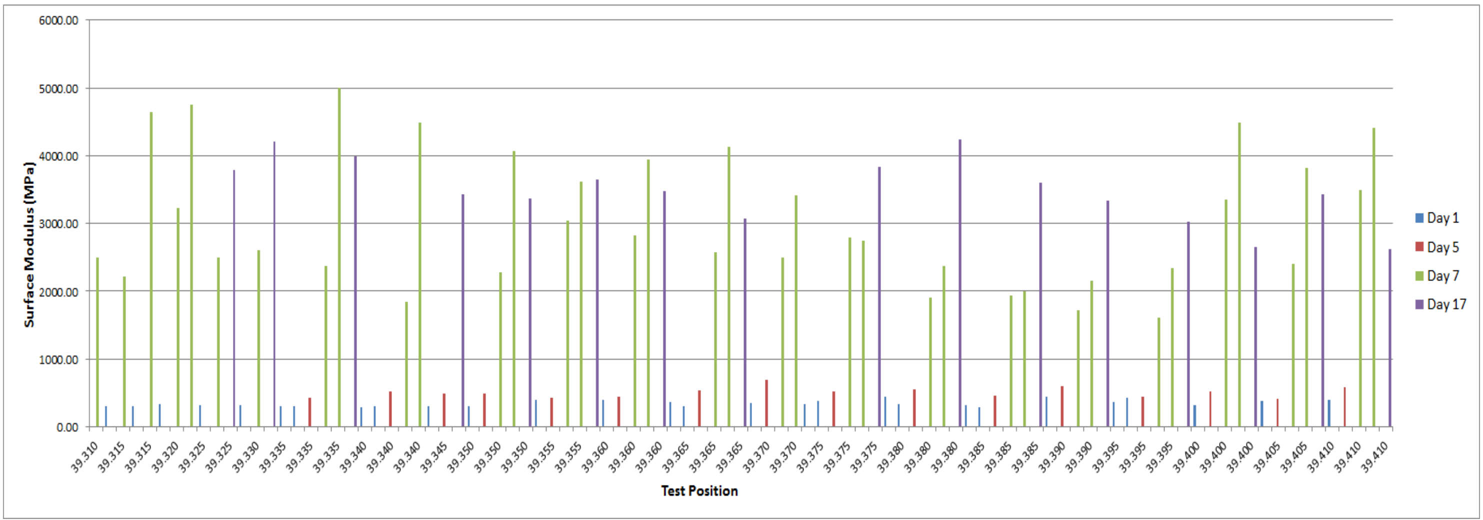

Figure 5.17: Surface modulus values for an ETB base layer one, five, seven and seventeen days after construction.

The time series data clearly indicate that the ETB pavement strength has increased relatively between the respective times of measurement.

5.2.3.3 Cement Treated Base

LFWD deflection measurements were sampled one, four and seven days after the pavement layer has been constructed. Table 5.6 and Figures 5.18 and 5.19 illustrate the relative increase in pavement strength with time. Due to construction and testing constraints, less deflection measurements were able to be recorded at later stages after the layer has been constructed.

Table 5.6: Average maximum deflection and surface moduli values for a CTB base layer, one, four and seven days after construction.

Average Maximum Deflection (micron)			Average Surface Modulus (MPa)		
Day 1	**Day 4**	**Day 7**	**Day 1**	**Day 4**	**Day 7**
403	340	244	266	807	855

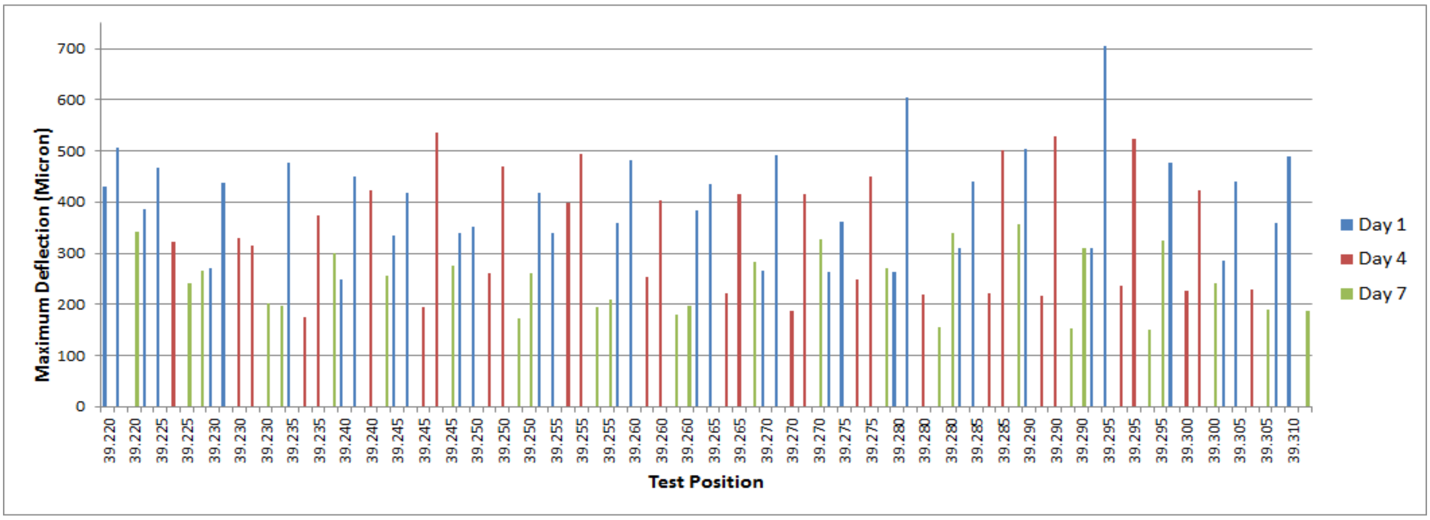

Figure 5.18: Maximum deflection values for a CTB base layer one, four and seven days after construction.

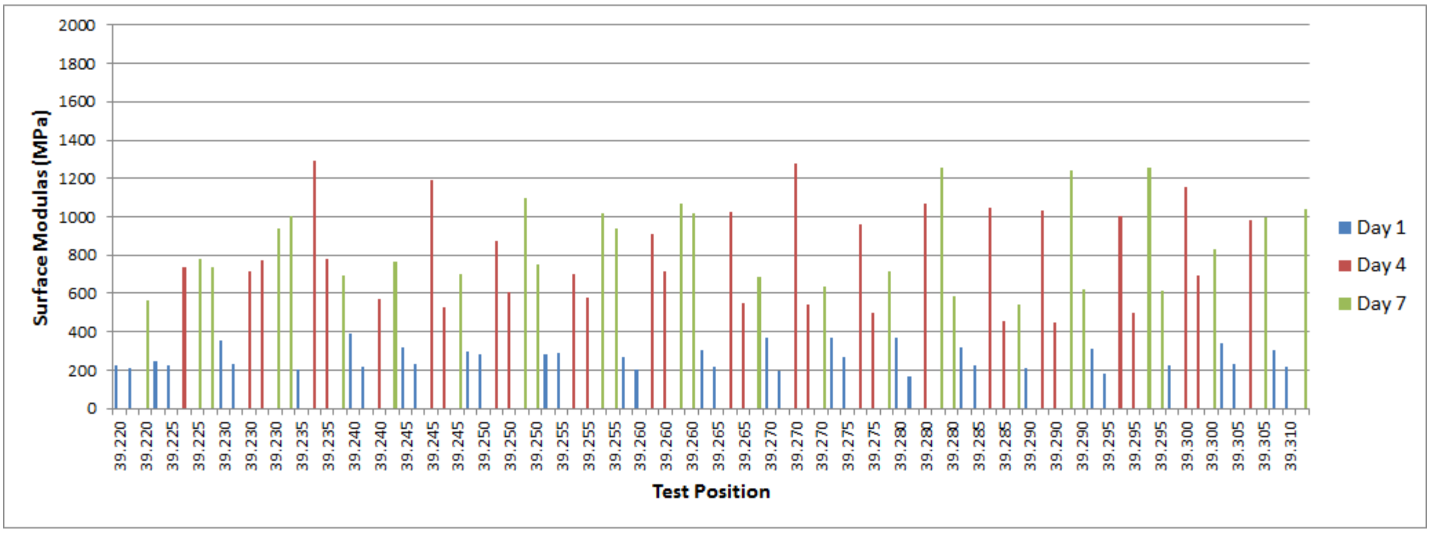

Figure 5.19: Surface modulus values for a CTB base layer one, four and seven days after construction.

The time series data clearly indicate that the CTB pavement strength has increased relatively between the respective times of measurement.

5.2.3.4 Bituminous Treated Base

LFWD deflection measurements were sampled one, three and seven days after the pavement layer has been constructed. Table 5.7 and Figures 5.20 and 5.21 present the maximum deflection and surface moduli values recorded.

Table 5.7: Average maximum deflection and surface moduli values for a BTB base layer, one, three and seven days after construction.

Average Maximum Deflection (micron)			Average Surface Modulus (MPa)		
Day 1	Day 3	Day 7	Day 1	Day 3	Day 7
529	428	426	200	240	250

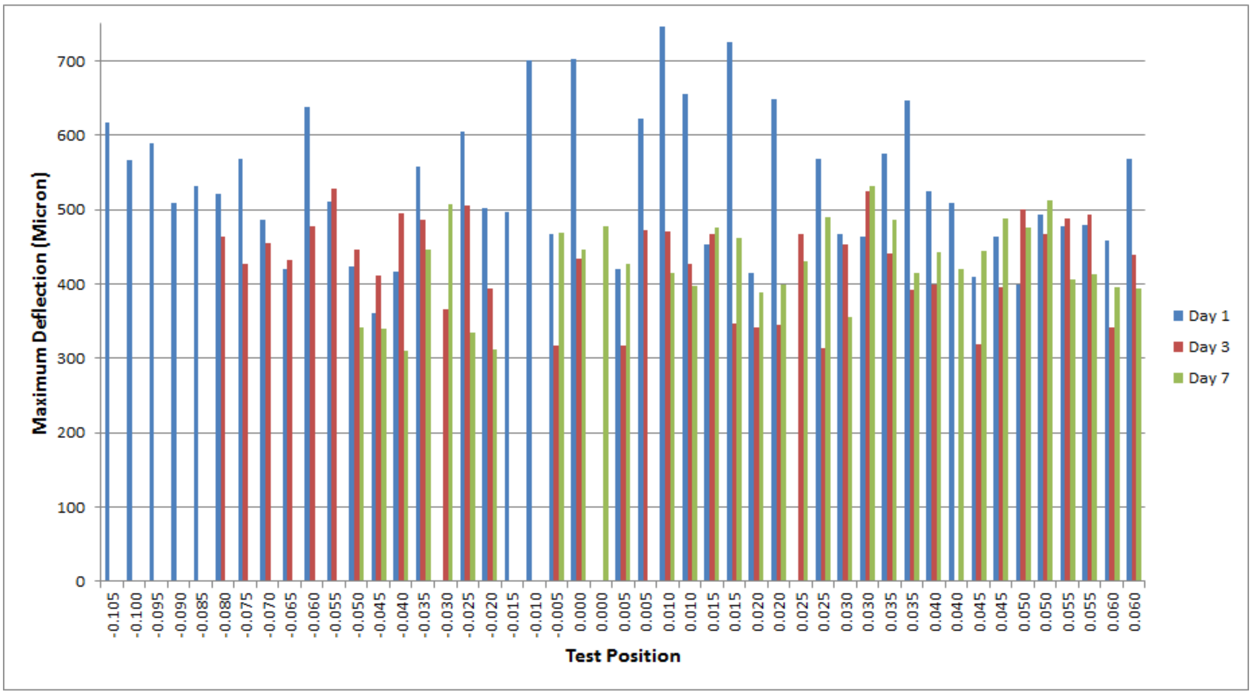

Figure 5.20: Maximum deflection values for a BTB base layer one, three and seven days after construction.

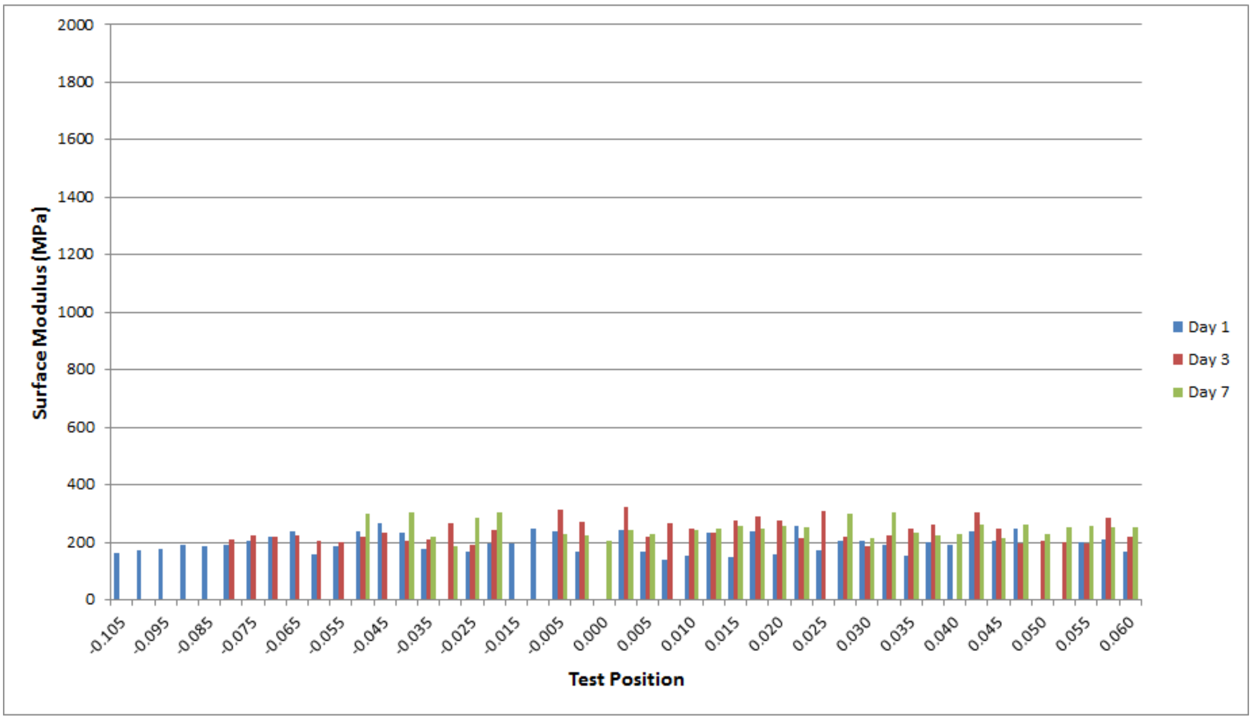

Figure 5.21: Surface modulus values for a BTB base layer one, three and seven days after construction.

The time series data indicate, as expected, that the BTB pavement strength has relatively stayed the same between the respective times of measurement. The surface moduli measurements are significantly lower than that of the other treated bases.

As would be expected, with the exception of the BTB base layer, all of the newly constructed pavement layers showed a relative increase in pavement strength. The LFWD has demonstrated its worth as a construction quality control tool due to its ability to monitor the relative increase of pavement strength of newly constructed layers.

5.2.4 R23 Greylingstad

LFWD deflection measurements were sampled on a construction site where two sections of the asphalt layer displayed distress soon after it was constructed. In both cases the wheel path with the distressed sections were surveyed as well as the sound sections in between. The LFWD geophone spacing was altered to 0 mm, 200 mm and 400 mm instead of the conventional 0 mm, 300 mm and 600 mm arrangement. The depth of influence of the LFWD limits it to the structural condition evaluation of the base and surfacing.

The closer spacing of the geophones to the loading plate becomes very prone to the compression wave which affects the accuracy and reliability of the outer two geophone recordings. Therefore no deflection bowl parameters such as RoC or BLI or MLI could be used to for the deflection bowl analyses. Only maximum deflection and derived surface modulus values could be used. Table 5.8 presents the maximum deflection and average surface moduli values for the sound and the distressed asphalt.

Table 5.8: Maximum deflection and average surface moduli values for sound and distressed asphalt.

Asphalt State	Average Maximum Deflection (Micron)	Average Surface Modulus (MPa)
Sound	231	1128
Distressed	433	595

Figures 5.22 to 5.24 depict the distinction in the maximum deflection values of the sound and distressed asphalt pavement layers.

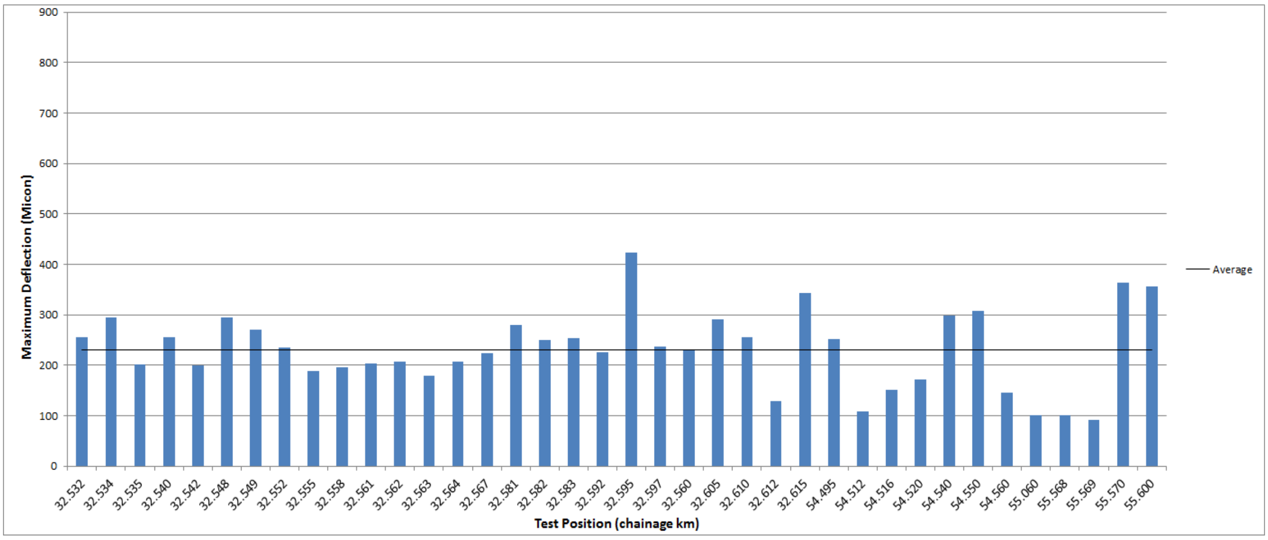

Figure 5.22: Maximum Deflection values of the sound asphalt pavement layer.

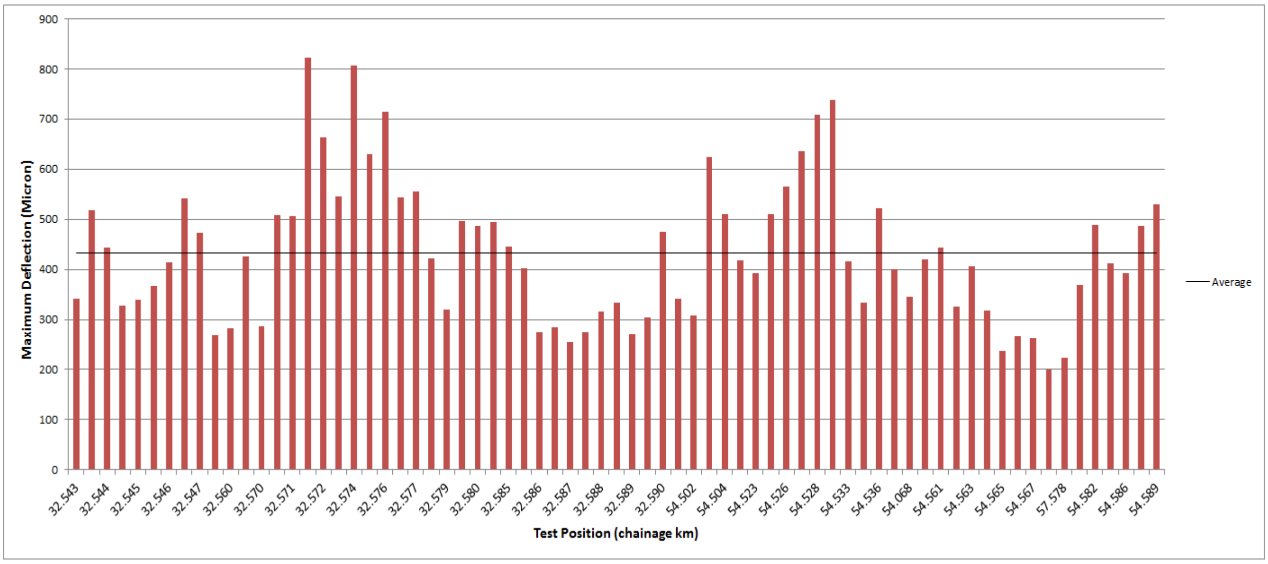

Figure 5.23: Maximum Deflection values of the distressed asphalt pavement layer.

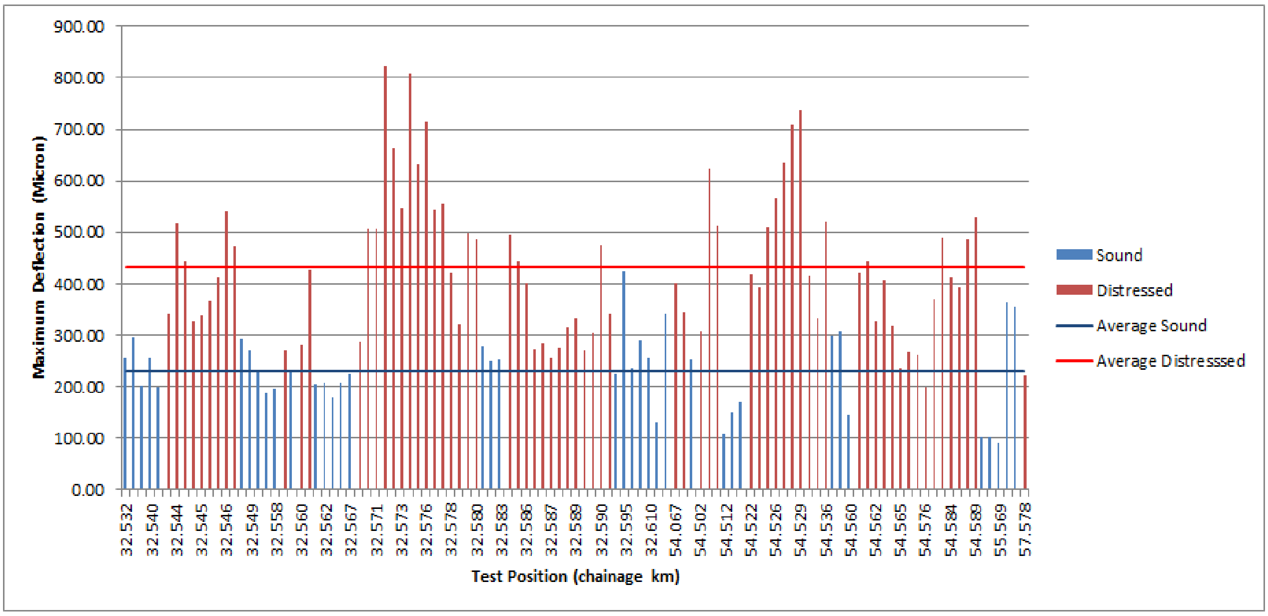

Figure 5.24: Maximum Deflection values of the sound and distressed asphalt pavement layers.

Figures 5.25 to 5.27 depict the distinction in the surface moduli values of the sound and distressed asphalt pavement layers.

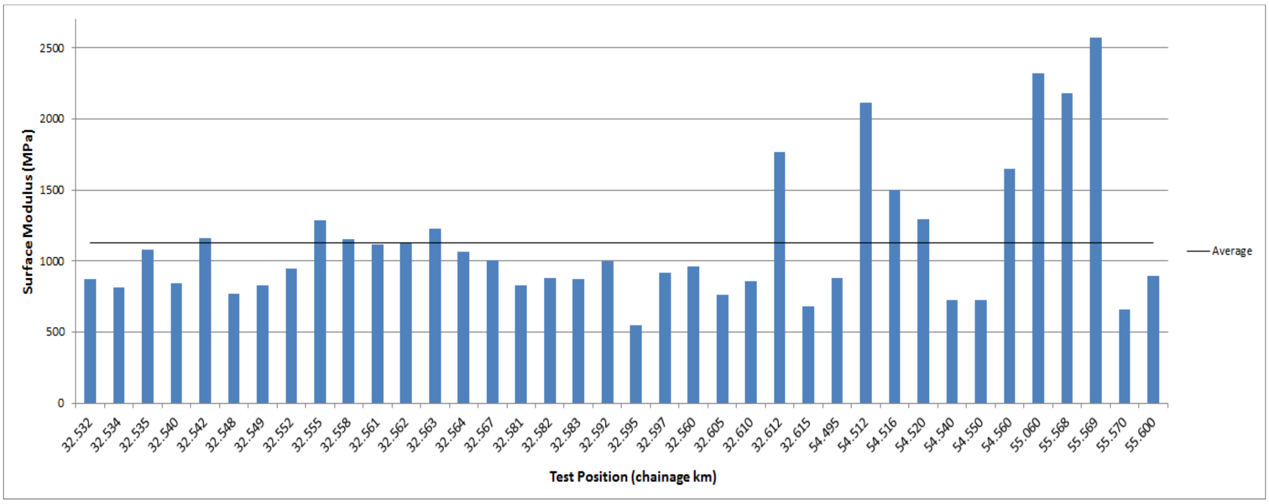

Figure 5.25: Surface Moduli of sound asphalt pavement layer.

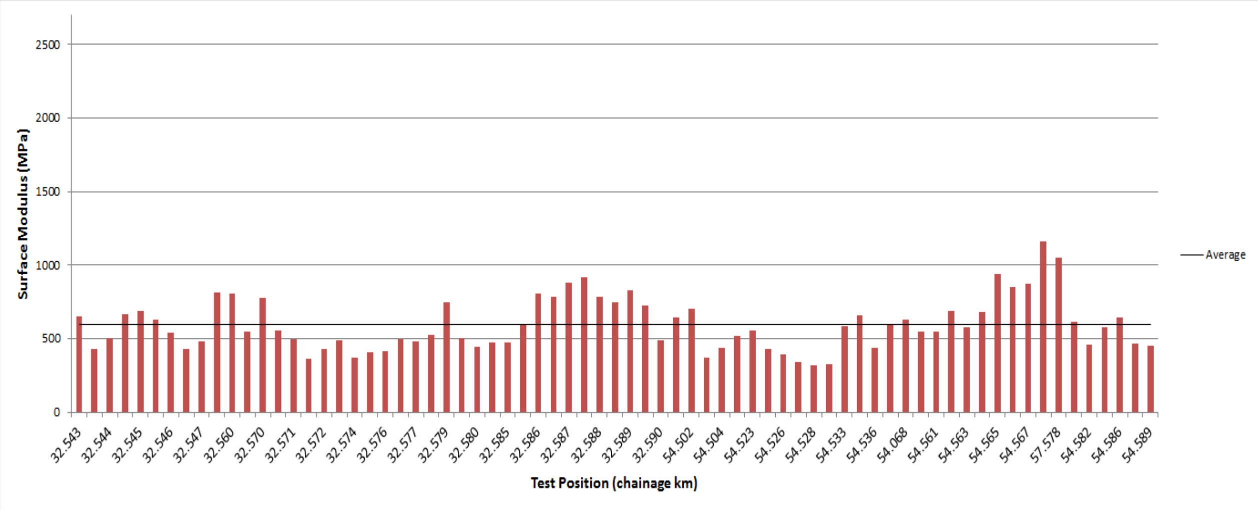

Figure 5.26: Surface Moduli of distressed asphalt pavement layer.

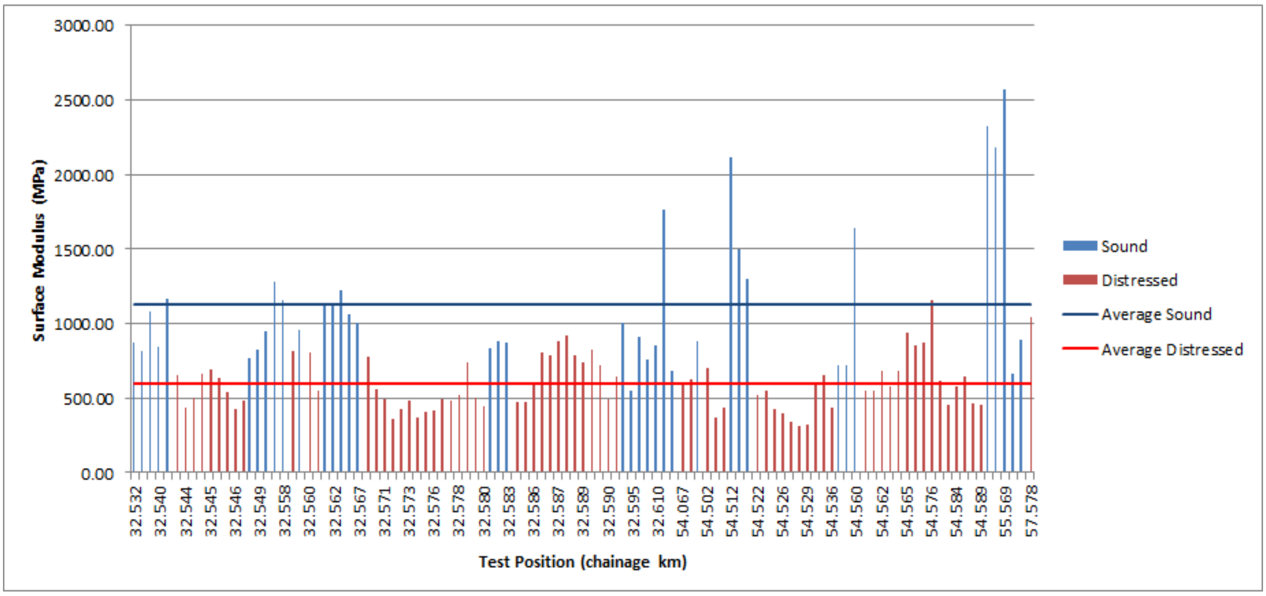

Figure 5.27: Surface Moduli of sound and distressed asphalt pavement layers.

The maximum deflection and surface moduli results clearly indicate that there are a significant dissimilarity between the sound and the distressed asphalt. Due to the limited amount of LFWD deflection data available on asphalt pavements, the deflection sound vs. distressed asphalt deflection measurements can only be utilised in a relative analysis application. The LFWD device could therefore be utilised during the construction stage as supplementary tool in a quality control application, even for asphalt layers.

5.3 SUMMARY

This chapter represented the analysis and interpretation of the test results from the different construction sites comprising of LFWD deflection measurements and routine material test results.

The calculated LFWD deflection bowl parameters in collaboration with the relative compaction of the WAFB pavement layers were analysed to determine whether a relationship exists. The data indicated that there exists a relationship between the pavement strength and the degree of compaction of the pavement layer. The relationship suggests that the pavement strength levels out with compaction close to and meeting specification. The interpreted data identifies a deficit in the spectrum of data as the available data are only representative of a pavement layer with satisfactory strength and not for a failing or below strength pavement layer. Additional LFWD deflection measurements were sampled on a pavement layer during the construction process in an attempt to attain a typical relationship between the pavement strength and the relative density of granular pavement layer. The data indicated that a strong relationship exists as the pavement layer strength levels of as the layer achieves greater compaction. The pavement layer strength converges when the layer achieves approximately 94% relative mod AASHTO density.

The LFWD deflection measurements of the WBM layer sampled at Walvis Bay Airport showed that it exhibits similar pavement strength characteristics to the G1 crushed stone base layer. The similar pavement strength characteristics between the two pavements reinforce the motion to use relative benchmarking methodology in order to add value to the construction quality control process.

The R104 construction site represents LFWD data measurements sampled on different pavement layers at different times after the layer was constructed. With the exception of the BTB base layer, all of the newly constructed pavement layers showed a relative increase in pavement strength with time.

LFWD deflection measurements sampled at the R23 construction site represent data from newly constructed asphalt layers with one section displaying distressed asphalt and the other sound conditions. The surface modulus and maximum deflection results clearly indicated that there were a significant dissimilarity between the sound and the distressed asphalt.

The LFWD demonstrated with the data sampled at all of the respective construction sites that it could therefore be utilised in collaboration with a relative benchmarking methodology as an effective supplementary tool in a quality control application during the construction stage.

5.4 REFERENCES

Horak, E., Emery, S. and Maina, J. (2015). *'Review of FWD benchmark analysis on road and runways'*, proceedings of the 11th South African Conference on Asphalt Pavements (CAPSA), August 2015, Sun City, South Africa.

Horak, E., Hefer, A. and Maina, J. (2015).*'Determining pavement number values for flexible pavements utilising falling weight deflectometer deflection bowl information'*, proceedings of the 34th South African Transport Conference (SATC), July 2015, Pretoria, South Africa.

Materials Manual (2006). *'Materials Manual : Chapter 16: Acceptance Control for Base layers'*, Department of Transport and Public Works: Western Cape Provincial Administration, Cape Town, South Africa.

Oman, M. (2004). *'Advancement of grading and base material testing'*, Minnesota Department of Transportation, Minnesota, U.S.A.

Umashankar, B., Hariprasad, C. and Kumar, G. (2015). *'Compaction Quality Control of Pavement Layers using LWD'*, Journal of Materials in Civil Engineering, 10.1061/(ASCE)MT.1943-5533.0001379.

6 BENCHMARK METHODOLOGY

6.1 INTRODUCTION

LFWD deflections cannot be used in a classical way to do back analysis to determine effective elastic moduli of the full pavement structure. At best, engineering properties of the top 200 mm to 300 mm of the layers can be evaluated. The FWD deflections are currently being used in a relative benchmark methodology with great success in typical preliminary investigations (Horak and Emery, 2006; Horak, 2008; Horak et al., 2015).

Benchmark methodology is best utilised as a screening tool for evaluation of pavement layers after construction to identify areas of potential structural defects. Such areas and zones of relative more distress than others can then be analysed in more detail by various other means.

The well-known Red, Amber, Green (RAG) condition rating system, often applied in pavement management systems (PMS) and pavement condition ratings, is utilised in this simplified deflection bowl parameter and surface modulus benchmark evaluation. The criteria for the RAG relative structural condition states are based on a semi-empirical model which provides for accurate benchmark or relative evaluation of pavement structural capability (Horak and Emery, 2006; Horak, 2008; Horak et al., 2015).

In this chapter the analysed LFWD deflection measurements sampled at WAFB is utilised to establish a benchmark methodology in collaboration with the RAG condition rating system. Measurements sampled at WAFB were used because the pavement structure was constructed with conventional pavement layers and materials typical to South Africa. The pavement structures present at the other testing sites comprise of unconventional pavement layers under different climatic and material conditions. Detailed benchmark methodology results are included in Appendix E.

6.2 DEFLECTION BOWL PARAMETERS

Sections 6.2.1 to 6.2.2 present the development and proposed benchmark ranges of the LFWD deflection bowl parameters.

6.2.1 Development of LFWD deflection bowl parameter benchmark ranges

The deflection bowl parameters with respective benchmark methodology are typically used with FWD data, however, could also be utilised for the interpretation of LFWD data.

The conventional FWD deflection bowl parameter benchmarking methodology for granular pavement layers are specifically based a contact pressure of 566 kPa. Previous research included benchmarking ranges for various contact pressures from 566 kPa up to 1 700 kPa. The ranges indicated for 566 kPa and 700 kPa are most commonly used for flexible road pavement structures and associated loading and those with contact pressures of 1 415 kPa and 1 700 kPa for airport pavement structures and their loading quanta (Horak and Emery, 2009; Horak et al., 2015).

These criteria are based on an extension downwards of criteria used with the FWD based on contact pressure versus deflection. The LFWD contact pressure for a 200 mm bearing plate used during this study was 312 kPa. The higher contact pressures achievable with variable weight drop versus deflections measured formed the basis of RAG criteria developed for roads and airports (Horak and Emery, 2006; Horak, 2008; Horak et al., 2015). Table 6.1 presents the FWD deflection bowl parameter benchmark ranges with 566 kPa contact pressure (40kN) on a granular base pavement.

Table 6.1: FWD deflection bowl parameter benchmark ranges for 566 kPa contact pressure (40kN) on a granular base (Horak and Emery, 2009).

Structural Condition Rating	Maximum Deflection (micron)	RoC (micron)	BLI (micron)
Sound	<500	> 100	< 200
Warning	500 to 750	50 to 100	200 to 400
Severe	> 750	< 50	> 400

It is of critical importance to note that there is a clear difference between the FWD and the LFWD deflection bowl parameter benchmark ranges. These benchmark ranges should not be confused with one another as the deflection bowl parameters do not represent the same corollary. The variance in dropped weight alters the contact pressure of the loading plate which consequently yields different deflection measurements (Horak et al., 2015).

Figures 6.1 to 6.3 and Tables 6.2 to 6.4 illustrate the downward extension of the established FWD contact pressure ranges to the LFWD contact pressure of 312 kPa.

Table 6.2: Maximum deflection benchmark ranges with varying contact pressures on a granular base pavement.

Contact Stress (kPa)	RAG Condition Rating		
	Sound	Warning	Severe
566 (40 kN)	< 500	500 to 750	> 750
700 (50 kN)	< 625	625 to 925	> 925
1415 (100 kN)	< 1250	1250 to 1900	> 1900
1700 (120 kN)	< 1500	1500 to 2250	> 2250

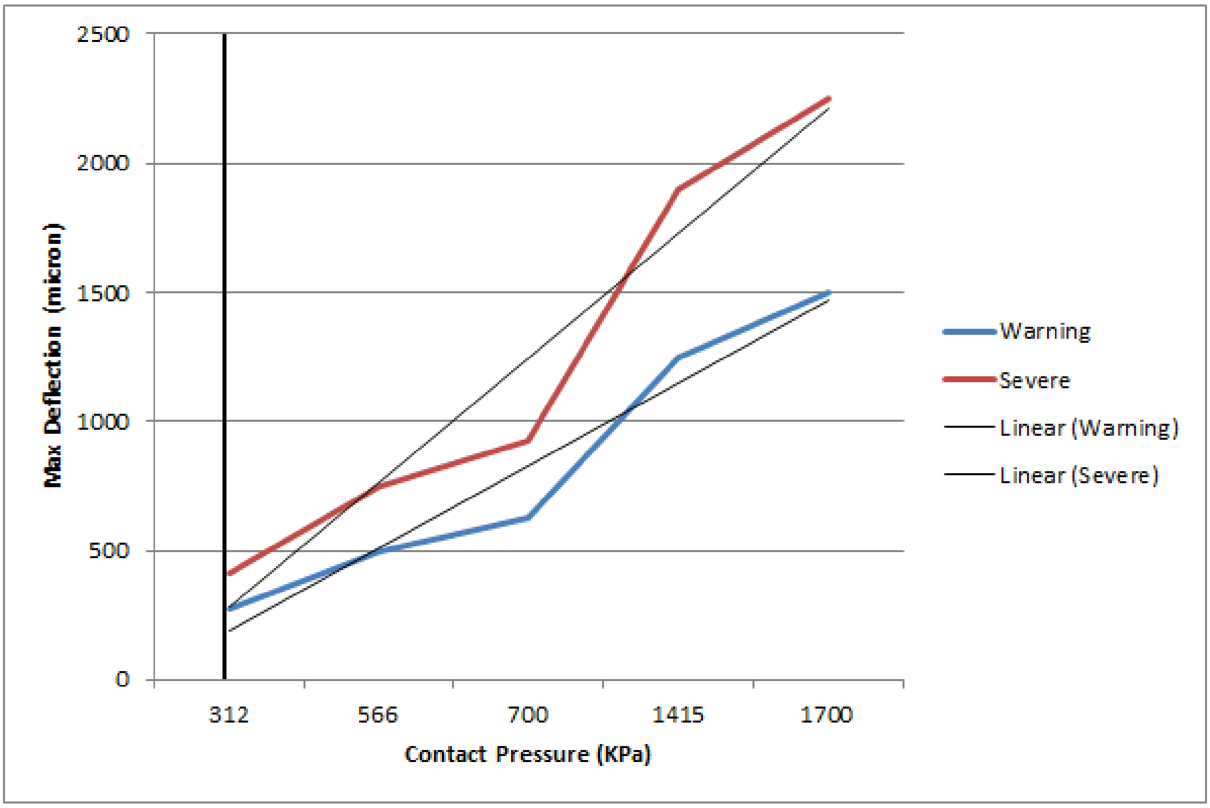

Figure 6.1: Maximum deflection benchmark ranges with varying contact pressures on a granular base pavement.

Table 6.3: RoC benchmark ranges with varying contact pressures on a granular base pavement.

Contact Stress (kPa)	RAG Condition Rating		
	Sound	Warning	Severe
566 (Standard FWD)	100	50	0
700	90	42	0
1415	70	28	0
1700	60	20	0

Normally LFWD geophones are placed at 0mm, 300mm and 600mm. This means that the RoC is calculated at an offset of 300 mm from the centre geophone while the RoC for FWD measurements is calculated at an offset of 200 mm from the centre geophone. The downward extension of the established FWD contact pressure ranges to the LFWD contact pressure is therefore hypothetically inaccurate. The difficulty with adjusting the LFWD geophone to the same 200 mm offset like that of the FWD, is that the closer spacing of the LFWD geophone to the loading plate becomes very prone to interference / disturbance from the compression wave.

These RoC benchmark ranges are consequently only utilised as a first step indicator to determining the appropriate RoC benchmark ranges.

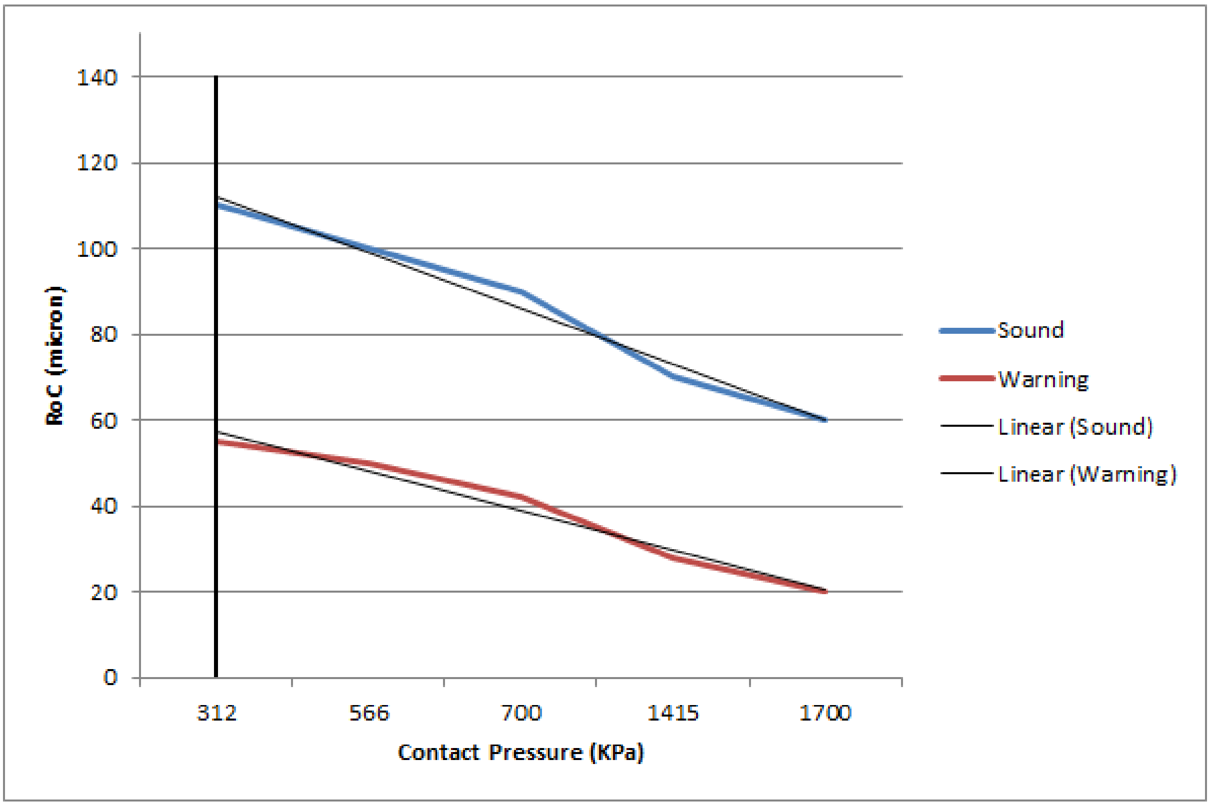

Figure 6.2: Roc benchmark ranges with varying contact pressures on a granular base pavement.

Table 6.4: BLI benchmark ranges with varying contact pressures on a granular base pavement.

Contact Stress (kPa)	RAG Condition Rating		
	Sound	Warning	Severe
312 (LFWD)	0	110	220
566 (Standard FWD)	0	200	400
700	0	250	475
1415	0	500	1000
1700	0	600	1200

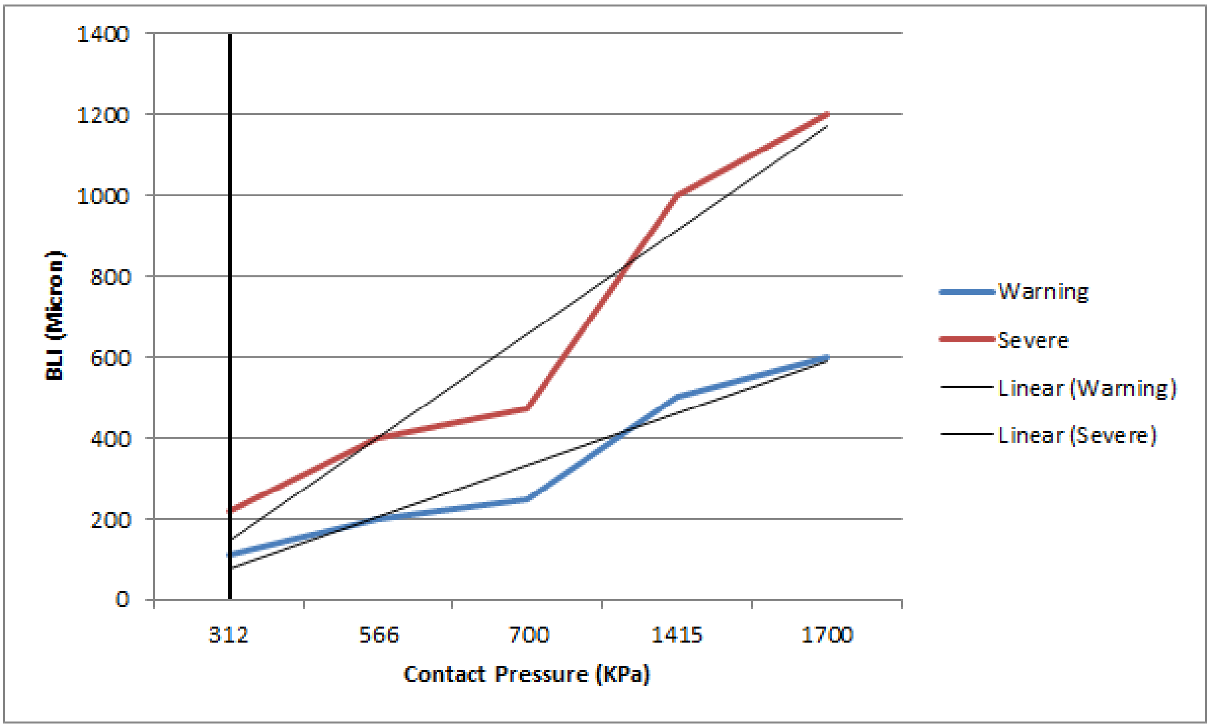

Figure 6.3: BLI benchmark ranges with varying contact pressures on a granular base pavement.

6.2.2 Proposed benchmark ranges for LFWD deflection bowl parameters

From Section 6.2.1 the proposed benchmark ranges for a Dynatest 3031 LFWD device with a contact pressure of 312 kPa on a granular base pavement is presented in Table 6.5.

Table 6.5: Proposed LFWD deflection bowl parameter benchmark ranges for a granular base.

Structural Condition Rating	Maximum Deflection (micron)	RoC (micron)	BLI (micron)
Sound	<500	> 110	< 400
Warning	500 to 700	55 to 110	400 to 600
Severe	> 700	< 55	> 600

These values have been rounded off to help simplify the analysis procedure which is largely graphical in nature which shows that there is enough room for further adjustments once the concept is understood. This is therefore merely a comparative benchmark and should not be confused with actual structural strength of the pavement structure or its layers. Figures 6.4 to 6.6 illustrate the proposed LFWD deflection bowl parameters benchmark ranges applied to the G1 base layer at WAFB.

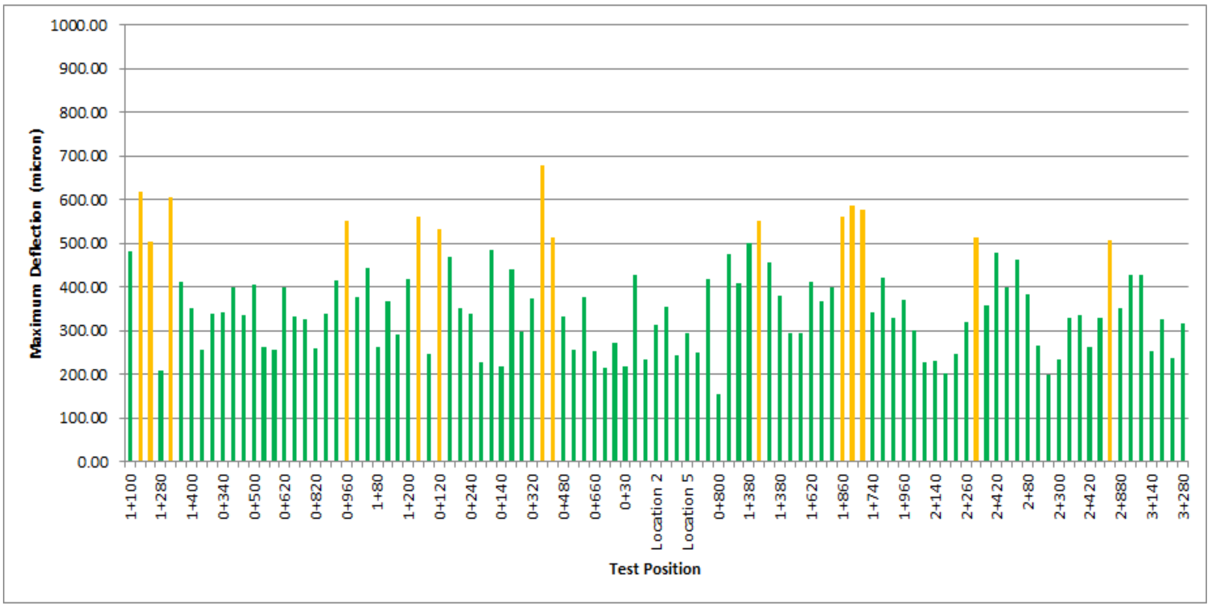

Figure 6.4: Proposed LFWD Maximum Deflection benchmark ranges applied to the WAFB G1 base layer.

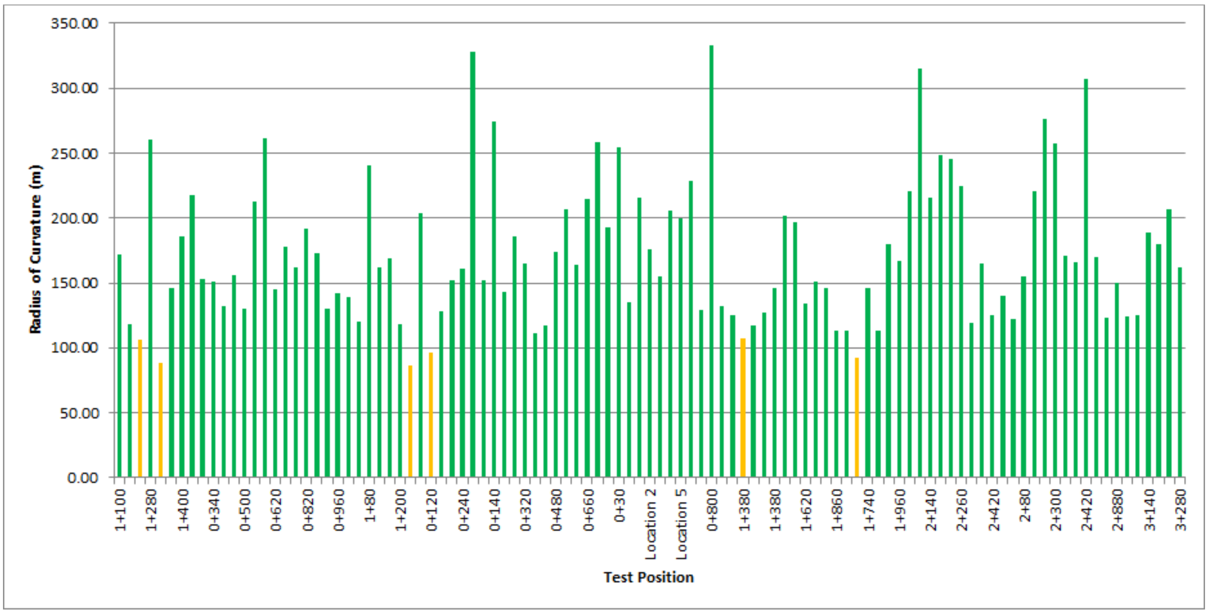

Figure 6.5: Proposed LFWD RoC benchmark ranges applied to the WAFB G1 base layer.

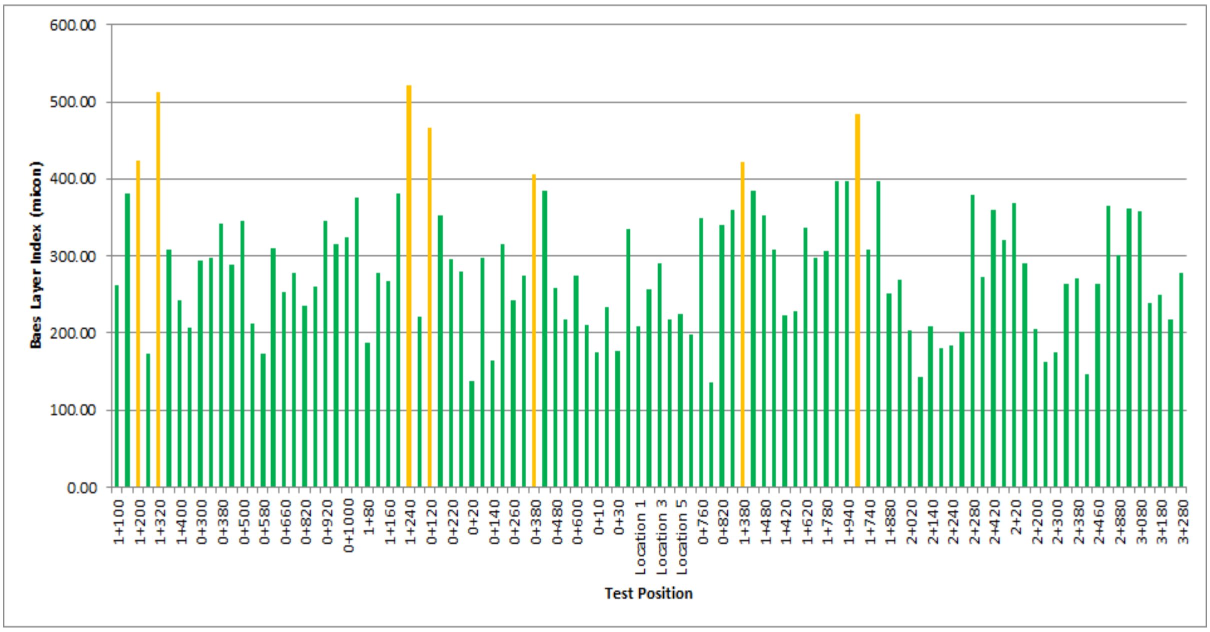

Figure 6.6: Proposed LFWD BLI benchmark ranges applied to the WAFB G1 base layer.

One of the shortcomings of the LFWD is the lower reliability of the deflection measurements of the offset geophones (300 mm and 600 mm). This is more pronounced on stiffer pavement layers and when the surface is cracked. It is a combination of surface wave interruptions and compression wave distortion close to the loaded plate edge which causes erratic measurements on the offset geophone closest to the loaded plate edge. The best measurement for benchmark analysis therefore is using the maximum deflection directly or the calculated surface modulus based on maximum deflection.

6.3 SURFACE MODULUS

The surface modulus is an average value and like all other effective moduli calculations specific to the test methodology and technology or equipment used (Ullidtz, 1987). Typically an effective elastic modulus or even surface modulus calculated with FWD data will be different from a surface modulus calculated from LFWD testing on the same material layer. Therefore surface modulus values determined with the LFWD is also best suited for relative comparison via benchmark analysis.

6.3.1 Proposed benchmark ranges for LFWD Surface Moduli

The surface modulus was found to be the most consistent method in determining whether a zone or area experiences distress and can therefore be benchmarked in the fashion suggested for the deflection bowl parameters. Table 6.6 shows the preliminary proposed criteria for the combined granular (G1 to G10) pavement layer surface modulus benchmark ranges.

Table 6.6: Proposed LFWD surface modulus benchmark ranges for a granular base.

Structural Condition Rating	Surface Modulus (MPa)
Sound	> 75
Warning	50 to 75
Severe	< 50

Similar to the proposed LFWD deflection bowl parameter benchmark ranges in the previous section, these values have been rounded off to help simplify the analysis procedure which is largely graphical in nature which shows that there is enough room for further adjustments once the concept is understood that this is merely a comparative benchmark and should not be confused with actual structural strength of the pavement structure or its layers. Figure 6.7 illustrates the proposed LFWD surface modulus benchmark ranges applied to the G1 base layer at WAFB.

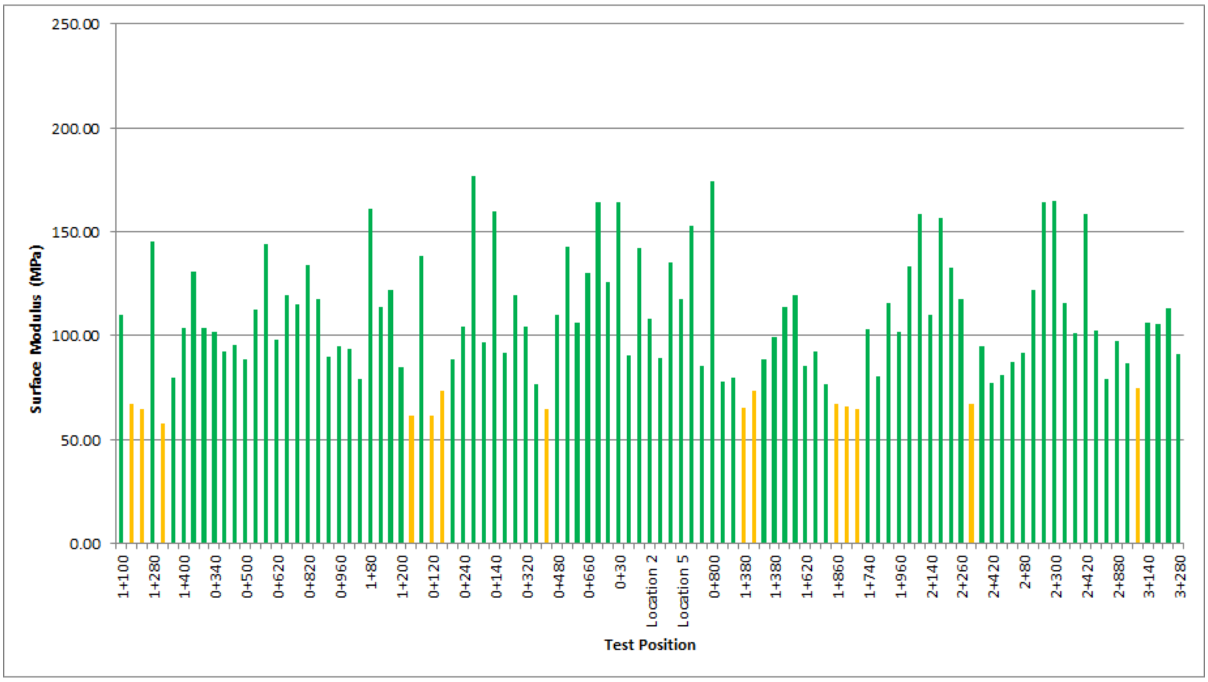

Figure 6.7: Proposed LFWD surface modulus benchmark ranges applied to WAFB G1 base layer.

The RAG criteria may also differ from site to site, but serves the purpose of identifying areas or spots where the granular base seems to be structurally less sound than elsewhere. Large amounts of LFWD deflection measurements are sampled that act as a screening tool. The deflection measurements can also be accompanied with a visual inspection while the tests are being conducted in order to improve the screening process. Additional standard quality control tests (density, grading, moisture etc.) can then be done to verify potential problems.

6.4 SUMMARY

In this chapter the analysed LFWD deflection measurements sampled at WAFB was utilised to establish a benchmark methodology in collaboration with the RAG condition rating system. Measurements sampled at WAFB were used because the pavement structure was constructed with conventional pavement layers and materials typical to South Africa. The pavement structures present at the other testing sites comprise of unconventional pavement layers under different climatic and material conditions

LFWD deflection bowl benchmark analysis using only the maximum deflection, BLI and RoC can in conjunction with the calculated surface modulus values can be effectively used as a first step screening tool in identifying areas or zones of distress in a newly constructed pavement layer. The ranges for the use of the RAG structural condition ratings for a contact pressure of 312 kPa have been slightly revised and rounded off for ease of use. Revised RAG ranges and updated LFWD derived deflection bowl parameters and proposed surface modulus values are suggested in summary for granular base pavements in Tables 6.5 and 6.6. It should be noted that that these parameters are biased towards the more flexible ranges of elastic response and not towards the very stiff pavements or upper ranges. In the absence of a large database these RAG criteria still have considerable subjectivity attached to such suggested ranges. In spite of the exactness of the current RAG criteria, it had been experienced that such a high sample density non-destructive test method and benchmarking can help identify areas or spots in a constructed layer which warrants additional conventional testing.

Additional research is however necessary to continuously improve and revise the proposed ranges even for the respective material types (G1 to G10) in order to achieve accurate and reliable flexible pavement quality and acceptance control procedures in the LFWD device.

6.5 REFERENCES

Horak, E. (2008). *'Benchmarking the structural condition of flexible pavements with deflection bowl parameters'*, Journal of the South African Institute of Civil Engineering, Vol. 50, No 2, June, pp 2-9.

Horak, E. and Emery, S. (2006). *'Falling Weight Deflectometer Bowl Parameters as an analysis tool for pavement structural evaluations'*, proceedings of the 22nd Australian Road Research Board (ARRB) International Conference, October 2006, Brisbane, Australia.

Horak, E. and Emery, S. (2009). *'Evaluation of airport pavements with FWD deflection bowl parameter benchmarking methodology'*, 2nd European Airport Pavement Workshop, 13-14 May 2009, Amsterdam, Netherlands.

Horak, E., Emery, S. and Maina, J. (2015). *'Review of FWD benchmark analysis on road and runways'*, proceedings of the 11th South African Conference on Asphalt Pavements (CAPSA), August 2015, Sun City, South Africa.

Horak, E., Hefer, A. and Maina, J. (2015). *'Determining pavement number values for flexible pavements utilising falling weight deflectometer deflection bowl information'*, proceedings of the 34th South African Transport Conference (SATC), July 2015, Pretoria, South Africa.

Ullidtz, P. (1987). *'Pavement Analysis'*, Elsevier Science, New York, U.S.A.

7 CONCLUSIONS AND RECOMMENDATIONS

7.1 CONCLUSIONS

The conclusions of this study are presented in terms of the research objectives as illustrated below:

1. Investigate the influence of various parameters on the surface moduli and deflection bowl parameters yielded by the LFWD.

   This objective was realised by achieving the following sub-objectives:

   a. Established an operation protocol for operating the Dynatest 3031 LFWD and for analysing the output data;
   b. Determined that a strong relationship exists between the pavement layer strength (as calculated from LFWD deflection measurements) and the relative density of a newly constructed pavement layer. Therefore this correlation relationship would enable LFWD measurements and calculations such as the surface modulus to indicate with confidence when such a constructed layer may in fact not meet the density requirements;
   c. Related the LFWD 'GN' target values established by the Minnesota Department of Transportation with the LFWD deflection measurements recorded at WAFB and found that the LFWD data and protocol is relatable between the different countries of testing;
   d. Established that the 'time series' LFWD data is an useful indicator in monitoring the curing period (i.e. observing the increase in pavement strength) for certain pavement layers, and
   e. Established that the maximum deflection and surface moduli measurements clearly indicate a distinction between sound and distressed asphalt pavements. The LFWD device could be utilised in a relative analysis application during the construction stage as supplementary tool in a quality control testing, even for asphalt layers.

2. Establish a reliable relationship between LFWD stiffness results, deflection bowl parameters and other pavement material parameters as used in the known benchmark method.

   A comparative benchmark methodology in collaboration with the RAG condition rating system was developed for the LFWD deflection bowl parameters as well as the LFWD surface moduli. These proposed benchmark ranges for a Dynatest 3031 LFWD device with a contact pressure of 312 kPa on a granular base pavement is presented in Table 7.1 and 7.2.

Table 7.1: Proposed LFWD deflection bowl parameter benchmark ranges for a granular base.

Structural Condition Rating	Maximum Deflection (micron)	RoC_{300} (micron)	BLI (micron)
Sound	<500	> 110	< 400
Warning	500 to 700	55 to 110	400 to 600
Severe	> 700	< 55	> 600

Table 7.2: Proposed LFWD surface modulus benchmark ranges for a granular base.

Structural Condition Rating	Surface Modulus (MPa)
Sound	> 75
Warning	50 to 75
Severe	< 50

3. Accurately predict the model or monitor the basic material characteristics and enhance standard construction quality control testing in a practical engineering quality control application.

   The findings of this this study confirm that that the LFWD can be utilised as a non-destructive quality control testing device in a practical engineering quality control application. In spite of the lack of exactness of the current RAG criteria, it had been experienced that such a high sample density non-destructive test method and benchmarking can help identify areas or spots in a constructed layer which warrants additional conventional testing. Additional research is however necessary to continuously improve and revise the proposed ranges in order to achieve accurate and reliable flexible pavement quality and acceptance control procedures for the LFWD device.

7.2 RECOMMENDATIONS

The opportunity exists to contribute directly to flexible pavement quality and acceptance control procedures that are utilised on construction sites. The LFWD deflection measurements are non-destructive and not time-consuming. Due to mobility of the LFWD a significant amount of test measurements are able to be taken ensuring a considerable distribution and sample size. The LFWD will best be utilised in a deflection bowl and surface modulus benchmark application in collaboration with the RAG condition rating system in identifying weaker or distressed zones where additional standard quality control tests can be done to verify any potential problems.

The following recommendations are presented:

1. A standard Dynatest 3031 LFWD operation protocol be utilised on all South African construction sites;
2. Even though previous research indicated the effective depth of influence of the LFWD to be between 200 mm and 300 mm, it was established during this study that for the most reliable and repeatable LFWD measurements, evaluation should be limited to the top 150 mm of a granular pavement structure, i.e. the top granular pavement layer;
3. Further LFWD deflection measurements should be recorded on pavement layers representing the full spectrum of pavement strength, i.e. partially compacted or failing pavement layers to fully compacted pavement layers with satisfactory pavement strength;
4. Additional LFWD deflection measurements should be sampled on all of the different granular pavement types ranging from G1 to G10 in order to create a relationship / model for each quality material pavement type;
5. Further research should be conducted to isolate the contribution of the underlying layers to the surface modulus of the granular pavement layer being constructed, and
6. The proposed LFWD deflection bowl parameters and surface modulus benchmark ranges should be utilised on construction sites as a comparative benchmark screening tool in identifying areas or spots where the granular layer seems to be structurally less sound than elsewhere. The ranges can be adjusted / amended accordingly when additional research has been completed.

8 REFERENCES

Abu-Farsakh, M., Alshibli, K., Nazzal, M. and Seyman, E. (2004). *'Assessment of In-situ Test Technology for Construction Control of Base Courses and Embankments*'. Louisiana Transportation Research Centre, Federal Highway Administration.

American Association for Highway Transportation Officials (AASHTO), (1928), M 145 or ASTM D3282, U.S.A.

Anochie-Boateng, J.K. (2007). *'Advance Testing and Characterisation of Transportation Soils and Bituminous Sands'*, PhD dissertation, University of Illinois, Urbana, U.S.A.

Apeagyei, A.K. and Hossain, M.S. (2010). *'Stiffness-Based Evaluation of Base and Subgrade Quality using Three Portable Devices'*, proceedings of the 89th Transportation Research Board (TRB) Annual Meeting, January 10 -14 2010, Washington. U.S.A.

Committee of Land Transport Officials (COLTO). (1998). *'Standard Specifications for Road and Bridge Works for State Road Authorities'*, South African Institution of Civil Engineering (SAICE), Halfway House, South Africa.

Davich, P., Camargo, F., Larsen, B., Roberson, R. and Siekmeier, J. (2006). *'Validation of DCP and LWD Moisture Specifications for Granular Materials'*, Minnesota Department of Transport, Minnesota, U.S.A.

Dawson, A. (2009). *'Water in Road Structures - Movement, Drainage and Effects'*, Geotechnical, Geological and Earthquake Engineering, Volume 5, Springer Science and Business Media B.V. (Based on WATMOVE study reported as COST Action No. 351).

De Beer, M. and Maina, J. (2008). *'Some Fundamental Definitions of the Elastic Parameters for Homogeneous Isotropic Linear Elastic Materials in Pavement Design and Analysis'*, proceedings of the 27th South African Transport Conference (SATC), July 2008, Pretoria, South Africa.

Du Tertre, A., Cascante, G. and Tighe, S.L. (2010). *'Combining PFWD and Surface wave Measurements for Evaluation of Longitudinal Joints in Asphalt Pavements'*, proceedings of the 89th Transportation Research Board (TRB) Annual Meeting, January 10 -14 2010, Washington. U.S.A.

Dynatest (2014). *'Dynatest 3031 Light Weight Deflectometer (LWD)'*, www.dynatest.com, (5 May 2014).

Edwards, P. and Flemming, P. (2009). *'LWD Good Practice Guide (Draft 9)'*, Pavement Foundation Group (PFG), Minnesota, U.S.A.

Elhakim, A.F., Elbaz, K. and Amer, K.I. (2014). 'The use of light weight deflectometer for in-situ evaluation of sand degree of compaction', Housing and Building National Research Center (HBRC), Cairo, Egypt.

Embacher, R.A. (2007). *'Intelligent Compaction and Lightweight Deflectometer Technology Transfer Workshop'*, IC and LWD Workshop, Minnesota Department of Transport, Minnesota, U.S.A.

Embacher, R.A. (2008). *'LWD Fundamentals'*, proceedings of the 12th Annual Minnesota Paving Conference, February 2008, Minnesota, U.S.A.

Flemming, P. (2008). *'Intelligent Compaction and Lightweight Deflectometer Technology Transfer Workshop',* IC and LWD Workshop, Minnesota Department of Transport, Minnesota, U.S.A.

Flemming, P.R., Frost, M.W and Lambert, J.P. (2007). *'A Review of the Lightweight Deflectometer (LWD) for Routine In-situ Assessment of Pavement Material Stiffness'*, proceedings of the 86th Transportation Research Board (TRB) Annual Meeting, July 7 -9 2007, Washington.

Gere, J.M. (2001). *'Mechanics of materials'*, Fifth Edition, Brooks/Cole, U.S.A.

Grading and Base Manual (2015). 'Minnesota Department of Transport : Grading and base manual', Geotechnical Section, Minnesota Department of Transport, Minnesota, U.S.A.

Guiamba, D.Z. (2011). *'Comparitive study of non-destructive field testing devices on bitumen emulsion stabilised materials'*, MSc. Thesis, University of Pretoria, Pretoria, South Africa.

Hicks, R.G. and Monismith, C.L. (1971). *'Factors influencing the resilient properties of granular materials'*, Transportation Research Record 345, Transportation Research Board (TRB), Washington, U.S.A.

Highways Department (2000). *'Guidance notes on backcalculation of layer moduli and estimation of residual life using falling weight deflectometer test data'*, Research and Development Division, Hong Kong, China.

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.

Horak, E. (2007). *'Surface Moduli Determined with the falling weight deflectometer used as a benchmarking tool*, proceedings of the 26th South African Transport Conference (SATC), July 2007, Pretoria, South Africa.

Horak, E. (2008). *'Benchmarking the structural condition of flexible pavements with deflection bowl parameters'*, Journal of the South African Institute of Civil Engineering, Vol. 50, No 2, June, pp 2-9.

Horak, E. and Emery, S. (2006). *'Falling Weight Deflectometer Bowl Parameters as an analysis tool for pavement structural evaluations'*, proceedings of the 22nd Australian Road Research Board (ARRB) International Conference, October 2006, Brisbane, Australia.

Horak, E. and Emery, S. (2009). *'Evaluation of airport pavements with FWD deflection bowl parameter benchmarking methodology'*, 2nd European Airport Pavement Workshop, 13-14 May 2009, Amsterdam, Netherlands.

Horak, E., Emery, S. and Maina, J. (2015). *'Review of FWD benchmark analysis on road and runways'*, proceedings of the 11th South African Conference on Asphalt Pavements (CAPSA), August 2015, Sun City, South Africa.

Horak, E., Hefer, A. and Maina, J. (2015).*'Determining pavement number values for flexible pavements utilising falling weight deflectometer deflection bowl information'*, proceedings of the 34th South African Transport Conference (SATC), July 2015, Pretoria, South Africa.

Horak, E. and Khumalo, T. (2006). *'Deflection bowl parameters correlation of a light and standard falling weight* deflectometer', proceedings of the 4th South African Road Federation (SARF) / International Road Federation (IRF), September 2006, Durban, South Africa.

Horak, E., Maina, J., Guiamba, D. and Hartman, A. (2008). *'Correlation study with the light weight deflectometer in South Africa'*, proceedings of the 27th South African Transport Conference (SATC), July 2008, Pretoria, South Africa.

Jorenby, B. N., and Hicks, R. J. (1986). *'Base Course Contamination Limits'*, Transportation Research Record 1095, TRB, National Research Council, Washington, U.S.A., pp. 86–101.

Lekarp, F., Isacsson, U. and Dawson, A. (2000). *'State of the art I : Resilient response of unbound aggregates'*, Journal of Transportation Engineering, Volume 126, No. 1, January / February, 2000, pp 66-75.

Lindemann, M., 2014. *'Nuclear Vs. Non-nuclear testing and transition development of curves'*, proceedings of the 93rd annual meeting of the Western Association of State Highway and Transportation Officials (WASHTO), New Mexico, U.S.A.

Materials Manual (2006). *'Materials Manual : Chapter 16: Acceptance Control for Base layers'*, Department of Transport and Public Works: Western Cape Provincial Administration, Cape Town, South Africa.

Mork, H. (2008). *'Light Weight Deflectometer, principles and Versatility'*, proceedings at the NVF/BRA Symposium, February 2008, Oslo, Norway.

Nazzal, M. (2003). *'Field Evaluation of - Test Technology QC/QA during Construction of Pavement Layers and Embankments'*, MSc Thesis, Louisiana State University, Louisiana, U.S.A.

Odemark, N., (1949). "Investigations as to the elasticity properties of soils and design of pavements according to the theory of elasticity." Report No,77, Statens Vaeginstitut, Stockholm, Sweden.

Oman, M. (2004). *'Advancement of grading and base material testing'*, Minnesota Department of Transportation, Minnesota, U.S.A.

Petersen, J.S., Romanoschi, S.A., Onyango, M. and Hossain, M. (2007). *'Evaluation of Prima Light FWD as a Quality Control Tool for the Compaction of Fine Grained Soils'*, proceedings of the 86th Transportation Research Board (TRB) Annual Meeting, January 21 -25 2007, Washington. U.S.A.

Pronk, A. (1994). *'Equivalent Layer Theories: State of the Art Report'*, Dienst Weg en Waterboukunde (DWW), Delft, Netherlands.

SAPEM (2014). *'South African Design Manual (SAPEM)'*, Second Edition, March 2014, South African National Roads Agency SOC Ltd (SANRAL), Pretoria, South Africa.

Seed, H.C., Chan, C.K. and Lee, C.E. (1962). *'Resilient characteristics of subgrade soils and their relation to fatigue failures in asphalt pavements'*, proceedings of International Conference on Structural Design of Asphalt Pavements, University of Michigan, U.S.A.

Senseney, C.T. and Mooney, M.A. (2010). *'Characterization of a two-layer soil system using a lightweight deflectometer with radial sensors'*, proceedings of the 88th Transportation Research Board (TRB) Annual Meeting, January 11 -15 2010, Washington. U.S.A.

Senseney, C.T., Grasmick, J. and Mooney, M.A. (2015). *'Sensitivity of lightweight deflectometer deflections to layer stiffness via finite element analysis'*, Canadian Geotechnical Journal, Vol 52, 2015, pp 961-970

Siddiki, N. (2012). *'Light Weight Deflectometer'*, Worksop, Office of Geotechnical Services, Indiana Department of Transportation, Indiana, U.S.A.

Siekmeier, J., Pinta, C., Merth, S., Jensen, J., Davich, P., Camargo, F. and Beyer, M. (2009). *'Using the Dynamic Cone Penetrometer and Light Weight Deflectometer for Construction Quality Assurance'*, Report no. MN/RC 2009-12, Minnesota Department of Transport, Minnesota, U.S.A.

Stamp, D.H. and Mooney, M.A. (2013). *'Influence of Lightweight Deflectometer Characteristics on Deflection Measurement'*, Geotechnical Testing Journal, Vol. 36, No. 2, 2013, pp. 216–226, doi:10.1520/GTJ20120034. ISSN 0149-6115.

Tan, D., Hill, K. and Khazanovich, L. (2014), *'Quantifying Moisture Effects in DCP and LWD Tests Using Unsaturated Mechanics'*, Minnesota Department of Transport, Minnesota, U.S.A.

Tan, D.J., Khazanovich, L., Siekmeier, J. and Hill, K.M. (2014). *'Discrete Element Modelling of the Effect of Moisture and Fine Particles in the Light Weight Deflectometer Test'*, proceedings of the 93rd Transportation Research Board (TRB) Annual Meeting, January 12 -16 2014, Washington. U.S.A.

TG 2 (2009). *'Technical Guideline 2: Bitumen Stabilised Materials'*, Second Edition, May 2009, Asphalt Academy, Pretoria, South Africa.

Theyse, H. (2006). *'The Suction Pressure, Yield Strength and Effective Stress of Partially Saturated Unbound Granular Pavement Layers'*, CSIR Built Environment, Pretoria, South Africa.

TIC Service Group (2011), *'Light Weight Deflectometer Measuring Dynamic Modulus and CBR on-site immediately'*, workshop, TIC Service Group, Australia.

TMH 1 (1985). *'Technical Methods Highways 1 : Standard test methods for roadbuilding materials'*, Department of Transport, Pretoria, South Africa.

TRH 14 (1985). *'TRH 14 : Guidelines for road construction materials'*, Department of Transport, Pretoria, South Africa.

TRH 4 (1996). *'Draft TRH 4 : Structural design of flexible pavements for interurban and rural roads'*, Department of Transport, Pretoria, South Africa.

TRH 12 (1997). *'Draft TRH 12 : Flexible pavement rehabilitation investigation and design'*, Department of Transport, Pretoria, South Africa.

Ullidtz, P. (1987). *'Pavement Analysis'*, Elsevier Science, New York, U.S.A.

Ullidtz, P. (2005). *'Modelling Flexible Pavement response and Performance'*, ISBN 8750208055, Elsevier, New York, 2005.

Ullidtz, P., Krakup, J. and Wahlman, T. (1994). *'Verification of pavement response models'*, Non-destructive testing of pavements and backcalculation of moduli (Second Volume), ASTM STP 1198, American Society for Testing and Materials (ASTM), Philadelphia, U.S.A.

Umashankar, B., Hariprasad, C. and Kumar, G. (2015). *'Compaction Quality Control of Pavement Layers using LWD'*, Journal of Materials in Civil Engineering, 10.1061/(ASCE)MT.1943-5533.0001379.

Van As, S. (2010). *'Applied Statistics for Civil Engineers'*, B.Eng Honours course material, University of Pretoria, Pretoria, South Africa.

Van Aswegen, E. (2013). *'Effect of Density and Moisture Content on the Resilient Response of Unbound Granular Material'*, PhD dissertation, University of Pretoria, Pretoria, South Africa.

Yoder, E.J. and Witczak, M.K. (1975). *'Principles of Pavement Design'*, Second Edition, John Wiley and Sons.

Zhang, J. (2010). *'Evaluation of Mechanistic based compaction measurements for earthwork QC/QA'*, MSc Thesis, Iowa State University, Iowa, U.S.A.

Zhang, Z., Claros, G., Manual, L. and Damnjavonic, I. (2003). *'Evaluation of the pavement structural condition at network level using falling weight deflectometer (FWD) data'*, Paper presented at 82nd Transportation Research Board (TRB) Annual Meeting, January 12 -16 2003, Washington, U.S.A.

Zhang, Z., Murphy, M.R. and Peddidhotla (2011). '*Implementation study of a structural condition index at the network level'*, proceedings of the 8th International Conference on Managing Pavement Assets (ICMPA), Paper ICPMA145, November 15 – 19 November 2011, Santiago, Chile.