DETERMINATION OF PAVEMENT NUMBER FOR FLEXIBLE PAVEMENTS USING FWD DEFLECTION BOWL INFORMATION

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ABSTRACT

Structural Number (SN) is a well-known pavement index methodology derived from the product of structural layer coefficients, layer thicknesses and environmental (and drainage) factors. Subsequently, the Adjusted Structural Number (SNP) included the influence of the subgrade on pavement strength. The Pavement Number (PN) was recently developed in South Africa as an index similar to the SNP. However, in the PN calculation Equivalent Long Term Stiffness (ELTS) values are derived from material class inputs in a knowledge-based system. An approach to calculate the Effective Pavement Number (PN_{eff}), is proposed which utilises the full deflection bowl more effectively in the calculation. It uses the Shape Factor (F_1) to determine equivalent layer thickness (H_e) and FWD deflections at offset of 300mm from the centre of loading to derive Surface Modulus (SM) inputs for calculating an ELTS value representing the total pavement structure, SM_{pav}. The product of the H_e and SM_{pav} thus provides a derived PN_{eff} value. A large database of flexible pavements was used to successfully validate this approach. It is demonstrated that PN_{eff}, thus derived from the utilisation of the full deflection bowl and without detailed information of pavement layer thicknesses can be used to complement initial or preliminary structural evaluation. It is illustrated how PN_{eff} is used in a benchmark methodology with FWD surveys. The well established FWD deflection bowl structural benchmark analysis method can then further enhance this preliminary structural analysis with PN_{eff} by assisting in a preliminary analysis and helping to determine origin of distress. Hereafter detailed structural analyses can follow with detailed material type and pavement layer information in a much more focussed fashion.

1. INTRODUCTION

Methods for pavement structural evaluation originating from the Benkelman Beam (BB) surveys were developed based on empirical relationships utilizing maximum deflection and became well entrenched world-wide as non-destructive evaluation tools. However, by the early 1980s, the Falling Weight Deflectometer (FWD) had become the non-destructive deflection measurement tool of choice. Although the FWD largely replaced the BB, the tendency to only use maximum deflection in pavement evaluations continued as if the FWD was merely an extension or modern

BB with improved measurement of maximum deflection as focus. Non-reliable conversions from BB to FWD maximum deflections thus followed from this simplistic use of the FWD with limited practical value. The wealth of structural response imbedded in the rest of the FWD deflection bowl therefore was largely ignored. (Horak and Emery, 2006).

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 (Horak and Emery, 2006 and Zhang et al., 2003 and 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, 2007 and 2008).

The basic slope deflection bowl parameters include Maximum Deflection (Y_{Max}) reflecting the total pavement response, Base Layer Index (BLI) reflecting the base and surfacing structural condition, Middle Layer Index (MLI) reflecting the subbase layer structural condition and Lower Layer Index (LLI) reflecting the subgrade and selected layer structural condition. These basic deflection bowl parameters are associated with different pavement layer zones in depth of the pavement structure. Therefore relative structural strength or condition of such layer zones can help to identify possible origin of distress of pavement layers without having detailed information on layer depth and material class yet. Subsequent correlations with a large database have found that Radius of Curvature (RoC_{200}) determined from deflections at 0 and 200mm from load centre, is a good indicator of the asphalt surfacing and top of the base layer structural condition. This is in-line with work previously done by Dehlen (Horak et al., 2006, and 2015 and Horak, 2007, 2008). Various new generation area parameters (dimensionless representation of the zones of area under the deflection bowl) also enhance such benchmark analysis considerably.

FWD based benchmark analysis is normally done early in the preliminary investigation phase with limited as-built knowledge of the pavement structure available. No detailed layer thickness knowledge is needed for such a flexible pavement preliminary analysis with this benchmark analysis. However, such detailed pavement layer information is a definite requirement for more detailed analysis when effective elastic moduli are determined via multi-layered linear elastic or finite element numerical models from measured deflection bowls (Maina et al., 2009).
This simplified FWD based benchmark analysis method 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 and Horak et al., 2007, 2008 and 2015). This benchmark methodology demonstrated that the inherent knowledge of the whole deflection bowl can be used effectively for structural evaluations in an initial or preliminary analysis stage.

Apart from sophisticated mechanistic analyses procedures and models, other simplified approaches such as the use of the Structural Number (SN) have been developed and used by the American Association of State Highway and Transport Officials (AASHTO) (Jooste and Long, 2007). The SN index value is basically determined by means of the accumulation of the product of layer thicknesses, an assigned material type coefficient and an environmental factor or drainage factor for each pavement layer. The SN value thus determined represents a pavement structural value for direct structural potential comparison and thus relative structural benchmarking.

The SN method is described as an index methodology and has found application world-wide. Typically the well-known Highway Development and Management Model (HDM) analysis tool (Paterson, 1987) made use of the modified SN values (SNC) determined in various ways in their latest software such as HDM4. In traditional calculations of SN or SNC, detailed information on materials and pavement layer thicknesses is required. Research and development work by Rohde (1994 and 1995) explored the use of the FWD deflections to develop correlations between SNC and at least two points on the deflection bowl. In his approach maximum deflection and a deflection on the outer regions of the deflection bowl at 1.5 times total thickness of the pavement structure are used to accurately determine an adjusted SN value, known as SNP. In Rohde's work the SNP value was improved by incorporating the subgrade effective elastic moduli or converted to the well-known California Bearing Ratio (CBR) value of the subgrade and thus contributing to the total pavement structural strength (Salt and Davies, 2001 and 2005 and Schnoor and Horak, 2012).

Better use of the whole deflection bowl, without needing to have detailed information on pavement layer material type and or thicknesses, therefore proved to be beneficial in initial or benchmark pavement structural analyses in determining effective SNP (SNP_{eff}) from FWD deflection bowl information alone.

The Pavement Number (PN) was developed as a simple index methodology for structural design and evaluation of flexible pavements and making provision for pavements with bitumen stabilized materials (BSM) (Jooste and Long, 2007). The current South African Mechanistic Design Method (SAMDM) did not, adequately, accommodate such materials and their behaviour including performance. A more simplified, robust design and analysis method was needed as the Mechanistic Empirical (ME) methods such as the current SAMDM is regarded by some researchers and practitioners as too complex and would normally require various detailed material and layer thickness information coupled with perceived questionable assumptions, extrapolations and simplification of data that lie hidden in the "darker recesses of the methodology" (Jooste and Long, 2007). The current SAMDM is under review and upgrade and will probably become more complex thus providing ample space for index based methods to be used in benchmark or first level analyses (Theyse et al, 2007).

Pavement Number (PN) index design and analysis methodology thus developed can quantify the long term load spreading capacity of the pavement system. The detail regarding the determination of PN will be described later, but similar to the original SNC or SNP, detailed knowledge of material class, properties and layer thickness is needed for accurate PN calculation. The need, therefore, arose to also determine PN with only the full extent of the deflection bowl measured with the FWD via an approximation method. This PN_{eff} thus determined for all flexible pavement types were correlated with the normal PN values determined for the large database of pavement information available (Hefer and Jooste, 2008) and showed very good correlation.

2. PAVEMENT NUMBER METHOD RATIONALE AND DEVELOPMENT

In this PN calculation the performance records of pavements (Jooste and Long, 2007) were incorporated by using a database including long term pavement performance (LTPP) data and accelerated pavement testing data via the South African developed Heavy Vehicle Simulator (HVS) and the analysis of the catalogue of designs for flexible pavements, the TRH4 (1996) (Hefer and Jooste, 2008). In all cases, the structural capacity was known with high certainty. Criteria were developed for the calibrated PN values thus determined to improve the certainty of the derived structural capacity from PN values. As such the method can be described as a knowledge-based method, or heuristic, design method that relies on established rules of thumb to guide a design process (Jooste and Long, 2007).

The development of the pavement number (PN) index method is closely linked to the development of design methods and analysis approaches for Bitumen Stabilised Materials (BMS) pavements. A novel classification of pavement materials as they behave and perform in an actual pavement system, the Design Equivalent Materials Class (DEMAC) concept was thus developed. This DEMAC is in support of important pavement materials design and characterisation guidelines (e.g. TRH 14 and TRH 4). This DEMAC material description methodology is contained in the Appendix A of the Technical Guideline 2 (TG2), Second Edition (Asphalt Academy, 2009). This improved material classification of all layers forms the basis for the derived rules of thumb developed in the determination of PN values.

The rules of thumb used as departure points for the PN-based design method are briefly summarised as follows;

- The subgrade material classification and known ranges of effective elastic modulus or stiffness values form the starting point of the design process.
- Each layer material class, coupled with Modular Ratio (MR) of the layer stiffness and the supporting layer stiffness, is used to ensure stress sensitivity in unbound materials is thus addressed. Higher MR values are assigned to cohesive materials subject to fatigue.
- The Effective Long Term Stiffness (ELTS) is determined for each layer, starting with the subgrade and linked to the MR limits prescribed. The subgrade ELTS in the PN model is determined by the material class, the climate and by the depth of cover over the subgrade.
- The general method for determining the ELTS of pavement layers relies on the modular ratio limit and the maximum allowable stiffness. For these parameters, different values are assigned to different material types and were calibrated using the available knowledge base of pavement structural capacity.
- The ELTS of a pavement layer is determined as the minimum of (a) the support stiffness multiplied by the material’s MR limit; and (b) the maximum allowable stiffness assigned to the material type.

- Further refinement includes a Base Confidence Factor (BCF) to ensure that inappropriate base types are not used or to prevent insensitivity to material placement which is the case in the traditional SN approach.
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The PN values of the pavement structures in the extensive data base (Hefer and Jooste, 2008) were determined as part of the development of a Pavement Performance Information System (PPIS) and were also used to validate the PN method (Long, 2008). The product of the ELTS (MPa) and layer thickness (mm) is divided by 10 000 to scale the PN_{calc} to a smaller number similar to that of SNP. These PN_{calc} values were thus calculated from known material qualities, layer thicknesses and environmental conditions. The original database used in the development of the FWD deflection bowl parameters benchmark analysis (Maree and Bellekens, 1991) was also used to determine their PN_{calc} values based on known material and layer thicknesses and environmental conditions.

3. PROPOSED APPROXIMATION OF PN USING DEFLECTION BOWL MEASUREMENTS

3.1. Introduction

The proposed PN approximation by means of FWD deflection bowl measurement alone, or known as Effective Pavement Number (PN_{eff}) makes use of two well known simple structural evaluation methods. The first method used is to convert the pavement layered structure above the subgrade to an ideal or theoretical equivalent elastic half space via Odemark's (1949) equivalent layer thickness (H_e) equations (Horak, 1988, Horak et al, 1989, Molenaar and van Gurp, 1980 and Molenaar, 1983). The second method of approximation is to use Boussinesq's equations, as described by Ullidtz (1987), to calculate the Surface Moduli (SM_i) values as "weighted mean modulus" of the idealised equivalent half space. These SM_i values can be calculated at any offset, *i*, from the centre point of loading. The equivalent or accumulated SM_i contribution of the pavement structure in total (SM_{pav}) can thus be determined by making a distinction of what the subgrade SM contribution is and subtracting it, or assuming the equivalent SM contribution of the pavement layered system is the same as for the subgrade as per the ideal elastic modulus half space.

Thus by converting the pavement structure in effect to a Boussinesq ideal elastic half space the equivalent layer thickness (H_e) is multiplied with the SM_{pav} representing an approximation of a weighted ELTS of all pavement layers combined. In short the PN_{eff} thus determined by the product of the SM_{pav} and H_e is in effect a simple two layered pavement system of which the subgrade is the lower layer and the converted total pavement structure as similar theoretically idealised material on top
(See Figure 1).

3.2. Determining equivalent layer thickness (He)

The original Odemark's equivalent layer thickness (1949) has as principle that the multi-layered pavement system is transformed into a single layer of equivalent thickness on top of the subgrade to create an ideal half space with an effective stiffness or elastic modulus equal to that of the subgrade. This concept of stress equalisation of vertical stress at subgrade interface is illustrated by means of a simple two layer system in Figure 1. The result is that the equivalent layer, therefore, has the same stiffness as the original layer (subgrade), but also that the same pressure distribution on top of the subgrade is created as by the original multi-layered pavement system (Horak, 1988 and Molenaar, 1983).

The equivalent layer thickness is normally calculated as follows;

$$H_e = a\ \Sigma^{L-1} h_i\ [E_i(1-v_s^2)/E_s(1-v_i^2)]^{1/3} \qquad (1)$$

Where, H_e = Equivalent layer thickness (m)

a = constant ranging between 0.85 to 0.9 for flexible pavements
L = number of layers
h_i = individual layer i thickness (m)
E_i = elastic modulus of layer i (MPa)
E_s = elastic modulus of subgrade (MPa)
v_s = Poisson ratio of the subgrade, normally assigned a value of 0.35
v_i = Poisson ratio of layer i, normally assigned a value of 0.35 for granular materials and 0.44 for bituminous material.

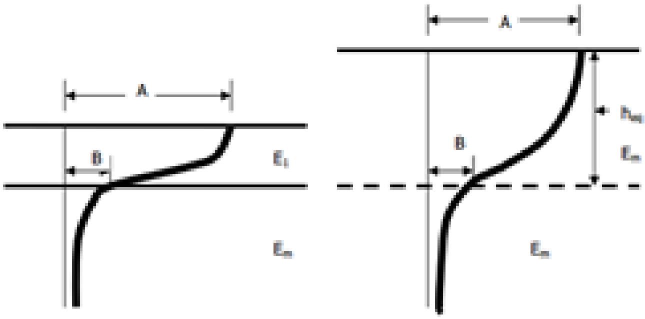

Figure 1. Odemark's equivalent layer thickness (h_{eq}) theory applied to equalise stress at subgrade interface for a two layer system (Molenaar, 1983)

Various researchers have shown that H_e can be correlated with a number of structural indicators derived from FWD deflections (Horak, 1988, Molenaar, 1983 and Horak et al, 1989). Therefore such correlations can be used to determine H_e in this approximation of PN as first step. Slope Deflection (SD) bowl parameter and the BLI ($BLI=D_0-D_{300}$ and D_0 and D_{300} measured in micron) were found to correlate very well with H_e for the typical flexible pavement structures used in the TRH4 (1996). However, SD and BLI correlations thus established are for specific ranges of subgrade effective elastic moduli and also different for granular base and bitumen base and cemented base pavements (Horak, 1988 and Horak et al., 1989). This makes it relatively difficult to use this SD or BLI bowl parameters to determine H_e directly for general use. The deflection bowl shape parameter F_1 ($F_1 = D_0-D_{600})/D_{300}$ and D_0, D_{300} and D_{600} measured in micron) was found by Horak (1988) and Horak et al (1989) to give the following correlation with H_e for flexible pavements irrespective of the subgrade modulus;

$$H_e = 10^{(\log F1 + 0.268)/(-1.432)} \qquad (2)$$

It was thus decided to use this deflection bowl parameter F_1, to determine H_e for flexible pavements in this approximation of PN from deflection bowl information.

3.3. Determining the equivalent pavement Surface Modulus (SMpav)

The Boussinesq equations used by Ullidtz (1987) to determine surface modulus (SM) for the idealised half space is calculated as follows;

$$SM_0 = 2*\sigma_0*(1-\upsilon^2)*(a/D_0) \qquad (3)$$

Where: SM_0 = Surface Modulus of the total pavement response at the point of maximum deflection in MPa

σ_0 = contact stress under the FWD loading plate (typically 566kPa contact stress for a 40kN drop weight)

υ = Poisson's ratio (usually set at 0.35)

a = radius of the loading plate (normally 150mm with diameter 300mm)

D_0 = maximum deflection taken at centre of loading plate measured in micron.

The general formula for Surface Moduli (SM_i) determined by any deflection (D_i) at any point *i* (in mm) away from the point of maximum deflection (D_0)

$$SM_i = \sigma_0*(1-\upsilon^2)*(a^2)/(i*(D_i)) \qquad (4)$$

Ullidtz (1987) determined that the gradient of the 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 SM, or SMD (such as SMD= SM_{600}- SM_{900}), can be used to determine whether the subgrade response is stress stiffening, or stress softening (Horak, 2008).

In Figure 2 the plots for all SM derived from deflections on a granular base pavement from the database used in the original deflection bowl benchmark development (Maree and Bellekens, 1991) is shown. It clearly exhibits various subgrade responses in the region from 300mm to 1200mm. It can however be seen from Figure 2 that at approximately 300mm from point of maximum deflection the SM_{300} is generally giving the most consistent and representative value for the subgrade response or put differently, it does not differ much from say SM_{900} or SM_{1200} if a linear elastic response is observed (Horak, 2008). It also overcomes the issue of unrealistic subgrade SM values due to either stress stiffening or stress softening. The SMD values used to characterise the subgrade response and defined above are also shown in Table 1.

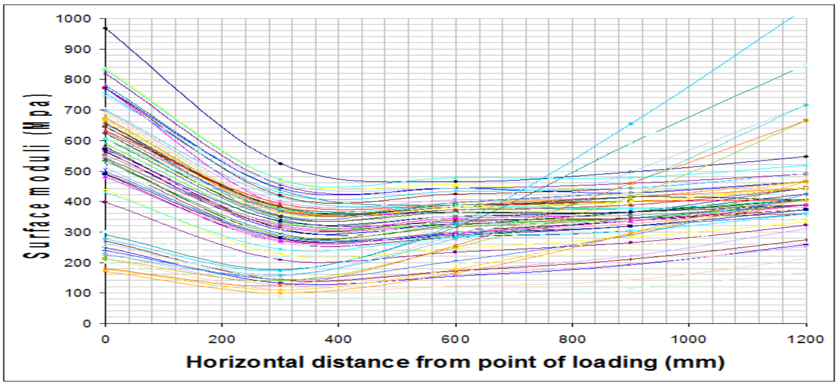

Figure 2. Surface modulus values versus horizontal distance from point of maximum deflection (Horak, 2008).

Thus PN_{eff} can be determined with the following equation;

$$PN_{eff} = (SM_{300} * H_e)/10 \quad (5)$$

Where SM_{300} is determined with equation (4) and H_e determined with equation (2). The H_e*SM_{300} product is divided by 10 to scale the result to a PN_{eff} value. H_e is already in meter (m) and differing from the PN_{calc} method where layer thickness is in mm (mm*1000=m) and therefore equal to the normal way of calculating PN where it is divided by 10 000 (Jooste and Long, 2007).

4. DETERMINING PNEFF FROM DEFLECTION BOWL MEASUREMENTS

The original database of FWD data and pavement detail used by Maree and Bellekens (1991) and Maree and Jooste (1999) was first used to determine whether the PN_{eff} values thus derived are realistic. The PN_{calc} (normal method as per Jooste and Long, 2007) and average values of PN_{eff} are shown in Table 1. The test for the stress softening or hardening behaviour of the subgrade is shown as SMD substantiating the selected SM_{300} value thus used as ELTS approximation for the pavement structure as a whole in the calculation of the PN_{eff}. The positive correlation with this smaller data base was followed with the larger data base for flexible pavements originally used by Hefer and Jooste (2008) to calculate the PN_{calc} average values shown in Table 1 for all pavement types. The PN_{eff} shown are the average values determined using equation (5).

Table 1. PN_{eff} versus PN_{calc} values

Road type	PN_{calc}	PN_{eff} average	SM difference average (SM_{600}-SM_{900})
Granular Base (Edenvale N3)	33	22.4	-63 (Stress stiffening)
Granular Base (Silwer Street)	28	29.6	-42 (Stress stiffening)
Bituminous Base (Schoeman street)	30.5	22.6	+9.9 (Stress softening)
Cement base (Pilansberg)	17.1	18.8	+9.1(Stress softening)
Granular base N1-16	16	8	-95 (Stress stiffening)
Granular base N1-26X	9	9.6	-54 (stress stiffening)
Granular base N7-1	14,16,22	10.4	-32 (stress stiffening)
Granular base TR16-3	8,10	4	-300 (Strongly stress stiffening)
Granular base TR77-1	14,16,18	12.9	12.3 (Stress softening)
Bitumen base N2-24	35, 39,43,44,48	35.6	6.6 (Stress softening)
Bitumen base N3-1	60, 61	38.9	28 (Stress softening)
Bitumen base N3-4	47	29.3	7.3 (Stress softening)
Cemented base N1-26X	4	9.6	-59.4 (stress stiffening)
Cement base N4-2	15	14.6	16.9 (Stress softening)

In Figure 3 the correlation between PN_{calc} and PN_{eff} is shown for all the pavement types from the two databases. The straight line correlation has a correlation coefficient (R^2) of 0.86. This is significant as it is accepted that PN_{eff} does vary over any of the roads sampled and PN_{calc} is also actually an average value for various sections of the pavement and therefore also vary as shown in Table 1. This good correlation implies that PN_{eff} can be used with confidence as a benchmark analysis approach on a project level as well as on a network level.

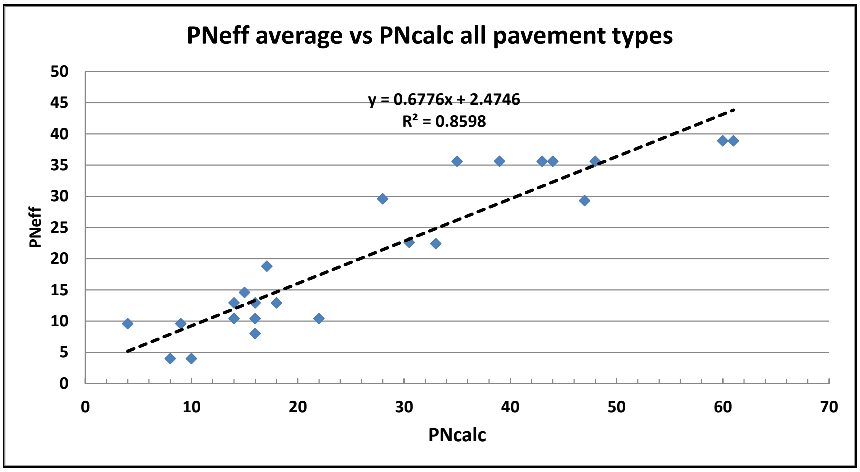

Figure 3. PN_{eff} versus PN_{calc} for all pavement types

5. BENCHMARK ANALYSIS WITH PNEFF

The PN_{eff} values determined by using the full deflection bowl information from FWD surveys can be used as a benchmark analysis during preliminary analyses on flexible roads to help identify sections of the road that may seem either high or low in PN_{eff} values relative to the rest of the road. The typical PN values determined for the TRH4 type pavement structures, as derived by Jooste and Long (2007) and Long (2008), can be used as reference value for a specific flexible pavement type (granular, asphalt of cemented).

In Figure 4 the PN_{eff} values determined from FWD survey data on a short sample road with a light pavement structure recently analysed in Gauteng is shown versus distance. In order to use it in a benchmark methodology, a PN_{eff} value more than 10 is deemed structurally sound, PN_{eff} between 5 and 10 deemed structurally warning and PN_{eff} less than 5 deemed in a severe structural condition. The result is shown in Figure 4 identified via the RAG (Red-Amber-Green) classification, representing Sound, Warning, and Severe, respectively. It is clear that sections at the start of the road length is in distress and interspersed short sections all along the road. However, the cause or origin of possible distress cannot be derived from this Figure 4. This first level benchmark analysis clearly and correctly identify uniform sections of the road which should be treated differently in terms of rehabilitation needs. The maximum deflection benchmark analysis in Figure 5 shows similar areas which are in severe and warning condition. This illustrates the problem associated with using a single point on the deflection bowl only (maximum deflection) for structural analyses. It can also identify possible areas of structural inadequacies, but like PN_{eff} benchmark analyses, it cannot identify the origin of distress within the pavement structure.

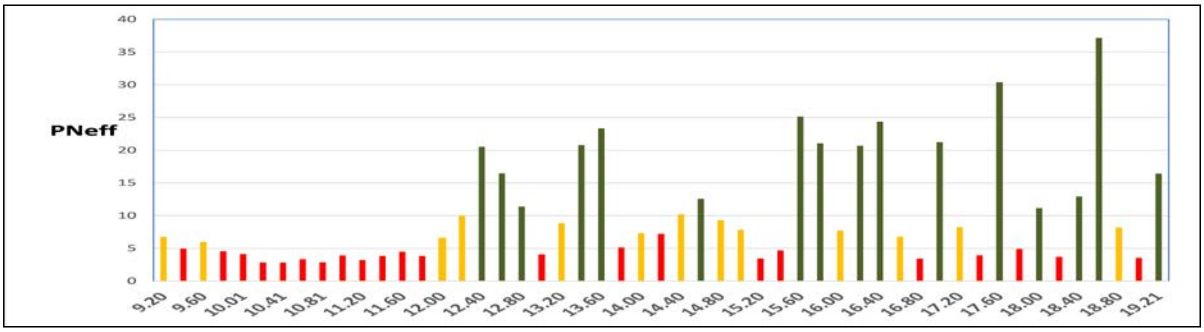

Figure 4. PN$_{eff}$ benchmark analysis for a short road section in Gauteng

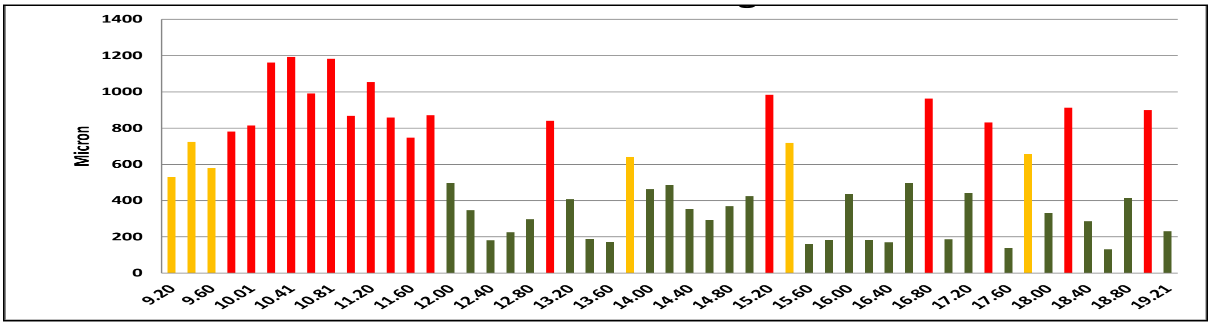

Figure 5. Maximum deflection benchmark analysis for a short road section in Gauteng

In order to complement the PN$_{eff}$ benchmark analysis as a preliminary structural analysis, a more detailed deflection bowl analysis is needed (Horak et al, 2015) where the embedded structural response associated with the whole deflection bowl is unlocked. In this case the order in which it will be revealed is basically in the same order road layers are built from the bottom up. In Figure 6 the LLI benchmark analysis shows that the origin of distress is not in the selected and subgrade layers as the whole section is sound and in the green. Therefore the origin of distress must be in the layers on top of the subgrade and selected layers.

In Figure 7 the MLI benchmark analysis is shown. It identifies severe and warning areas which are very well correlated with the PN$_{eff}$ benchmark analysis. If the benchmark analysis of the BLI, shown in Figure 8, describing the structural condition of the base and surfacing combination, is viewed in conjunction it identifies that largely the same areas and zones in warning and severe structural condition persist. It also further coincides remarkably with the PN$_{eff}$ areas in warning and distress. This implies the origin of distress is largely in the subbase as the base layer did not ‘bridge” or improve the subbase weaknesses, but rather reflected it through due to the lack of support.

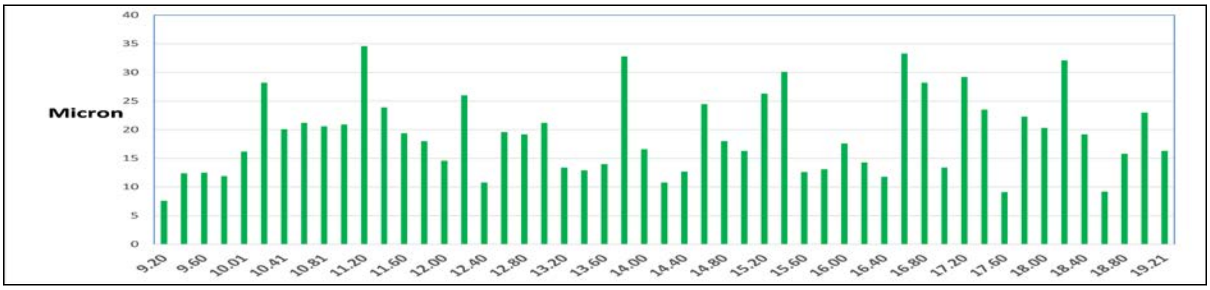

Figure 6. Lower layer index (LLI) benchmark analysis for a short road section in Gauteng

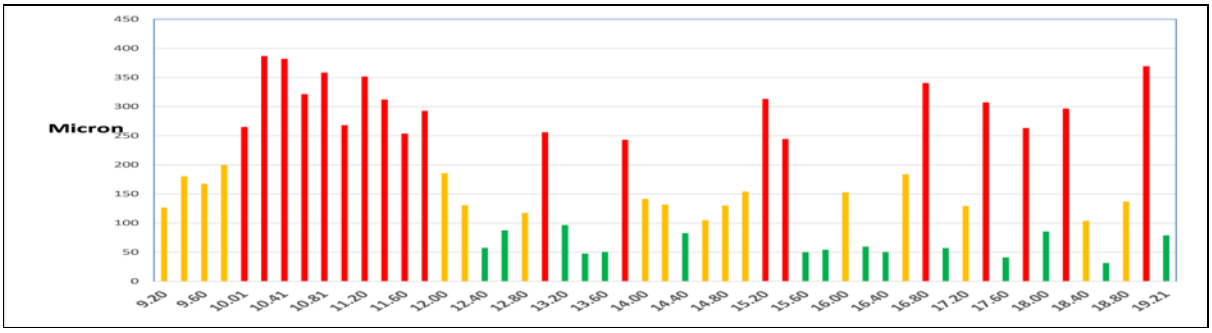

Figure 7. Middle layer index (MLI) benchmark analysis for a short road section in Gauteng

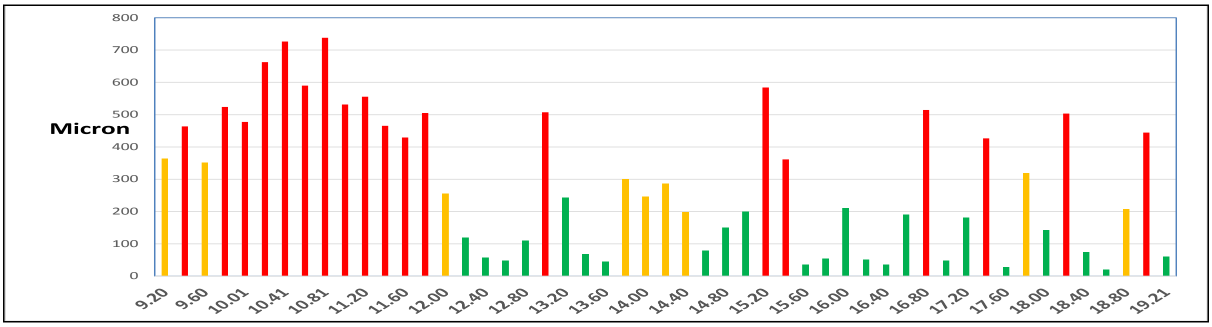

Figure 8. Base layer index (BLI) benchmark analysis for a short road section in Gauteng

6. CONCLUSIONS AND RECOMMENDATIONS

- Benchmark methodology used with deflection bowl parameters have proved the concept that considerable embedded structural response information can be used in preliminary investigations of flexible pavements.
- The Pavement Number (PN) was developed in South Africa as an index similar to the well-known adjusted Structural Number (SNP).
- It is possible to determine an approximation or effective structural Number (SNP_{eff}) from FWD deflection bowl information alone.
- An approach to calculate PN (defined as PN_{eff}) similar to the determination of SNP_{eff} also utilising the embedded structural response knowledge of the whole deflection bowl, was thus developed.
- The deflection bowl shape factor, $F_{1,}$ is used to determine equivalent layer thickness (H_e) and other FWD deflections are used to derive surface modulus

(SM) inputs for calculating an approximation of Equivalent Long Term Stiffness (ELTS) representing the total pavement structure, SM_{pav}.
- The product of the H_e and SM_{pav} thus provides PN_{eff}.
- For actual or reference PN calculations, layer thickness and ELTS for each layer is needed and summed up to provide the PN_{calc} value.
- A large database of flexible pavements was used to correlate PN_{eff} and PN_{calc} positively.
- PN_{eff} values thus determined via this FWD deflection bowl utilisation can be used to complement initial or preliminary structural evaluation in a benchmark comparison if FWD surveys are available.
- PN_{eff} will not be able to determine indications of actual cause or origin of distress, but this can be identified with the well-established benchmark analysis with deflection bowl analyses linked to structural condition of zones of the flexible pavement layers.

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