IMPROVED CHARACTERISATION OF UNBOUND PAVEMENT MATERIALS – DEVELOPMENT, VALIDATION AND IMPLEMENTATION

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ABSTRACT

Current work in the characterisation of unbound pavement materials being conducted in Australia focuses on bridging of the gaps between research and practical applications. This has been demonstrated through the adoption of a simple repeated load triaxial (RLT) test as a National laboratory test that can be used to obtain materials data for use in performance-based material specifications, construction standards and mechanistic pavement design procedures. With the collaboration of other laboratories and industry, RLT testing equipment and test procedures have been standardised and field trials conducted to establish relationships between RLT test results and field performance. Potential changes in the current material specifications, construction standards and mechanistic pavement design procedures based on the use of RLT test results are identified and discussed. Strategies for the interim and full implementation of the test method into practical applications are also proposed in the paper.
1. INTRODUCTION

In Australia, because of the vast area of the continent and the long distances involved and for reasons of climate and economy, roads are typically low-cost, light construction granular pavements. Currently, about A$6 billion is spent annually on enhancing and preserving the Australia’s 810,000 km road network, which consists of nearly 500,000 km of unsealed granular roads and 280,000 km of sealed granular roads. Thus, any improvements in material specifications, construction standards, new construction/rehabilitation design procedures and maintenance strategies for granular pavements would represent a significant reduction in total operation cost of the road network.

Laboratory and field characterisation methods for material and pavement behaviour and performance have played an important role in the development of material specifications, construction standards, new construction/rehabilitation design procedures and maintenance strategies. This paper presents an overview of recent development and validation of the advanced laboratory repeated load triaxial (RLT) test for characterisation of unbound pavement materials. Based on results obtained from extensive RLT testing programs on various unbound materials, potential changes in the current material specifications, construction standards and design procedures are identified and discussed. The strategies for the interim and full implementation of the test method into practical applications are also outlined.

2. BACKGROUND

Australia has had a long and successful history in building, using and maintaining road network with granular pavement type with thin bituminous surface seals. Characteristically, the majority (about 78%) of the sealed roads were constructed in the fifties and sixties for lightly-traffic rural and urban roads (with a design life of <10^6 Equivalent Standard Axles). Extensive experience in building rural roads resulted in typical pavements of full width construction (i.e. with single carriageway with crown cross-section with unsealed shoulders) and with 200 to 300mm of locally raised natural gravels or quarried and crushed materials to support bituminous “chip” seals. For urban roads, boxed construction was used to reduce the moisture effects on pavement performance. In the seventies, in competing with heavy-duty bound pavements, heavy-duty asphalt surface granular pavements were also successfully built for heavily-trafficked arterial roads and state highways to meet the increasing volume and mass of road freight vehicles. Different from the rural roads, these pavements had multiple-lanes with one-way cross-falls and with sealed shoulder to reduce the moisture effects on pavement performance.

The age and condition of the network with sealed roads suggests that significant costs of major re-construction/rehabilitation works and maintenance/pavement preservation will be spent in the next two decades, if it is to continue to meet the road users needs and expectations. Thus, there are needs to develop:
- improved performance-based material specifications, construction standards, new construction/rehabilitation design procedures for unbound granular pavements; and
- cost-effective asset management strategies for the aging road network.

These will assist the road managers in decision making, in terms of fund allocation for road works, selection of road treatment and the timing of that treatment.

In principle, low-cost unbound granular pavements have the following common performance characteristics.
- Major ‘structural distresses’ are deformation (rutting, shoving, depression, corrugation), surface cracking of the thin asphalt surface layer or the surface seal, and surface defects (ravelling, pothole formation).
Pavement and subgrade properties can be highly variable and sensitive to compaction, moisture and applied load. Therefore, there is a high risk of local pavement failure, which is the attribute of the increase in roughness (functional distress) during the pavement life.

Seal may have a relative shorter life than pavement deformation life and require frequent minor seal works, which can also influence the development of structural distresses and roughness during the pavement life.

Therefore, it is essential that laboratory and field characterisation methods for unbound material pavements be able to directly (or indirectly) measure the above performance characteristics and assess the risks associated with local pavement failure due to variable compaction, moisture entry and overloading. In addition, these test methods must meet the requirements of a practical tool, i.e. low cost, simplicity, reliability and reproducibility. On the above basis, many simple laboratory/field tests for aggregates and in service pavement behaviour and performance have been developed for use in the past, such as:

- Basic aggregate tests for material specifications, such as hardness and durability (Los Angeles abrasion, Washington degradation), particle size distribution (PSD), shape (Flakiness Index), fines (Liquid Limit, Linear Shrinkage, Plasticity Index), water absorption (WA), permeability, etc.
- Compaction, density and moisture tests for compaction and moisture specifications, such as Standard and Modified compaction, Sand Replacement.
- Laboratory loading tests for investigation of material behaviour and performance for design purpose, such as California Bearing Ratio (CBR), static triaxial shear test.
- Field loading tests for investigation of in situ properties and pavement behaviour for design purpose, such as Dynamic Cone Penetration, Benkelman beam, etc.
- Surveying methods for maintenance purpose, such as rutting (straight edge) and roughness (NAASRA roughness meter).

Comprehensive reviews of most aspects of material specifications, construction standards, pavement design and road maintenance of unbound pavement materials are contained in NAASRA (1975a, b, and 1996). In principle, current material specifications, construction standards and pavement design procedures adopted by different SRAs were developed based on basic aggregate tests and simple engineering test (e.g. CBR), and their relationships with observed field performance and/or results of simple engineering tests. Different tools were used by different SRAs, and their nature was often empirical and mainly for ranking purpose. In addition, interpretation of their results was also based on previous local experience, local material, local construction technique, local environment and local traffic. Different levels of conservatism applied in design procedures and pavement maintenance strategies were also applied for different pavement classes in different states. This was reflected by the differences in design terminal structural condition for rutting and cracking and maintenance acceptable standards for roughness. As a result, these material specifications, construction standards, pavement design procedures and pavement maintenance strategies were empirical and were significantly different. Although they are performance-based, it is difficult to compare and validate them.

In recent years there has been widespread acceptance of new ‘mechanistic’, or ‘structural’, pavement design procedures, such as those adopted in the Austroads (1992) Pavement Design Guide. They provide an analytical framework for the selection of the most appropriate design thickness for different materials, loading and environmental conditions. However, the Austroads mechanistic design procedures for granular pavements with thin bituminous surfacings do not explicitly provide for the varying permanent deformation characteristics of unbound pavement materials. The contribution of a granular layer to the overall pavement performance is merely based on ‘assumed’ values of layer moduli and no consideration is given to the particular permanent deformation characteristics of the individual granular material. Therefore, the Austroads procedures do not enable quantification of the effects on performance of different material specifications and construction standards.
To combat with these demands has led to an evolution of advanced laboratory and field characterisation tools and performance models associated with these tools for use in improved performance-based material specifications, construction standards, mechanistic design procedures and rationalised maintenance strategies. Among those, laboratory testing methods for the estimation of the engineering properties of pavement materials, which are related to field performance, is considered one of the most effective and economical means of linking performance-based specifications, construction standards and mechanistic pavement design.

3. DEVELOPMENT OF IMPROVED LABORATORY CHARACTERISATION METHOD

Having recognised the potential of the laboratory repeated load triaxial (RLT) test (APRG 1991, 1993, 1995), Austroads committed itself to improving the existing routine test method based on the simple RLT test (Standards Australia 1995). With the collaboration of laboratories throughout Australia, Austroads has funded both inter-laboratory precision studies to standardise the testing equipment and test procedures, and studies to establish relationships between laboratory RLT test results and field performance. Austroads is now in a position where it can focus on using RLT test results to improve material specifications and construction standards and to provide input into mechanistic pavement design procedures.

The improved Austroads RLT test method is described in Vuong and Brimble (2000). This test method covers the determination of stress dependent characteristics of the permanent deformation and resilient modulus of unbound pavement materials with a maximum particle size not exceeding 19 mm using repeated load triaxial equipment with static confining pressure and external vertical displacement measuring devices, under drained (or undrained) conditions, without pore pressure measurement.

Extensive interlaboratory studies have been carried out by the APRG Working Group of RLT Users (AWGRU) (Vuong 1997, Vuong et al. 1998, Vuong and Tepper 2000) to assist in the development of sample preparation procedures and specifications of testing equipment and software for this test method. They also allowed the limitations of the routine RLT testing method to be identified and assisted in the development of procedures for resilient modulus and permanent strain testing and for the interpretation of test results. They are briefly described below.

Sample Preparation Procedure

Vuong (1997a) demonstrated that the effects of the method of compaction (and hence degree of anisotropy) on resilient modulus and permanent deformation were very significant (see Figure 1). In the absence of field moduli and permanent strain data, it was decided that only one sample preparation procedure, namely dynamic compaction method, be used in the test method, with the possibility of including other methods when more reliable field data became available.

Interlaboratory studies (Vuong and Tepper, 2000) has also demonstrated that different compaction patterns produced by automatic (mechanical) and hand (manual) compaction apparatus significantly influenced the test results. Therefore, the automatic (mechanical) compaction apparatus, which permits a continuous and even compaction mode, was adopted. Hand compaction apparatus was also allowed, but with application of a continuous compaction pattern as that applied by automatic compaction equipment.

Specifications of Testing Equipment and Software

Interlaboratory studies conducted by AWGRU (Vuong 1997, Vuong et al. 1998, Vuong and Tepper 2000) identified a number of factors related to RLT testing apparatus and software that significantly influenced the test results. The following modifications to the testing equipment and software were subsequently made to improve the repeatability and reproducibility of the test results:
• Sample resilient strain is now measured with two 5 mm external displacement transducers mounted externally on the loading shaft to reduce errors due to noise and sample bending.
• Loading friction in the triaxial cell is reduced so that no correction would have to be made for the effects of loading friction on the measured resilient modulus.
• Improved loading system to effectively control dynamic vertical stress (viz. reducing static seating stress to <5 kPa) and static confining stress (viz. reducing the dynamic stress to <1 kPa with the use of an air-water interface).
• Improved software to control dynamic vertical stress and static confining stress, and record and report their loading characteristics (static seating stress, noise level, etc) during resilient modulus and permanent strain testing. The 10 points running average filtering technique (rather than the 2 points running average) was incorporated into the software to further reduce noise levels and hence increase the allowable ranges of applied stress and sample stiffness.
• The software is now more user-friendly.

An equipment calibration procedure was also introduced to calibrate the stiffness of the testing system using the proving rings, and to check noise levels in the system outputs. This provides a means to correct the modulus measured with external displacement transducers for system stiffness. Up to 30% correction is allowed. Above this range, two 5 mm internal displacement transducers should be mounted between the top and bottom loading caps to measure the sample resilient modulus.

**Testing Procedures and Test Results**

**Permanent Deformation Testing**

The simplified permanent deformation testing procedure characterises the vertical permanent deformation at three stress conditions in the bases, viz. using three levels of dynamic vertical stress of 350, 450 and 550 kPa and a static lateral stress of 50 kPa, each stress condition consisting 10,000 repetitions. Based on the test results, stress-dependent characteristics of permanent strain for the material can be determined. Multiple tests at different density and moisture conditions may be required to assess the sensitivity of moisture and density of the material.

![Figure 2](image1.png) shows typical results obtained from permanent deformation testing. Several test values (deformation rate per 1000 cycles, incremental deformation after the first 100 cycles, maximum deformation after each loading stage, etc) can be extracted from the test results for use in assessing the potential for permanent deformation in the field. There is concern that permanent deformation developed in the first few cycles can significantly vary depending on the initial imperfections in each sample. Therefore, the total permanent strain of the first loading stage, if it is small, is not as reliable and consistent as the ‘incremental permanent strain’ measured after some pre-loading cycles.

**Resilient Modulus Testing**

The resilient modulus testing procedure characterises the vertical resilient strain response over sixty stress conditions using combinations of applied dynamic vertical and static lateral stresses in the ranges of 100-600 kPa and 20-150 kPa, respectively. Based on the test results, stress-dependent characteristics of resilient modulus for the material can be determined.

![Figure 3](image2.png) shows typical results obtained from resilient modulus testing. Test values at representative stress conditions in the unbound layers can be extracted from the test results for use in assessing the layer stiffness in the field.

**Repeatability and Reproducibility**

Interlaboratory precision studies of permanent strain and resilient modulus (Vuong and Tepper 2000) indicated that the modifications to the testing equipment, software and test procedures
have resulted in repeatable results of permanent strain and resilient modulus (see Figure 4). Therefore, practitioners should now be able to use these parameters in practical applications with confidence.

4. VALIDATION OF RLT RESULTS USING FIELD AND FIELD PERFORMANCE

Three field trials have been conducted, or being conducted, and one of the aims of these trials is to obtain relationships between RLT test results (i.e. resilient modulus and permanent deformation) and observed field performance under service conditions. These are as follows:

- Load Equivalency and Insitu Stabilisation ALF Trial, Dandenong, Victoria;
- Deer Park Quarry haul road field trial, Victoria; and.
- Penrice Quarry haul road field trial, South Australia.

Dandenong ALF Trial

The Dandenong ALF trial involved the trafficking of two unbound granular bases, namely a high quality crushed rock and an ‘oversize’ marginal sandstone. The pavement structure was seen as typical of arterial road applications, i.e. an bituminous seal 30 mm thick and a total crushed rock thickness of 200 mm on a subgrade with a laboratory soaked CBR of 3. The results of the trial are reported in Vuong and Sharp (1997). The results of resilient modulus obtained from the laboratory testing program conducted by ARRB TR using three different compaction methods (static, vibratory and dynamic compaction) are also reported in Vuong (1998a). The results of permanent strain obtained from the laboratory testing program conducted by Transport SA using static compaction are also reported in Andrews (1997).

Field layer moduli of the crushed rock and sandstone were estimated from back-calculation of pavement deflection bowls measured with the Falling Weight Deflectometer (Vuong 1998a). Comparisons between the back-calculated and laboratory-predicted layer moduli of the crushed rock and sandstone (see Figure 5) indicated that:

- The back-calculated crushed rock layer moduli appeared to be very similar to the laboratory-based moduli of crushed rock specimens prepared using vibratory and dynamic compaction, but were much higher than those of crushed rock specimens prepared using static compaction.
- The back-calculated sandstone layer moduli appeared to be much higher than the laboratory-based moduli. It should be noted that because large crushed stone particles (>20 mm) were excluded in the preparation of the laboratory sandstone specimens, the laboratory and field particle size distributions were different. However, it was not possible to quantify the effects of particle size and size distribution on the resilient modulus of sandstone used in this study. Therefore, there were uncertainties regarding the relationships between the laboratory-predicted and back-calculated layer moduli of the sandstone base.

The results from this trial supported the use of dynamic compaction in the current Austroads RLT test method. However, further laboratory testing to quantify the effects of particle size and size distribution on the modulus of sandstone is required to establish the test procedures for ‘oversize’ materials.

RLT test results were also used as input into NONCIRL to predict permanent deformation of the crushed rock and sandstone pavements (Vuong and Sharp 1997). Comparisons between the observed pavement deformation and laboratory-predicted pavement deformation of the crushed rock pavement (see Figure 6) indicated that the laboratory-predicted pavement deformation was:

- higher than the measured deformation over the first 10 kcycles, when surface deformation was less than 10 m, but
- lower in the later loading stages, when the surface deformation was more than 15 m and the AC seal was cracked.
It should be noted that the prediction was based on sound AC condition, which is different from the condition of the cracked AC during the “phase 2” (after cracking) life of the pavements. Therefore, there were uncertainties regarding the relationships between the observed and laboratory-predicted pavement deformation, particularly during phase 2 (after cracking). A more comprehensive analysis is required to simulate the material condition in both phases of the pavement life. Laboratory permanent deformation data for three different compaction methods (static, vibratory and dynamic compaction) is also required to compare with field performance and select the most appropriate compaction method for permanent strain testing.

**Deer Park Quarry Haul Road Field Trial, Victoria**

The trial was established in January 1999 by Boral, VicRoads and ARRB TR. In this trial, one quality crushed rock (S2) and three marginal crushed rocks (S1, S4, and S5) and a marginal sandstone (S3) are being tested. The pavement structures were granular pavements with sprayed seal, with a total pavement thickness of 300 mm being placed on an existing pavement, which already had a crushed rock base thickness of 100-250 mm on a subgrade of CBR 10-25. The results of the trial are reported in Vuong et al. (2000). The results of laboratory results obtained from the associated laboratory testing program using the current Austroads RLT test method (using dynamic compaction) are reported in Vuong and Tepper (2000b).

The construction of the trial pavements did not meet the expectations of the trial design in terms of uniformity in thickness (see Figure 7) and to a lesser extent density (see Figure 8). However, in practice this was to be expected considering the differences between the materials being placed and the differences in the moisture content at compaction. It is important that the practicalities and issues raised in the construction of this trial be noted for future reference where other trial pavements are being considered.

Although there were significant differences in pavement stiffness between the trial pavements (see Figure 9), all pavements appeared to perform satisfactorily in terms of rutting and roughness in the past 14 months (see Tables 1 and 2).

<table>
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<tr>
<th>Lane</th>
<th>Wheelpath</th>
<th>Offset (m)</th>
<th>Roughness IRI (m/km) (NAASRA (c/km))</th>
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<th>27/03/99</th>
<th>11/6/99</th>
<th>11/11/99</th>
<th>24/3/00</th>
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<tr>
<td>West Bound</td>
<td>IWP</td>
<td>5.0</td>
<td>4.33 (113)</td>
<td>4.17 (109)</td>
<td>4.19 (110)</td>
<td>4.19 (110)</td>
<td>4.35 (114)</td>
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<tr>
<td>West Bound</td>
<td>OWP</td>
<td>3.2</td>
<td>4.42 (116)</td>
<td>4.18 (109)</td>
<td>4.01 (105)</td>
<td>4.19 (110)</td>
<td>4.09 (107)</td>
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<td>IWP</td>
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<td>4.15 (109)</td>
<td>3.94 (103)</td>
<td>4.30 (113)</td>
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<tr>
<td>East Bound</td>
<td>OWP</td>
<td>8.8</td>
<td>-</td>
<td>3.63 (95)</td>
<td>3.64 (95)</td>
<td>3.76 (98)</td>
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<table>
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<th>Max. Rut Depth (mm)</th>
<th>Mean Rut Depth (mm)</th>
<th>Max. Rut Depth (mm)</th>
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</table>

This indicates that material ranking based on stiffness may not necessarily agree with material ranking based on deformation (rutting). Given the 2-3 mm mean rutting observed after 14 months trafficking, it is anticipated that the Haul Road will need to be monitored for at least 5 years before reliable data on the relative performance of the five test materials can be obtained.
Initial back-analyses of layer moduli from HWD deflection (Vuong et al. 2000) indicated that the back-calculated layer moduli of the top base layer (plus sprayed seal) varied significantly with the layer thickness (see Figure 10). There was also concern that there was significant variation in moisture and density in the top layer that could influence the layer modulus. Therefore, laboratory modulus testing of field samples of the surface seal and top base layer is required to confirm the range of back-calculated modulus of this layer. Further density and moisture testing using the Nuclear Density Gauge is also required to correct the moisture in the top base layer (for the effect of the bituminous seal on the gauge reading) and to determine the variation of moisture in the top base layer.

Back-calculated moduli for the subbase layer the depth between 100-200 mm were found to be more stable. Figure 11 shows the preliminary comparison of the subbase layer moduli of the five materials of different quality (S1, S2, S3, S4 and S5) with laboratory results at the stress stage with dynamic deviator stress of 350 kPa and a static confining pressure of 50 kPa. The results indicated that the laboratory-predicted sub-base moduli appeared to be very similar to the back-calculated moduli. This was also considered as most encouraging.

Penrice Quarry Haul Road Field Trial, South Australia

In this trial, three marginal materials are being tested, namely a 20 mm rubble, a 30 mm scalps, and a by-product of soda ash production (70:30 blended 30 mm aggregate and limestone grits). The trial was established in December 1997 by Transport South Australia (TSA). Pavement response and field performance is being monitored by TSA, and laboratory RLT testing of the materials will be conducted by ARRB TR in order that relationships between the RLT results and field performance can be established. Results of the trial will be reported in a later stage.

5. POTENTIAL CHANGES IN CURRENT PRACTICE

One of the objectives in the development of improved performance-base material specification, and construction standards is to investigate the potential changes in the limits applied in the current material specifications and construction standards using this device and their links with the mechanistic design procedure. For this purpose, extensive RLT testing programs on granular materials have been conducted to examine and compare the limits applied in the current specifications and construction standards to those that meet the requirements for modulus and permanent deformation. Some findings from this investigation are given below.

Improved Construction Standards and Moisture Specifications

Current specifications of density and moisture content for base materials vary between state authorities, e.g. 98% modified (or 102% standard) and 70% OMC (or 70% saturation), but the reasons for these differences are not clear. It has been shown in laboratory RLT testing that the effects of compaction and moisture on permanent deformation and resilient modulus can be very significant and that the variation in permanent deformation and resilient modulus with compaction and moisture was greater for some unbound materials than for others (see Figure 12 and Figure 13). Therefore, it is possible to specify different compaction standards and moisture specifications to different materials based on RLT test results.

Improved Performance-based Material Specifications

Current specifications of fines-plasticity, percentage fines and grading for base materials vary between state authorities. It has also been shown in laboratory RLT testing that the effects of fines-plasticity and fines content on permanent strain and resilient modulus are very significant and also vary differently with different ranges of density and relative moisture content (see Figure 14 and Figure 15). However, for the range of grading accepted for both base and subbase materials (i.e. grading exponent between 0.3-0.5), the effects of grading on permanent deformation and resilient modulus were found to be insignificant for at high compaction
 (>98% MDD). Therefore, it is possible to relax the limits of plasticity index, fines content and grading for different materials and different moisture and compaction levels.

**Improved Mechanistic Design Procedures**

Given that permanent strain is more sensitive to material properties, compaction and moisture than resilient modulus, it is a critical design parameter for granular pavements. Current Austroads mechanistic design procedures (Austroads 1992) do not enable quantification of the effect on performance of different permanent deformation characteristics of granular materials. RLT test results will provide material inputs to take into account deformation characteristics of the granular layers for different materials at different compaction standards and moisture specifications. This will lead to more reliable and uniform mechanistic design procedure that can be used in different environments.

Preliminary studies have been carried out to develop procedures for predicting pavement rutting and shoving from laboratory-based permanent deformation and resilient modulus, which can be used to improve the current the Austroads mechanistic design procedures (e.g. using the computer model NONCIRL developed by Vuong 1991). Emphasis has been placed on the development of simple equations for both permanent deformation and resilient modulus for the following reasons:

- Limitation of the simple RLT test, i.e. the test cannot simulate stress conditions in actual pavements under rolling wheel loads.
- Limitation of the linear-elastic layer model CIRCLY adopted by Austroads, i.e. CIRCLY cannot simulate no-tension behaviour of unbound material and, therefore, cannot accurately predict horizontal stresses and strain in unbound layers.
- Inability of linear elastic models to simulate variation in modulus with horizontal stress within a layer, i.e. for a specified unbound layer (or sub-layer), it requires only a representative stress condition to calculate the layer deformation and layer modulus.

**Relationships for Permanent Deformation**

Two simple relationships for permanent deformation are considered as given in Equations (1) and (2).

\[
\varepsilon_{p,N} = A N^\alpha \\
\varepsilon_{p,N} - \varepsilon_{p,100} = B \log_{10} \left( \frac{N}{100} \right)
\]

where \( \varepsilon_{p,N} \) = total vertical permanent strain for the Nth cycle
\( \varepsilon_{p,100} \) = total vertical permanent strain for the 100th cycle
\( \varepsilon_r \) = vertical elastic strain
\( N \) = number of loading cycles
A, B and \( \alpha \) = material parameters, which can vary depending on stresses and strains

Equation (1) is used to fit the total permanent strain. Equation (2) is used to fit the incremental strain after 100 loading cycles to avoid the problems associated with bedding errors in the first 100 cycles as mentioned previously. Both equations were found to fit closely well with experimental results for the first loading stage in the permanent strain testing (see Figure 16).

It also requires a procedure for deriving the model parameters A, B and \( \alpha \) from the results of the vertical permanent deformation at other stress conditions applied in the permanent strain testing. In this case, the NONCIRL procedure (Vuong 1991, 1994) as illustrated in Figure 17 can be used to calculate equivalent loading cycles of a reference stress (N\text{Equivalent}, \sigma_{\text{Reference}}) that results in the same permanent deformation as that under a number load cycles of applied
stresses \( N_{\text{Applied}}, \sigma_{\text{Applied}} \). This procedure assumes a hardening rule in the calculation of cumulative deformation.

Typical examples of permanent strain curves that have been fitted with Equations (1) and (2) using the NONCIRL procedure for calculating equivalent loading cycles are given in Figure 18. The results indicate that the calculated permanent strain loading curves fit very closely to experimental results. Further interlaboratory testing on various materials is required to confirm the applicability of this interpretation procedure for practical applications.

It should be noted that most structural models (particularly linear-elastic layer models) could not simulate no-tension behaviour of unbound material and, therefore, could not accurately predict horizontal stresses and strain in unbound layers (Vuong 1985, Vuong et al. 1987). Therefore, it is more appropriate to express the parameters A, B and \( \alpha \) in Equations (1) and (2) as a function of vertical strain or vertical stress. Further interlaboratory testing on various materials is required to confirm the applicability of these equations in routine testing.

**Relationships for Resilient Modulus**

Two 2-parameter relationships for resilient modulus have been considered for use as given in Equations (3) and (4).

\[
E_r = K_1 (\sigma_m/\sigma_{\text{ref}})^{K_2}. \\
E_r = [(A +B qr)/qr]. \sigma_m
\]

where \( \sigma_m = (\sigma_1 + 2 \sigma_3)/3 = \text{mean normal stress} \)

\( qr = (\sigma_1 - \sigma_3) = \text{dynamic deviator stress} \)

\( \sigma_1, \sigma_3 = \text{vertical and confining stress} \)

\( \sigma_{\text{ref}} = \text{reference stress (100 kPa or 0.1 MPa)} \)

Equation (3) is adopted in the Austroads Pavement Design Guide. Equation (4) was developed by Nadjamadtu (1991). Both equations were found to fit closely with experimental results in elastic region (with inverse stress ratios higher than 0.15 or stress ratios lower than 7), but not fitted well with results with high stress ratios near failure condition (see Figure 19).

Other 3-parameter models such as that expressed in Equation (5) can be used to enable better fitting of experimental results obtained over a larger stress range.

\[
E_r = K_1 (\sigma_m/\sigma_{\text{ref}})^{K_2}. \sigma_3/\sigma_1)^{K_3}
\]

However, further interlaboratory testing on various materials is required to confirm the applicability of these equations in routine testing.

**Evaluation of Non-Standard Materials**

“Non-standard” materials include industrial waste products such as slag, wastes from quarrying generation, crushed concrete as well as local materials. Currently, there is no performance-based specifications for non-standard materials.

Figure 20 shows the values of number of loading cycles to failure strain (selected as 1% strain) and resilient modulus at different loading stresses, which are derived from the permanent strain testing on a non-standard material (sandstone) and standard bases and subbases (crushed rocks). At high loading stress (typical of that in a base layer), the high quality base had a higher deformation life and higher modulus (hence lower subgrade deformation) than the non-standard material and subbases. However, a reverse trend was observed at a low stress level (typical of that in lower sub-base layer). This demonstrates the ability of the RLT test to predict/assess (i) the relative performance of different materials in terms of number of loading cycles to failure.
strain, (ii) the relative load damage factor for the materials concerned, and (iii) the relative performance of the materials for use in different layers in pavements and under different loading conditions.

The use of the RLT test to determine the resilient modulus and permanent deformation characteristics of non-standard materials will enable their characteristics to be compared with the properties of standard materials. This should encourage the wider use of non-standard materials and also the evaluation of other new or innovative materials. It is also possible to extend the use of RLT testing program to the evaluation of lightly-stabilised (modified) materials, which are considered to behave as unbound materials.

It should be also noted that past construction experience indicated that the requirements of construction (compaction and material handling), drainage design (permeability) and material performance (strength, stiffness and permanent deformation) can contradict each other. Therefore, for new materials that do not have previous field performance data, it is essential that a full characterisation testing program (viz. using multiple tests at different density and moisture conditions) must be carried out to allow the assessment of the sensitivity of moisture, density and loading of the material as compared to that of standard crushed rocks. The use of a new non-standard material must also be supported by field trials to ensure that all the construction and drainage requirements are met.

6. STAGING OF IMPLEMENTATION

As already discussed previously, the RLT test provides a means of linking performance-based-specifications, construction standards and mechanistic pavement design procedures. However, the development of a National procedure based on RLT testing has not yet reached the stage where RLT testing can be used to estimate the absolute performance of materials. Further laboratory RLT and field trials are still required to (i) fully validate the relationships between RLT results and field performance and (ii) establish procedures for incorporating RLT results into performance-based-specifications, construction standards and mechanistic pavement design procedures. Therefore, the full implementation of this testing method into practical application is still some time away.

In the interim, the development of relationships between RLT test results (resilient modulus and permanent strain) and observed field performance (stiffness and rutting) will enable the relative performance (rather than the absolute performance) of materials to be evaluated. On this basis, it is possible to use the test to determine the relative performance of materials and hence current empirical specification limits. It is also possible to use the test to assess/quantify the risks (in terms of relative performance) associated with changes in moisture, compaction and loading. This may lead to more uniform SRA material specifications and compaction standards, and also encourage more use of “non-standard” materials.

The implementation of interim procedures for the use of RLT results is considered essential in the development of the final procedures, as it will:
- increase awareness of the potential use of the RLT test among practitioners;
- assist in the smooth transition from empirical material specifications, construction standards and pavement design procedures to more performance-based specifications and improved mechanistic pavement design procedures, and
- encourage more laboratory and field data to be collated, which will assist in the development, validation and enhancement of performance-based specifications, construction standards and mechanistic pavement design procedures.

7. SUMMARY

This paper has described the development and validation of a National routine laboratory RLT test method, which can assist in the development of rational performance-based specifications, improved construction standards and improved methods for predicting pavement performance.
With the collaboration of ARRB TR, the SRAs and industry in Australia, Austroads has been able to:
- develop the Australian Standard specifications for test equipment and testing procedures for the RLT test and develop low-cost equipment and software which meets the required standards; and
- establish and conduct field trials for the derivation of relationships between laboratory RLT test results and field performance.

The results obtained from inter-laboratory precision studies of resilient modulus and permanent strain testing conducted by Austroads Working Group of RLTT Users indicated that the improved testing equipment, software and test procedures could produce repeatable and reliable results between laboratories. Limited field studies to date have also indicated that, although the test may not produce absolute results, there were direct relationships between the RLT results and field performance. This is regarded as most encouraging and practitioners can now have more confidence in applying the test to applications ranging from the ranking of materials to input into mechanistic pavement design procedures.

Some potential changes in current material specifications, construction standards and pavement design procedures by adopting the test method have been identified in this paper. To fully implement this testing method into practical application requires further laboratory RLT and field trials to (i) validate the relationships between RLT results and field performance and (ii) establish procedures for incorporating RLT results into performance-based specifications, construction standards and mechanistic pavement design procedures.

It is propose that the interim implementation of the test method into practical applications be adopted to assist in the smooth transition from the current empirical material specifications to performance-based specifications, and also the implementation of quality assurance contracts and mechanistic pavement design procedures that have been recently introduced in Australia.

As over 95% of Australia's sealed road network consists of unbound pavement materials with a thin bituminous surfacing, it is anticipated that the adoption of this National routine test will lead to significant reduction in road agency costs, through:
- the more effective use of unbound materials;
- more cost-effective testing protocols;
- improved procedures for the assessment of non-standard, recycled and modified unbound materials;
- the availability of a wider information base on the use of these materials and associated innovative practice; and
- ecologically sustainable development in relation to roads.
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The views expressed in this paper are solely those of the Author and do not represent those of mentioned organisations or others.
Montrose crushed rock: 75% OMC, 98% MDD

(a) Permanent strain

(b) Resilient modulus

*Figure 1 - Comparison of permanent strain and resilient modulus obtained with different laboratory compaction methods*
Figure 2- Typical results obtained from permanent deformation testing
Figure 3 - Typical results obtained from resilient modulus testing
Repeatability and Reproducibility of Corrected Permanent Strain
(6 laboratories using automatic compaction method)

(a) Permanent strain

Repeatability and Reproducibility of Resilient Modulus

(b) Resilient modulus

Figure 4 - Repeatability and reproducibility values of permanent strain produced by laboratories using automatic compaction method
Figure 5 - Comparisons between the back-calculated and laboratory-predicted layer moduli (Dandenong ALF trial)
Figure 6 - Comparison of measured and predicted maximum deformation (Dandenong ALF trial)
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(a) Density ratio

(b) Moisture Ratio

Figure 8 - Variation in base layer compaction and moisture ratio (Deer Park Trial)
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(a) Maximum Deflection

(b) Curvature (D0-D200)
Figure 10 – Variation of back-calculated modulus with thickness and depth
Figure 11 - Preliminary Comparison of Laboratory and Field Moduli
Stress Condition 1

0.00 0.25 0.50 0.75 1.00 1.25 1.50 1.75 2.00
90 92 94 96 98 100 102 104
Relative Dry Density (%)

Permanent Strain between 1 and 10 kcycles (%)

B1-1 : 60
B1-1 : 71
B1-1 : 77
R2-1 : 71

Material : RMC(%)

y = 12.413x - 913.76
y = 9.8759x - 709.23
y = 15x - 1290
y = 15x - 1200
y = 8x - 570
0 50 100 150 200 250 300 350 400
85 90 95 100 105 110
Relative Dry Density (%)

K1max (MPa)

B1-1 : 82
B1-1 : 60
B1-1 : 71
R2-1 : 69
B4 : 100
G2 : 100
G3 : 100
H2 : 100

(c) Resilient Modulus

Figure 12- Variation in permanent strain and resilient modulus with relative dry density

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(a) Permanent Strain

(b) Resilient Modulus

Figure 13- Variation in permanent strain and resilient modulus with moisture content
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Figure 15 - Variation in permanent strain and resilient modulus with Percentage Fines passing sieve 0.075 mm (PF)
Figure 16 - Simple deformation laws for unbound granular materials
Figure 17 – Procedure for calculating equivalent loading cycles
Figure 18 – Calculation of accumulative permanent deformation under different loading stages

(a) Power law for total deformation

(b) Logarithm law for incremental deformation
(a) Modulus as function of normal stress

(b) Modulus as function of normal stress and deviator stress

Figure 19 – Stress-dependent characteristics of resilient modulus
(a) Loading cycles to failure strain

(b) Resilient modulus

Figure 20 – Evaluation of stress-dependent characteristics of permanent deformation and resilient modulus for various materials