Development of a basecourse/sub-base design criterion

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Abbreviations and acronyms

AASHTO	American Association of State Highway and Transportation Officials
ASR	alkali-silica reaction
CalTrans	California Department of Transportation
CAPTIF	Canterbury Accelerated Pavement Testing Indoor Facility
CBR	California bearing ratio
DOS	degree of saturation
ESA	equivalent standard axle pass
FWD	falling weight deflectometer
HMA	hot mix asphalt
MDD	maximum dry density
MnDOT	Minnesota Department of Transport
NHDOT	New Hampshire Department of Transportation
OMC	optimum moisture content
RLT	repeated load triaxial
SAR	standard axle repetitions
Transit NZ	Transit New Zealand
UCS	unconfined compressive strength
WSDOT	Washington State Department of Transportation

Contents

Executive summary

Current Austroads pavement design procedures use CIRCLY software to compute strains within the pavement. These strains are used in equations to check the fatigue life of bound pavement layers and the rutting life of subgrade soils. This design process does not consider rutting in the granular pavement layers, which has been shown to contribute to at least half the rutting. Early pavement failures are generally a result of rutting and shoving within the granular pavement layers. In a parallel research project on rut depth prediction for granular pavements (Arnold and Werkmeister 2010) a range of pavement lives was determined using models derived from repeated load triaxial (RLT) tests. These predictions were used in this project to validate a simple method for obtaining a design strain criterion for basecourse and sub-base aggregates from RLT tests and for use in CIRCLY to predict pavement life. The following conclusions were made:

- Linear extrapolation of each stage of the RLT test data to a permanent strain value of 3.3% (this value was based on 10mm of rutting within a 300mm aggregate layer as found from earlier research on RLT testing at the Canterbury Accelerated Pavement Testing Indoor Facility (CAPTIF) to be a suitable failure criteria) was a simple method to obtain the number of load cycles N as a certain resilient strain when failure occurred.
- Plotting life versus resilient strain for 63 RLT test results on basecourse aggregates showed a common trend defining upper and lower bounds.
- Plotting on a log-log plot to calculate the slope and intercept was used to determine the constants for the design strain criterion.
- An adjustment factor (used to multiply the constant in the strain criterion found from the RLT test) was needed so that CIRCLY predicted lives for the aggregate layers matched those found from full pavement rut depth predictions in the parallel study (Arnold and Werkmeister 2010).
- Using the new basecourse and sub-base strain criterion would always result in the calculation of pavement lives that were the same as or less than the current method of pavement design using CIRCLY and the Austroads procedures, because the life was limited by rutting in the granular layers.
- Maximum vertical compressive strain computed by CIRCLY in the basecourse occurred at a depth of around 80mm.
- The maximum vertical compressive strain computed by CIRCLY in the sub-base layer always occurred at the top of the sub-base.
- It was more convenient in CIRCLY to compute the strains at the top or bottom of a layer, and hence a relationship was found to convert the strain at the bottom of the basecourse to the maximum strain for use within the design criteria.
- Designers should conduct their own RLT tests to obtain the constants in the design strain criteria for sub-base and basecourse aggregates. The range of values found in this study are shown in table ES.1.

Table ES.1 Constants and exponent values for CIRCLY design strain criteria

				Sub-base linear extrapolation to 3.3%		Basecourse linear extrapolation to 3.3%
N = (f.a.k/micro-strain)^{exp} f=2.0 (see equations 5.1 and 5.2)						
Strain criterion		k	exp		k	exp
Upper		80,000	3.4		700,000	2.4
Middle		66,000	3.4		400,000	2.4
Lower		55,000	3.4		250,000	2.4

Note: The factor f is simply an adjustment factor to convert a strain criterion found from RLT test data to one that can be used in CIRCLY and gives pavement lives validated at CAPTIF (using these criteria will result in the same or lesser life as predicted using the Austroads pavement design procedures).

Initial analysis using CIRCLY showed that applying a strain criterion to basecourse and sub-base aggregates from RLT tests resulted in a prediction of the same pavement life to that found from full rut depth models which considered rutting in the granular layers. It is recommended these proposed strain criteria be tested on a range of pavement designs including stabilised materials. The results should be presented to an industry meeting to consider their adoption or refinement of the adjustment factor (f, equation 5.2). Adopting these strain criteria would be beneficial in terms of reducing the risk of early granular pavement failure, as the use of fully unbound granular pavements would be limited to low traffic volumes. Structural asphalt pavements and/or modified granular materials with cement or lime would be required for higher traffic volumes. Based on experience, designers are already moving away from full depth granular materials to reduce the risk of failure. The use of basecourse and sub-base strain criteria would give designers the tools to prove their alternative designs were more effective than full depth granular pavements in reducing the risk of failure and would also be suitable for the design traffic.

The determination of the appropriate extrapolation method for rut depth progression (eg linear after a certain number of loads or a continual decrease in the rate of rutting) was valid for rut depths measured during CAPTIF tests and was considered conservative, but it still left an approximation that required further validation with actual field data.

As shown in the Pavespec Ltd test database of RLT tests there was a wide performance range for basecourses and sub-bases complying to the same specifications. We recommend designers conduct RLT tests on the specific aggregates for their projects and derive their own design strain criteria.

Abstract

The Austroads pavement design guide is currently used in New Zealand for pavement design. It includes a design criterion for the subgrade limiting the subgrade strain value. In the last few years a significant number of early granular pavement failures on high-volume roads have occurred. Investigations into these failed pavements found that most of the surface rutting was from deformation of the granular layers with little or no visible contribution from the subgrade. Therefore, the Austroads design criterion for the subgrade is adequate in terms of providing enough pavement depth to protect the underlying subgrade soil but does not prevent failure in the granular layers. In a parallel research project on rut depth prediction for granular pavements (Arnold and Werkmeister 2010) a range of pavement lives was determined using models derived from repeated load triaxial (RLT) tests. These predictions were applied in this project to validate a simple method for obtaining a design strain criterion for basecourse and sub-base aggregates from RLT tests and for use in CIRCLY to predict pavement life.

1 Introduction

1.1 Background – current pavement design method

Austroads (2004) *Pavement design – a guide to the structural design of road pavements* is currently used in New Zealand for pavement design. This includes a design criterion for the subgrade limiting its strain value. In the last few years a significant number of early granular pavements have failed. Investigations of these pavements found that most of the surface rutting was from deformation and shoving of the granular layers causing shallow shear with little or no visible contribution from the subgrade. Therefore, the Austroads design criterion for the subgrade is adequate in terms of providing enough pavement depth to protect the underlying subgrade soil, but does not prevent failure in the granular layers. This is because the Austroads pavement design process does not have a design criterion for granular pavement materials and assumes that transport agency specifications will ensure they have adequate shear strength for the design life. This gap in design method applies only to granular pavements as structural asphalt pavements require a rut resistance mix that is checked using laboratory wheel tracking devices and/or the mix design.

Within the Austroads design procedure, a strain criterion limiting the vertical elastic subgrade strain is used to determine the pavement depth required to limit rutting in the subgrade. Equation 1.1 shows the correlation between the pavement life (number of standard axle repetitions (SAR) to pavement failure) and the compressive elastic strain at the top of the subgrade used by Austroads.

$$Nf = \left(\frac{9\ 300}{\mu\varepsilon}\right)^7 \qquad \text{(Equation 1.1)}$$

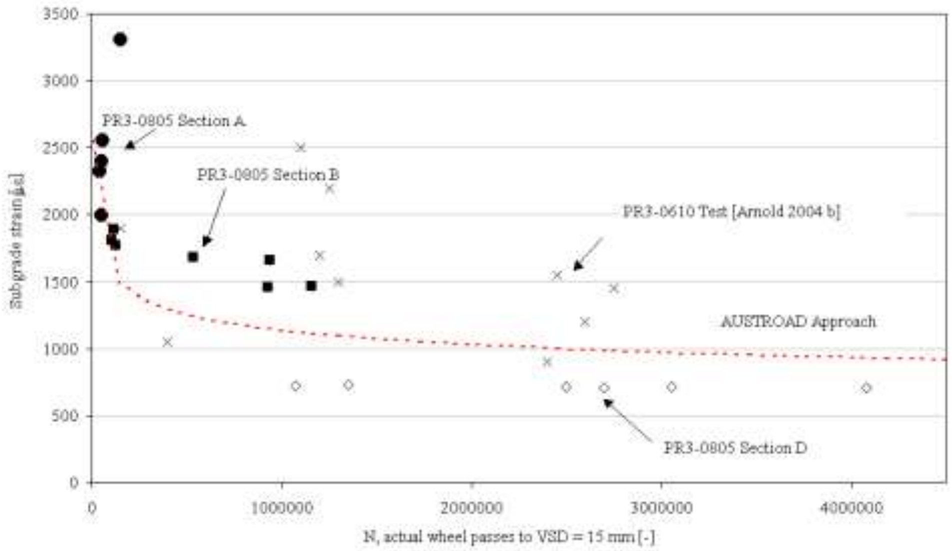
where:

N_f [-] number of SAR to failure

$\mu\varepsilon$ [10^{-6} m/m] compressive elastic strain at the top of the subgrade produced by the load (Austroads 2004).

In addition to the subgrade strain criterion, the basecourse/sub-base materials must comply with material specifications such as grading limits. However, these methods do not explicitly consider the plastic deformation performance of the basecourse/sub-base layers. Hence, the predicted life in terms of equivalent standard axle passes (ESAs) using the Austroads approach can sometimes indicate a long pavement life. To assess the validity of the Austroads approach, a comparison between Austroads predicted life from the subgrade strain criterion and actual pavement lives was conducted by Arnold (2004) and Werkmeister (2006) using the NZTA's accelerated pavement testing facility's (CAPTIF) test results. The Austroads approach was applied to falling weight deflectometer (FWD) measurements taken immediately after compaction to determine the linear elastic properties of the pavement. The analysis was undertaken for selected pavement segments in the PR3-0805 and PR3-0610 CAPTIF tests. The calculated subgrade strain using FWD results was plotted against the pavement life as shown in figure 1.1. The dotted line shown in figure 1.1 represents the Austroads approach.

Figure 1.1 Subgrade strain at each section plotted against pavement life from vertical surface deformation data (Werkmeister et al 2006)



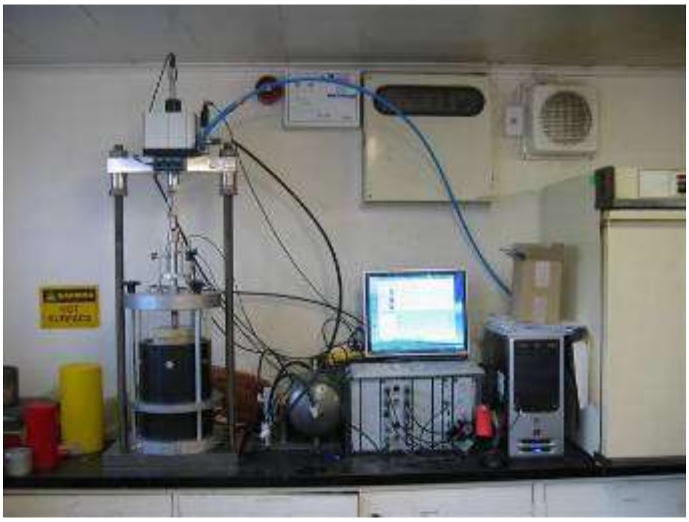
It can be concluded from figure 1.1 that the subgrade strain criterion cannot be used to limit the risk of rutting within the basecourse/sub-base. Hence, within the current Austroads design procedure no basecourse/sub-base deformation criterion exists. However, rutting resulting from further compaction and shear movement (shoving) within the basecourse/sub-base is one of the main causes of damage on New Zealand's roads and latest studies dealing with the improvement of design methods for flexible pavements have pointed out the key role played by plastic deformations in the basecourse/sub-base. For instance, the basecourse in the CAPTIF pavements contributed up to 70% of the total amount of the surface rutting (Steven 2005). In spite of this, adequate methods for predicting plastic basecourse/sub-base deformations are lacking.

1.2 Potential to use repeated load triaxial test results for granular layer design criterion

The repeated load triaxial (RLT) apparatus (figure 1.2) applies repetitive loading on cylindrical materials for a range of specified stress conditions; the output is deformation (shortening of the cylindrical sample) versus the number of load cycles (usually 50,000) for a particular set of stress conditions. Multi-stage RLT tests are used to obtain deformation curves for a range of stress conditions to develop models for predicting rutting. The method developed by Arnold (2004) for interpreting the RLT results involves relating stress to permanent deformation found from the test. From stresses computed in a pavement model of a standard cross-section at CAPTIF the permanent deformation is calculated using the relationship found from RLT testing. This approach effectively predicts the amount of rutting that would have occurred in a test at CAPTIF if the aggregate tested in the RLT apparatus was used in the pavement. A range of deformation parameters are calculated from the simulated CAPTIF test as detailed in table 1.1. One parameter, the number of heavy axle passes to achieve 10mm of rutting within the aggregate layer is calculated and is deemed the design traffic loading limit. This method of assessment was validated with accelerated pavement tests at CAPTIF (Arnold 2004; Arnold et al 2008).

Arnold et al (2008) simplified the RLT test to a six-stage test and the rut depth prediction method to enable an approximate prediction of the traffic loading limit (number of passes to a 10mm rut) to be obtained from the average slope from the RLT test. A draft specification, TNZ T/15 (Transit NZ 2007), was developed to incorporate the simplified RLT test and analysis. It is currently being revised based on the results of commercial RLT tests on many different aggregates and to take into consideration the use of an RLT test at saturated undrained conditions. These tests have been conducted commercially with some interesting results.

Figure 1.2 Repeated load triaxial apparatus



Werkmeister (2007) also used RLT test data to predict rutting of granular pavements. This approach used a relationship between resilient strain and permanent strain found from RLT test data together with a 3D finite element model developed in Dresden.

The saturated undrained test is a repeat of the RLT test detailed in TNZ T/15 (Transit NZ 2007) but the sample is soaked for at least two hours in a water bath (figure 1.3) until all the voids are filled with water. After soaking and while still in the water bath the platens are placed top and bottom and sealed to prevent drainage and to ensure saturation throughout the test. This test is considered to be severe and testing has shown that all unbound aggregates (ie TNZ M4 basecourses) show varying degrees of poor performance (ie traffic loading limit < 2 million ESAs), while stabilised aggregates generally show good results but can on occasions show poor results. Thus the saturated test is recommended when considering aggregates for use on high-traffic state highways where a stabilised/modified aggregate is probably more appropriate.

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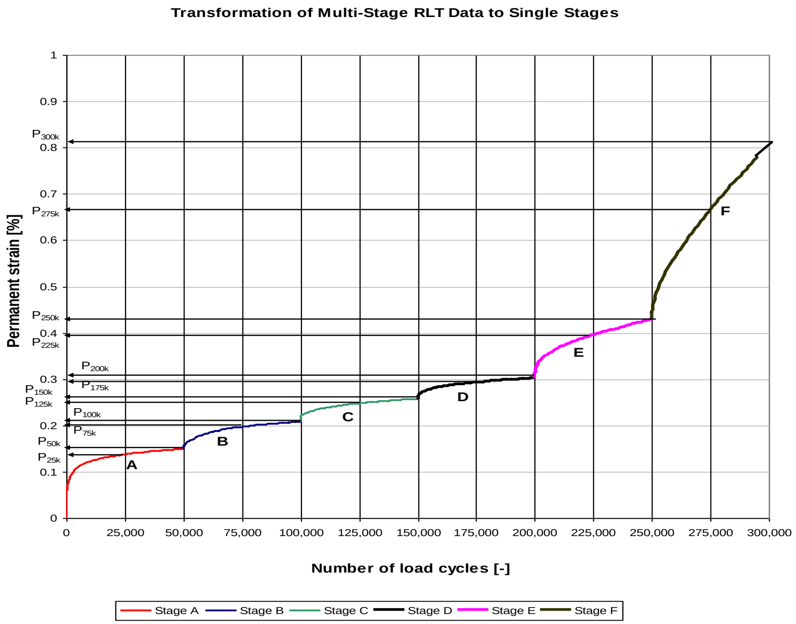
Table 1.1 Description of outputs from analysis of RLT test results

	CAPTIF Pavement 300mm Aggregate over 10CBR Subgrade				
	Total Pavement	**Aggregate only**	**Aggregate only**	**Aggregate**	**Slope %/1M from 25k to 50k same as TNZ T/15**
Material	**N, ESAs to get 25mm rut**	**N, ESAs to get 10mm rut in aggregate.**	**Long term rate of rutting within aggregate**	**Resilient Modulus at Top of Pavement (MPa)**	**Average Slope**
	Million ESAs	*Million ESAs*	*mm per 1 Million ESAs*		
Description of the aggregate and if applicable stabilisation method used. Further information than reported here is required to describe the aggregate and stabilisation method. In particular density and moisture content are important factors which will influence the result. Hence the RLT results reported are only valid for this aggregate at one particular set of testing conditions.	This the amount of heavy axle passes until a rut depth of 25mm occurs and includes rutting in both the aggregate and subgrade. It represents the result as if the aggregate tested was used at CAPTIF (Transit NZ accelerated pavement testing facility).	The amount of heavy axle passes until 10mm of rutting occurs within the aggregate layer and it is this value which is considered the traffic loading limit to be used in Transit NZ specifications. Values >15 M ESA result in no restrictions of aggregate use provided the pavement does not become saturated.	This is the amount of rutting that will occur within the aggregate for every 1 Million heavy axle passes and it ignores the initial seating in and compaction that occurs at the beginning of the RLT test, hence a more consistant measure when comparing aggregates. Values <0.5 mm/1M ESA are excellent.	The RLT test gives a Resilient Modulus for all stress stages tested, this modulus shown is for the top layer of a thin surfaced pavement, if the aggregate is covered with Asphalt then a different value should be used.	This is a simplistic analysis of the RLT result by simply looking at the slope in the RLT raw results as shown in the Figure. Values < 0.5%/1M are excellent.



RLT Test Stage (Table 2)	[2]Permanent Strain (%) (see Figure 1)	[1]Permanent Strain Slope (%/1M) (Slopes)
Stage A	P_{25k} P_{50k}	$=(P_{50k}-P_{25k})/0.025M$
Stage B	P_{75k} P_{100k}	$=(P_{100k}-P_{75k})/0.025M$
Stage C	P_{125k} P_{150k}	$=(P_{150k}-P_{125k})/0.025M$
Stage D	P_{175k} P_{200k}	$=(P_{200k}-P_{175k})/0.025M$
Stage E	P_{225k} P_{250k}	$=(P_{250k}-P_{225k})/0.025M$
Stage F	P_{275k} P_{300k}	$=(P_{300k}-P_{275k})/0.025M$
Average		$= P_{avg} = (\sum Slopes)/6$

Figure 1.3 Soaking sample for a saturated undrained RLT test

Although, a simplified parameter was found from the six-stage RLT test for specification purposes, some further analysis of the results found it was possible to readily obtain a relationship between resilient elastic strain and permanent strain rate. Figure 1.4 shows on one hand there was a relationship between the elastic and plastic (long-term) deformation behaviour and on the other the plastic strains measured during the RLT tests were close to those occurring at CAPTIF. Figure 1.5 shows a typical relationship between resilient strain and life for a basecourse aggregate found from RLT tests. Thus, the new approach developed showed potential for use in pavement design and this research project aimed to use the strain approach to derive a pavement design criterion for the basecourse/sub-base. The criterion would have to be similar to the Austroads subgrade strain criterion which relates the resilient elastic strain to pavement life (ie the number of ESAs). The resulting design criterion for the basecourse and sub-base could then be used in CIRCLY to produce pavement designs that considered the rut resistance/life of the granular pavement materials along with the subgrade soil. For high-trafficked roads it was expected that the design emphasis would be on the quality and rut resistance of the materials in the upper layers of the pavement rather than simply increasing pavement depth to increase pavement life as per the current design procedure. Undertaking RLT tests on the basecourse and sub-base aggregates would allow the development of material-specific design strain criteria as all materials behave differently in regards to their resistance to rutting.

Figure 1.4 Axial elastic strain versus plastic strain rate for CAPTIF 1 material (Greywacke from Pounds Rd Quarry), RLT test results and CAPTIF results

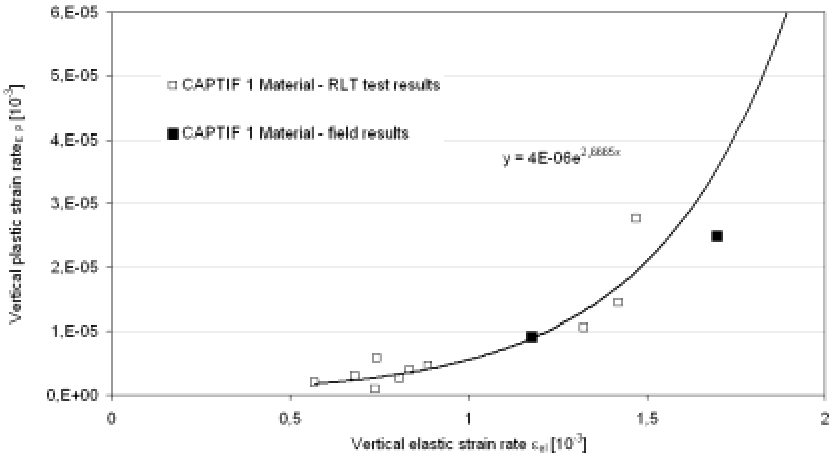
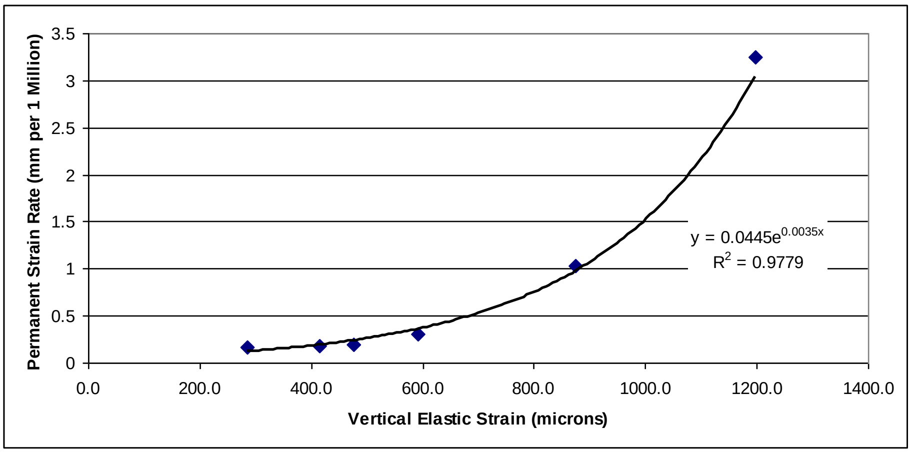


Figure 1.5 Axial elastic strain versus permanent strain rate from a typical RLT test result for basecourse aggregate



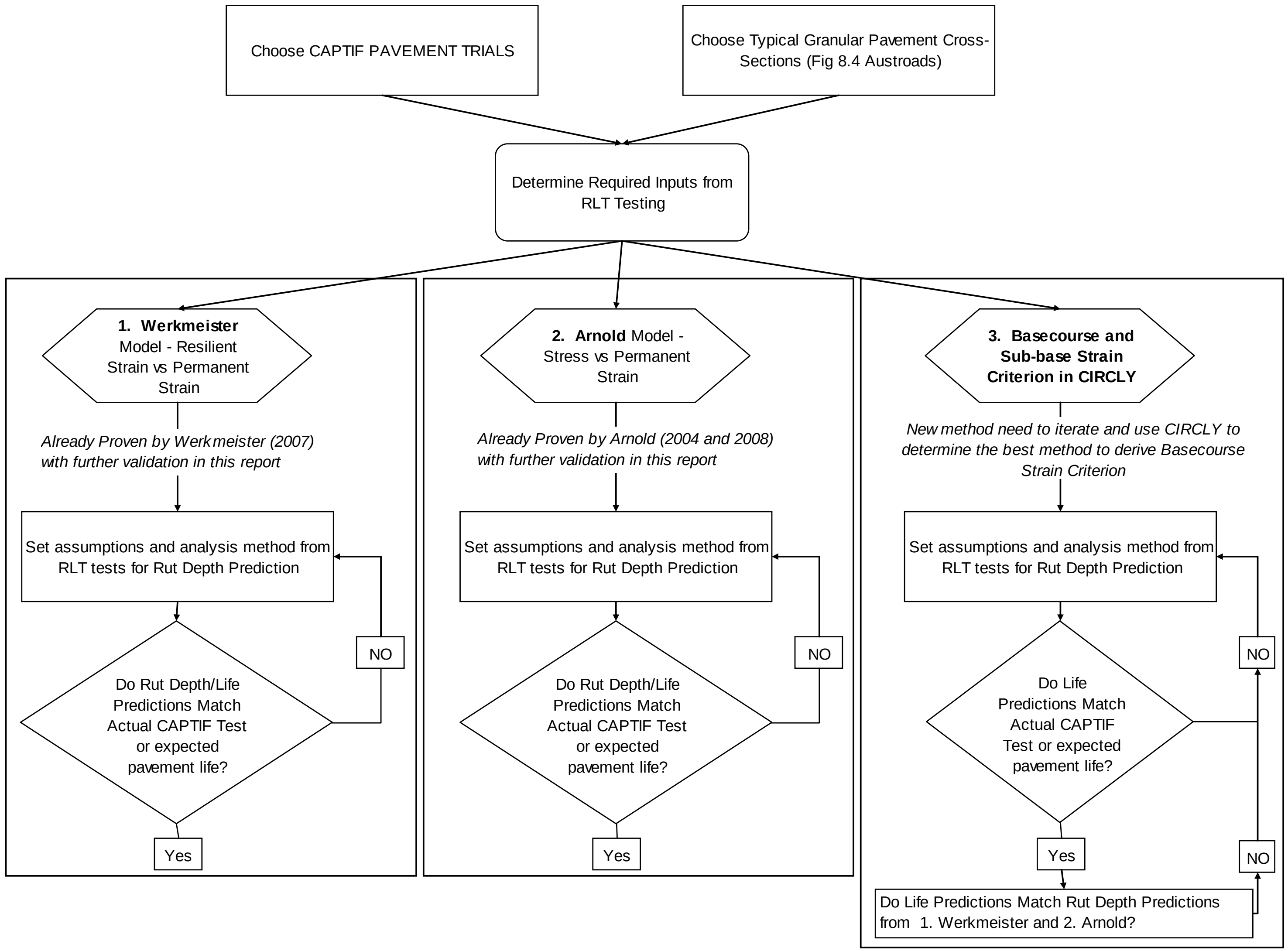
1.3 Development of a design criterion for basecourse and sub-base materials

The Austroads pavement design method using the pavement design software programme CIRCLY allows the user to define new strain criteria for any pavement material in the same form as equation 1.1. Therefore, it is possible to input a strain criterion for a basecourse aggregate derived from RLT testing as shown in figure 1.5 into the CIRCLY program. However, for the research, there were several parameters that needed defining first to ensure an accurate prediction of pavement life:

1. Where in the basecourse layer should the basecourse strain criterion apply (there could be one or several places)? CIRCLY only checks strains on the top of user-defined pavement layers.
2. Where in the sub-base layer should the sub-base strain criterion apply (there could be one or several places)? CIRCLY only checks strains on the top of user-defined pavement layers.
3. What was the permanent strain value from the RLT test that defined the end of life for both the sub-base and basecourse aggregate (this was needed to convert permanent strain values to number of load cycles to reach the end of life)? How to extrapolate the permanent strain data to the end of life was also related (although a simplified linear approach was initially proposed to simplify the process for future application).
4. Which shift factor (f) needed to be applied to convert the RLT test-derived strain criterion to one suitable for predicting life in real pavements?

The purpose of this research project was to find answers for the above four parameters. An iterative process was used until the chosen assumptions (1 to 4 above) were such that the resulting predictions were in agreement with the actual pavement life achieved in selected pavement tests at CAPTIF and, when used for other pavement designs, were close to predictions from validated rut depth models developed by Arnold (2004 and 2008) and Werkmeister (2007).In this project, the Arnold (2004 and 2008) and Werkmeister (2007) methods were further validated using recent CAPTIF tests and RLT test results on subgrade soils and basecourse aggregates. The development of the basecourse/sub-base design strain criterion and further validation of the rut depth prediction methods are described in the flow chart in figure 1.6.

Figure 1.6 Flow chart describing method of basecourse and sub-base pavement design criterion



The equation parameters required for the basecourse materials would be obtained using Pavespec Ltd's RLT test database. Testing of sub-base aggregates is uncommon and so this project involved RLT tests on typical sub-base aggregates. RLT test results for a range of subgrade soils were taken from a parallel NZTA research project, 'Pavement thickness design charts derived from a rut depth finite element model' (Arnold and Werkmeister 2010).

The aim was not to produce a generic relationship design strain criterion for all basecourses and sub-bases as these varied in quality but rather a methodology for developing a material-specific strain criterion from RLT testing. Relationships found for typical weak, medium and high-quality basecourses and sub-bases where RLT testing had been conducted would be reported.

1.4 Research objectives

The objectives of the research project were to:

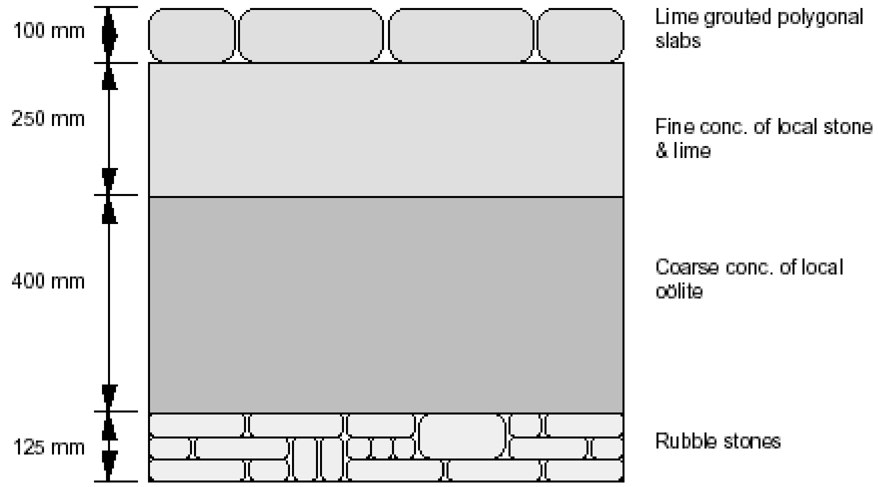
1. Conduct and analyse RLT test results on different basecourse/sub-base materials regarding the elastic strain/ plastic strain rate relationship.
2. Develop a new basecourse/sub-base strain criterion based on the RLT test and CAPTIF results.
3. Validate the basecourse/sub-base strain criterion to observed field performance at CAPTIF.
4. Implement the RLT test method to determine the basecourse/sub-base strain criterion in Transit NZ's (2007) RLT testing specification and revise the NZTA's *NZ supplement to the Austroads pavement design guide* to incorporate the basecourse/sub-base strain criterion.

2 Background

The Romans constructed the first roads in Europe mainly for military purposes. A typical Roman road structure (figure 2.1), as seen in the United Kingdom, consisted of four basic layers[1]:

1. Summa Crusta (surfacing). Smooth, polygonal blocks embedded in the underlying layer.
2. Nucleus. A kind of base layer composed of gravel and sand with lime cement.
3. Rudus. A layer, which was composed of rubble masonry and smaller stones also set in lime mortar.
4. Statumen. Two or three courses of flat stones set in lime mortar.

Figure 2.1 Roman pavement structure near Radstock, England[1]



As can be seen, Roman pavements were quite thick (almost 0.9m), with basic lime cements used to hold their large stones together. In the late 1700s and early 1800s, binder material was no longer used in pavement structures and aggregate interlock was relied on to provide cohesion.

Bituminous binding materials and surface layers were first used in pavements in the early 1800s. The first pavements made from true hot mix asphalt (HMA) were called sheet asphalt pavements. The HMA layers in this pavement were premixed and laid hot. Sheet asphalt became popular during the mid-1800s with the first ones built on the Palais Royal and the Rue St. Honore in Paris in 1858.[1]

The modern asphalt pavement structure in Europe, according to the pavement design guides (eg HMSO 1994; TRL 1993), has a high structural strength where one or more unbound granular layers with a uniform grading are laid over the subgrade (soil foundation). The asphalt layer thickness on top is dependent on the design traffic loading. According to the German pavement design guide (RStO 01 2001), the asphalt layer is up to 340mm thick for very high-trafficked roads (up to more than 32 million 10-t standard axles during the pavement life), and usually 100mm thick for low-trafficked roads (up to 100,000 10-t standard axles during the pavement life). This type of pavement is called ‘flexible’ since the total pavement structure bends (or flexes) to accommodate traffic loads.

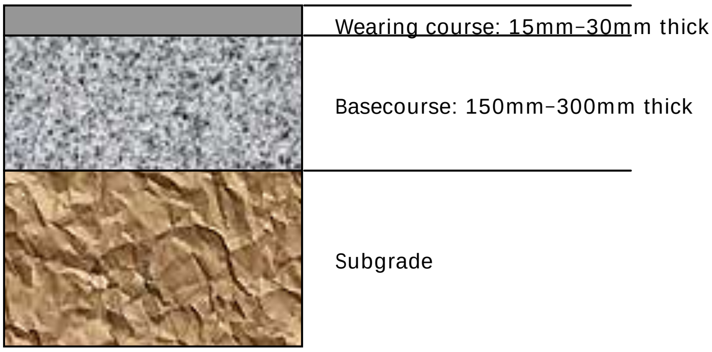
[1] WSDOT pavement guide webpage: http://training.ce.washington.edu/WSDOT/

Over the last few years, and as a consequence of the drive towards economic utilisation of non-renewable natural resources and recycling of existing road materials, the development of new, more innovative types of pavement structures has become essential. Hence, ‘low-volume roads’ are being used increasingly on a worldwide basis. At the high end, a low-volume road is a two-lane asphalt paved road with up to 2000 vehicles per day, but in remote areas they consist of only a single lane with gravel or a natural surface. However, the low-volume road type considered in this research was an asphalt paved road used for low-trafficked roads in developed areas such as Europe.

The pavement structure of a asphalt paved low-volume road is usually divided into three zones:

- The waterproof wearing layer is a thin asphalt layer or a chip seal.
- The structural pavement layer is a basecourse layer or granular layer made of gravel or crushed rock.
- The subgrade usually comprises the in-situ subgrade (figure 2.2).

Figure 2.2 Low-volume road pavement structure



Traditionally, the design of a low-volume road pavement structure is not a specific field of engineering. The pavement engineers who had to design low-volume roads used the best information available. They extended their experience and training in high-standard asphalt pavements to low-volume road situations, even though they may have recognised the standards as excessive.

There are two basic approaches to high-standard pavement design. Asphalt pavements have traditionally been designed using empirical design methods, ie the material types and layer thicknesses of the different structural layers have been selected in accordance with very inflexible, predetermined design criteria. A typical feature of many empirical design methods is that they have been progressively calibrated over many years by means of either systematic road tests or observations made from actual road structures as well as back calculations. As a result, the design and construction of the pavements have traditionally been directed towards more or less standardised cross sections and road construction materials.

Hence, current empirical pavement design methods are in most cases inadequate for the analysis and design of new structural solutions like low-volume roads. Nonetheless, there are increasing worldwide efforts towards developing analytical approaches to solve this problem. The analytical or mechanistic design method aims to model the behaviour of each pavement layer based on the basic mechanical and physical properties of the structural materials. The key idea is to evaluate the stresses and strains under real traffic loads at critical points in the structure based on the analysis of the stress-strain conditions of the whole pavement, taking into consideration the climatic conditions. Based on the values of stresses and strains, the service life of the pavement can thus be estimated.

The pavement design criteria applied in current analytical pavement design methods are intended to guard against excessive plastic deformation originating within the subgrade (rutting) and cracks initiating at the underside of the bound layers (fatigue). These criteria are usually expressed as a relationship between load-induced elastic stresses or strains and the permissible number of load applications expressed in terms of standard units of equivalent applied traffic axles. The criterion for the subgrade is normally observed by applying a permissible limiting value for the compressive vertical strain at the top of the subgrade that has been derived from analysis of data originating from the American Association of State Highway Officials road test. These pavement design guides assume that rutting occurs only in the subgrade soil foundation. The thickness of the granular layer is, thus, determined from the subgrade condition (California bearing ratio (CBR) and/or vertical compressive strain) and design traffic (including traffic during construction). The assumption that rutting with repetitive traffic loading occurs only within the subgrade is assumed to be assured through the requirement of the unbound granular materials to comply with material specifications. These specifications for unbound granular materials are recipe based and typically include criteria for aggregate strength, durability, cleanliness, grading and angularity, none of which is a direct measure of resistance to rutting caused by repeated loading.

The RLT test simulates dynamic pavement loading on basecourse materials similar to what is happening in the pavement structure. Plastic strain tests in the RLT apparatus commonly show a wide range of performances for granular material even though all comply with the same specification (Thom and Brown 1989; Arnold and Werkmeister 2006). RLT tests conducted by Arnold and Werkmeister (2006) showed that unbound granular materials all complying with the specification for basecourse materials (TNZ M/4) (Transit NZ 2002) resulted in significantly different pavement rutting performance. Hence, current specifications (eg TNZ M/4) due to their empirical/recipe approach to selecting aggregates cannot distinguish differences in deformation performance between granular material types. Accelerated pavement tests showed the same results and also reported that 70% to 90% of the surface rutting of low-volume roads was attributed to the granular layer (Arnold 2004; Little 1993; Pidwerbesky 1996; Korkiala-Tanttu et al 2003; Steven 2005).

However, granular layers play the most important role in low-volume roads. They are required to provide a working platform for the construction of the surface layer and reduce compressive stresses on the subgrade and tensile stresses in the asphalt layer. For low-volume roads, the granular layer or basecourse contributes to the full structural strength of the pavement. It is therefore important that the basecourse shows sufficient performance (adequate stiffness and does not deform/rut). Hence, current analytical pavement design methods are insufficient for the analysis and design of low-volume roads where the basecourse plays the most important role. They cannot distinguish differences in plastic deformation performance between granular material types. Consequently, analytical design methods, which are able to model the behaviour of each pavement layer based on the basic mechanical and physical properties of the material, will ensure the pavement design life can be met. One advantage of such an analytical design method is that basecourse materials from different sources, including marginal or local materials, can be used in appropriate locations.

The fewer road users, the less funding is available for road observation and maintenance too. Traditional methods for evaluating the structural capacity of high-strength flexible pavements might not be transferable to low-volume roads or are too expensive. Hence, new cost-effective methods to evaluate the structural capacity/rutting performance of low-volume roads have to be developed.

3 Basecourse RLT results

3.1 Introduction

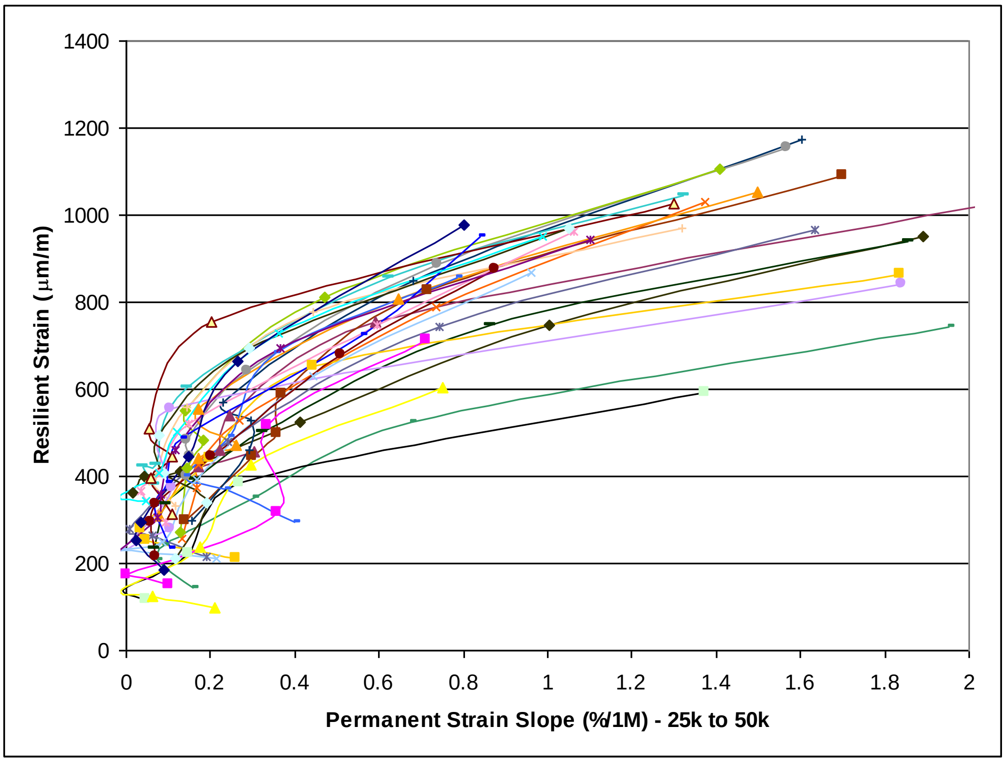
Multi-stage RLT permanent strain tests following the procedure developed by Arnold et al (2008) detailed in the draft specification TNZ T/15 (Transit NZ 2007) were conducted in this research on sub-base aggregates. Tests were supplemented with a vast testing database by Pavespec Ltd on basecourse aggregates together with tests on subgrade soils conducted in a parallel research project (Arnold and Werkmeister 2010). The RLT apparatus and test method are described in section 1.2 and in Arnold et al (2008).

3.2 Basecourse strain criteria

Over the past two years Pavespec Ltd has tested a wide range of basecourse aggregates complying with TNZ M4 (Transit NZ 2002) for a range of clients. These test results were re-analysed to determine the range of relationships between resilient strain and permanent strain rate. At first it appeared there was a total of 110 RLT results on basecourses. However, after examining the results it was found some of the tests were at saturated conditions that exhibited high deformations causing the test to finish early. Results from tests that failed prematurely were not suitable due to the erratic nature of the material with nearly infinite permanent strain rates for some resilient strains/stress conditions. The final dataset comprised 63 basecourse RLT test results conducted at 95% maximum dry density (MDD) and 100% optimum moisture content (OMC) at drained conditions in accordance with TNZ T/15.

Each RLT test in accordance with TNZ T/15 could be divided into six different RLT test results representing a particular stress/loading condition (table 1.1). As the loading/stress level was constant for each stage then the resilient strain also stabilised to a constant value. The cumulative permanent strain value increased after each loading cycle. However, the permanent strain rate from 25k to 50k load cycles in each stage was reasonably constant. Therefore, the permanent strain rate (or slope as per table 1.1) was determined for each of the six loading stages and plotted against the constant resilient strain. The result was a relationship between the permanent strain rate and resilient strain for each RLT test as shown in figure 3.1.

Figure 3.1 Relationships found between permanent strain rate and resilient strain for TNZ M4 basecourse aggregates tested by Pavespec Ltd



The end of pavement life was determined by assuming the rate of permanent strain was linear from zero (ie ignoring initial compaction) for calculating the number of load cycles to reach a defined permanent strain value at failure. This method was a simplification as it ignored any initial compaction and stabilising resulting in decreasing rates of permanent strain as shown in figures 3.2 and 3.3. Figure 3.3 shows that ignoring the initial compaction and linear extrapolation to the permanent strain at failure resulted in only a small error in the number of load cycles to failure compared with linear extrapolation when the post compaction was taken into consideration. Using a power law to extrapolate the test data led to an unrealistically high number of load cycles to failure (eg to a permanent strain value of 3.3%) as shown in figure 3.3. Both Arnold (2004) and Werkmeister (2007) found a linear extrapolation of the RLT test results gave the best predictions of thin-surfaced granular pavements. Although Arnold (2004) and Arnold et al (2008) extrapolated the data initially to 500k load cycles and then extended the data linearly from 100k through the 500k point using a function (equation 3.1), this same process of extrapolation was used for all the analyses and is illustrated in figure 3.3.

$$\varepsilon p = AN^{B} + C \qquad \text{(Equation 3.1)}$$

Where:

ε_p = permanent strain

N = number of load cycles

A, B, C = constants

Figure 3.2 RLT test data (stage F) used to demonstrate extrapolation method used shown in figure 3.3

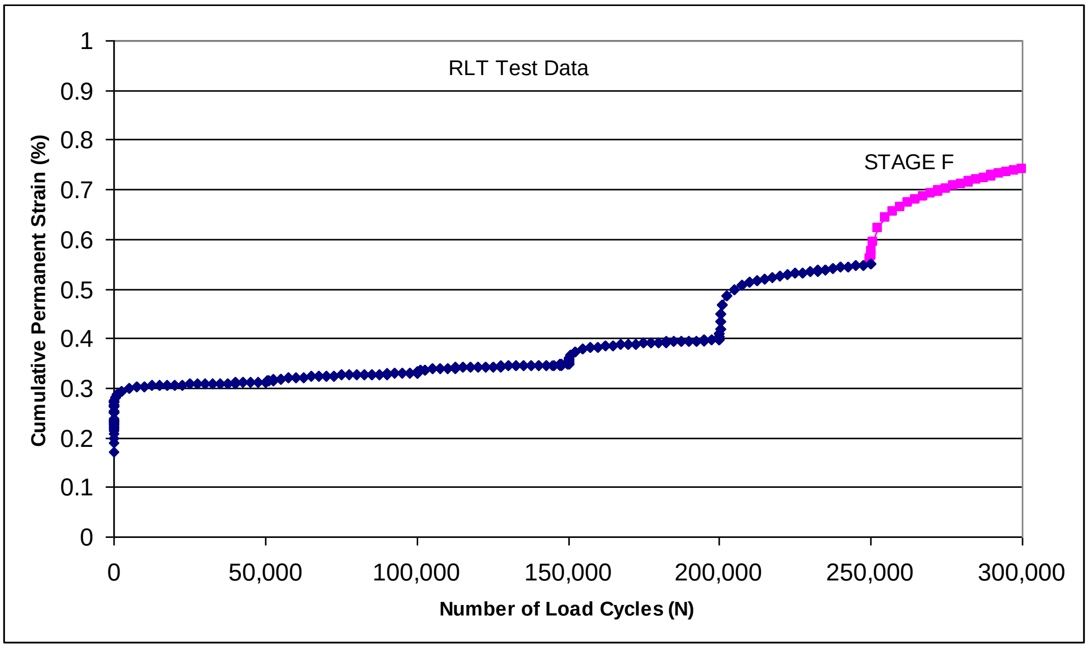
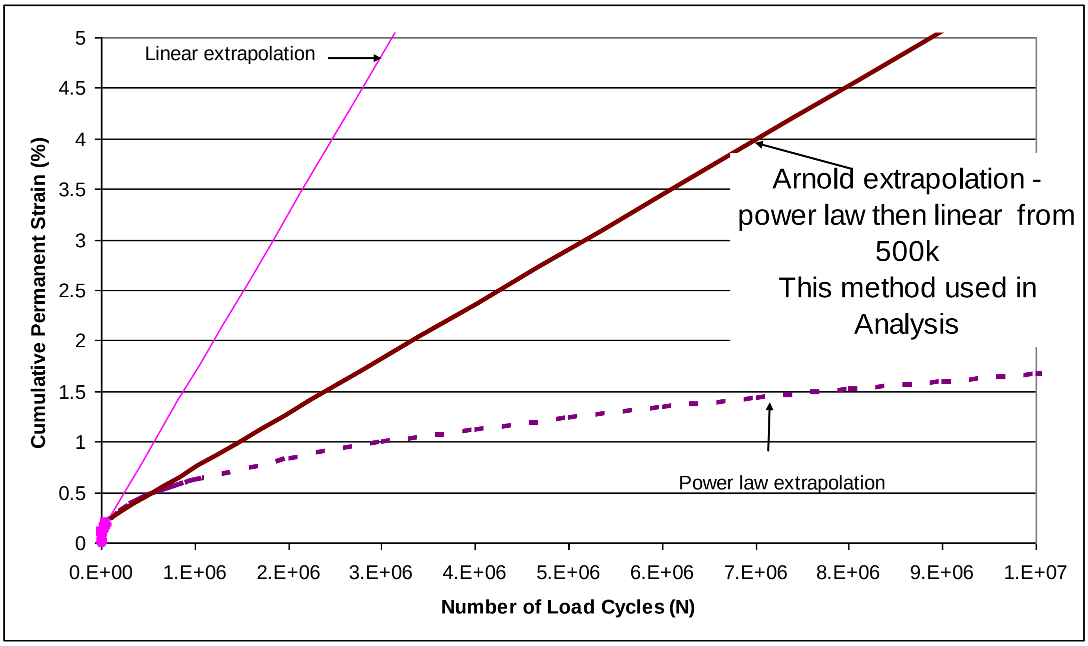


Figure 3.3 Diagram explaining the different methods of extrapolating RLT test data to determine number of load cycles to reach permanent strain at failure



Another reason for choosing the simplified method was its potential to give predictions of life that were less than what would actually occur. The simple approach could be used effectively in a design guide as per its intended purpose. Thus, the validation process did highlight this inaccuracy which resulted in a shift factor (f) being applied to the results. As an initial assumption, the end of life was assumed when the permanent strain reached a value of 3.3%. This permanent strain value was chosen as it represented a 10mm rut in a 300mm deep pavement. This cross-section is commonly used in CAPTIF tests and was chosen by Arnold et al (2008) as a failure criterion for basecourse aggregates. Life was then determined for each of the six stages in the RLT test by the permanent strain at failure (3.3%) divided by the permanent strain rate. Results of life versus resilient strains are plotted in figure 3.4. Fitting an equation of the same form as the Austroads subgrade strain criterion (equation 3.1) to the RLT vs life data resulted in a range of equations as detailed in figure 3.5 and table 3.1.

The determination of the appropriate extrapolation (Arnold method, figure 3.3) was derived from rut depths measured during CAPTIF tests that often showed the rut depth decreasing as a power law function until 500k load cycles and then becoming a steady linear rate of rutting. This extrapolation method is considered conservative (life calculated will be less than that expected to occur), but it still leaves an approximation requiring further validation with actual field data.

Figure 3.4 Relationships found from basecourse RLT test data between resilient strain and life (load cycles to reach 3.33% permanent strain)

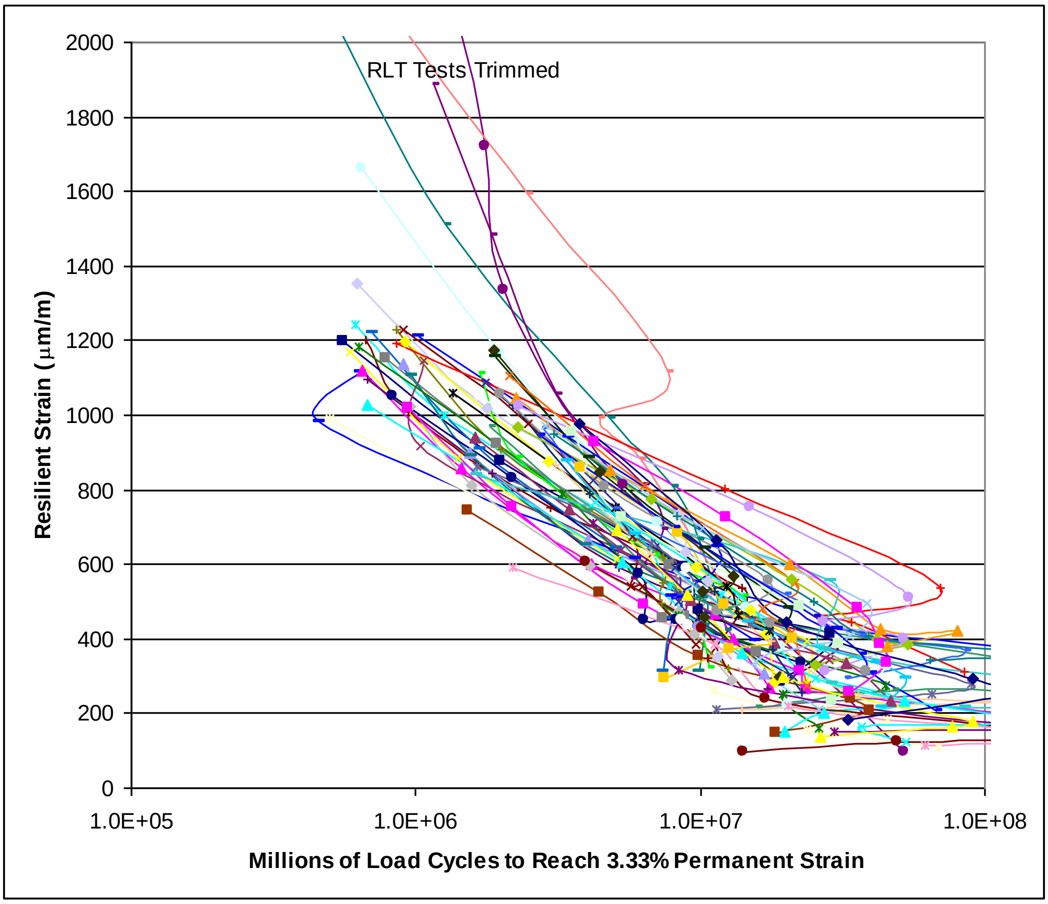


Figure 3.5 Basecourse strain criterion found by linear extrapolation of permanent strain data to 3.3% using the slope from 25k to 50k load cycles

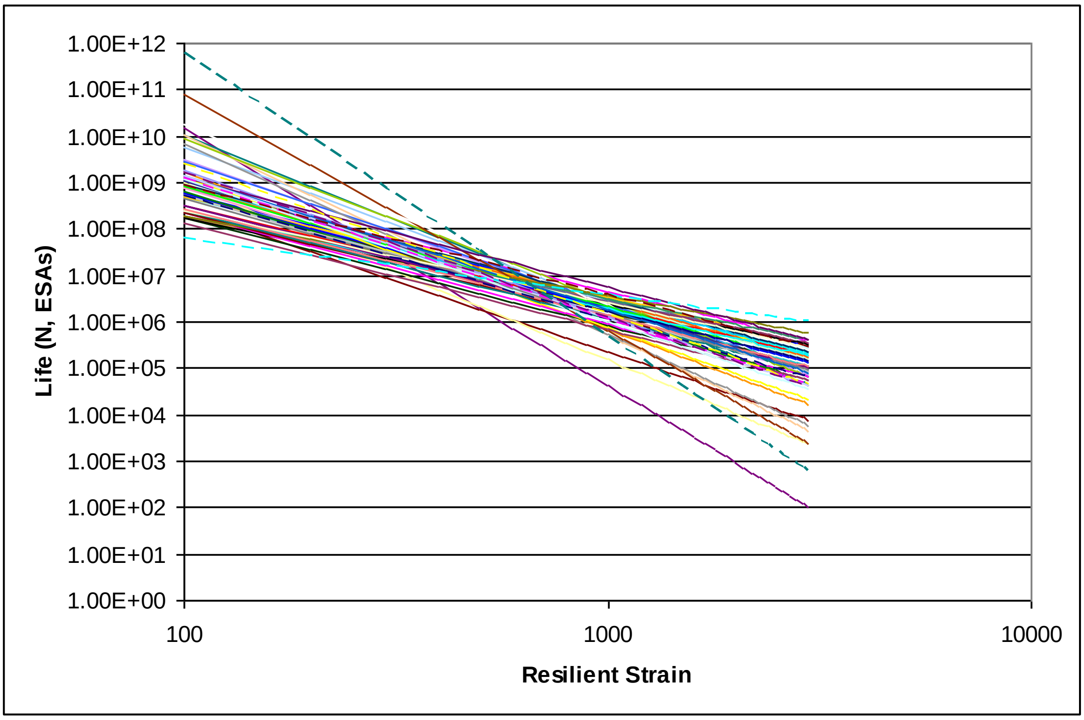


Table 3.1 Range of basecourse strain constants and exponents found from linear extrapolation of permanent strain data to 3.3% using the slope from 25k to 50k load cycles

	90%ile	10%ile	Average	Median	75%ile	25%ile	Number
k	2.2E+06	4.4E+04	4.6E+06	3.1E+05	7.3E+05	8.8E+04	62
exp	3.8	1.9	2.8	2.5	3.1	2.3	62

Table 3.1 shows the exponent value on average is 2.8 and the constant is 4.6 million for a basecourse strain criterion. Changing the permanent strain value at failure only affects the constant, k as the slope or exponent value remains the same in the basecourse strain criterion. This fact is useful when calibrating a basecourse strain criterion to predict life at CAPTIF, as the permanent strain at failure will be changed until the correct life is predicted rather than adding an additional adjustment factor. On reviewing the plot of basecourse strain criteria it appears that the majority of the basecourse strain criteria can be defined within upper and lower boundaries. These upper and lower boundaries along with a middle value were defined by iteration and plotted in figure 3.6. The upper, lower and middle basecourse strain criteria all have an exponent of 2.4 with the constant ranging from 250,000 to 700,000.

Figure 3.6 Upper and lower boundaries fitted to basecourse strain criterion found by linear extrapolation of permanent strain data to 3.3% using the slope from 25k to 50k load cycles

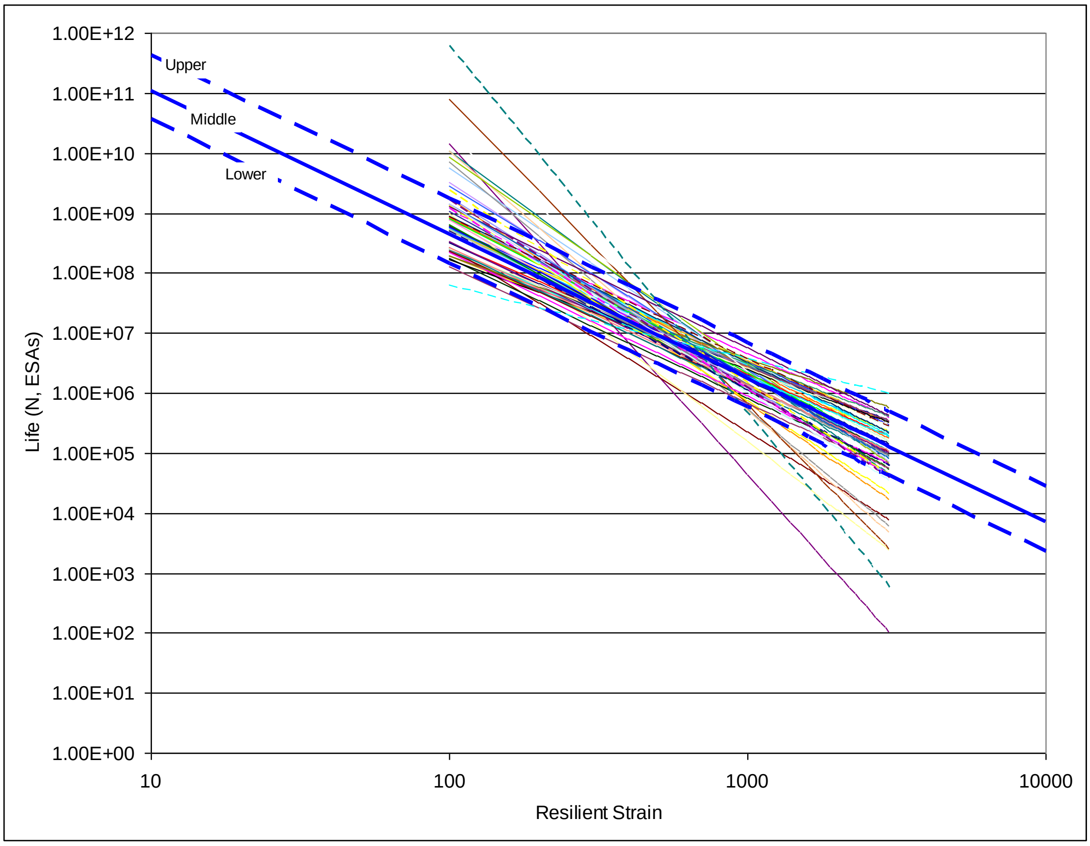


Table 3.2 Upper, middle and lower boundaries of basecourse strain constants and exponents found from linear extrapolation of permanent strain data to 3.3% using the slope from 25k to 50k load cycles

	Middle	Lower	Upper	Number that fits inside upper and lower
k	4.0E+05	2.5E+05	7.0E+05	46
exp	2.4	2.4	2.4	46

4 Sub-base RLT test results

4.1 Introduction

Typical pavement design cross-sections include a sub-base aggregate. Therefore, this research project undertook RLT tests on a range of sub-base aggregates with the intention of developing a design criterion for the sub-base layer. The same RLT test conducted on basecourse aggregates is used for sub-base aggregates. Although the final two stress stages in the RLT test may be considered severe for a sub-base layer the results are still used in the modelling. This is because the RLT test gives the relationship between resilient elastic strain and permanent strain which is used to calculate rutting from actual strains in the pavement. The sub-base aggregate which is located at depth in the pavement will have lower elastic strains and hence less rutting is calculated. Conversely, if a sub-base aggregate is used in the upper layer as a basecourse then higher rutting is calculated.

4.2 Scalping methods

Sub-base aggregates are generally a AP65 or GAP65 with a grading that results in nearly 50% being between 37.5mm and 65mm. The standard RLT sample size is 150mm diameter by 300mm in length. In the TNZ T/15 specification the maximum particle size is 37.5mm derived from the ability to compact the sample in the mould and from recommendations in the literature. The Association of American State Highway and Transportation Officials T307 (AASHTO 1999) recommends for untreated granular base material, the tested sample should have a diameter greater than five times the maximum particle size of that material. This would limit the maximum particle size to 30mm for the 150mm diameter mould. However, it was decided to allow a maximum particle size of 37.5mm in the mould for the New Zealand draft test procedure (TNZ T/15) for two reasons: 1) The proposed Austroads method (Standards Australia, 1995) allows 5% oversize particles to be left in the sample; 2) All basecourse aggregates in New Zealand have a maximum particle size of 37.5mm and it was often found there were only two to five stones greater than 30mm and less than 37.5mm, which had a minimal effect on the sample.

Although all of the basecourse aggregate can be used in the RLT test this is not the case for the sub-base aggregates with a maximum particle size of 65mm. Therefore, the 65mm sub-base materials require scalping to remove material greater than 37.5mm for the RLT sample. There are several possible methods for scalping material >37.5mm:

- Scalp > 37.5mm and discard – this is the most simplistic method, but generally not recommended if more than 5% of the material is scalped.
- Scalp > 37.5mm and replace with the next size down of large stones – this method attempts to keep the same proportion of large stones in the mix compared with the amount of fines.
- Scalp > 37.5mm and mathematically adjust the grading to result in the same grading integer, *n*, as the original AP65 aggregate where:

The PSD of a well graded aggregate can be described as:

$$p = 100\left(\frac{d}{D}\right)^n \qquad \text{(Equation 4.1)}$$

Where

p = percent passing sieve size d

D = maximum particle size

n is an integer which commonly has a range between 0.3 and 0.6.

This scalping and mathematical adjustment to the third grading (see the third bullet point in section 4.2) may be more theoretically correct but requires more work for the laboratory to split the sample down to different sieve fractions and recombining to a calculated grading.

To test the three different scalping methods a sub-base quality GAP40 was used and scalped down to a maximum size of 19mm. The original GAP40 was tested in the RLT apparatus to enable comparison with the different scalping methods. Both standard/dry and saturated RLT tests were conducted along with rut depth predictions assuming they were used in a basecourse in a CAPTIF test (Arnold et al 2008). Results of these tests are shown in figures 4.1 and 4.2 and table 4.1.

Results show the original material (not scalped) had more than half the deformation of all the other scalping methods. Interestingly all the scalping methods showed similar results to each other. The scalp and discard method was the best, closely followed by the scalp and mathematically adjust the grading method.

Figure 4.1 RLT test results for dry/drained conditions comparing the different scalping methods (refer to table 4.1 for description)

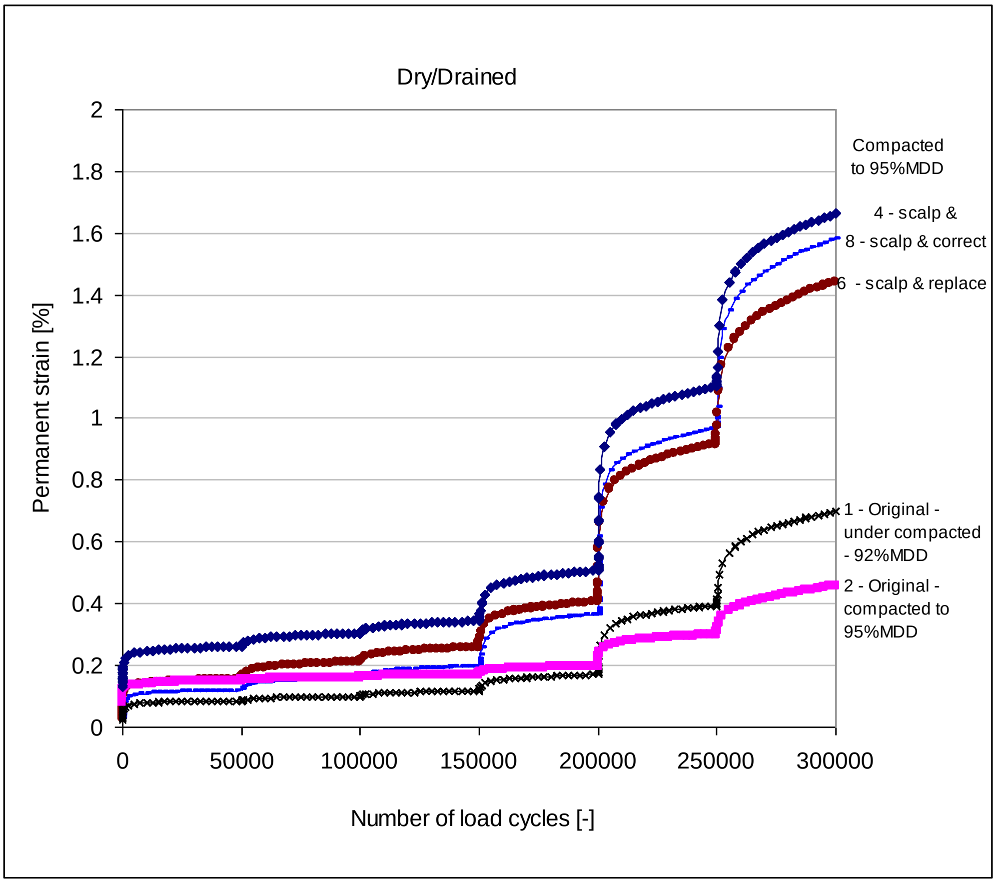


Figure 4.2 RLT test results for saturated/undrained conditions comparing the different scalping methods (refer to table 4.1 for description)

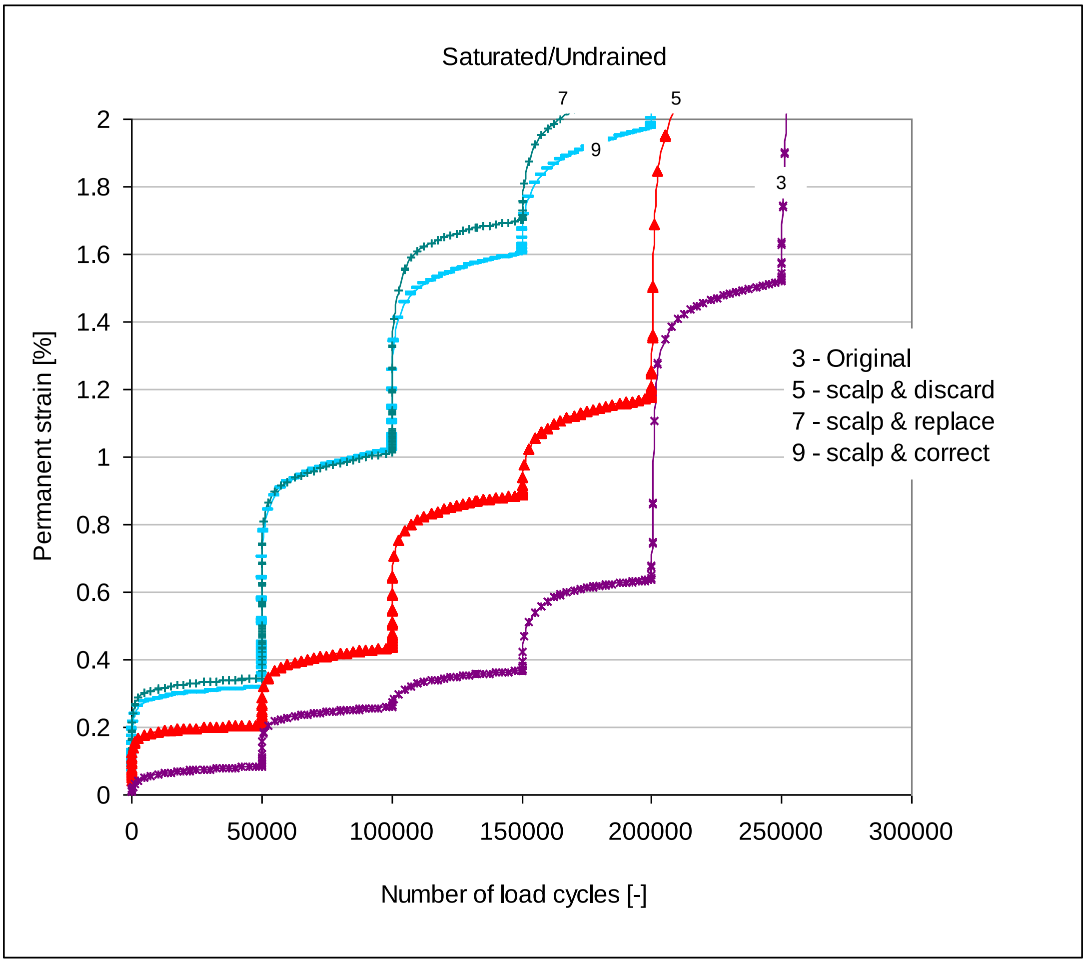


Table 4.1 Rut depth predictions from RLT tests on various different methods for scalping large stones in a sub-base aggregate

Rut depth prediction for CAPTIF pavement - 300mm aggregate over subgrade CBR=10			Subgrade and aggregate	Aggregate only	Aggregate only	Aggregate only	
RLT test in accordance with draft TNZ T15: 2007			N, ESAs to get 25mm rut	N, ESAs to get 10mm rut	Long term rate of rutting within aggregate	Vertical resilient modulus in top pavement layer1,2	RLT average slope 25k to 50k - %/M
(Rut depth predictions as per Arnold's doctorate)							
DQ40 - PS0025 test #:	Grading	Density and moisture content of RLT sample	Million ESAs	Million ESAs (see note 1)	mm per 1M ESAs	MPa	
Test 1 - Standard test - 93% MDD; 100%OMC	*actual grading*	93.3%MDD (DD=1.923 t/m3) ; 62.1%OMC (MC=5.9%)	2.82	6.04	1.5	558	0.561
Test 2 - Standard test - 95% MDD; 100%OMC	*actual grading*	94.8%MDD (DD=2.011 t/m3) ; 62.4%OMC (MC=5.9%)	3.31	19.66	0.5	535	0.359
Test 3 - Saturated undrained	*actual grading*	94.4%MDD (DD=2.002 t/m3) ; 122.5%OMC (MC=11.6%)	1.00	0.42	10.5	399	2.651
Test 4 - Standard test - 95% MDD; 100%OMC	*scalped >19mm*	95%MDD (DD=1.956 t/m3) ; 77.3%OMC (MC=7.3%)	2.73	5.97	1.3	515	1.106
Test 5 - Saturated undrained - 95% MDD; 100%OMC	*scalped >19mm*	95%MDD (DD=1.956 t/m3) ; 104.4%OMC (MC=9.9%)	0.02	0.01	121.0	353	511.21
Test 6 - Standard - 95% MDD; 100%OMC	*scalped >19mm & replace*	94.6%MDD (DD=1.815 t/m3) ; 47.3%OMC (MC=4.7%)	2.27	2.60	3.0	575	1.11
Test 7 - Saturated - 95% MDD; 100%OMC	*scalped >19mm & replace*	95.4%MDD (DD=1.832 t/m3) ; 140.2%OMC (MC=14%)	0.004	0.002	130.4	261	677.87
Test 8 - Standard - 95% MDD; 100%OMC	*scalped >19mm & correct*	94.5%MDD (DD=1.975 t/m3) ; 92.9%OMC (MC=8.4%)	2.59	4.99	1.4		1.13
Test 9 - Saturated - 95% MDD; 100%OMC	*scalped >19mm & correct*	94.7%MDD (DD=1.979 t/m3) ; 114.5%OMC (MC=10.3%)	0.011	0.004	129.6	558	527.15

4.3 Other sub-base RLT test results

RLT tests were conducted on a range of sub-base aggregates with the aim of developing typical design strain criteria for sub-bases. A database of test results could not be used as sub-base aggregates had not been tested before. Therefore samples of sub-base aggregates were obtained and tested in the RLT apparatus. Sub-base materials tested are summarised in table 4.2.

Table 4.2 Sub-base materials tested in the RLT apparatus

Test #	Test reference	Material	Saturated or dry RLT test
1	PS0025 Test 1	Drury Quarry GAP40 – 93%MDD	Dry
2	PS0025 Test 2	Drury Quarry GAP40 – 95%MDD	Dry
3	PS0025 Test 3	Drury Quarry GAP40 – 95%MDD	Saturated
10	PS0025 Test 10	Rotorua Rainbow Mountain – scalped GAP65 – 95%MDD	Dry
11	PS0025 Test 11	Rotorua Rainbow Mountain – scalped GAP65 – 95%MDD	Saturated
12	PS0025 Test 12	Wellington Kapiti Blue – scalped GAP65 – 95%MDD	Dry
13	PS0025 Test 13	Wellington Kapiti Blue – scalped GAP65 – 95%MDD	Saturated
14	PS02502 Test 1	Huntly Quarry GAP40 – 94%MDD	Dry
15	PS02502 Test 2	Huntly Quarry GAP40 – 94%MDD	Saturated
16	PS02502 Test 3	Huntly Quarry GAP40 – 95%MDD	Dry
17	PS25005 Test 1	Auckland GAP40	Dry
18	PS25005 Test 2	Auckland GAP40	Saturated
19	PS0028 Test 1	Waikato Awakino scalped GAP65	Dry
20	PS0028 Test 2	Waikato Awakino scalped GAP65	Saturated
21	PS0031 Test 5	Horokiwi scalped GAP65	Dry
22	PS0031 Test 6	Horokiwi scalped GAP65	Saturated

Results of the RLT tests on sub-bases at both dry and saturated are shown in figures 4.3 and 4.4. Material number 2 (Drury GAP40 at 95%MDD) performed the best when dry and was similar to the performance of an average basecourse. All saturated RLT tests showed very poor performance and were much worse than the TNZ M4 basecourse aggregates as the sample often failed before the test was completed.

Figure 4.3 RLT plots for sub-base aggregates – dry/drained tests

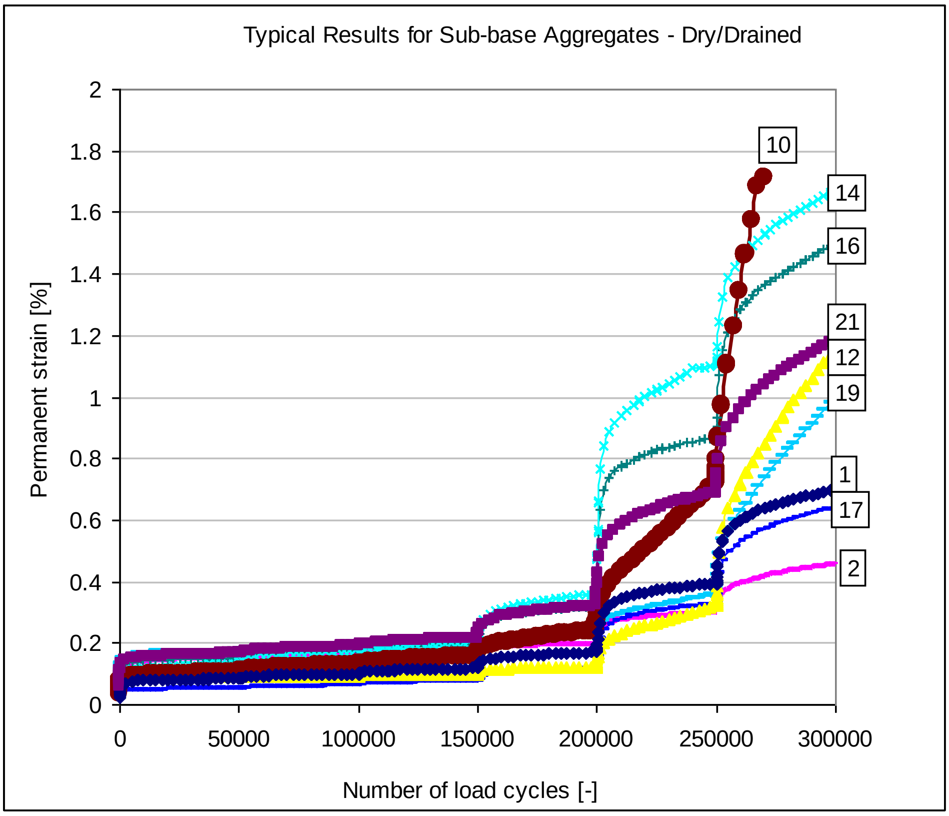
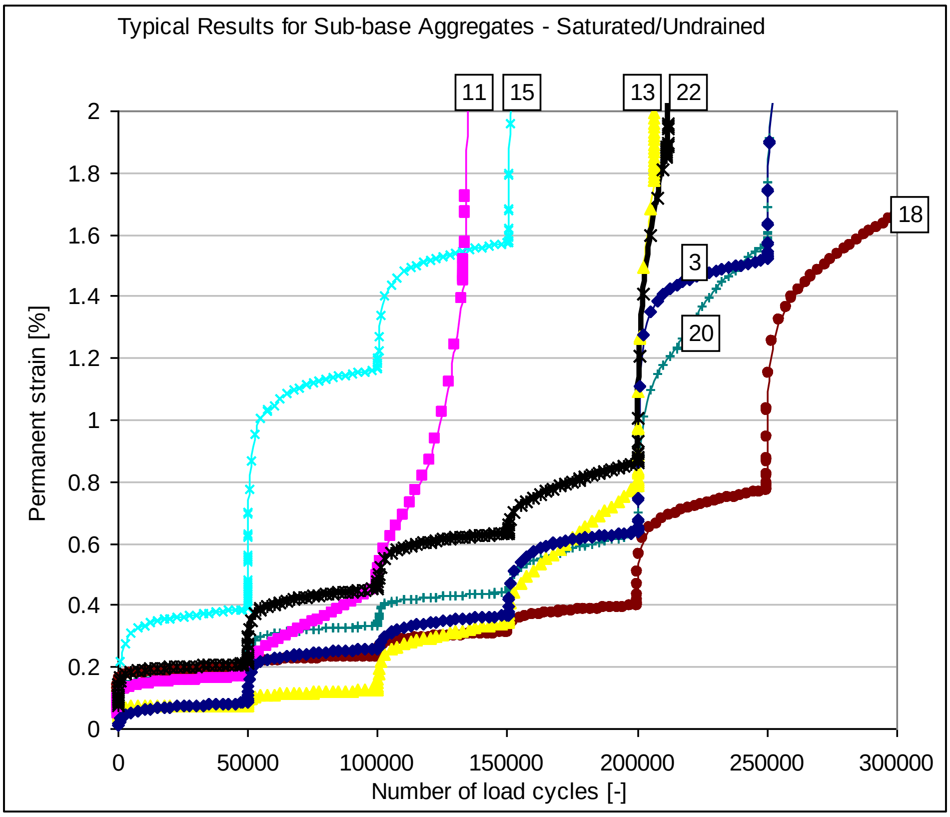


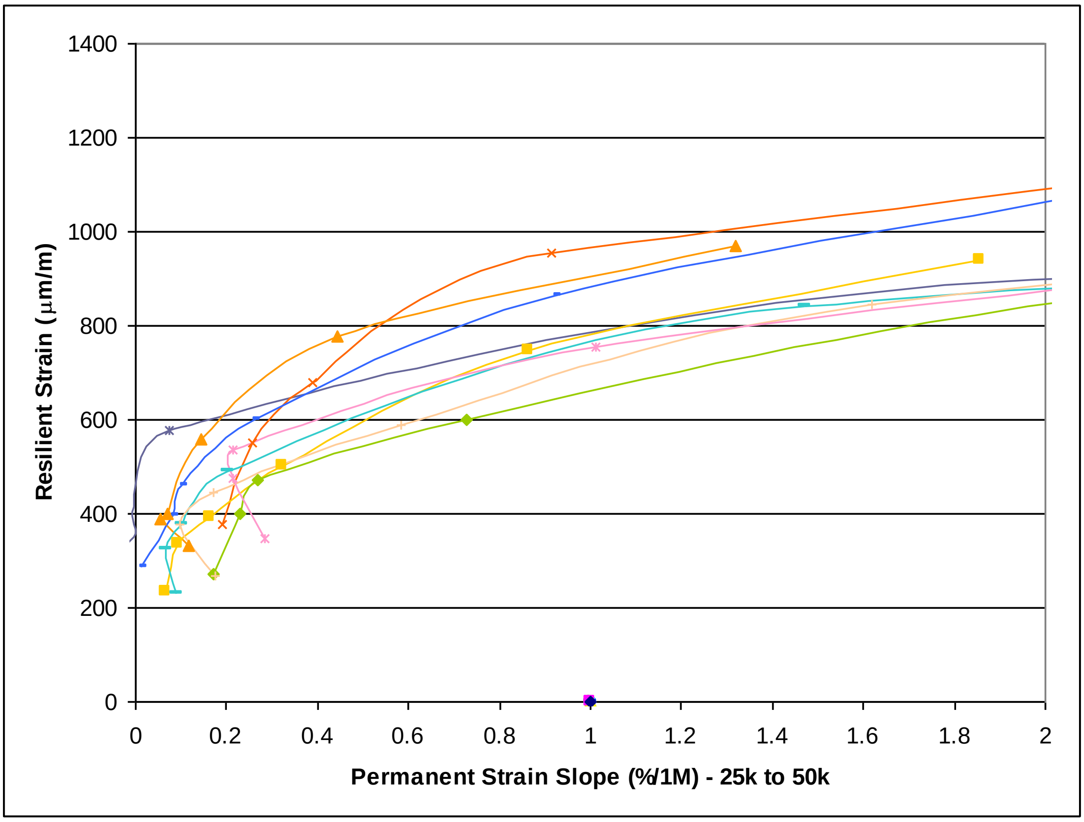
Figure 4.4 RLT plots for sub-base aggregates – saturated/undrained tests



4.4 Sub-base strain criteria

The RLT sub-base results were analysed to determine strain criteria using the same method as in section 3.2. This used the slope at each individual loading stage that had been linearly extrapolated to a specified failure permanent strain. As in section 3.2, a relationship between permanent strain slope (from N=25k to 50k) and resilient strain for the sub-base aggregates was determined as detailed in figure 4.5 The first calculation was the upper and lower percentiles (10th and 25th) and median as found from the data assuming a normal distribution. The results from the statistical analyses (table 4.3) were of interest only. A more appropriate assessment of the data was to assume the same exponent and determine the upper and lower bounds of the data as shown in table 4.4 and figure 4.10.

Figure 4.5 Relationships found between permanent strain rate and resilient strain for TNZ M4 basecourse aggregates tested by Pavespec Ltd



The end of pavement life was determined by assuming the rate of permanent strain was linear from zero (ie ignoring initial compaction) for calculating the number of load cycles to reach a defined permanent strain value at failure. This rate of strain value was taken as the slope in each loading stage from 25k to 50k. As with the analysis of the basecourse RLT results, an initial assumption of the end of life was made when the permanent strain reached a value of 3.3%. Thus, the number of load cycles to reach this criteria was determined and plotted against resilient strain (figure 4.6). A sub-base strain criterion was determined by regression analysis and plotted in figure 4.6. Apart from the data point of resilient strain and life for the first loading stage the data showed a close fit to the sub-base strain criterion with a regression of >0.97. Table 4.3 details the range of exponents and constants obtained for the sub-base strain criteria. Interestingly the exponent value was relatively constant around 3.40.

Figure 4.6 Relationships found from sub-base RLT test data between resilient strain and life (load cycles to reach 3.33% permanent strain)

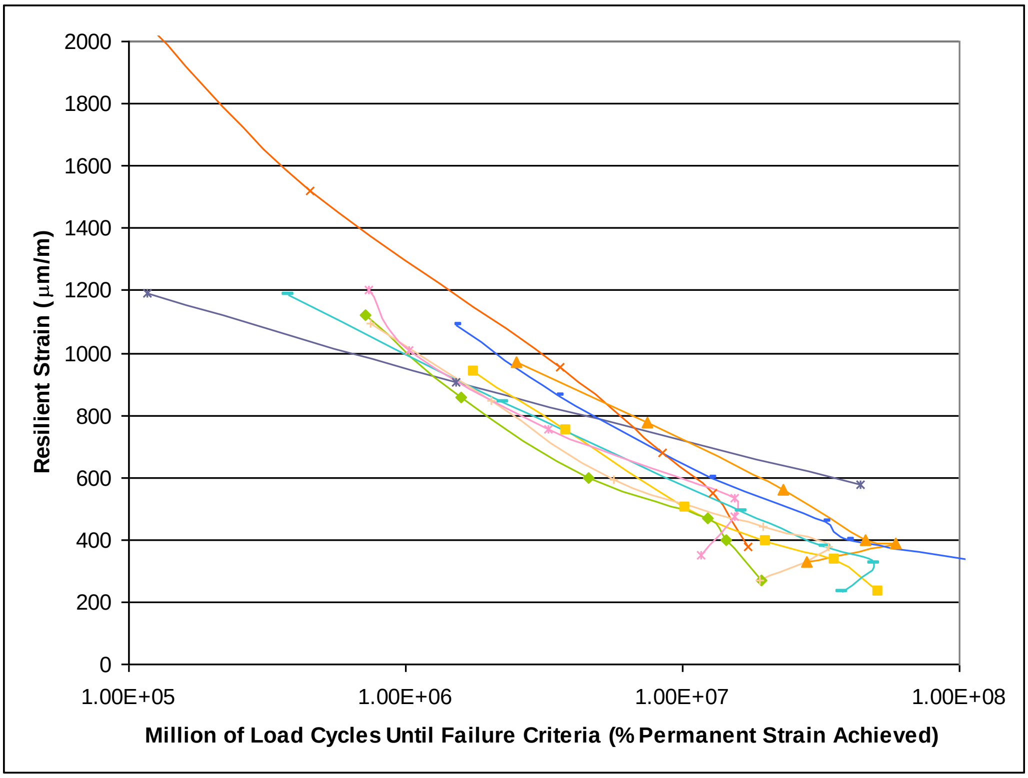


Figure 4.7 Sub-base strain criterion found by linear extrapolation of permanent strain data to 3.3% using the slope from 25k to 50k load cycles

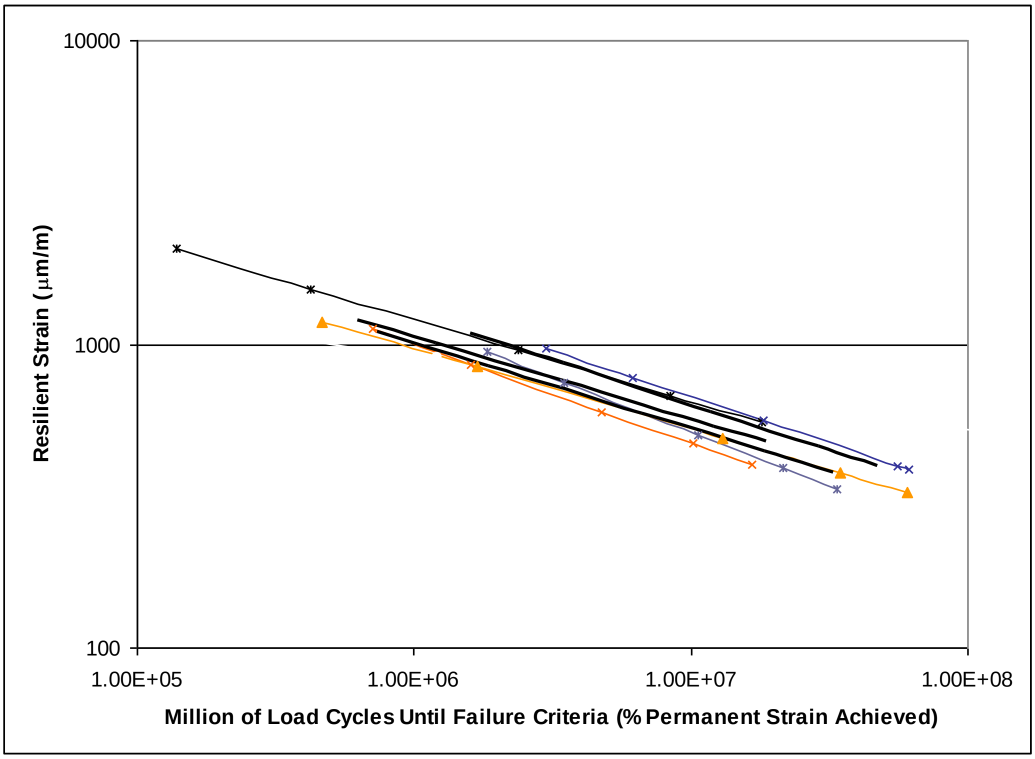


Table 4.3 Range of sub-base strain constants and exponents found from linear extrapolation of permanent strain data to 3.3% using the slope from 25k to 50k load cycles

	90%ile	10%ile	Average	Median	75%ile	25%ile	Number
k	110,457	43,869	74,815	64,400	89,199	47,650	8
exp	3.72	2.99	3.40	3.46	3.67	3.24	8

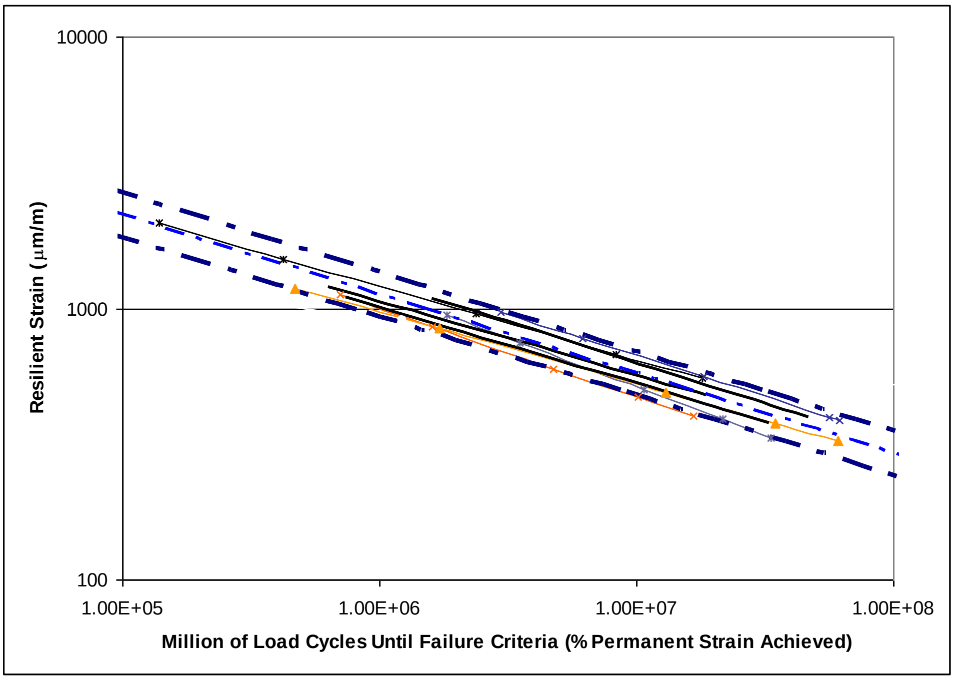
	90%ile	10%ile	Average	Median	75%ile	25%ile	Number
k	213,147	19,338	91,148	63,792	119,918	27,715	8
exp	4.98	3.00	3.88	3.61	4.48	3.37	8

Reviewing the sub-base strain criteria it was found they could all fit within upper and lower boundaries with a constant exponent value of 3.4 as shown in table 4.4 and figure 4.8.

Table 4.4 Upper and lower range of sub-base strain constants and exponents found from linear extrapolation of permanent strain data to 3.3% using the slope from 25k to 50k load cycles

Sub-base strain criterion	k	exp
Upper	80,000	3.4
Middle	66,000	3.4
Lower	55,000	3.4

Figure 4.8 Sub-base strain criterion found by linear extrapolation of permanent strain data to 3.3% using the slope from 25k to 50k load cycles with upper and lower boundaries



A note of interest was that the sub-base RLT data was re-analysed by using a different method to determine the number of load cycles to reach a failure permanent strain of 3.3% for each stage. This was the Arnold extrapolation method which used a power law for the first 500k cycles and then linear as illustrated in figure 4.9. The resulting sub-base strain criteria are shown in figure 4.10 and table 4.5.

Figure 4.9 Diagram explaining the different methods of extrapolating RLT test data to determine the number of load cycles to reach permanent strain at failure (*note: this used the simple linear extrapolation method where an adjustment factor was found in later validation*)

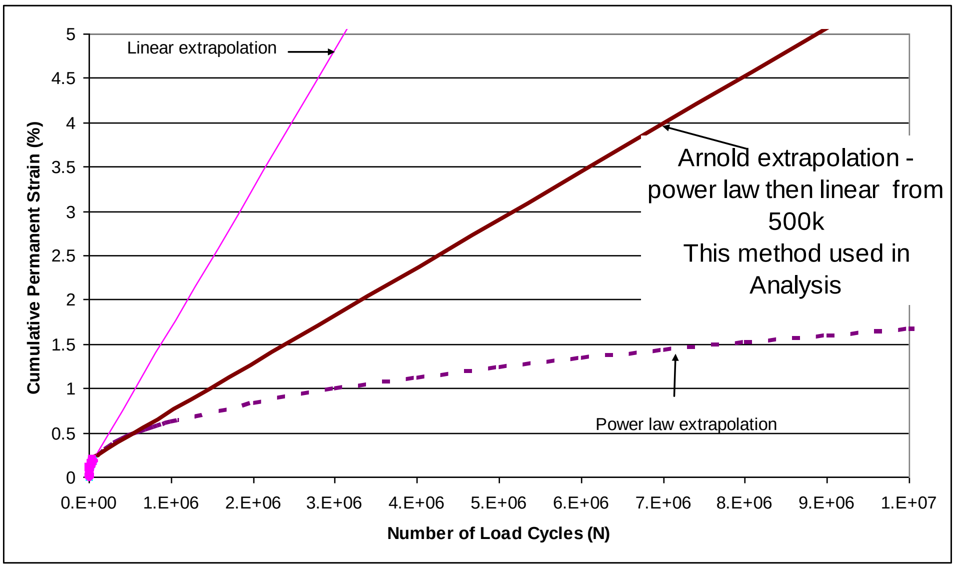


Figure 4.10 Sub-base strain criterion found by using the Arnold method of extrapolation of permanent strain data to 3.3% with upper and lower boundaries

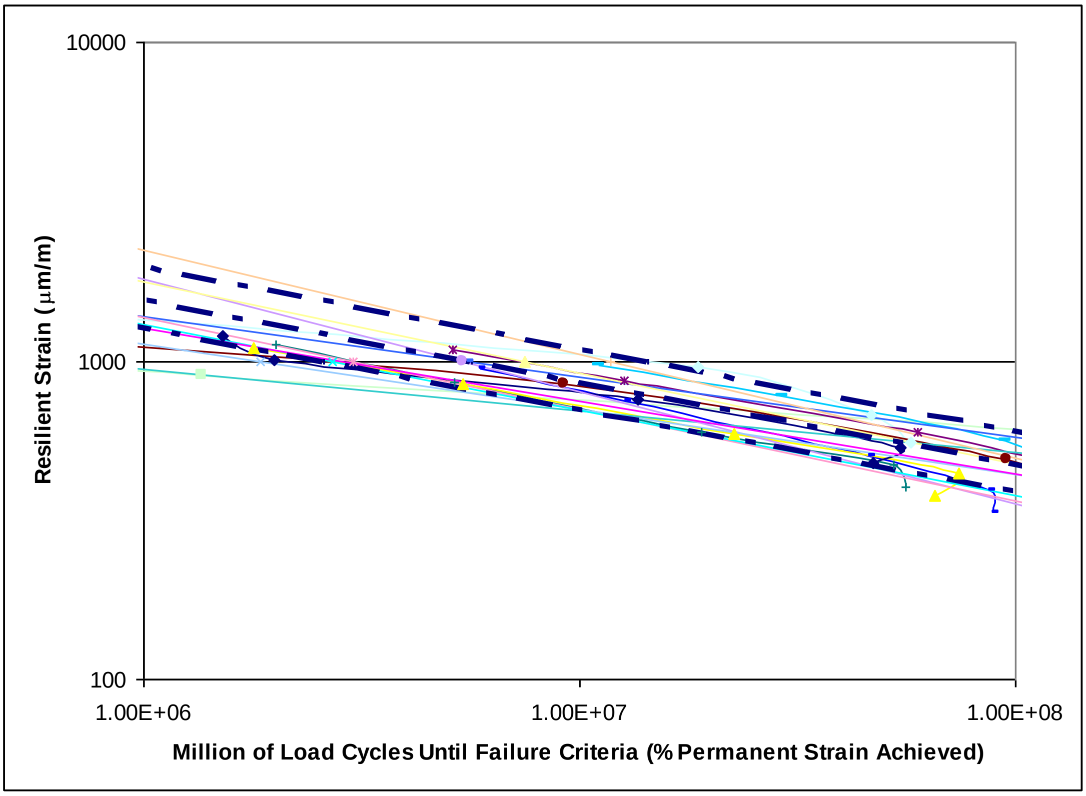


Table 4.5 Sub-base strain criterion found using the Arnold extrapolation method for each permanent strain stage of the RLT test

k	exp
5,829	7.60
19,118	5.26
19,432	4.86
30,476	4.35
53,690	3.72
73,894	3.47
92,329	3.50
202,684	3.06
237,562	2.83

Table 4.6 Range of sub-base strain constants and exponents found from the Arnold method of extrapolation of permanent strain data to 3%

	90%ile	10%ile	Average	Median	75%ile	25%ile	Number
k	213,147	19,338	91,148	63,792	119,918	27,715	8
exp	4.98	3.00	3.88	3.61	4.48	3.37	8

Table 4.7 Upper and lower range of sub-base strain constants and exponents found from the Arnold method of extrapolation of permanent strain data to 3%

Sub-base strain criterion	k	exp
Upper	70,000	3.88
Middle	55,000	3.88
Lower	45,000	3.88

Table 4.8 shows the comparison between sub-base strain criteria using different methods of extrapolation (figure 4.10). The method chosen for validating the prediction of pavement life was the linear method of extrapolation which is simple and easy to calculate, despite the Arnold method being more appropriate expected behaviour. An adjustment factor (f) was calculated to ensure the calculated pavement life using the linear method of extrapolation was close to the life determined from rut depth modelling in a parallel project (Arnold and Werkmeister 2010). As a comparison, the strain criterion found for basecourse aggregates is included in table 4.8 which shows the life for the basecourse aggregate is 5 to 10 times higher than the sub-base aggregate for the same level of strain.

Table 4.8 Strain criteria derived from RLT test data for sub-base and basecourse aggregates

$N = (k/\text{micro-strain})^{exp}$	Sub-base Arnold extrapolation (Figure 3.7)			Sub-base linear extrapolation (simple method used in later validation)			Basecourse linear extrapolation (simple method used in later validation)	
Strain criterion	k	exp		k	exp		k	exp
Upper	70,000	3.88		80,000	3.4		700,000	2.4
Middle	55,000	3.88		66,000	3.4		400,000	2.4
Lower	45,000	3.88		55,000	3.4		250,000	2.4

5 Validation and use in CIRCLY pavement design

A parallel project (Arnold and Werkmeister 2010) predicted rutting from a range of pavement cross-sections from rut depth models and finite element modelling with RLT data for subgrades and aggregates (sub-base and basecourse) as inputs. These rut depth predictions were validated with CAPTIF data and will be used to validate basecourse and strain criterion in CIRCLY for pavement design. Plots below (figures 5.1 and 5.2) show predicted lives from rut depth models, compared with those currently given in the Austroads pavement design guide. Pavement depths greater than in the Austroads guide are those where pavement life is governed by aggregate deformation. These are the pavements where the basecourse and sub-base strain criteria will be validated/refined to ensure similar lives are obtained from full rut depth models.

Figure 5.1 Pavement lives predicted for poor, average and very good quality granular materials over a subgrade CBR of 8%

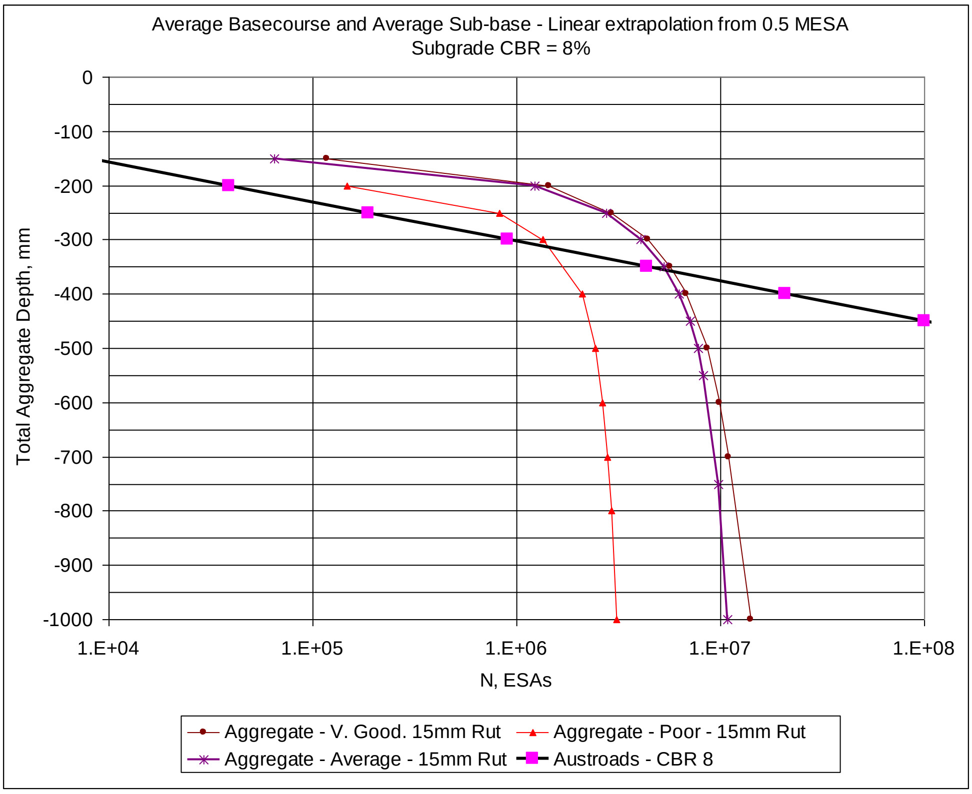
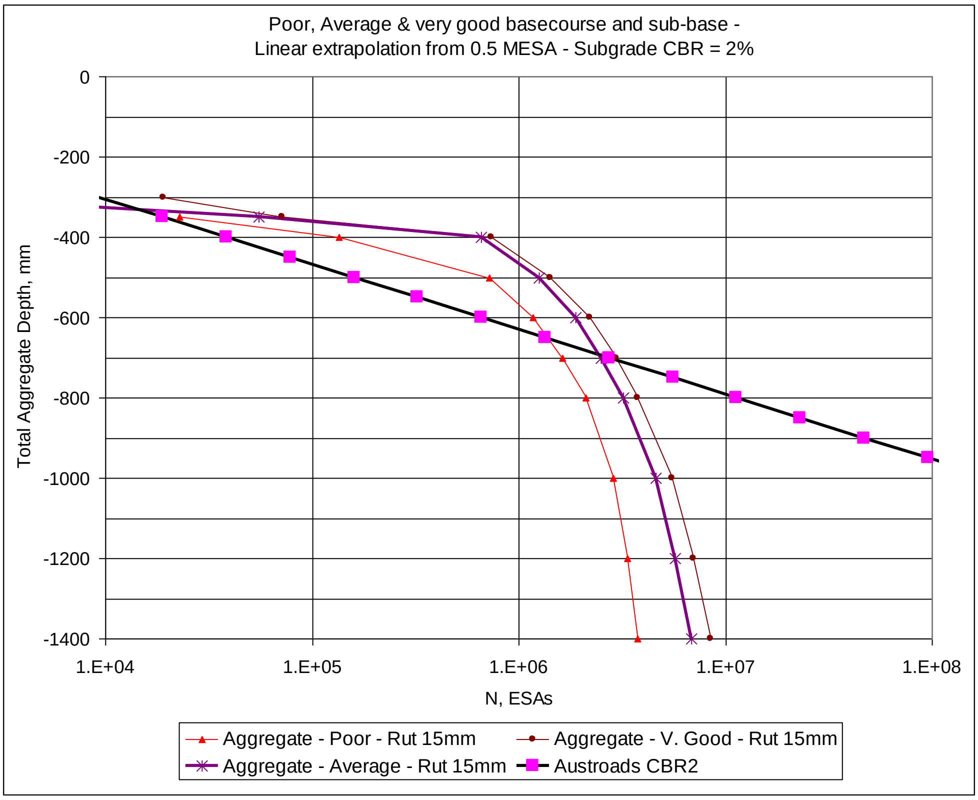


Figure 5.2 Pavement lives predicted for poor, average and very good quality granular materials over a subgrade CBR of 8%



Many CIRCLY analyses were undertaken on a full range of granular pavements on CBRs of 2% and 8%. Vertical compressive strains from CIRCLY were computed throughout the pavement to find the location of maximum vertical strains within the basecourse and sub-base layers (figures 5.3 and 5.4).

Figure 5.3 Vertical compressive strains calculated using CIRCLY for granular pavements on a subgrade CBR of 2%

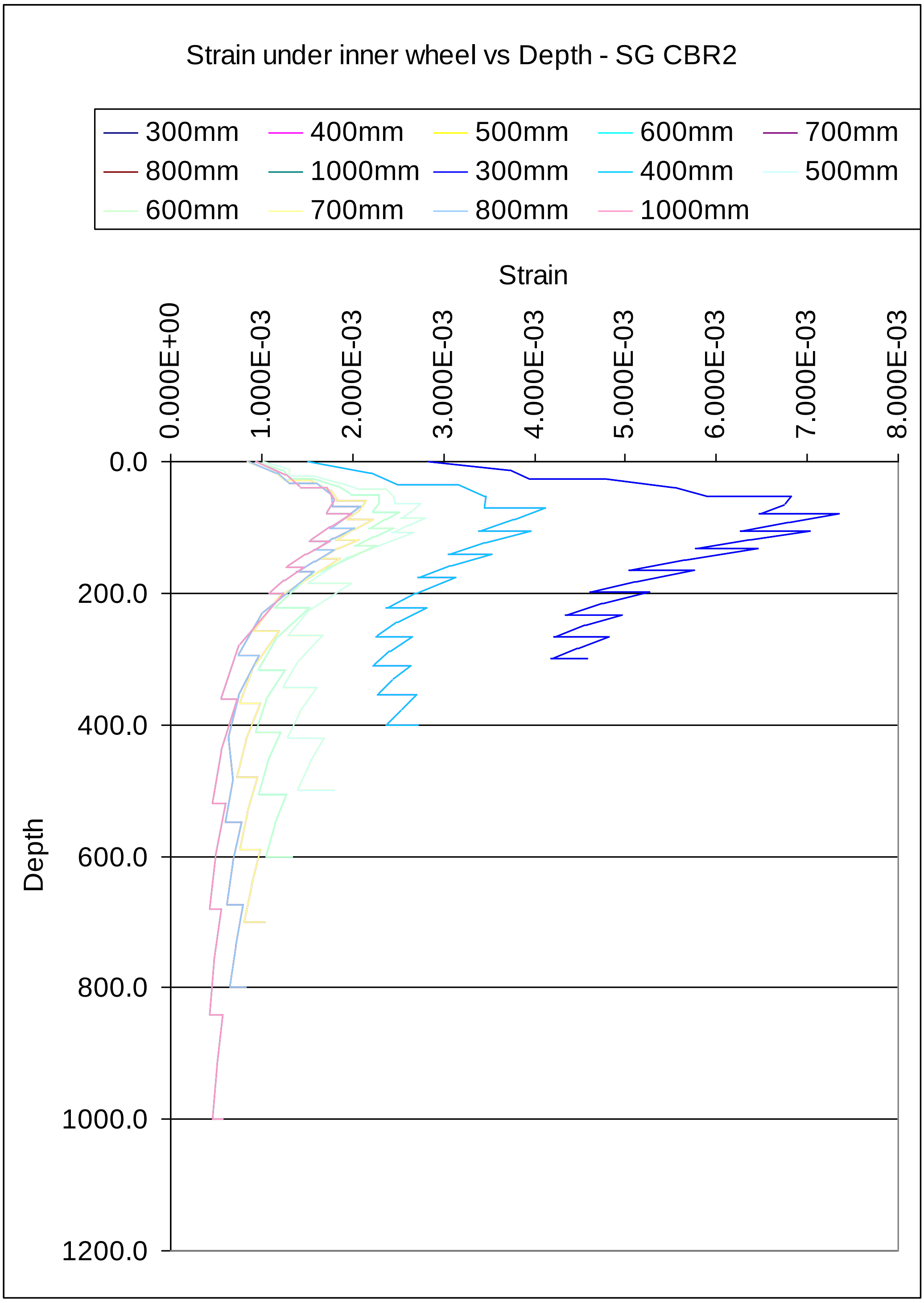
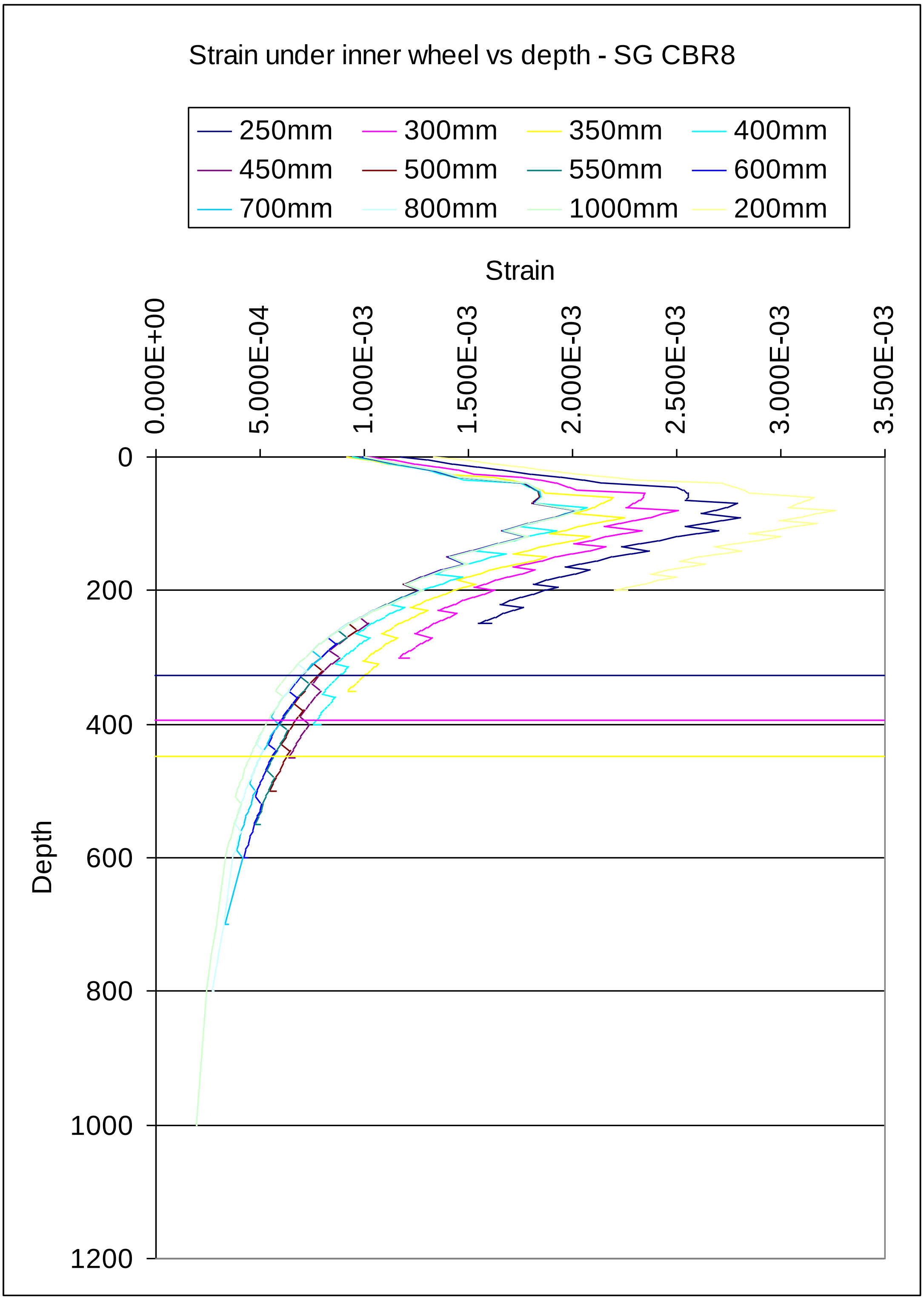


Figure 5.4 Vertical compressive strains calculated using CIRCLY for granular pavements on a subgrade CBR of 8%



The CIRCLY analyses showed the maximum strain in the sub-base aggregate was always at the top of the sub-base while the maximum strain in the basecourse was at a depth of 80mm within the basecourse layer. CIRCLY automatically checks the life of a pavement layer at the top or bottom of the layer. Therefore, any aggregate strain criteria developed will be based on strains at the bottom of the basecourse and top of the sub-base.

Initial strain criteria for the basecourse and sub-base aggregate were derived from the same RLT test data used in the rut depth modelling to generate the thickness design chart shown in figures 5.1 and 5.2. The method of derivation required the plotting of the log of traffic life (ESAs) versus the log of resilient strain found from the slope of the RLT data from 25k to 50k load cycles. The slope of the log/log plot gave the exponent while the intercept gave the constant k. Results for an average basecourse and average sub-base aggregates are shown in tables 5.1 and 5.2 and figure 5.5.

Table 5.1 Average basecourse design strain criterion derived from RLT test data

<table>
<tr><th>Resilient strain</th><th>Permanent strain rate</th><th>Traffic at failure</th><td rowspan="9">Average basecourse strain criterion
N = (f.k/resilient strain)^exp

k = 353,848

f. = adjustment factor found in validation process

exp = 2.47</td></tr>
<tr><td>microns</td><td>[Slope in % per 1 million cycles from 25k to 50k as per TNZ T/15]</td><td>N (ESA) to get to 3.3% permanent strain</td></tr>
<tr><td>A</td><td>B</td><td>C=3.3/B*(1000,000)</td></tr>
<tr><td>286</td><td>0.165</td><td>3.77E+07</td></tr>
<tr><td>415</td><td>0.176</td><td>4.91E+07</td></tr>
<tr><td>476</td><td>0.199</td><td>3.29E+07</td></tr>
<tr><td>591</td><td>0.310</td><td>1.62E+07</td></tr>
<tr><td>875</td><td>1.026</td><td>2.24E+06</td></tr>
<tr><td>1197</td><td>3.254</td><td>3.77E+05</td></tr>
</table>

Table 5.2 Average sub-base design strain criterion derived from RLT test data

<table>
<tr><th>Resilient strain</th><th>Permanent strain rate</th><th>Traffic at failure</th><td rowspan="9">Average sub-base strain criterion

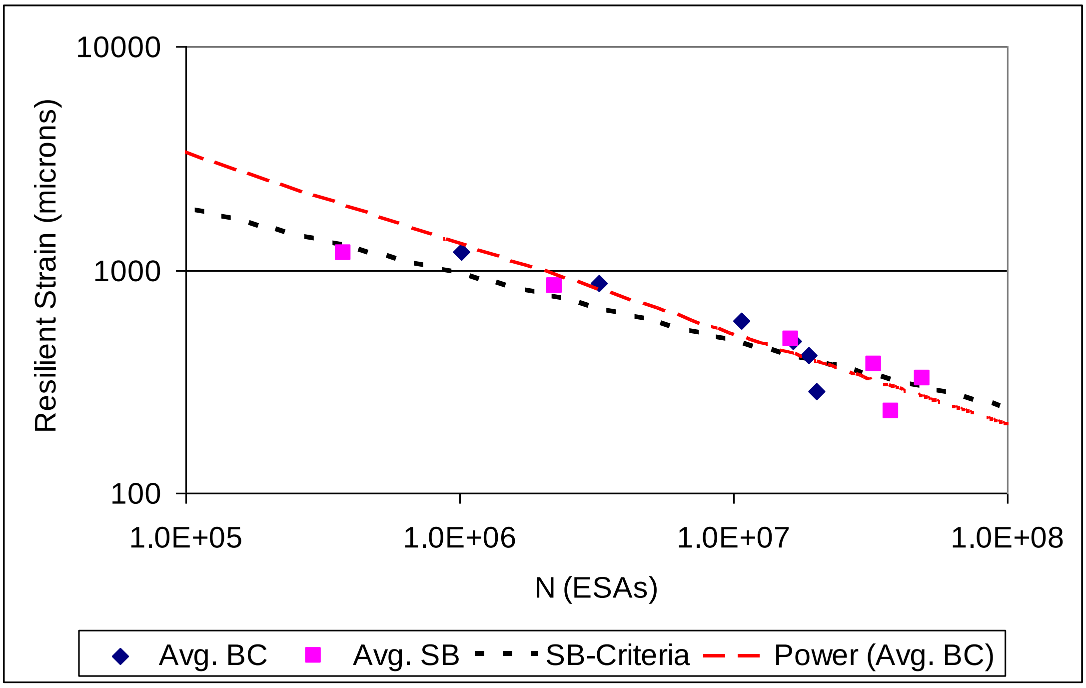
N = (f.k/resilient strain)^exp

k = 60,071

f. = adjustment factor found in validation process

exp = 3.35</td></tr>
<tr><td>microns</td><td>[Slope in % per 1 million cycles from 25k to 50k as per TNZ T/15]</td><td>N (ESA) to get to 3.3% permanent strain</td></tr>
<tr><td>A</td><td>B</td><td>C=3.3/B*(1000,000)</td></tr>
<tr><td>231</td><td>0.088</td><td>3.77E+07</td></tr>
<tr><td>326</td><td>0.067</td><td>4.91E+07</td></tr>
<tr><td>379</td><td>0.100</td><td>3.29E+07</td></tr>
<tr><td>491</td><td>0.204</td><td>1.62E+07</td></tr>
<tr><td>842</td><td>1.472</td><td>2.24E+06</td></tr>
<tr><td>1185</td><td>8.762</td><td>3.77E+05</td></tr>
</table>

Figure 5.5 Log plots of average basecourse and sub-base strain criterion



The strain criteria for the sub-base and basecourse aggregates were applied to strains calculated using CIRCLY at the point of maximum strain. The point of maximum strain in a basecourse with no thickness of surfacing is at a depth of around 80mm, while the maximum strain for the sub-base is at the top of the sub-base. As CIRCLY uses design criterion at the top or bottom of pavement materials an additional adjustment is made to convert the basecourse strain at the bottom to a strain equal to the maximum strain calculated in the basecourse layer. Conveniently the strains at the bottom of the basecourse could be readily converted to the same as maximum strains using the formula in equation 5.1.

BC strain (max) = BC strain (bottom) x BC depth (mm) x 0.00905 (Equation 5.1)

Where:

BC strain (max) = the maximum strain in the basecourse layer in a thin surfaced granular pavement

BC strain (bottom) = the strain calculated at the bottom of the basecourse layer

BC depth (mm) = the depth or thickness of the basecourse layer

Equation 5.1 can be applied within the design strain criterion (equation 5.2) as another factor to multiply the constant k.

N_{BC} = (a.f.k_{BC}/resilient strain bottom of BC)^exp_{BC} (Equation 5.2)

Where:

N_{BC} =life of basecourse in equivalent standard axles (ESAs)

a = constant to adjust strain at bottom of basecourse to a maximum strain in the basecourse

a = 1/(BC depth (mm) x 0.00905) – derived from equation 5.1

f = adjustment factor determined from validation to ensure calculated life from stain criterion is equal to life calculated from rut depth modelling

k_{BC} = constant found from RLT testing shown in table 5.1

exp_{BC} = constant found from RLT testing shown in table 5.1

resilient strain bottom of BC = resilient strain at the bottom of the basecourse layer.

The life of the sub-base aggregate layer is found from equation 5.3:

$$N_{SB} = (f.k_{SB}/\text{resilient strain top of SB})\hat{}exp_{SB} \qquad \text{(Equation 5.3)}$$

Where:

N_{SB} = life of basecourse in ESAs

f = adjustment factor determined from validation to ensure calculated life from stain criterion is equal to life calculated from rut depth modelling

k_{SB} = constant found from RLT testing shown in table 5.2

exp_{SB} = constant found from RLT testing shown in table 5.2

resilient strain top of SB = resilient strain at the top of the sub-base layer.

Results of CIRCLY analysis incorporating basecourse and sub-base design strain criteria (equations 5.2 and 5.3) in comparison with life calculated from rut depth modelling and Austroads design guide are shown in table 5.3 and figure 5.6 for a subgrade CBR of 2%. It was found that an adjustment factor (f, equations 5.2 and 5.3) of 2.5 was needed to ensure the calculated life matched the life calculated from the rut depth models.

Table 5.3 dBasecourse and sub-base life calculated from CIRCLY strains in comparison with rut depth models and Austroads for average quality aggregates over a subgrade of CBR of 2%

SG CBR	2	2	2	2	2	2	2
Total depth	300	400	500	600	700	800	1000
BC depth	132	177	107	127	148	168	200
S/B depth	168	223	393	473	552	632	800
BC max strain	7340	4118	2802	2516	2223	2084	1986
BC bottom strain	5779	2724	2430	2017	1642	1385	1087
Sub-base top strain	6454	3131	2679	2257	1865	1578	1239
	f	k	n				
BC max strain	2.5	3.54E+05	2.47				
life (ESAs)	1.37E+05	5.69E+05	1.47E+06	1.92E+06	2.60E+06	3.05E+06	3.44E+06
	f	k	n				
BC bottom strain	2.5	3.54E+05	2.47				
a:	*0.84*	*0.62*	*1.03*	*0.87*	*0.75*	*0.66*	*0.55*
life (ESAs)	1.59E+05	4.93E+05	2.26E+06	2.35E+06	2.67E+06	2.98E+06	3.52E+06
	f	k	n				
Sub-base top strain	2.5	6.01E+04	3.35				
life (ESAs)	3.75E+04	4.22E+05	7.10E+05	1.26E+06	2.39E+06	4.17E+06	9.38E+06
Min. life ESAs	3.75E+04	4.22E+05	7.10E+05	1.26E+06	2.39E+06	2.98E+06	3.44E+06
Rut depth models							
life (ESAs)	1.41E+03	6.57E+05	1.26E+06	1.89E+06	2.50E+06	3.20E+06	4.59E+06
Austroads							
life (ESAs)	8.84E+03	3.70E+04	1.55E+05	6.50E+05	2.73E+06	1.14E+07	2.01E+08

Figure 5.6 Basecourse and sub-base life calculated from CIRCLY strains in comparison with rut depth models and Austroads for average quality aggregates over a subgrade CBR of 2%, f=2.5

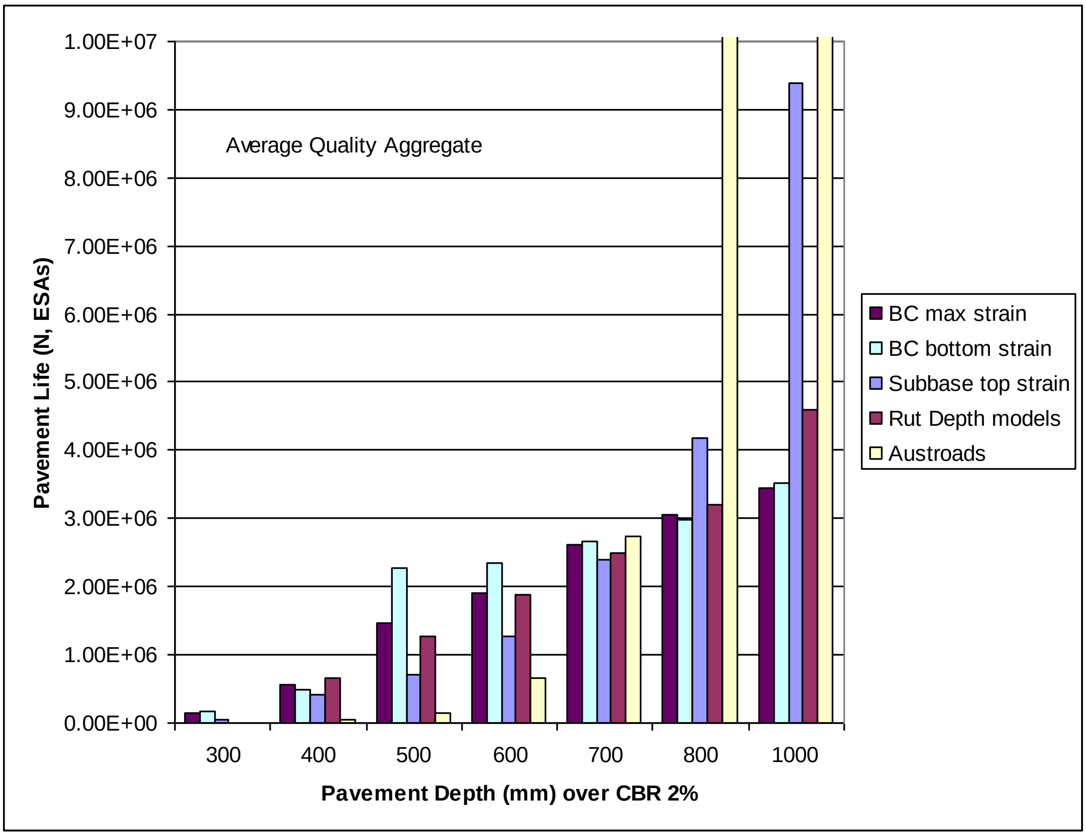


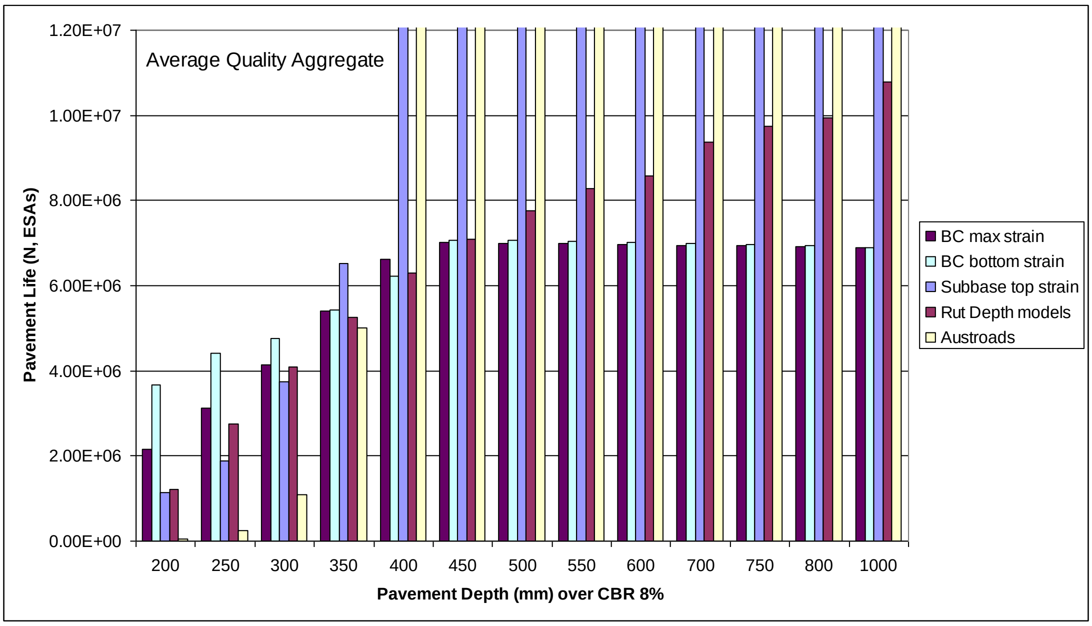
Figure 5.6 shows that in granular pavements with a depth of up to 600mm over a subgrade CBR of 2%, the life of the subgrade dominated as determined by the Austroads strain criterion (yellow 'Austroads' bar). At a depth of 700mm over a subgrade CBR of 2%, pavement lives determined from Austroads (subgrade strain criterion), basecourse and sub-base strain criteria were similar. With the pavement depth increased to 800mm, Austroads showed a huge exponential jump in pavement life while only a marginal increase in the sub-base and basecourse lives. There was a significant increase in sub-base life where the total granular pavement depth was 1000mm. This was because the strain at the top of the sub-base reduced significantly with 200mm of basecourse, while other pavement depths had less basecourse cover. Another point to note is that in granular pavements on top of a subgrade CBR of 2%, the maximum life achieved was 4 million ESAs regardless of the thickness of the granular pavement.

CIRCLY analysis incorporating design criterion for aggregates was also completed for a subgrade CBR of 8%. Results are shown in table 5.4 and figure 5.7 where an adjustment factor of 3.4 was required to ensure the life in the aggregate layers matched the life found from rut depth modelling.

Table 5.4 Basecourse and sub-base life calculated from CIRCLY strains in comparison with rut depth models and Austroads for average quality aggregates over a subgrade of CBR 8%

SG CBR	8	8	8	8	8	8	8
Total depth	300	400	500	550	600	700	800
BC depth	132	177	200	200	200	200	200
S/B depth	168	223	300	350	400	500	600
BC max strain	2507	2071	2025	2027	2028	2031	2034
BC bottom strain	1980	1325	1115	1116	1118	1120	1122
Sub-base top strain	2216	1504	1267	1269	1272	1275	1279
	f	k	n				
BC max strain	3.4	3.54E+05	2.47				
life (ESAs)	4.13E+06	6.62E+06	7.00E+06	6.99E+06	6.98E+06	6.95E+06	6.93E+06
	f	k	n				
BC bottom strain	3.4	3.54E+05	2.47				
a:	*0.84*	*0.62*	*0.55*	*0.55*	*0.55*	*0.55*	*0.55*
life (ESAs)	4.77E+06	6.24E+06	7.06E+06	7.05E+06	7.01E+06	6.98E+06	6.95E+06
	f	k	n				
Sub-base top strain	3.4	6.01E+04	3.35				
life (ESAs)	3.75E+06	1.37E+07	2.43E+07	2.42E+07	2.40E+07	2.38E+07	2.36E+07
Min. life ESAs	3.75E+06	6.24E+06	7.00E+06	6.99E+06	6.98E+06	6.95E+06	6.93E+06
Rut depth models							
life (ESAs)	4.08E+06	6.30E+06	7.76E+06	8.27E+06	8.59E+06	9.36E+06	9.95E+06
Austroads							
life (ESAs)	1.10E+06	2.29E+07	4.79E+08	2.19E+09	1.00E+10	2.09E+11	4.38E+12

Figure 5.6 Basecourse and sub-base life calculated from CIRCLY strains in comparison with rut depth models and Austroads for average quality aggregates over a subgrade CBR of 8% (f=3.4)



Reviewing the results of the CIRCLY analysis showed the adjustment factor (f, equations 5.2 and 5.3) depended on the subgrade CBR. For a subgrade CBR of 2% the adjustment factor was f = 2.5, while for a CBR of 8%, f=3.4 was required to ensure the predicted life from the basecourse and sub-base strain criteria matched the life predicted from the rut depth models (Arnold and Werkmeister 2010).

The analysis was repeated using RLT data for poor quality basecourse and sub-base aggregates. It was found in CIRCLY with repeat runs that changing the modulus of the upper aggregate layers did not change the vertical compressive strains within the aggregate layers that were automatically sub-layered using Austroads procedures (2004). Hence, the same vertical compressive strains within the granular layers were used but with different constants for the basecourse and sub-base strain criteria representing the poor quality aggregates. Using the same adjustment factors as found for the average quality aggregate (f=2.5 for a CBR of 2% and f=3.4 for a CBR of 8%) resulted in only a small reduction in aggregate life compared with the life for the average quality aggregate (figures 5.7 and 5.8).

Using RLT data for a poor basecourse and poor sub-base aggregate resulted in the application of an adjustment factor, f=2.0, to both CBR 2% and 8% subgrades. This calculated lives from the CIRCLY strains close to those predicted in the rut depth modelling (figures 5.9 and 5.10). In fact, the adjustment factor of f=2.0 also worked for the very good basecourse and sub-base aggregates (figures 5.11 and 5.12). Since this study began, many more RLT tests have been conducted on aggregates and the RLT data for the very good basecourse and sub-base aggregate was a more typical result. It is recommended that the adjustment factor of 2.0 be used despite a different result found for the average quality aggregate.

Figure 5.7 Poor quality basecourse and sub-base life calculated from CIRCLY strains over a subgrade CBR of 2% with the same validated adjustment factor as for average aggregate, f=2.5

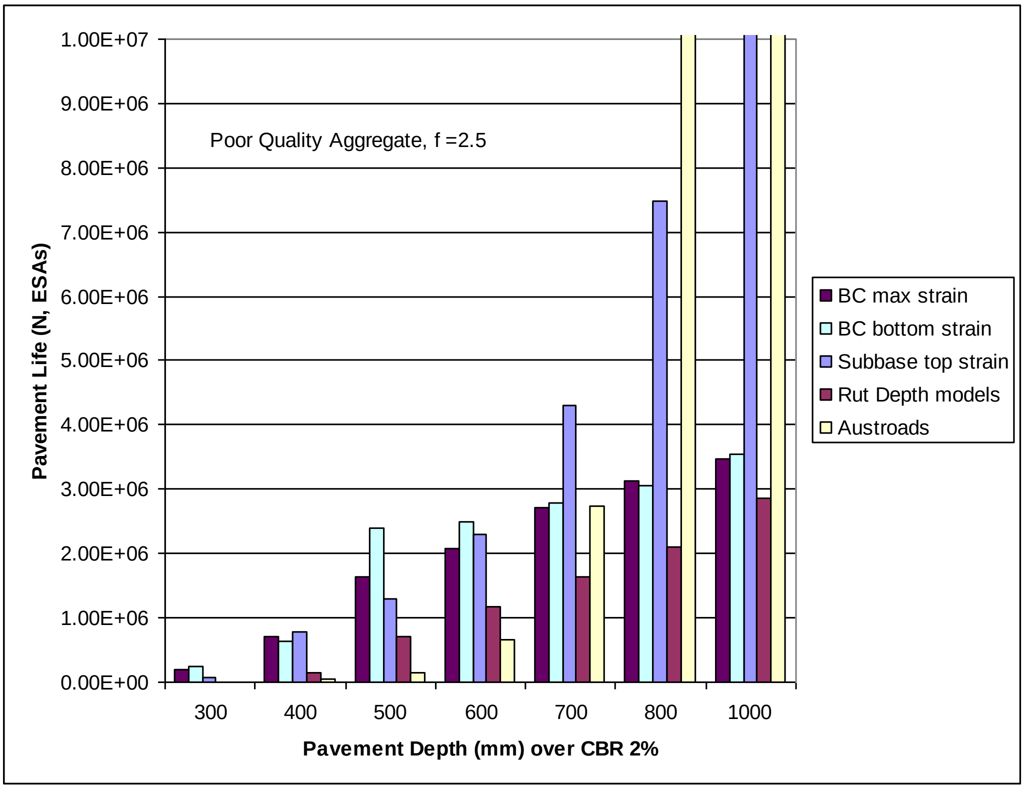


Figure 5.8 Poor quality basecourse and sub-base life calculated from CIRCLY strains over a subgrade CBR of 8% with the same validated adjustment factor as for average aggregate, f=3.4

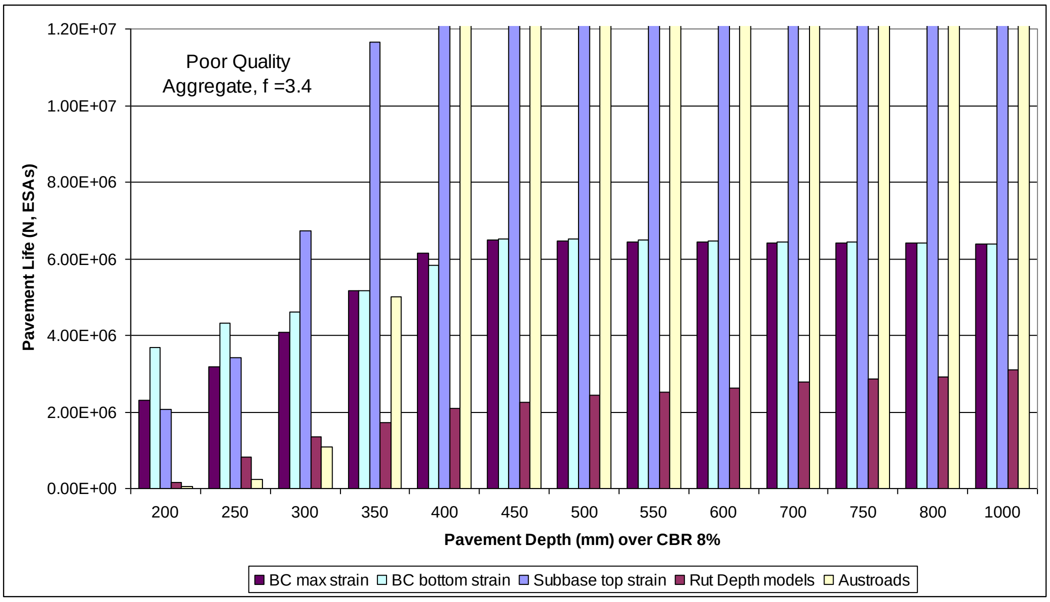


Figure 5.9 Poor quality basecourse and sub-base life calculated from CIRCLY strains over a subgrade CBR of 2% with a validated adjustment factor, f=2.0

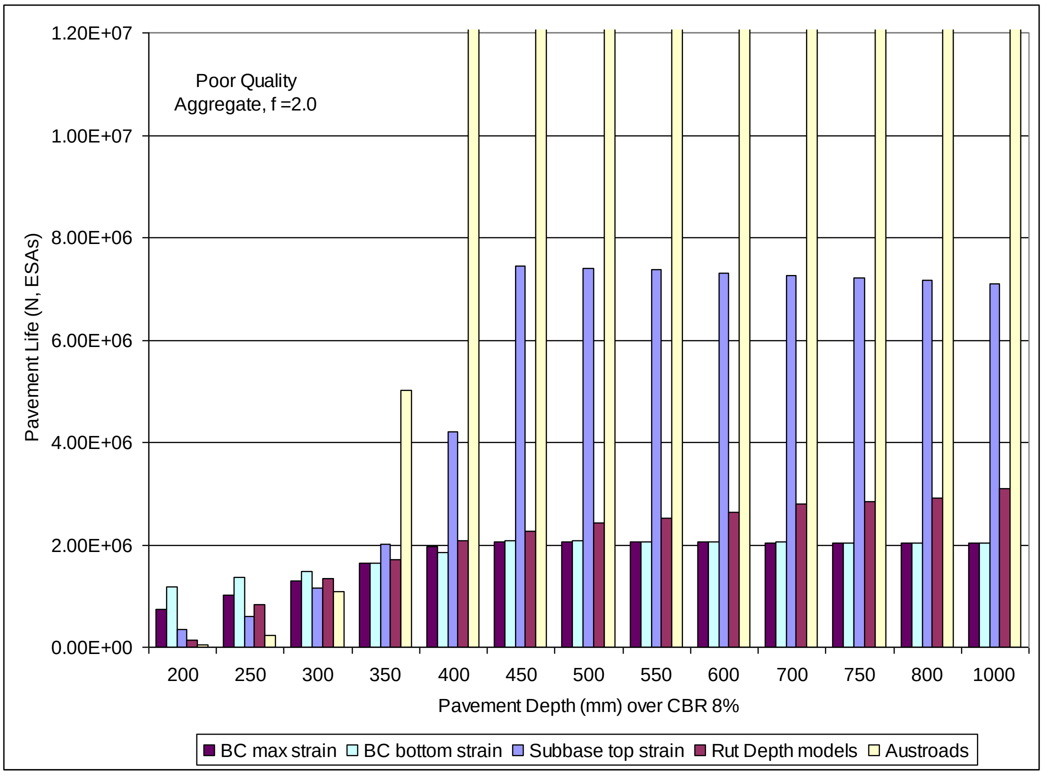


Figure 5.10 Poor quality basecourse and sub-base life calculated from CIRCLY strains over a subgrade CBR of 8% with a validated adjustment factor, f=2.0

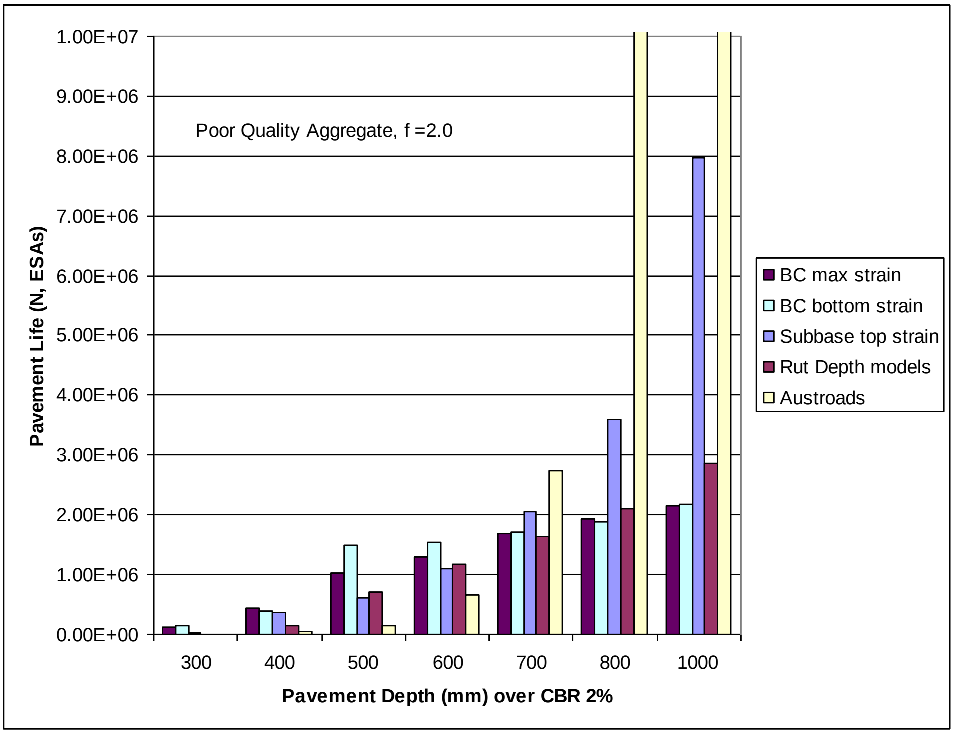


Figure 5.11 Very good quality basecourse and sub-base life calculated from CIRCLY strains over a subgrade CBR of 2% with a validated adjustment factor, f=2.0

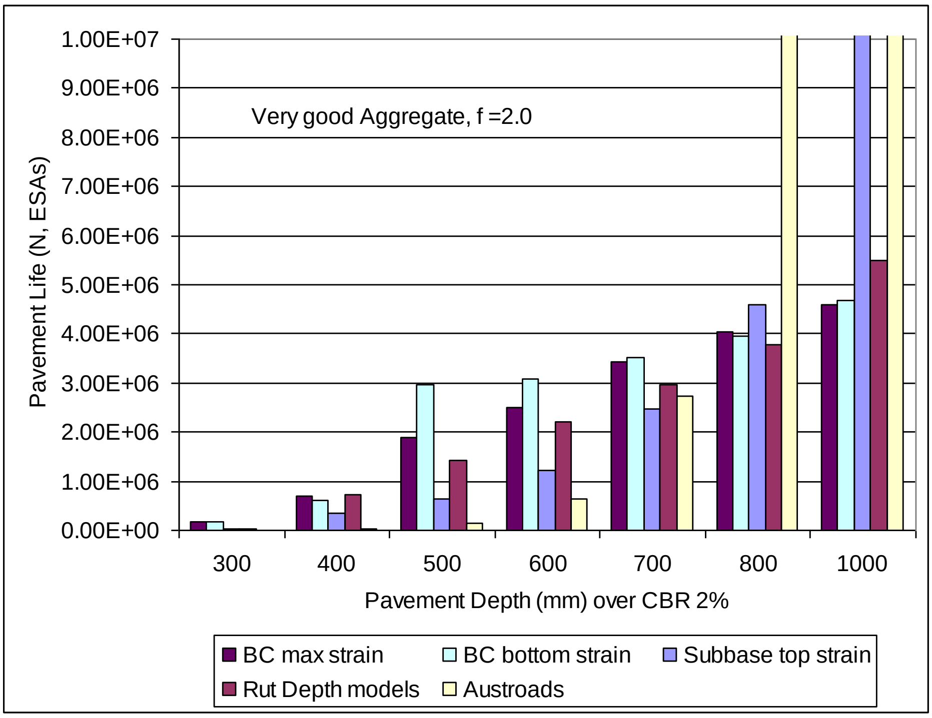


Figure 5.12 Very good quality basecourse and sub-base life calculated from CIRCLY strains over a subgrade CBR of 8% with a validated adjustment factor, f=2.0

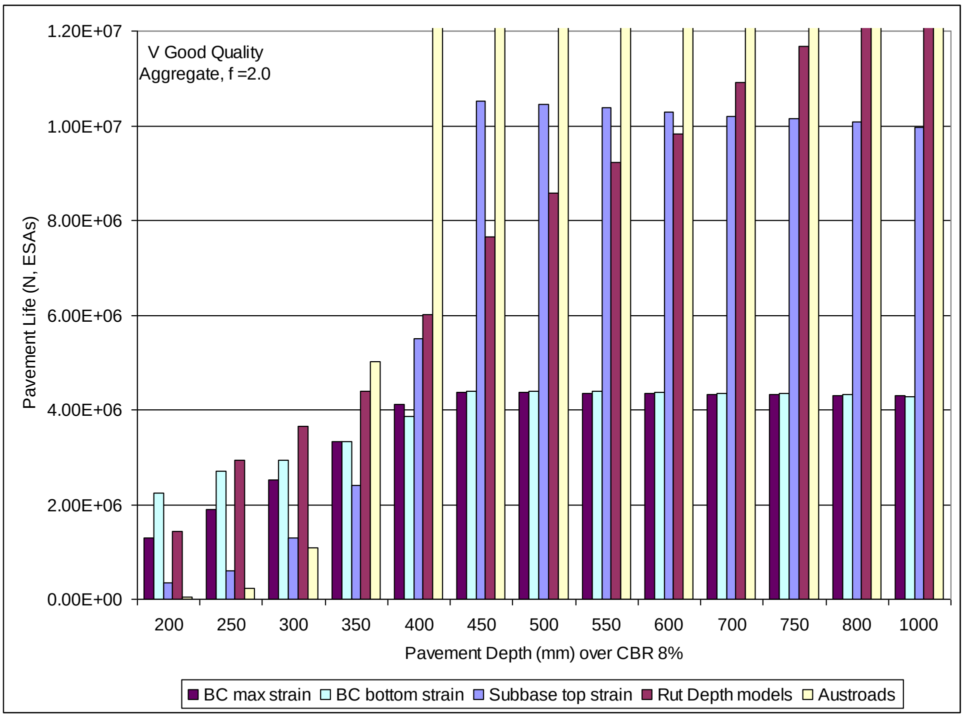
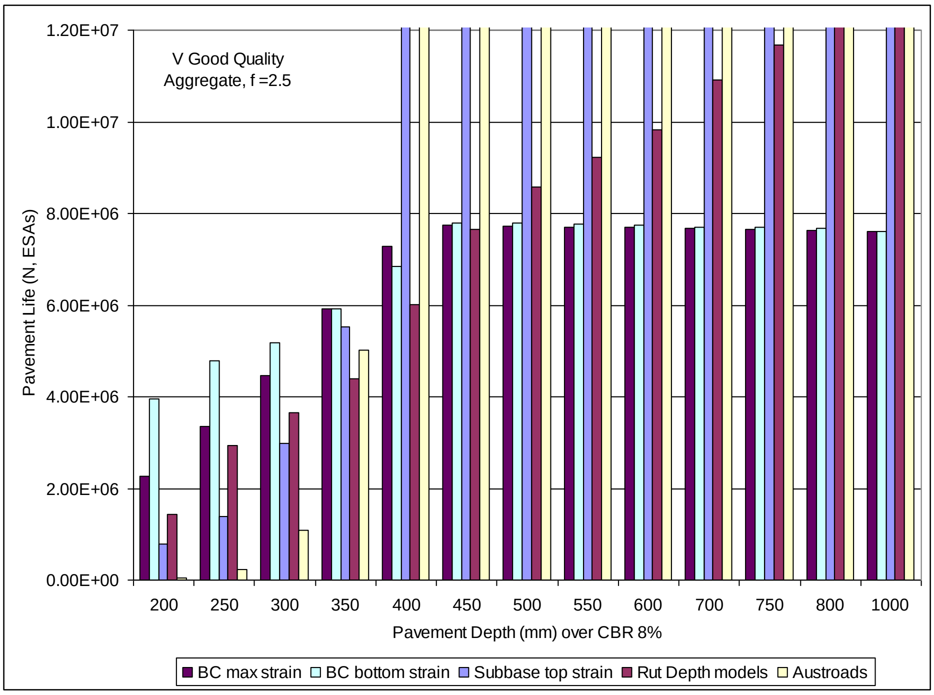


Figure 5.13 Very good quality basecourse and sub-base life calculated from CIRCLY strains over a subgrade CBR of 8% with a validated adjustment factor, f=2.5



Both the poor and very good quality aggregates over a CBR of 2% required the same adjustment factor of 2.0, while the average quality aggregate required an adjustment factor of 2.5. For the CBR 8% pavements, the poor quality aggregate required an adjustment factor of 2.0, very good aggregate f=2.5 and average aggregate f=3.4. It is likely that the use of the poor aggregate in pavement design would also result in significantly higher vertical compressive strains and thus lives would be shorter and an adjustment factor of f=2.5 would be appropriate. The unusual adjustment factor of 3.4 found with the average quality aggregate can be ignored as since this study began the RLT test has been applied to many more basecourses where the most common result for a NZTA M4 basecourse would be similar to the 'very good' aggregate used in this study. The effect of this would be conservative in the calculation of shorter lives. An adjustment factor of f=2.0 (equations 5.2 and 5.3) is therefore recommended as this worked for both the poor and very good aggregates at two subgrade strengths.

5.1 Accounting for a reduction in subgrade rutting

Full rut depth modelling, as undertaken in a parallel research project (Arnold and Werkmeister 2010), considered the combined contribution of rutting by all pavement layers. Therefore, as the granular pavement thickness increased, the amount of rutting in the subgrade decreased. At the same time the amount of rutting in the granular layers increased. Using a basecourse and sub-base strain criterion did not take into account the reduced rutting of the subgrade by increasing the thickness of the granular materials. The result was a ceiling in the pavement life limited by the strain criterion in the granular layers that did not change regardless of the depth of pavement, as the strain criterion was only applied in two places (on top of the sub-base and at a depth of 80mm within the basecourse layer).

Thus, increasing the thickness of a granular pavement over the subgrade did not reduce the vertical compressive strains in the basecourse layer. The result was not surprising given the same surface tyre stresses applied where the maximum strain was always around 80mm below the surface. The increase in life found from rut depth modelling, as the depth increased, was a result of the continued reduction in rutting of the subgrade. An additional adjustment factor could be used to take this into account. It was found that the proportional increase in life needed, so the calculated aggregate lives matched those resulting from rut depth modelling, was the same proportional increase in pavement depth above the depth where aggregate life governed. This was about 500mm for the CBR 8% pavements and 1000mm for the subgrade CBR 2% pavements.

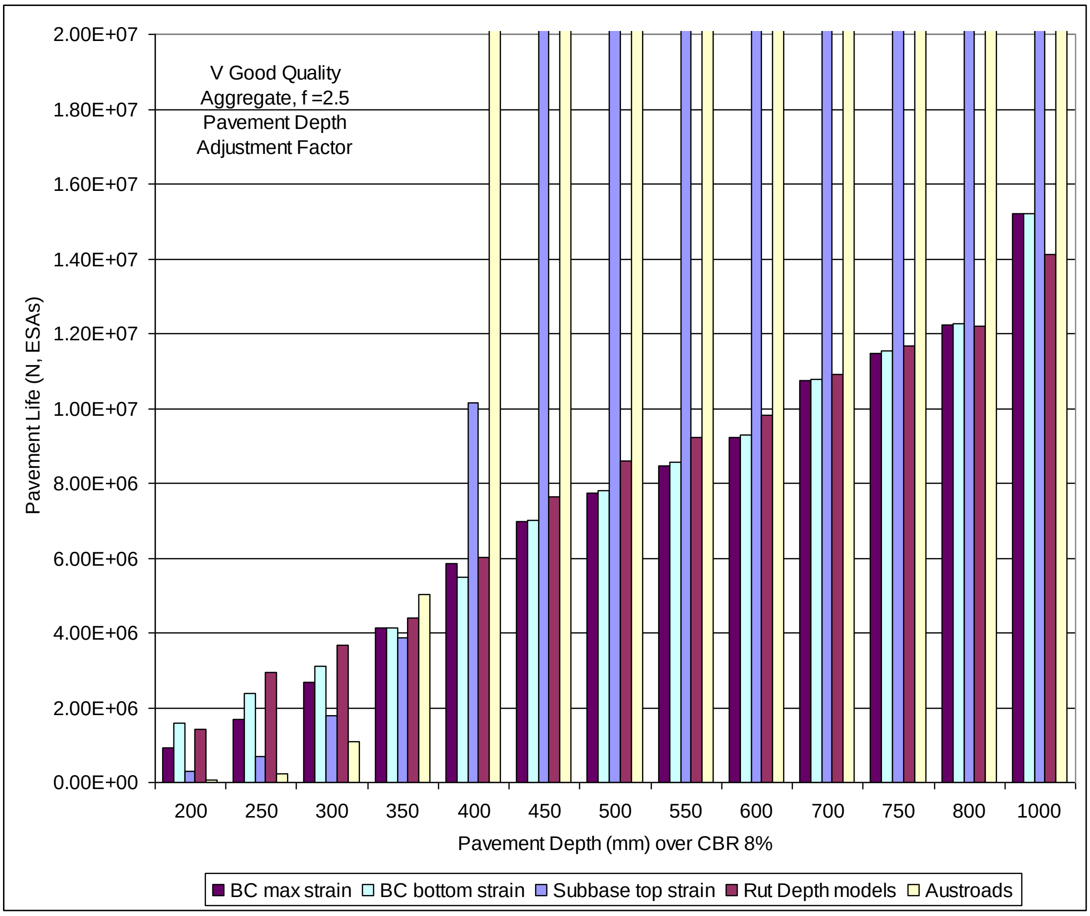
Table 5.5 Aggregate life multiplier from pavement depth resulting in reduced rutting in the subgrade

Subgrade CBR%	Pavement depth (mm) when aggregate life influences (D)	Aggregate life multiplier M (ie multiply computed life by M) up to a maximum of M=1.8.
2	1000	M = total pavement depth/D
3	854	
4	750	
5	670	
6	604	
7	548	
8	500	
9	458	
10	420	
11	385	
12	354	
13	325	
14	298	
15	273	

A conservative approach, however, would be to ignore the effect an increase in pavement depth had on subgrade rutting as this would require the designer to change materials (eg stabilised) rather than keep increasing the depth to increase life.

The effect of applying this pavement depth adjustment for the CBR 8% pavements is shown in figure 5.13. On reviewing the results it would be prudent to limit the aggregate life multiplier to 1.8 in order to limit excessive increases in life by adding more thickness of granular materials.

Figure 5.13 Very good quality basecourse and sub-base life calculated from CIRCLY strains over a subgrade CBR of 8% with a validated adjustment factor, f=2.5 and the application of a pavement depth adjustment factor (table 5.5)



6 Discussion

The aim of this research was to develop a sub-base and basecourse strain criterion derived from a simple interpretation of multi-stage RLT tests as per TNZ T/15. This simple method was validated against full depth pavement modelling which used a complicated method for analysing the RLT test data. Thus, differences in predicted lives using the same RLT data was expected from the simple approach used in this study and the complex full depth rut models used in a parallel study (Arnold and Werkmeister 2010).

Nevertheless, it was found possible to use the simple approach to predict life of the aggregates from a strain criterion derived from RLT tests. Before adopting the method proposed for use in CIRCLY pavement design there needs to be discussion with the NZTA and industry because of the implications that granular pavements cannot be used past a certain traffic loading. Thus, the method of determining the design strain criterion from RLT test data can be adjusted up (resulting in longer pavement lives) or down (resulting in shorter pavement lives). The amount of adjustment up or down depends on field validation and needs industry as a whole to agree where the traffic loading limit for granular pavements should lie.

The current adjustment factor applied to the RLT data for determining basecourse and sub-base strain criterion will result in approximately the same predictions of pavement life for granular pavements as found in the parallel rut depth modelling research project shown in figure 6.1 (Arnold and Werkmeister 2010). However, the design strain criteria for the basecourse and sub-base granular materials as shown in figure 6.2 (design method using CIRCLY) are more versatile and allow the option of increasing asphalt cover and exploring stabilisation that could further increase pavement life.

Figure 6.1 Recommended pavement thickness design chart for average quality aggregate combing Austroads and rut depth predictions (Arnold and Werkmeister 2010)

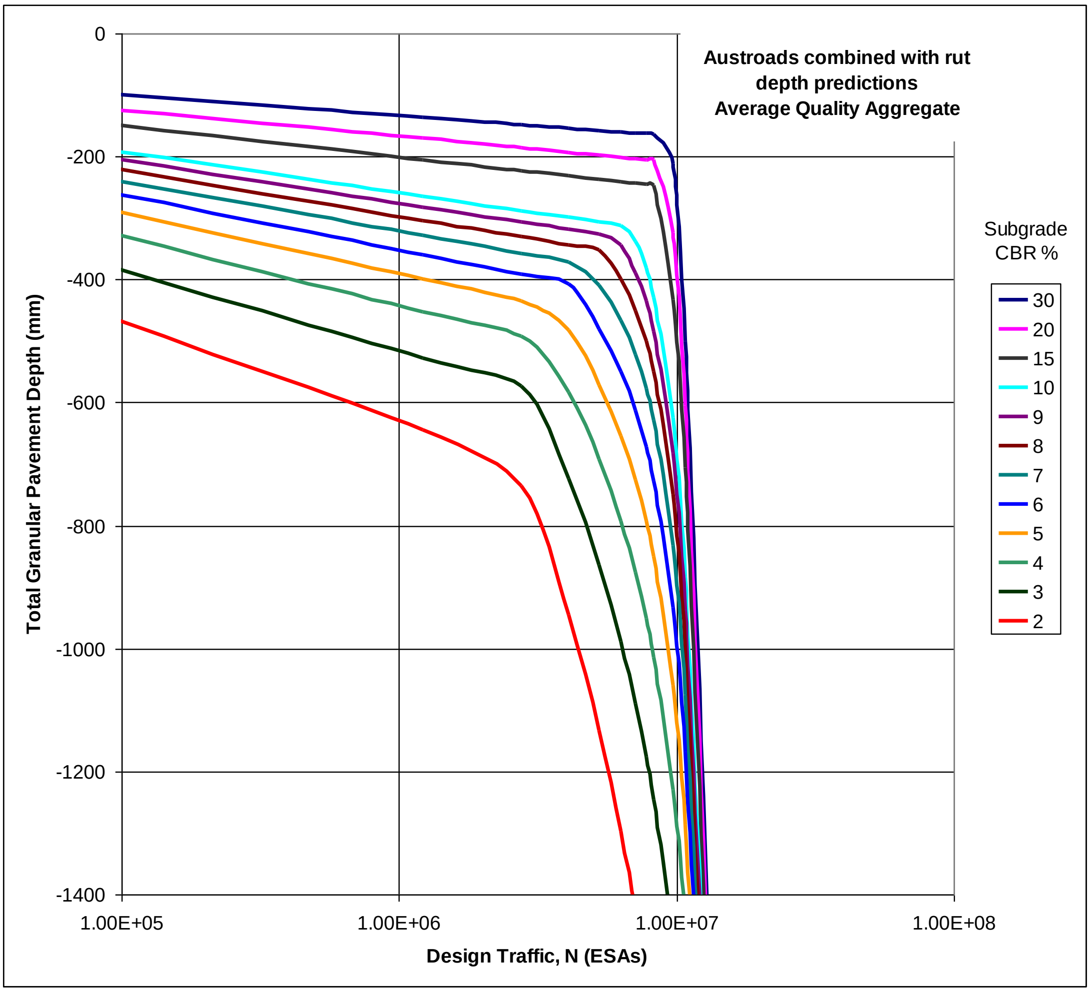
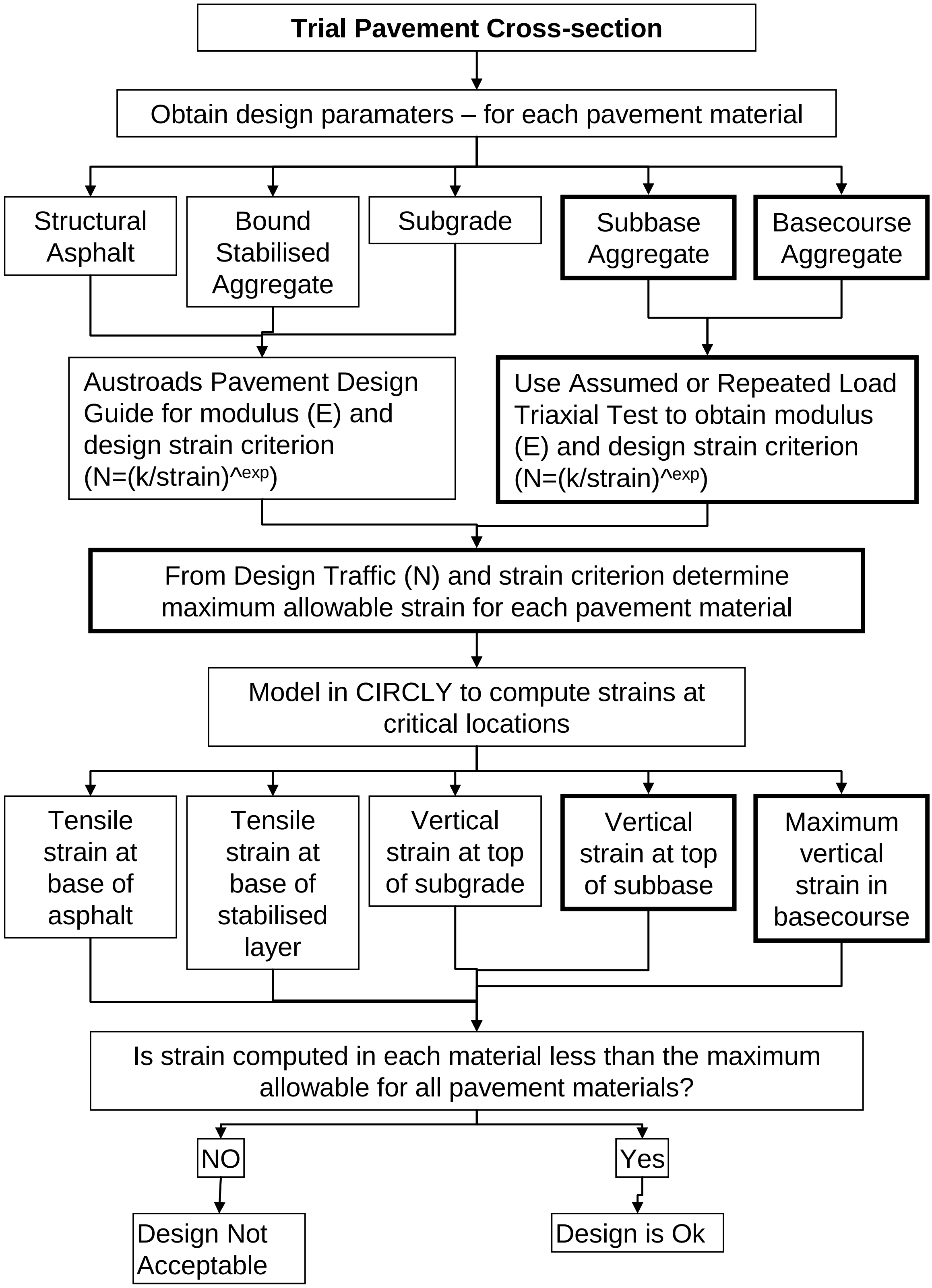


Figure 6.2 Pavement design using basecourse and sub-base strain criterion with CIRCLY



The adjustment factor mentioned in the validation process as being a constant of 2.0 is needed to adjust the RLT-derived strain criterion to one that when used with CIRCLY will calculate reasonable design lives as found at CAPTIF and in more complicated rut depth modelling with finite element modelling (figure 6.1). This is not a multiplier of CIRCLY pavement lives, but is the same for all materials as it relates to the same RLT laboratory test. A different laboratory test such as beam fatigue would probably require a different adjustment factor. Differences in material performance are picked up in the differences found in the RLT test.

7 Conclusions

Current Austroads pavement design procedures use CIRCLY software to compute strains within the pavement. These strains are used in equations to check the fatigue life of bound pavement layers and the rutting life of subgrade soils. This design process does not consider rutting in the granular pavement layers which have been shown to contribute to at least half the rutting. Early pavement failures are generally a result of rutting and shoving within the granular pavement layers. In a parallel research project on rut depth prediction for granular pavements (Arnold and Werkmeister 2010), a range of pavement lives were determined using models derived from RLT tests. These predictions were used in this project to validate a simple method for obtaining design strain criterion for basecourse and sub-base aggregates from RLT tests for use in CIRCLY to predict pavement life. The following conclusions were made:

- Linear extrapolation of each stage of the RLT test data to a permanent strain value of 3.3% was a simple method to obtain the number of load cycles N as a certain resilient strain when failure occurred.
- Plotting life versus resilient strain for 63 RLT test results on basecourse aggregates showed a common trend defining upper and lower bounds.
- Plotting on a log-log plot to calculate the slope and intercept was used to determine the constants for the design strain criterion.
- An adjustment factor (used to multiply the constant in the strain criterion found from the RLT test) was needed so that CIRCLY predicted lives for the aggregate layers matched those found from full pavement rut depth predictions (figure 6.1) in the parallel study (Arnold and Werkmeister 2010).
- Using the new basecourse and sub-base strain criterion would always result in the calculation of pavement lives that were the same as or less than the current method of pavement design using CIRCLY and the Austroads procedures, because the life was limited by rutting in the granular layers.
- Maximum vertical compressive strain computed by CIRCLY in the basecourse occurred at a depth of around 80mm.
- The maximum vertical compressive strain computed by CIRCLY in the sub-base layer always occurred at the top of the sub-base.
- It was more convenient in CIRCLY to compute the strains at the top or bottom of a layer, and hence a relationship was found to convert the strain at the bottom of the basecourse to the maximum strain for use within the design criteria.
- Designers should conduct their own RLT tests to obtain the constants in the design strain criteria for sub-base and basecourse aggregates. The range of values found in this study is shown in table 7.1.

Table 7.1 Constants and exponent values for CIRCLY design strain criteria

				Sub-base linear extrapolation to 3.3%		Basecourse linear extrapolation to 3.3%
N = (f.a.k/micro-strain)^{exp} f=2.0 (see equations 5.1, 5.2 and 5.3 6.1 and 6.2)						
Strain criterion		k	exp		k	exp
Upper		80,000	3.4		700,000	2.4
Middle		66,000	3.4		400,000	2.4
Lower		55,000	3.4		250,000	2.4

Note: the factor f is simply an adjustment factor to convert a strain criterion found from RLT test data to one that can be used in CIRCLY and give pavement lives validated at CAPTIF (using these criteria will result in the same or lesser life than that predicted using the Austroads pavement design procedures).

8 Recommendations

Initial analysis using CIRCLY showed that applying a strain criterion to basecourse and sub-base aggregates found from RLT tests resulted in a prediction of the same pavement life to that found from full rut depth models which considered rutting in the granular layers. It is recommended these proposed strain criteria be tested on a range of pavement designs including stabilised materials. These results should be presented to an industry meeting for consideration of their adoption or refinement of the adjustment factor (f, equation 5.2). Adopting these strain criteria into policy would be beneficial in terms of reducing the risk of early granular pavement failure as the use of fully unbound granular pavements would be limited to low traffic volumes. Structural asphalt pavements and/or modified granular materials with cement or lime would be required for higher traffic volumes. Based on experience, designers are already moving away from full depth granular materials to reduce the risk of failure. The use of basecourse and sub-base strain criteria gives designers the tools to prove their alternative designs will be more effective than full depth granular pavements in reducing the risk of failure and will be suitable for the design traffic.

The determination of the appropriate extrapolation method for rut depth progression (eg linear after a certain number of loads or a continual decrease in the rate of rutting) is valid against past rut depth progression measured at CAPTIF tests and is considered conservative, but it still leaves an approximation that requires further validation with actual field data.

As was shown in the Pavespec Ltd test database of RLT tests there is a wide range of performance for basecourses and sub-bases complying with the same specifications. It is therefore recommended that designers conduct RLT tests on the specific aggregates for their projects and derive their own material-specific design strain criteria.

As an optional guideline it is recommended that the New Zealand supplement to the Austroads pavement design guide be amended to include a description of the methodology for designing with a basecourse and sub-base strain criterion found in this research project. Proposed text for the New Zealand supplement is given in appendix A.

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Appendix A: Proposed changes to the New Zealand supplement to the Austroads pavement design guide

This appendix sets out suggested changes to chapter 6 of the *NZ supplement to the 2004 Austroads pavement design guide* (NZTA 2007).

Chapter 6 Pavement materials

6.1 General

(Add)

Designers are encouraged to use the new design strain criteria, developed for New Zealand granular and cemented materials, with CIRCLY. Section 6.2.2 details strain criteria to use for unbound and modified granular materials while section 6.4.2 details tensile strain criteria for cemented granular materials. These new design criteria are material specific and require repeated load triaxial (RLT) test data as per NZTA T/15 and/or flexural tensile strength from beam breakage tests or derived from indirect tensile strength tests. Presumptive values are given but should be used cautiously with the design being refined by using test data on actual materials from the project.

In the absence of CIRCLY and a new design criterion, figure 8.4 in the Austroads guide (2004) should be replaced with figures 6.1a and 6.1b for designing thin-surfaced granular pavements. These new design charts were developed from rut depth modelling (Arnold and Werkmeister 2010).

Figure 6.1a – Recommended pavement thickness design chart for average quality aggregate combining Austroads and rut depth predictions

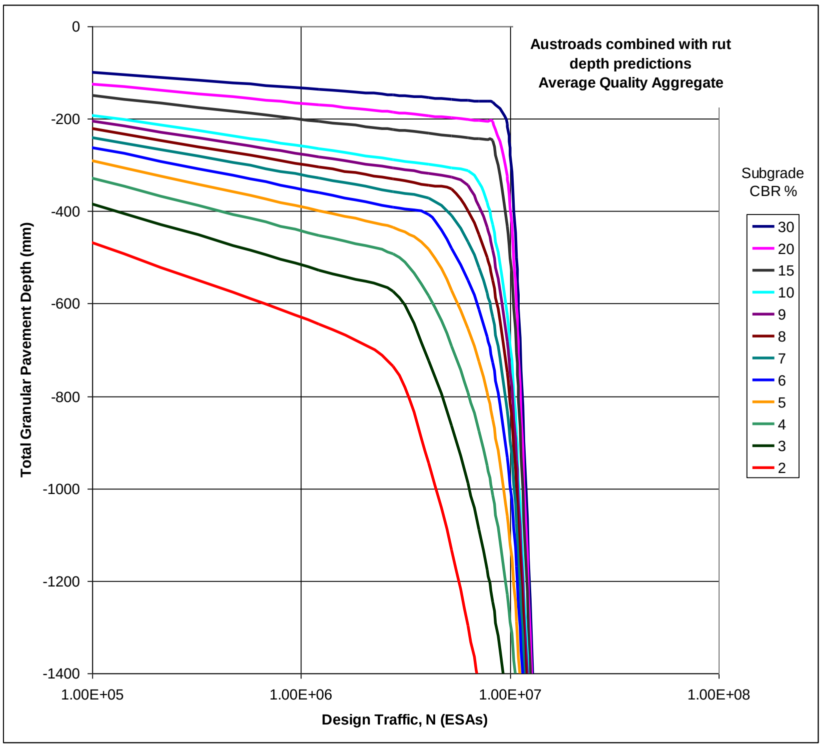
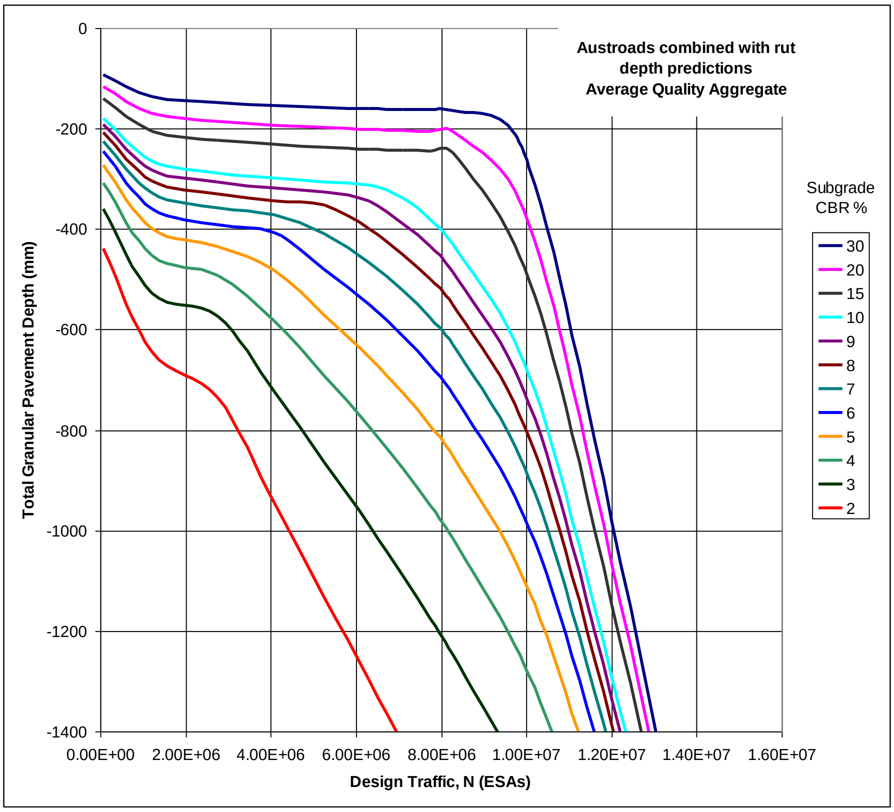


Figure 6.1b Pavement thickness design chart for average quality aggregate derived from the Austroads design guide and from rut depth modelling plotted on a linear scale



6.2 Unbound granular materials

6.2.1 Introduction

6.2.2 Basecourse and sub-base design strain criteria for CIRCLY pavement design

For basecourse aggregate covered with a thin surface of less than 50mm the vertical compressive strain at the bottom but within the basecourse layer is limited by equation 6.1. For cases where the cover is greater than 50mm then the basecourse will be treated as a sub-base for design as per equation 6.2.

$$N_{BC} = M*[(a.f.k_{BC}/\text{resilient strain bottom of BC})\hat{}\,exp_{BC}] \qquad \text{(Equation. 6.1)}$$

Where:

N_{BC} = life of basecourse in ESAs (equivalent standard axles)

a = constant to adjust strain at bottom of basecourse to a maximum strain in the basecourse

a = 1/(BC depth (mm) x 0.00905) – derived from equation 6.1

f = 2.0 – adjustment factor determined from validation to ensure calculated life from the stain criterion is equal to life calculated from rut depth modelling

k_{BC} = constant found from RLT testing (NZTA T/15 and appendix B, presumptive values shown in table 6.1)

exp_{BC} = constant found from RLT testing (NZTA T/15 and appendix B, presumptive values shown in table 6.1) resilient strain bottom of BC = resilient strain at the bottom of the basecourse layer as calculated using CIRCLY

M = pavement depth multiplier due to reduced rutting in subgrade (table 6.2)

The life of the sub-base aggregate layer is found from equation 6.2:

$$N_{SB} = M*[(f.k_{SB}/\text{resilient strain top of SB})\text{^}exp_{SB}] \qquad \text{(Equation. 6.2)}$$

Where:

N_{SB} = life of sub-base or basecourse if covered by more than 50mm of bound material in ESAs

f = 2.0 – adjustment factor determined from validation to ensure calculated life from stain criterion is equal to life calculated from rut depth modelling

k_{SB} = constant found from RLT testing (NZTA T/15 and appendix B, presumptive values shown in table 6.1)

exp_{SB} = constant found from RLT (NZTA T/15 and appendix B, presumptive values shown in table 6.1)

resilient strain top of SB = resilient strain at the top of the sub-base layer

M = pavement depth multiplier due to reduced rutting in subgrade (table 6.1)

Table 6.1 Aggregate life multiplier from pavement depth resulting in reduced rutting in the subgrade

Subgrade CBR%	Pavement depth (mm) when aggregate life influences (D)	Aggregate life multiplier M (ie multiply computed life by M) up to a maximum of M=1.8.
2	1000	M = total pavement depth/D
3	854	
4	750	
5	670	
6	604	
7	548	
8	500	
9	458	
10	420	
11	385	
12	354	
13	325	
14	298	
15	273	

It is recommended that designers conduct their own RLT tests to obtain the constants in the design strain criteria for sub-base and basecourse aggregates, while the range of values found in unbound aggregates from the Pavespec Ltd database of RLT tests are shown in table 6.2. The use of modified and cemented granular materials will require independent RLT tests to determine appropriate constants for the design stain criterion as detailed in Appendix B and NZTA T/15. Further, the constants in table 6.2 were derived from dry tests in the RLT apparatus. A separate design is needed if the case for saturation of the granular layers is considered using equation constants derived from saturated RLT tests.

Table 6.2 Constants and exponent values for CIRCLY design strain criteria

N = (f.a.k/micro-strain)^{exp} f=2.0 (see equations 6.1 and 6.2)		Sub-base linear extrapolation to 3.3% (NB: K for Circly = b*2 – see Appendix A)			Basecourse linear extrapolation to 3.3% (NB: K for Circly = b*2 – see Appendix A)	
Strain criterion		b	exp		b	exp
Upper (best)		80,000	3.4		700,000	2.4
Middle		66,000	3.4		400,000	2.4
Lower (poor)		55,000	3.4		250,000	2.4

(see below for details how to obtain these constants from RLT tests)

Appendix B: Method to determine vertical compressive strain criterion from RLT test data

Step 1:

Determine the average slope (%/1M) as per table B.1 as measured in the RLT test and resulting load cycles to achieve a permanent strain limit (3.3%).

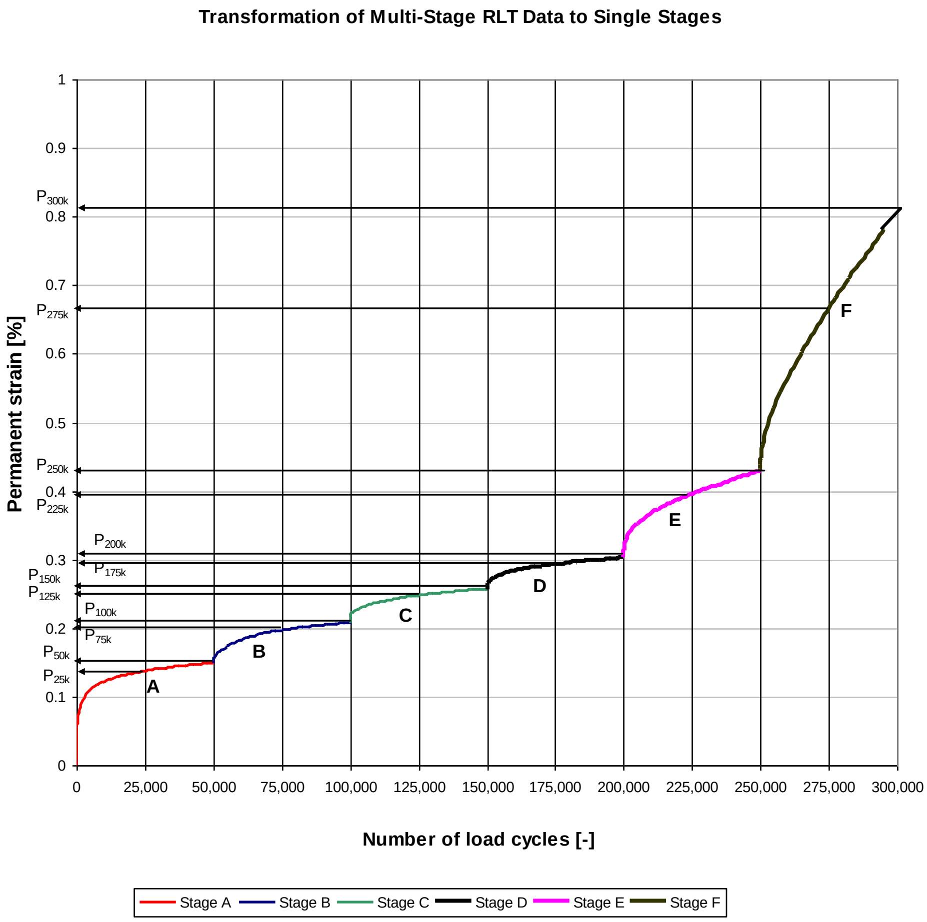
Table B.1 Calculation of average permanent strain slope from 6-stage RLT test

RLT test stage (table 2)	[2]Permanent strain (%) (see figure 1)	[1]Permanent strain slope (%/1M) (slopes) A	Number of load cycles (N) to achieve a permanent strain of 3.3% N = 3.3/A * 10^6
Stage A	P_{25k}	$=(P_{50k}-P_{25k})/0.025M$	$= 3.3 / [(P_{50k}-P_{25k})/0.025M]$
	P_{50k}		
Stage B	P_{75k}	$=(P_{100k}-P_{75k})/0.025M$	$= 3.3 / [(P_{100k}-P_{75k})/0.025M]$
	P_{100k}		
Stage C	P_{125k}	$=(P_{150k}-P_{125k})/0.025M$	$= 3.3 / [(P_{150k}-P_{125k})/0.025M]$
	P_{150k}		
Stage D	P_{175k}	$=(P_{200k}-P_{175k})/0.025M$	$= 3.3 / [(P_{200k}-P_{175k})/0.025M]$
	P_{200k}		
Stage E	P_{225k}	$=(P_{250k}-P_{225k})/0.025M$	$= 3.3 / [(P_{250k}-P_{225k})/0.025M]$
	P_{250k}		
Stage F	P_{275k}	$=(P_{300k}-P_{275k})/0.025M$	$= 3.3 / [(P_{300k}-P_{275k})/0.025M]$
	P_{300k}		
Average		$= P_{avg} = (\sum Slopes)/6$	

Note 1: If any of the loading stages do not complete the full amount of loading cycles because the deformation limit of 1.0% was achieved, then these table B.1 calculations will not strictly apply. In this situation the average tangential permanent strain slope achieved is used to change the value from 25k to 50k load cycles.

Note 2: Permanent strain values for any given load cycle are the average of the previous 10 readings in the RLT test to account for any noise in the data.

Figure B.1 Permanent strain points for determination of permanent strain slopes



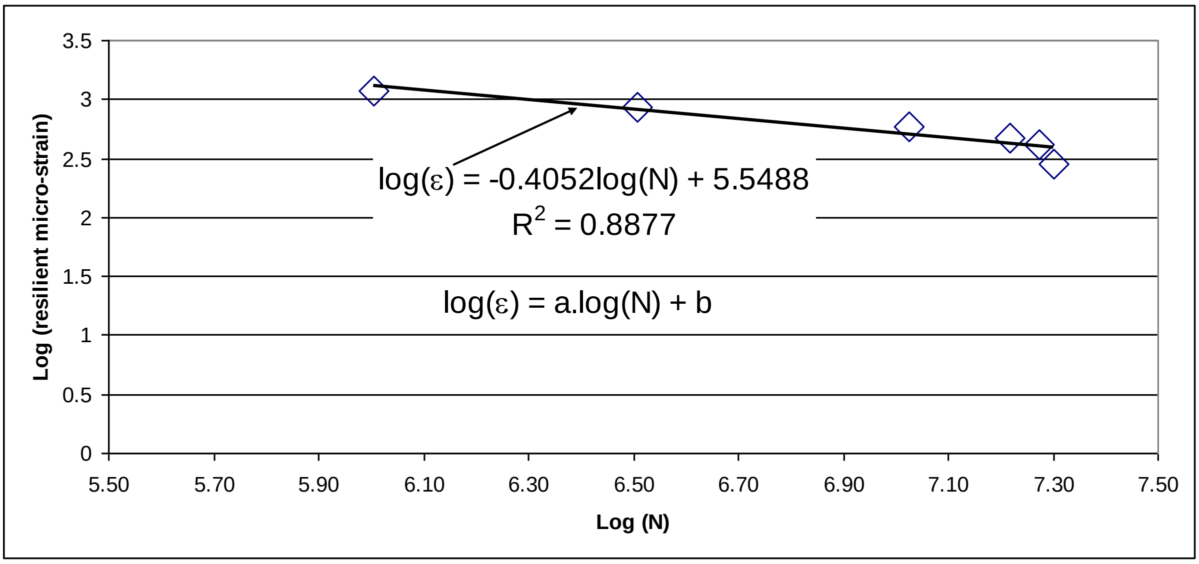
Step 2:

Determine the relationship between life (N, Table 1) and resilient elastic strain as recorded in the RLT test. Then plot log (N) versus log (micro-strain) and determine the line of best fit for slope and intercept constants (*a* and *b*) as shown in figure B.2.

Table B.2 Calculation of average permanent strain slope from 6-stage RLT test

RLT test stage (table B.2)	Vertical resilient strain	Number of load cycles (N) to achieve a permanent strain of 3.3% $N = 3.3/A * 10^6$	Log10 both sides and calculate slope (*a*) and intercept (*b*) (see figure B.1) – $\text{Log}(\varepsilon) = a.\log(N) + b$ Log (ε)	Log (N)
Stage A	ε_A	$= 3.3 / [(P_{50k}-P_{25k})/0.025M]$		
Stage B	ε_B	$= 3.3 / [(P_{100k}-P_{75k})/0.025M]$		
Stage C	ε_C	$= 3.3 / [(P_{150k}-P_{125k})/0.025M]$		
Stage D	ε_D	$= 3.3 / [(P_{200k}-P_{175k})/0.025M]$		
Stage E	ε_E	$= 3.3 / [(P_{250k}-P_{225k})/0.025M]$		
Stage F	ε_F	$= 3.3 / [(P_{300k}-P_{275k})/0.025M]$		

Figure B.2 Example plot of log(N) versus log(strain) for calculating line of best fit for slope and intercept constants (a and b)



Step 3:

From line of best fit for slope and intercept constants (*a* and *b*) as shown in figure B.2 in step 2 determine power law exponent and constant for strain criterion uses in CIRCLY (equation B.1):

$$N = (K/\textit{micro-strain})^{exp} \qquad \text{(Equation B.1)}$$

Where

N = fatigue life in equivalent standard axles (ESAs)

K = $[10^{b}]$. f

B = Intercept constant, b in log(N) vs log(strain) relationship (figure 1)

F = 2.0 – adjustment factor determined from validation to ensure calculated life from stain criterion is equal to life calculated from rut depth modelling

exp = (1/a)*(-1)

a = slope constant, a in log(N) vs log(strain) relationship (figure B.2)

micro-strain = Vertical compressive resilient strain at the top of the sub-base aggregate layer or at a depth of 80mm from the surface in the basecourse layer.