# SOME INFLUENCES OF LAYER THICKNESS VARIATIONS ON BACKCALCULATION AND REHABILITATION DESIGN

**FRITZ JOOSTE**

Modelling and Analysis Systems (cc), P O Box 634, La Montagne, 0184
e-mail: fritzj@icon.co.za

## INTRODUCTION

Since the late 1980's pavement surface deflection measurements have played an increasingly important role in pavement condition assessment. Several types of pavement deflection devices are commonly used, with the Falling Weight Deflectometer (FWD) being perhaps the most frequently used for network surveys and rehabilitation design studies. Pavement surface deflections can be used at several levels, each of which is suited to a specific analysis need. Some uses of pavement surface deflections include:

- The use of deflection bowl parameters to obtain a fast and relative indication of pavement structural capacity (used at the project and network level);
- The use of the deflection bowl to obtain an estimated pavement structural number (Rohde, 1994), and
- The use of the deflection bowl to backcalculate the stiffness of the various pavement layers (used mostly at project level).

Of these uses of surface deflections, the backcalculation of layer stiffnesses has perhaps had the greatest effect on the manner in which pavement rehabilitation design is approached today. Almost any project aimed at the evaluation of pavement structural capacity will include some form of backcalculation to assess pavement structural capacity.

The process of backcalculating pavement layer stiffnesses from surface deflections comprise the following steps:

1. An indication is obtained of the quality and type of the subgrade and the pavement layers, as well as of the thickness of the various pavement layers;
2. Information on the layer type and quality is used to estimate likely values for the stiffnesses of the various pavement layers;
3. The estimated layer stiffnesses are used in a computer model (typically a layered elastic model), in order to calculate the pavement surface deflections;
4. The calculated and the measured deflections are compared and adjustments are made to the estimated layer stiffnesses to improve the agreement between measured and calculated deflections. Repeat steps 3 and 4 until an acceptable agreement between measured and calculated deflections is obtained;

Pavement layer stiffnesses calculated in this manner are typically used to construct a model of the pavement situation. This model is used to estimate stresses and strains in the existing pavement structure. The calculated stresses and strains are then used in conjunction with a design method such as the South African mechanistic design method (Theyse et al, 1996), in order to evaluate the remaining life of the existing pavement structure before and after rehabilitation.

As noted above, the estimation of the pavement layer thickness is one of the first steps in the backcalculation process. The layer thickness can be estimated in several ways ranging from historical (as-built) data to detailed surveys comprising of trial pits and Dynamic Cone Penetrometer (DCP) readings.

In this paper, the impact of layer thickness estimation on the backcalculation process is evaluated by means of a simulation study. A typical lower category South African pavement is used in the simulation and the impact of various strategies of layer thickness determination on backcalculated stiffnesses is determined. Conclusions are documented and recommendations are made for optimising layer thickness data in backcalculation analyses.

## STUDY OBJECTIVES AND METHODOLOGY

The primary objective of this study was to evaluate the impact of layer thickness estimates on backcalculated stiffnesses for a typical South African pavement structure. A secondary objective was to formulate a broad strategy for most effectively using available layer thicknesses in backcalculation analyses.

In view of time and funding constraints, the study was primarily aimed at the formulation of coarse guidelines rather than developing comprehensive recommendations. The study thus focused on a single case study, which was selected to represent a typical lower category South African pavement structure.

The methodology followed in the study consisted of the following:

- Simulate a typical population of layer thicknesses in a pavement structure over a medium to short section of road;
- From this population, obtain layer thickness estimates by simulating different sampling strategies;
- Assuming a single set of layer stiffnesses at all positions within the pavement, use a layered elastic program to generate deflection bowls at 50 metre intervals by using the actual layer thickness at each point;
- Use the generated deflection bowls together with the layer thickness estimates from different sampling strategies, and backcalculate the layer stiffnesses at 50 metre intervals.
- Compare the actual layer stiffness with the backcalculated layer stiffness for each of the sampling strategies.

The pavement used in this study is summarized in Table 1. This pavement is typical of a Category B structure recommended for use in dry regions and for design traffic of 3 to 10 million standard axles (TRH4, 1996). Also shown in Table 1 are the layer stiffnesses used to generate the deflection bowls at 50 m intervals. It will be noted from Table 1 that the assumed pavement model included a semi-stiff substrate at a depth of 1 m below the top of the subgrade. This layer was included to simulate the stress-stiffening effect that is likely to take place with increasing depth and overburden pressure in sandy materials.

Previous studies (Rohde, 1991) have suggested that the inclusion of such an effective stiff layer leads to better agreement between measured and calculated deflections, and more appropriate backcalculated stiffnesses for the subgrade.

Table 1. Pavement Structure Properties Assumed for Simulation

| **Layer** | **Average Thickness (mm)** | **Thickness Range (mm)** | **Coefficient of Variation for Thickness** | **Assumed Stiffness (MPa)** |
|---|---|---|---|---|
| Asphalt Surfacing | 43 | 32 to 55 | 16 % | 2500 |
| Granular Base | 136 | 115 to 160 | 9% | 350 |
| Granular Subbase | 270 | 200 to 315 | 12% | 175 |
| Upper Subgrade | 1000 | No Variation | Not Applicable | 60 |
| Lower Substrata | Semi-infinite | Not Applicable | Not Applicable | 400 |

Note: Poisson's ratio for all layers was set to 0.4 (also for subsequent calculations)

Figure 1 shows the simulated layer thicknesses for the pavement over a typical 3.7 km section of road. The layer thickness simulation was controlled to ensure that the final coefficient of variation for all layers is in line with published results. In this regard, the publications of Darter et al (1973) and Hughes (1996) were used as guidelines.

It should also be noted that the simulated pavement section shown in Figure 1 does not represent a newly constructed pavement. Rather, it represents an older pavement structure in which significant compaction of layers had already taken place, and which may have undergone some form of rehabilitation on some parts. This scenario is more typical of the pavement structures on which backcalculation for rehabilitation purposes are performed.

Before the analysis of thickness sampling strategies was undertaken, a backcalculation of layer stiffnesses was performed using the actual layer thicknesses at each deflection point. This calculation was undertaken to determine the degree of systematic error inherent in the backcalculation model, in order to ensure that this error is not confused with the error caused by variation in layer thicknesses.

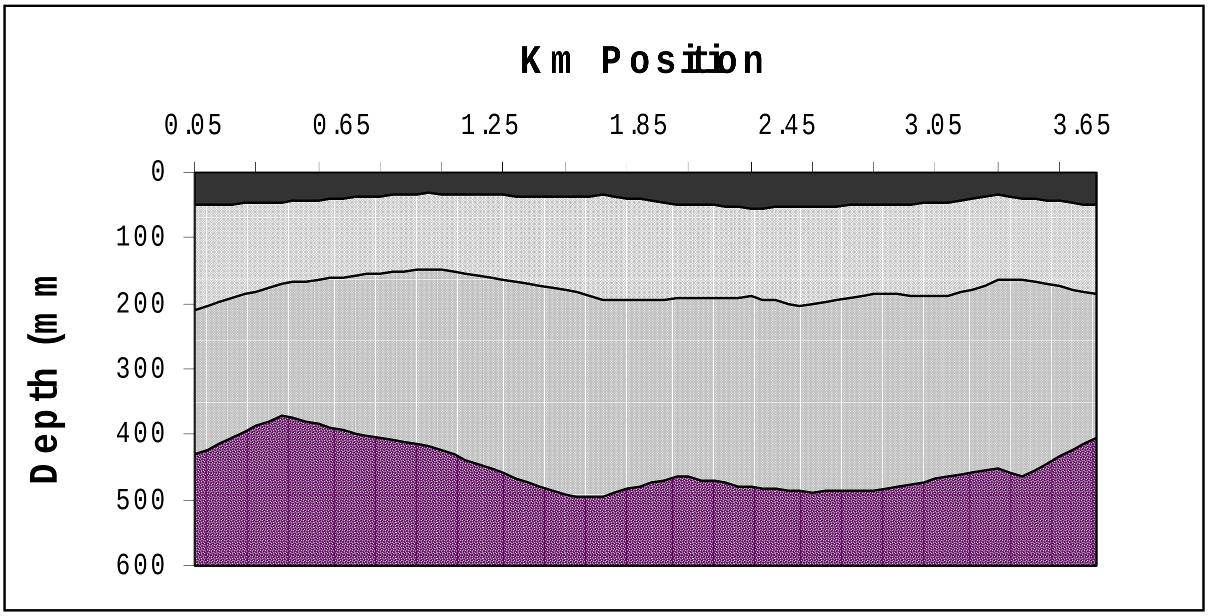

Figure 1. Simulated Pavement Structure Showing Thicknesses of Pavement Layers

Table 2 shows the details of the backcalculated stiffnesses for the condition in which the correct layer thicknesses were used for each deflection bowl. All backcalculation was performed using the backcalculation module of the RUBICON2 software for rehabilitation design planning and analysis (Jooste, 2002). This program implements the WESLEA layered elastic subroutine (Van Cauwelaert et al, 1989) in conjunction with a regression type algorithm for estimating backcalculated stiffnesses.

Table 2. Comparison Between Actual and Backcalculated Stiffnesses for the Case where the Correct Layer Thickness was Used at Each Deflection Bowl Position

| **Layer** | **Backcalculation Search Range** | **Actual Stiffness (MPa)** | **Backcalculation Results (MPa)** | |
|---|---|---|---|---|
| | | | **Average** | **Range** |
| Asphalt | 2500 (fixed) | 2500 | 2500 | Not Applicable |
| Granular Base | 150 to 500 | 350 | 348 | 342 to 353 |
| Granular Subbase | 100 to 300 | 175 | 178 | 174 to 184 |
| Subgrade | 40 to 120 | 60 | 59 | 57 to 61 |
| Substrate | 200 to 600 | 400 | 459 | 439 to 480 |

Table 2 shows that the backcalculation algorithm used in the RUBICON2 software proves an accurate and relatively precise estimate of the actual layer stiffnesses for the case where the correct layer thicknesses are provided at each deflection bowl position. There is a slight overestimate of the substratum stiffness, but this does not seem to have a significant effect on the backcalculated stiffness of the upper pavement layers. It should be noted that the stiffness of the asphalt surfacing was fixed during the backcalculation, owing to the relatively low thickness of this layer.

## SAMPLING STRATEGIES ANALYZED

For this study, three sampling strategies were evaluated. These are:

1. Single estimate of layer thickness over the 3.7 km road length;
2. Three evenly spaced estimates of layer thickness over the 3.7 km road length;
3. Layer thickness estimates taken at 500 m intervals;

For strategies 2 and 3, two methods of utilizing the available thickness data during backcalculation were analysed. These are (i) use the mean value of the sampled thicknesses, and (ii) for each deflection bowl, use the layer thickness situated closest to the bowl position. Sampling locations and layer thickness estimates for the three sampling strategies are summarized in Table 3.

To ensure a consistent backcalculation process, the backcalculation for each strategy was performed using the same search ranges for each layer. The ranges used are those shown in column 2 of Table 2.

Table 3. Layer Thicknesses Obtained for Each Sampling Strategy

| Strategy | Sampling location (Km) | Sampled Thickness (in mm) for Layer (values in brackets denote averages) | | |
|---|---|---|---|---|
| | | **Surfacing** | **Base** | **Subbase** |
| Single Point (at location representing average deflection) | 1.55 | 38 | 140 | 315 |
| Three evenly spaced points | 0.9; 1.8; 2.7 | 34;39;51 (41) | 117;155;140 (137) | 260;290;295 (282) |
| Sampled at 500 m intervals | 0.05; 1.0;1.5;2.0; 2.5;3.0;3.5 | 43;32;37;48;53; 47;43 (43) | 123;115;138; 145;150;142; 128 (134) | 213;270;311; 270;284;283; 273 (272) |

## BACKCALCULATION RESULTS FOR THICKNESS SAMPLING STRATEGIES

A statistical summary of the backcalculation results obtained for each thickness sampling strategy is shown in Tables 4 to 8. Since the thickness of the relatively thin asphalt layer was kept fixed during backcalculation, this layer is not represented in Tables 4 to 8. The stiffness of the substratum is not of significance for structural evaluation purposes and is therefore also not represented in Tables 4 to 8.

Table 4. Backcalculation Results for Sampling Strategy 1 (single thickness estimate over 3.7 km)

| Statistical Parameter | Backcalculated Stiffness (in MPa) | | |
|---|---|---|---|
| | **Granular Base** | **Subbase** | **Subgrade** |
| Mean | 404 | 154 | 59 |
| Maximum | 500 | 177 | 61 |
| Minimum | 306 | 124 | 58 |
| 15th Percentile | 342 | 132 | 58 |
| *Actual Value* | *350* | *175* | *60* |

Table 5. Backcalculation Results for Sampling Strategy 2(i) (three evenly spaced thickness samples, using average thickness value)

| Statistical Parameter | Backcalculated Stiffness (in MPa) | | |
|---|---|---|---|
| | **Granular Base** | **Subbase** | **Subgrade** |
| Mean | 399 | 164 | 58 |
| Maximum | 500 | 191 | 61 |
| Minimum | 299 | 129 | 58 |
| 15th Percentile | 334 | 138 | 58 |
| *Actual Value* | *350* | *175* | *60* |

Table 6. Backcalculation Results for Sampling Strategy 2(ii) (three evenly spaced thickness samples, using closest thickness value)

| Statistical Parameter | Backcalculated Stiffness (in MPa) | | |
|---|---|---|---|
| | **Granular Base** | **Subbase** | **Subgrade** |
| Mean | 373 | 167 | 59 |
| Maximum | 500 | 213 | 62 |
| Minimum | 250 | 133 | 56 |
| 15th Percentile | 308 | 155 | 56 |
| *Actual Value* | *350* | *175* | *60* |

Table 7. Backcalculation Results for Sampling Strategy 3(i) (seven evenly spaced thickness samples, using average thickness value)

| **Statistical Parameter** | **Backcalculated Stiffness (in MPa)** | | |
|---|---|---|---|
| | **Granular Base** | **Subbase** | **Subgrade** |
| Mean | 399 | 182 | 57 |
| Maximum | 500 | 211 | 59 |
| Minimum | 295 | 143 | 56 |
| 15th Percentile | 332 | 154 | 56 |
| *Actual Value* | *350* | *175* | *60* |

Table 8. Backcalculation Results for Sampling Strategy 3(ii) (seven evenly spaced thickness samples, using closest thickness value)

| **Statistical Parameter** | **Backcalculated Stiffness (in MPa)** | | |
|---|---|---|---|
| | **Granular Base** | **Subbase** | **Subgrade** |
| Mean | 355 | 180 | 59 |
| Maximum | 468 | 233 | 61 |
| Minimum | 291 | 162 | 57 |
| 15th Percentile | 326 | 168 | 57 |
| *Actual Value* | *350* | *175* | *60* |

## DISCUSSION OF BACKCALCULATION RESULTS

The results shown in Tables 4 to 8 prompt the following observations:

- Variations in the pavement layer thickness have a small influence on the backcalculated subgrade stiffness. Thus Tables 4 to 8 suggest that the sampling frequency for layer thickness does not have a significant influence on the backcalculation of subgrade stiffness. This observation agrees with the findings of Briggs *et al* (1996) and Siddhartan *et al* (1996).
- For the structure analysed in this study, the influence of layer thickness variation on backcalculated subbase stiffness appears to be small. Except for the first sampling strategy, all other sampling strategies result in mean backcalculated stiffnesses for the subbase that agrees fairly well with the actual subbase stiffness.
- For the structure analysed in this study, the layer thickness variation appears to influence the base stiffness more than any other layer. Significant variations in base layer stiffness are observed for all sampling strategies, where the backcalculated base stiffness varied from approximately 300 to 500 MPa. This variation is apparent only, and is caused by the erroneous layer thickness assumed for the different deflection bowls, and not by actual variations in layer stiffness.

Perhaps the most significant observation is that the mean backcalculated stiffness for all layers agrees fairly well with the actual layer stiffness, regardless of the sampling strategy. However, the stiffness at individual points can be significantly different from the actual layer stiffness, owing to erroneous assumptions with regard to layer thickness.

Figure 2 shows the maximum, mean and minimum values for the backcalculated base stiffness for each sampling strategy. As expected, sampling strategy 3 (ii) resulted in the most accurate estimate of mean layer stiffness. Compared to the other strategies, this strategy relied on a larger sample size and used the sampled layer thickness that is closest to each deflection bowl (as opposed to the average layer thickness).

The use of the mean layer thickness did not improve the accuracy of the mean backcalculated stiffness, regardless of the sample size. As expected, the use of the layer thickness set that is sampled closest to each individual deflection bowl (i.e. strategies 2 (ii) and 3 (ii)) clearly results in a more accurate estimate of layer stiffness.

It is important to note that all sampling strategies resulted in a mean estimate of layer stiffnesses that is relatively accurate if the results are not interpreted in a very precise manner. For example, for the base, all strategies estimated a mean stiffness of roughly 350 to 400 MPa. Thus all strategies suggest a fairly competent and stiff base (if one considers that the layer is supported by a flexible layer and not a stabilized subbase). Thus in a qualitative sense, and based on the mean values, all sampling strategies gave the same result: a medium stiff base typical for G2 or G4 material on un-stabilized support.

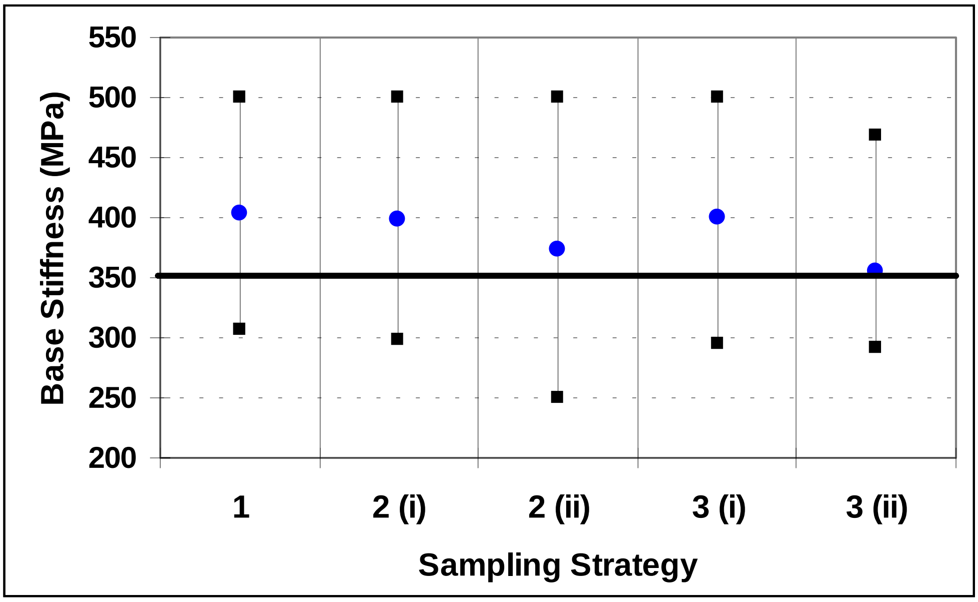

Figure 2. Maximum, Mean and Minimum Backcalculated Base Stiffnesses for Different Sampling Strategies (dark horizontal line denotes the actual stiffness)

If, however, one attempts to interpret the results in a more precise manner, then the errors at individual deflection bowls become more relevant. In particular, it is important to note that all sampling strategies showed roughly the same range of backcalculated stiffnesses (which can be interpreted as an error band). Thus it can be expected that the backcalculated stiffness at individual data points will always contain some degree of error owing to the variations in layer thickness. The influence of these errors on the assessment of structural capacity is discussed in the following section.

## IMPLICATIONS FOR STRUCTURAL CAPACITY EVALUATION

To evaluate the influence of errors in backcalculated stiffness on the predicted structural capacity at individual points, two results sets were extracted from the backcalculation results obtained when sampling strategy 3 (ii) was used. For these two results sets, the backcalculated stiffness and assumed layer thickness is shown in Tables 9 and 10. Also shown in these tables are the actual layer thicknesses and actual stiffnesses used to generate the deflection bowls at these two points.

Table 9. Estimated and Actual Pavement Situation at Km 0.1

| **Situation** | **Parameter** | **Surfacing** | **Base** | **Subbase** | **Subgrade** |
|---|---|---|---|---|---|
| Based on sample | Thickness (mm) | 43 | 123 | 213 | N/A |
| | Stiffness (MPa) | 2500 | 460 | 226 | 57 |
| Actual | Thickness (mm) | 49 | 155 | 219 | N/A |
| | Stiffness (MPa) | 2500 | 350 | 175 | 60 |

Table 10. Estimated and Actual Pavement Situation at Km 1.85

| **Situation** | **Parameter** | **Surfacing** | **Base** | **Subbase** | **Subgrade** |
|---|---|---|---|---|---|
| Based on sample | Thickness (mm) | 48 | 145 | 270 | N/A |
| | Stiffness (MPa) | 2500 | 306 | 183 | 59 |
| Actual | Thickness (mm) | 41 | 153 | 285 | N/A |
| | Stiffness (MPa) | 2500 | 350 | 175 | 60 |

For each variation of the two structures summarized in Tables 9 and 10, typical design parameters were calculated at the bottom of the asphalt layer and at the top of the subgrade. For these calculations, the RUBICON1 design software (Jooste, 2002), which employs the WESLEA layered elastic subroutine, was used. In this calculation, a standard dual wheel load with a 40 kN total load, 750 kPa contact stress and 350 mm spacing between tyres was assumed. The Poisson's ratio of all layers was kept constant at 0.4. The calculated design parameters for the different situations are summarized in Table 11.

Table 11. Influence of Layer Thickness Variation on Design Parameters

| **Location** | **Situation** | **Horizontal Tensile Strain in Asphalt (microstrain)** | **Vertical Compressive Strain on Subgrade (microstrain)** |
|---|---|---|---|
| Km 0.10 | Actual | 330 | 611 |
| | Estimated | 249 (25% error) | 663 (9% error) |
| Km 1.85 | Actual | 321 | 533 |
| | Estimated | 368 (15 % error) | 566 (6 % error) |

The results shown in Table 11 suggest that the variation in layer thickness can have a significant impact on the design parameters calculated at individual deflection bowl positions. As expected from the observations noted in the preceding section, this error is greatest in the upper pavement layers. Errors in the estimated subgrade vertical compressive strain are generally below 10 per cent, while those in asphalt tensile strain can be as great as 25 per cent.

This observation is considered significant in view of the fact that the results shown in Tables 9 and 10 are representative of the most thorough sampling strategy considered here. It can be expected that for the more simplified sampling strategies, the error in calculated design parameters is likely to be greater than those noted in Table 11.

## SUMMARY AND RECOMMENDATIONS

In this study, a simulated pavement situation was used to assess the significance of layer thickness variations on backcalculated stiffness and pavement structural capacity evaluation. The findings of this study are largely in agreement with previous studies (Jooste et al, 1998, Briggs et al, 1996, and Siddharthan et al, 1996) that evaluated layer thickness effects on backcalculated results. For the pavement structure analysed in this study, the following observations apply:

- Layer thickness variations do not have a significant influence on the backcalculated stiffness of the subgrade.
- Layer thickness variations have the greatest influence on the backcalculated stiffness of the base layer.
- The mean backcalculated stiffness for the section of road compared well to the actual layer stiffness, regardless of the sampling strategy that was used. As expected, accuracy was best when a higher sampling frequency was used.
- Using the mean layer thickness did not improve the accuracy of the mean backcalculated stiffness, even when a higher sampling frequency was used.
- The use of a higher sampling frequency, and then using the sampled layer thickness point that is closest to the deflection bowl being considered, resulted in the best agreement between actual and backcalculated stiffnesses.
- Errors at individual deflection bowls can be significant and can also have a significant influence on calculated response parameters, and hence, on structural capacity evaluation.

Based on the results obtained during this study, the following approach is recommended for structural capacity evaluation performed as part of rehabilitation investigations:

1. Sample layer thicknesses at as many as possible locations allowed by time and budget constraints. Trial pits and Dynamic Cone Penetrometer readings can be used to evaluate layer thicknesses.
2. When performing backcalculation, use the layer thickness that was sampled closest to the backcalculation bowl that is being considered. To speed up this process, the RUBICON2 software allows layer thicknesses sampled at different locations to be read in from a spreadsheet file. During backcalculation, these data are used to automatically select the layer thickness sample that is located closest to the current deflection bowl position.
3. Do not use mean layer thickness values as a single input when performing backcalculation over a long section of road.
4. Use the results of the backcalculation survey, in conjunction with rut, roughness and visual survey data, to identify uniform subsections. Calculate the mean backcalculated stiffnesses for each subsection, and use these mean values to evaluate the structural capacity of each subsection. This method utilizes averaging over a uniform subsection to remove some of the random error that will be present at individual data points.

Finally, since the base layer condition is frequently a key parameter for rehabilitation design, designers should note that the backcalculated stiffness of the base layer appears to be the most sensitive to layer thickness variations. This observation suggests that rehabilitation design should never be based solely on the basis of backcalculated stiffness data, but that such data should always be augmented by trial pit observations, DCP tests as well as laboratory testing and material classification.

## REFERENCES

Briggs, R.C., T. Scullion, and K.R. Maser. 1996. Asphalt Thickness Variation on Texas Strategic Highway Research Program Sections and Effects on Backcalculated Moduli. In **Transportation Research Record 1377**, TRB, National Research Council, Washington, D.C. pp. 7-38.

Darter, M.I., W.R. Hudson, and J.L. Brown. 1973. Statistical Variation of Flexible Pavement Properties and Their Consideration in Design. In: **Proc., Asphalt Paving Technology**, Association of Asphalt Pavement Technologists, Vol 42, 1973, pp. 589-615.

Hughes, C.S. 1996. **Variability in Highway Pavement Construction**. NCHRP Synthesis of Highway Practice 232. Transportation research Board, National Research Council, Washington, D.C.

Jooste, F.J. 2002. **RUBICON Pavement Design and Analysis Software: User Guidelines**. Modelling and Analysis Systems, Pretoria, South Africa.

Jooste, F.J., S.V. Kekwick and M. Muthen. 1998. Effect of Allowable Thickness Variation on Backcalculated Moduli. In **Transportation Research Record 1639**, TRB, National Research Council, Washington, D.C., pp. 43-52.

Rohde, G.T. and R.E. Smith. 1991. **Determining Depth to Apparent Stiff Layer from FWD Data**. Research Report 1159-1. Texas Transportation Institute. College Station, Texas.

Rohde, G.T. 1994. Determining Pavement Structural Number from FWD Testing. In **Transportation Research Record 1448**, TRB, National Research Council, Washington, D.C., pp. 61-68.

Siddhartan, R., P.E. Sebaaly, and M. Javaregowda. 1996. Influence of Statistical Variation in Falling Weight Deflectometers on Pavement Analysis. In **Transportation Research Record 1377**, TRB, National Research Council, Washington, D.C.

Theyse, H, M de Beer and F.C. Ruts. 1996. Overview of the South African Mechanistic Pavement Design and Analysis Method. In: **Transportation Research Record 1539**, TRB, National Research Council, Washington, D.C., 1996, pp. 6-17.

TRH4. **Structural Design of Inter-Urban and Rural Road Pavements**. 1996. Committee of State Road Authorities, Department of Transport, Pretoria, South Africa (Draft TRH4, 1996).

Van Cauwelaert, F.J, D.R. Alexander, T.D. White and W.R. Barker. 1989. Multilayer Elastic Program for Backcalculating Layer Moduli in Pavement Evaluation. In **Nondestructive Testing of Pavements and Backcalculation of Moduli**. STP 1026, ASTM, Philadelphia, Pa.

# SOME INFLUENCES OF LAYER THICKNESS VARIATIONS ON BACKCALCULATION AND REHABILITATION DESIGN

**FRITZ JOOSTE**

Modelling and Analysis Systems (cc), P O Box 634, La Montagne, 0184
e-mail: fritzj@icon.co.za

## Curriculum Vitae: Dr. Fritz Jooste

After graduating from the Rand Afrikaans University in 1990, Dr. Jooste worked at Stewart Scott International where he was mainly involved in pavement rehabilitation design. In 1993, he started graduate studies at Texas A&M University, and completed his doctorate in Civil Engineering in 1996 with a dissertation that focussed on the modelling of pavement response using finite element and layered elastic models. Between 1996 and 1999, he worked as a research engineer at Transportek, CSIR, where he contributed to research on bituminous materials, performance related testing of materials as well as pavement model development. In 1999, Dr. Jooste started working as a private consultant and later founded Modelling and Analysis Systems (cc), which focuses on the development of software for pavement rehabilitation design and analysis.