Transfund Project PR 3 0511
Performance-Based Specifications Using Deflection Measurements

Modular Ratios for Unbound Granular Pavement Layers

– Their Basis and Use as Performance Indicators for
New Pavement Construction Assurance, and Maintenance Contracts.

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Summary

Unbound granular pavement layers show a characteristic increase in moduli from the subgrade to the surface. The ratio of moduli between successive layers provides a direct and effective measure of pavement quality that makes due allowance for site conditions and seasonal effects beyond a contractor's control. The modular ratio is therefore an effective indicator for performance-based specifications. Modular ratios are readily determined from back-analyses of deflection monitoring. Their applications to new construction quality assurance and performance-based network maintenance contracts are described.

1. Background

The modulus of any unbound pavement layer is not an intrinsic property of the component material, but is primarily dependent on the stiffness of the underlying material. The rationale is that an unbound material cannot be properly compacted on a soft subgrade, or alternatively, if a stiff dense layer is placed on a yielding foundation, then tensile strains will develop and the upper layer will de-compact if it is unbound (ie cannot sustain tension).

In a multi-layer system, Heukelom and Foster (1960) found using linear elastic analyses, that the ratio of the modulus of an unbound base layer E_i to that of the underlying soil E_{i+1} was limited to $E_i / E_{i+1} < 2.5$. Otherwise tensile horizontal stresses would develop at the bottom of layer i. Under repeated loading these stresses would lead to de-compaction of the overlying unbound layer until its stiffness reduced to a limiting value at which tensile stresses would not occur.

In practice, mechanistic analysis procedures in common use assume that the modulus of an unbound granular basecourse or subbase layer is constant over a nominal thickness with steps in moduli between layers. Sub-layering may be invoked but the same stepped modulus pattern is assumed. The modular ratio therefore relates to the increase in average effective modulus between successive layers. The average effective modulus should be close to the true modulus at the mid-depth of each layer, but in practice, the unbound layer moduli will vary continuously with depth.

Dorman and Metcalf (1965) used the concept of modular ratio limitations in successive unbound layers to propose the relationship:

$$E_i / E_{i+1} = 0.2\, h_i^{\,0.45} \text{ and } 2 < E_i / E_{i+1} < 4 \quad \text{…. Eqn (1)}$$

where h_i is the height of the overlying layer in mm.

Subsequently, Brown and Pappin (1985) found using more rigorous non-linear finite element analyses, that the above limitations were too restrictive and reported:

$$1.5 < E_i / E_{i+1} < 7.5 \qquad \text{….. Eqn (2)}$$

AUSTROADS (1992), recommends sub-layering of granular materials placed directly on the subgrade with constraints that the sub-layer thickness must be approximately in the range of 50-150 mm and that the ratio of moduli of adjacent sublayers does not exceed 2.

Moffat & Jameson (1998a) used sub-layering in multi-layer linear elastic models to refine the original AUSTROADS procedures for mechanistic design of new unbound granular pavements and proposed the following:

(a) Divide the granular materials into 5 layers of equal thickness

(b) Adopt the vertical modulus for the top sub-layer from:

$$E_{v\ top\ of\ base} = E_{v\ subgrade} \times 2^{(total\ granular\ thickness/125)} \qquad \text{….. Eqn (3)}$$

(But not exceeding tabulated upper bounds for the materials.)

(c) Determine the modular ratio of successive sub-layers from:

$$R = [E_{v\ top\ of\ base} / E_{v\ subgrade}]^{1/5} \qquad \text{….. Eqn (4)}$$

(d) Calculate the modulus of each layer beginning with that immediately overlying the subgrade of known modulus.

Moffat and Jameson (1998b) recommend upper bounds for unbound granular moduli of 500 MPa (with application of modified compactive effort) or 350 MPa (standard compactive effort) under thin surfacings subject to standard axle loadings. Thicker surfacings, providing more effective loadspread, result in reduced values owing to the stress dependence of unbound layer moduli. The moduli presented, assume anisotropy with the vertical modulus twice the horizontal modulus in each layer.

The above relationships are intended for forward design. However back-analysed moduli (eg from deflection surveys) should be checked using the above criteria to check that a reasonable pavement model has been obtained when carrying out sensitivity analyses with respect to varying layer thicknesses. Clearly, only unbound layer moduli are restricted in this manner as the moduli of bound materials are influenced much less by the stiffnesses of underlying layers.

2. Comparison of Relationships

The Moffat and Jameson procedure, can be transformed to show the effect of layer thickness explicitly, allowing direct comparison with the Dorman and Metcalf relationship, as shown in Figure 1. The transformation also allows the same principle to be adapted to layers of differing thickness (generally encountered in existing pavements) which will be discussed below in relation to back analysis of deflection results.

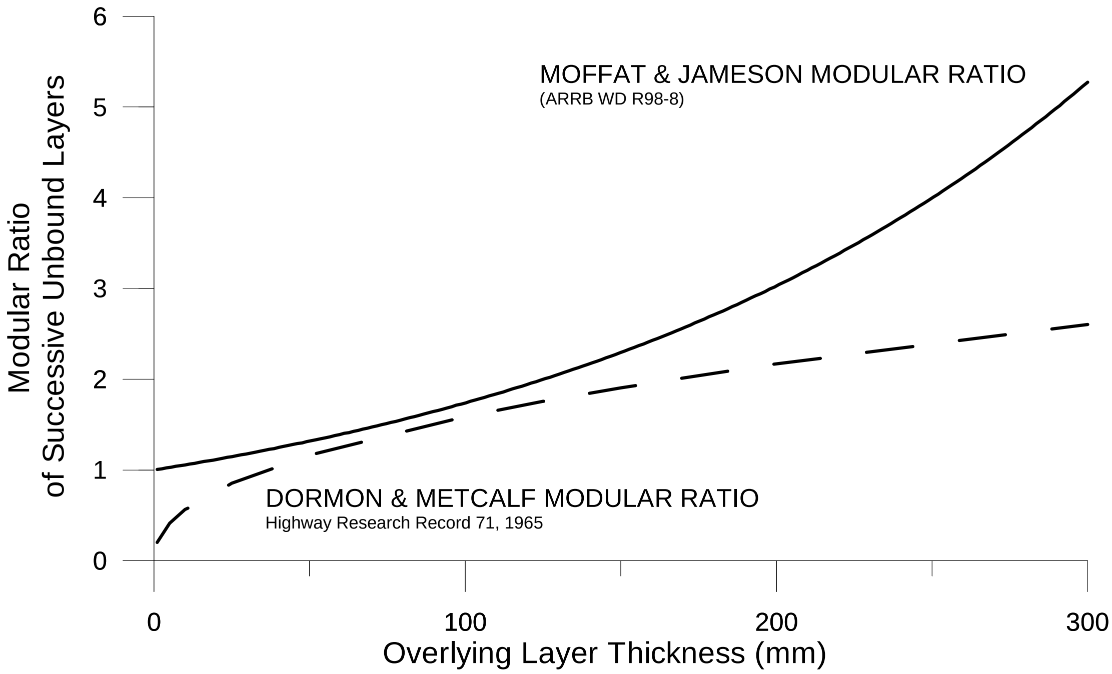


Figure 1. Comparison of modular ratios from alternative relationships

Typically, mechanistic analyses of pavements would consider layer thicknesses of 100-150 mm and it is evident that both of the above relationships yield similar modular ratios for this range, ie the stiffness approximately doubles with each 125 mm of granular material applied. Logically it would be expected that as the thicknesses of both layers tend to zero, then the modular ratio would tend to unity and the Moffat & Jameson relationship would be more valid.

For the case where the thickness of the underlying layer is say 150 mm and the upper layer thickness tends to zero, then neither equation is applicable as the modular ratio should be significantly greater than unity (from the continuous variation in moduli within each layer as discussed above). However, the boundary values (2.0 from Dorman & Metcalf, or 1.5 from Brown & Pappin) would give a more reasonable result than the equation developed from the Moffat & Jameson procedure.

It appears that a more general constitutive relationship would use the distance between the mid-heights of successive layers, and adopt a form which includes any thickness of layers. The Moffat and Jameson method was developed from use with CIRCLY which uses a finite layer thickness for the uppermost layer of the subgrade. However, other software packages in common use, assume subgrade moduli that vary continuously with depth and their outputs focus on the subgrade modulus at the top surface of the subgrade. In this case the Moffat & Jameson method, applied directly, would overestimate the modulus of the first granular sub-layer immediately overlying the subgrade. However by using a zero thickness layer at the top of the subgrade and using the distance between layers for calculating modular ratios, both forms of subgrade modulus characterisation can be accommodated.

Adapting from the Moffat & Jameson procedure, if layer thicknesses are unequal or if there are other than 5 layers or isotropic moduli are adopted, it is proposed that modular ratios may be calculated from:

$$E_i / E_{i+1} = 2^{(h_{i\_i+1}/125)} \qquad \text{Eqn (5)}$$

where h_{i_i+1} is the distance in mm between the mid heights of layer i and i+1.

Comparing different numbers of granular layers that could be considered for a given pavement total thickness, it is evident that Equation 5 is not entirely consistent in theory. This is the result of using steps in moduli rather than a continuous function, and a small correction (K_{NL}) is required to give consistent models if the number of layers is much less than 5 (as nominated by Moffat & Jameson), ie.

$$E_i / E_{i+1} = 2^{(h_{i\_i+1}/125)} \times K_{NL} \qquad \text{Eqn (6)}$$

where NL is the number of layers and K_1 =0.83, K_2= 0.94, K_3=0.98, K_4= 0.99

(The resulting small amendment has significance only in relation to assessment of construction uniformity discussed below.) With more than 5 layers, the system for practical purposes approximates to a continuous variation in modulus and no correction factor need be applied.

For the specific case where there are 5 equal-thickness, anisotropic, unbound layers, Equations 5 and 6 give identical results to that of Moffat & Jameson (1998a). Values from Equation 5 are listed in Table 1 and as discussed below, are supported by back-analyses of deflection measurements carried out on local projects. Therefore, as an interim measure Equation 5, (or Equation 6 if there are fewer than 5 layers) is suggested as a standard modular ratio, that may be expected in newly constructed unbound granular pavements. Maximum moduli for granular layers may be adopted, either as reported by Moffat & Jameson (1998b) for anisotropic moduli, or alternative values discussed by Salt & Stevens (2001) for isotropic moduli derived from deflection measurements.

Distance between layers (mm)	Modular Ratio (5 layer system)
0	1.00
25	1.15
50	1.32
75	1.52
100	1.74
125	2.00
150	2.30
175	2.64
200	3.03
225	3.48
250	4.00

Table 1. Standard Modular Ratios for New Pavements – After Moffat & Jameson (1998).

3. Application

New Pavement Design and Construction Assurance

The design of new unbound granular pavements is usually carried out most efficiently using Figure 8.4 from Austroads (1992). The Moffat & Jameson procedure (or Table 1) would allow a multi-layer elastic analysis using appropriate layer moduli. However a useful application of the modular ratio concept is for construction assurance using deflection monitoring. Irrespective of how soft or variable conditions the subgrade may present, the improvement in modulus obtained in successive overlying layers is a direct performance measure of construction effectiveness as well as uniformity.

Back analyses of deflection bowls (examples given below) suggest that the modular ratios from Table 1, are realistically achievable in newly constructed pavements. Well trafficked pavements tend to develop higher modular ratios as repeated loadings cause compaction, then in the longer term degradation of the unbound layers will eventually lead to a decrease in modular ratio.

After back-analyses of as-constructed layer moduli (assuming design or as-built layer thicknesses are made available), it is a straightforward exercise to calculate the average modular ratio (working upward from the subgrade) for any pavement, and compare it with the Equation 5 value (Table 1). A representative average is found using the geometric mean, weighted by the layer thicknesses. Dividing the average modular ratio of a given pavement by the expected standard for the same layer thicknesses, provides a normalised modular ratio. Values above 1.0 indicate performance above the standard and vice versa.

The normalised modular ratio is therefore a readily measured, impartial performance indicator which quantitatively determines whether the unbound granular layers of any pavement have been constructed as well as could be expected, given the prevailing subgrade conditions. (In some cases, other quality assurance may need to be assessed separately to determine whether the subgrade had been adequately prepared.) However, regardless of any subgrade non-uniformity, the normalised modular ratio also provides an independent measure of the uniformity of construction within the unbound granular layers and will identify any points which have the capacity for improvement, given the current limitations of the subgrades at those specific points. If alternative construction procedures (plant type, moisture or additive content, layer thickness etc) are being trialed in close proximity, areas of high modular ratios will provide an immediate indicator of the best practice techniques to be adopted for the conditions. At the same time as modular ratios are determined, the mechanistic analysis also outputs the as-constructed stresses and strains in each layer for comparison with design expectation, allowing decisions on appropriate corrective action if required.

In some cases, back analysis of deflection results may require multiple layers in one section but only 1 or 2 pavement layers to be modelled in an adjacent section. To compare uniformity between sections, consistent models are required (independent of layer thickness and number of layers) and this is the reason for the correction using Equation 6. (Moffat & Jameson, 1998a, intended their model to be used only with 5 layer sequences.)

Case history examples are given below. When normalising all modular ratios, the actual standard values adopted are not important ie amendments to Table 1 (eg regional preferences) may adopted if found necessary when further data become available.

Network Maintenance

Currently, performance-specified maintenance contracts are using network deflection surveys undertaken at the same season (usually winter) each year to assess whether the average structural capacity of the pavement has been maintained or improved over time. Mechanistic analyses may be carried out to provide parameters such as the Adjusted Structural Number, residual life distribution, or current overlay volumes for a 25 year pavement life.

If a subgrade is susceptible to varying moisture conditions and abnormally wet or dry conditions are experienced at the time of testing, then the above parameters alone may produce a temporarily biased measure of long term structural capacity. As a result they would not provide a fair measure of the current standard of maintenance during an annual assessment. A correction needs to be applied to assess and account for subgrade changes caused by moisture variation and this procedure, while straightforward, is relatively time consuming. However, if the pavement is of unbound granular construction and the normalised modular ratio is compared in successive years, then an impartial quantitative performance indicator of pavement maintenance is readily generated. The procedure does not require an accurate knowledge of pavement layer thicknesses, or details of the extent and thickness of any overlays applied. Layer thickness assumptions are made for the first year's deflection survey (usually by interpretation of mechanistic analyses), and the same layer thicknesses are used for subsequent years. Any pavement layer deterioration, or improvements (eg overlays) will be duly recognised in the subsequent changes in the cumulative distribution curve for the normalised modular ratio while any bias due to subgrade seasonal condition will be eliminated. The result is an equitable performance indicator of the long term structural condition of the pavement at a given point in time. (A separate measure to ensure effective drainage has been adequately maintained would still be required.)

4. Case Histories

New Construction

Figure 2 shows the moduli determined from back-analysis of deflection data on a newly reconstructed highway on a firm subgrade and includes a transition section from old pavement to new at the start of the section. Figure 3 shows the same output from a new pavement which begins on a soft subgrade then traverses firm ground for the remainder. In this example some tests give results marginally below expectation (eg Chainage 1.2 km) and if more pronounced would warrant investigations of construction technique locally. Both case histories indicate that a minimum value of 1.0 for the average normalised modular ratio appears very appropriate, ie supporting

Moffat & Jameson's studies, and defining an effective baseline target value for the normalised modular ratio.

Figure 2. Back-calculated Moduli and Normalised Ratios for Firm Subgrade

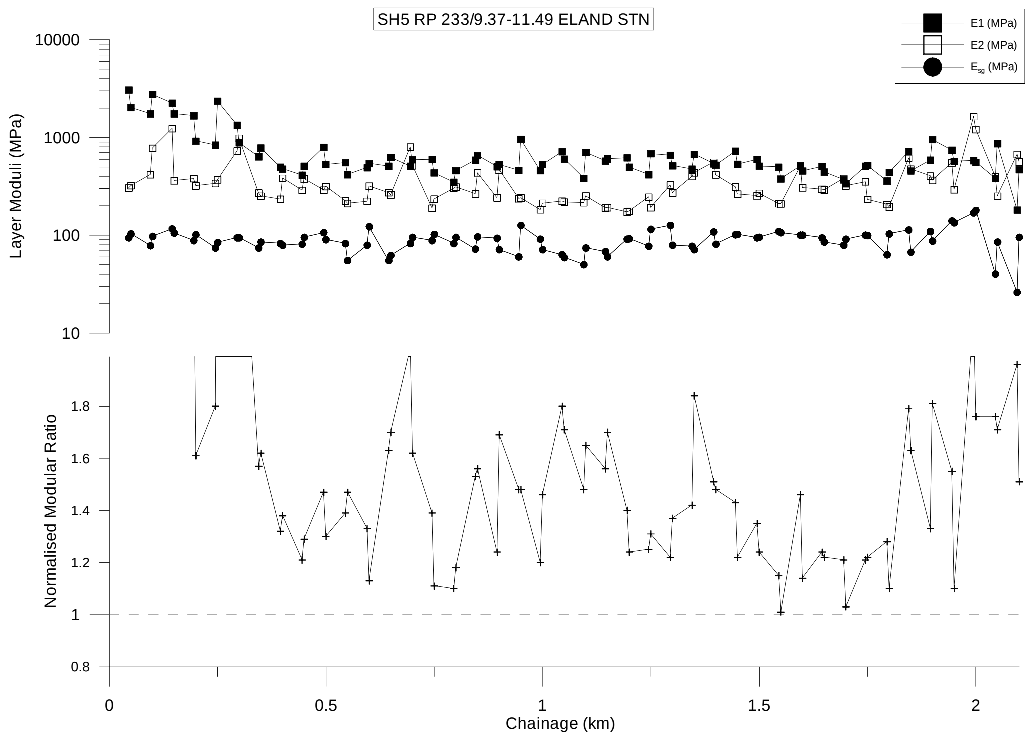


Figure 3. Moduli and Normalised Ratios for Variable Subgrade

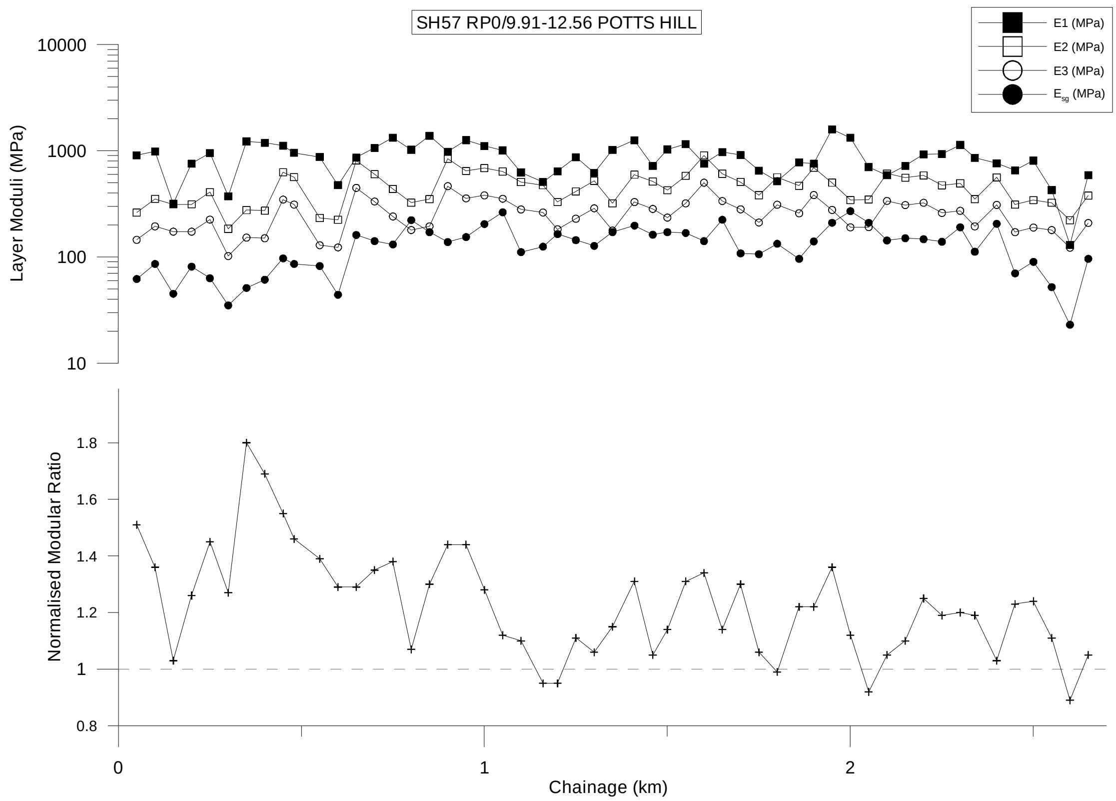


Figure 4 gives subgrade moduli in 1999 and 2000 at Transit's Benchmark Site 01, showing a significant decrease in subgrade stiffness, presumably due to seasonal effects, consequently the Adjusted Structural Number has also increased (Figure 5). However Figure 6, from the same site, shows little if any significant change in the normalised modular ratio, confirm confirming no permanent change has occurred due to deterioration of the pavement's granular layers.

Figure 4. TNZ BMS 1.
Cumulative Distribution of Subgrade Modulus in Successive years.

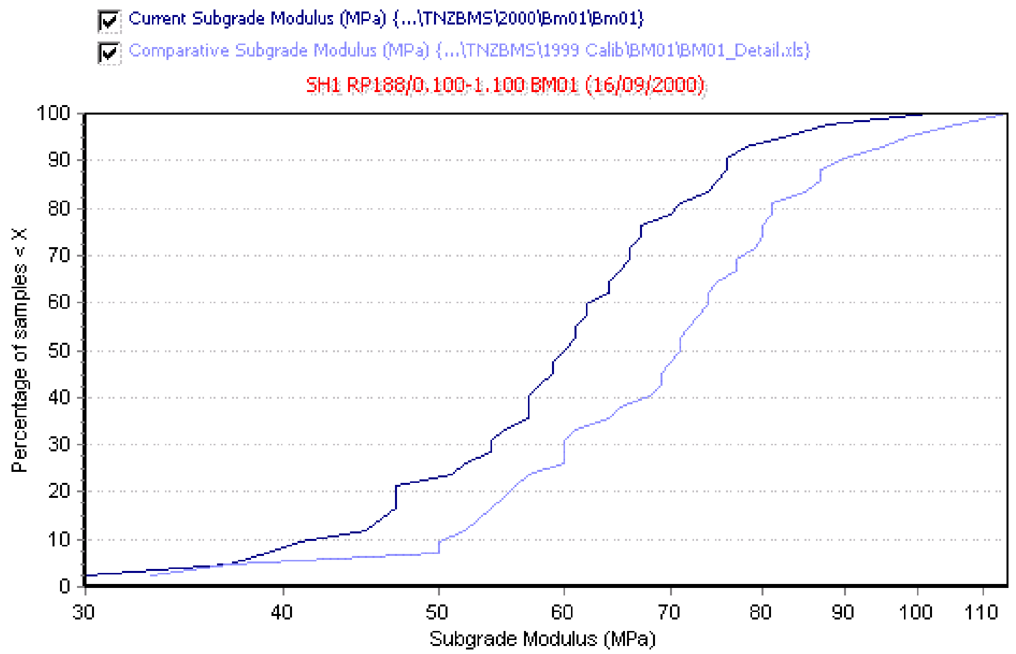


Figure 5. TNZ BMS 1.
Cumulative Distribution of SNP in Successive years

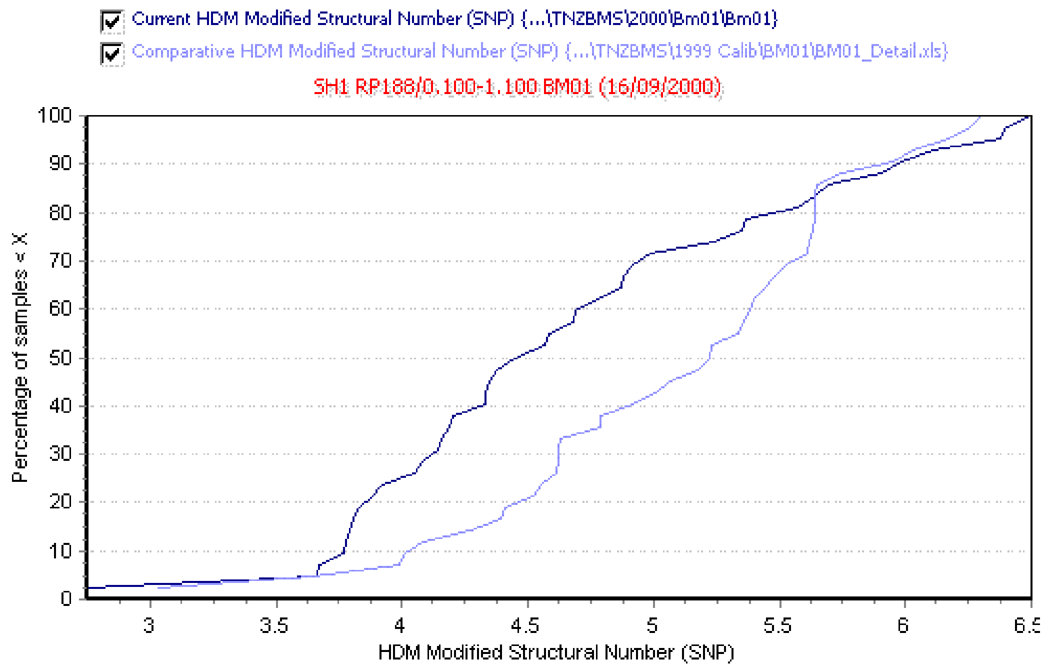


Figure 6. TNZ BMS 1.
Cumulative Distribution of Normalised Modular Ratios in Successive years

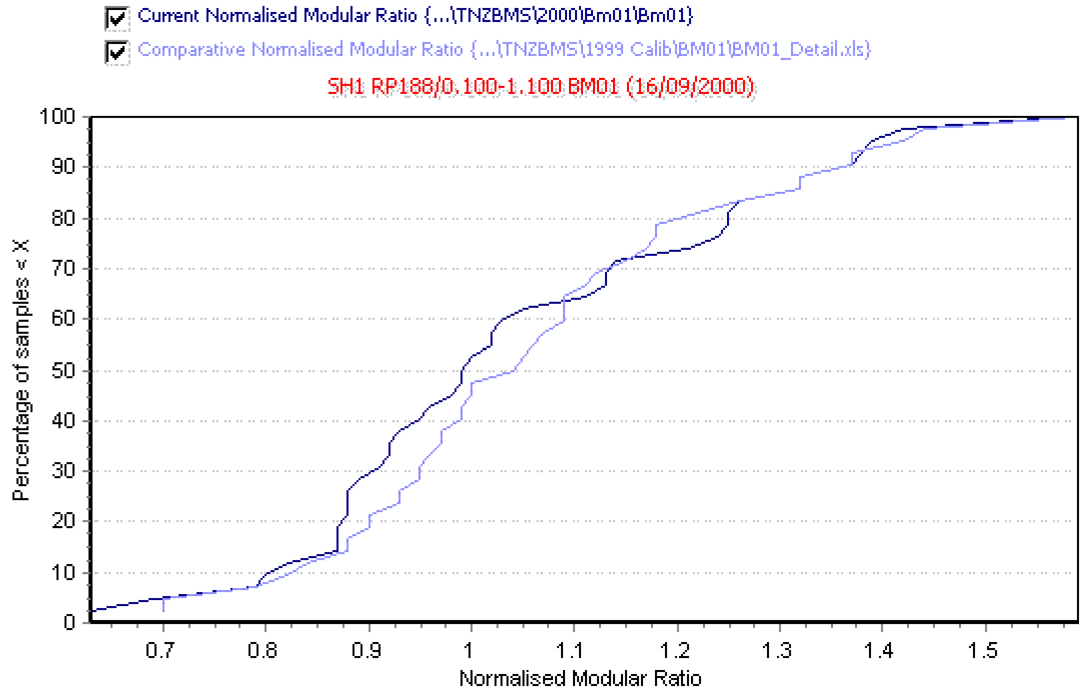
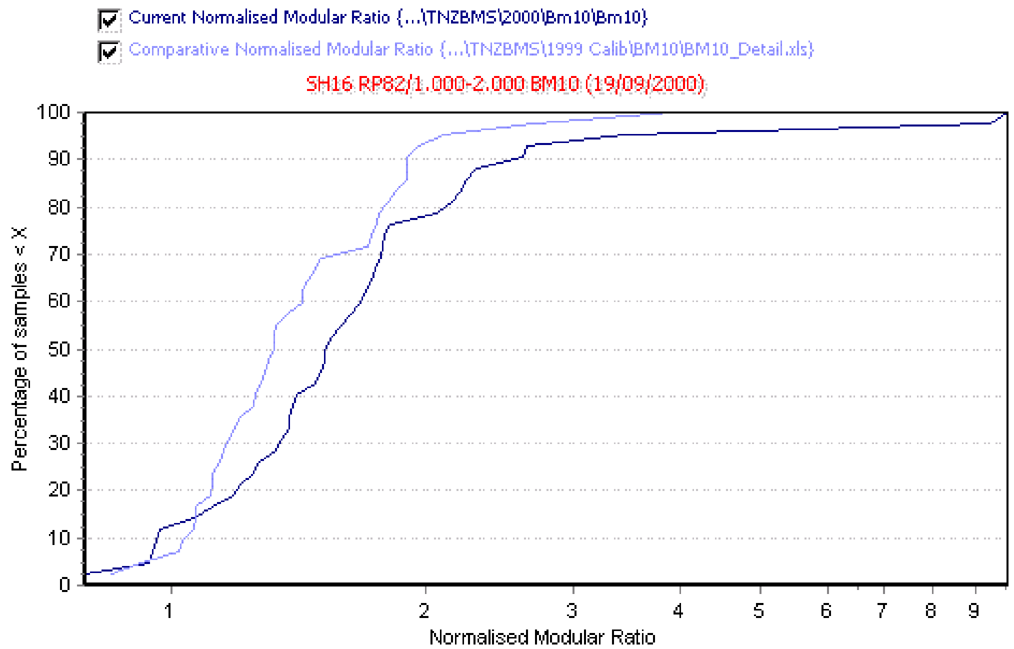


Figure 7 shows a marked increase in modular ratios over a short period, and on further enquiry it appears that rehabilitation including stabilisation was carried out over this interval, as shown by normalised modular ratios in excess of 2 (characteristic of cement stabilised layers).

Figure 7. TNZ BMS 10. Moduli increase due to basecourse stabilisation.



5. Conclusions

1. Unbound granular pavement layers show a characteristic increase in moduli from the subgrade to the surface. The ratio of moduli between successive layers provides a direct and effective measure for performance-based specifications.

2. For construction of new unbound granular pavements, standard modular ratios have been established. Deflection measurements (preferably taken prior to sealing and ideally during construction as well) allow as-constructed modular ratios to be compared with expected results from known good practice, thereby giving an immediate performance indicator. The normalised modular ratio is a quantitative measure of construction uniformity and stiffness of the pavement layers, relative to the subgrade. The performance indicator is independent of subgrade weaknesses or non-uniformity. At the same time as modular ratios are determined, the mechanistic analysis also outputs the as-constructed stresses and strains in each layer for comparison with design expectation, allowing decisions on appropriate corrective action if required.

3. For monitoring of network maintenance contracts of unbound granular pavements, average modular ratios determined in successive years provide direct unbiased performance indicators of the standard of maintenance of the pavement layers, irrespective of seasonal variations of subgrade conditions, outside the contractor's control.

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