SURFACE MODULI DETERMINED WITH THE FALLING WEIGHT DEFLECTOMETER USED AS BENCHMARKING TOOL

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ABSTRACT

A semi-mechanistic semi-empirical analysis technique has been developed in South Africa whereby deflection bowl parameters, measured with the falling weight Deflectometer (FWD), are used in a relative benchmarking methodology in conjunction with standardised visual survey methodology to give guidance on individual layer strengths and pinpoint rehabilitation needs. This benchmarking methodology can be enhanced by the use of calculated surface moduli based on the use of Boussinesq's equations. The calculation of such surface moduli can be enhanced by determining the gradient of the surface moduli as correlated with the subgrade layer and the elastic response characteristics. Such benchmark calculations are done without complicated and detailed multi-layered linear elastic modelling and software and enables the determination of the relative structural condition of the pavement without detailed as-built data being required.

1. INTRODUCTION

A semi-mechanistic-empirical analysis procedure was developed in South Africa which makes use of deflection bowl descriptors or parameters of the deflection bowls as measured with the falling weight Deflectometer (FWD). The benchmarking process is based on these deflection bowl descriptors or deflection bowl parameters and their correlations developed with structural layers or zones of the pavement structure (Maree and Jooste, 1999; Horak and Emery, 2006). These correlations are based on past development work which was included in the standard rehabilitation design procedure for flexible pavements, the Technical Recommendations for Highways 12 (TRH 12) (CSRA, 1997) and subsequent improvements to this procedure to analyse flexible pavements in rehabilitation analyses (Jordaan, 2006).

The basis for this deflection bowl parameter benchmark methodology is briefly described here with the help of Figure 1. In Figure 1 it is shown that a deflection bowl measured under a loaded wheel can be described in terms of three distinct zones over the deflection bowl. In zone 1, close to the point of loading, the deflection bowl has a positive curvature. This zone will normally be within a radius not more than 300mm from the point of loading. Zone 2 represents the zone where the deflection bowl switches from a positive curvature to a reverse curvature and is often referred to as the zone of inflection. The exact position of the point of inflection in zone 2 depends on specific pavement layer structural compositional factors and zone 2 normally varies from about 300mm to about 600mm from the point of loading. Zone 3 is furthest away from the point of loading where the deflection bowl has switched to a reverse curvature and extends to the normal road surface, i.e where deflection reverts back to zero. Zone 3 normally stretches from about 600mm to

2000mm although the extent of this zone will depend on the actual depth of the pavement structure and is dependant on the structural response of the subgrade layer.

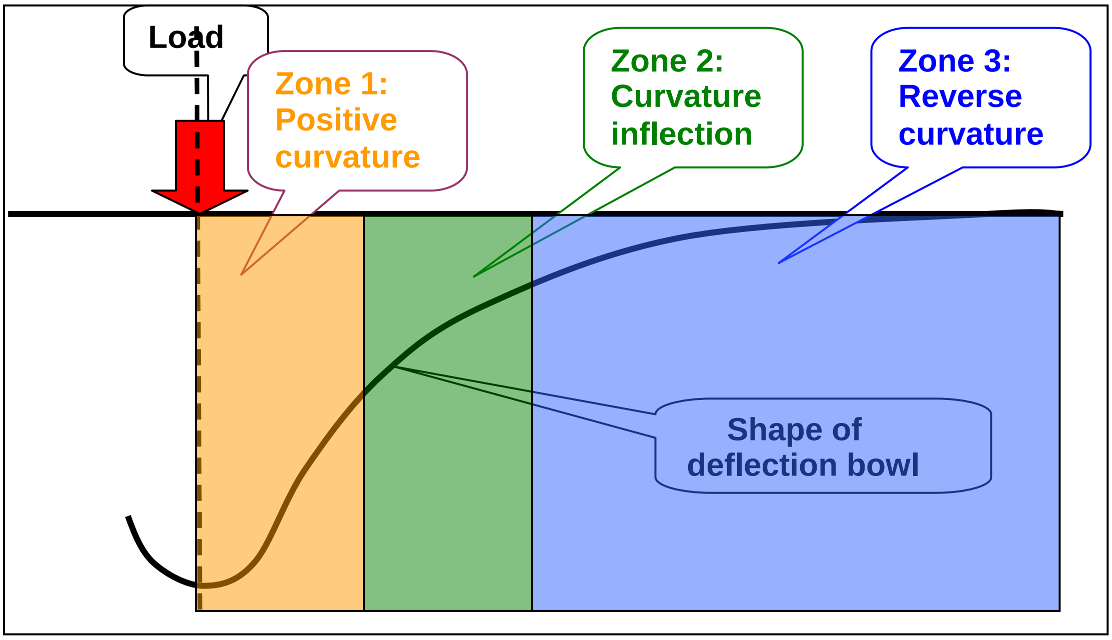

Figure 1. Curvature zones of a deflection bowl

In Table 1 a selected number of deflection bowl parameters and their formulae are summarized as linked to the deflection bowl zones and their formulae based on the measured deflection bowls (Horak, 1988; Horak et al, 1989; Rohde and van Wijk, 1996; Maree and Bellekens, 1989 and Maree and Jooste, 1999). Radius of Curvature (RoC) and Base Layer Index (BLI) have been found to correlate well with zone 1 (mostly surfacing and base layers), Middle Layer Index (MLI) with zone 2 (mostly subbase layer) and Lower Layer Index (LLI) correlates with zone 3 (mostly selected and subgrade layers). Due to the closeness of the geophone at 200mm to the edge of the loading plate and associated surface disturbances observed, RoC is used with less confidence and BLI is used with more confidence to describe zone 1 (Horak and Emery, 2006).

The concept of behaviour states of flexible pavements, originally described by Freeme (1983), made use of maximum deflection to classify a pavement structural conditions in terms of their elastic response. Behaviour state classification was subsequently expanded by Horak (1988) to include the other deflection bowl parameters which gave better representation of the whole deflection bowl and was subsequently included in TRH12 (CSRA,1997). Behaviour state classification was used as basis for the further development of this deflection bowl parameter benchmark methodology (Jordaan, 1990 and 2006).

In Table 2 such a benchmarking classification for various pavement types, thus developed, is shown. The colour coding and rating system normally also used in visual condition survey classification in graphical plots are also used, namely sound, warning or severe.

Table 1. Summary of deflection bowl parameters

Parameter	Formula	Zone correlated to (see Figure 1)
Maximum deflection	D_0 as measured at point of loading	1,2 and 3
Radius of Curvature (RoC)	$RoC = \dfrac{(L)^2}{2D_0(1-D_{200}/D_0)}$ Where L=127mm in the original Dehlen curvature meter and 200mm for the FWD	1
Base Layer Index (BLI)	$BLI=D_0-D_{300}$	1
Middle Layer Index (MLI)	$MLI=D_{300}-D_{600}$	2
Lower Layer Index (LLI)	$LLI=D_{600}-D_{900}$	3

The relative structural strength contribution of zones of layers in the pavement structure can thus be linked to the visual condition rating using the same condition rating system. Relative or benchmarked structural deficiencies of the related structural layers in the pavement structure can be identified over the length of a road. In this fashion the possible cause of structural deficiencies can be deduced from similarly rated and colour coded visual condition surveys. In this way a diagnostic cause and effect of observed visual conditions can be established at an early stage of the investigation with limited complicated analysis.

Table 2: Deflection bowl parameter structural condition rating criteria for various pavement types

	Structural condition rating	Deflection bowl parameters				
		D_0 (µm)	RoC (m)	BLI (µm)	MLI (µm)	LLI (µm)
Granular Base	**Sound**	<500	>100	<200	<100	<50
	Warning	500-750	50-100	200-400	100-200	50-100
	Severe	>750	<50	>400	>200	>100
Cementi-tious Base	**Sound**	<200	>150	<100	<50	<40
	Warning	200-400	80-150	100-300	50-100	40-80
	Severe	>400	<80	>300	>100	>80
Bituminous Base	**Sound**	<400	>250	<150	<100	<50
	Warning	400-600	100-250	150-300	100-150	50-80
	Severe	>600	<100	>300	>150	>80

Note: These criteria can be adjusted to improve sensitivity of the benchmarking

2. SURFACE MODULUS CALCULATIONS

The deflection of the subgrade typically contributes between 60 to 80 percent of the centre deflection (D_0) directly under the load. The load is normally spread from the top layers to the subgrade through load transfer by the layers through a cone of about 45 degrees as shown in Figure 2. 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. The surface modulus is the “weighted mean modulus” of the equivalent half space calculated from the surface deflection using Boussinesq’s equations (Ullidtz, 1987). The surface modulus (SM) directly under the point of loading at maximum deflection D_0 is calculated as follows:

$$SM_{(0)} = 2 \bullet \sigma_0 \bullet \left(1-\mu^2\right) \bullet \left(a/d_{(0)}\right) \qquad (r = 0)$$

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

$$SM_{(r)} = \sigma_0 \bullet \left(1-\mu^2\right) \bullet \left(\frac{a^2}{r \bullet d_{(r)}}\right)$$

Where:

SM(r) = Surface modulus at a distance r from centre of loading plate (Mpa)
σ= Physical thickness of a layer
μ= Poisson’s ratio, usually chosen as 0.35
a = Radius of the loading plate
d(r) = Deflection at distance r
r = Radial distance from the centre of loading where r>0

Figure 2 illustrates typical surface moduli plots for pavement structures. The surface moduli calculated at horizontal distance r is representative of the compressed material in the zone of influence below depth z. As the horizontal distance increases a point is reached where only the subgrade falls within the zone of influence and the surface moduli thus only reflects the moduli of the subgrade material.

Ullidtz (1987and 2005) determined that the gradient of the surface modulus (SM) plot over more or less the distance defined by zones two and three of the deflection bowl (see Figure 1) can be used to identify whether the subgrade has stress softening, stress hardening behaviour or whether it is exhibiting linear elastic behaviour. This is illustrated in Figure 2 where the gradients of that zone of the SM graphs are linked with the elastic response classification.

The surface modulus differential (SMD) of the surface modulus (SM) at 600mm and that at 1200mm can thus be used to as indicator of the gradient of the SM graph determined from the zone 3 of the SM graph. In Table 2 ranges of SMD thus determined are shown to benchmark the subgrade response.

Table 2: Subgrade Response Benchmarking with Surface Modulus Differentials

Response classification	Surface Modulus Differential (SMD) Ranges (MPa)
Stress softening	> 20
Linear elastic	20 to -20
Stress stiffening	< -20

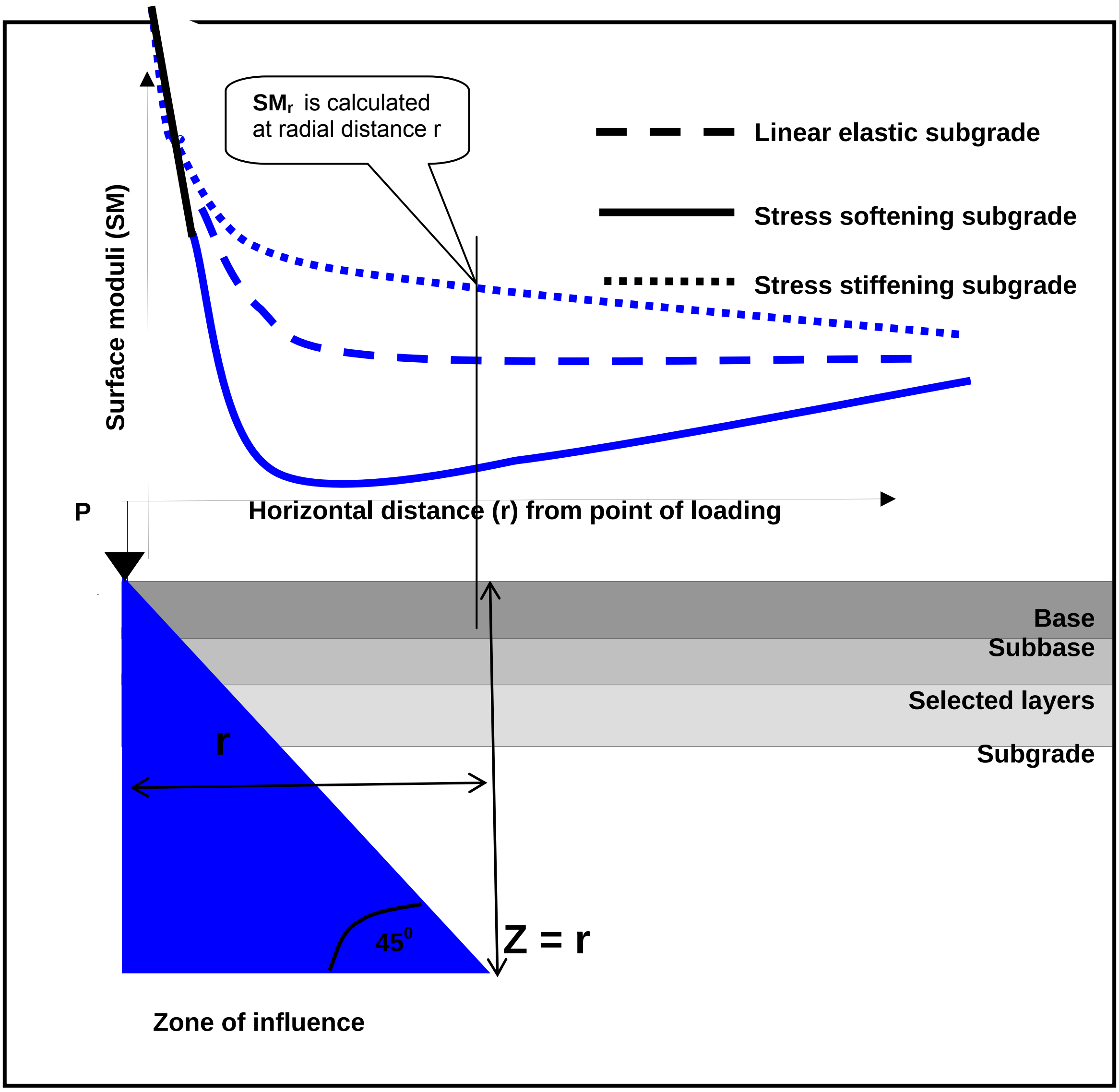

Figure 2: Typical surface moduli plots for pavement structures (Ullidtz, 1987).

3. STRUCTURAL BENCHMARKING OF SUBGRADE RESPONSE

In Figure 3 the application of this SMD benchmarking application is shown for the centre line of the main runway of Bloemfontein International Airport (BIA) which is currently under rehabilitation investigation. The FWD survey, in this case done with a 40kN load on the centre line, was used to calculate the SM values at the off sets of the geophones described earlier. These SM values were used to calculate the SMD values for zone 3, as defined above, and are graphically represented versus distance. The subgrade response criteria defined in Table 2 (stress stiffening, linear elastic or stress softening) were superimposed in colour bands to enhance the benchmarking. It is known that BIA has a clayey and silty subgrade and this subgrade response benchmarking with the surface moduli differentials (SMDs) confirmed that the majority of the runway 0220 (main runway) shows stress softening response as would be expected from such a clayey subgrade. Incidentally the stress softening response was also observed more intensely with FWD survey results at the higher loads used in the survey, as would be expected from stress softening response at higher stress situations.

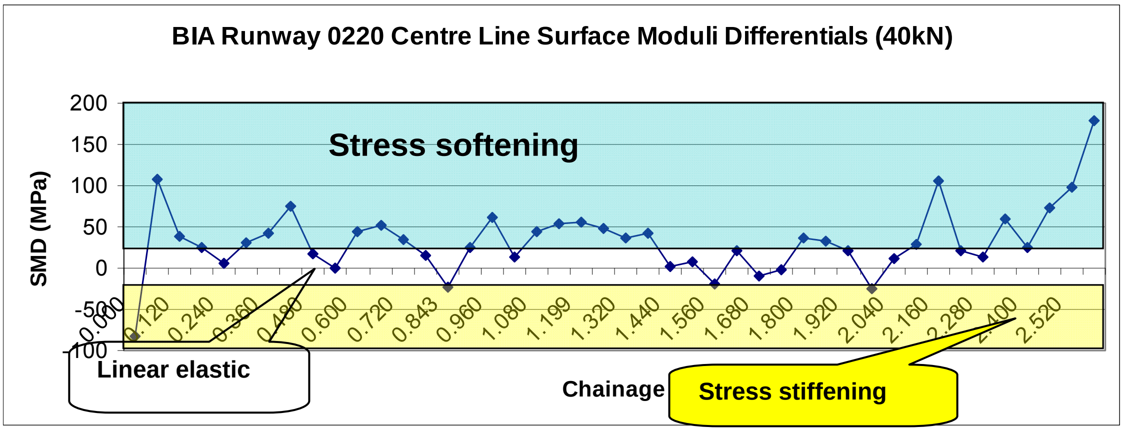

Figure 2. Subgrade response benchmarking of main runway of Bloemfontein International Airport on the centre line (40kN)

4. ZONE SPECIFIC STRUCTURAL BENCHMARKING

The calculated surface moduli (SMs) can be used in a number of ways to help benchmark the structural capacity of the pavement. If the premise of the three zones described in Figure 1 is taken as departure point the SM values associated with these zones can be used in parallel with the deflection bowl parameters, linked with these specific zones.

4.1. Zone 3 and subgrade benchmarking

The SM determined at 1200mm from the point of loading happens to describe the structural strength in the 3rd zone well. The relative structural strength of this 3rd zone is also described well by the LLI deflection bowl parameter. In Figure 3 such benchmarking is provided for LLI and SM_{1200} for runways 0220 (main) and 1230 (secondary) of Bloemfontein International Airport (BIA) for demonstration purposes.

The fact that the survey was done at 120kN only serves to emphasize the comparative nature of this benchmarking to help identify relative weaker structural areas in the subgrade. It clearly provides for a direct comparison between the two runways which clearly shows that at such a high wheel load runway 0220 (main) has a structurally stronger subgrade than that of runway 1230 (secondary).

It shows that the largest part of runway 0220 is in a sound condition while the subgrade of runway 1230 is in a warning and severe structural condition. This difference can also be seen when the SM_{1200} values are compared as they correlate understandably well with the observations made based on LLI benchmarking alone.

4.2. Zone 2 and subbase benchmarking

In Figure 4 the benchmarking of the zone 2 associated MLI and SM_{600} is shown. It clearly shows that the subbase region of runway 0220 (main) is structurally better than the subbase of runway 1230 (secondary) over the first 1440m of both runways. After 1440m their structural capacity is more or less equal up to the end of both runways. The SM_{600} benchmarking also confirms this observation.

It is also possible to use either MLI or SM_{600} to see how the subbase quality is varying over the length of the runways. The MLI benchmarking shows that the subbase of runway 1230 (secondary) is in the structurally severe benchmarked condition over that first 1440m while the subbase of runway 0220 (main) is in a sound to warning condition.

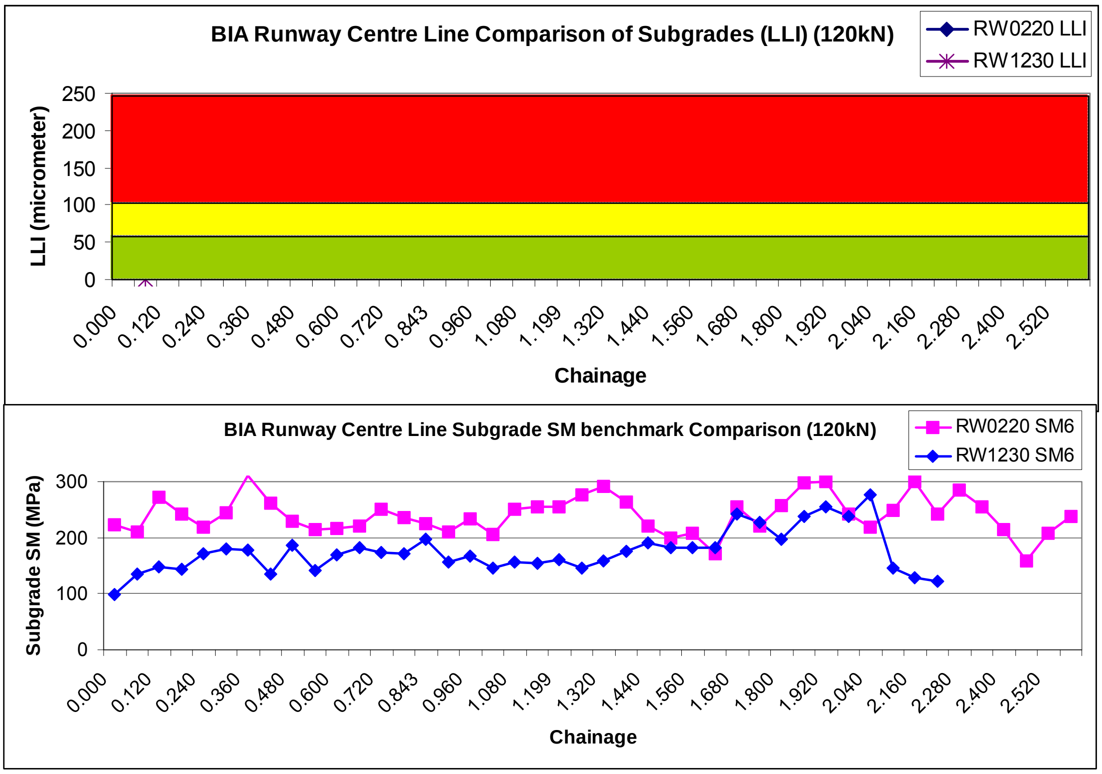

Figure 3. Lower layer index benchmarking and subgrade surface moduli illustration

4.3 Zone 1 and base benchmarking

It is suggested that the surface modulus differential (SMD) between 0mm and 300mm is used as representative of the base SM. This SMD for the base and the BLI values determined at 120kN on the centerlines of both runways of BIA are shown in Figure 5. The BLI values show that the base layer of both runways are now in a structurally severe condition over most of their lengths. Up to 1900m they are both structurally inadequate, but thereafter runway 1230 (secondary) improves slightly. This variance over the length of the runways can also be seen from the SM values benchmarked. The relative better structural support which the base of runway 0220 has implies that the structural deficiency origin of runway 0220 can be pinpointed largely to this structural deficient base layer.

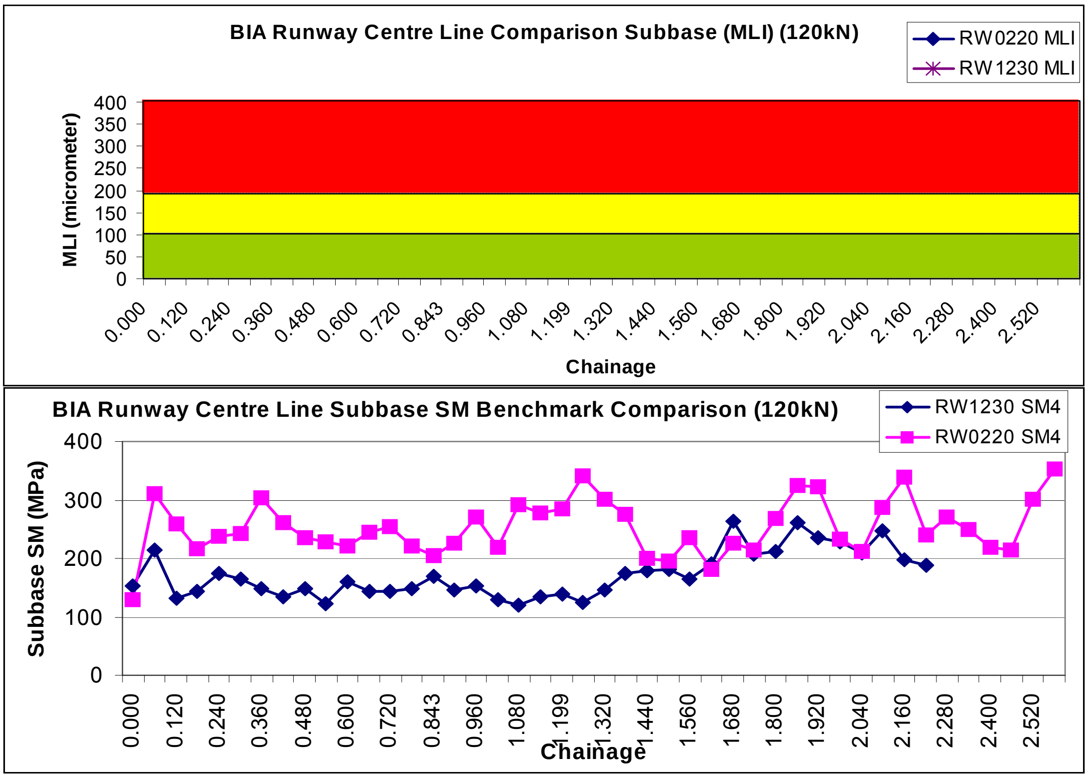

Figure 4. Middle layer index benchmarking and subbase surface moduli illustration

5. CONCLUSIONS

Correlations between a number of deflection bowl parameters, description of behaviour states of flexible pavements and mechanistically determined structural evaluations of a number of pavement types have been used in a semi empirical-mechanistic fashion to develop a relative comparison or benchmarking procedure. Such a deflection bowl parameter benchmarking procedure can be used in a complementary fashion with visual condition surveys and other assessment methodologies to describe pavement structural layers as sound, warning and severe regarding their structural capacity and pavement behaviour states.

This benchmarking methodology with the associated condition ratings helps to accurately identify uniform sections and pinpoint the cause of structural distress, often seen only as various forms of surface distress, and helps to explain the mechanism of deterioration. It enables to focus on such distressed areas with further investigations such as field and laboratory testing and sampling. The basis of this benchmarking approach to condition rate the individual structural layers is based on the premise that specific deflection bowl parameters correlate with three distinct zones on the deflection bowl.

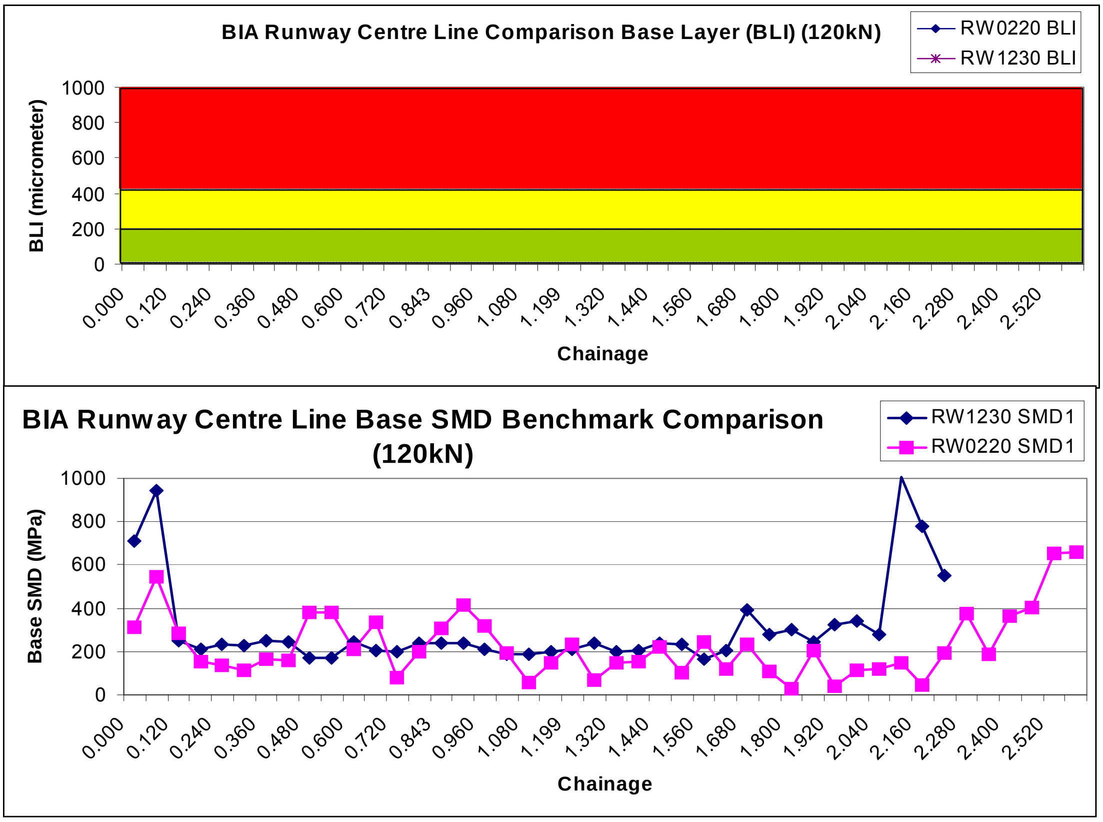

Figure 5. Base layer index benchmarking and base surface moduli illustration

Surface modulus (SM) can also be calculated by means of Boussinesq formulae without detailed or complicated linear elastic theory or models. SM values represent structural values of an equivalent elastic half space. The gradient of the zone 3 of the SM curve is also a strong indicator of subgrade elastic response and the gradient thus calculated can be used to benchmark the subgrade as either linear elastic, stress stiffening or stress softening in behaviour. This is an important input into the later detailed analysis of flexible pavement structures as the subgrade characteristics largely determine the structural analysis of the rest of the pavement structure.

Various sections or points on the SM graph can be linked with the three zones on the deflection bowl and used in similar fashion to benchmark the structural response of the pavement structure. In using this relative benchmarking approach distress locations can be identified in the pavement layers as well as early identification of relative cause of defects as correlated with observed visual surveys. This benchmarking approach can be used to direct further detailed structural analysis more effectively.

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