Modular ratios for unbound granular pavement layers

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ABSTRACT: 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-analysis of Falling Weight Deflectometer bowls recorded during construction monitoring or long-term structural condition studies. Their applications to new construction quality assurance and performance-based network maintenance contracts are described.

I 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 granular aggregate cannot be properly compacted on a soft subgrade, or alternatively, if a stiff dense layer is placed on a yielding foundation, then during trafficking, tensile strains will develop and the upper layer will de-compact if it is unbound (i.e. cannot sustain significant horizontal tensile stresses).

In a multi-layer system, Heukelom and Foster (1960) carried out linear elastic analyses of pavements using typical compacted layer thicknesses. They found 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 relates to the increase in average effective modulus between successive layers. The average effective modulus should approximate the true modulus near the mid-depth of each layer. However in practice, the unbound layer moduli will change continuously with depth (but not quite linearly) within each layer.

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

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

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:

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

For mechanistic design, AUSTROADS (1992, 2004) 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 sub-layers 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:

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

(but not exceeding tabulated upper bounds for the materials)

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

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

(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 (high standard) or 350 MPa (normal standard) 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 (viz. from Falling Weight Deflectometer 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 stiffness of underlying layers.

II 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.

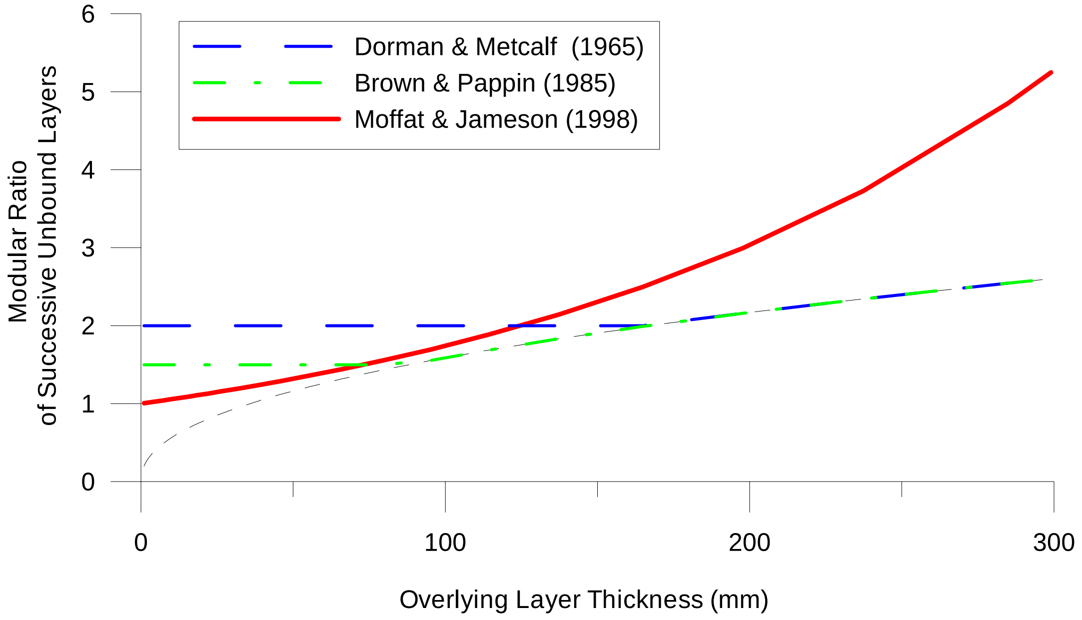

Figure 1. Comparison of modular ratios from alternative relationships.

Typically, mechanistic analyses of pavements would consider layer thicknesses of 75 - 150 mm and it is evident that the above relationships yield generally similar modular ratios for this range, i.e. 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. The other relationships require their imposed lower bounds because the general form of the original equation (shown above and trending to values much less than unity) is clearly not reasonable for thin layers. For the case where the thickness of the underlying layer is say 150 mm and the upper layer thickness tends to zero, then none of the above equations are 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 thicknesses of layers. The Moffat and Jameson method was developed from use with CIRCLY; a linear elastic pavement layer model which uses a finite layer thickness for the uppermost layer of the subgrade. However, other software packages in common use (eg ELMOD, used in this study) 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. For this reason, a refinement of the Moffat & Jameson procedure is suggested in the following.

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:

$$E_i / E_{i+1} = 2^{\,(hi\_i+1\ /125)} \qquad (5)$$

where $h_{i\ i+1}$ is the distance in mm between the mid heights of layer i and i+1. In Equation 5 the mid height of the subgrade is taken to be the top of the subgrade.

By examining a range of numbers of layers and corresponding sub-layer thicknesses that could be used to make up a given total pavement thickness, Equation 5 may need some adjustment to give the same combined effective stiffness for other than 5 layers. This is the result of using discrete steps in moduli rather than a continuous function. These discrete steps less well approximate the true continuous function in the case of few sub-layers, and in the case of fewer than three, it can be necessary to apply a correction factor K_{NL} as follows:

$$E_i / E_{i+1} = 2^{(hi\_i+1 /125)} \times K_{NL} \tag{6}$$

where NL is the number of layers. The factor K_{NL} will depend on the number of granular layers and their thicknesses, but for practical purposes may be taken as 1.0 if either there are three or more layers, or if each layer is less than 250 mm. Otherwise calibration (determining equivalent stiffnesses) should be carried out using the same elastic analysis software routine that is used in design.

These changes to the Moffat and Jameson procedure are minor but are necessary in order to extend the application of the modular ratio concept. For the specific case where there are 5 equal-thickness 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 appropriate) is suggested as a standard modular ratio that may be expected in newly constructed unbound granular pavements. Maximum moduli for granular layers need to be assigned in the usual manner, either as reported by Moffat & Jameson (1998b) for anisotropic moduli, or alternative values as discussed by Salt & Stevens (2001) for isotropic moduli derived from deflection measurements.

Table 1. Standard modular ratios for new pavements – After Moffat & Jameson (1998).

Distance between layers (mm)	Modular ratio
0	1.00
100	1.74
125	2.00
150	2.30
250	4.00

III APPLICATION

3.1 *General*

The modular ratio concept has been used traditionally to assign moduli to unbound granular materials for mechanistic design. The following proposes to extend the use of modular ratios for quality assurance of new construction and to improve procedures for the assessment of the long-term structural condition of roading networks.

3.2 *New Pavement Design and Construction Assurance*

The design of new unbound granular pavements is usually carried out most efficiently using an empirical chart yielding total granular depth as a function of number of loading cycles and CBR. 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 Falling Weight Deflectometer (FWD) 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 at the top of the aggregate layers. In the longer term, degradation of the unbound layers could, in a weak aggregate, 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 of the unbound layers (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. 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. If the surface layer is bound (eg asphaltic concrete, not governed by the underlying modulus) it is not included in the calculation.

The normalised modular ratio (NMR) 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 trialled 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.

At any given point along a pavement, the normalised modular ratio may be low between the subgrade and subbase, yet compensated by a high ratio between the subbase and basecourse. Such effects may be real (from construction non-uniformity) or apparent (from simplifications inherent in most back-calculation procedures or an irregular deflection bowl which has poor goodness of fit to elastic theory). However, by determining the normalised modular ratio as a weighted average as described above, a meaningful evaluation still results.

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 i.e. amendments to Table 1 (eg regional preferences) may adopted if found necessary when further data become available. Meanwhile, the majority of pavements studied so far support Equation 6 very closely.

3.3 *Network Maintenance*

Currently, performance-specified maintenance contracts are using network deflection surveys (FWD) undertaken in the same season each year (usually winter or spring) 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 an intended (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 should, in theory, be largely eliminated. Case histories support this hypothesis. 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.)

IV CASE HISTORIES

4.1 *New Construction*

Figure 2 shows the moduli determined from back-analysis (ELMOD) of FWD data on a newly reconstructed unbound granular pavement 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 another new pavement (again subject to only a few weeks trafficking) which begins on a soft subgrade then traverses firm ground for the remainder. If any normalised modular rations are below expectation, this would warrant investigations of construction technique locally. Both case histories indicate that a minimum (say 5 percentile) value of 1.0 for the normalised modular ratio (computed from the weighted average over successive layers) appears very appropriate, i.e. supporting Moffat & Jameson's studies, and defining an effective baseline target value.

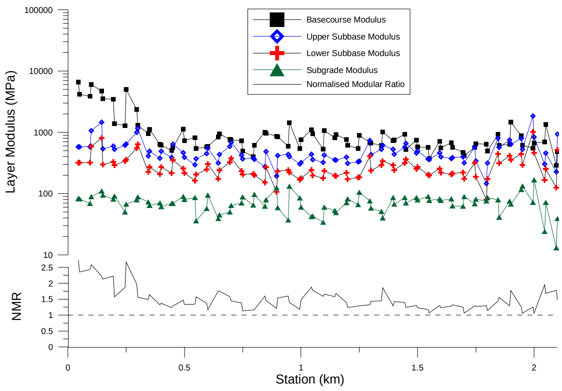

Figure 2. Back-calculated Moduli and Normalised Modular Ratios (NMR) for Firm Subgrade.

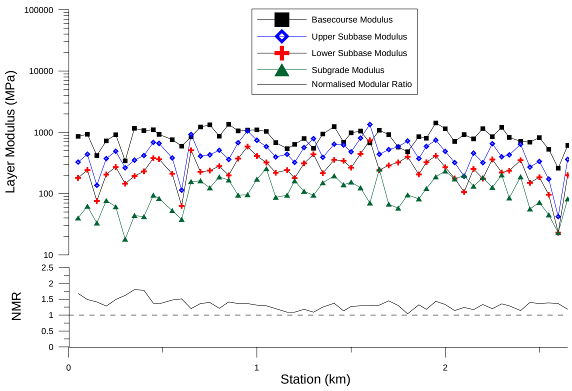

Figure 3. Moduli and Normalised Modular Ratios for Variable Subgrade.

The two cases above both have similar distributions, particularly for their lower bounds as may be appreciated from the cumulative distributions shown in Figure 4 below.

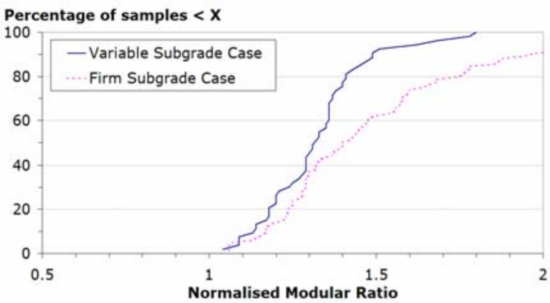

Figure 4. Cumulative Normalised Modular Ratio Distributions for New Trafficked Pavements.

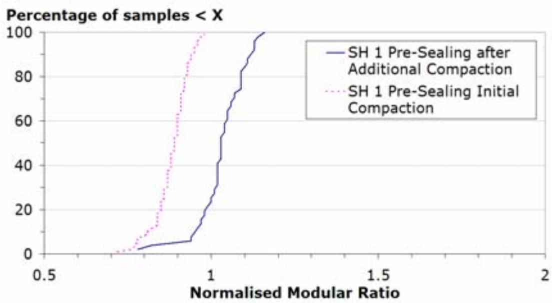

Figure 5. Increase in Normalised Modular Ratio with Additional Compaction.

The above cases are from unbound granular pavements where some trafficking has been experienced allowing shakedown of the granular layers. Where only construction compaction has occurred, modular ratios can be expected to be lower. One recent case of new construction studied monitored the first compaction attempt on the basecourse. This showed normalised modular ratios in the range of 0.8 to 0.9, i.e. clearly less than 1 (Figure 5). Sealing was deferred and further compaction applied giving a marked increase in modular ratios with only about 10% less than unity. After trafficking, further shakedown would be expected, i.e. it is likely that ratios may increase by 10-30% in the early life of most unbound granular pavements, depending on how well they have been compacted during construction.

Further research on this aspect is in progress, but untrafficked unbound granular pavements with 10 percentile normalised modular ratios lower than 0.9 may, if already sealed, show some early life rutting due to ongoing densification of the granular layers. For cement bound or structural asphaltic pavements, the normalised modular ratio still provides an effective quality control measure, most readily assessed from FWD testing immediately prior to laying the asphalt or other bound layers.

Where subgrade stabilisation has been carried out, it is sometimes difficult to separate the moduli of the improved layer from the original subgrade, making assessment of all modular ratios less reliable. In this case, while absolute values of normalised modular ratios may not be definitive, values can still be compared along the length of the new construction to identify any relatively weaker sections.

4.2 *Network Maintenance*

Figure 6 gives subgrade moduli in 2000 and 2001 at one benchmark site set up for Long Term Performance (LTPP) evaluation, and shows a significant decrease in subgrade stiffness, presumably due to a wetter period leading up to the 2001 testing. Consequently, the Adjusted Structural Number (SNP) has also decreased (Figure 7). However Figure 8, from the same site, shows little, if any, significant change in the normalised modular ratio, confirming no permanent change has occurred due to deterioration of the pavement's granular layers.

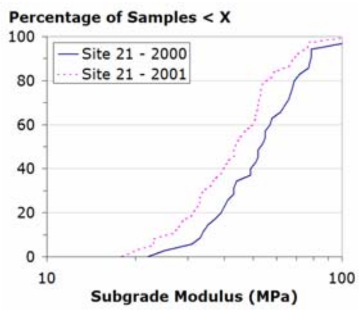

Figure 6. LTPP Site 21. Cumulative Distribution of Subgrade Modulus in Successive years.

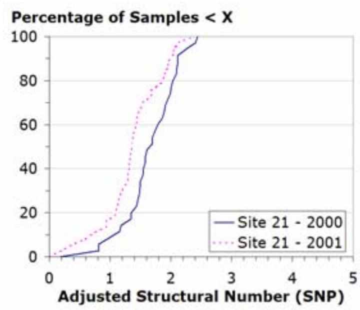

Figure 7. LTPP Site 21. Cumulative Distribution of Adjusted Structural Number (SNP) in Successive years.

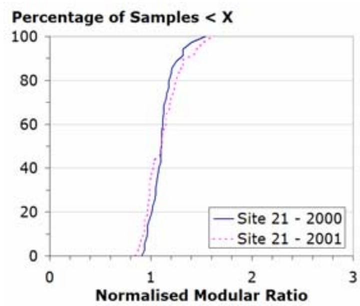

Figure 8. LTPP Site 21. Cumulative Distribution of Normalised Modular Ratios in Successive years.

The results of the 3rd successive set of tests on LTPP Site 21 in 2002 are given in Figures 9, 10 and 11. The subgrade modulus has increased (suggesting a drier year) along with SNP, while the normalised modular ratio again remains effectively invariant.

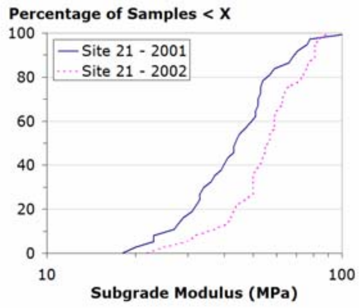

Figure 9. LTPP Site 21. Cumulative Distribution of Subgrade Modulus in Successive years.

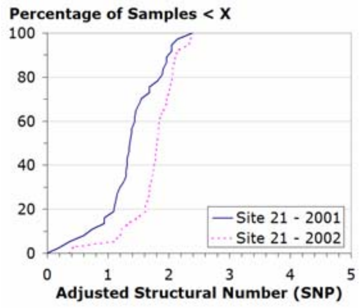

Figure 10. LTPP Site 21. Cumulative Distribution of HDM Modified Structural Number (SNP) in Successive years.

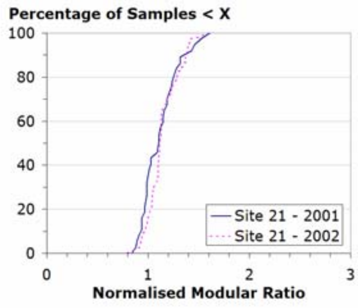

Figure 11. LTPP Site 21. Cumulative Distribution of Normalised Modular Ratios in Successive years.

Not all LTPP sites show completely invariant normalised modular ratios from year to year as each contains only a relatively small number of test points. The median results from all sites are shown in Figures 12 and 13. These indicate:

(a) There is a significant trend for a change in SNP with change in subgrade modulus between successive years; hence there will be a corresponding change in calculated overlay requirements.
(b) There is no significant trend for change in normalised modular ratio with change in subgrade modulus.

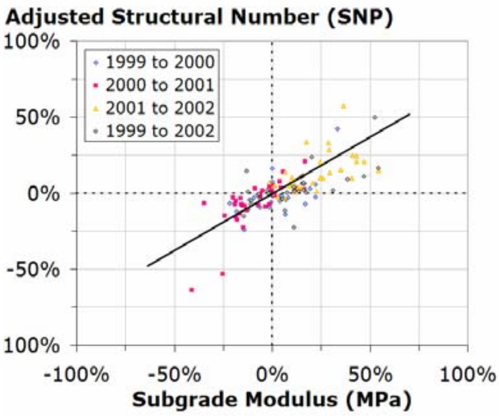

Figure 12. Trend showing change in Adjusted Structural Number (SNP) versus change in Subgrade Modulus (Es) for all LTPP sites.

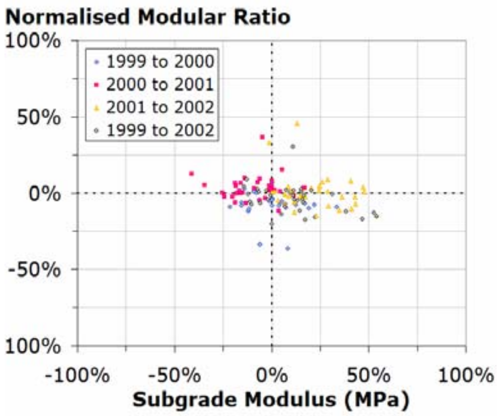

Figure 13. Independence of Normalised Modular Ratio (NMR) for all LTPP sites.

Each LTPP site represented by the above points corresponds to only about 1 km of highway, i.e. the samples are relatively small which contributes to some scatter. However, when all are combined (Figure 14), over 50 km is represented and, in this case, the cumulative distribution clearly indicates that when averaged over moderate lengths of highway in a total period of 2 years, the normalised modular ratio is a parameter that is essentially invariant. The parameter therefore appears to provide the requisite properties for a key performance indicator of the structural condition of a network, i.e. it is a relative strength measure enabling comparisons of a network in successive years and is unbiased by seasonal variations.

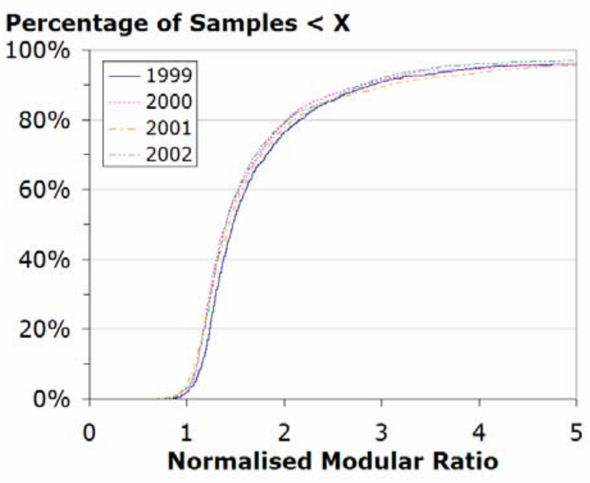

Figure 14. Cumulative distribution of Normalised Modular Ratio (NMR) for all LTPP sites.

V CONCLUSIONS

5.1 Unbound granular pavement layers show a characteristic increase in moduli from the subgrade to the surface. Standard ratios of moduli between successive layers have formerly been proposed for the mechanistic design of pavements. However, a study of Long Term Pavement Performance sites indicates that the normalised modular ratio concept has applications as direct and effective measures for performance-based specifications.

5.2 For construction of new unbound granular pavements, standard modular ratios for successive layers have been established. The same principles apply to pavements with bound layers if FWD testing is carried out immediately prior to placing of the bound layer. FWD back analyses allow as-constructed modular ratios to be compared with expected results from known good practice thereby giving an immediate performance indicator of construction effectiveness, identifying areas which would benefit from further compaction. 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 subgrade 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.

5.3 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.

5.4 A rationalised and more generalised form of the equation for modular ratios of unbound granular materials has been proposed. FWD back calculated modular ratios are consistent with Equation 6.

5.5 The modular ratio concept can be used to improve back-calculated moduli for intermediate layers which are composed of unbound granular materials. Most back calculation packages generate reliable subgrade moduli and reasonable top layer moduli, but the residual bowl fitting process yields intermediate layer moduli that are highly sensitive to adopted layer thicknesses. In practice, thicknesses may vary markedly between points of known reliability (eg test pit locations). By using specified modular ratios to constrain the total granular thickness of a fully unbound granular pavement, the “effective” thickness of construction may be inferred.

VI RECOMMENDATIONS FOR APPLICATION

6.1 For construction of unbound granular pavements, back-analysis of FWD testing after compaction of the final layer provides a fast and reliable measure of whether full compaction has been achieved throughout the depth of the granular layers at each test point. It is therefore an overall check that required densities have been obtained throughout all layers. The normalised modular ratio determines how the overall stiffness of any depth of pavement, irrespective of subgrade type and condition, compares with the stiffness known to be practically achievable by the industry under the same conditions. The same principle applies to bound pavements if testing is carried out on the underlying unbound layer immediately prior to placing the bound layer.

6.2 An effectively compacted section of pavement is characterised by normalised modular ratios greater than 1. Less than 5% of test results can be expected below this value after trafficking. If the 5%ile normalised modular ratio is less than 0.75 before trafficking, significant early rutting can be expected; hence additional compaction should be specified prior to application of surfacing to ensure refusal has been reached, but more importantly, the field compaction methodology and target densities should be re-appraised.

6.2 After shakedown trafficking of a new pavement (at least 10,000 ESA), close to full compaction will be achieved; hence if FWD measurements are taken after that time, the normalised modular ratio concept may be used to determine the “effective” thickness of a new pavement and thereby identify any points where lesser than design thicknesses may have been constructed, irrespective of varying subgrade characteristics.

6.3 Performance specified maintenance contracts of unbound granular pavements, which use total overlay requirements as a structural measure, can be affected by subgrade moisture changes. When comparing results in successive years, an unusually wet (or dry) year may cause bias which can be simply identified by comparing the cumulative distributions of subgrade moduli. In such cases, there is an alternative measure, i.e. in structural terms, no effective deterioration of the network would be demonstrated where the cumulative distribution of normalised modular ratio has not decreased in successive years.

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