Prediction of Pavement Performance from Repeat Load Tri-axial (RLT) Tests on Granular Materials

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Contents

APPENDICES

Executive Summary

Introduction

An accelerated pavement test was conducted at CAPTIF[1], Christchurch, New Zealand, between 1999 and 2001, for the purpose of validating the use of the Repeat Load Tri-axial (RLT) apparatus. Both resilient and permanent deformation characteristics of unbound granular materials obtained using this test were compared to the measured results from the pavement test that was run previously. The aim was to ascertain if the few RLT tests that are conducted on unbound granular materials do provide viable results that can be used to predict performance for roads constructed with these materials.

The pavement was constructed in three segments (A, B and C). Each segment had the same subgrade type and asphalt thickness (25mm), and only the type of unbound granular material (basecourse) was changed. New Zealand (Material A) and Australian (Material C) good quality crushed rock basecourse aggregates were used. The third material (Material B) was New Zealand good quality crushed rock (Material A) but deliberately modified by adding additional fines in excess of quantities acceptable in the Transit New Zealand Specification M/4:1995, *Specification for Crushed Basecourse Aggregate*. The basecourses for Segments A, B and C were constructed from Materials A, B and C respectively.

Pavement Test

The pavement test was subjected to 1 million wheel passes where primarily surface rutting was measured at regular intervals. Strains and stresses were measured within the pavement under a range of tyre loads. Surface rutting was averaged for each segment (Segments A, B and C) of different granular materials (Materials A, B and C), and the stresses and strains were used to compute the resilient modulus. Segment C with the Australian material had the lowest rutting (3.3mm after 1000k) followed closely by Segment A (4.3mm after 1000k), while Segment B with the poorest material had the highest rutting (5.8mm after 1000k). Resilient moduli obtained from in-situ stresses and strains showed Material C to have the highest moduli relative to bulk stress (approximately 230MPa at a bulk stress of 150kPa), followed by Material A (approximately 187MPa at a bulk stress of 150kPa), and then Material B (approximately 155MPa at a bulk stress of 150kPa).

RLT Tests

RLT tests for resilient modulus and permanent strain were conducted on all three granular materials. The moduli results were compared directly to those determined from the CAPTIF pavement test and interpreted by three different methods (theoretically rigorous, AUSTROADS auto-sublayering from contact stress and from bulk stress) applied to mechanistic design using CIRCLY (a multi-layered linear elastic computer program). Permanent strain test results were extrapolated linearly, exponentially, and by combined extrapolation (using Ullidtz equations) to predict the surface rut depth after a range of load cycles had been applied.

In contrast to the CAPTIF pavement test in which stresses and strains were measured, RLT tests on the three materials showed little differences in moduli values. Material A had the highest moduli followed closely by Materials B and then C. Further, the RLT-derived moduli were significantly lower than those determined from measured stresses and strains (CAPTIF tests).

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[1] Canterbury Accelerated Pavement Testing Indoor Facility

However, the use of RLT-derived moduli in mechanistic pavement design using CIRCLY resulted in stresses and strains at critical locations (i.e. near the top of subgrade) that were close to those measured. The method using the AUSTROADS auto-sublayering feature and the RLT-derived moduli appropriate to the bulk stress for the top layer produced the closest match between computed and measured resilient pavement response.

Permanent Deformation Modelling

Permanent deformation modelling showed that the linear and exponential methods of extrapolating RLT permanent strain results had the same ranking of material deformation resistance as those measured in the CAPTIF pavement test. The combined extrapolation method for calculating deformation resulted in rut depth prediction that was within 2mm of those measured at the CAPTIF test. However the ranking in material deformation resistance was not the same.

The linear method of predicting deformation showed the greatest difference in the magnitude of deformations between the three materials. Further, the linear method was the only method that would have rejected the use of Material B (which was the material modified with additional fines added). Therefore, it is recommended that this method be used for material evaluation.

Evaluation of Materials

A key to material evaluation based on deformation resistance is to choose the RLT test stress conditions that correspond to the worst conditions in the pavement. However, prediction of accurate stresses within a pavement is difficult. For example, linear elastic analysis resulted in tensile stresses within the granular material. Such stress conditions would be associated with shear failure in the granular material, but this does not occur in a real pavement as tension cannot be sustained in unbound granular materials.

Further research is required to determine with more accuracy the stress conditions that exist spatially within the pavement, but it is expected that the layered elastic computational methods currently available to pavement engineers will never be able to fully model these real conditions.

Conclusions

- Resilient moduli derived directly from measured stresses and strains in the CAPTIF pavement, showed clear differences between Materials A, B and C. Material C (Australian crushed rock) had the highest moduli, followed closely by Material A (crushed rock), while Material B (crushed rock with high plastic fines) had significantly lower moduli.

- RLT tests on the three materials showed little differences in moduli values. Material A had the highest moduli, followed closely by Materials B and C.

- RLT-derived moduli were lower than those determined from measured stresses and strains in the CAPTIF test pavement.

- The use of RLT-derived moduli in mechanistic pavement design using CIRCLY (a multi-layered linear elastic program) resulted in stresses and strains at critical locations (i.e. near the top of the subgrade) close to those measured in the CAPTIF pavement. The method using the AUSTROADS auto-sublayering feature and the RLT-derived moduli appropriate to the bulk stress for the top layer produced the closest match between computed and measured pavement stresses.

- Computed stresses on top of the subgrade for three different methods of using RLT-derived moduli and the three Segments and Materials (A, B, and C) showed very little difference in results. This suggests that subgrade stress is not sensitive to the moduli of granular materials when using the currently available AUSTROADS 1992 design process.
- Permanent deformation modelling showed the linear and exponential methods of extrapolating RLT permanent strain results to have the same ranking of material deformation resistance as measured in the CAPTIF pavement test. Material and Segment C had the least amount of rutting, followed closely by Material and Segment A, and deformation in Material and Segment B was significantly different.
- The combined extrapolation method of predicting deformation resulted in rut depth prediction within 2mm of those measured at the CAPTIF test. However the ranking in material deformation resistance was not the same.
- The linear method of predicting deformation showed the greatest difference in the magnitude of deformations between the three materials.
- Prediction of stresses within a pavement using linear elastic analysis results in tensile stresses within the granular material. This causes difficulties when determining the combination of vertical and horizontal stresses that has the most detrimental effect on the granular material for use in the RLT permanent strain test.

Recommendations

- The results of this project were from controlled environmental conditions, both in the RLT test and the CAPTIF pavement, and therefore should be used cautiously when applied to pavements in the field.
- Further RLT permanent strain tests should be conducted at a range of stress conditions and moisture contents to determine the effect of these variables. These further tests should be in conjunction with research currently being conducted at the University of Nottingham, UK.
- Transfer functions for the RLT results should be developed to take into account factors such as environment, maintenance regimes, etc.
- Finite element modelling combined with a determination of residual stresses of a thin-surfaced unbound granular pavement should be conducted to determine the stresses within the granular material. This is to aid in determining the appropriate stress conditions for the RLT permanent strain test.
- The finite element modelling should be combined with a thorough literature review of the topic of estimating stresses within a granular material.
- The current AUSTROADS design method should continue to be used and to take precedence until transfer functions can be developed for the RLT results, that take into account factors such as environment, maintenance regimes, etc.
- Deformation modelling should be used for comparative purposes when evaluating materials in performance-based specifications such as Transit New Zealand Specification B/3:1999, *Design and Construction of Unbound Granular Pavements*.

- Further accelerated loading tests should be undertaken at CAPTIF with the following objectives:
  - measurement of stress and strain distributions in different pavement thicknesses and materials,
  - calibrating Finite Element Models,
  - development of RLT transfer functions,
  - measurement of locked-in stresses and strains at different depths.

Abstract

An accelerated pavement test was conducted at CAPTIF (Canterbury Accelerated Pavement Testing Indoor Facility), Christchurch, New Zealand, between 1999 and 2001, for the purpose of validating the use of the Repeat Load Tri-axial (RLT) apparatus. Both resilient and permanent deformation characteristics of unbound granular materials obtained using this test were compared to the measured results from the pavement test that was run previously. The aim was to ascertain if the few RLT tests that are conducted on unbound granular materials do provide viable results that can be used to predict performance for roads constructed with these materials.

The pavement test was subjected to 1 million wheel passes where primarily surface rutting was measured at regular intervals. Strains and stresses were measured within the pavement under a range of tyre loads. RLT tests for resilient modulus and permanent strain were conducted on all three granular materials, and permanent deformation modelling was also carried out. Materials evaluation based on deformation resistance depends on choosing RLT test stress conditions that correspond to the worst conditions in the pavement.

Further research is required to determine with more accuracy the stress conditions that exist spatially within the pavement, but it is expected that the layered elastic computational methods currently available to pavement engineers will never be able to fully model these real conditions.

1. Introduction

1.1 Overview

Research is currently being undertaken in Australia and New Zealand, using the Repeated Load Tri-axial (RLT) apparatus to characterise the resilient and plastic properties of granular and subgrade materials for use in design and performance-based specifications for construction of pavements. The research outputs are to develop standard testing procedures for the RLT apparatus and to determine the precision limits. Both resilient and permanent deformation characteristics of unbound granular materials obtained using the RLT test were compared to the measured results from the CAPTIF[1] pavement test that was run previously. The aim was to ascertain if the few RLT tests that are conducted on unbound granular materials do provide viable results that can be used to predict performance for roads constructed with these materials. The research was carried out between 1999 and 2001.

Steven et al. (1998) reported that measured strains in the asphalt (tensile), basecourse (compressive), sub-base (compressive), and subgrade (compressive) layers obtained from a test on a CAPTIF pavement, ranged from 2 to 10 times the strains computed from a multi-layer linear elastic model developed from RLT tests carried out concurrently on the pavement materials. This result questions the validity of using RLT test results in design and prompted the initiation of this research project.

Current performance-based specifications (TNZ B/3:1999, M/22:1999) for materials give limits to the amount of permanent deformation that is acceptable to observe in a granular basecourse tested in the RLT apparatus. The method of evaluating a granular material from RLT permanent deformation tests has been expanded by Alabaster (1998) into a newly developed method to predict surface rutting in a pavement. His research aimed to validate this method of assessment through accelerated pavement testing.

To this end, a test pavement at CAPTIF was constructed in three segments. The constructed pavement consisted of a thin surfacing with unbound granular material (basecourse), overlying a silty subgrade. The only difference between the three segments was the unbound granular material used. Each segment was instrumented with a three-dimensional array of stress and strain sensors. The pavement was subjected to accelerated loading, and the resulting stresses and strains as well as surface rutting were measured over the duration of the test.

The CAPTIF performance data were used to compare the predicted performance obtained by testing the granular materials with the laboratory RLT apparatus. The RLT apparatus applies a pulsating vertical load to aggregates confined by a cell pressure inside a cylinder.

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[1] Canterbury Accelerated Pavement Testing Indoor Facility

Strains are measured during the test at different loading conditions (i.e. both vertical and cell pressures are varied), to estimate the relationship between bulk stress and resilient modulus. In addition, the pulsating load in the RLT test can be applied over several thousand cycles (i.e. >50,000) to estimate permanent strain for predicting rutting in a pavement. Further information on the RLT apparatus is given in Section 1.3 of this report.

The overall aim of this project was to improve the current method of pavement design (i.e. as provided by the 1992 AUSTROADS Pavement Design Guide). This was to be achieved by meeting the following objectives:

- Utilise pavement material characteristics obtained by the RLT apparatus to ensure that the computed deflections, strains and stresses at critical locations in the pavement, are close in value to actual measured values.
- Undertake accelerated pavement tests at CAPTIF to evaluate the performance of three different depths of granular material over the same subgrade.
- Measure the three dimensional stress and strain response of the pavement under actual loading.
- Conduct a series of laboratory RLT tests using in-service stresses and strains as the test parameters.
- Develop and validate a design method that predicts the rut depth of a thin-surfaced unbound granular pavement for a specified-design traffic loading of a pavement utilising permanent deformation characteristics obtained in the RLT apparatus for the materials used.

1.2 Canterbury Accelerated Pavement Testing Indoor Facility (CAPTIF)

CAPTIF is located in Christchurch, New Zealand. It consists of a 58m long (on the centreline) circular track contained within a 1.5m deep x 4m wide concrete tank, so that the moisture content of the pavement materials can be controlled and the boundary conditions are known. A centre platform carries the machinery and electronics needed to drive the system. Mounted on this platform is a sliding frame that can move horizontally by 1m. This radial movement enables the wheel paths to be varied laterally and can be used to have the two "vehicles" operating in independent wheel paths. An elevation view is shown in Figure 1.1.

At the ends of this frame, two radial arms connect to the Simulated Loading and Vehicle Emulator (SLAVE) units shown in Figure 1.2. These arms are hinged in the vertical plane so that the SLAVEs can be removed from the track during pavement construction, profile measurement, etc., and in the horizontal plane to allow vehicle bounce.

CAPTIF is unique among accelerated pavement test facilities in that it was specifically designed to generate realistic dynamic wheel forces. This is different from other accelerated pavement testing facility designs which attempt to minimise dynamic loading.

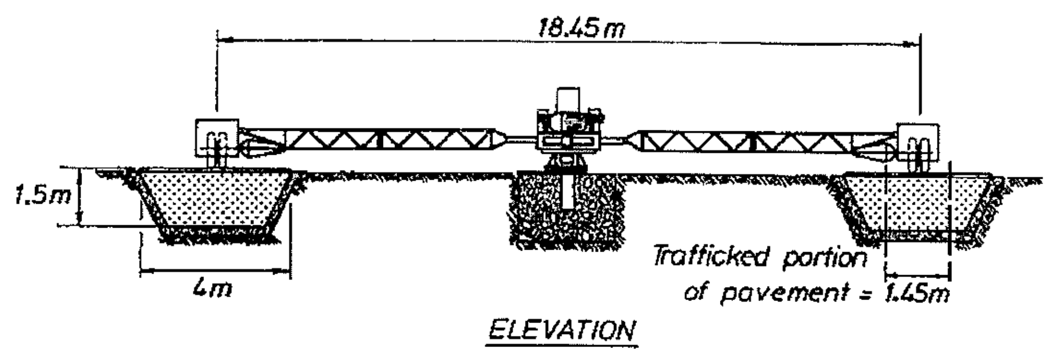


Figure 1.1 **Elevation view of CAPTIF.**

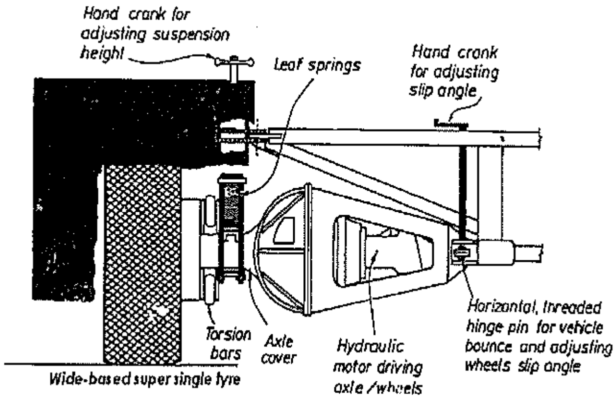


Figure 1.2 **The CAPTIF SLAVE unit.**

The SLAVE units at CAPTIF are designed to have sprung and unsprung mass values of similar magnitude to those on actual vehicles and use, as far as possible, standard heavy vehicle suspension components. The net result of this is that the SLAVEs apply dynamic wheel loads to the test pavement that are similar in character and magnitude to those applied by real vehicles. A summary of the characteristics of the SLAVE units is given in Table 1.1. The configuration of each vehicle, with respect to suspensions, wheel loads, tyre types and tyre numbers, can be identical or different, while carrying out simultaneous testing of different load characteristics.

Pavement instrumentation which can be used at CAPTIF includes: EMU coil sensors for measuring vertical, transverse and longitudinal strains in the basecourse, sub-base and subgrade layers of the pavement, h-bar strain gauges for measuring horizontal strains at the bottom of the asphalt layer, pressure gauges for measuring vertical, transverse and longitudinal stress in the basecourse, sub-base and subgrade layers of the pavement, and partial depth gauges for measuring the pavement layer deflections. Temperature probes are also used to monitor pavement and air temperatures.

The vehicle instrumentation consists of accelerometers mounted on both the sprung and unsprung masses of each "vehicle", and displacement transducers to measure suspension displacements. As the "vehicles" are a fairly simple quarter vehicle structure, wheel forces can be calculated by combining the two accelerometer signals weighted by appropriate mass factors.

Other measurement systems used at CAPTIF during testing are: a Falling Weight Deflectometer (FWD), the CAPTIF Deflectometer, which is a modified Benkelman beam, a laser profilometer, and a transverse profilometer. For measurement convenience, the track is divided into 58 equally spaced stations, which are 1m apart on the centreline wheel path.

A more detailed description of the CAPTIF and its systems is given by Pidwerbesky (1995).

Table 1.1 Characteristics of SLAVE units.

Test wheels	Dual- or single-tyres; standard or wide-base; bias or radial ply; tube or tubeless; maximum overall tyre diameter of 1.06m
Mass of each vehicle	21kN to 60kN, in 2.75kN increments
Suspension	Air bag; multi-leaf steel spring; single or double parabolic
Power drive to wheel	Controlled variable hydraulic power to axle; bi-directional
Transverse movement of wheels	1.0m centre-to-centre; programmable for any distribution of wheel paths
Speed	0-50km/h, programmable, accurate to 1km/h
Radius of travel	9.2m

1.3 Repeat Load Tri-axial Apparatus

The Repeat Load Tri-axial (RLT) apparatus tests cylindrical samples of soils or granular materials, and Figure 1.3 illustrates a typical RLT test set-up. For repeat load tests, the axial load supply is cycled for as many cycles as programmed by the user, and the axial load type is usually programmed as a sinusoidal vertical pulse with a short rest period. Although possible for some forms of RLT apparatus, in this study the cell pressure was not cycled simultaneously with vertical load, but held constant. Two types of test are usually conducted: a resilient test and a permanent deformation test.

The resilient test determines the resilient (or elastic) modulus and Poisson's ratio (though only if radial strains are measured in the test) for a full range of vertical and horizontal (cell pressure) combinations.

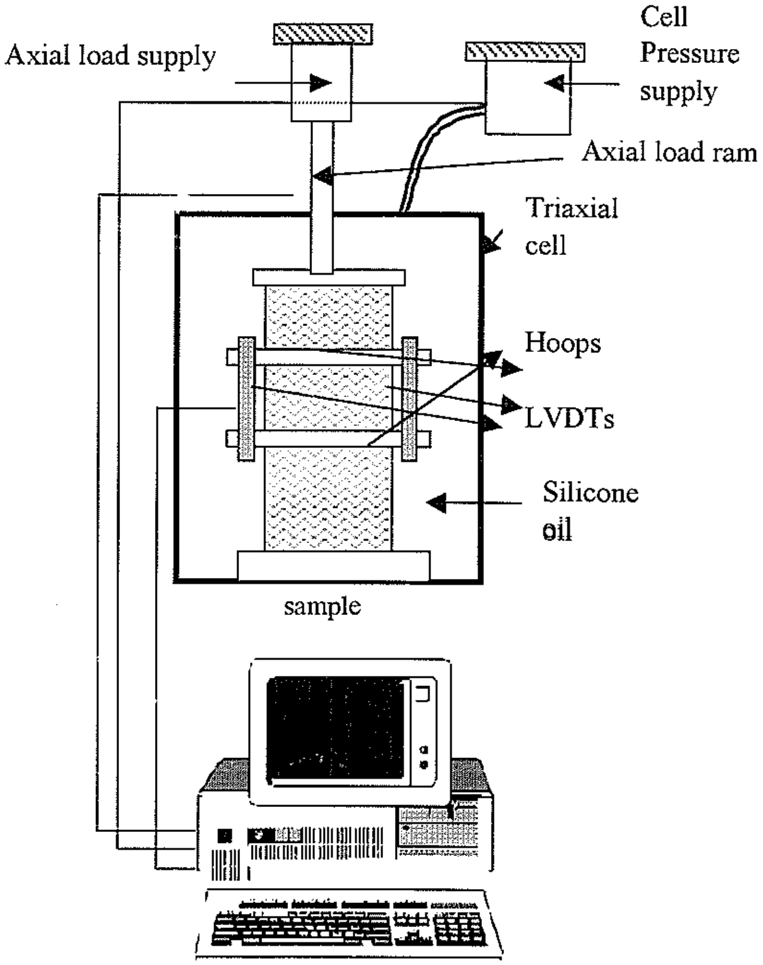
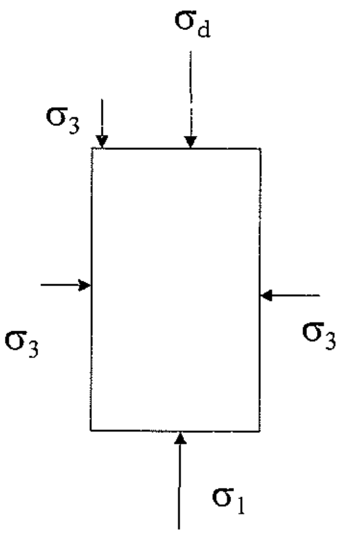


Figure 1.3 **RLT apparatus set up for a repeat load test.**

(LVDT - linear voltage displacement transducer)

In an RLT test, the principal stress in the x and y direction is the cell pressure, and in the z direction the principal stress is the cell pressure plus the applied axial load (as cell pressure acts all over the specimen including the top of the sample). Figure 1.4 shows the stresses acting on an RLT specimen during a test. The resilient test provides the elastic parameters needed for mechanistic pavement design (Section 1.4 of this report). The permanent deformation test provides data on the deformation resistance of the materials under particular environmental and loading conditions.

During an RLT test, vertical load, cell pressure, radial and vertical displacements on the specimen are recorded. The difference between the maximum and minimum displacements divided by the length over which this occurs, gives the strain. Resilient modulus is then calculated by dividing the applied vertical stress (load divided by area) by the axial strain for a constant cell pressure test (Equation 1.1). The Poisson's ratio is defined by Equation 1.2. Noting the minimum axial strain after each load cycle gives the permanent axial strain result for a test in which σ_d changes.



where:

σ_1 = major principal stress [kPa]

σ_3 = minor principal (confining) stress [kPa]

σ_d = cyclic deviator stress [kPa]

$\sigma_1 = \sigma_d + \sigma_3$

Figure 1.4 Stresses on a specimen in an RLT test.

Resilient Modulus (M_r):

$$M_r = \frac{\sigma_d}{\varepsilon_a} \qquad \text{Equation 1.1}$$

Poisson's ratio (υ):

$$\upsilon = \frac{-\varepsilon_r}{\varepsilon_a} \qquad \text{Equation 1.2}$$

where:

σ_d = maximum cyclic deviator axial stress
ε_r = radial strain
ε_a = axial strain

The resilient modulus (E_r) of a material calculated according to 3-D Hooke's Law equation is given by:

$$E_r = \frac{(\sigma_{1d} - \sigma_{3d})(\sigma_{1d} + 2\sigma_{3d})}{\varepsilon_{1r}(\sigma_{1d} + \sigma_{3d}) - 2\varepsilon_{3r}\sigma_{3d}} \qquad \text{Equation 1.3}$$

with:

E_r [MPa] = calculated equivalent E-modulus
ε_{1r} [-] = measured axial resilient strain
ε_{3r} [-] = measured radial resilient strain
σ_{1d} [kPa] = difference in maximum and minimum principal axial stress
σ_{3d} [kPa] = difference in maximum and minimum principal radial stress

This assumes the material behaves linear-elastically for any individual stress stage.

For unbound granular materials resilient modulus is usually reported as versus bulk stress, because the material's stiffness is highly stress-dependent. Established research suggests a general relationship between these parameters (Hicks & Monismith 1971):

$$M_r = k_1(\Sigma\sigma)^{k2}$$ Equation 1.4

where:

$k1, k2$ = constants

$\Sigma\sigma$ = is the bulk stress, being the sum of the three principal stresses (i.e. sum of the stresses in the x, y and z directions)

For a permanent deformation test, at least 50,000 loading cycles are applied at one vertical and horizontal (cell pressure) stress combination. The amount of permanent strain versus load cycles is plotted. Currently in pavement design, the result of the permanent strain test is simply to assess the suitability of a material for use in a pavement at the stress level being tested. If the permanent strain decreases with increased numbers of load cycles, then the material is considered suitable for use at the stress level tested. This research attempts to expand the use of the results of the permanent deformation test to a design procedure that will be able to predict rutting in unbound granular pavements.

1.4 AUSTROADS Pavement Design using Mechanistic Analysis

In mechanistic analysis, the pavement is modelled as multiple layers of linear elastic materials subjected to an equivalent standard axle (ESA) load in a computer program such as CIRCLY (Figure 1.5). The vertical compressive strain is computed at the top of the subgrade. This value is then used to determine the maximum allowable ESAs using the AUSTROADS Subgrade Strain Criterion (Equation 1.5) and/or other criteria. For design purposes, the pavement thickness (or overlay) is increased until the maximum allowable ESAs are greater than the design ESAs. The AUSTROADS Subgrade Strain Criterion is:

$$Max\ allowable\ ESAs = \left(\frac{const}{strain}\right)^{exp}$$ Equation 1.5

where:

$const$ = 0.008411

exp = 7.14

$strain$ = vertical compressive strain at the top of the subgrade (ε_{cvs}, Figure 1.5)

The aim of modelling the pavement using mechanistic analysis as calculated in CIRCLY is to accurately compute the strains in the pavement. These strains are then used to predict pavement life using the relevant performance criterion (e.g Equation 1.5, for the subgrade). Values of strain in the pavement are governed by how the pavement layers are characterised. CIRCLY requires material characteristics for each pavement layer and subgrade to enable computation of the strains needed for design (i.e. strains at points 1, 2 and 3 in Figure 1.5).

AUSTROADS assumes cross-anisotropic behaviour and, as such, the CIRCLY program requires horizontal and vertical moduli, Poisson's ratio, and layer depths. These material characteristics are usually determined using presumptive values, and/or relationships with CBR (California Bearing Ratio). For rehabilitation design of existing pavements, the material characteristics can be determined through back-analysis of FWD deflection bowls using appropriate software. Material characteristics of unbound granular materials can also be obtained from tests at various stress levels performed using the RLT apparatus.

The predominant pavement types in New Zealand are thin-surfaced, unbound, granular materials over a natural soil subgrade. The granular materials in these pavements are usually characterised in CIRCLY by defining the elastic parameters of the top granular layer and the subgrade. An automatic procedure in CIRCLY will then sub-layer the granular material according to the rule in the AUSTROADS Pavement Design Guide (1992), and define each layer with different moduli. The AUSTROADS rule will decrease the modulus of each granular layer with depth, to approximate the reduction of modulus with the decreasing stress (i.e. bulk stress) which occurs for all point-loaded unbound granular materials as their depth increases.

Alternatively, and arguably the more correct method of determining the modulus of each granular layer, is to use the relationship between bulk stress and resilient modulus that is obtained from the RLT test. The modulus of each granular layer is the value from the RLT test that is appropriate to the bulk stress computed in the middle of the layer. Iterative computations are required until the moduli for all the granular layers are appropriate for the level of bulk stress which is computed in a layer using the value of modulus previously assumed for that layer. This method of using RLT results to define the granular layers in design is investigated in this project.

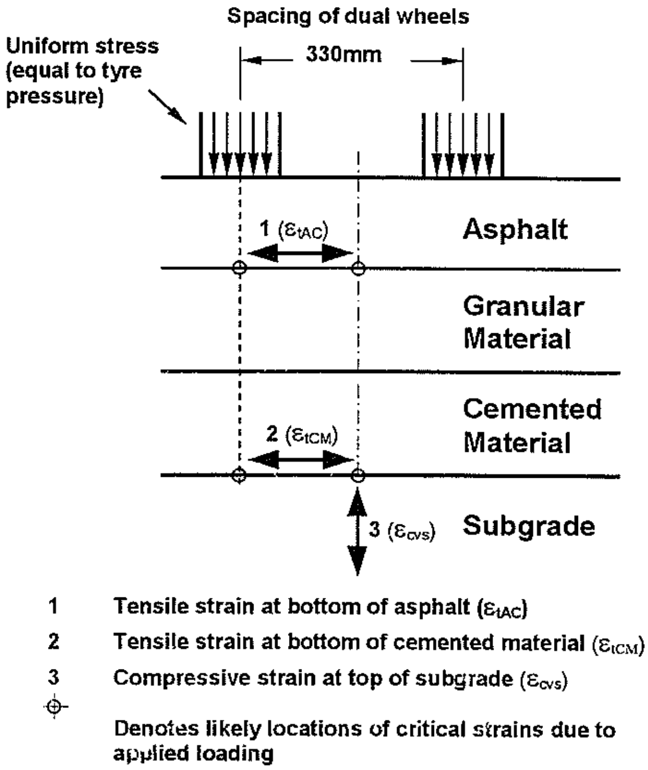


Figure 1.5 Mechanistic analysis of a pavement, consisting of multi-layered linear elastic materials.

2. CAPTIF Pavement Test

Two research projects were conducted simultaneously using CAPTIF. These projects were undertaken for quite different objectives. The report presented here is for the project which is examining the relationships between Repeat Load Tri-axial testing and pavement test results.

The main objective of this project was to improve the current method of pavement design (i.e. according to the 1992 AUSTROADS Pavement Design Guide) through developing guidelines for utilising the pavement material characteristics that are obtained using the RLT apparatus.

The pavement test was subjected to 1 million wheel passes, during which time surface rutting was measured at regular intervals. Strains and stresses were measured within the pavement under a range of tyre loads in the inner wheel path. Surface rutting was averaged and the stresses and strains were summarised for the three segments (Segments A, B and C), each of which had a different granular material (Materials A, B and C).

The concurrent project entitled *Effect of pavement wear of an increase in mass limits for heavy vehicles* (de Pont et al. 2001) proposed to undertake a direct comparison of pavement wear between 8.2 tonne and 10 tonne dual-tyred axle loads on a typical New Zealand pavement. The basic method is to conduct an accelerated pavement test using CAPTIF on a thin-surfaced, unbound, granular pavement. Two SLAVE units (8.2 t and 10 t each) followed different circumferences around the CAPTIF test track (i.e. corresponding the inner and outer wheel paths respectively), for direct comparison of pavement wear manifested as rutting. The results from this test will be used to determine the appropriate wear component of the Road User Charges (RUC) for a 10-tonne dual-tyred axle, and the effect on pavement life for this increase in axle load.

2.1 Pavement Design

The pavement constructed at CAPTIF was required to be a typical New Zealand pavement consisting of a thin-surface layer with unbound granular basecourse overlying a soil subgrade. In addition, the pavement test was required to produce an adequate result (sufficient rutting) by 1 million wheel passes of a standard dual-tyred wheel load (half axle = 40kN). However, as a result of the other project, the test was also required to exhibit reasonably low rutting behaviour as would be observed in the field. The decision was made in the project proposal stage, to divide the CAPTIF pavement in three test segments. A different granular material was to be used in each test segment.

The aim of the pavement design and choice of unbound granular basecourse materials was to produce results using both CAPTIF and the RLT apparatus, that showed a measurable difference in both resilient and permanent deformation performance of the granular materials. The hope was that differences in performance obtained during the CAPTIF test would be mirrored in the RLT results, to validate the use of the RLT apparatus.

RLT testing on a range of granular materials in New Zealand was not available to compare performances, from which suitable materials of different performance could have been chosen for testing at CAPTIF. Therefore, the choice of material was based on the Transit New Zealand standard specification for unbound granular basecourse (TNZ M/4:1995). Material complying with TNZ M/4 was assumed to result in superior performance to materials that do not (or nearly do not) comply with the specification. It was also assumed that increasing the fines content would result in poorer performance (Thom & Brown 1988). This analogy in choosing materials for testing was based on a previous Transfund research project investigating RLT tests on granular materials (Dodds et al. 1999).

Another decision was that the same aggregate material should be used, and to have three different basecourses manufactured by changing the grading and plastic fines content of material originating from the same source. Initially, one of the materials chosen was manufactured so that it would fail the TNZ M/4 specification through non-compliance with grading and plastic fines (i.e. having an excess of fines). However, the segment constructed with this material had many soft spots which developed shallow shear failures during rolling. Obviously this segment would neither survive the surfacing construction traffic nor any passes with the wheel. Therefore, this poor material was removed and replaced with the Australian basecourse that was available from a previous CAPTIF test (Steven et al. 2000). Another reason for using the Australian material was in part related to pending interest from AUSTROADS in funding some future work at CAPTIF to measure strains and stresses under various wheel types and loads. The granular materials chosen for testing at CAPTIF are summarised below:

- ***Material A***, a clean (nil plastic fines), crushed, graded aggregate with a maximum particle size of 40mm complying with TNZ M/4:1995;
- ***Material B,*** a dirty, crushed, graded aggregate with a maximum particle size of 40mm that is the same as Material A, but with additional plastic fines added in excess of the quantities acceptable in TNZ M/4 specification;
- ***Material C***, a clean, crushed, graded aggregate with a maximum particle size of 20mm, from Montrose quarry in Melbourne, Australia, complying with TNZ M/4.

These material parameters are further summarised in Table 2.1 and Figure 2.1.

Table 2.1 Material parameters of the three granular materials (A, B, C).

Sample	M/4 Grading	Sand Equivalent	% Passing 75 µm	Plasticity Index
A	Pass	48	3	0
B	Pass	31	10	9
C	Pass	31	10	0

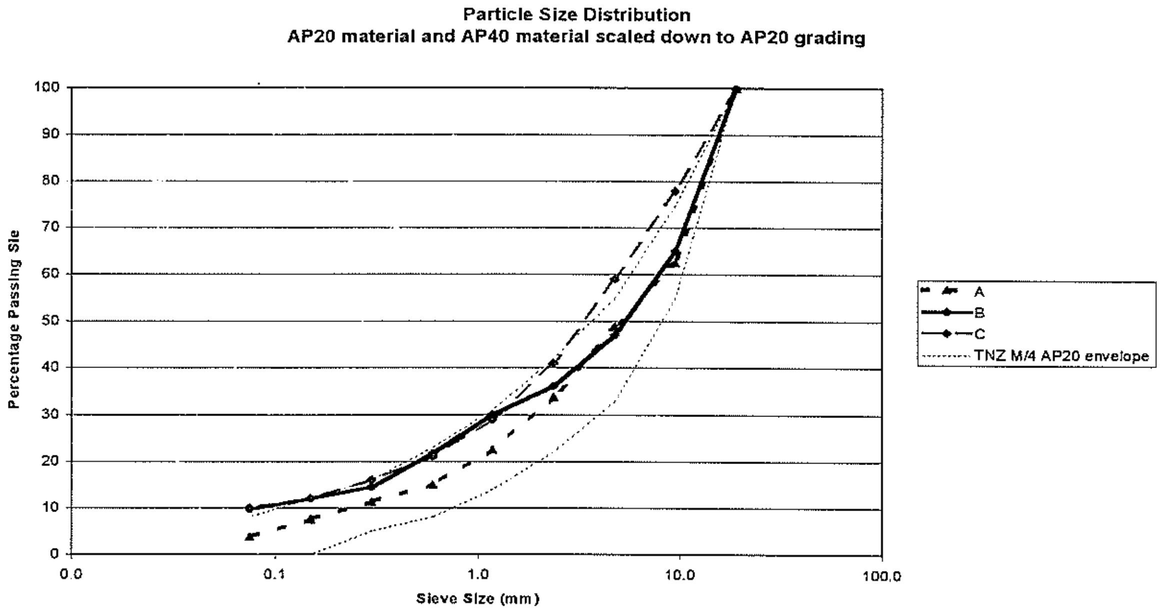


Figure 2.1 **Grading envelopes of materials A, B and C, compared with the TNZ M/4:1995 grading envelope.**

The subgrade for all the segments was a silty clay which has a nominal in-situ CBR value of 11%. While a New Zealand pavement typically has a chipseal surfacing, a 25mm-thick layer of fine asphaltic concrete was used at CAPTIF. A chipseal surfacing was not used because it was highly likely to fail by flushing before the end of the test. The pavement design was a compromise between the mass limits used in the concurrent project, and partly based on past performance in previous CAPTIF tests to ensure that a result would occur within 1 million load cycles. The final targeted pavement thicknesses are shown in Figure 2.2.

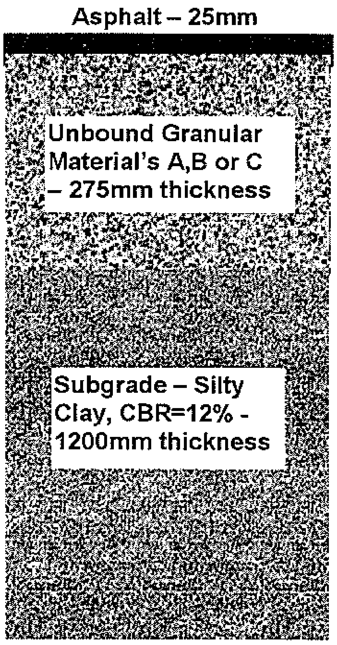


Figure 2.2 **CAPTIF pavement cross-section showing target layer thicknesses.**

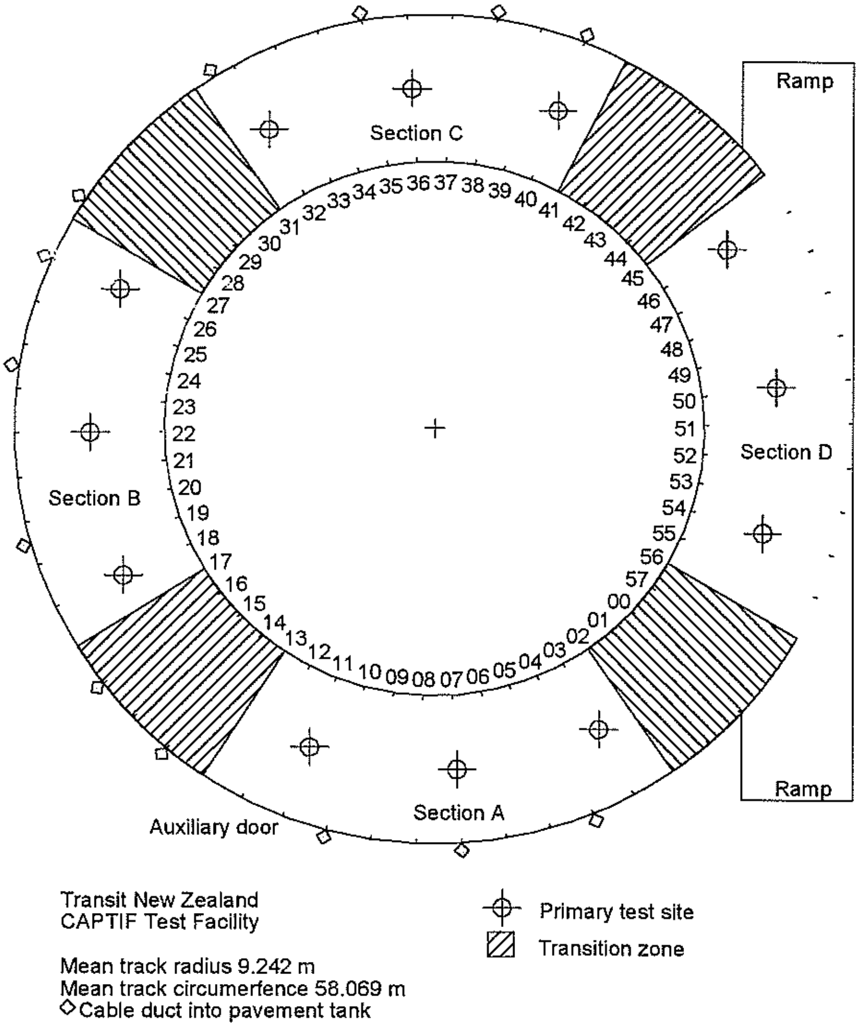


Figure 2.3 **CAPTIF pavement test layout.**

The three segments of the track (Figure 2.3) were constructed as follows:

- Segment A of 15m of the track was constructed with Material A;
- Segment B of 14m was constructed with Material B;
- Segment C, also of 14m, was constructed with Material C.
- The remaining 15m of track, which includes the entry ramps, was a transition zone constructed with a recycled concrete basecourse.

2.2 CAPTIF Pavement Test Layout

The CAPTIF test track is circular and around the circumference are station numbers. These station numbers are a permanent fixture and are used as test locations. Figure 2.3 details the final test layout at CAPTIF.

2.3 Vehicle Configuration

This project was conducted simultaneously with the other project (that was investigating the effect on pavement life with increasing mass limits of heavy vehicles). To achieve the objectives of both projects in the one test, each vehicle was set to run on a different wheel path by changing the length of the SLAVE arms. The vehicle load for this project was set at the current legal load in New Zealand for a dual-tyred axle which is 8.2 tonnes (i.e. 4.1 tonnes or 40kN for the half axle vehicle). This standard load has advantages as the stresses induced in the pavement do not exceed the capacity of the RLT apparatus when replicating the within-pavement stress conditions for material testing. Further, the standard load is equal to 1 ESA used in pavement design (AUSTROADS 1992) and was used as a basis for comparison of damage with the other vehicle.

The vehicle was fitted with 11R22.5 dual tyres inflated to the tyre manufacturer's recommended inflation pressure. Steel multi-leaf suspension was fitted to the vehicle, and a vehicle wander was set to ±50mm with a normal distribution. Accelerated pavement loading was conducted at a speed of 45km/h for a total of 1 million vehicle passes.

2.4 Pavement Construction

An extensive measurement programme was specified for this test. Before construction, a series of tests were conducted to provide information on material properties for design and construction purposes. The unbound granular materials were subjected to vibrating hammer compaction tests in accordance with NZS 4402:1986 *Test 4.1.3, Vibrating Hammer Density Test* (SANZ 1986), to determine optimum moisture content and maximum dry densities. These results were then used to determine the target dry density and moisture content for construction in accordance with the Transit New Zealand Specification TNZ B/2:1999.

The construction of the pavement was monitored intensively. The subgrade soil and crushed unbound granular basecourse were placed in lifts not exceeding 150mm in thickness. At the completion of each lift the density was measured, because an important requirement was to strictly control longitudinal variability and to keep transverse variability to an absolute minimum. The large number of transverse measurements was aimed to demonstrate this, the results of which can be found in de Pont et al. (2001).

The material was compacted using a vibrating steel roller and the levels of each layer were determined using a profile beam, with measurements being taken every 1m interval around the circumference and at 0.025m intervals radially. The basecourse was placed in order to avoid segregation, and the basecourse surface was compacted using a pneumatic-tyred roller. The asphalt surfacing was placed by paving machine in one lift.

During construction, the consistency of the pavement's structural capacity was monitored using the Loadman portable falling weight deflectometer (FWD). The Loadman is a self-contained portable FWD, of Finnish design, comprising an aluminium tube that accommodates a 10kg sliding mass (Bartley Consultants Ltd 1998). This monitoring was done at the top surface of each newly compacted subgrade and unbound granular layers.

2.5 Pavement Instrumentation

The response of the pavement during the test was monitored using instruments installed in each of the three CAPTIF pavement segments. All the three different basecourses were instrumented with 36 Emu coils (for measuring strain in three dimensions) and three stress gauges. Figures 2.4 and 2.5 detail the layout of the instrumentation in a CAPTIF test segment. A 3D representation of the Emu coil arrangements is detailed in Figure 2.6.

The soil strain instrumentation previously used at CAPTIF, developed by the University of Canterbury under licence from the Saskatchewan Highways and Transport facility in Canada, was replaced by the Emu strain system purchased from the University of Nottingham. Emu coils used for measuring strain with the Emu system were fabricated at CAPTIF using University of Nottingham guidelines. The relay boards, triggering systems, and software were developed at the University of Canterbury.

This system operates as follows: a static reading on the Emu coils is taken for reference, with the vehicles stationary and away from the Emu coil locations. The SLAVE is then run up to the test speed and the measurement parameters are entered into the controlling computer. When the vehicle speed is within the acceptable tolerance (±0.5km/h) of the test value, the operator begins readings. Infrared trigger beams detect the approach of the vehicle to be measured. A pair of sensors in the array is scanned simultaneously when triggered so that a continuous bowl shape of strain versus distance travelled is obtained.

The Emu coil strain sensors work on the principle of inductance coupling of free-floating wire-wound disks. Sets of Emu coils act in pairs and can measure vertically, horizontally or longitudinally. One coil can act as a pair for any adjacent coil and triggering of pairs is controlled from the relay board. A signal is transmitted from one coil and measured in the other. The distance between the gauges is proportional to the strength of the measured signal. By placing arrays of 3 coils above each other it is possible for vertical, horizontal and transverse strains to be recorded at different depths in the pavement material and subgrade material.

The system measures displacement relative to each Emu coil as the wheel load passes above on the surface. These recorded displacements are converted to strain by dividing by the distance between the Emu coils. Vertical stress was measured at subgrade surface level using the Dynatest stress gauges.

Figure 2.4 Pictorial representation of instrument layout in each of the three CAPTIF test segments.

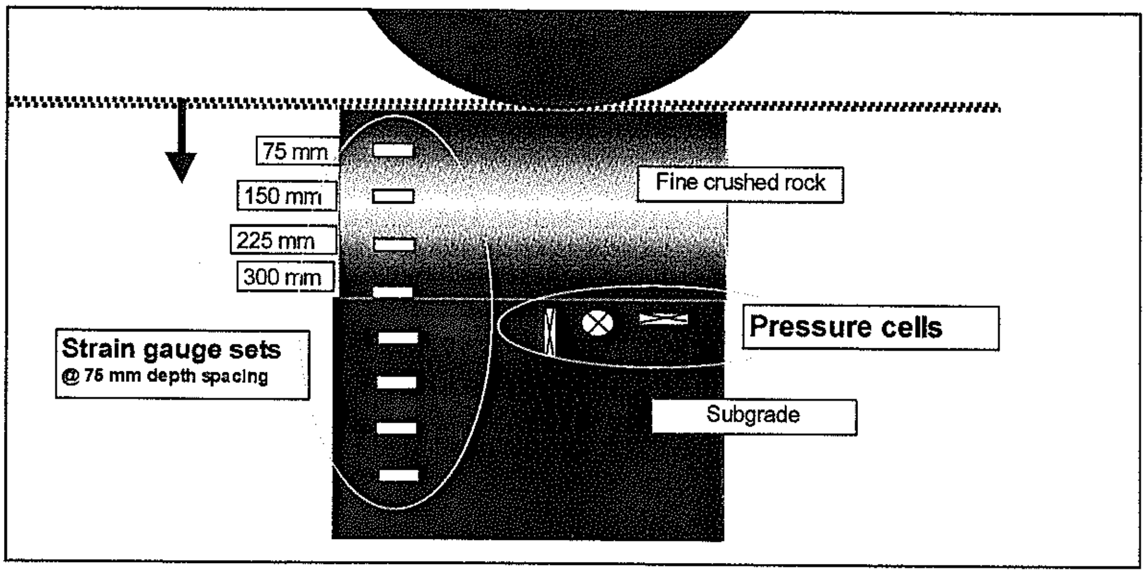
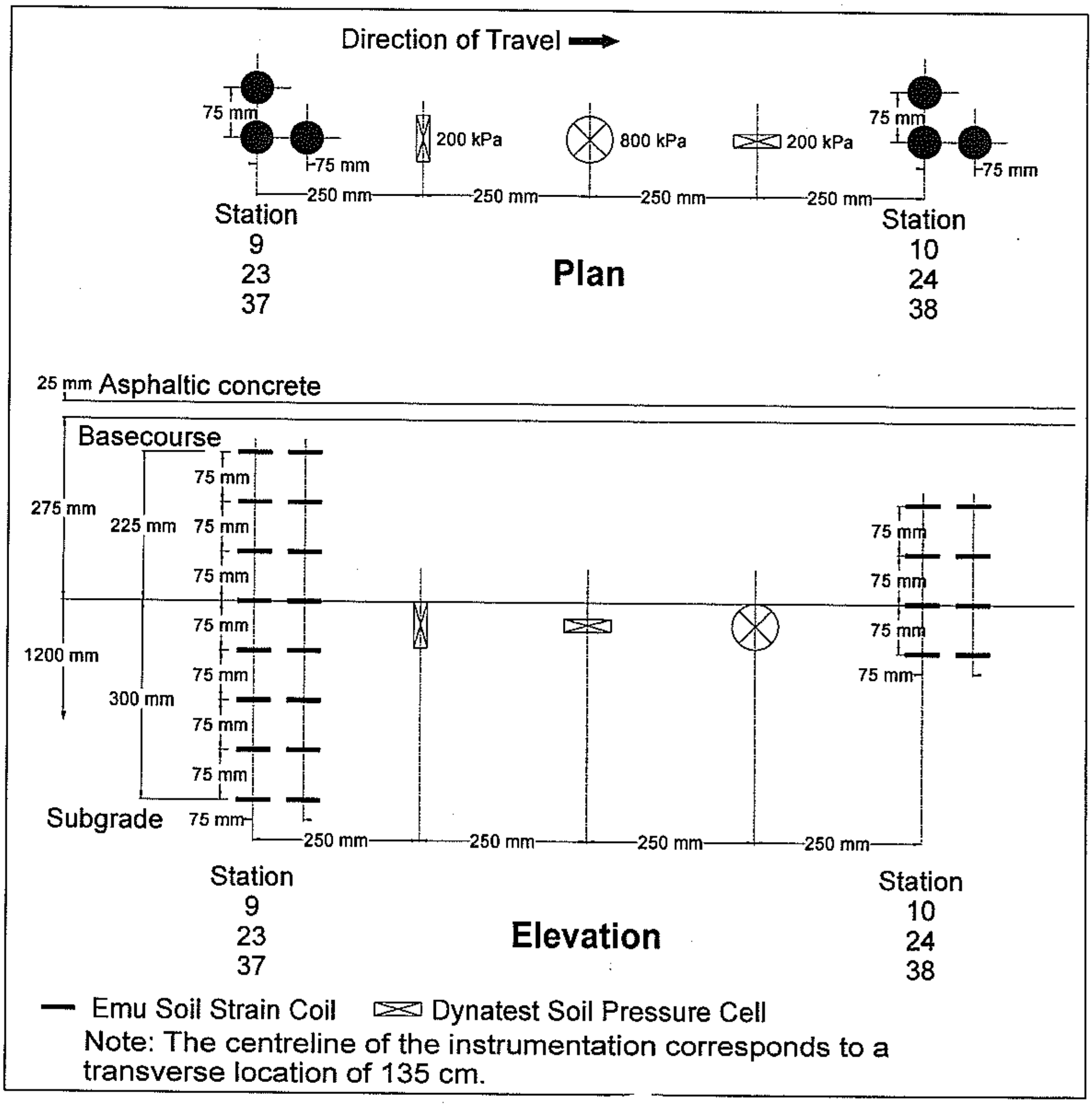
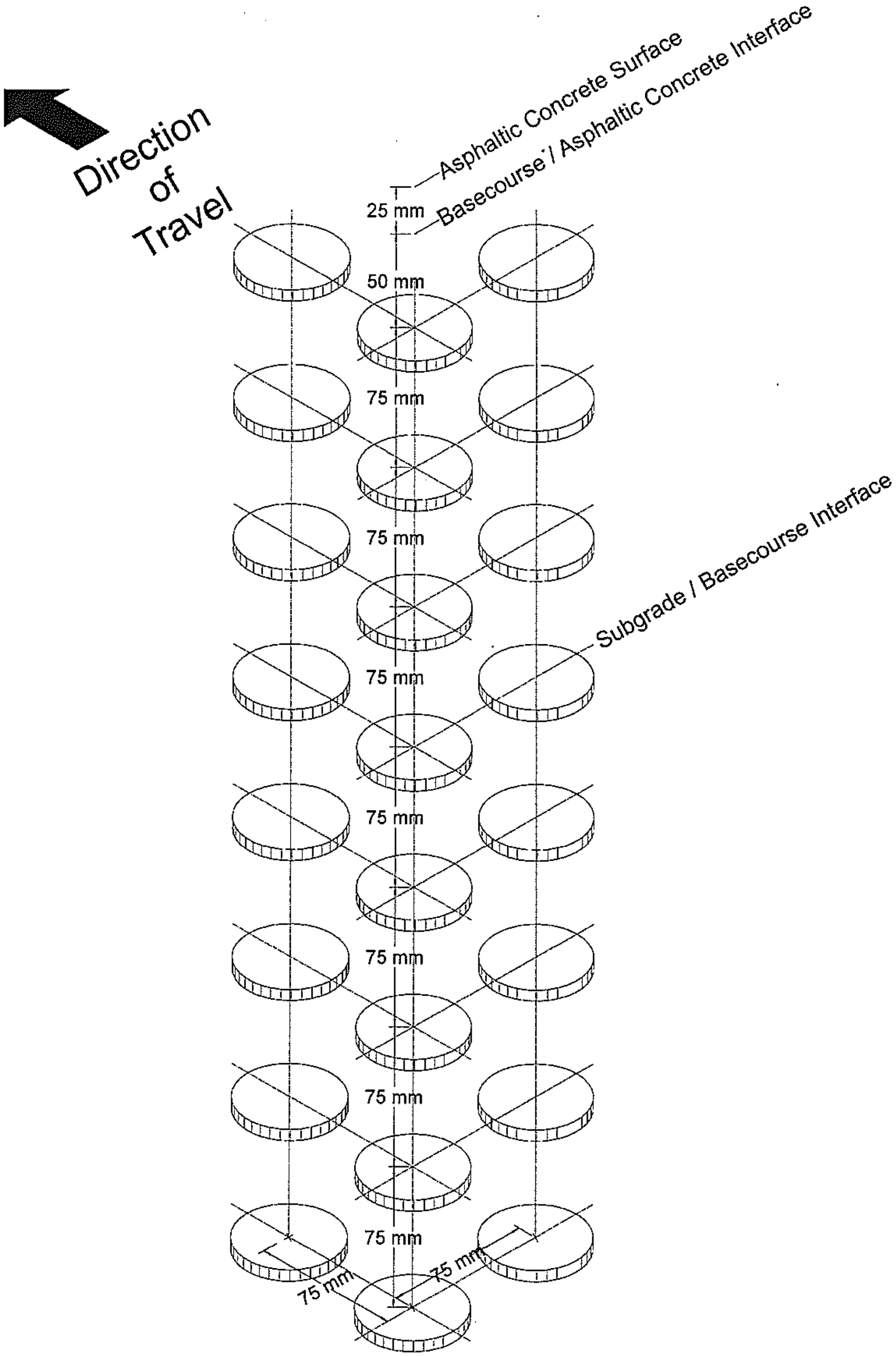


Figure 2.5 Instrument layout in each of the three CAPTIF test segments.



Note: The centreline of the instrumentation corresponds to a transverse location of 135 cm.

Figure 2.6 3D representation of Emu coil locations in a test segment.



2.6 Pavement Testing

2.6.1 Pre-loading

Before loading the newly constructed pavement, the as-constructed structural capacity of the pavement was measured using the CAPTIF deflectometer. The CAPTIF deflectometer measures the deflection under the wheel load at various distances from the load in a way similar to an FWD. Deflections were measured on the track centreline at each station. Although the FWD is the preferred device for measuring structural capacity, an FWD was not available immediately after construction. However, it was used on subsequent measurements of structural capacity during pavement loading.

The following tests were undertaken before trafficking in order to characterise the as-built condition of the pavement test sections, as follows:

- Manual profile beam readings at the stations that were measured during the pavement construction;
- Transverse profilometer readings at all stations;
- Longitudinal profile readings with the Laser unit at the following positions: 085, 130, 175, 220 and 265cm (the 130 and 220 positions are the centrelines of the two wheel paths, 175 is the track centreline between the wheel paths, 085 and 265 are untrafficked areas inside and outside the trafficked area respectively);
- Loadman measurements at each station.

A number of these tests were undertaken as part of the other project conducted simultaneously and will not be reported here.

2.6.2 Pavement Loading

At the completion of 15, 25, 35, 50, 100, 150, 200, 250, 300, 400, 500, 600, 700, 800, 900 and 1000 thousand (k) load cycles, the following tests were undertaken as detailed below.

(i) ***Complete Data Set*** – collected at the end of every third loading interval

***Performance measurements** (assessing deformation)*:

- Longitudinal profile was measured in each wheel path centreline and at 0.45m either side of each wheel path, using the laser profiler;
- Transverse profile was measured at each of the 58 stations around the track, using the CAPTIF profilometer.

Structural condition measurements:

The structural condition of the pavement was measured using the Dynatest FWD at each station in each wheel path.

In-situ strain and stress response measurements:

The pavement response to vehicle loading was measured by recording the Emu coil signals with the vehicle passing at the test speed (45km/h), at 15km/h and at

6km/h. Each coil pair/pressure cell was measured over 3 laps to verify the repeatability of the measurements.

(ii) Reduced data set –the complete data set was not collected

Performance measurements (assessing deformation):

- Longitudinal profiles were measured only in the wheel paths;
- Transverse profiles were measured at every station in the instrumented sections of track, but only at every sixth station over the remainder.

In-situ strain and stress response measurements:

The pavement response to vehicle loading was measured by recording the Emu coil signals with the vehicle passing over the coils at the test speed (45km/h), 15km/h and at 6km/h. Each coil pair/pressure cell was measured over 3 laps to verify the repeatability of the measurements.

2.6.3 Pavement Response to Different Wheel Loads & Tyre Types

At the end of 1 million load passes, strain and stress measurements in each of the three segments were measured for a range of different wheel loads and tyre types. These data were collected as part of an AUSTROADS-funded project to assess the damaging effect on a pavement of a range to tyre types, loads and pressures (Vuong & Sharp 2001).

The results of these tests enabled the in-situ elastic response of a granular material to be determined for a range of stresses (i.e. different tyre loads, etc.). Thus the results were compared to the resilient response of the granular materials measured in the RLT apparatus at the same range of stresses. Table 2.2 lists the range of tyre types, loads and pressures that were used in this study of resilient pavement response.

Table 2.2 Range of tyre types and loads used in pavement response study.

Test No.	Tyre Type	Load (kN)	Pressure (kPa)
1	11 R 22.5	40	650
2	11 R 22.5 and Super Single	40	750
3	11 R 22.5 and Super Single	50	750
4	11 R 22.5	60	750
5	11 R 22.5 and Super Single	40	850
6	11 R 22.5 and Super Single	50	850
7	11 R 22.5 and Super Single	60	850

2.6.4 Post-loading

At the conclusion of the test, after 1 million wheel passes, a final complete dataset as defined in Section 2.6.3 was collected. Then the pavement response to different wheel loads and tyre types was undertaken, and an additional 300k cycles of 50kN loading where applied to the inner wheel path as part of the alternative project. Finally, three trench locations were selected for each segment (i.e. in A, B and C).

The locations of the trenches in each segment corresponded as close as possible to the locations of minimum, average and maximum rut depths for that particular segment. The following tests were carried out at each trench:

Asphaltic concrete surface testing *(at the trench location):*
- Manual transverse profilometer readings;
- Nuclear Density tests at the track centreline and plus/minus 0.5m and 1.0m.

Subgrade surface testing *(at the trench location):*
- Manual transverse profilometer readings;
- A 38mm-diameter undisturbed core sample was taken from the subgrade near to the centreline for density and moisture content tests.

2.7 Pavement Test Results

A significant amount of test data is collected during the pavement test and particularly during construction. As this project was combined with another, only the results relevant to this project are recorded in this report (Appendices A-H). Further, the construction data collected are primarily to ensure uniformity of the subgrade and pavement layers, so generally has not been reported here.

2.7.1 Loadman Results

The Loadman uses Boussinesq theory to convert the deflection measured during a test to a resilient modulus value. As Boussinesq theory is limited to a single material layer, the Loadman result will effectively be a single-layer, elastic, isotropic modulus. The device cannot provide a detailed analysis of multiple material layers. The results of the Loadman tests are detailed in Appendix A.

2.7.2 Pavement Layer Thicknesses

The thickness of each pavement layer was carefully measured in order to obtain uniform depths. Also the data provided a baseline for the later transverse (e.g. rut depth) and profile measurements. This project is concerned with trafficking only on the inner wheel, and these results are summarised in Table 2.3. Figure 2.7 shows a plot of the resulting pavement thicknesses for the inner wheel path.

Table 2.3 Summary of asphalt (upper) and basecourse (lower) thicknesses (mm) in inner wheel path for each of the three segments.

Segment	Average	Minimum	Maximum	Std Deviation	Range
Asphalt thickness (mm)					
A (0-15)*	30.0	12.4	41.6	9.3	29.3
B (16-29)	32.5	26.4	40.0	3.7	13.6
C (30-43)	26.9	22.6	30.5	2.5	7.9
Basecourse thickness (mm)					
A (0-15)*	282.3	269.3	293.4	7.1	24.1
B (16-29)	272.8	257.5	289.9	8.4	32.4
C (30-43)	273.5	263.8	283.9	6.1	20.1

* Numbers in brackets are station numbers falling within the segment

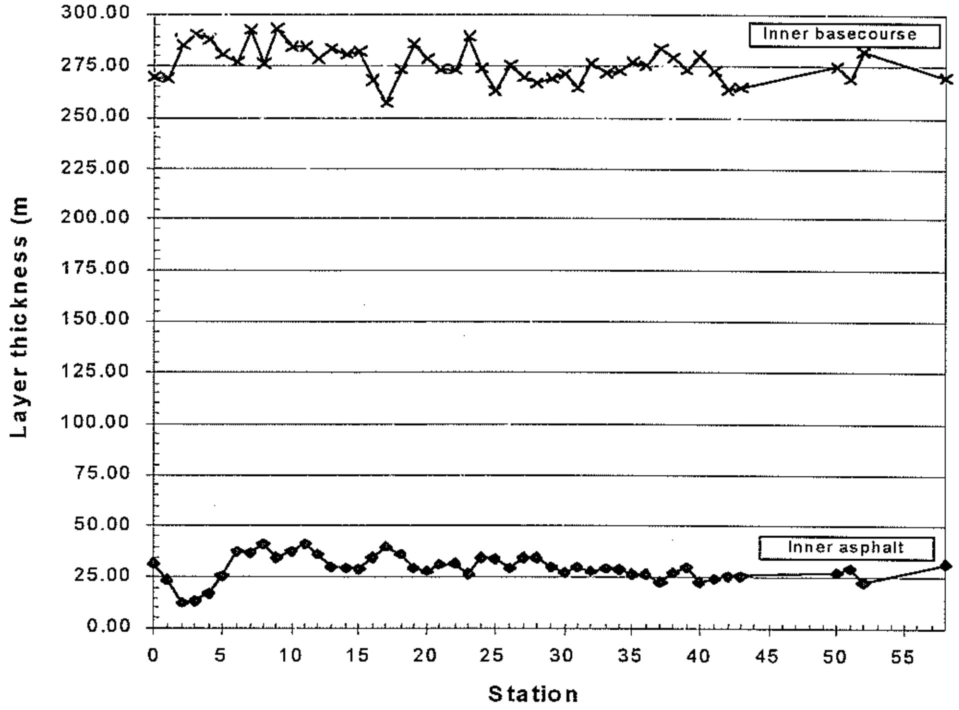


Figure 2.7 **Inner wheel path layer thicknesses (mm) for each station, for the asphalt surface and basecourse layers.**

The pavement layer thicknesses used in the mechanistic analysis were those measured at the instrument locations (i.e stress and Emu coil locations). Table 2.4 summarises the thicknesses used in mechanistic pavement design for each segment.

Table 2.4 **Average asphalt and basecourse thicknesses (mm) at instrument locations, as used in the pavement design.**

Station	Asphalt	Basecourse
A (9-10)*	36	289
B (23-24)	31	282
C (37-38)	25	282

* Numbers in brackets are stations where instruments are located

2.7.3 Surface Rutting

During the pavement loading, rut depths were calculated using a virtual 2m straight-edge, from the measured transverse profiles at each station. Figures 2.8 and 2.9 summarise the rutting results up to 1 million wheel passes for each segment. The results are as expected, where the best quality basecourse Materials A (clean crushed rock) and C (Australian material) show the least amount of rutting.

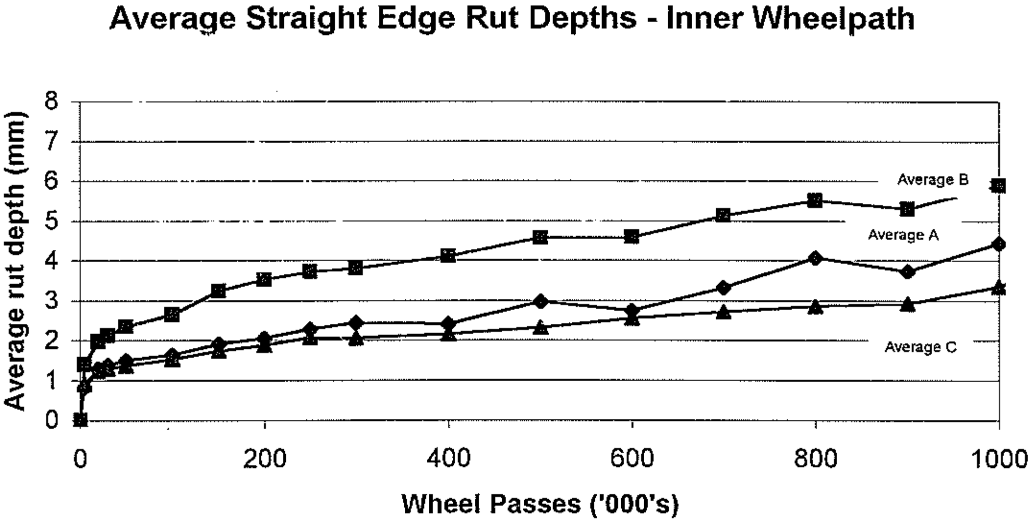


Figure 2.8 Average surface rut depths measured by 2m straight-edge for each segment for inner wheel paths.

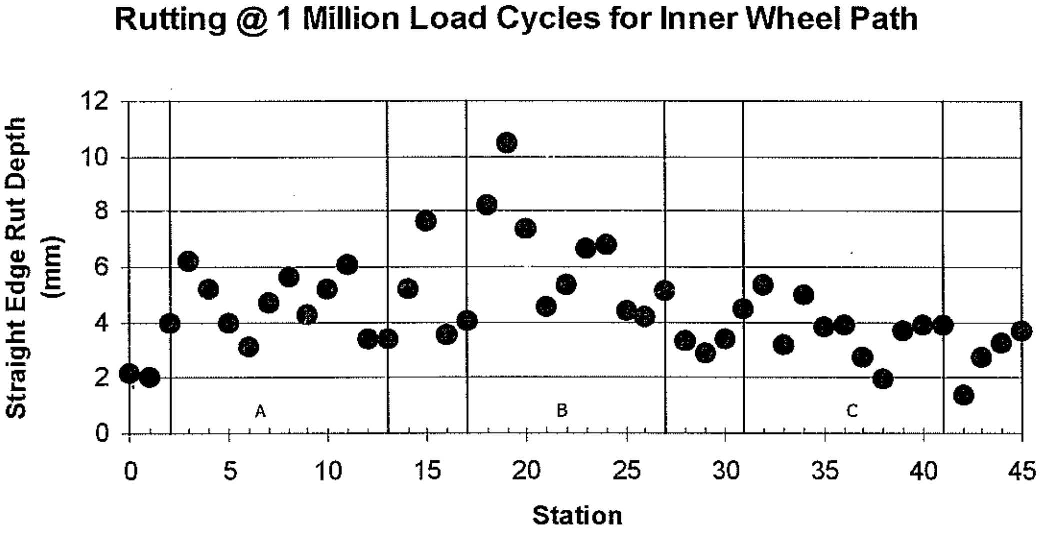


Figure 2.9 Rut depths (mm) measured by a 2m straight-edge at each station after 1 million wheel passes.

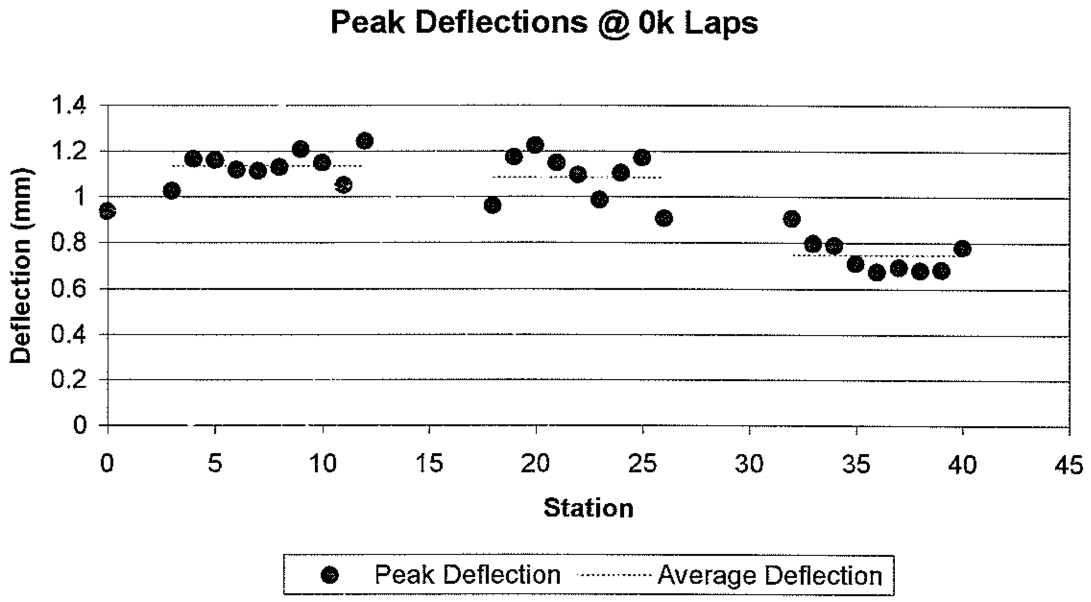


Figure 2.10 Peak FWD deflections for inner wheel path at 0k (zero) wheel passes (i.e. before pavement trafficking).

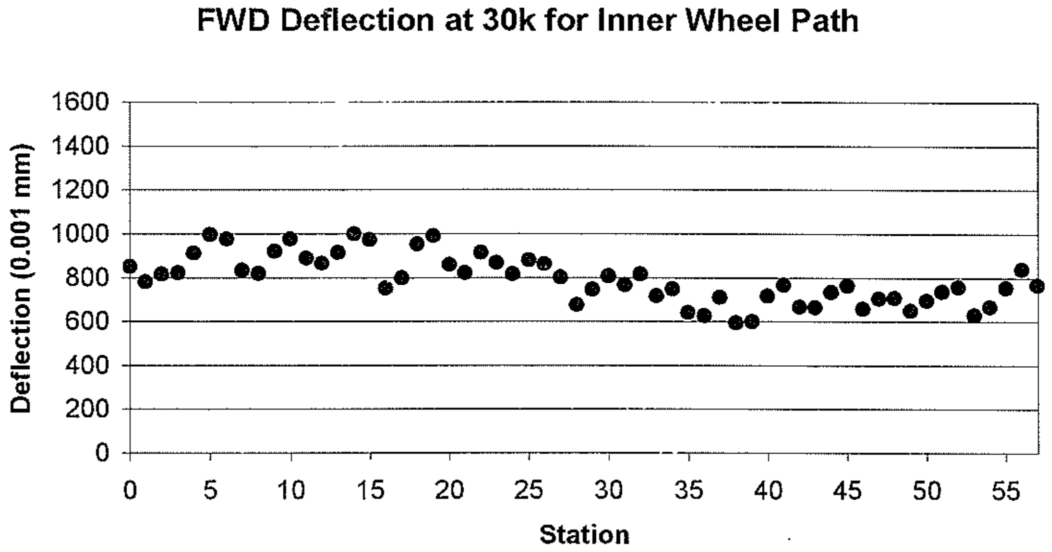


Figure 2.11 Peak FWD deflections for inner wheel path at 30k wheel passes.

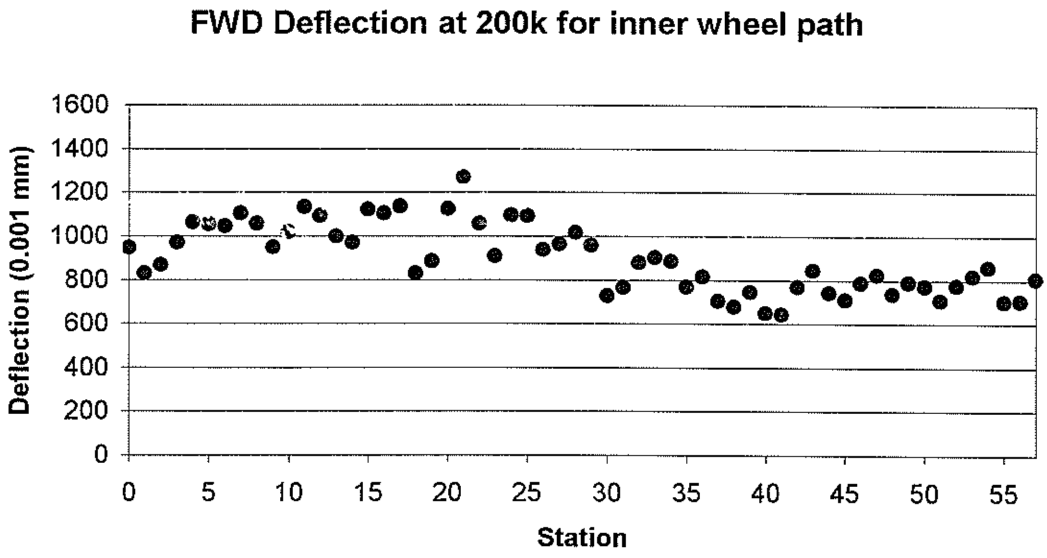


Figure 2.12 Peak FWD deflections for inner wheel path at 200k wheel passes.

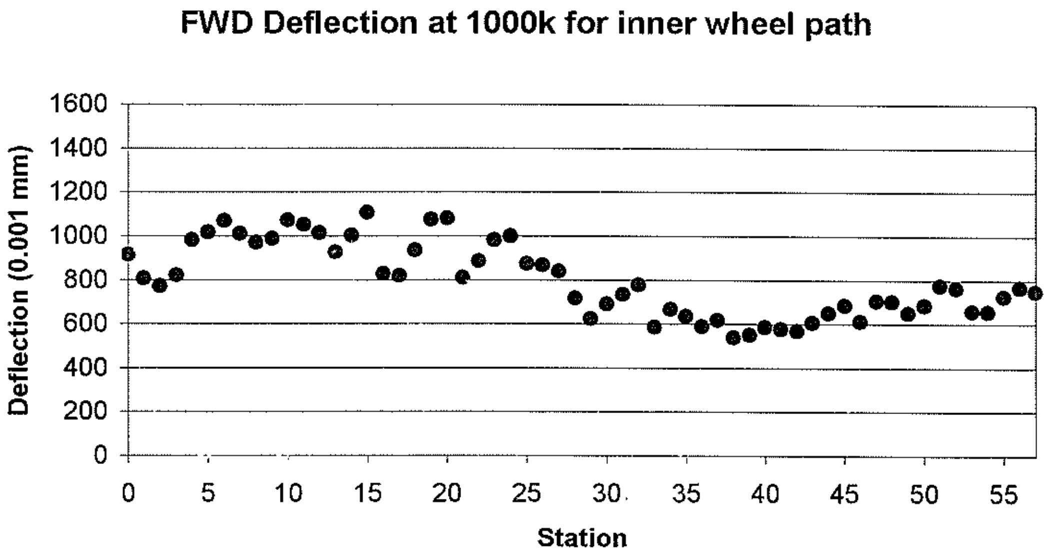


Figure 2.13 Peak FWD deflections for inner wheel path at 1 million wheel passes.

2.7.4 Pavement Deflections

Pavement deflections were measured first with the CAPTIF deflectometer, and subsequently with the Dynatest FWD at various intervals during the testing. The deflection measurements were not back-analysed to estimate pavement layer moduli as this was not needed for this study. Rather, the peak deflections have been plotted and compared to computed deflections in the subsequent analysis using RLT-derived moduli for pavement design. Figures 2.10, 2.11, 2.12 and 2.13 show plots of the peak deflections measured in the inner paths after 0k, 30k, 200k and 1000k wheel passes.

Table 2.5 Moduli from measured stresses and strain in the pavement for Material A (from Appendix C). (*measured; ** calculated values)

Tyre	Weight (kN)	Tyre Pressure (kPa)	Speed (km/h)	262.5 strain* (10^{-6})	300 stress* (kPa)	262.5 stress** (kPa)	Modulus, E (MPa)
11R22.5	40	750	45	720	61	70	97
11R22.5	40	650	45	700	61	70	100
11R22.5	40	850	45	680	64	73	107
11R22.5	40	750	20	760	70	80	105
11R22.5	40	800	6	660	72	82	124
11R22.5	40	650	20	700	72	82	118
11R22.5	40	750	6	780	77	88	113
11R22.5	40	850	20	720	88	100	139
11R22.5	50	750	20	800	88	100	125
11R22.5	50	850	45	780	90	102	131
11R22.5	50	850	20	800	91	104	129
11R22.5	40	850	6	720	95	108	150
11R22.5	40	650	6	720	96	110	153
11R22.5	50	750	45	800	107	122	153
11R22.5	50	750	6	760	117	133	176

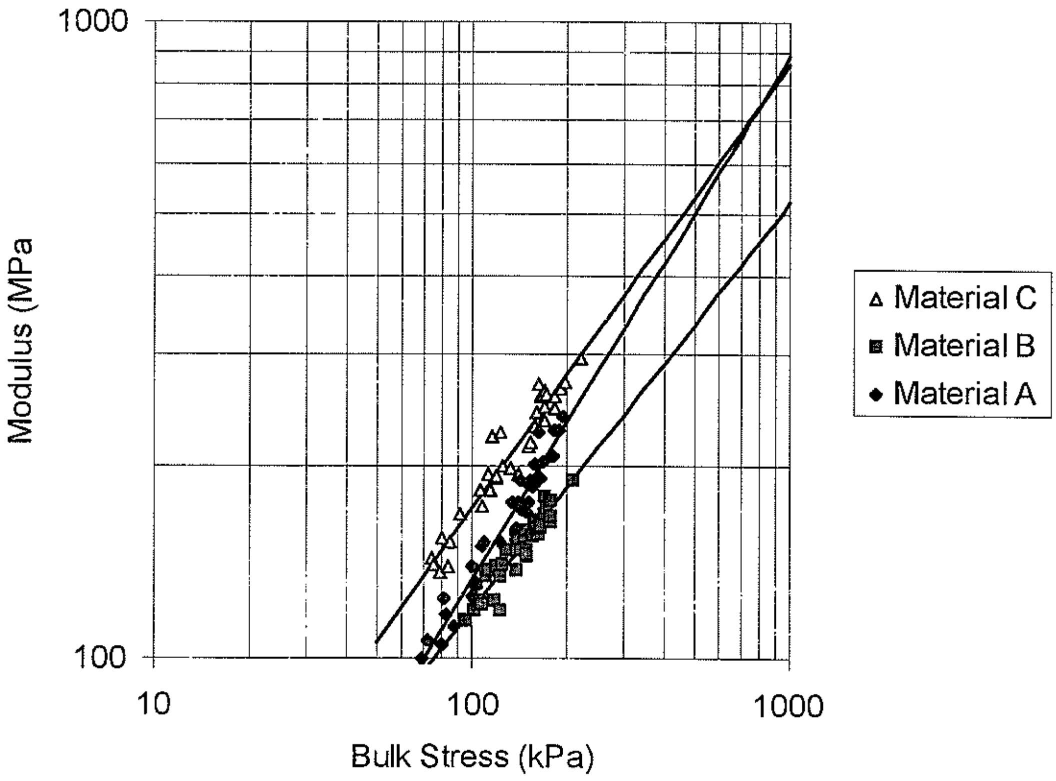


Figure 2.14 Moduli from measured stresses and strains in the pavement.
(NB: in the pavement horizontal stresses were assumed to be nil, so bulk stress shown is equal to vertical stress.)

2.7.5 Pavement Responses

Vertical strains and stresses were measured under the range of loads and speeds detailed in Table 2.2. The results of the pavement response data have been reported directly and are detailed in Appendix B. The strains and stresses measured in the bottom of the granular layer were also analysed to calculate the resilient modulus. Linear elastic analysis shows that horizontal stresses directly beneath the centre of the wheel load in the bottom of the granular layer are negligible. However, in a pavement which has locked-in aggregate, a level of confinement or horizontal stresses will always occur. This level of confinement was unknown and for this analysis it was assumed that the horizontal stresses are nil. The confinement from the surrounding aggregate is discussed later as a possible reason for the mismatch between within pavement moduli and those measured in the RLT apparatus. Therefore, the resilient modulus calculated was simply the measured vertical stress divided by the measured vertical strain. Further, for comparison with RLT results (i.e. resilient modulus varies with bulk stress), the vertical stress can be assumed to be equal to the bulk stress as horizontal stresses are nil.

The vertical stress measured at 300mm depth (subgrade surface) was factored up to estimate the stress at a depth of 262.5mm (i.e. depth midway between the two strain gauges in the bottom granular layer). This factor was determined by comparing results of a CIRCLY analysis of the CAPTIF pavement with the stresses computed at 300mm and 262.5mm depth. Even though these stresses may not be the same as those in the CAPTIF sections, their relationship with each other can be used directly, as a first approximation.

Results of this analysis are tabled in Appendix C and summarised in Figure 2.14. To explain this analysis, a few results for Segment A and Material A (from Appendix C) are shown in Table 2.5. All the columns except for the last two show information recorded for each strain and stress measurement. The stress at 262.5mm depth was calculated by multiplying the stress measured at 300mm depth by 1.14. The factor 1.14 was determined by undertaking a CIRCLY analysis of the pavements using parameters determined from back-analysis of FWD deflection bowls at CAPTIF as recorded in a concurrent Transfund research project, *Performance-based Specifications using the FWD*. The ratio of computed stress at 262.5mm depth to the stress at 300mm depth was used as the factor. Finally, modulus values in the last column were calculated by dividing the stress at 262.5mm depth by the strain at 262.5mm depth.

3. RLT Testing Results

RLT testing was conducted on the three granular materials tested at CAPTIF to measure their resilient and permanent deformation properties. Both resilient and permanent deformation properties (Section 3.1) were measured over a range of stress conditions.

3.1 Elastic Properties (Resilient Modulus)

The resilient modulus was calculated from tests conducted in the RLT apparatus at a range of stress conditions for all three unbound granular materials. Figure 3.1 is a plot of resilient modulus versus bulk stress for Materials A (clean aggregate), B (dirty aggregate), and C (Australian aggregate). A relationship between bulk stress and resilient modulus is obvious. Further, the log-log plot shows that Material A has the highest resilient moduli while there is little difference between Materials B and C.

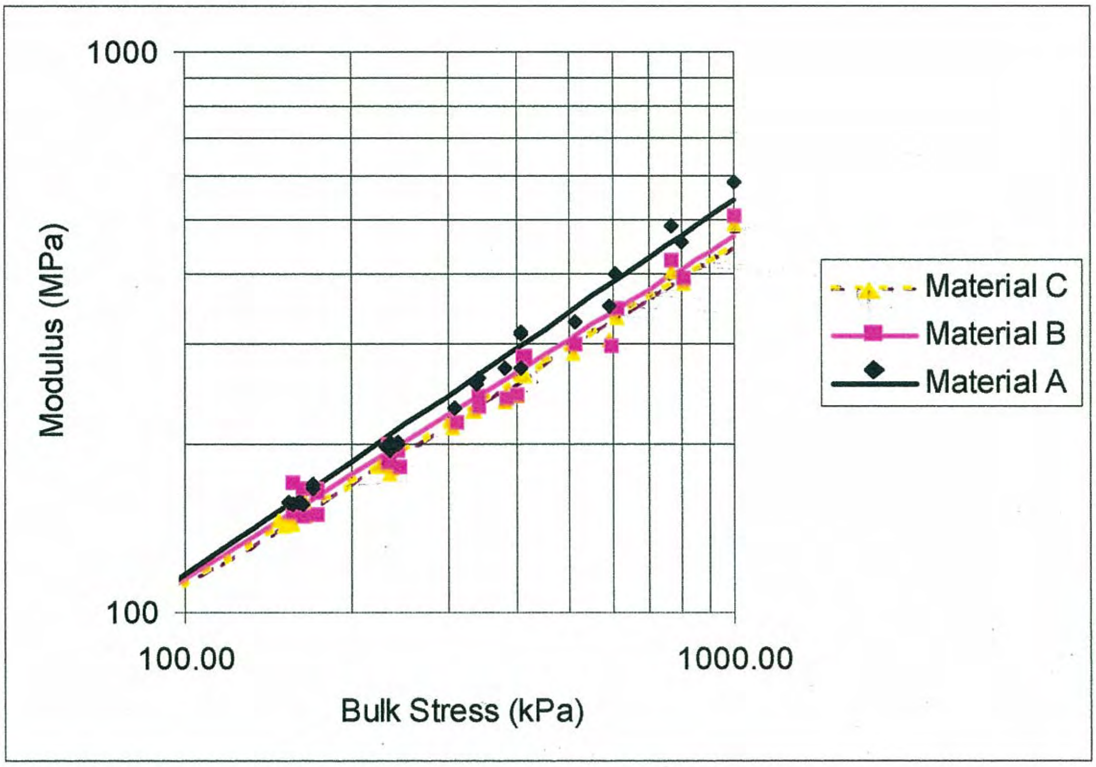


Figure 3.1 **Resilient moduli versus bulk stress for the three materials tested in the RLT apparatus.**

3.2 Permanent Deformation Properties

Spatially in a pavement, stress conditions caused by a passing wheel vary substantially. This range of stress conditions can be covered during resilient modulus tests because only 100 load pulses per stress condition are required on the one sample in order to obtain a relationship between resilient modulus and stress. However, permanent deformation tests are conducted at a chosen stress condition on one sample for at least 50,000 load cycles. A permanent deformation test at a different stress condition requires a new sample. Permanent deformation testing was conducted at two stress levels (high and low) for each of the granular materials (A, B and C) and for the subgrade soil.

The high and low stress conditions were estimated from CIRCLY analysis to cover the range of stresses expected in the pavement under a moving wheel load. Table 3.1 lists the stress conditions used in the permanent deformation test. The average stress p and deviator stress q as detailed in Table 3.1 were also calculated as this is a common geotechnical method for comparing stress conditions.

Table 3.1 RLT stress conditions for permanent deformation tests of granular materials and subgrade.

Material/High or Low Stress	σ_1 [kPa][2]	σ_3 [kPa][3]	$p = 1/3(\sigma_1+2\sigma_3)$ [kPa][4]	$q = \sigma_1 - \sigma_3$ [kPa]
UGM[1] (A, B & C) / High Stress	550	50	217	500
UGM[1] (A, B & C) / Low Stress	83	8	33	75
Subgrade / High Stress	83	8	33	75
Subgrade / Low Stress	58	8	24.67	50

Notes:
1 Unbound Granular Material
2 Maximum cyclic vertical stress plus confining pressure
3 Stress in horizontal direction = confining pressure
4 Equation valid where $\sigma_3 = \sigma_2$ (i.e. stresses in all horizontal directions are the same)

Permanent strain results for the high and low stress conditions in Materials A, B, C and the subgrade are plotted in Figures 3.2, 3.3 and 3.4. Initially the proposal was to test the subgrade Materials A, B and C in the RLT apparatus at the in-situ stress measured in each test segment of the pavement, but as the results were similar, it was decided to use the same stress for each RLT test. A method of obtaining an estimate of the total surface rutting is detailed in Section 5. Extrapolation methods are applied to the RLT test results to determine deformation in the pavement appropriate to the stress level and number of load cycles.

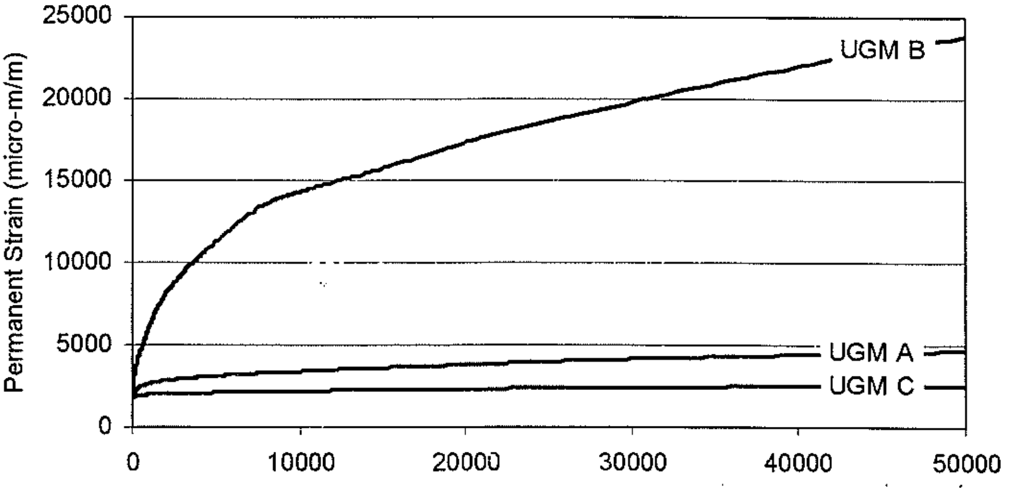


Figure 3.2 RLT permanent strain test results for unbound granular materials (UGM) at high stress conditions (i.e. p = 217kPa, q = 500kPa).

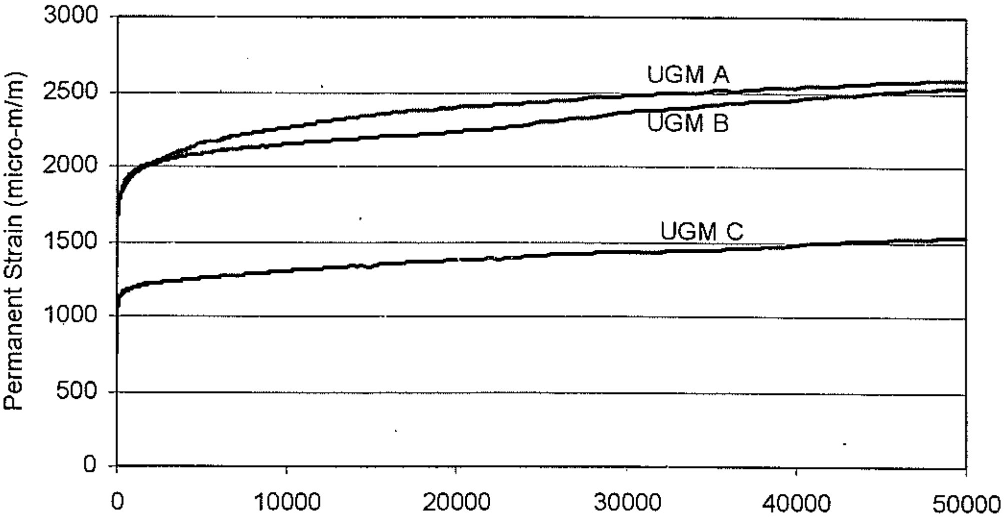


Figure 3.3 RLT permanent strain test results for unbound granular materials (UGM) at low stress conditions (i.e. p = 33kPa, q = 75kPa).

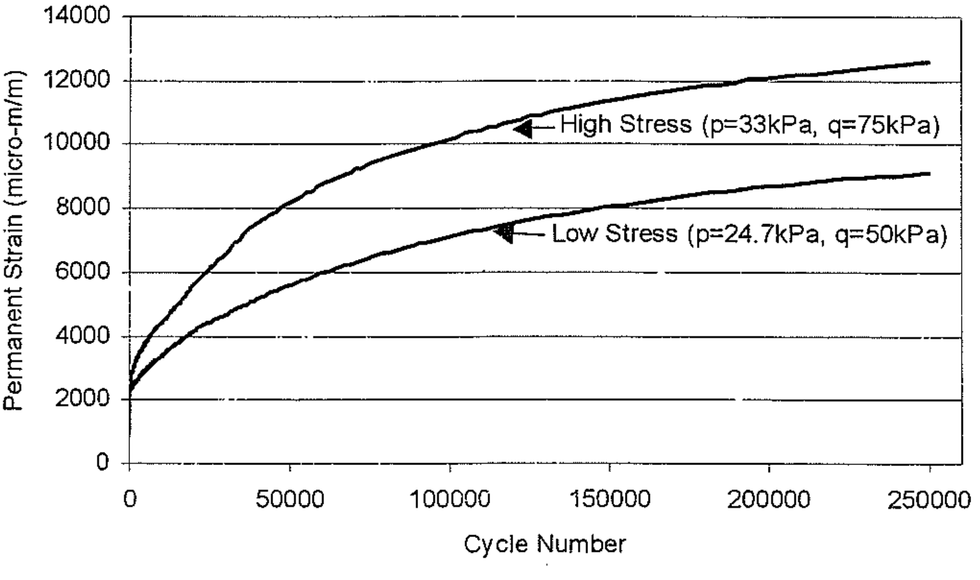


Figure 3.4 RLT permanent strain test results for subgrade material at high (p = 33kPa, q = 75kPa) and low (p = 24kPa, q = 50kPa) stress conditions.

4. Mechanistic Analysis using RLT-Derived Moduli

4.1 Introduction

The resilient moduli derived from the RLT tests for the granular materials were used in three different methods in order to define the properties of the layered linear elastic model of the CAPTIF pavement. CIRCLY (Wardle 1996), a linear elastic program, was then used to compute strains and stresses at the instrument locations within the pavement. These strains and stresses were later compared to measured stresses and strains.

The three different methods described in Sections 4.2.1, 4.2.2, 4.2.3 relate to defining the resilient properties of the granular layers in the pavement. Assumptions common to all the designs were utilised to define the other layers and degree of anisotropy. Table 4.1 lists those design assumptions.

Table 4.1 Design assumptions used to define resilient properties of the granular pavement layers.

Layer:	Asphalt	Granular	Subgrade
Segment Thickness *	**(mm)**		
A	36	289	1200
B	31	282	
C	25	282	
Resilient Modulus	**(MPa)**		
Vertical modulus:	2000	Derived from RLT test results as per Sections 4.2.2, 4.2.3	1.5(Loadman modulus)*
Horizontal modulus:	2000	= ½(vertical modulus)	= ½(vertical modulus)
Poisson's Ratio	0.35	0.35	0.45

* Loadman moduli and thicknesses used were the average values measured in the inner wheel path at the two instrumented stations in each of the 3 Segments A, B and C

The Loadman modulus values were used for the subgrade as the result related to an in-situ response. Also the use of Loadman modulus better reflected typical pavement design as RLT data are not usually available for subgrade materials.

For the mechanistic analysis applied in CIRCLY, the dual wheel loads were modelled as a single circular load. Previous experience with CIRCLY using dual tyres sometimes created tensile vertical strains directly between the two tyres (i.e. bulging upwards) The single circular load overcame this difficulty.

4.2 Methods for Utilising RLT-derived Moduli

Three methods were used to utilise the RLT-derived and stress-dependent moduli of the granular materials for pavement design. The methods described in this Section 4.2 all relate to the design assumptions listed in Table 4.1. In particular, the horizontal modulus is always half the vertical modulus, as recommended in the AUSTROADS Pavement Design Guide (1992).

4.2.1 Theoretically Rigorous Method

Ideally, the "correct" modulus needs to be used at each depth in the pavement, based on the stress at that depth and the stiffness versus stress relationship derived from the RLT results. This method is as follows:

Step 1: From the RLT test results determine the relationship between stress (e.g. log-log relationship with bulk stress) and resilient modulus.

Step 2: Define a first guess layered elastic model of the pavement, where typically:
the asphalt is defined as one layer;
the granular material is split into at least three layers; and
the subgrade is defined as one layer of infinite thickness.
(NB: three layers were chosen to reduce analysis time but theoretically, the more layers chosen, the more accurate the result. However, as the approach is a manual iterative procedure, an exact solution is difficult to find and the use of more layers will not necessarily give a more accurate result, but in fact could increase difficulties in finding a solution.)

Step 3: Using the model defined in Step 2, compute stresses at the middle of the granular layers.

Step 4: From the relationship between resilient modulus and stress, as in Step 1, determine the appropriate resilient modulus for the stress computed in Step 3 for each granular layer.

Step 5: Change the granular layer moduli in the layered elastic model of the pavement to those determined in Step 4.

Step 6: Using the model defined in Step 5, compute stresses at the middle of the granular layers.

Step 7: Repeat Steps 4 to 6 until negligible change is recorded in granular moduli when undertaking Step 5.

This method is time consuming and complicated. Therefore, two other, more common and less complicated, methods for utilising RLT-derived resilient moduli for pavement design were evaluated.

4.2.2 AUSTROADS Auto-sublayering Method (RLT moduli from contact stress)

This method is not an iterative approach, and the automatic sub-layering feature in the CIRCLY program is utilised. The vertical modulus of the top granular layer is equal to the value of resilient modulus obtained from the RLT test, at a bulk stress that is the same as the tyre surface contact stress (e.g. 750kPa).

4.2.3 AUSTROADS Auto-sublayering Method (RLT moduli from bulk stress)

The automatic sub-layering feature in the CIRCLY program is utilised as in Section 4.2.2. However, the vertical modulus of the top granular layer is equal to the value of resilient modulus obtained from the RLT test, at a bulk stress that is the same as the estimate of bulk stress in the top granular layer. The tyre contact stress is multiplied by a factor to obtain an estimate of the bulk stress at 50mm below the surface (i.e. within the top granular layer). This factor was obtained from previous CIRCLY runs on CAPTIF pavements by comparing the tyre contact stress with the bulk stress at 50mm depth. This is similar to the approach used in Section 2.7.5. As a reminder, the bulk stress from CIRCLY is obtained by summing all the stresses in the x, y and z directions (Section 1.3).

4.3 Results from Methods utilising RLT-derived Moduli

The design assumptions (Table 4.1) and the three different methods (Sections 4.2.1, 4.2.2, and 4.2.3) for characterising the granular properties were used to define the layered linear elastic pavement structures for the range of tyre loads listed in Table 2.2. Stresses and strains were computed at the same locations where these parameters were measured in the CAPTIF pavement. Surface deflections were also calculated for later comparison with those measured. Further, the bulk stress at the middle of the granular layers and the corresponding RLT-derived modulus for this bulk stress were determined. The stresses, strains and deflections were reported in terms of the ratio of computed to measured values. These results are detailed in Appendices D, E and F, and are discussed and summarised in Section 6, in which CAPTIF and RLT results are compared.

5. Permanent Deformation Modelling from RLT Tests

5.1 Background

Transit New Zealand's performance-based specification for unbound materials (TNZ M/22:1999) utilises the RLT permanent deformation test. The deformation limits are set on the basis of results achieved with good quality M/4 basecourse. However, this method does not account for the full design and performance of the pavement. For example, it does not allow the designer to increase the cover of a lower quality basecourse to cater for its strength deficiency, or to use this material in a low volume road.

A method to overcome these deficiencies was proposed by Alabaster (1998) (Appendix H). This method predicts the rutting of a granular material based on RLT permanent deformation results, and stresses within the pavement computed by CIRCLY. This method followed the same concept as that used by Ullidtz (1987) and is detailed in Section 5.2.3. However, the method has not been validated by Transit New Zealand and therefore has not been adopted as policy.

Three methods were used to predict deformation. These methods differ in terms of the function used to extrapolate the RLT data. The first method uses a linear function, while the second and third methods assume an exponential function. The linear (Section 5.2.1) and first of the exponential (Section 5.2.2) methods apply a first principles approach as detailed in the following steps. The combined extrapolation method (Section 5.2.3) combines steps 1, 2 and 4 using equations derived from a first principles approach.

Step 1: From the RLT deformation test results, determine the equation of the line for the two stress levels (high and low) used for extrapolating the results (i.e. either linear or exponential): this enables the permanent strain to be calculated as a function of number of load cycles (e.g. 10^6).

Step 2: Calculate from the equations determined in Step 1, for the high and low stress tests, the permanent strain for the number of load cycles of interest.

Step 3: Divide the pavement into multiple linear layers and compute, using CIRCLY or similar computer program, the vertical stress directly beneath the load at the middle of each layer.

Step 4: Determine the permanent strain appropriate for each vertical stress computed in Step 3, using exponential interpolation between the values obtained from the high and low stress tests as in Step 2.

Step 5: Multiply the permanent strain values by their corresponding layer thicknesses, and sum the results to compute the total vertical deformation.

These five steps seem to afford a logical approach in predicting the rut depth in a pavement using RLT permanent deformation tests. However, there are some key flaws in the method, which are discussed in Section 8.2.2. In particular the assumption that strain varies exponentially with stress, as per step 4, may not be valid. However, for each material only two RLT tests at different stress levels were conducted and two results are insufficient to find the appropriate non-linear relationship between stress and deformation.

Appropriately chosen stress conditions in the RLT tests are expected to improve the result, and then the method will provide a means of comparing the use of different materials and pavement layer cover depths. Although the resulting computed rut depth may not be exactly correct, the relative differences between different materials and designs should be.

5.2 Extrapolation of RLT Permanent Deformation Test Results

The results from the RLT permanent deformation tests were extended to 1 million load cycles to match the number of wheel passes over the CAPTIF pavement. Three methods were used to extend the RLT data. The first method assumes that the rate of change of deformation after 20,000 load cycles is linear, while the second and third methods assume that the rate of deformation decreases with increasing load cycles as defined by either a log-log relationship or exponential.

The methods proposed are based on matching a curve to the resulting trend shown with the RLT results after 20,000 load cycles, rather than fitting a curve to all the results. This approach was considered valid as the aim is to extend the RLT results from 50,000 load cycles to 1 million load cycles. However, as RLT results do not stabilise and do not show an obvious trend until after 20,000 load cycles, using the RLT results for less than 20,000 load cycles could distort the extrapolation of the results away from the later trend. Further, the aim was to evaluate methods that were simple to apply and were similar to the method developed earlier by Alabaster (1998) which uses the Ullidtz (1987) equations (Appendix H). To keep the approach simple, only two points on the RLT curve were fitted to the equations.

Many different equations have been developed by other researchers, which are based on curve-fitting their RLT results. These methods are summarised in a paper by Lekarp et al. (2000). A range of logarithmic and exponential equations are presented in their report that are used to calculate permanent strain based on stress level and number of load cycles. Some of these equations should be researched further, although a significant number of RLT permanent strain tests are required at more stress levels in order determine the parameters needed for the equations.

However, Lekarp et al. (2000) recommended that a single equation is not suitable to model the permanent strain of granular materials. This is because the permanent strain response of a granular material can either be tending to a limiting value (asymptotic, which may be logarithmic), linear or exponential, or to eventual failure. The response is dependent on the applied stress level.

Testing granular materials at a range of stress conditions is currently being undertaken at the University of Nottingham, in order to develop a method of predicting permanent strain performance based on the "shakedown" concept. The shakedown concept accepts that more than one equation (dependent on stress level) defines the permanent strain response of granular materials. A shakedown limit is defined in principal stress space. A shakedown limit is defined in principal stress space (mean of principle stresses in x, y, z directions versus principle stress difference or major minus minor principle stress). Stress combinations below the shakedown limit will result in permanent strains stabilising (i.e. decreasing with increasing load cycles).

The three methods described in Sections 5.2.1-5.2.3 differ only by the method used to extend the RLT results beyond the number of load cycles tested. All three methods use an exponential equation to interpolate for the appropriate stress level.

5.2.1 Linear Extension (Method 1)

A simple method for the extension of RLT results for permanent deformation modelling simply involves drawing a straight line through user-defined points where the deformation results become linear. If the results show scatter, then a best-fit approach for linear extrapolation would be more appropriate.

For the granular materials, the RLT results chosen were at load cycles of 20,295 (ε_{p20k}) and 50,001 (ε_{p20k}).

For the subgrade materials, the RLT results chosen were at load cycles of 203,226 (ε_{p203k}) and 250,001 (ε_{p250k}), where the results appear linear. An equation for a linear line defining permanent strain (ε_{pN}) as a function of load cycles (N) is defined as:

$$\varepsilon_{pN} = a(N) + c \qquad \text{Equation 5.1}$$

where:

ε_{pN} = Permanent strain after N load cycles.

The constants a and c can be found by solving two simple simultaneous equations:

$$\varepsilon_{pN1} = a(N_{pt1}) + c \qquad \text{Equation 5.2}$$

$$\varepsilon_{pN2} = a(N_{pt2}) + c \qquad \text{Equation 5.3}$$

where:

ε_{pN1} = Permanent strain after N_{pt1} load cycles (i.e. the first point chosen where the data looks linear);

ε_{pN2} = Permanent strain after N_{pt2} load cycles (i.e usually last data point).

Solving for a and c gives:

$$a = (\varepsilon_{pN2} - \varepsilon_{pN2})/(N_{pt2} - N_{pt1}) \qquad \text{Equation 5.4}$$

$$c = \varepsilon_{pN2} - a(N_{pt2}) \qquad \text{Equation 5.5}$$

The results of this linear extrapolation for all the RLT deformation tests conducted at high and low stresses are given in Table 5.1. The calculated permanent strains at 250k, 500k, 900k and 1 million load cycles are also listed and are used in predicting rut depths, for comparison with the CAPTIF pavement test results (Section 6).

Table 5.1 Linear extension of RLT permanent deformation data.

Material	Vert. Stress	RLT Permanent Strain (μm/m)		$\varepsilon_{pN} = a(N) + c$ where:		Calc. Permanent Strain, ε_{pN} (μm/m)			
		(ε_{p20k})	(ε_{p50k})	*a* = ..	*c* = ..	*250k*	*500k*	*900k*	*1000k*
Granular A	94	2400	2585	6.23E-03	2274	3831	5387	7879	8501
A	507	3803	4615	2.73E-02	3248	10082	16916	27849	30583
B	95	2238	2535	1.00E-02	2035	4535	7034	11033	12033
B	559	17335	23757	2.16E-01	12948	66994	121040	207514	229133
C	94	1372	1532	5.39E-03	1263	2609	3956	6110	6649
C	556	2294	2547	8.52E-03	2121	4250	6380	9786	10638
Subgrade		(ε_{p203k})	(ε_{p250k})						
	66	8707	9089	8.17E-03	7047	9089	11131	14397	15214
	91	12090	12588	1.06E-02	9926	12588	15250	19508	20573

An exponential function as used by Ullidtz (1987) was used for describing the change in permanent strain with increasing stress. This exponential extension is considered by many researchers as not always appropriate (Lekarp et al. 2000). However, as only two stress levels were tested in the RLT apparatus as part of this project, an appropriate relationship of permanent strain with stress could not be determined. The exponential function used and its constants are defined as follows:

$$\varepsilon_{p\sigma_{vN}} = b\left(\frac{\sigma_{vN}}{\sigma_r}\right)^d \qquad \text{Equation 5.6}$$

where:

$\varepsilon_{p\sigma_{vN}}$ = Permanent strain for a vertical stress σ_{vN} after *N* load cycles;

σ_r = Reference stress of 100kPa used to keep units consistent.

The constants *b* and *d* can be are determined using the following equations:

$$d = \frac{\log(\varepsilon_{p\sigma_{vNpt2}}) - \log(\varepsilon_{p\sigma_{vNpt1}})}{\log\left(\frac{\sigma_{vNpt2}}{\sigma_r}\right) - \log\left(\frac{\sigma_{vNpt1}}{\sigma_r}\right)} \qquad \text{Equation 5.7}$$

$$b = \frac{\varepsilon_{p\sigma_v Npt2}}{\left(\frac{\sigma_{vNpt2}}{\sigma_r}\right)^d} \qquad \text{Equation 5.8}$$

where:

$\varepsilon_{p\sigma_v Npt1}$ = Permanent strain for low vertical stress (σ_{vNpt1}) after *N* load cycles;

$\varepsilon_{p\sigma_v Npt2}$ = Permanent strain for high vertical stress (σ_{vNpt2}) after *N* load cycles.

Table 5.2 lists the constants for the equation defining permanent strain as a exponential function of vertical stress for the range of load cycles of interest.

Table 5.2 Constants for the equation for determining permanent strain as an exponential function of stress.

Material	**Constants *b* and *d* for, $\varepsilon_{p\sigma_{vN}} = b\left(\frac{\sigma_{vN}}{\sigma_r}\right)^d$, for each load cycle:**			
	250k	***500k***	***900k***	***1000k***
Granular A: b =	3973.7430	5626.398	8265.025	8924.284
d =	0.5735	0.6780	0.7482	0.7586
B: b =	4883.0150	7606.386	11960.163	13048.385
d =	1.5212	1.6073	1.6576	1.6645
C: b =	2654.7940	4023.412	6213.188	6760.631
d =	0.2742	0.2686	0.2647	0.2641
Subgrade: b =	12587.9890	15249.668	19508.353	20573.024
d =	1.0003	0.9670	0.9331	0.9268

5.2.2 Exponential Extension (Method 2)

It is often more appropriate to extend the RLT permanent deformation data using an exponential function, because it better matches RLT results that show a decreasing permanent strain rate with increasing load cycles. Constant increase in permanent strain with increasing load cycles would suggest the linear extension method is more appropriate. Results from Materials A and C showed a decrease in permanent strain rate and therefore an exponential function is considered the best method to extend RLT results. Ullidtz (1987) also uses an exponential function of the following form:

$$\varepsilon_p = k(N)^m \qquad \text{Equation 5.9}$$

where:

k and *m* are constants;

N = number of load cycles.

The constants *k* and *m* are found by choosing two points to fit this function of the RLT permanent deformation plots. Ullidtz (1987) chose the points at 1000 and 100,000 load cycles The points chosen from the RLT test results for the granular Materials A, B and C were at load cycles of 1,005 (ε_{p1k}) and 50,001 (ε_{p50k}), and for the subgrade materials at load cycles of 1,001 (ε_{p1k}) and 250,001 (ε_{p250k}).

The constants k and m can be determined using the following equations:

$$m = (\log(\varepsilon_{pN2}) - \log(\varepsilon_{pN1}))/(\log(N_{pt2}) - \log(N_{pt1})) \qquad \text{Equation 5.10}$$

$$k = (\varepsilon_{pN2})/((N_{pt2})^{m}) \qquad \text{Equation 5.11}$$

where:

ε_{pN1} = Permanent strain after N_{pt1} load cycles
(i.e. the first point chosen, usually at 1000 load cycles);
ε_{pN2} = Permanent strain after N_{pt2} load cycles (i.e. usually last data point).

The results of this exponential extension for all the RLT deformation tests conducted at high and low stresses are given in Table 5.3. This table also lists the permanent strains at 250k, 500k, 900k and 1000k (1 million) load cycles for later use in predicting rut depths for comparison with the CAPTIF pavement test results.

Table 5.3 Exponential extension and equation constants for RLT deformation results.

Material	**Vert. Stress**	**RLT Permanent Strain (µm/m)**		$\varepsilon_{pN} = k(N)^m$ ***where:***		**Calc. Permanent Strain, ε_{pN} (µ/m)**			
		(ε_{p1k})	(ε_{p50k})	*m = ..*	*k = ..*	***250k***	***500k***	***900k***	***1000k***
Granular A	94	1950	2585	0.07215	1184	2903	3052	3184	3209
A	507	2622	4615	0.14471	964	5825	6440	7012	7119
B	95	1963	2535	0.06545	1249	2817	2947	3063	3084
B	559	6017	23757	0.35149	530	41828	53368	65615	68091
C	94	1193	1532	0.06401	766	1698	1775	1843	1856
C	556	1968	2547	0.06601	1247	2832	2965	3082	3104
Subgrade		(ε_{p1k})	(ε_{p250k})						
	66	2420	9089	0.23988	461	9089	10733	12358	12675
	91	2922	12588	0.26475	469	12588	15124	17670	18170

For estimating the permanent strain at vertical stress levels other than those measured, an exponential function is, once again, used. The exponential function and constants are defined, as in Section 5.2.1, in Equations 5.6, 5,7, and 5.8. Table 5.4 lists the constants for the equation that defines permanent strain as a exponential function of vertical stress for the range of load cycles of interest.

Table 5.4 Constants for the equation for determining permanent strain as a function of stress for exponential extension of RLT data.

Materials	**Constants b and d for, $\varepsilon_{p\sigma_{vN}} = b\left(\frac{\sigma_{vN}}{\sigma_r}\right)^d$, for each load cycle:**			
	250k	***500k***	***900k***	***1000k***
Granular A:b =	2978	3137	3278	3304
d =	0.413	0.443	0.468	0.473
B: b =	3045	3205	3347	3373
d =	1.522	1.634	1.729	1.746
C: b =	1729	1807	1877	1889
d =	0.288	0.289	0.289	0.289
Subgrade: b =	12588	15124	17670	18170
d =	1.014	1.068	1.113	1.121

5.2.3 Combined Extrapolation (Method 3)

This method uses the Ullidtz (1987) single equation that defines vertical strain as a function of vertical stress and load cycles. This equation is an exponential function and can be considered as a simplification of Method 2 (Section 5.2.2). However, this simplification does effect the results. Equation 5.12 defines this relationship, and Equations 5.12, 5.13, 5.14, and 5.15 are used to determine the constants for the relationship.

$$\varepsilon_p = A * N^b \left(\frac{\sigma_1}{\sigma_r}\right)^c$$ Equation 5.12

where:

$$b = \frac{Log\left(\varepsilon_{p,c1,N_{pt1}}\right) - Log\left(\varepsilon_{p,c1,N_{pt2}}\right)}{Log\left(N_{pt1}\right) - Log\left(N_{pt2}\right)}$$ Equation 5.13

$$c = \frac{Log\left(\varepsilon_{p,c1,N_{pt2}}\right) - Log\left(\varepsilon_{p,c2,N_{pt2}}\right)}{Log\left(\frac{\sigma_{1,c1}}{\sigma_r}\right) - Log\left(\frac{\sigma_{1,c2}}{\sigma_r}\right)}$$ Equation 5.14

$$A = \frac{\varepsilon_{p,c2,N_{pt2}}}{\left(N_{pt2}\right)^b \left(\frac{\sigma_{1,c2}}{\sigma_r}\right)^c}$$ Equation 5.15

c1 = curve 1 of RLT permanent strain data results for low vertical stress test;

c2 = curve 2 of RLT permanent strain data results for high vertical stress test;

$\sigma_{1,c1}$ = vertical stress used in an RLT test to generate curve 1 data (c1) or the low vertical stress, kPa;

$\sigma_{1,c2}$ = vertical stress used in a RLT test to generate curve 1 data (c2) or the high vertical stress, kPa;

σ_r = reference vertical stress set = 100kPa to ensure consistent units;

N_{pt1} = first data point chosen usually = 1000 load cycles;

N_{pt2} = second data point chosen usually last data point and is typically = 50,000 or 100,000 load cycles (dependent length of RLT test);

$\varepsilon_{p,c1,N_{pt1}}$ = permanent strain for RLT curve 1 (c1, low stress) at N_{pt1} load cycles;

$\varepsilon_{p,c1,N_{pt2}}$ = permanent strain for RLT curve 1 (c1, low stress) at N_{pt2} load cycles;

$\varepsilon_{p,c2,N_{pt1}}$ = permanent strain for RLT curve 2 (c2, high stress) at N_{pt1} load cycles;

$\varepsilon_{p,c2,N_{pt2}}$ = permanent strain for RLT curve 2 (c2, high stress) at N_{pt2} load cycles.

Table 5.5 lists the constants derived from the RLT data for Materials A, B and C (at 1000 and 50,000 load cycles), and subgrade (at 1000 and 250,000 load cycles).

Table 5.5 **Parameters defining permanent strain as a function of stress and strain.**

Material	**Vert. Stress**	**RLT Permanent Strain (μm/m)**		$\varepsilon_p = A * N^b \left(\frac{\sigma_1}{\sigma_r} \right)^c$ **where:**			**Calculated Permanent Strain, ε_{pN} (μm/m)**			
		(ε_{p1k})	(ε_{p50k})	A =..	b =..	c =..	*250k*	*500k*	*900k*	*1000k*
Granular A	94	1950	2585	922	0.07215	0.5112	2190	2302	2402	2420
A	507	2622	4615				5183	5449	5685	5729
B	95	1963	2535	1039	0.06545	1.4069	2181	2282	2372	2388
B	559	6017	23757				26396	27621	28704	28903
C	94	1193	1532	613	0.06401	0.4267	1322	1382	1435	1445
C	556	1968	2547				2823	2951	3065	3085
		(ε_{p1k})	(ε_{p250k})							
Subgrade	66	2420	9089	1036	0.23988	5.1337	2420	2858	3290	3375
	91	2922	12588				12588	14865	17116	17554

5.3 Calculating Vertical Deformation

After determining the functions for extrapolating the RLT data, both in terms of number of load cycles and stress, the vertical deformation is calculated. For comparison, the vertical deformations (i.e. surface rutting) of the CAPTIF pavement for each Segment A, B and C were calculated, as follows.

Step 1: Divide the pavement into a number of layers and calculate the vertical stress in the middle of each layer.

Step 2: Calculate the permanent strain for this stress using the equations for stress determined from the RLT data at the number of load cycles of interest.

Step 3: Multiply the permanent strain by the layer thickness to obtain a deformation value.

Step 4: Sum the deformations for each layer to obtain the total deformation.

5.3.1 CIRCLY Analysis

To determine the vertical stresses within the pavement, the design assumptions given in Table 4.1 were used in a CIRCLY analysis of the CAPTIF pavement Segments A, B and C. The granular material was divided into 5 layers of equal thickness, while the subgrade was also divided into 5 layers of various thicknesses (100, 150, 200, 300, 450mm). The modulus of the granular layers were determined using the iterative approach described in Section 4.2.1, to ensure that the moduli are close to the values obtained in the RLT apparatus at the same bulk stress computed in the CIRCLY analysis. Table 5.6 summarises the resulting vertical stresses and pavement layer moduli used in the CIRCLY analysis for computing vertical stress. The choice of the number of layers is arbitrary as the greater the number of layers the greater the accuracy. However the computation time is greatly increased.

Table 5.6 Vertical stress results from CIRCLY analysis.

Layer	Segment A				Segment B				Segment C			
	Thick-ness (mm)	Mid depth (mm)	Mod-ulus (MPa)	Vert. Stress (kPa)	Thick -ness (mm)	Mid depth (mm)	Mod-ulus (MPa)	Vert. Stress (kPa)	Thick -ness (mm)	Mid depth (mm)	Mod-ulus (MPa)	Vert. Stress (kPa)
BC	58	65	**382**	**553**	56	59	**349**	**580**	56	53	**369**	**600**
BC2	58	123	**280**	369	56	116	**266**	**398**	56	110	**268**	**422**
BC3	58	181	**208**	**237**	56	172	**204**	**260**	56	166	**208**	**278**
BC4	58	238	**158**	**160**	56	228	**160**	**175**	56	222	**163**	**187**
BC5	58	296	**126**	**115**	56	285	**130**	**125**	56	279	**133**	**134**
SG1	100	375	**108**	**80**	100	363	**107**	**86**	100	357	**115**	**91**
SG2	150	500	**108**	**51**	150	488	**107**	**54**	150	482	**115**	**57**
SG3	200	675	**108**	**32**	200	663	**107**	**33**	200	657	**115**	**34**
SG4	300	925	**108**	**20**	300	913	**107**	**20**	300	907	**115**	**21**
SG5	450	1300	**108**	**13**	450	1288	**107**	**13**	450	1282	**115**	**13**

BC – Basecourse unbound granular material
SG – Subgrade (NB: moduli were determined from Loadman tests)

Table 5.7 Vertical deformation results calculated from RLT data using the three extrapolation methods.

Vert.Deformation	of Whole Pavement			of Basecourse		
Method*	1	2	3	1	2	3
Segment A						
Load cycles 250k	6.2	5.4	1.8	2.0	1.3	1.1
500k	8.5	6.1	2.0	3.2	1.4	1.1
900k	12.1	6.7	2.2	5.1	1.5	1.2
1000k	**13.0**	**6.9**	**2.2**	5.6	1.5	1.2
Segment B						
Load cycles 250k	12.9	9.7	4.6	8.5	5.3	3.5
500k	20.4	11.5	4.9	14.9	6.5	3.6
900k	32.4	13.3	5.3	25.1	7.8	3.8
1000k	**35.4**	**13.7**	**5.3**	27.6	8.0	3.8
Segment C						
Load cycles 250k	5.6	5.2	2.1	1.0	0.7	0.6
500k	7.3	5.9	2.4	1.5	0.7	0.6
900k	10.0	6.6	2.7	2.3	0.7	0.7
1000k	**10.7**	**6.7**	**2.7**	2.5	0.7	0.7

* Methods:
Method 1 Linear extension (Section 5.2.1)
Method 2 Exponential extension (Section 5.2.2)
Method 3 Combined extrapolation (Section 5.2.3)

Vert. Deformation – vertical deformation

5.3.2 Calculated Deformation Results

The three different methods described in Section 5.2 were used to extrapolate the RLT test data, both in terms of stress and number of load cycles. Tables 5.1, 5.3 and 5.5 show the results of the three extrapolation methods. The stresses in Table 5.6 were used to calculate the permanent strain for the three different methods (same extrapolation method in terms of stress but different method extrapolating for number of load cycles). The permanent strain was then multiplied by the layer depth to obtain a vertical deformation. Appendix F summarises the vertical deformations calculated for each layer and segment for the three RLT extrapolation methods used. Table 5.7 shows the resulting total vertical deformations for the three methods for each of the Segments A, B and C.

The vertical deformation modelling results are compared in Section 6 to those measured in the CAPTIF pavement test.

6. Comparison of RLT & CAPTIF Test Results

6.1 Elastic (Resilient Modulus) Properties

Figure 6.1 shows the resilient modulus for each of the three Materials (A, B and C), calculated using both CAPTIF and RLT test results. The range of results is limited to those determined from CAPTIF-measured stresses and strains. There are clear differences in the resilient moduli derived from measured stresses and strains in the CAPTIF pavement. CAPTIF-derived moduli show that Materials C followed by A, are the best performers. These differences and rankings in material moduli are not mirrored in the results from the RLT tests. Further, the RLT test did not show that Material B with high plastic fines content has the least stiffness, as was shown from the CAPTIF test results.

The lines drawn through the data points in Figure 6.1 are the best-fit lines when plotted in a log-log relationship. The CAPTIF results show the moduli determined from measured vertical stress divided by measured vertical strain. The RLT results relate the moduli with bulk stress.

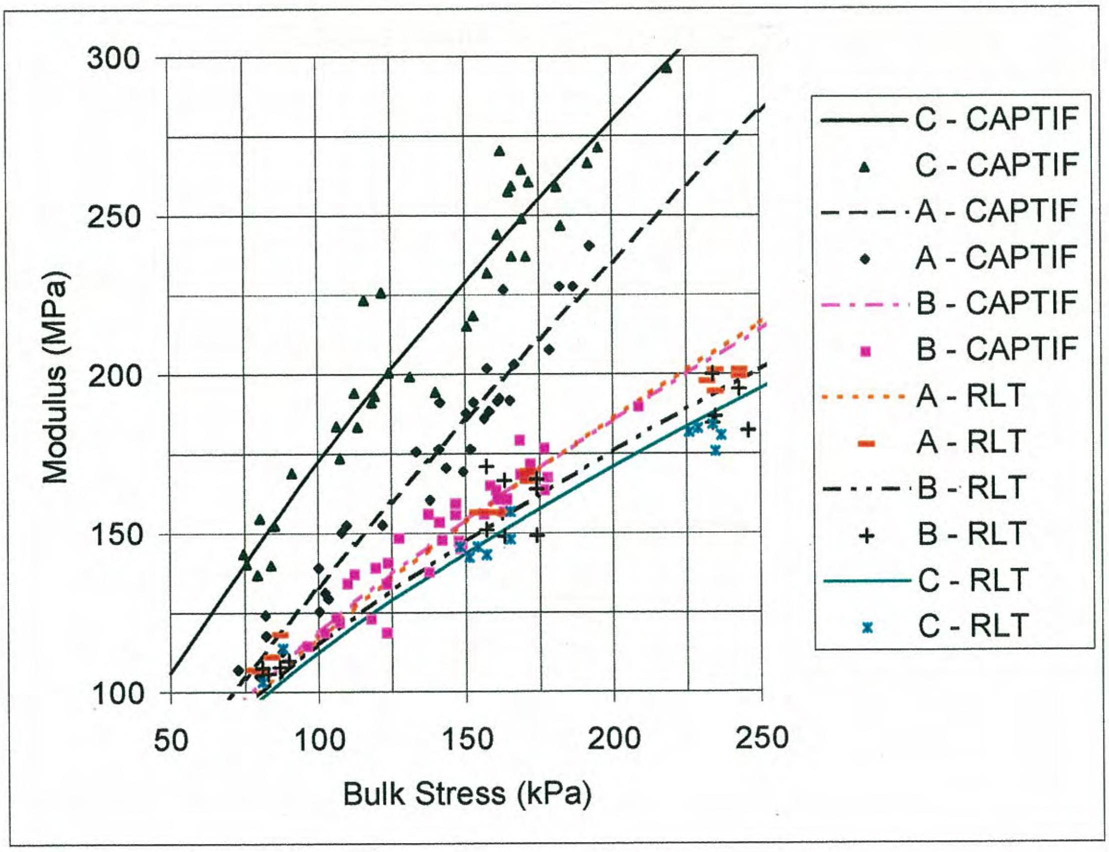


Figure 6.1 **Comparison of resilient moduli determined from CAPTIF and RLT test results.**

The main reason for conducting an RLT test is to determine the resilient properties for use in pavement design. Therefore, the RLT-derived resilient moduli were used in pavement design, and the stresses and strains computed in the pavement model were also compared to those measured. Three different methods of interpreting the RLT-derived moduli for design were possible, one for each pavement modelling approach as described in Section 4.2. Appendix D shows the full results of this analysis, while Table 6.1 summarises the results.

On reviewing the results it is difficult to determine the best method to use for applying the RLT results. Table 6.2 shows the actual measured values for the 40kN/650kPa load of stresses, strains and deflections (loads other than these also show the same trends). It shows that the measured strains in the subgrades for Segments A and B are over twice the value of the computed strains. Further, the strains measured in the subgrades for Segments A and B could not be replicated in initial RLT tests without the specimen failing. However, the measured surface deflections are higher than those computed, which suggests that the modulus assumed for the subgrade should be lower. A lower subgrade modulus for Segments A and B would result in a closer match between the computed and measured strains in the subgrade. The mismatch between RLT-measured strains and those measured in the CAPTIF pavement is being further investigated by one of the authors (B. Steven). In the meantime all the subgrade results for Segments A and B were excluded from the analysis.

Table 6.1 Average ratios of computed to measured pavement responses using three different methods for interpreting RLT data for design.

Layer	**Depth (mm)**	**Computed/Measured Strain** (average ratios for each segment and method)								
		Segment A			**Segment B**			**Segment C**		
		4.2.1	*4.2.2*	*4.2.3*	*4.2.1*	*4.2.2*	*4.2.3*	*4.2.1*	*4.2.2*	*4.2.3*
BC	112.5	1.2	1.3	0.8	1.5	1.6	1.1	1.6	1.7	1.1
BC	187.5	1.6	1.5	1.1	1.8	1.7	1.3	1.7	1.6	1.2
BC	262.5	**1.4**	**1.4**	**1.1**	**1.3**	**1.3**	**1.0**	2.0	2.0	1.6
SG	337.5	0.4	0.4	0.4	0.3	0.3	0.2	**0.9**	**0.9**	**0.8**
SG	412.5	0.3	0.3	0.3	0.4	0.4	0.4	0.7	0.7	0.6
SG	487.5	0.3	0.3	0.2	0.4	0.4	0.4			
SG	562.5	0.4	0.4	0.4	0.5	0.5	0.4	0.4	0.4	0.4
		Computed/Measured Stress								
SG	300	**1.3**	**1.3**	**1.3**	**1.1**	**1.1**	**1.0**	**1.4**	**1.4**	**1.3**
		Computed/Measured Peak Deflection								
Surface	0	**0.6**	**0.6**	**0.5**	**0.7**	**0.7**	**0.6**	**1.1**	**1.1**	**0.9**

Sections 4.2.1 Theoretically rigorous method
4.2.2 AUSTROADS auto-sublayering (RLT moduli from contact stress) method
4.2.3 AUSTROADS auto-sublayering (RLT moduli from bulk stress) method
BC Basecourse; SG Subgrade

Table 6.2 Average values of measured strains, stresses and deflections for the 40kN/650kPa dual-wheel load used on the CAPTIF test pavement.

Layer	Depth (mm)	Segment/ Basecourse Material		
		A	B	C
		Strain (μm/m)		
BC	112.5	827	767	787
BC	187.5	653	660	793
BC	262.5	707	840	580
SG	337.5	2053	3813	1053
SG	412.5	2247	1800	1020
SG	487.5	1907	1353	
SG	562.5	873	947	960
		Stress (kPa)		
SG	300	76	97	77
		Peak Deflection (mm)		
AC	0	1.0	1.0	0.7

Segments A, B, C represent the different basecourse Materials A, B, C respectively
BC, SG, AC represent the position or depth in the pavement cross section
BC Basecourse; SG Subgrade; AC Asphalt concrete

The comparison of computed to measured deflections indicates the accuracy of the design assumptions (and especially the moduli) used for all the materials, including the asphalt and subgrade. Segment C shows the best match for deflections, while the same design assumptions used for Segments A and B gave a poor match in deflections. For design of unbound granular pavements using the current AUSTROADS Pavement Design Guide (1992), a key parameter is the vertical strain at the top of the subgrade. Therefore, when considering the best method for interpreting RLT results for use with the AUSTROADS method, the ratio of computed to measured strains and stresses near or within the top of the subgrade were the key factors (see values highlighted in bold in Table 6.1). The results suggest that the AUSTROADS auto-sublayering (RLT moduli from bulk stress) (Section 4.2.3) is the best method for interpreting RLT results for design. Further, this method is as quick to apply because the auto-sublayering features in the CIRCLY program are utilised.

The computed strains are within 10% of those measured, which suggests that the RLT apparatus is adequate for characterising the resilient properties of the granular materials.

6.2 Permanent Deformation Properties

The RLT permanent deformation test results were extrapolated in terms of both load cycles and stress using three different methods. These extrapolation methods were: linear (Section 5.2.1), exponential (Section 5.2.2), and combined extrapolation (Section 5.2.3). Figure 6.2 shows the results for all three methods (linear, exponential and combined) and also, for comparison, the results of the average measured rutting in the CAPTIF test for each of the three Segments.

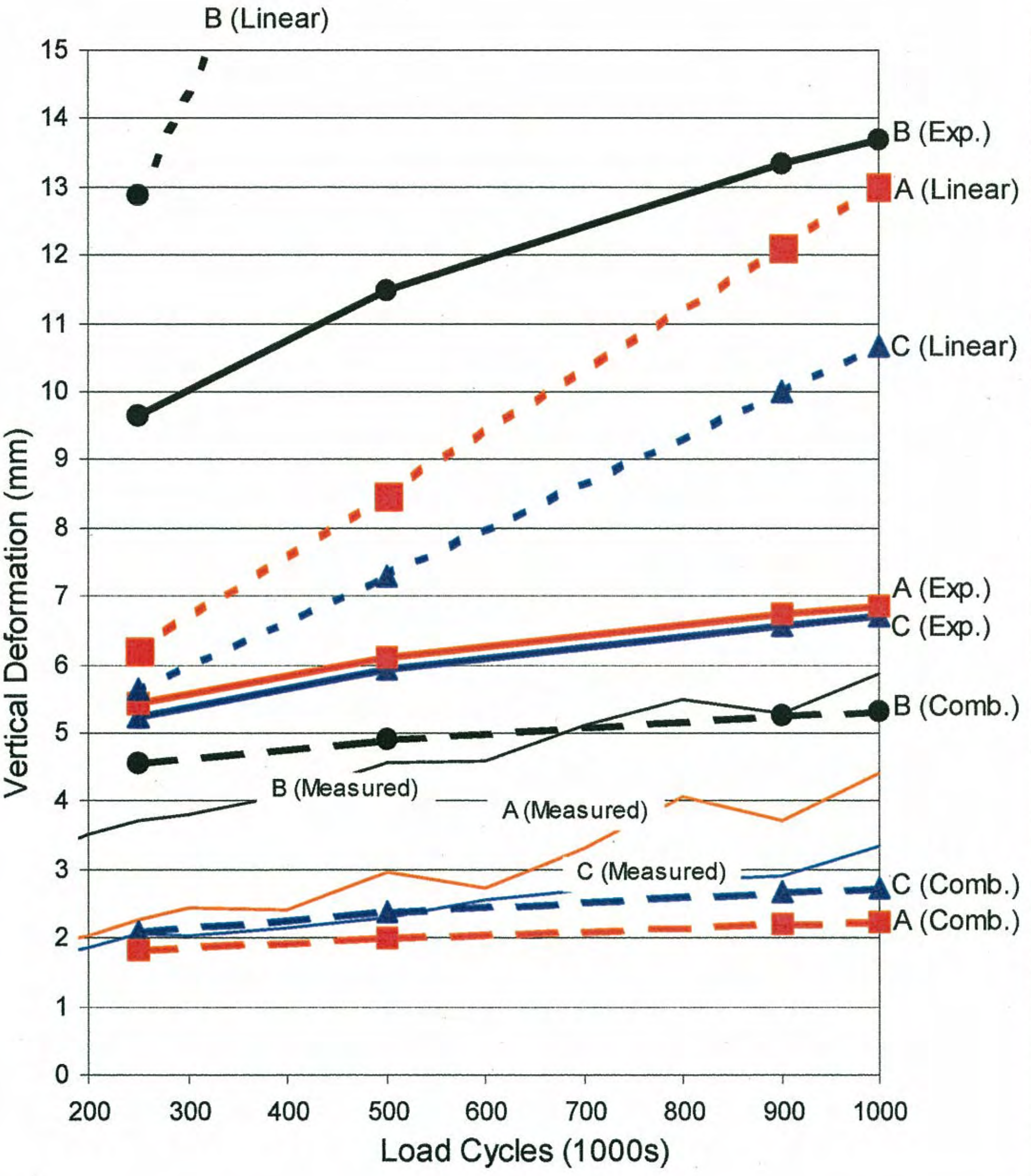


Figure 6.2 Permanent deformation modelling results.

Materials A, B, C in Segments A, B, C were tested by 4 methods:

A, B, C (Linear) – linear method results	----	■, ●, ▲
A, B, C (Exp.) – exponential method results	___	■, ●, ▲
A, B, C (Comb.) – combined method results	_ _ _	■, ●, ▲
A, B, C (Measured) – CAPTIF measured results	____	■, ●, ▲

The linear and exponential methods both predict Segment C to have the least amount of deformation. Segment A is a close second while it is predicted that Segment B will result in significantly greater permanent deformation. This result matches the rutting measured during the CAPTIF test. Further, the result is as expected since both Materials A and C are good quality, clean, crushed aggregate, while Material B was deliberately modified by adding extra fines. Despite the good match in material rankings, the magnitudes in deformation were higher than those measured. The linear method predicted deformations over 3 times those measured, while the exponential method were 1.5 times those measured.

Results from the combined extrapolation method showed the deformation magnitudes were close to those measured. The difference in predicted to measured was less than 1mm for Segments B and C, while the difference for Segment A was less than 2mm. However, the ranking of materials in terms of deformation performance was not the same as from the measured rutting results. Therefore, the linear method appears best for ranking resistance of materials to deformation, while the combined method is best for estimating magnitude of deformation.

7. Unbound Material Evaluation

7.1 Introduction

A key output of this research is the ability to evaluate with confidence the performance of an unbound granular material within a pavement. The methods used to predict rutting (Section 5.3) show that the combined extrapolation method gave the best prediction of rut depth, while the linear method better distinguished the difference in performance of the materials.

A seemingly ideal approach to material evaluation and pavement design is predicting the rut depth from RLT tests. However, the RLT test results are from a specific set of moisture, density and stress conditions, while a pavement experiences a wide range of stresses, density (caused by variations in construction), and moisture conditions. Apart from research projects, possibly only one RLT permanent strain test on a granular material would be carried out. Further, this tested material is typically only the basecourse material, while the subgrade and sub-base materials generally are not tested in the RLT apparatus.

The current method of pavement design for thin-surfaced unbound granular pavements relies on empirically derived thickness design charts and/or a subgrade strain performance criterion. These methods are based on the performance of previous pavements and take account of other factors like environment, maintenance regimes, etc. Therefore, these methods of design should continue and take precedence until transfer functions that can take into account these other factors (such as environment, maintenance regimes, etc.) can be developed for the RLT results. Deformation modelling should continue to be used for comparative purposes when evaluating materials for assessment of performance-based specifications such as Transit New Zealand Specification B/3:1999, *Design and construction of unbound granular pavements*.

The results from the deformation modelling were further analysed, with the view to develop a method of material evaluation in which the results from one RLT test on a basecourse granular material are sufficient for compliance with performance-based specifications such as Transit New Zealand B/3:1999. However, a major limitation is the extrapolation of stress level with permanent strain results. As only two stress levels were measured in this study, an appropriate relationship cannot yet be developed. Further, RLT tests are recommended in conjunction with current research at the University of Nottingham, UK, where the use of the "shakedown" concept to predict performance is being investigated.

7.2 Proposed Method

This proposed method is based on one RLT test for the granular material using the conservative linear extrapolation method (Section 5.2.1).

Further, it is assumed and paramount to this proposed simplistic method that the pavement has been designed using current Transit New Zealand policy (i.e. AUSTROADS 1992).

The review of the permanent deformation results shows that deformation of the pavement is not primarily confined to the top layers, and that deformation is spread throughout the layers (Table 7.1). Therefore, a thick pavement will have more deformation in the granular layers than in those of a thin pavement. To cater for the evaluation of granular materials in different thicknesses of pavement, it is proposed to place a limit on the percentage of deformation relative to the layer thickness.

The limiting percentage chosen was 5% using a linear method of extrapolation. From the results, a 5% deformation in the top layer resulted in approximately 9mm of rutting for the full depth of granular material (or an average of 3% deformation). Further, the limit is based on the conservative assumption that Material B would, for a real road, be rejected for use as a basecourse. Table 7.1 summarises the deformation results for Materials A, B and C using the linear method of extrapolation.

Table 7.1 Deformation prediction results for 1000k load cycles using the linear method of extrapolating RLT data.

Layer	Thickness T(mm)	Deformation Results (D)					
		Material A		Material B		Material C	
		D (mm)	D/T (%)	D (mm)	D/T (%)	D (mm)	D/T (%)
BC1	56	1.9	*3.3*	13.7	*24.3*	0.6	*1.1*
BC2	56	1.4	*2.4*	7.3	*13.0*	0.6	*1.0*
BC3	56	1.0	*1.7*	3.6	*6.4*	0.5	*0.9*
BC4	56	0.7	*1.3*	1.9	*3.3*	0.4	*0.8*
BC5	56	0.6	*1.0*	1.1	*1.9*	0.4	*0.7*
Subtotal	**282**	**5.6**	*1.9*	**27.6**	*9.8*	**2.5**	*0.9*
SG1	100	1.7	*1.7*	1.8	*1.8*	1.9	*1.9*
SG2	150	1.6	*1.1*	1.7	*1.2*	1.8	*1.2*
SG3	200	1.4	*0.7*	1.5	*0.7*	1.5	*0.8*
SG4	300	1.4	*0.5*	1.4	*0.5*	1.5	*0.5*
SG5	450	1.4	*0.3*	1.4	*0.3*	1.4	*0.3*
Subtotal	**1200**	**7.4**	*0.6*	**7.8**	*0.7*	**8.1**	*0.7*
TOTAL	**(mm)**	**13.0**		**35.4**		**10.6**	
%BC		*43*		*78*		*24*	
%SG		*57*		*22*		*76*	

The procedure proposed consists of the following sequence of steps.

Step 1: Design the pavement as per current policy (i.e. AUSTROADS 1992) using CIRCLY, and compute the stresses in the x, y and z directions directly under the dual wheel load that is approximated as a singular circular patch, at depth increments of 25mm within the granular material.

Step 2: Determine the worst set of stress conditions (i.e. in y and z directions) from the stresses computed in Step 1.

Step 3: Undertake an RLT permanent strain test for 50,000 load cycles at the worst set of stress conditions, as determined from Steps 1 and 2, and the moisture content of the material is the highest moisture content that it will experience in a pavement.

Step 4: If the sample tested as per step 3 fails before the end of the test, or the resulting permanent deformation when extrapolated linearly (assuming that a straight line between the permanent deformation results at 40k and 50k load cycles) for the design load is >5%, then start again at Step 1 where a re-design (e.g. increase cover depth) is required. As well carry out another RLT test at the new set of less severe stresses that have been determined in the repeat of Step 1.

Step 5: If sample passes step 4, then the pavement design and material are suitable for the design load. The permanent strain extrapolated linearly for the design load can be used for comparison with other materials.

It is also recommended that a database of RLT results is kept. This will allow comparison between the results to enable a judgement on the appropriate use of the material (e.g. base or sub-base).

7.3 RLT Test Conditions

The procedure for evaluating materials relies on choosing the set of stress conditions that represents the worst conditions the material will experience within a pavement. Linear elastic analysis reports negative horizontal or tension stresses within the granular material (Table 7.2). Thus, based on the Mohr-Coulomb criteria, these locations with negative horizontal stresses would be considered as the worst stress conditions, and a shear failure would result. But this does not occur in a pavement, and finite element analysis is needed to determine accurately the principal stresses spatially within a pavement.

Stresses computed from a CIRCLY analysis for an unbound granular pavement surfaced with a chipseal are listed in Table 7.2. Common geotechnical convention is to report the principal stresses in p–q[1] stress space. Stresses in the horizontal direction less than zero were assumed to be zero in the calculation of the p-q stresses from the CIRCLY analysis. Figure 7.1 shows a plot in p-q space of the CIRCLY-computed stresses and, for comparison, yield strengths in tri-axial shear failure tests on a good quality Belfast, UK, crushed rock aggregate have been included.

The results in the p-q stress plot indicate that shear failure would be likely for the Belfast aggregate at RLT test stresses computed from CIRCLY, at depths below 100mm. Points close to the surface have high and positive stresses in both the vertical and horizontal directions. The result is a stress condition well away from the yield line, as shown by the points with high values of p in Figure 7.1.

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[1] p average of principal stresses; q difference between major and minor principal stresses

Table 7.2 Principal stresses directly under wheel load at 25mm incremental depths obtained from CIRCLY analysis.

Z (mm)	σ_1(x)	σ_2 (y)	σ_3 (z)	p^1	q^2	q/p
0	635	635	750	673	115	0.2
25	430	430	741	534	311	0.6
50	244	244	706	398	462	1.2
100	22	22	554	199	532	2.7
125	-6	-6	472	157	472	3
150	-40	-40	395	132	395	3
175	-70	-70	330	110	330	3
200	-26	-26	277	92	277	3
225	-37	-37	234	78	234	3
250	-18	-18	201	67	201	3
275	-21	-21	174	58	174	3
300	-24	-24	152	51	152	3

1 $p = 1/3(\sigma_1 + \sigma_2 + \sigma_3)$ where σ_1 and σ_2 are >0 otherwise $p=1/3(\sigma_3)$

2 $q = \sigma_3 - \sigma_1$ where σ_1 and σ_2 are >0 otherwise $q= \sigma_3$. Z (z) = depth (mm)

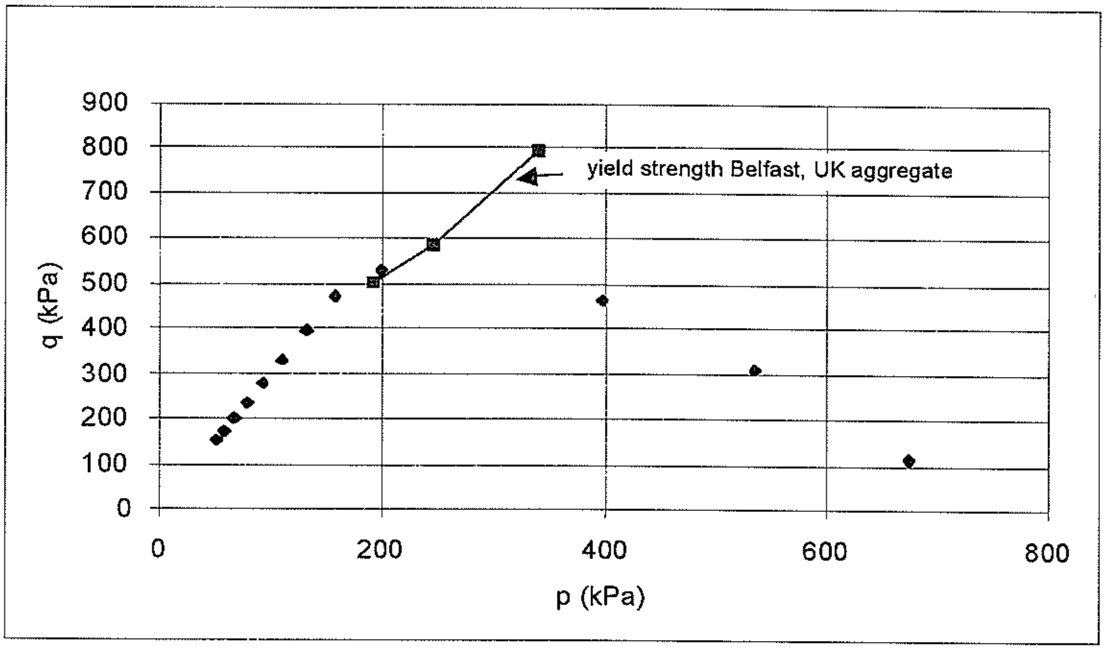

Figure 7.1 Principal stresses from CIRCLY analysis, plotted in p-q stress space. (p = average principal stress; q = difference in major and minor principal stresses.)

Ullidtz (1987) reports that there are limitations in linear elastic analysis when reporting stresses for the purpose of assessing shear failure risk. However, without the stress values computed from a finite element model, the worst stress condition is difficult to determine with confidence. Further, residual stresses adding to the confinement of granular materials are not included in the linear elastic analysis.

RLT tests for this project at the worst conditions were conducted at confining pressures of 50kPa and cyclic vertical load (q) of 550kPa. These test conditions seemed to result in an adequate prediction of pavement rutting. Also, assuming that the residual horizontal stress in the pavement is 50kPa, the following is recommended for determining the worst test stress:

- cyclic vertical load in the RLT apparatus = maximum *q* (difference between major and minor stresses) computed from CIRCLY, and is usually located at a depth of approximately 100mm;
- constant confining pressure = 50kPa.

For the computed stresses shown in Table 7.2 based on the above requirements, the material should be tested at a cyclic vertical load of 532kPa at a constant confining pressure of 50kPa.

The steps described in the material evaluation method could involve several expensive RLT tests to find a suitable stress level for a marginal quality material. Current research at the University of Nottingham, UK. suggests that a multi-stage test on one sample maybe suitable as follows:

- An RLT permanent strain test is conducted on one sample for 50,000 load cycles, at a cyclic vertical load of 300kPa, at a constant confining pressure of 50kPa.
- At the end of the first test, a new test at a higher cyclic vertical load (e.g. an increase of 50kPa to 350kPa) is conducted for another 50,000 load cycles.
- If the sample survives, a new test at an incremental higher vertical load is conducted.
- The result is deformation curves for the range of stress conditions, and the strain values should be the total cumulative strain resulting after each test stage.

Moisture content was measured in-situ using Time Domain Reflectometery equipment as part of a European-funded project (COURAGE 1999). The most severe moisture conditions encountered were those recorded in Iceland, where continuous recording clearly showed the fluctuations in moisture content which take place in the base and sub-base layers, especially between the months of January and May each year. The gravimetric moisture content ranged from a minimum value of 6.1% (the optimum – 4.7%) in late September 1998, to a maximum of 14.1% (the optimum + 3.3%) during the spring thaw in April 1999. Based on this data, a conservative moisture content for RLT testing to model uncracked pavements would be 120%.

8. Discussion

The purpose of this project was to validate the use of the RLT apparatus for determining the resilient properties (i.e. resilient modulus) and permanent deformation properties. In order to validate the RLT-derived resilient moduli two methods were used: direct comparison with moduli computed from measured stress and strain in the CAPTIF test pavement; and in mechanistic design by comparing the computed values, based upon RLT input data, to the measured pavement response.

Permanent deformation properties obtained from the RLT apparatus were validated by extrapolating the data and summing the deformations in each layer. Non-linearity with stress was only partially approximated by dividing the granular material into a number of different layers.

8.1 Elastic (Resilient Modulus) Properties

8.1.1 Direct Validation of RLT-Derived Moduli

Material B was the same as Material A but had been deliberately modified by adding more fines. Material B was expected to be the poorest performer in both resilient and deformation properties, and this was shown to be the case from the CAPTIF pavement test results. Moduli from measured stresses and strains in the pavement clearly showed Material B to have the least stiffness. On the other hand however, the resilient modulus test obtained from the RLT apparatus did not show Material B to have the least stiffness.

The possibly higher moisture content in the CAPTIF test track was likely to have had an effect on Material B with its higher plastic fines content, which means it is affected by small changes in moisture content and therefore its strength is affected. Resilient modulus from the RLT test alone cannot be used to rank the expected performance of materials in a pavement (Thom & Brown 1989).

The resilient moduli computed from measured strains and stresses for all three materials were higher than the RLT-derived moduli. The assumption derived from linear elastic analysis, that the bulk stress directly under the load is equal to the vertical stress (as horizontal stresses are nil), is incorrect within the pavement. This is due to the locked-in stresses caused by compaction of the granular layer, which results in an increase in confining stress, and thus bulk stress (which is a sum of the principle stresses in the vertical and horizontal directions).

Locked-in stresses within the granular pavement result in added confinement, which will increase the stiffness of the granular material. Therefore, the use of RLT-derived moduli in a linear elastic analysis, where locked-in stresses are not considered, gives conservative results The magnitude of the locked-in stresses is unknown but an increase of bulk stress of only 50kPa for the CAPTIF-derived moduli will result in a better match with the RLT-derived moduli.

However, the match for Material B (with high plastic fines) is poor, because of the likely higher moisture content in the CAPTIF pavement.

8.1.2 Validation of RLT Moduli using Mechanistic Design

From the results shown in Table 6.1, the conclusion is that the use of RLT moduli in mechanistic design will result in an adequate prediction of stresses and strains. However, the RLT-derived moduli are approximately the same for the three materials. Therefore, the computed stresses and strains for each material are similar. The variations in the ratio between computed and measured responses are a result of the variations in measured stresses and strains within the pavement, rather than in differences in computed values. Table 8.1 shows the computed strains, stresses and peak deflections for the three methods (see Sections 4.2.1, 4.2.2, 4.2.3) used to interpret the RLT data.

Table 8.1 Computed pavement responses using RLT-derived moduli on centreline of loading.

Layer	Depth (mm)	Segment A			Segment B			Segment C		
		4.2.1	*4.2.2*	*4.2.3*	*4.2.1*	*4.2.2*	*4.2.3*	*4.2.1*	*4.2.2*	*4.2.3*
		Computed Strain (μ/m)								
BC	112.5	968	1047	626	1157	1256	821	1281	1364	880
BC	187.5	1020	996	691	1157	1141	845	1326	1288	929
BC	262.5	1010	983	764	1096	1076	872	1188	1132	925
SG	337.5	880	890	821	1071	1053	944	973	973	893
SG	412.5	674	674	621	729	729	686	714	719	651
SG	487.5	508	518	445	554	561	522			
SG	562.5	387	387	358	451	455	424	416	416	398
		Computed Stress (kPa)								
SG	300	**98**	**99**	**99**	**106**	**107**	**98**	**108**	**109**	**99**
		Computed Peak Deflection (mm)								
Surface	0	**0.62**	**0.62**	**0.49**	**0.70**	**0.70**	**0.58**	**0.70**	**0.70**	**0.57**

Section 4.2.1 Theoretically rigorous method
Section 4.2.2 AUSTROADS auto-sublayering (RLT moduli from contact stress) method
Section 4.2.3 AUSTROADS auto-sublayering (RLT moduli from bulk stress) method
BC – basecourse; SG – subgrade

Overall, there is only a 10% difference irrespective of methods used to interpret RLT data. Therefore as the strain is stress divided by Modulus, and if the same subgrade modulus is used, the subgrade strain also would vary by only 10% between the methods and materials used. Segments B and C show an almost identical response in terms of computed stresses and deflections This result further highlights the fact that the RLT resilient modulus test showed very little difference in stiffness between Materials B (high plastic fines) and C (good quality). The current method of design (AUSTROADS 1992) using the subgrade strain to predict life, would not predict a difference in the performance between the three materials (because subgrade strain remains the same if the same subgrade modulus were used).

This result shows the importance that the permanent strain properties of the granular layers have on the pavement life. Future design methods of unbound granular pavements should move towards a rut-prediction approach based on RLT permanent strain results.

From the results comparing computed to measured pavement response (Section 4.3), it was concluded that the best method to use RLT-derived moduli is the AUSTROADS auto-sublayering (RLT moduli from bulk stress) (Section 4.2.3). Using this method the computed stress in the subgrade layer is nearly exactly the same for the three different materials (A = 99kPa, B = 98kPa, and C = 99kPa).

Also the use of the AUSTROADS auto-sublayering feature in CIRCLY requires only the resilient properties of the top granular layer. The range of bulk stresses in the top granular layer is small and therefore RLT resilient tests could be limited to this range of stresses. However, no real time saving is made in reducing the number of test stresses as most of the time is taken in sample preparation and not in testing.

Further RLT resilient modulus tests should be undertaken at different test conditions, which should primarily vary the moisture content and the drainage conditions. Test conditions which show the difference in stiffness between the materials are best.

8.2 Permanent Deformation Properties

8.2.1 Results

The permanent strain tests obtained from the RLT apparatus clearly showed that Material B had the highest deformation. This result matches expectation and the rutting results in the CAPTIF test. Further, the RLT results were extrapolated in both load cycles and stress using different methods to predict the surface rutting of the pavement. The combined extrapolation method resulted in the closest match in terms of magnitude of deformation. However, the exponential and linear methods showed the correct ranking of materials in terms of deformation performance.

There is potential to use the permanent deformation modelling methods for material evaluation. This allows the decision to discard a material (or increase its cover), based on a prediction of resulting rut depth caused by the design traffic, although the use of the exponential and combined methods would have shown that all Materials A, B and C are acceptable (rut depths <20mm). This also proved to be the case in the CAPTIF test. However, in a real road where the materials are not protected from moisture, this result may not be the case. For example, Material B with the high plastic fines content, if used as a basecourse in a highway, would be expected to fail early by other mechanisms such as catastrophic shear failure. Ideally, this CAPTIF experiment should be replicated on an actual highway as a long-term study of performance using the three different materials.

A clearer distinction of material deformation performance resulted when using the linear method. After 1 million wheel loads, the linear method predicted rut depths of 11, 13 and 35mm for Segments and Materials C, A and B respectively. Material B with the high plastic fines content was expected to perform poorly (more than 20mm rut depth), while a rut depth of less than 10mm, based on previous CAPTIF tests, was estimated for the Segments with Materials A and C (good quality materials). At this stage, adopting a conservative approach for evaluating the suitability of an unbound granular material as a base or sub-base material would seem appropriate, and the linear extrapolation method should be used.

8.2.2 Limitations

The methods used for predicting rut depth rely on extrapolating permanent strain results from RLT tests. Extrapolating for the higher load cycles seems straightforward, as it is a simple extension of the permanent deformation versus load cycle curve. Extending the deformation curve is also generally accepted, as usually after 50,000 load cycles a clear pattern in deformation results has emerged.

Currently, extrapolating RLT data to determine deformations at other stress levels is based on the principle vertical stress. This method of extrapolation only considers the stress in one direction. However, the combination of vertical and horizontal stresses affects the permanent deformation results of granular materials. The horizontal confining stresses have a significant effect on deformation resistance of a granular material. The effect is similar to the effect on shear strength commonly defined by the classic Mohr-Coulomb criteria in that, as the horizontal or confining stress increases, the shear strength increases for a granular material.

Granular materials are highly non-linear with respect to stress. This non-linearity relationship is commonly different for each material, and therefore, the assumption of one relationship fitted to only two RLT tests at different stress levels could result in large errors.

A key factor working against the ability to predict the rutting of a road from only a limited number of RLT permanent strain tests is the environment. Moisture entering the pavement can significantly affect the strength, permanent deformation resistance, and modulus of the materials. The result could be shallow shear failures.

To evaluate a material's suitability for use as a base or sub-base material requires a carefully designed range of horizontal and vertical stress combinations. Ideally the tests should then be repeated at other moisture contents to determine the climatic effect. Further, finite element modelling using a non-linear elastic model and a limited tensile strength for the granular material is required to accurately determine the principle stresses occurring spatially within the pavement. This is to determine the combination and location of stresses that will have the *worst* effect on the deformation of a granular material. The location having the worst effect is likely to be not directly beneath the wheel load but to one side, as the classical bearing capacity failure of a wedge pushing into the soil would suggest.

A linear elastic analysis will not accurately predict the principal stresses spatially in a granular material, because a linear elastic analysis results in a large part of the pavement having negative principal stresses in the horizontal directions.

The Mohr-Coulomb criteria for a granular material will predict shear failure at these points of negative horizontal stresses. However, negative horizontal stresses cannot occur in a real pavement as a granular material cannot be in tension.

Current research at the University of Nottingham, UK, is investigating the full range of stresses affecting permanent deformation. In addition, finite element modelling will be undertaken to more accurately predict stresses within a pavement. To add to this study further RLT tests on the materials used in CAPTIF will be suggested. After such testing, a methodology for the evaluation of the performance of granular materials could then be established with more confidence.

9. Conclusions

Conclusions of this research report are as follows:

- Resilient moduli, derived directly from measured stresses and strains in the CAPTIF pavement, showed clear differences between Materials A, B and C. Material C (Australian crushed rock) had the highest moduli, followed closely by Material A (crushed rock), while Material B (crushed rock with high plastic fines) had significantly lower moduli.
- RLT tests on the three materials showed little differences in moduli values. Material A had the highest moduli, followed closely by Materials B and C.
- RLT-derived moduli were lower than those determined from measured stresses and strains in the CAPTIF test pavement.
- The use of RLT-derived moduli in mechanistic pavement design using CIRCLY (a multi-layered linear elastic program) resulted in stresses and strains at critical locations (i.e. near the top of the subgrade) close to those measured in the CAPTIF pavement. The method using the AUSTROADS auto-sublayering feature and the RLT-derived moduli appropriate to the bulk stress for the top layer, produced the closest match between computed and measured pavement stresses.
- Computed stresses on top of the subgrade for three different methods of using RLT-derived moduli and the three Segments and Materials (A, B, and C) showed very little difference in results. This suggests that subgrade stress is not sensitive to the moduli of granular materials when using the currently available AUSTROADS 1992 design process.
- Permanent deformation modelling showed the linear and exponential methods of extrapolating RLT permanent strain results to have the same ranking of material deformation resistance as measured in the CAPTIF pavement test. Material and Segment C had the least amount of rutting, followed closely by Material and Segment A, and that deformation in Material and Segment B was significantly different.
- The combined extrapolation method of predicting deformation resulted in rut depth prediction within 2mm of those measured at the CAPTIF test. However the ranking in material deformation resistance was not the same.
- The linear method of predicting deformation showed the greatest difference in the magnitude of deformations between the three materials.
- Prediction of stresses within a pavement using linear elastic analysis results in tensile stresses within the granular material. This causes difficulties when determining the combination of vertical and horizontal stresses that has the most detrimental effect on the granular material for use in the RLT permanent strain test.

10. Recommendations

The following actions are recommended:

- The results of this project were from controlled environmental conditions, both in the RLT test and the CAPTIF pavement, and therefore should be used cautiously when applied to pavements in the field.

- Further RLT permanent strain tests should be conducted at a range of stress conditions and moisture contents to determine the effect of these variables. These further tests should be in conjunction with research currently being conducted at the University of Nottingham, UK.

- Transfer functions for the RLT results should be developed to take into account factors such as environment, maintenance regimes, etc.

- Finite element modelling combined with a determination of residual stresses of a thin-surfaced unbound granular pavement should be conducted to determine the stresses within the granular material. This is to aid in determining the appropriate stress conditions for the RLT permanent strain test.

- The finite element modelling should be combined with a thorough literature review of the topic of estimating stresses within a granular material.

- The current AUSTROADS design method should continue to be used and to take precedence until transfer functions can be developed for the RLT results, that take into account factors such as environment, maintenance regimes, etc.

- Deformation modelling should be used for comparative purposes when evaluating materials in performance-based specifications such as Transit New Zealand Specification B/3:1999, *Design and Construction of Unbound Granular Pavements*.

- Further accelerated loading tests should be undertaken at CAPTIF with the following objectives:
    - measurement of stress and strain distributions in different pavement thicknesses and materials,
    - calibrating Finite Element Models,
    - development of RLT transfer functions,
    - measurement of locked-in stresses and strains at different depths.

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Appendix A

Loadman portable falling weight deflectometer results obtained during pavement construction at CAPTIF

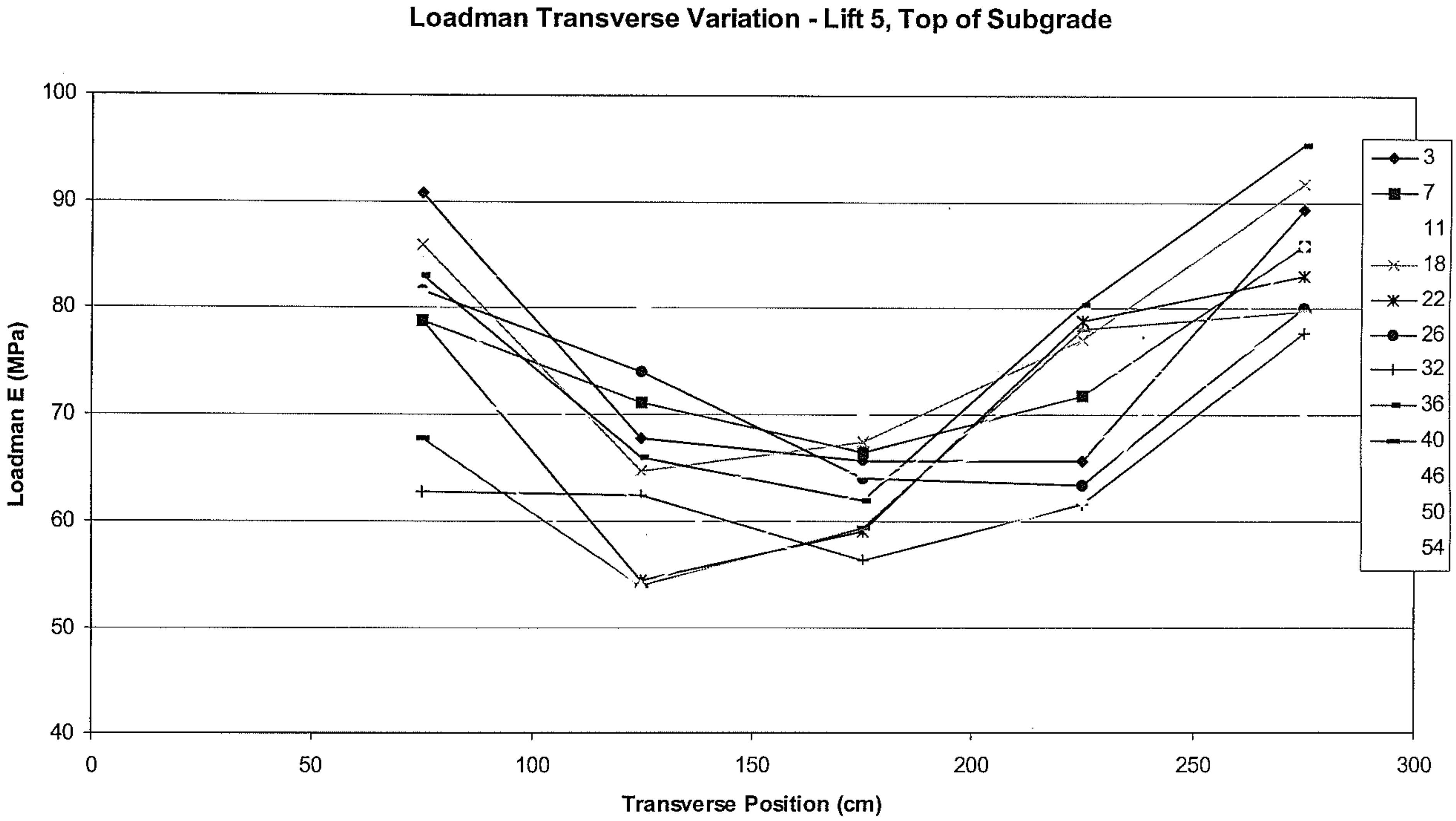


Figure A1 - Loadman isotropic modulus results for top of subgrade (NB: the legend represent station numbers).

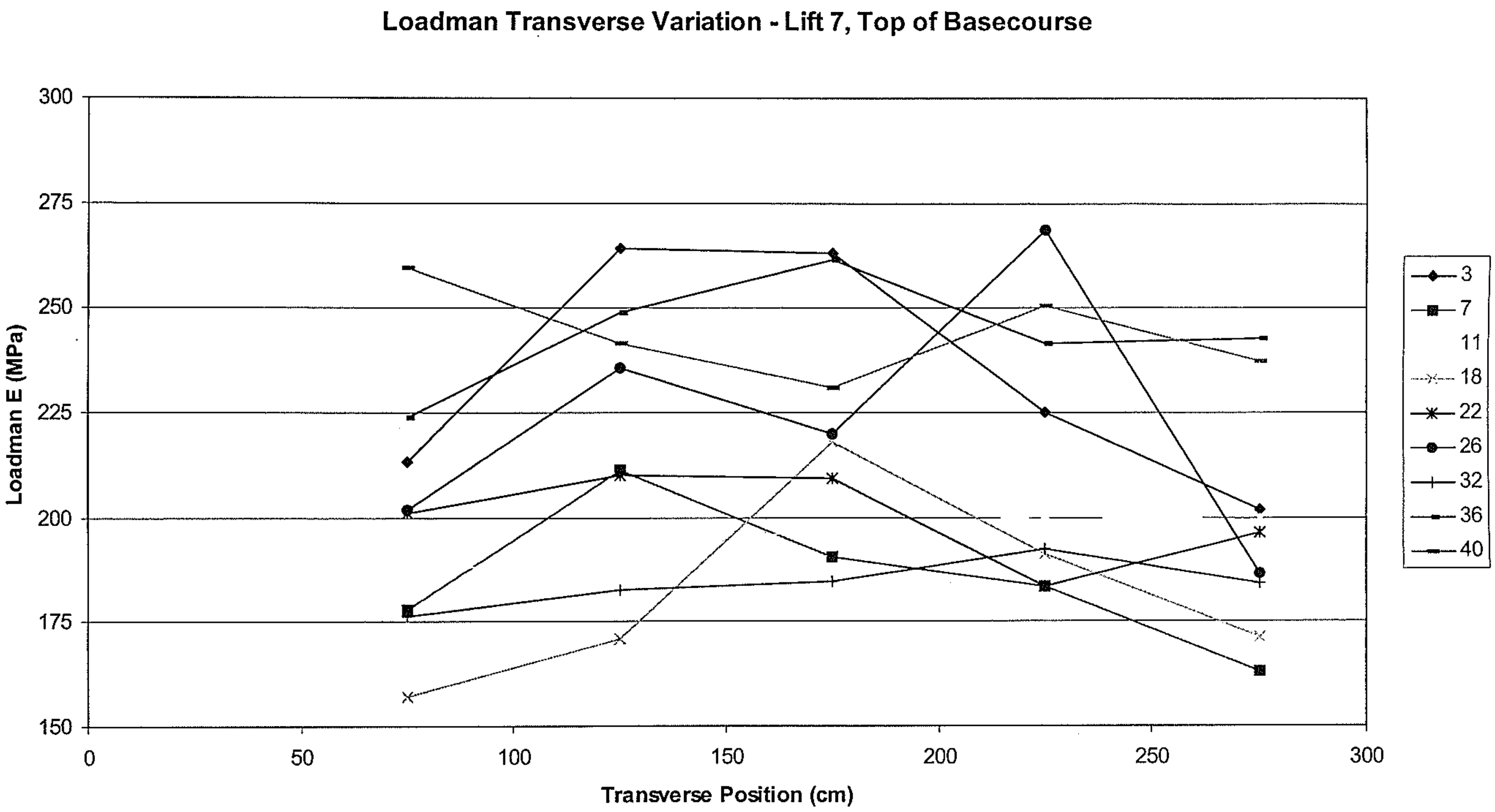


Figure A1 - Loadman isotropic modulus results for top of the unbound granular basecourse (NB: the legend represent station numbers).

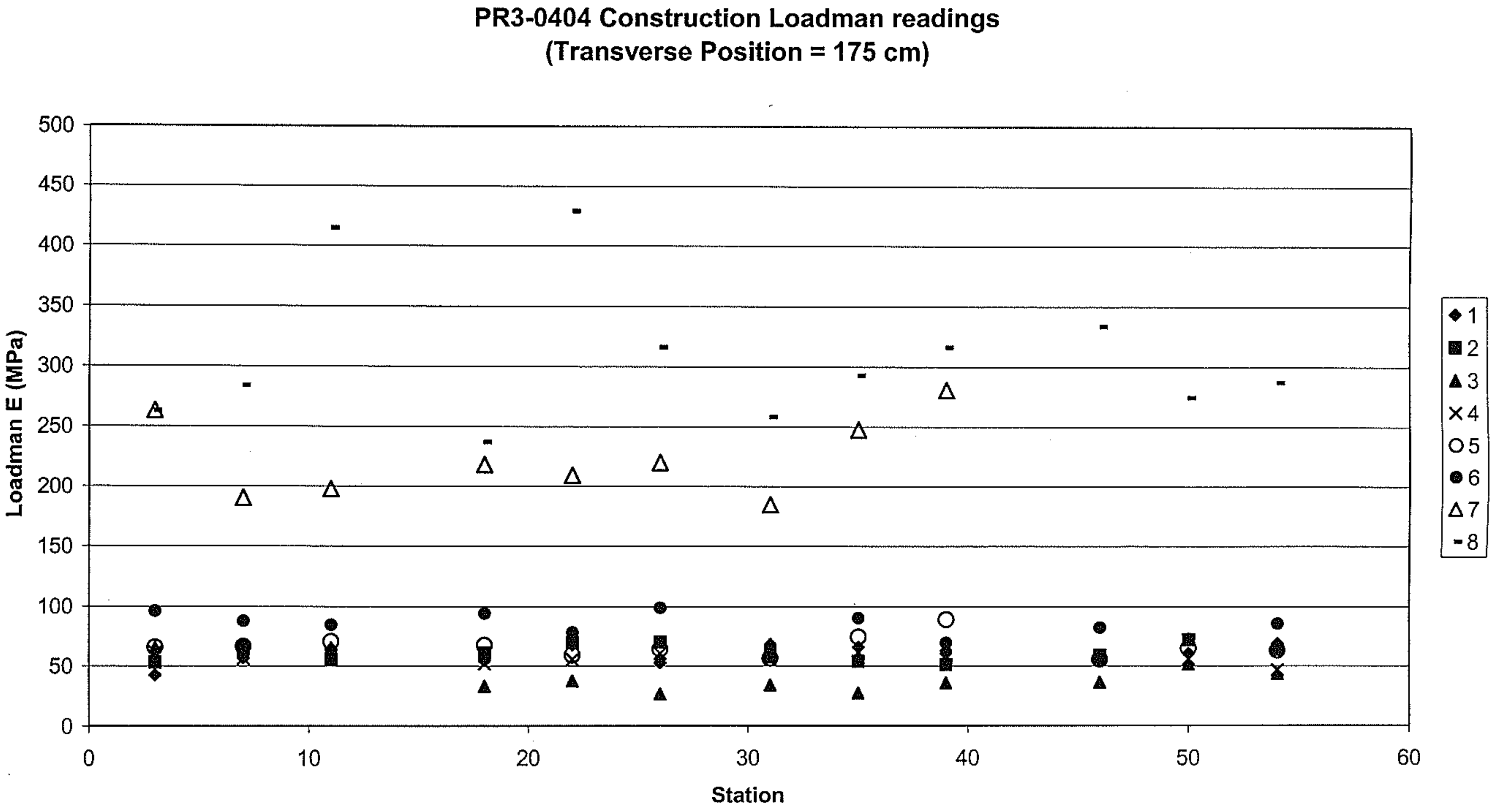


Figure A2 - Summary of Loadman isotropic moduli as each pavement layer constructed (NB: legend represents lift number where: 1 to 5 are subgrade layers; 6 and 7 granular layers; and lift 8 is top of asphalt surface).

Appendix B

Measured Stresses & Strains for a Range of Tyre Types, Loads & Speeds during CAPTIF Pavement Testing

Table B 1 - Measured pavement response in CAPTIF Segment A.

	Measured Vertical Strain and Stress in CAPTIF Segment A						
Load(kN)/Stress(kPa):	**40/650**	**40/750**	**50/750**	**60/750**	**40/850**	**50/850**	**60/850**
6km/h							
Depth:112.5	880	880	980	1000	900	920	1040
187.5	600	720	680	800	620	740	820
262.5	720	780	760	860	720	800	880
337.5	2160	2240	2560	2880	2320	2580	3080
412.5	2400	2500	2780	3260	2500	2820	3440
487.5	2000	2100	2340	2860	2060	2400	3020
562.5	920	1000	1140	1400	960	1160	1480
20km/h							
Depth:112.5	800	820	940	1000	800	880	1020
187.5	660	740	740	760	680	740	840
262.5	700	760	800	820	720	800	860
337.5	2040	2060	2640	2960	1980	2480	3160
412.5	2200	2120	2900	3340	2160	2660	3620
487.5	1860	1780	2460	2980	1820	2280	3220
562.5	860	860	1180	1440	840	1060	1580
45km/h							
Depth:112.5	800	760	960	940	740	840	980
187.5	700	720	820	760	700	760	840
262.5	700	720	800	800	680	780	840
337.5	1960	1940	2780	2720	1940	2500	3120
412.5	2140	2020	2980	3000	2020	2740	3500
487.5	1860	1720	2560	2660	1720	2320	3100
562.5	840	780	1200	1280	780	1080	1520
Stress (300mm)							
6km/h	96	77	117	133	95	124	131
20km/h	72	70	88	146	88	91	145
45km/h	61	61	107	134	64	90	142
Peak Deflection – average of 2 stations over instruments for load/stress = 40kN/550kPa (i.e. standard FWD load)							
0k (Defl)	1.18	1.18	1.18	1.18	1.18	1.18	1.18
FWD_30k	0.95	0.95	0.95	0.95	0.95	0.95	0.95
FWD_200k	0.99	0.99	0.99	0.99	0.99	0.99	0.99
FWD_1000k	1.03	1.03	1.03	1.03	1.03	1.03	1.03

Table B 2 - Measured pavement response in CAPTIF Segment B.

	Measured Vertical Strain and Stress in CAPTIF Segment B						
Load(kN)/Stress(kPa):	**40/650**	**40/750**	**50/750**	**60/750**	**40/850**	**50/850**	**60/850**
6km/h							
Depth:112.5	780	740	860	780	800	900	860
187.5	660	700	740	740	660	800	800
262.5	820	860	880	980	820	920	1000
337.5	3800	3700	4180	4560	3880	4200	4760
412.5	1740	1780	1960	2300	1760	2080	2400
487.5	1260	1320	1440	1740	1260	1580	1780
562.5	880	940	1000	1180	900	1080	1220
20km/h							
Depth:112.5	760	740	820	840	800	820	860
187.5	640	700	740	760	720	740	780
262.5	840	880	940	1000	860	960	1000
337.5	3740	3700	4200	4560	3940	4400	4640
412.5	1760	1820	2120	2320	1880	2200	2320
487.5	1340	1320	1580	1720	1420	1640	1760
562.5	920	920	1140	1220	960	1120	1220
45km/h							
Depth:112.5	760	800	820	800	800	840	860
187.5	680	720	720	720	700	760	740
262.5	860	920	920	940	880	960	1000
337.5	3900	4020	4140	4360	4040	4360	4620
412.5	1900	1940	2040	2080	1980	2180	2320
487.5	1460	1480	1560	1600	1500	1640	1760
562.5	1040	1040	1080	1120	1060	1160	1240
Stress (300mm)							
6km/h	97	92	119	139	96	123	140
20km/h	83	93	127	149	89	103	147
45km/h	110	107	127	146	108	138	154
Peak Deflection – average of 2 stations over instruments for load/stress = 40kN/550kPa (i.e. standard FWD load)							
0k (Defl)	1.05	1.05	1.05	1.05	1.05	1.05	1.05
FWD_30k	0.84	0.84	0.84	0.84	0.84	0.84	0.84
FWD_200k	1.00	1.00	1.00	1.00	1.00	1.00	1.00
FWD_1000k	0.99	0.99	0.99	0.99	0.99	0.99	0.99

Table B 3 - Measured pavement response in CAPTIF Segment C.

	Measured Vertical Strain and Stress in CAPTIF Segment C						
Load(kN)/Stress(kPa):	**40/650**	**40/750**	**50/750**	**60/750**	**40/850**	**50/850**	**60/850**
6km/h							
Depth:112.5	740	760	720	840	720	820	860
187.5	740	740	740	820	740	820	860
262.5	620	540	540	600	620	620	640
337.5	1120	980	1180	1260	1140	1200	1320
412.5	940	1000	1040	1240	960	1180	1280
487.5	rejected	rejected	rejected	rejected	rejected	rejected	rejected
562.5	880	980	960	1240	880	1120	1260
20km/h							
Depth:112.5	760	760	820	840	760	820	840
187.5	780	740	800	820	800	800	860
262.5	520	540	580	660	560	580	640
337.5	1060	1160	1280	1400	1020	1360	1460
412.5	1080	1100	1260	1380	980	1320	1460
487.5	rejected	rejected	rejected	rejected	rejected	rejected	rejected
562.5	1000	1000	1160	1400	940	1240	1420
45km/h							
Depth:112.5	860	760	780	820	780	800	820
187.5	860	740	800	760	780	800	820
262.5	600	520	620	640	580	620	660
337.5	980	980	1320	1320	880	1300	1440
412.5	1040	940	1280	1320	880	1260	1400
487.5	rejected	rejected	rejected	rejected	rejected	rejected	rejected
562.5	1000	880	1220	1360	840	1180	1400
Stress (300mm)							
6km/h	91	77	103	137	100	101	140
20km/h	68	64	90	136	72	95	139
45km/h	71	63	105	143	67	96	145
Peak Deflection – average of 2 stations over instruments for load/stress = 40kN/550kPa (i.e. standard FWD load)							
0k (Defl)	0.69	0.69	0.69	0.69	0.69	0.69	0.69
FWD_30k	0.65	0.65	0.65	0.65	0.65	0.65	0.65
FWD_200k	0.69	0.69	0.69	0.69	0.69	0.69	0.69
FWD_1000k	0.58	0.58	0.58	0.58	0.58	0.58	0.58

Appendix C

Moduli Calculated from Measured Stresses & Strains for a Range of Tyre Types, Loads & Speeds during CAPTIF Pavement Testing

Table C 1 - Moduli from measured stresses and strain in the pavement for Material A.

Moduli from Measured Stress and Strain for Material A (clean crushed rock)							
Tyre	Weight (kN)	Pressure (kPa)	Speed (km/h)	262.5 – strain (10^{-6}) measured	300 - stress (kPa) measured	262.5 - stress (kPa) calc	Modulus, E (MPa)
11R22.5	40	750	45	720	61	70	97
11R22.5	40	650	45	700	61	70	100
11R22.5	40	850	45	680	64	73	107
11R22.5	40	750	20	760	70	80	105
11R22.5	40	800	6	660	72	82	124
11R22.5	40	650	20	700	72	82	118
11R22.5	40	750	6	780	77	88	113
11R22.5	40	850	20	720	88	100	139
11R22.5	50	750	20	800	88	100	125
11R22.5	50	850	45	780	90	102	131
11R22.5	50	850	20	800	91	104	129
11R22.5	40	850	6	720	95	108	150
11R22.5	40	650	6	720	96	110	153
11R22.5	50	750	45	800	107	122	153
11R22.5	50	750	6	760	117	133	176
Super Single	40	750	6	860	121	138	161
11R22.5	50	850	6	800	124	141	176
Super Single	50	750	20	740	124	141	191
Super Single	40	850	6	840	126	143	171
11R22.5	60	850	6	880	131	149	169
Super Single	40	850	45	800	132	150	188
11R22.5	60	750	6	860	133	152	176
11R22.5	60	750	45	800	134	153	191
Super Single	40	750	45	840	137	156	186
Super Single	50	750	6	780	138	157	202
Super Single	40	850	20	840	139	158	188
Super Single	40	750	20	840	141	161	191
11R22.5	60	850	45	840	142	162	192
Super Single	50	750	45	720	143	163	227
11R22.5	60	850	20	860	145	165	192
11R22.5	60	750	20	820	146	167	203
Super Single	50	850	6	860	157	179	208
Super Single	50	850	20	800	160	182	228
Super Single	50	850	45	820	164	187	228
Super Single	60	850	6	800	169	192	240

Table C 2 - Moduli from measured stresses and strain in the pavement for Material B.

Moduli from Measured Stress and Strain for Material B (dirty crushed rock)							
Tyre	Weight (kN)	Pressure (kPa)	Speed (km/h)	262.5 – strain (10^{-6}) measured	300 - stress (kPa) measured	262.5 - stress (kPa) calc	Modulus, E (MPa)
11R22.5	40	650	20	840	83	96	115
11R22.5	40	850	20	860	89	102	119
11R22.5	40	750	6	860	92	106	123
11R22.5	40	750	20	880	93	107	122
11R22.5	40	850	6	820	96	110	134
11R22.5	40	650	6	820	97	112	137
11R22.5	50	850	20	960	103	118	123
11R22.5	40	800	6	860	104	120	139
11R22.5	40	750	45	920	107	123	134
Super Single	50	750	20	1040	107	123	119
11R22.5	40	850	45	880	108	124	141
11R22.5	40	650	45	860	110	128	148
11R22.5	50	750	6	880	119	137	156
Super Single	40	850	20	1000	120	138	138
11R22.5	50	850	6	920	123	141	153
Super Single	40	750	20	960	123	142	148
11R22.5	50	750	20	940	127	146	156
11R22.5	50	750	45	920	127	146	159
Super Single	40	750	6	1000	128	148	148
Super Single	40	850	6	1020	129	148	145
Super Single	50	750	45	1020	129	149	146
Super Single	40	850	45	1000	136	156	156
11R22.5	50	850	45	960	138	158	165
11R22.5	60	750	6	980	139	160	164
11R22.5	60	850	6	1000	140	161	161
Super Single	50	850	20	1040	142	163	157
Super Single	40	750	45	1020	142	164	161
Super Single	50	850	45	1020	143	164	161
11R22.5	60	750	45	940	146	168	179
11R22.5	60	850	20	1000	147	169	169
11R22.5	60	750	20	1000	149	172	172
11R22.5	60	850	45	1000	154	177	177
Super Single	50	850	6	1080	154	177	164
Super Single	50	750	6	1060	154	178	168
Super Single	60	850	6	1100	182	209	190

Table C 3 - Moduli from measured stresses and strain in the pavement for Material C.

Moduli from Measured Stress and Strain for Material C (Australian crushed rock)							
Tyre	**Weight (kN)**	**Pressure (kPa)**	**Speed (km/h)**	**262.5 – strain (10^{-6}) measured**	**300 - stress (kPa) measured**	**262.5 - stress (kPa) calc**	**Modulus, E (MPa)**
11R22.5	40	750	45	520	63	75	143
11R22.5	40	750	20	540	64	76	140
11R22.5	40	850	45	580	67	79	137
11R22.5	40	650	20	520	68	80	155
11R22.5	40	650	45	600	71	84	140
11R22.5	40	850	20	560	72	85	152
11R22.5	40	750	6	540	77	91	169
11R22.5	50	750	20	580	90	107	184
11R22.5	40	650	6	620	91	108	174
11R22.5	50	850	20	580	95	113	194
11R22.5	50	850	45	620	96	114	184
11R22.5	40	800	6	520	98	116	223
11R22.5	40	850	6	620	100	119	191
11R22.5	50	850	6	620	101	120	193
11R22.5	50	750	6	540	103	122	226
11R22.5	50	750	45	620	105	124	201
385/65R22.5	40	750	20	660	111	131	199
385/65R22.5	40	850	20	720	118	140	194
385/65R22.5	40	850	6	700	127	151	215
385/65R22.5	40	750	6	700	129	153	218
385/65R22.5	40	850	45	680	133	158	232
11R22.5	60	750	20	660	136	161	244
11R22.5	60	750	6	600	137	162	270
11R22.5	60	850	20	640	139	165	257
11R22.5	60	850	6	640	140	166	259
385/65R22.5	50	850	20	700	140	166	237
11R22.5	60	750	45	640	143	169	265
385/65R22.5	40	750	45	680	143	169	249
385/65R22,5	50	850	45	720	144	171	237
11R22.5	60	850	45	660	145	172	260
385/65R22.5	50	750	45	700	153	181	259
385/65R22.5	50	850	6	740	154	183	247
385/65R22.5	50	750	6	720	162	192	266
385/65R22.5	50	750	20	720	165	195	271
385/65R22.5	60	850	6	740	185	219	296

Appendix D

Ratio of Computed to Measured Stresses, Strains & Deflections for the Theoretically Rigorous Method

Table D 1 - Ratio of computed to measured for CAPTIF Segment A where the granular elastic properties are defined using the *Theoretically Correct Method.*

Ratio of Computed to Measured for CAPTIF Segment A –
Granular elastic properties defined using Theoretically Correct Method

Load(kN)/Stress(kPa):	**40/650**	**40/750**	**50/750**	**60/750**	**40/850**	**50/850**	**60/850**
6km/h							
Depth:112.5	1.1	1.2	1.1	1.1	1.1	1.2	1.1
187.5	1.8	1.5	1.7	1.5	1.7	1.6	1.5
262.5	1.4	1.3	1.5	1.4	1.5	1.4	1.4
337.5	0.4	0.4	0.4	0.4	0.4	0.4	0.4
412.5	0.3	0.3	0.3	0.3	0.3	0.3	0.3
487.5	0.3	0.2	0.3	0.3	0.2	0.3	0.2
562.5	0.4	0.4	0.4	0.4	0.4	0.4	0.4
20km/h							
Depth:112.5	1.2	1.2	1.1	1.1	1.3	1.2	1.1
187.5	1.6	1.5	1.6	1.6	1.6	1.6	1.5
262.5	1.5	1.4	1.4	1.4	1.5	1.4	1.4
337.5	0.5	0.4	0.4	0.4	0.5	0.4	0.4
412.5	0.3	0.3	0.3	0.3	0.3	0.3	0.3
487.5	0.3	0.3	0.3	0.2	0.3	0.3	0.2
562.5	0.5	0.5	0.4	0.4	0.5	0.5	0.4
45km/h							
Depth:112.5	1.2	1.3	1.1	1.1	1.4	1.3	1.1
187.5	1.5	1.5	1.4	1.6	1.5	1.5	1.5
262.5	1.5	1.4	1.4	1.5	1.5	1.4	1.4
337.5	0.5	0.5	0.4	0.5	0.5	0.4	0.4
412.5	0.3	0.3	0.3	0.3	0.3	0.3	0.3
487.5	0.3	0.3	0.2	0.3	0.3	0.3	0.2
562.5	0.5	0.5	0.4	0.5	0.5	0.5	0.4
Stress (300mm)							
6km/h	1.1	1.4	1.1	1.1	1.1	1.0	1.1
20km/h	1.5	1.5	1.5	1.0	1.2	1.4	1.0
45km/h	1.7	1.8	1.2	1.1	1.7	1.4	1.0
Peak Deflection – average of 2 stations over instruments for load/stress = 40kN/550kPa (i.e. standard FWD load)							
0k (Defl)	0.5	0.5	0.6	0.7	0.5	0.6	0.7
FWD_30k	0.7	0.7	0.8	0.8	0.7	0.8	0.8
FWD_200k	0.6	0.6	0.7	0.8	0.6	0.7	0.8
FWD_1000k	0.6	0.6	0.7	0.8	0.6	0.7	0.8

Table D 2 - Granular moduli compared with RLT derived moduli appriate to bulk stress for CAPTIF Segment A where the granular elastic properties were defined using the *Theoretically Correct Method.*

Granular Moduli cf RLT Derived Moduli Appropriate to Bulk Stress for CAPTIF Segment A – *Granular elastic properties defined using Theoretically Correct Method*							
Load(kN)/Stress(kPa):	**40/650**	**40/750**	**50/750**	**60/750**	**40/850**	**50/850**	**60/850**
Granular Vertical Moduli (MPa)							
Depth (approx, mm):							
25-117	446	482	500	512	516	536	550
117-208	243	252	272	288	260	282	299
208-300	150	151	170	186	151	171	187
Subgrade Vertical Moduli (MPa):	108	108	108	108	108	108	108
Bulk Stress (kPa)							
Depth(mm): 50	727	813	869	912	895	961	1012
150	287	303	345	379	317	364	402
250	142	144	171	196	145	174	199
Corrected Granular Moduli for RLT Result Appropriate for Bulk Stress							
Depth (approx, mm): 25-117	441	475	497	513	507	531	550
117-208	237	246	268	285	253	277	297
208-300	148	149	168	183	150	169	186
Ratio of Moduli -Actual/Corrected							
Depth (approx, mm): 25-117	1.01	1.02	1.01	1.00	1.02	1.01	1.00
117-208	1.02	1.03	1.02	1.01	1.03	1.02	1.01
208-300	1.01	1.01	1.01	1.01	1.01	1.01	1.01

Table D 3 - Ratio of computed to measured for CAPTIF Segment B where the granular elastic properties are defined using the *Theoretically Correct Method.*

Ratio of Computed to Measured for CAPTIF Segment B –
Granular elastic properties defined using Theoretically Correct Method

Load(kN)/Stress(kPa):	**40/650**	**40/750**	**50/750**	**60/750**	**40/850**	**50/850**	**60/850**
6km/h							
Depth:112.5	1.5	1.6	1.4	1.6	1.5	1.4	1.5
187.5	1.8	1.7	1.7	1.8	1.8	1.6	1.7
262.5	1.3	1.3	1.4	1.3	1.4	1.3	1.3
337.5	0.3	0.3	0.3	0.3	0.3	0.3	0.3
412.5	0.4	0.4	0.4	0.4	0.4	0.4	0.4
487.5	0.4	0.4	0.5	0.4	0.4	0.4	0.4
562.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5
20km/h							
Depth:112.5	1.5	1.6	1.5	1.5	1.5	1.5	1.5
187.5	1.8	1.7	1.7	1.8	1.7	1.8	1.8
262.5	1.3	1.2	1.3	1.3	1.3	1.3	1.3
337.5	0.3	0.3	0.3	0.3	0.2	0.3	0.3
412.5	0.4	0.4	0.4	0.4	0.4	0.4	0.4
487.5	0.4	0.4	0.4	0.4	0.4	0.4	0.4
562.5	0.5	0.5	0.5	0.5	0.4	0.5	0.5
45km/h							
Depth:112.5	1.5	1.5	1.5	1.6	1.5	1.5	1.5
187.5	1.7	1.7	1.8	1.9	1.7	1.7	1.9
262.5	1.3	1.2	1.3	1.4	1.3	1.3	1.3
337.5	0.2	0.2	0.3	0.3	0.2	0.3	0.3
412.5	0.4	0.4	0.4	0.5	0.4	0.4	0.4
487.5	0.4	0.4	0.4	0.5	0.4	0.4	0.4
562.5	0.4	0.4	0.5	0.5	0.4	0.4	0.5
Stress (300mm)							
6km/h	1.1	1.2	1.1	1.1	1.2	1.1	1.1
20km/h	1.3	1.2	1.0	1.0	1.3	1.3	1.1
45km/h	1.0	1.0	1.0	1.0	1.0	1.0	1.0
Peak Deflection – average of 2 stations over instruments for load/stress = 40kN/550kPa (i.e. standard FWD load)							
0k (Defl)	0.7	0.7	0.8	0.8	0.7	0.8	0.8
FWD_30k	0.8	0.8	0.9	1.0	0.8	0.9	1.0
FWD_200k	0.7	0.7	0.8	0.9	0.7	0.8	0.9
FWD_1000k	0.7	0.7	0.8	0.9	0.7	0.8	0.9

Table D 4 - Granular moduli compared with RLT derived moduli appriate to bulk stress for CAPTIF Segment B where the granular elastic properties were defined using the *Theoretically Correct Method.*

Granular Moduli cf RLT Derived Moduli Appropriate to Bulk Stress for CAPTIF Segment B –
Granular elastic properties defined using Theoretically Correct Method

Load(kN)/Stress(kPa):	**40/650**	**40/750**	**50/750**	**60/750**	**40/850**	**50/850**	**60/850**
Granular Vertical Moduli (MPa)							
Depth (approx, mm):							
25-117	391	419	432	441	445	460	463
117-208	226	234	251	264	241	260	273
208-300	147	148	165	179	149	166	183
Subgrade Vertical Moduli (MPa):	107	107	107	107	107	107	107
Bulk Stress (kPa)							
Depth(mm): 50	728	813	866	907	895	957	1006
150	294	311	353	387	325	372	413
250	147	149	177	202	151	180	207
Corrected Granular Moduli for RLT Result Appropriate for Bulk Stress							
Depth (approx, mm): 25-117	386	413	429	442	438	456	471
117-208	222	230	249	263	236	257	273
208-300	146	147	163	177	148	165	179
Ratio of Moduli -Actual/Corrected							
Depth (approx, mm): 25-117	1.01	1.01	1.01	1.00	1.02	1.01	0.98
117-208	1.02	1.02	1.01	1.01	1.02	1.01	1.00
208-300	1.01	1.01	1.01	1.01	1.00	1.01	1.02

Table D 5 - Ratio of computed to measured for CAPTIF Segment C where the granular elastic properties are defined using the *Theoretically Correct Method.*

Ratio of Computed to Measured for CAPTIF Segment C –
Granular elastic properties defined using Theoretically Correct Method

Load(kN)/Stress(kPa):	**40/650**	**40/750**	**50/750**	**60/750**	**40/850**	**50/850**	**60/850**
6km/h							
Depth:112.5	1.6	1.6	1.8	1.6	1.8	1.6	1.6
187.5	1.6	1.7	1.8	1.7	1.7	1.6	1.7
262.5	1.8	2.1	2.3	2.2	1.8	2.0	2.1
337.5	0.8	1.0	1.0	1.0	0.8	0.9	1.0
412.5	0.7	0.7	0.8	0.8	0.7	0.7	0.8
487.5							
562.5	0.5	0.4	0.5	0.5	0.5	0.4	0.5
20km/h							
Depth:112.5	1.6	1.6	1.6	1.6	1.7	1.6	1.6
187.5	1.6	1.7	1.7	1.7	1.6	1.7	1.7
262.5	2.2	2.1	2.1	2.0	2.0	2.1	2.1
337.5	0.9	0.8	0.9	0.9	0.9	0.8	0.9
412.5	0.6	0.6	0.7	0.7	0.7	0.6	0.7
487.5							
562.5	0.4	0.4	0.4	0.4	0.4	0.4	0.4
45km/h							
Depth:112.5	1.4	1.6	1.7	1.6	1.6	1.7	1.7
187.5	1.4	1.7	1.7	1.8	1.6	1.7	1.7
262.5	1.9	2.2	2.0	2.0	2.0	2.0	2.0
337.5	1.0	1.0	0.9	1.0	1.1	0.9	0.9
412.5	0.7	0.7	0.6	0.7	0.8	0.7	0.7
487.5							
562.5	0.4	0.5	0.4	0.4	0.5	0.4	0.4
Stress (300mm)							
6km/h	1.3	1.5	1.3	1.2	1.2	1.4	1.2
20km/h	1.7	1.8	1.5	1.2	1.6	1.5	1.2
45km/h	1.6	1.8	1.3	1.1	1.7	1.5	1.1
Peak Deflection – average of 2 stations over instruments for load/stress = 40kN/550kPa (i.e. standard FWD load)							
0k (Defl)	1.0	1.0	1.2	1.3	1.0	1.2	1.3
FWD_30k	1.1	1.1	1.2	1.3	1.1	1.2	1.4
FWD_200k	1.0	1.0	1.1	1.3	1.0	1.2	1.3
FWD_1000k	1.2	1.2	1.4	1.5	1.2	1.4	1.5

Table D 6 - Granular moduli compared with RLT derived moduli appriate to bulk stress for CAPTIF Segment C where the granular elastic properties were defined using the *Theoretically Correct Method.*

Granular Moduli cf RLT Derived Moduli Appropriate to Bulk Stress for CAPTIF Segment C –
Granular elastic properties defined using Theoretically Correct Method

Load(kN)/Stress(kPa):	**40/650**	**40/750**	**50/750**	**60/750**	**40/850**	**50/850**	**60/850**
Granular Vertical Moduli (MPa)							
Depth (approx, mm):							
25-117	381	409	420	429	434	447	457
117-208	223	231	247	260	238	256	269
208-300	147	148	164	178	148	165	180
Subgrade Vertical Moduli (MPa):	115	115	115	115	115	115	115
Bulk Stress (kPa)							
Depth(mm): 50	736	824	875	916	907	968	1015
150	301	319	361	395	334	381	419
250	153	155	184	210	157	187	214
Corrected Granular Moduli for RLT Result Appropriate for Bulk Stress							
Depth (approx, mm): 25-117	375	401	416	428	425	442	455
117-208	219	226	244	257	233	252	267
208-300	145	147	162	176	148	164	178
Ratio of Moduli -Actual/Corrected							
Depth (approx, mm): 25-117	1.02	1.02	1.01	1.00	1.02	1.01	1.00
117-208	1.02	1.02	1.01	1.01	1.02	1.01	1.01
208-300	1.01	1.01	1.01	1.01	1.00	1.01	1.01

Appendix E

Ratio of Computed to Measured Stresses, Strains & Deflections for AUSTROADS Auto-sublayering (RLT moduli from contact stress) Method

Table E 1 - Ratio of computed to measured for CAPTIF Segment A where the granular elastic properties are defined using the Austroads auto-sublayering (RLT moduli from contact stress) method.

Ratio of Computed to Measured for CAPTIF Segment A –
Granular elastic properties defined using Austroads auto-sublayering (RLT moduli from contact stress) method

Load(kN)/Stress(kPa):	**40/650**	**40/750**	**50/750**	**60/750**	**40/850**	**50/850**	**60/850**
6km/h							
Depth:112.5	1.2	1.2	1.2	1.2	1.2	1.2	1.2
187.5	1.7	1.4	1.7	1.6	1.6	1.5	1.5
262.5	1.3	1.2	1.5	1.5	1.3	1.4	1.4
337.5	0.4	0.4	0.4	0.5	0.4	0.4	0.4
412.5	0.3	0.3	0.3	0.3	0.3	0.3	0.3
487.5	0.3	0.2	0.3	0.3	0.2	0.3	0.2
562.5	0.4	0.4	0.4	0.4	0.4	0.4	0.4
20km/h							
Depth:112.5	1.4	1.3	1.2	1.2	1.3	1.3	1.2
187.5	1.6	1.4	1.5	1.7	1.4	1.5	1.5
262.5	1.4	1.2	1.4	1.5	1.3	1.4	1.5
337.5	0.5	0.4	0.4	0.4	0.5	0.4	0.4
412.5	0.3	0.3	0.3	0.3	0.3	0.3	0.3
487.5	0.3	0.3	0.3	0.3	0.3	0.3	0.2
562.5	0.5	0.5	0.4	0.4	0.5	0.5	0.4
45km/h							
Depth:112.5	1.4	1.4	1.2	1.3	1.4	1.4	1.2
187.5	1.5	1.4	1.4	1.7	1.4	1.5	1.5
262.5	1.4	1.3	1.4	1.6	1.3	1.4	1.5
337.5	0.5	0.5	0.4	0.5	0.5	0.4	0.4
412.5	0.3	0.3	0.3	0.3	0.3	0.3	0.3
487.5	0.3	0.3	0.2	0.3	0.3	0.3	0.2
562.5	0.5	0.5	0.4	0.5	0.5	0.5	0.4
Stress (300mm)							
6km/h	1.1	1.4	1.1	1.1	1.1	1.0	1.2
20km/h	1.5	1.5	1.5	1.0	1.2	1.4	1.0
45km/h	1.8	1.8	1.2	1.1	1.7	1.4	1.1
Peak Deflection – average of 2 stations over instruments for load/stress = 40kN/550kPa (i.e. standard FWD load)							
0k (Defl)	0.5	0.5	0.6	0.7	0.5	0.6	0.7
FWD_30k	0.7	0.7	0.8	0.9	0.6	0.8	0.9
FWD_200k	0.6	0.6	0.7	0.8	0.6	0.7	0.8
FWD_1000k	0.6	0.6	0.7	0.8	0.6	0.7	0.8

Table E 2 - Granular moduli compared with RLT derived moduli appropriate to bulk stress for CAPTIF Segment A where the granular elastic properties were defined using the Austroads auto-sublayering (RLT moduli from contact stress) method.

Granular Moduli cf RLT Derived Moduli Appropriate to Bulk Stress for CAPTIF Segment A – *Granular elastic properties defined using Austroads auto-sublayering (RLT moduli from contact stress) method.*

Load(kN)/Stress(kPa):	**40/650**	**40/750**	**50/750**	**60/750**	**40/850**	**50/850**	**60/850**
Granular Vertical Moduli (MPa)							
Depth (approx, mm):							
25-117	402	450	450	450	497	497	497
117-208	259	280	280	280	299	299	299
208-300	167	174	174	174	180	180	180
Subgrade Vertical Moduli (MPa):	108	108	108	108	108	108	108
Bulk Stress (kPa)							
Depth(mm): 50	1105	1238	1307	1364	1363	1444	1511
150	372	395	436	467	414	461	498
250	188	189	224	255	189	225	258
Corrected Granular Moduli for RLT Result Appropriate for Bulk Stress							
Depth (approx, mm): 25-117	612	670	699	723	723	757	784
117-208	258	271	293	310	281	306	325
208-300	150	151	173	191	151	174	193
Ratio of Moduli -Actual/Corrected							
Depth (approx, mm): 25-117	0.7	0.7	0.6	0.6	0.7	0.7	0.6
117-208	1.0	1.0	1.0	0.9	1.1	1.0	0.9
208-300	1.1	1.2	1.0	0.9	1.2	1.0	0.9

Table E 3 - Ratio of computed to measured for CAPTIF Segment B where the granular elastic properties are defined using the Austroads auto-sublayering (RLT moduli from contact stress) method.

Ratio of Computed to Measured for CAPTIF Segment B –
Granular elastic properties defined using Austroads auto-sublayering (RLT moduli from contact stress) method

Load(kN)/Stress(kPa):	40/650	40/750	50/750	60/750	40/850	50/850	60/850
6km/h							
Depth:112.5	1.6	1.7	1.6	1.8	1.6	1.5	1.6
187.5	1.7	1.6	1.7	1.9	1.7	1.6	1.8
262.5	1.3	1.2	1.4	1.4	1.2	1.3	1.4
337.5	0.3	0.3	0.3	0.3	0.2	0.3	0.3
412.5	0.4	0.4	0.4	0.4	0.4	0.4	0.4
487.5	0.4	0.4	0.5	0.4	0.4	0.4	0.4
562.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5
20km/h							
Depth:112.5	1.7	1.7	1.6	1.7	1.6	1.6	1.6
187.5	1.8	1.6	1.7	1.9	1.5	1.7	1.8
262.5	1.2	1.2	1.3	1.4	1.2	1.2	1.4
337.5	0.3	0.3	0.3	0.3	0.2	0.3	0.3
412.5	0.4	0.4	0.4	0.4	0.4	0.4	0.4
487.5	0.4	0.4	0.4	0.5	0.4	0.4	0.4
562.5	0.5	0.5	0.5	0.5	0.4	0.5	0.5
45km/h							
Depth:112.5	1.7	1.6	1.6	1.8	1.6	1.6	1.6
187.5	1.7	1.6	1.8	2.0	1.6	1.7	1.9
262.5	1.2	1.1	1.3	1.5	1.1	1.2	1.4
337.5	0.2	0.2	0.3	0.3	0.2	0.3	0.3
412.5	0.4	0.4	0.4	0.5	0.4	0.4	0.4
487.5	0.4	0.4	0.4	0.5	0.4	0.4	0.4
562.5	0.4	0.4	0.5	0.6	0.4	0.4	0.5
Stress (300mm)							
6km/h	1.1	1.2	1.1	1.1	1.2	1.1	1.1
20km/h	1.3	1.2	1.1	1.0	1.2	1.3	1.1
45km/h	1.0	1.0	1.1	1.1	1.0	1.0	1.0
Peak Deflection – average of 2 stations over instruments for load/stress = 40kN/550kPa (i.e. standard FWD load)							
0k (Defl)	0.7	0.7	0.8	0.9	0.7	0.8	0.9
FWD_30k	0.8	0.8	1.0	1.1	0.8	1.0	1.1
FWD_200k	0.7	0.7	0.8	0.9	0.7	0.8	0.9
FWD_1000k	0.7	0.7	0.8	0.9	0.7	0.8	0.9

Table E 4 - Granular moduli compared with RLT derived moduli appriate to bulk stress for CAPTIF Segment B where the granular elastic properties were defined using the Austroads auto-sublayering (RLT moduli from contact stress) method.

Granular Moduli cf RLT Derived Moduli Appropriate to Bulk Stress for CAPTIF Segment B – *Granular elastic properties defined using Austroads auto-sublayering (RLT moduli from contact stress) method*

Load(kN)/Stress(kPa):	**40/650**	**40/750**	**50/750**	**60/750**	**40/850**	**50/850**	**60/850**
Granular Vertical Moduli (MPa)							
Depth (approx, mm):							
25-117	352	391	391	391	428	428	428
117-208	237	253	253	253	269	269	269
208-300	159	164	164	164	169	169	169
Subgrade Vertical Moduli (MPa):	107	107	107	107	107	107	107
Bulk Stress (kPa)							
Depth(mm): 50	1098.1	1230.7	1297.5	1351.6	1356.6	1433.9	1497.8
150	379.3	403.6	445.3	476.7	423.6	471.6	508.9
250	192.7	194.7	230.4	262.2	195.7	232.8	266.5
Corrected Granular Moduli for RLT Result Appropriate for Bulk Stress							
Depth (approx, mm): 25-117	515	559	581	598	600	624	644
117-208	239	250	268	282	259	279	295
208-300	146	147	167	183	148	168	185
Ratio of Moduli -Actual/Corrected							
Depth (approx, mm): 25-117	0.68	0.70	0.67	0.65	0.71	0.69	0.66
117-208	0.99	1.02	0.95	0.90	1.04	0.96	0.91
208-300	1.09	1.11	0.99	0.90	1.14	1.01	0.92

Table E 5 - Ratio of computed to measured for CAPTIF Segment C where the granular elastic properties are defined using the Austroads auto-sublayering (RLT moduli from contact stress) method.

Ratio of Computed to Measured for CAPTIF Segment C –
Granular elastic properties defined using Austroads auto-sublayering (RLT moduli from contact stress) method

Load(kN)/Stress(kPa):	**40/650**	**40/750**	**50/750**	**60/750**	**40/850**	**50/850**	**60/850**
6km/h							
Depth:112.5	1.8	1.7	1.9	1.7	1.8	1.7	1.7
187.5	1.6	1.6	1.8	1.8	1.5	1.6	1.7
262.5	1.7	1.9	2.2	2.3	1.6	1.9	2.1
337.5	0.8	1.0	1.0	1.0	0.8	0.9	1.0
412.5	0.7	0.7	0.8	0.8	0.7	0.7	0.8
487.5							
562.5	0.5	0.4	0.5	0.5	0.5	0.4	0.5
20km/h							
Depth:112.5	1.7	1.7	1.7	1.7	1.7	1.7	1.8
187.5	1.5	1.6	1.6	1.8	1.4	1.6	1.7
262.5	2.0	1.9	2.1	2.1	1.8	2.0	2.1
337.5	0.9	0.8	0.9	0.9	0.9	0.8	0.9
412.5	0.6	0.6	0.7	0.7	0.7	0.6	0.7
487.5							
562.5	0.4	0.4	0.4	0.4	0.4	0.4	0.4
45km/h							
Depth:112.5	1.5	1.7	1.8	1.8	1.7	1.8	1.8
187.5	1.4	1.6	1.6	1.9	1.4	1.6	1.8
262.5	1.7	1.9	1.9	2.1	1.7	1.9	2.1
337.5	1.0	1.0	0.9	1.0	1.1	0.9	0.9
412.5	0.7	0.7	0.7	0.7	0.8	0.7	0.7
487.5							
562.5	0.4	0.5	0.4	0.4	0.5	0.4	0.4
Stress (300mm)							
6km/h	1.3	1.5	1.4	1.2	1.2	1.4	1.2
20km/h	1.7	1.8	1.6	1.2	1.6	1.5	1.2
45km/h	1.6	1.8	1.3	1.1	1.7	1.5	1.1
Peak Deflection – average of 2 stations over instruments for load/stress = 40kN/550kPa (i.e. standard FWD load)							
0k (Defl)	1.0	1.0	1.2	1.3	1.0	1.2	1.3
FWD_30k	1.1	1.1	1.2	1.4	1.1	1.2	1.4
FWD_200k	1.0	1.0	1.2	1.3	1.0	1.2	1.3
FWD_1000k	1.2	1.2	1.4	1.6	1.2	1.4	1.6

Table E 6 - Granular moduli compared with RLT derived moduli appriate to bulk stress for CAPTIF Segment C where the granular elastic properties were defined using the Austroads auto-sublayering (RLT moduli from contact stress) method.

Granular Moduli cf RLT Derived Moduli Appropriate to Bulk Stress for CAPTIF Segment C –
Granular elastic properties defined using Austroads auto-sublayering (RLT moduli from contact stress) method

Load(kN)/Stress(kPa):	**40/650**	**40/750**	**50/750**	**60/750**	**40/850**	**50/850**	**60/850**
Granular Vertical Moduli (MPa)							
Depth (approx, mm):							
25-117	343	381	381	381	417	417	417
117-208	238	255	255	255	271	271	271
208-300	165	171	171	171	176	176	176
Subgrade Vertical Moduli (MPa):	115	115	115	115	115	115	115
Bulk Stress (kPa)							
Depth(mm): 50	1093	1226	1290	1343	1352	1427	1489
150	385	410	452	484	430	479	517
250	197	199	236	268	200	238	273
Corrected Granular Moduli for RLT Result Appropriate for Bulk Stress							
Depth (approx, mm): 25-117	500	543	564	580	583	606	625
117-208	235	246	264	277	255	275	291
208-300	145	146	165	181	147	166	183
Ratio of Moduli -Actual/Corrected							
Depth (approx, mm): 25-117	0.7	0.7	0.7	0.7	0.7	0.7	0.7
117-208	1.0	1.0	1.0	0.9	1.1	1.0	0.9
208-300	1.1	1.2	1.0	0.9	1.2	1.1	1.0

Appendix F

Ratio of Computed to Measured Stresses, Strains & Deflections for AUSTROADS Auto-sublayering (RLT moduli from bulk stress) Method

Table F1 - Ratio of computed to measured for CAPTIF Segment A where the granular elastic properties are defined using the Austroads auto-sublayering (RLT moduli from bulk stress) method.

Ratio of Computed to Measured for CAPTIF Segment A –
Granular elastic properties defined using Austroads auto-sublayering (RLT moduli from bulk stress) method

Load(kN)/Stress(kPa):	**40/650**	**40/750**	**50/750**	**60/750**	**40/850**	**50/850**	**60/850**
6km/h							
Depth:112.5	0.8	0.7	0.7	0.7	0.7	0.7	0.7
187.5	1.2	1.0	1.2	1.1	1.1	1.0	1.1
262.5	1.0	0.9	1.1	1.2	1.0	1.1	1.1
337.5	0.4	0.4	0.4	0.4	0.4	0.4	0.4
412.5	0.3	0.2	0.3	0.3	0.2	0.3	0.3
487.5	0.2	0.2	0.2	0.2	0.2	0.2	0.2
562.5	0.4	0.4	0.4	0.4	0.4	0.4	0.4
20km/h							
Depth:112.5	0.8	0.8	0.7	0.7	0.8	0.8	0.7
187.5	1.1	0.9	1.1	1.2	1.0	1.0	1.0
262.5	1.1	1.0	1.1	1.2	1.0	1.1	1.1
337.5	0.4	0.4	0.4	0.4	0.4	0.4	0.4
412.5	0.3	0.3	0.3	0.3	0.3	0.3	0.2
487.5	0.3	0.3	0.2	0.2	0.3	0.2	0.2
562.5	0.4	0.4	0.4	0.4	0.4	0.4	0.3
45km/h							
Depth:112.5	0.8	0.9	0.7	0.8	0.9	0.8	0.7
187.5	1.0	1.0	1.0	1.2	1.0	1.0	1.0
262.5	1.1	1.0	1.1	1.2	1.0	1.1	1.2
337.5	0.4	0.4	0.4	0.4	0.4	0.4	0.4
412.5	0.3	0.3	0.2	0.3	0.3	0.3	0.2
487.5	0.3	0.3	0.2	0.3	0.3	0.2	0.2
562.5	0.5	0.5	0.4	0.4	0.5	0.4	0.4
Stress (300mm)							
6km/h	1.0	1.2	1.0	1.0	1.0	0.9	1.0
20km/h	1.3	1.4	1.3	0.9	1.1	1.3	0.9
45km/h	1.6	1.6	1.1	1.0	1.5	1.3	0.9
Peak Deflection – average of 2 stations over instruments for load/stress = 40kN/550kPa (i.e. standard FWD load)							
0k (Defl)	0.4	0.4	0.5	0.6	0.4	0.5	0.6
FWD_30k	0.5	0.5	0.6	0.7	0.5	0.6	0.7
FWD_200k	0.5	0.5	0.6	0.7	0.5	0.6	0.7
FWD_1000k	0.5	0.5	0.6	0.7	0.5	0.6	0.7

Table F 2 - Granular moduli compared with RLT derived moduli appriate to bulk stress for CAPTIF Segment A where the granular elastic properties were defined using the Austroads auto-sublayering (RLT moduli from bulk stress) method.

Granular Moduli cf RLT Derived Moduli Appropriate to Bulk Stress for CAPTIF Segment A – *Granular elastic properties defined using Austroads auto-sublayering (RLT moduli from bulk stress) method*

Load(kN)/Stress(kPa):	**40/650**	**40/750**	**50/750**	**60/750**	**40/850**	**50/850**	**60/850**
Granular Vertical Moduli (MPa)							
Depth (approx, mm):							
25-117	672	762	762	762	851	851	851
117-208	365	397	397	397	428	428	428
208-300	199	207	207	207	215	215	215
Subgrade Vertical Moduli (MPa):	108	108	108	108	108	108	108
Bulk Stress (kPa)							
Depth(mm): 50	1135	1266	1347	1415	1390	1483	1561
150	342	361	400	429	377	420	455
250	165	165	196	224	164	196	225
Corrected Granular Moduli for RLT Result Appropriate for Bulk Stress							
Depth (approx, mm): 25-117	625	682	716	744	734	773	805
117-208	242	252	274	289	261	285	303
208-300	136	136	156	173	135	155	174
Ratio of Moduli -Actual/Corrected							
Depth (approx, mm): 25-117	1.1	1.1	1.1	1.0	1.2	1.1	1.1
117-208	1.5	1.6	1.5	1.4	1.6	1.5	1.4
208-300	1.5	1.5	1.3	1.2	1.6	1.4	1.2

Table F 3 - Ratio of computed to measured for CAPTIF Segment B where the granular elastic properties are defined using the Austroads auto-sublayering (RLT moduli from bulk stress) method.

Ratio of Computed to Measured for CAPTIF Segment B –

Granular elastic properties defined using Austroads auto-sublayering (RLT moduli from bulk stress) method

Load(kN)/Stress(kPa):	**40/650**	**40/750**	**50/750**	**60/750**	**40/850**	**50/850**	**60/850**
6km/h							
Depth:112.5	1.1	1.1	1.0	1.2	1.0	1.0	1.1
187.5	1.3	1.2	1.3	1.4	1.2	1.2	1.3
262.5	1.0	1.0	1.1	1.2	1.0	1.1	1.1
337.5	0.2	0.2	0.3	0.3	0.2	0.3	0.3
412.5	0.4	0.4	0.4	0.4	0.4	0.4	0.4
487.5	0.4	0.4	0.4	0.4	0.4	0.4	0.4
562.5	0.5	0.4	0.5	0.5	0.4	0.5	0.5
20km/h							
Depth:112.5	1.1	1.1	1.1	1.1	1.0	1.1	1.1
187.5	1.3	1.2	1.3	1.4	1.1	1.3	1.3
262.5	1.0	0.9	1.1	1.1	0.9	1.0	1.1
337.5	0.2	0.2	0.3	0.3	0.2	0.2	0.3
412.5	0.4	0.4	0.4	0.4	0.3	0.4	0.4
487.5	0.4	0.4	0.4	0.4	0.3	0.4	0.4
562.5	0.4	0.4	0.4	0.5	0.4	0.4	0.5
45km/h							
Depth:112.5	1.1	1.0	1.1	1.1	1.0	1.0	1.1
187.5	1.3	1.2	1.3	1.5	1.2	1.2	1.4
262.5	1.0	0.9	1.1	1.2	0.9	1.0	1.1
337.5	0.2	0.2	0.3	0.3	0.2	0.2	0.3
412.5	0.3	0.3	0.4	0.4	0.3	0.4	0.4
487.5	0.3	0.3	0.4	0.5	0.3	0.4	0.4
562.5	0.4	0.4	0.5	0.5	0.4	0.4	0.5
Stress (300mm)							
6km/h	1.0	1.1	1.0	1.0	1.0	1.0	1.0
20km/h	1.2	1.1	1.0	1.0	1.1	1.2	1.0
45km/h	0.9	0.9	1.0	1.0	0.9	0.9	0.9
Peak Deflection – average of 2 stations over instruments for load/stress = 40kN/550kPa (i.e. standard FWD load)							
0k (Defl)	0.5	0.5	0.6	0.7	0.5	0.6	0.7
FWD_30k	0.7	0.7	0.8	0.9	0.7	0.8	0.9
FWD_200k	0.6	0.6	0.7	0.8	0.6	0.7	0.8
FWD_1000k	0.6	0.6	0.7	0.8	0.6	0.7	0.8

Table F 4 - Granular moduli compared with RLT derived moduli appriate to bulk stress for CAPTIF Segment B where the granular elastic properties were defined using the Austroads auto-sublayering (RLT moduli from bulk stress) method.

Granular Moduli cf RLT Derived Moduli Appropriate to Bulk Stress for CAPTIF Segment B – *Granular elastic properties defined using Austroads auto-sublayering (RLT moduli from bulk stress) method*

Load(kN)/Stress(kPa):	**40/650**	**40/750**	**50/750**	**60/750**	**40/850**	**50/850**	**60/850**
Granular Vertical Moduli (MPa)							
Depth (approx, mm):							
25-117	543	608	608	608	673	673	673
117-208	316	340	340	340	364	364	364
208-300	183	191	191	191	197	197	197
Subgrade Vertical Moduli (MPa):	107	107	107	107	107	107	107
Bulk Stress (kPa)							
Depth(mm): 50	1123	1255	1331	1394	1379	1466	1540
150	354	375	414	445	392	437	473
250	174	175	207	236	174	208	239
Corrected Granular Moduli for RLT Result Appropriate for Bulk Stress							
Depth (approx, mm): 25-117	523	567	591	611	607	634	657
117-208	227	237	255	268	245	265	280
208-300	136	136	154	170	136	155	171
Ratio of Moduli -Actual/Corrected							
Depth (approx, mm): 25-117	1.0	1.1	1.0	1.0	1.1	1.1	1.0
117-208	1.4	1.4	1.3	1.3	1.5	1.4	1.3
208-300	1.3	1.4	1.2	1.1	1.4	1.3	1.2

Table F 5 - Ratio of computed to measured for CAPTIF Segment C where the granular elastic properties are defined using the Austroads auto-sublayering (RLT moduli from bulk stress) method.

Ratio of Computed to Measured for CAPTIF Segment C –
Granular elastic properties defined using Austroads auto-sublayering (RLT moduli from bulk stress) method

Load(kN)/Stress(kPa):	**40/650**	**40/750**	**50/750**	**60/750**	**40/850**	**50/850**	**60/850**
6km/h							
Depth:112.5	1.1	1.1	1.3	1.1	1.2	1.1	1.1
187.5	1.2	1.1	1.3	1.3	1.1	1.1	1.2
262.5	1.4	1.5	1.8	1.9	1.3	1.6	1.7
337.5	0.8	0.9	0.9	1.0	0.7	0.9	0.9
412.5	0.7	0.6	0.7	0.7	0.6	0.6	0.7
487.5							
562.5	0.4	0.4	0.5	0.5	0.4	0.4	0.4
20km/h							
Depth:112.5	1.1	1.1	1.1	1.1	1.1	1.1	1.1
187.5	1.1	1.1	1.2	1.3	1.0	1.2	1.2
262.5	1.6	1.5	1.7	1.7	1.4	1.7	1.7
337.5	0.8	0.7	0.8	0.9	0.8	0.8	0.8
412.5	0.6	0.6	0.6	0.7	0.6	0.6	0.6
487.5							
562.5	0.4	0.4	0.4	0.4	0.4	0.4	0.4
45km/h							
Depth:112.5	1.0	1.1	1.2	1.1	1.1	1.1	1.2
187.5	1.0	1.1	1.2	1.4	1.0	1.2	1.3
262.5	1.4	1.6	1.6	1.7	1.4	1.6	1.7
337.5	0.9	0.9	0.8	0.9	1.0	0.8	0.8
412.5	0.6	0.7	0.6	0.7	0.7	0.6	0.6
487.5							
562.5	0.4	0.4	0.4	0.4	0.5	0.4	0.4
Stress (300mm)							
6km/h	1.2	1.4	1.2	1.1	1.0	1.3	1.1
20km/h	1.6	1.6	1.4	1.1	1.5	1.3	1.1
45km/h	1.5	1.7	1.2	1.0	1.6	1.3	1.0
Peak Deflection – average of 2 stations over instruments for load/stress = 40kN/550kPa (i.e. standard FWD load)							
0k (Defl)	0.8	0.8	1.0	1.1	0.8	1.0	1.1
FWD_30k	0.9	0.9	1.0	1.2	0.9	1.0	1.2
FWD_200k	0.8	0.8	1.0	1.1	0.8	1.0	1.1
FWD_1000k	1.0	1.0	1.2	1.3	1.0	1.1	1.3

Table F 6 - Granular moduli compared with RLT derived moduli appriate to bulk stress for CAPTIF Segment C where the granular elastic properties were defined using the Austroads auto-sublayering (RLT moduli from bulk stress) method.

Granular Moduli cf RLT Derived Moduli Appropriate to Bulk Stress for CAPTIF Segment C – *Granular elastic properties defined using Austroads auto-sublayering (RLT moduli from bulk stress) method*

Load(kN)/Stress(kPa):	**40/650**	**40/750**	**50/750**	**60/750**	**40/850**	**50/850**	**60/850**
Granular Vertical Moduli (MPa)							
Depth (approx, mm):							
25-117	539	602	602	602	664	664	664
117-208	322	346	346	346	370	370	370
208-300	192	199	199	199	206	206	206
Subgrade Vertical Moduli (MPa):	115	115	115	115	115	115	115
Bulk Stress (kPa)							
Depth(mm): 50	1118	1250	1325	1386	1375	1460	1532
150	359	380	420	451	398	444	479
250	177	178	211	241	178	213	244
Corrected Granular Moduli for RLT Result Appropriate for Bulk Stress							
Depth (approx, mm): 25-117	508	551	574	594	590	616	638
117-208	223	233	251	264	241	261	276
208-300	134	135	153	168	135	153	169
Ratio of Moduli -Actual/Corrected							
Depth (approx, mm): 25-117	1.1	1.1	1.0	1.0	1.1	1.1	1.0
117-208	1.4	1.5	1.4	1.3	1.5	1.4	1.3
208-300	1.4	1.5	1.3	1.2	1.5	1.3	1.2

Appendix G

Calculation of Vertical Deformations

Table G 1 - Vertical deformation modelling results for Segment A.

	Segment A – Vertical Deformation Results from RLT Data for the Three Modelling Methods (mm)											
Lay-er	**Linear**				**Exp**				**Ullidtz**			
N	***250k***	***500k***	***900k***	***1000k***	***250k***	***500k***	***900k***	***1000k***	***250k***	***500k***	***900k***	***1000k***
BC1	0.613	1.037	1.718	1.889	0.349	0.387	0.422	0.429	0.313	0.329	0.344	0.346
BC2	0.486	0.788	1.269	1.389	0.295	0.323	0.349	0.354	0.255	0.268	0.279	0.281
BC3	0.377	0.584	0.912	0.994	0.246	0.266	0.284	0.287	0.203	0.214	0.223	0.225
BC4	0.301	0.447	0.678	0.736	0.209	0.223	0.236	0.238	0.166	0.175	0.182	0.184
BC5	0.249	0.357	0.530	0.573	0.182	0.193	0.202	0.204	0.140	0.147	0.154	0.155
SG1	1.005	1.227	1.581	1.670	1.002	1.189	1.375	1.412	0.643	0.760	0.875	0.897
SG2	0.955	1.184	1.549	1.641	0.946	1.096	1.241	1.269	0.093	0.109	0.126	0.129
SG3	0.793	0.998	1.328	1.410	0.780	0.881	0.977	0.995	0.011	0.013	0.015	0.015
SG4	0.745	0.953	1.288	1.372	0.729	0.803	0.871	0.884	0.001	0.002	0.002	0.002
SG5	0.711	0.923	1.267	1.353	0.691	0.743	0.790	0.799	0.000	0.000	0.000	0.000
TOTAL	**6.234**	**8.498**	**12.121**	**13.028**	**5.430**	**6.104**	**6.748**	**6.871**	**1.826**	**2.017**	**2.200**	**2.235**

Table G 2 - Vertical deformation modelling results for Segment B.

	B											
Lay-er	**Linear**				**Exp**				**Ullidtz**			
	250k	***500k***	***900k***	***1000k***	***250k***	***500k***	***900k***	***1000k***	***250k***	***500k***	***900k***	***1000k***
BC1	3.993	7.237	12.429	13.728	2.495	3.197	3.944	4.096	1.568	1.641	1.705	1.717
BC2	2.255	3.957	6.669	7.347	1.409	1.731	2.060	2.126	0.924	0.967	1.005	1.012
BC3	1.178	1.993	3.287	3.611	0.736	0.862	0.985	1.009	0.507	0.531	0.551	0.555
BC4	0.646	1.056	1.707	1.870	0.403	0.452	0.497	0.506	0.291	0.304	0.316	0.318
BC5	0.388	0.616	0.980	1.071	0.242	0.261	0.279	0.282	0.182	0.190	0.197	0.199
SG1	1.085	1.321	1.698	1.792	1.083	1.290	1.497	1.538	0.952	1.124	1.294	1.328
SG2	1.015	1.255	1.639	1.736	1.006	1.169	1.328	1.358	0.126	0.149	0.172	0.176
SG3	0.830	1.043	1.386	1.472	0.818	0.925	1.028	1.048	0.014	0.016	0.019	0.019
SG4	0.770	0.984	1.329	1.415	0.754	0.832	0.904	0.918	0.002	0.002	0.002	0.002
SG5	0.729	0.946	1.297	1.385	0.709	0.763	0.812	0.821	0.000	0.000	0.000	0.000
TOTAL	**12.889**	**20.407**	**32.423**	**35.426**	**9.654**	**11.481**	**13.335**	**13.701**	**4.566**	**4.925**	**5.263**	**5.327**

Table G 3 - Vertical deformation modelling results for Segment C.

	C											
Lay-er	**Linear**				**Exp**				**Ullidtz**			
	250k	***500k***	***900k***	***1000k***	***250k***	***500k***	***900k***	***1000k***	***250k***	***500k***	***900k***	***1000k***
BC1	0.245	0.367	0.563	0.612	0.163	0.171	0.178	0.179	0.165	0.172	0.179	0.180
BC2	0.222	0.334	0.513	0.558	0.148	0.154	0.161	0.162	0.142	0.148	0.154	0.155
BC3	0.198	0.299	0.459	0.499	0.131	0.137	0.142	0.143	0.118	0.124	0.129	0.129
BC4	0.178	0.269	0.414	0.450	0.117	0.122	0.127	0.128	0.100	0.105	0.109	0.109
BC5	0.162	0.245	0.378	0.412	0.106	0.111	0.115	0.116	0.087	0.091	0.094	0.095
SG1	1.152	1.399	1.795	1.895	1.150	1.375	1.600	1.645	1.294	1.528	1.759	1.804
SG2	1.068	1.319	1.720	1.821	1.060	1.235	1.406	1.439	0.165	0.195	0.224	0.230
SG3	0.867	1.088	1.443	1.532	0.854	0.969	1.079	1.099	0.017	0.020	0.023	0.024
SG4	0.797	1.017	1.371	1.460	0.780	0.862	0.939	0.953	0.002	0.002	0.003	0.003
SG5	0.748	0.970	1.329	1.419	0.728	0.785	0.836	0.846	0.000	0.000	0.000	0.000
TOTAL	**5.637**	**7.306**	**9.986**	**10.657**	**5.237**	**5.922**	**6.583**	**6.710**	**2.090**	**2.385**	**2.674**	**2.730**

Appendix H

Proposed Alabaster (1998) Method for Materials Evaluation by Predicting Rut Depth using the Ullidtz (1987) Equations

APPENDIX H: ASSESSMENT OF UNBOUND GRANULAR MATERIALS

The assessment of the rutting potential for granular materials is as follows:

1. Determine initial granular layer depths from the AUSTROADS Charts

2. The total allowable rut depth in the entire pavement over the design life is 25 mm

3. Determine proportion of rut depth to be allowed in the granular layers, use 10 mm where the contribution of the subgrade can not be evaluated, ie 5 mm in the basecourse and 5 mm in the Sub-base. Allowing 15 mm in the subgrade. (Note that in the current AUSTROADS guide no allowance is made for deformation in the granular layers.)

4. Split each granular layer, ie the base course and sub-base, into five sub layers for analysis.

5. Using CIRCLY or a similar analysis package, determine the maximum principal stresses occurring at the mid height of each sub layer (note that at higher levels in the base course this may occur directly beneath the wheel). The principal stresses can be calculated in the windows version of CIRCLY by changing the SOLVE line in the input data to SOLVE, P and running the input file in CIRCLY32.exe in dos (Appendix C: CIRCLY32 INPUT DATA, CIRCLY MANUAL).

6. For each sub layer determine the plastic strain occurring in the middle of the sub-layer using the formula from Ullidtz (1987). (Note, this formula can only be used for materials exhibiting stable behaviour, ie the amount of plastic strain accumulating is decreasing with increasing load cycles.)

$$\in_{pi} = A\,N^{B}\left(\frac{\sigma_1}{\sigma'}\right)^{C}$$

Where

$\in_{pi}$ = *Permanent Strain in Sub - layer i*

N = *Number of Stress Applications*

A, B, C = *Experimently determined coefficients*

σ_1 = *Maximum Principal Stress at mid height of layer i*

σ' = *Reference Stress (0.1 MPa)*

7. Multiply the sub layer thickness with the plastic strain for the sub-layer to obtain the rut depth for that sub layer.

8. Sum the rut depths for each layer to get the total rut depth occurring in the granular layers.

$$RD = \Sigma \in_{pi} \cdot h_i$$

Where

$$RD = Rut\ Depth\ in\ granular\ layers$$
$$\in_{pi} = Permanent\ Strain\ in\ Sub\text{ - }layer\ i$$
$$h_i = Thickness\ of\ Sub\text{ - }layer\ i$$

9. If RD is larger than the allowable figure determined in Part 3 a better material may be required. Or if the subbase is being considered the basecourse may need to be thicker to reduce the stress on the subbase.

Determination of Parameters for the Model.

The parameters for the model can be determined by conducting two RLT tests on each material at different stress levels. For materials which are to be used as base course it is recommended that the upper stress level for the testing should have the following parameters, 1 equals the tyre contact stress and 3/ 1 = 0.4 (as per AS1289.6.8.1 for resilient modulus testing). The lower level stress values should be determined by analysis with CIRCLY. For materials to be used as subbase both the upper and lower values of stress to be used in the RLT tests should be determined from an initial analysis with CIRCLY.

The RLT tests should be conducted as saturated, undrained tests to be conservative and the samples compacted to 95% MDD as per the current standard for construction.

If only one RLT test has been conducted an estimate of the parameter A can be made from the equation (Ullidtz, 1987)

A = (5/CBR) * 0.07

and the parameters B and C can be determined from the RLT.

Formulae for calculating the parameters are given in Example 1 below:

Example: 1 RLT & CBR Design Method for Basecourse

1. Design pavement depth (100, 000 ESA)

	Depth (mm)	Ev (MPa)
Basecourse	150	500
Subbase	240	Sub layer
Subgrade		50

2. Total allowable rut depth in pavement 25 mm.

3. Total allowable rut depth in basecourse 5 mm.

4. Sublayer basecourse in 5 layers

Layer	Depth (mm)		Mid depth (mm)
	From	To	
1	0	30	15
2	30	60	45
3	60	90	75
4	90	120	105
5	120	150	135

5. Circly analysis

Layer	Mid depth (mm)	Principal Stress (MPa)	
		$\sigma1$	$\sigma3$
1	15	0.5455	0.3904
2	45	0.5046	0.2165
3	75	0.4247	0.06954
4	105	0.3495	0.009974
5	135	0.2629	-0.0284

6. Plastic Strains

$$\epsilon_p = A * N^b \left(\frac{\sigma_1}{\sigma'} \right)^c$$

A	0.0011294
N	100,000 Cycles
b	0.306
c	2.4071982
	0.1 MPa

Layer	Stress (MPa) σ1	Strain (%)
1	0.5455	2.272327
2	0.5046	1.883620
3	0.4247	1.243880
4	0.3495	0.778117
5	0.2629	0.392084

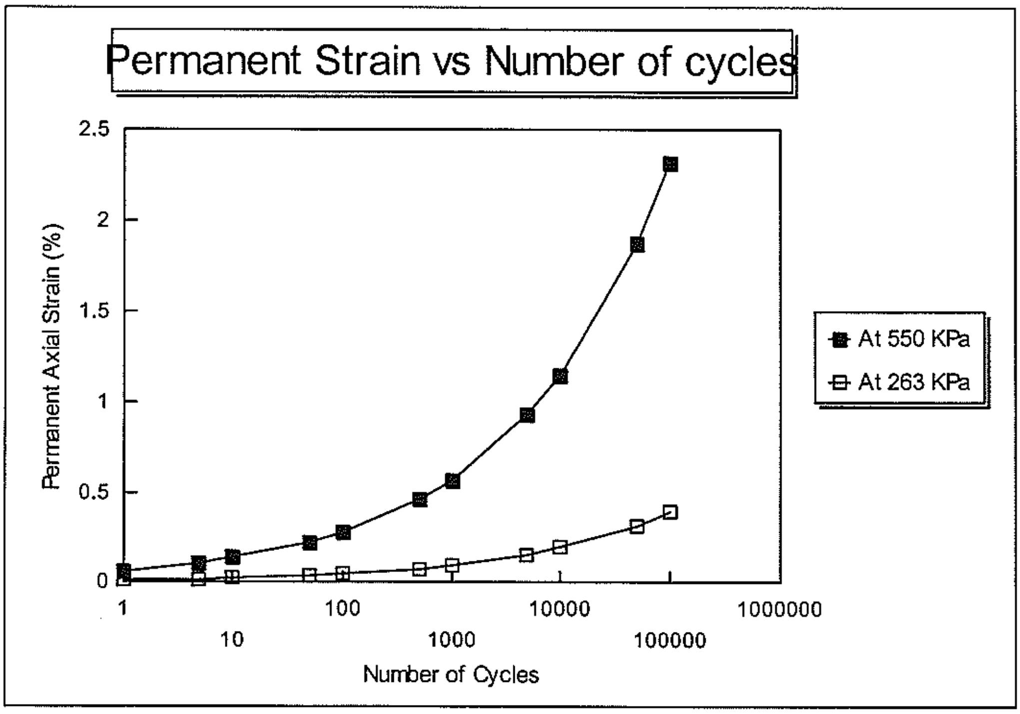
7. Multiply sublayer thickness with plastic strain to get rut depth for sublayer

Layer	Strain	Layer Depth (mm)	Rut depth (mm)
1	0.02272327	30	0.682
2	0.01883620	30	0.565
3	0.0124388	30	0.373
4	0.00778117	30	0.233
5	0.00392084	30	0.118

8. Total Rut depth, RD = Σ 1.971

9. Check RD is less than allowable value in section 3.

1.971 < 5mm OK



<u>**Notes :**</u>

Determining parameters for Ullidtz Equation

Using the Circly analysis repeat load triaxial tests have been conducted at 550 kPa and at 263 kPa

Work out parameters from Curve 1 (550 kPa) experimental data only

CBR	309.9		
Curve	Strain	n	sigma 1
Curve 1	0.566317	1000	0.55
Curve 1	2.317713	100000	0.55

Calculations

A	0.0011294
b	0.306
c	2.4072145

Where

$$b = \frac{Log\left(\varepsilon_{p,c1,n=1,000}\right) - Log\left(\varepsilon_{p,c1,n=100,000}\right)}{Log(1,000) - Log(100,000)}$$

$$c = \frac{Log\left(\varepsilon_{p,c1,n=100,000}\right) - Log(A) - bLog(100,000)}{Log\left(\frac{\sigma_{1,c1}}{0.1}\right)}$$

$$A = 0.07\left(\frac{5}{CBR}\right)$$

Work out parameters from Curve 1 (550 kPa) and Curve 2 (263 kPa) experimental data

Curve	Strain	n	sigma1
Curve 1	0.566316996	1000	0.55
Curve 1	2.317712675	100000	0.55
Curve 2	0.392442989	100000	0.263

Calculations

b	0.306
c	2.4071982
A	0.001129431

Where

$$b = \frac{Log\left(\varepsilon_{p,c1,n=1,000}\right) - Log\left(\varepsilon_{p,c1,n=100,000}\right)}{Log(1,000) - Log(100,000)}$$

$$c = \frac{Log\left(\varepsilon_{p,c1,n=100,000}\right) - Log\left(\varepsilon_{p,c2,n=100,000}\right)}{Log\left(\frac{\sigma_{1,c1}}{0.1}\right) - Log\left(\frac{\sigma_{1,c2}}{0.1}\right)}$$

$$A = \frac{\varepsilon_{p,c2,n=100,000}}{100,000^{b}\left(\frac{\sigma_{1,c2}}{0.1}\right)^{c}}$$