University of Southern Queensland

Faculty of Health, Engineering and Sciences

An Analysis of Roadbase Materials used in Foamed Bitumen Stabilisation

A dissertation submitted by

Mr Adam O'Callaghan

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Limitations of Use

Abstract

Foamed bitumen Stabilisation is an insitu stabilisation process which uses foamed, or expanded, bitumen as a binding agent. The process produces a bound pavement which acts as a flexible pavement. The process can be used for improvement of both road base and sub-base materials. The reconstruction of a road pavement can be complete within a day and the road can be reopened to traffic after the final compaction is complete with no detrimental effects on the pavement.

The application of foamed bitumen stabilisation is not limited to use on good quality pavement materials. The purpose of this project is to examine the material properties of road base materials used in foamed bitumen stabilisation, the effects on the pavement strength and the serviceability of the pavement.

The methodology used to complete this project involved a detailed analysis of road base materials used in foamed bitumen stabilisation from various sites in New South Wales, Queensland and Victoria. This analysis involved conducting a number of tests on samples from different sites along Eastern Australia and using some historical data from testing conducted over the last 15 years.

The key outcomes of this project are to determine the effects of variations in material properties, bitumen content and if marginal materials can be successfully used in in foamed bitumen stabilisation.

Candidates Certification

I certify that the ideas, designs and experimental work, results, analysis and conclusions set out in dissertations are entirely my own efforts, except where otherwise indicated and acknowledged.

I further certify that the work is original and has not been submitted for assessment in any other course or institution, except where specifically stated.

Adam O'Callaghan

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The purpose of this project is to examine the material properties of road base materials used in foamed bitumen stabilisation, the effects on the pavement strength and the serviceability of the pavement. To achieve this purpose I plan to

- Research foamed bitumen and foamed bitumen stabilisation, the properties of materials used for foamed bitumen stabilisation and the design methods, requirements and specification of foamed bitumen stabilisation.

- Analyse road base materials used in foamed bitumen stabilisation from various sites in New South Wales, Queensland and Victoria

- Evaluate the effect that the material properties have on the pavement strength and the expected design life in ESA's

- Analyse the effect of changes in the material properties of road base materials on the resilient modulus through laboratory testing

- Analyse the effect of bitumen content on marginal materials used in foamed bitumen stabilisation
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- If "marginal materials" can be used in foamed bitumen stabilisation and still provide a serviceable pavement comparable to a pavement produced using ideal materials. If marginal material can be used satisfactorily then foamed bitumen stabilisation can be performed in a wider range of situations.

- The effect variations in material properties have on the strength of a foamed bitumen stabilised pavement to identify what material properties are most critical to a foamed bitumen stabilisation and the sensitivity of variation on these properties.

- If the air void content of the compacted stabilised material has an effect on the strength and what impact this will have on the thickness of the design pavement.

- If variations in bitumen content effects the strength and air voids content of the compacted stabilised material what impact this will have on the thickness of the design pavement.

1 Introduction

Australia has the one of the most kilometres of sealed road pavement per capita in the world making innovation in pavements rehabilitation of critical importance. Motorsports and driving are integral parts of the broader Australian culture, increasing volumes road traffic (both light and heavy vehicles) along with an ever increasing reliance on road transport; the quality and strength of pavements will need to improve to ensure sufficient pavement performance and life.

The rehabilitation of a road pavement involves extending the life of an existing road by improving or modifying the material by one form or another. One method of doing this is through pavement stabilisation, or the addition of a binder to improve the pavement material. Foamed bitumen is one way of achieving this goal. To be able to successfully use foamed bitumen we first need to understand how the different pavement materials and properties respond to this form of stabilisation.

In this age of sustainability renewable resources are of growing importance. Foamed bitumen stabilisation reuses the old pavement material reducing the drain on ever dwindling resources. However guidelines and specifications put limits on the quality of the material that can be used in this process. If “marginal” or “unsuitable” materials could be used to some extent this could make this rehabilitation process used in a wider range of situations.

2 Background and Literature Review

Foamed bitumen is an insitu stabilisation process which uses expanded bitumen as a binding agent. The process produces a bound pavement which acts as a flexible pavement. The process can be used for improvement of both road base and sub-base materials.

The application of foamed bitumen stabilisation is not limited to use on good quality pavement materials. Foamed bitumen stabilisation is used all around the world but is most prolific in South Africa, America, New Zealand and Australia. The design processes and application of foamed bitumen between these countries varies quite extensively while the process remains the same.

2.1 History of Foamed Bitumen

The ability to use Foamed bitumen as a binder was first trialled at the Iowa State University's Engineering Experiment Station by Dr Ladi Csanyi in 1956. Csanyi original concept involved injecting steam into hot bitumen to cause the bitumen to foam. This process was ideal for use in asphalt plants however it was not practical for insitu stabilisation.

In the late 1960's Mobile bought the rights to the foamed bitumen process and brought it to Australia. At this time the steam was replaced with cold water making the process more transportable and practical for both plant production and insitu stabilisation.

During the 1980's the application of foamed bitumen in insitu stabilisation in Australia fell away. With the introduction of more modern technologies and more specialised stabilisation plant in the late 1990's foamed bitumen stabilisation underwent resurgence. Today the use of foamed bitumen is continually increasing. The author has noticed that this increase is not limited to insitu stabilisation of roads but extended to application in airports and port facilities.

2.2 What is Pavement Stabilisation

Pavement stabilisation process is a of insitu pavement recycling, where the pavement materials are improved through mechanical, or chemical processes. Mechanical stabilisation involves the incorporation of a better quality material, typically an imported quarry gravel, to improve the physical properties of the pavement layer. Chemical stabilisation involves the addition of a binding agent which chemically alters the pavement material. Chemical stabilisation includes the use of cementitious binders, polymers and bitumen.

Pavement stabilisation can occur in new road pavements or as a way of rehabilitating an old road pavement. Wilmot and Vorobieff (1997) note that there are a number of reasons for pavement stabilisation, these are to;

- Correct mechanical defects in unbound pavements. i.e. imported gravel to improve grading deficiencies
- Improvement of the strength characteristics of weaker pavement materials by increasing the pavements compressive strength.
- Increases the bearing capacity of the pavement
- Reduce constructions cost by recycling the old pavement
- Reduce the moisture sensitivity and permeability of the pavement to reduce the risk of strength loss in the materials.
- Improve weak or reactive subgrades materials for construction.
- Improve compaction of an unbound pavement

In mechanical stabilisation the physical properties of the pavement materials is improves by incorporating a material with the required properties. Andrews (2006) notes that quality gravel is usually mixed in to the pavement to increase the strength by improving the mechanical interlock of the pavement.

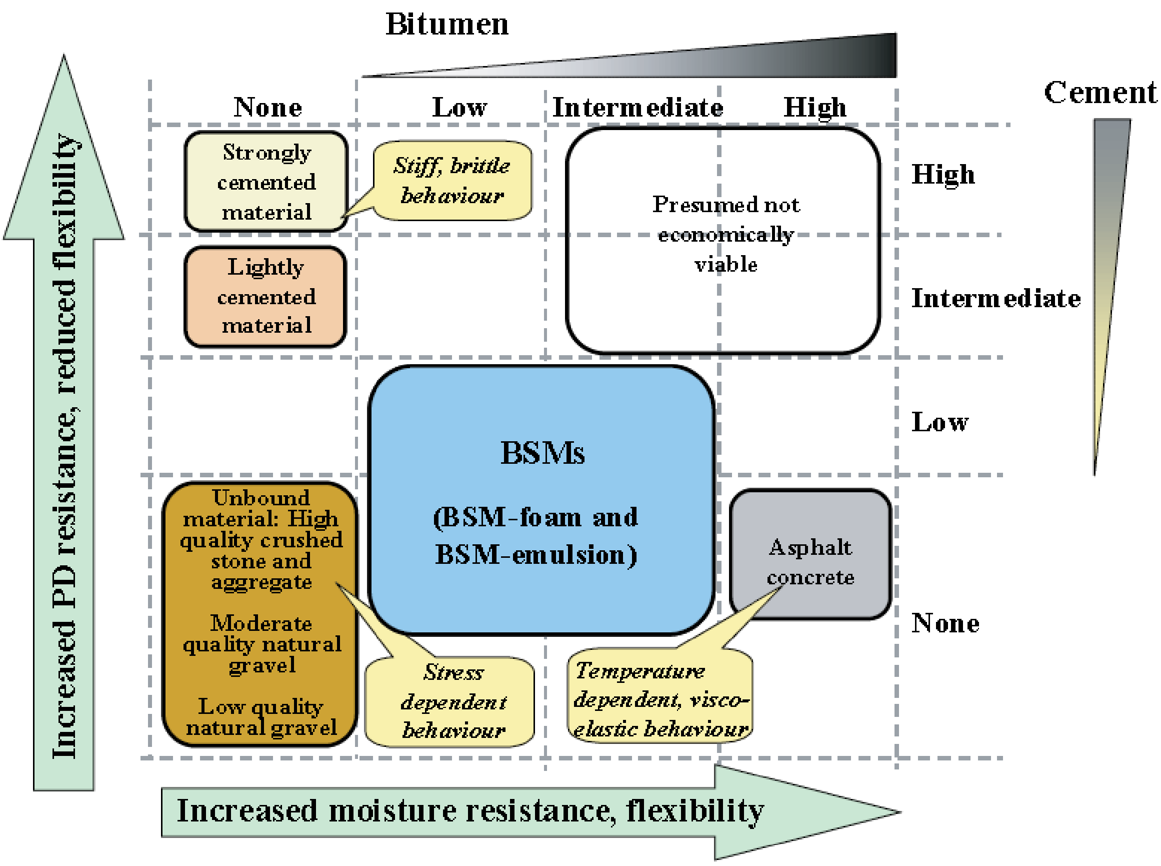

Figure 2-1: Characteristics of Pavement Materials. Asphalt Academy (2009)

More commonly used stabilisation processes use cementitious binders such as cement, lime, fly ash, ground granulated blast furnace slag and blends of these. Cementitious binders used in pavement stabilisation produce a ridge pavement. In cementitious stabilisation, the cementitious binder hydrates with the addition of water and cement the particles together as it cures. During the curing process, the strength of the pavement increases gradually over time. Vorobieff (2012) notes that cementitious bound pavements have a limited working life, a time period by which the material can be worked before the point where proper compaction is able to be achieved. Bound pavements using cementitious binders can have strengths up to that of lean mix concrete. Pavements stabilised using cementitious binders are prone to shrinkage cracking and erosion.

More commonly stabilisation involves a mix of mechanical and chemical stabilisation. This occurs when the contractor undertakes either cross blending or lateral blending of the existing pavement where extensive patching has happened previously, or when they mill the into the subgrade prior to the addition of a binder to the pavement.

2.3 Foamed Bitumen

Foamed bitumen is process by which hot bitumen is caused is mixed with air and cold water. This causes the mixture to rapidly expand. To manufacture foamed bitumen, the bitumen is heated to a temperature of 160 to 190°C and combined with air and water at 15 to 20°C in the expansion chamber and forced out through the foaming nozzle. Uncontrolled this can result in an explosive situation, but in the proportions used for foamed bitumen , 98% bitumen, 1% water and 1% air, a rapid volume expansion of greater than 10 results.

The amount of water used in the foaming process will affect the characteristics of the foam produced. As more water is added to the bitumen the expansion ratio increases while the half-life of the foam decreases. The expansion ratio refers to the rate of volume increase of the bitumen. The half-life of the foam is the time for the bitumen foam to collapse to half its expanded volume.

Ramanujam, Jones and Janosevic (2009) suggest a good foamed bitumen mix has an minimum expansion ratio of 10 times and a half-life of at least 20 seconds, which can typically be achieved with a moisture content of 2.5%. If the expansion ration of the foamed bitumen is <10 times the bitumen may not create enough volume to coat the fine particles in the pavement and result in the formation of bitumen lumps, dags and strings. If the half-life is too short the bitumen may not hold up for long enough to be mixed into the pavement before if collapses, resulting in insufficient mixing through the pavement material, causing the formation of bitumen lumps, dags and strings.

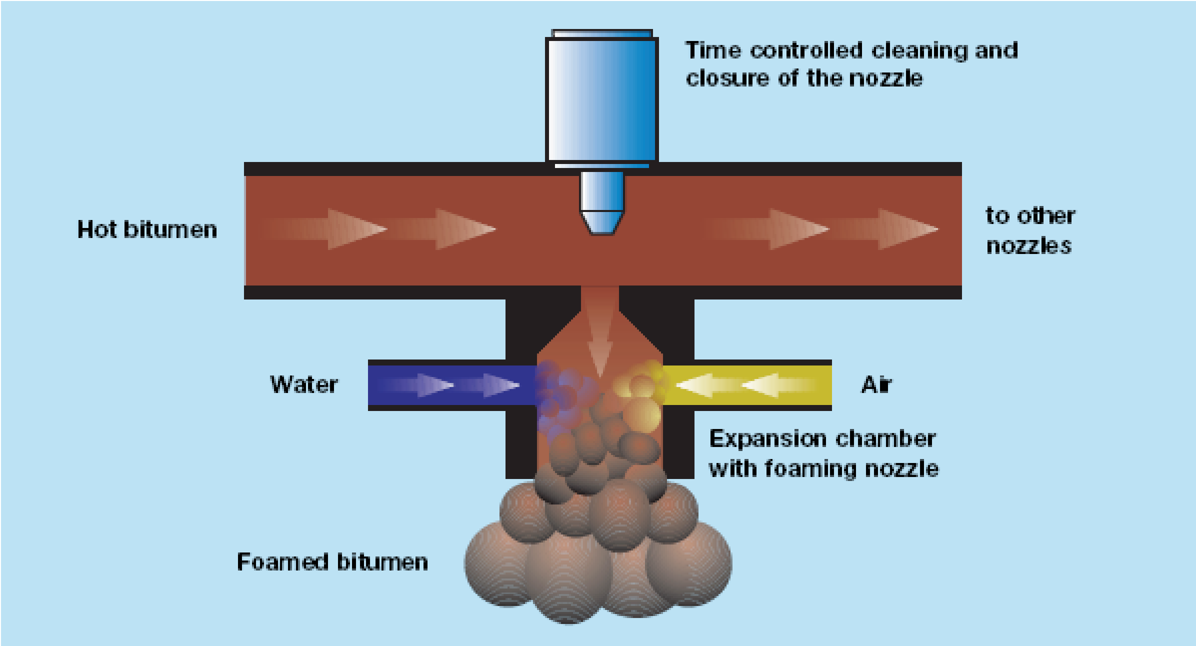

Figure 2-2: The manufacture of foamed bitumen (Ramanujam, Jones & Janosevic 2009)

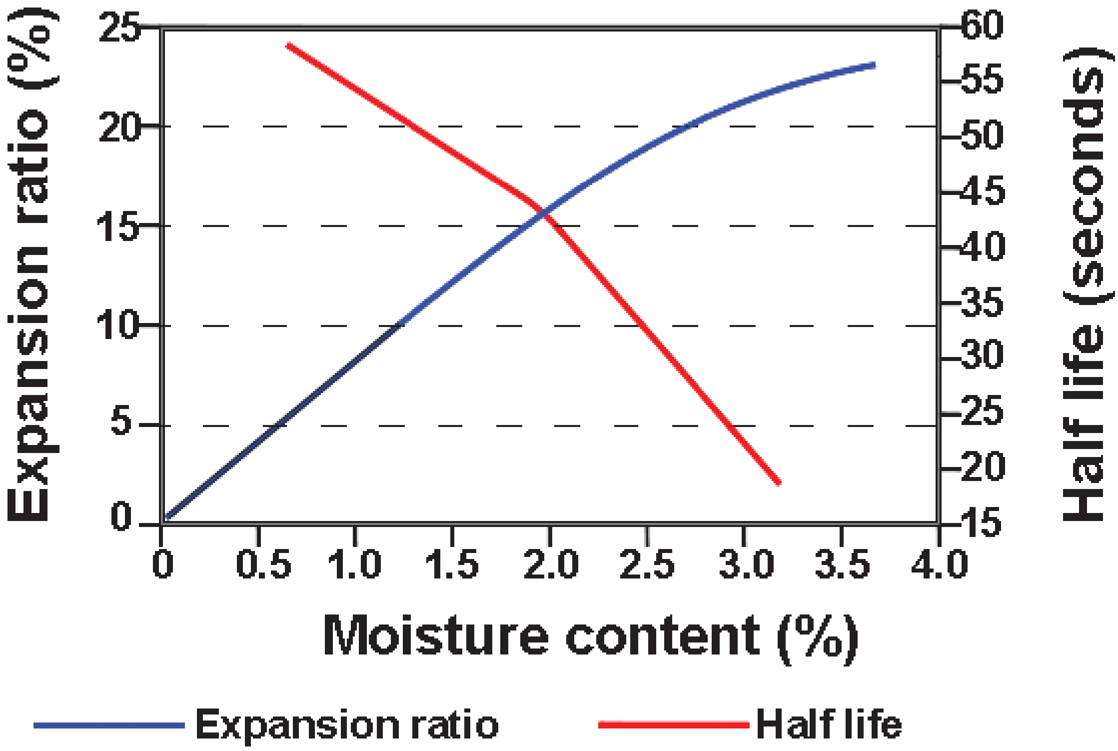

Figure 2-3: Typical plot of moisture content vs. expansion ratio and half-life (Ramanujam, Jones & Janosevic 2009)

Leek and Jameson (2011) identifies that foamed bitumen is characterised by:

- The expansion ratio – The ratio of the maximum expanded volume of the foamed bitumen to the volume of the non-foamed bitumen, taken either before foaming or after the foam has completely collapsed. The greater the expansion ratio the further the bitumen will be spread through the pavement. The expansion ratio is influenced by two factors, temperature and bitumen water content. By increasing the temperature of the bitumen or increasing the amount of water to cause the bitumen to foam will increase the expansion of the foam. A minimum of 10 times expansion is recommended by most sources while 15 times expansion is mostly preferred. However, as the expansion ratio gets larger the stability of the foam decreases, resulting in a decreased half-life of the foam.

- The half-life – The time taken for the expanded foamed bitumen to collapse to half the maximum expanded volume. A minimum half-life of 20 – 40 seconds is usually preferred, to ensure sufficient for the foamed bitumen to be mixed in to the pavement material. The half-life can be increased by using a more viscous class of bitumen (i.e. C320 bitumen), lower water bitumen content, decreased bitumen temperature, or the addition of a foaming agent (i.e. Teric). The using of a higher class of bitumen is not common except in hot climates. The use of a foaming agent will result in more stable foam with a longer half-life and higher expansion ratio.

Figure 2-4 demonstrates these properties and the order in which they occur during the foaming process. The initial rapid expansion, followed by the exponential decay as the foam collapses back to its unexpanded volume.

2.4 Foamed Bitumen Stabilisation

Foamed Bitumen stabilisation is an insitu stabilisation process used predominantly in road construction and pavement improvement. This involves the mixing of foamed bitumen into a pavement material. Andrews (2006) notes that, in its foamed state, bitumen is suited to mixing with fine material as the large surface area will readily bond with the fine particles. This is the primary concept behind foamed bitumen stabilisation. The bitumen coats the fine particles, and once the foam collapses and the material is compacted, the fine particles bind the coarser particles together. The bitumen coats the particles <75μm size. The Asphalt Academy (2009) describes foamed bitumen as "producing 'spot welds' of a mastic of bitumen droplets and fines". This can be seen in Figure 2-5: Foamed bitumen aggregate and binder bond where the bitumen coats the fine particles and form droplets which bind the larger aggregate.

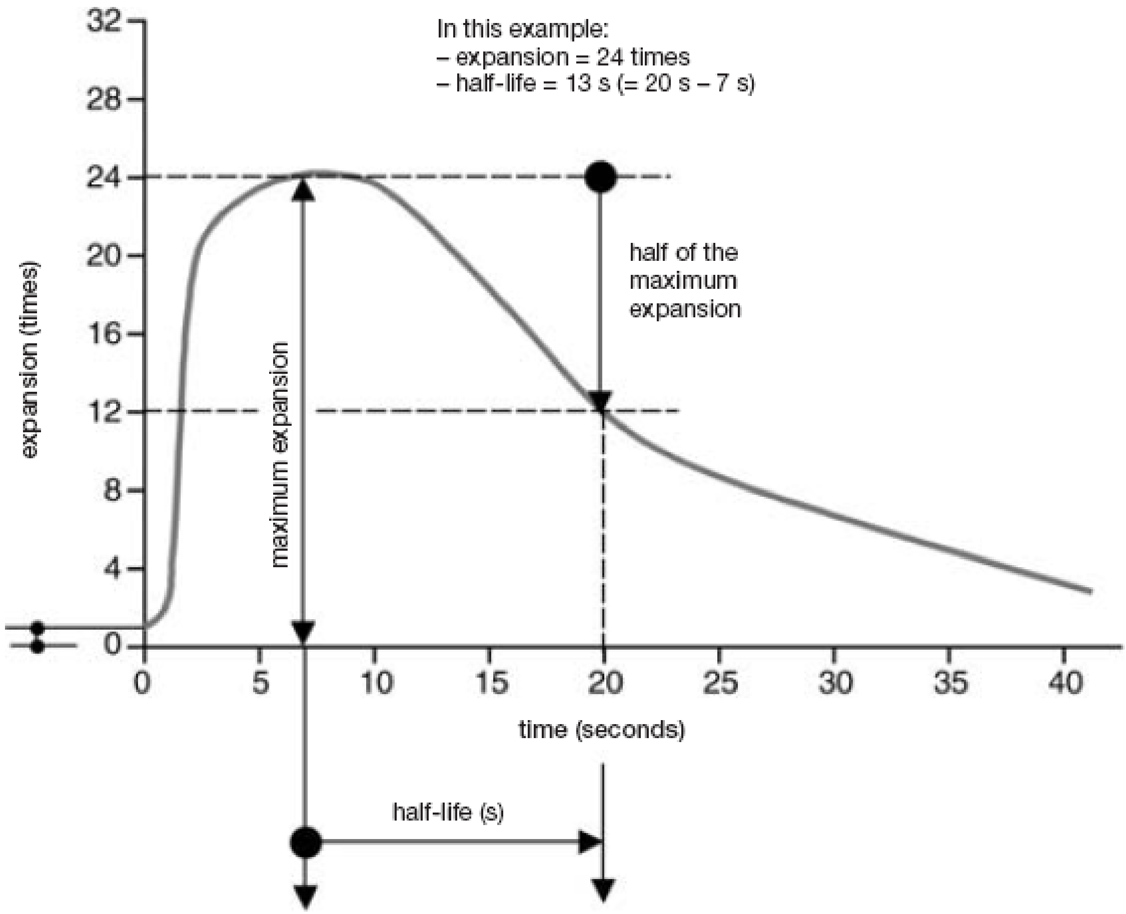

Figure 2-4: Bitumen foaming properties schematics. (Leek & Jameson 2011)

Foamed bitumen stabilisation produces a pavement which is a flexible pavement. The pavement is not prone to shrinkage cracking as a cementitious bound pavement is. Austroads (2012) suggests that the predominant performance relationship is that used for asphalt fatigue. Asphalt fatigue is the result of repeated tensile failure.

$$N = RF\left[\frac{6918(0.856V_B + 1.08)}{S_{mix}^{0.36}\mu\varepsilon}\right]^5 SAR5$$

Equation 2-1: Asphalt fatigue

Where;

$$N = Allowable\ number\ of\ repetitions\ of\ the\ load\ (SAR5)$$
$$SAR5 = The\ average\ number\ of\ Standard\ Axle\ Repetitions\ for\ asphalt\ fatigue$$
$$\mu\varepsilon = Tensile\ strain\ produced\ by\ the\ Standard\ Axle\ (microstrains)$$
$$V_S = Percentage\ volume\ of\ bitumen\ (\%)$$
$$E_{mix} = Modulus\ of\ the\ mix\ (MPa)$$
$$RF = reliability\ factor\ for\ asphalt\ fatigue$$

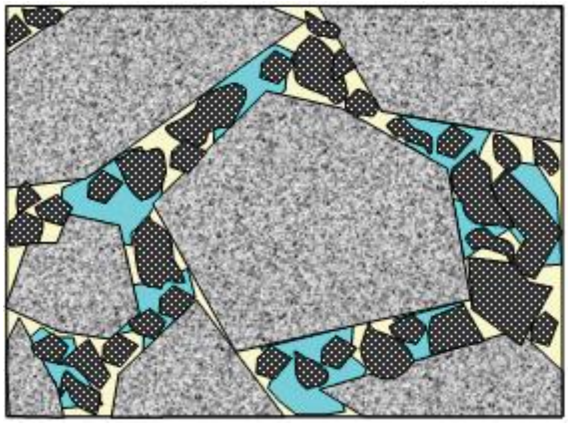

Figure 2-5: Foamed bitumen aggregate and binder bond (Asphalt Academy 2009)

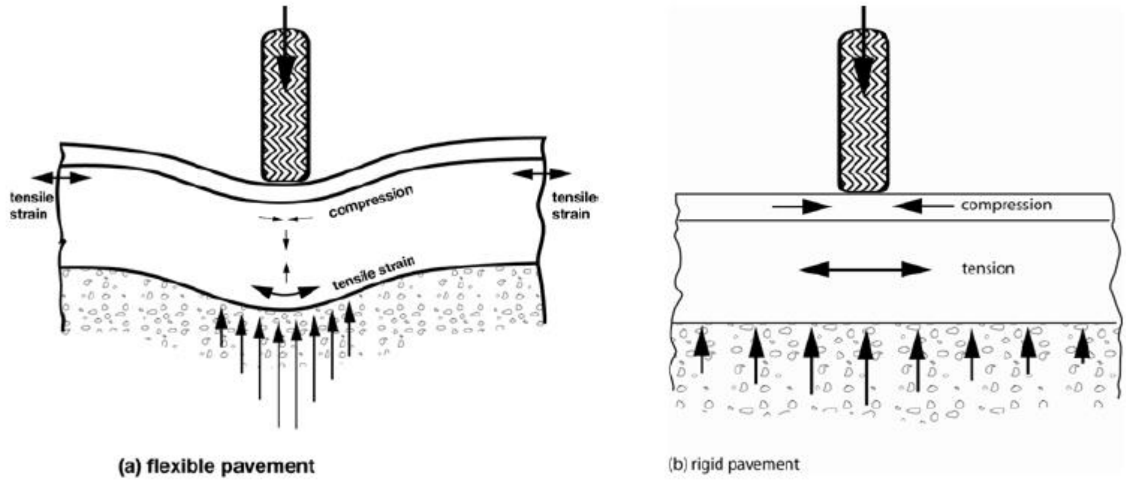

Figure 2-6: Flexible and Rigid pavements (Sharp 2009)

As shown in Figure 2-6 the loading of a flexible pavement is quite a bit different to that of a ridged pavement.

Vorobieff (2012) notes that the advantages of foamed bitumen stabilisation are:

- Cost reductions – transport are reduces in that the amount of water required for the foaming process in minimal (typically 2% of the bitumen used), and binder costs are reduced because standard bitumen is used.
- Duration of road closure is reduced – the road can be opened to traffic immediately after the mixing and compaction is complete.
- Workability – foamed bitumen does not have a "working life' in the same way that a cementitious stabilised pavement does, and remains workable for some time. The process can continue during adverse weather and not suffer from the usual problems like aggregate washout.

2.5 Material Properties

2.5.1 Material Testing

2.5.1.1 Particle Size Distribution

The particle Size distribution of a material is a means by sieving a material to determine the distribution of particle sizes of a material. From this distribution a physical classification can be determined.

The PDS is determined by a sieve analysis, or mechanical analysis, where the material is put through a nest of sieves of decreasing coarseness. Particles are retained on the sieves they are unable to pass through.

2.5.1.2 Plasticity Index

The plasticity index is a measure of the plasticity of a material. The plasticity index is found by first determining the "Plastic Limit" and the "Liquid Limit". The plastic limit is the moisture content where the material stops behaving elastically and starts to behave plastically. The liquid limit is the moisture content where the material enters a liquid phase.

The Plasticity Index is the difference between the moisture content at the Liquid Limit and the moisture content at the Plastic Limit. The higher the plasticity index the more reactive to moisture the fines will be.

2.5.1.3 Compaction, or Proctor Test

This test is used to determine the maximum dry density and optimum moisture content of a material. The material is compacted in to a mould with a specified number of blows from a drop hammer of specific weight and drop. This is then repeated at different moisture. When the dry density of the compacted material is plotted against the moisture content at each determination the maximum dry density a peak of the graph, and the optimum moisture content is the corresponding moisture content.

2.5.1.4 Moisture Content

The amount of water relative to the dry mass of solids expressed as a percentage.

2.5.2 Material Requirements

The requirements for pavement material to be stabilised with foamed bitumen has slight variations between some of the different state authorities, national road associations and between different countries. In Australia most state road authorities follow the guidelines set by Austroads, while the Queensland Department of Transport and Main Roads have their own specifications based on their own research. More recently, In NSW, the Roads and Maritime Services have set out to define their own material specifications. The main debate has been around which specification to adopt, The Queensland model, the Austroads model, the South African model, or develop their own.

Austroads (2011a), Asphalt Academy (2009) and TMR (2012) identify the following material properties as being critical to a being important to an ideal material for foamed bitumen stabilisation. Some of these properties have had limits specified while others are notes for consideration when selecting material for stabilisation. These properties are:

- Particle Size Distribution

Austroads and the Asphalt Academy have similar grading envelopes for suitable materials while the Queensland TMR envelope tends to be finer as shown in Figure 2-7.

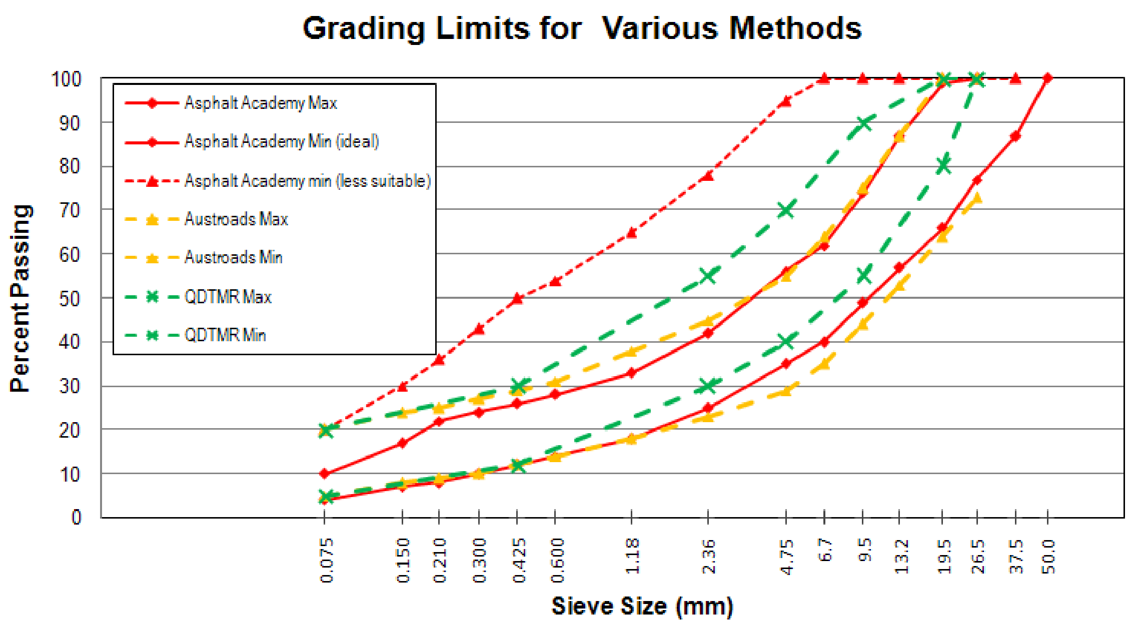

Figure 2-7: Foamed Bitumen grading envelopes (Leek & Jameson 2011)

Sieve size (mm)	Percentage passing			
	Austroads Part 4D	TMR	TG2	Proposed for base with > 1000 ESA/day
26.5	73–100	100	77–100	100
19.5	64–100	80–100	66–99	80–100
9.5	44–75	55–90	49–74	55–90
4.75	29–55	40–70	35–56	40–70
2.36	23–45	30–55	25–42	30–55
1.18	18–38		18–33	22–45
0.600	14–31		14–28	16–35
0.425		12–30	12–26	12–30
0.300	10–27		10–24	10–24
0.150	8–24		7–17	8–19
0.075	5–20	5–20	4–10	5–15

Table 2-1: Preferred Particle Size Distribution for material for foamed bitumen stabilisation (Leek & Jameson 2011)

- Plasticity

The plasticity relates the clay content of the material and how readily the soil will lose shear strength as the moisture content of the soil increases. The plasticity of the pavement material is inversely proportional to the shear strength, as plasticity increases the shear strength of the pavement material increases. As the shear strength of a pavement decreases the chance of the pavement failing by rutting or shoving increases. This in turn means that the stabilised pavement may have a reduced design.

Typically the material should have a plasticity index (PI) of less than 12. Materials with a PI greater than 12 will usually require treatment with a cementitious binder, typically lime prior to the application of the foam bitumen.

- Aggregate Angularity

Aggregate angularity relates to the shape of the aggregate pieces and the degree of angularity or roundness of these pieces. The more angular the aggregate the better the aggregate will interlock to form a stronger pavement. Rounded particles do not tend the interlock but are more inclined to slide past each other, leading to early rutting and pavement failure.

Leek and Jameson (2011) identify aggregate angularity, especially the fine aggregate, as "an excellent indicator of suitability for foamed bitumen". The angularity of the aggregate and the degree of aggregate interlock influences the stability of foamed asphalt. The Asphalt Academy (2009) has a recommended particle index of greater than 10 to prevent premature rutting of the pavement.

- Aggregate Durability

The durability of the aggregate is an important factor in the strength of the pavement. Asphalt Academy (2009) identifies the durability of the untreated aggregate as being one of the most important factors relating to the suitability for a successful pavement. The durability relates to the in service breakdown of the untreated aggregate as well as moisture susceptibility of the stabilised pavement. Breakdown of the aggregate, both in service and during mixing, can result in the formation of plastic and non-plastic fines.

2.5.3 Moisture Content of the Pavement Material

The moisture content of the material is critical to producing successful test specimens and a successful stabilised pavement. Foley (2002) recommends a moisture of the pavement material, prior to the addition of foam bitumen, to be between 70% and 90% of the optimum moisture content of the parent material. TMR (2012) identifies that the material should be 70% of the optimum moisture content for the material unless the insitu moisture content of the pavement is >70% OMC and cannot be dried out then the laboratory testing should be at the filed moisture content. Asphalt Academy(2009) has the pavement material is tested at 80% the unmodified OMC and suggests that this moisture content facilities compaction process.

2.5.4 Bitumen Moisture Content

Two things are required to successfully create foamed bitumen; hot bitumen and water. The bitumen moisture content relates to the amount of water required to achieve the required expansion of the bitumen. As illustrated in Figure 2-8,Figure 2-3 with an increasing water addition rate to the foam, greater expansion results, i.e. increased expansion ratio, while the foam is less stable and decays quicker, i.e. shorter half-life (Asphalt Academy (2009)).

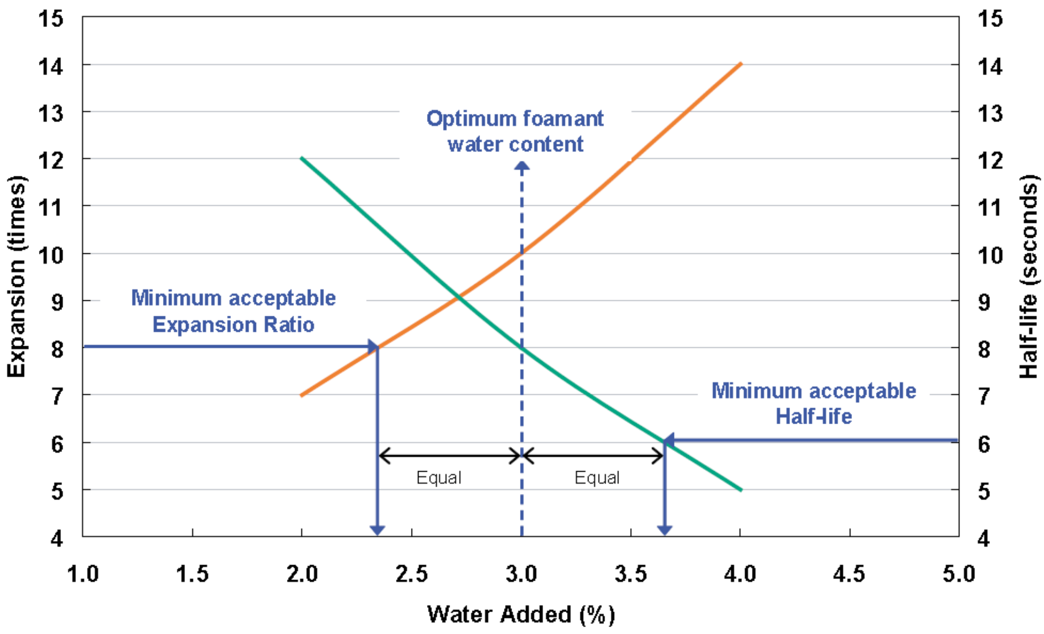

Figure 2-8: Optimum Foamant Water Content (Asphalt Academy (2009))

Ramanujam, Jones and Janosevic (2009) suggest that 2.5% is a typical addition rate for the foamant water to achieve the required expansion ratio. The TMR (2012) agree with this addition rate and recommend that laboratory testing undertaken to confirm this rate each time minor variations in the foamant water rate can have serious effects on the expansion ratio and half-life.

The Asphalt Academy (2009) identifies the influence of the application rate of the foamant water of equal importance to the bitumen temperature on the quality of the foamed bitumen produces.

2.5.5 Secondary Binders

Secondary binders are commonly used in Australia for a number of reasons. Andrews (2006) has noted the following uses for secondary binders;

- To stiffen the bitumen
- Act as an anti-stripping agent – Typically lime is used
- Assist in the dispersion of the bitumen through the mix
- Improve early stiffness
- Improve rut resistance
- Reduce moisture sensitivity of the stabilised pavement
- Increase the % of material passing the 75µm size
- Decrease the plasticity of the material – Lime is usually used

The most commonly used secondary binders are quicklime and cement, either General Purpose (GP) or General Blend (GB) cement. Cement tends to stiffen the bitumen more than the lime and can make the pavement slightly more ridged as it usually increases the strength of the pavement material. Andrews also notes that the secondary binder is added the pavement material at the same time as the foamed bitumen to ensure the performance of the mix.

2.5.6 Bitumen

Bitumen comes is different classes. These classes, or classification, are related to the viscosity of the bitumen at 60°C (Standards Australia. (1997). The different classes of bitumen are:

Class	Viscosity at 60°C (Pa.s)
C50	50 to 60
C170	140 to 200
C320	260 to 380
C600	500 to 700

Table 2-2: Residual bitumen classes (Standards Australia(1997))

Each different class of bitumen is stiffer than the previous class. Class C170 bitumen is typically used for it for foamed bitumen. Other classes of bitumen can be used, however the foam produced is either more expansive but less stable (shorter half-life) or less expansive and more stable (longer half-life). For example C50 bitumen will have a greater expansion than C170 bitumen but the half-life of the C50 bitumen is less than that of the C170 and as such produces a less stable foam. Likewise, C320 bitumen will have a longer half-life and sore stable foam, than the C170 bitumen but the C320 will not have the same expansion but will have more stable foam. Additives used in bitumen production can have an effect on the ability of the bitumen to foam.

2.5.7 Ideal Materials

A material is considered to be ideal for foamed bitumen stabilisation if it complies with one of the grading envelopes shown in Figure 2-7. Materials are preferred to have a PI of less than 12; materials with a PI greater than 12 may require treatment with a secondary binder like quicklime.

Asphalt Academy (2009) identifies the following material types as being suitable for foamed bitumen stabilisation;

- Crushed stone – any type of sound quarried stone

- Untreated natural gravels – including basalt, granite, limestone, dolerite, dolomite, quartz and sandstone gravels,

- Reclaimed asphalt – blended with a crushed stone or gravel

- Reclaimed pavement materials – consisting of sound road base graves and crushed stone and previously stabilised pavements.

In Australia, the suitability of the material is based primarily on the particle size distribution of the material. Leek and Jameson (2011) note that while the particle size distribution of a material may indicate suitability there is no guarantee of producing a pavement with sufficient strength.

2.5.8 Marginal Materials

Materials that have a higher content of sand size or finer particles are considered to be a marginal material, i.e. materials that tend to be on the finer side of the grading envelopes in Figure 2-7: Foamed Bitumen grading envelope. Materials that have undergone some form of breakdown as a result of the weathering process or prone to breakdown during construction may also be considered as marginal materials. This is due to the increase the proportions of the fine material (Asphalt Academy 2009).

These marginal materials may not need to be excluded from the foamed bitumen process, and may make suitable stabilised pavements; however further testing of the material for modulus is required to ensure the success of the pavement.

Materials where breakdown during construction is prone to occur may not be suitable for foamed bitumen stabilisation. If the material produces excess fine material as a result of compaction than pockets of unstabilised materials may occur resulting in areas of localised weakness and site of potential future failure.

2.5.9 Recycled Materials

Collings and Thompson (2007) note that the most common application of foamed bitumen stabilisation is in pavement rehabilitation and insitu stabilisation using recycled pavements. Also, for recycled pavement materials to be successfully used, sufficient investigation into the existing pavement must be undertaken. They observe that little can be done with the road recycler to vary the nature of the material in the pavement except to change the grading, so areas on similar material need to be identified and where the pavement quality drops, cross-blending should be considered to reduce variation in the pavement.

2.5.10 Secondary Binders

Secondary binders are commonly used in foamed bitumen stabilisation. The most commonly used binders are lime and cement. The secondary binder is mixed into the pavement prior to the introduction of the foamed bitumen. Each has a different effect on the pavement and influence on the foamed bitumen. Asphalt Academy (2009) comments that it is impossible to determine which secondary binder will be suitable without first completing laboratory trials.

2.5.10.1 Lime

Lime is a commonly used secondary binder used in foamed bitumen stabilisation. Of the three types of lime available (agricultural lime, hydrated lime and quicklime) quicklime is the preferred form of lime for stabilisation, while hydrated lime can be used it is more expensive as 30% more hydrated lime is required when compared to quicklime. Quicklime needs to be slaked prior to mixing into the pavement resulting in the following reaction;

$$\begin{array}{cccc} CaO & +H_2O \rightarrow & Ca(OH)_2 & +heat \\ Calcium\ Oxide & & Calcium\ Hydroxide & \\ Hydrated\ Lime & & Hydrated\ Lime & \end{array}$$

Equation 2-2: Hydration reaction of Quicklime

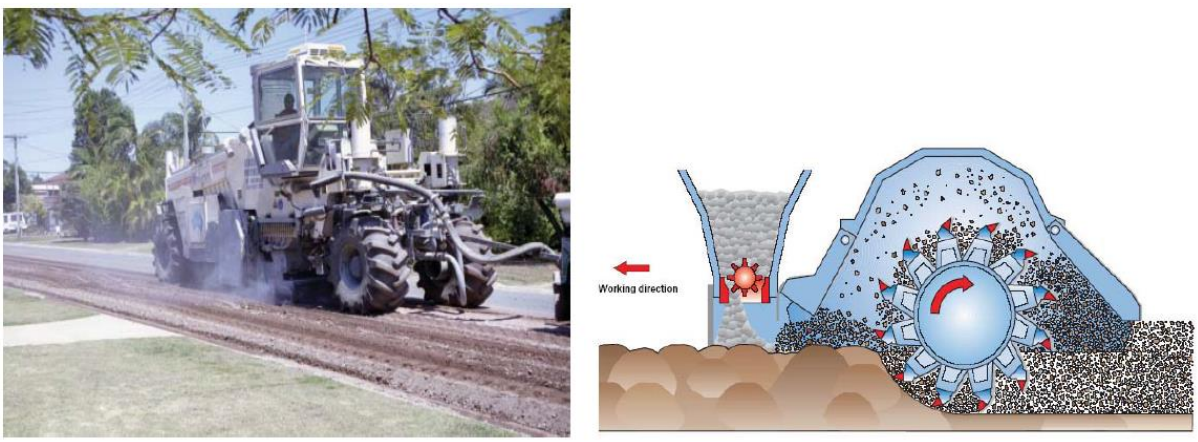

Figure 2-9: Direct injection spreading and mixing of lime (Ramanujam, Jones & Janosevic 2009)

Lime can be added at different times prior to the introduction of the foamed bitumen. If the lime is mixed and left for a period of time, prior to the foamed bitumen stabilisation, its purpose is to reduce the plasticity in highly plastic pavement materials and subgrades. If the lime is immediately before the foamed bitumen, Andrews (2006) notes the following effects on the pavement and the stabilisation process;

- A stiffening of the bitumen
- The lime will act as an anti-stripping agent
- Assistance in moving the bitumen through the material
- A reduction in moisture sensitivity of the material after stabilisation
- An improved early stiffness and early rut resistance allowing an immediate return of traffic to the road.

Quicklime is used in the stabilisation process while in the laboratory testing hydrated lime is used. Hydrated lime is a safer option during the laboratory design trial because quicklime is highly corrosive to the skin.

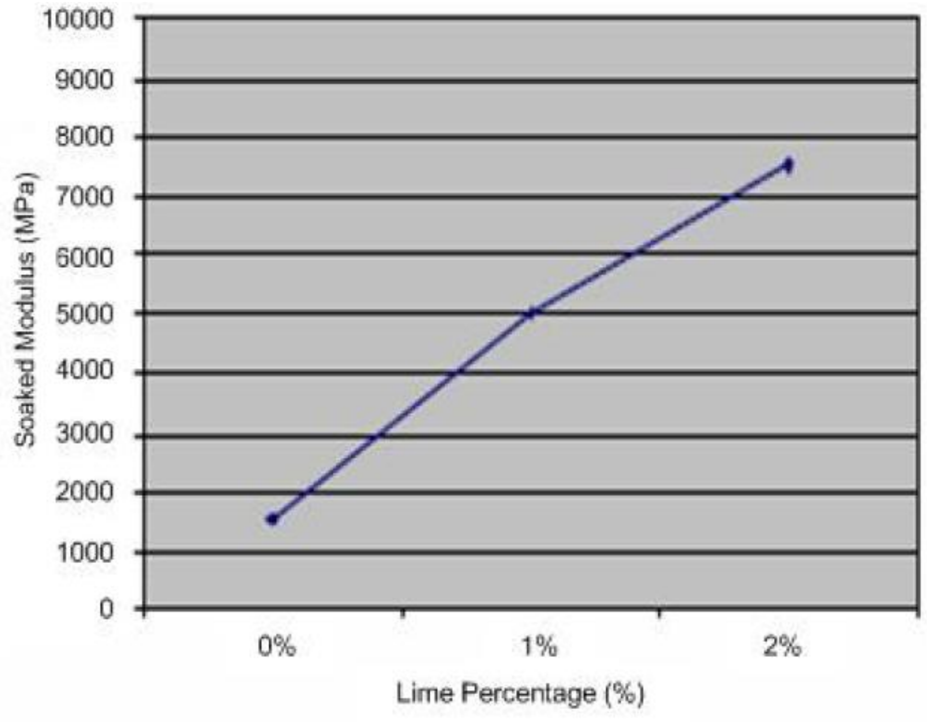

Figure 2-10: Influence of Lime on MATTA Results (TMR (2012))

Quicklime has 1.32 times the equivalent $Ca(OH)_2/unit\,mass$ of hydrated lime, so when hydrated lime is used in the laboratory testing the quantity of quicklime used in the field needs to be reduced accordingly. The addition of lime to the pavement will increase in the modulus, as illustrated in Figure 2-10 where the modulus is shown to increase with increasing lime content. TMR (2012) indicates that lime will also reduce the moisture sensitivity of the pavement. However Andrews (2006) and the Asphalt Academy(2009) recommend testing to confirm the ideal lime addition rate and warn against the addition of excessive amounts of lime, 1.5% Asphalt Academy (2009) and 2%(TMR 2012), as the flexibility of the mix may be significantly compromised. Kendal et al. (1999) observed an increased number of voids in samples that where treated with 3% lime, and attribute this to the effect of the lime as it reduces the plasticity of the materials, resulting in an open structure in the stabilised material.

2.5.10.2 Cement

Cement as a secondary binder is not as common as lime. Both Andrews (2006) and the Asphalt Academy (2009) note that the use of cement as a secondary binder will increase the stiffness of the mix while significantly reducing the flexibility of the material. Andrews and the Asphalt Academy both comment that the percentage of cement used should be limited to 1% by dry mass the benefits of using the foamed bitumen is lost.

2.6 Pavement Design

When planning a pavement design where foamed bitumen is to be used Ramanujam, Jones and Janosevic (2009) describe a process of "trench investigation, testing and mechanistic pavement design". During the trench investigation of the pavement importance should be places on;

- pavement profile, including classification of the material and moisture condition of the pavement, and layer thickness
- determining the type and cause of any failure in the existing pavement
- determining the condition of the subgrade, including moisture condition and location of ground water (if possible), and the strength of the subgrade by dynamic cone penetrometer

After the pavement investigation laboratory testing of samples taken, including particle size distribution and plasticity index to determine the pavement materials suitability for foamed bitumen stabilisation. Leek and Jameson (2011) suggest that if the grading curves of materials taken from the same section of pavement vary by <10% for fraction greater than 2.36mm or <5% for the material passing 2.36mm, than then the materials should be combined and treated as a single pavement material. If the material is found to be suitable than MATTA testing should commence for design assessment.

In Australia, no pavement design process specific to foamed bitumen stabilisation exists. The pavement design process is based on the 'Guide to Pavement Technology: Part 2 - Pavement Structural Design' (Austroads 2012) and for stabilised materials the 'Guide to Pavement Technology Part 4D: Stabilised Materials' (Andrews 2006). These are either used directly or are adapted by local council or state authorities to suit local and regional conditions. Commonly state authorities produce a supplementary document to assist designers, like in NSW the Roads and Maritime Service produces the "RMS Austroads Guide Supplement to Austroads Guide to Pavement Technology: Part 2 – Pavement Structural Design" (Tamsett 2013). These supplementary guides are intended to assist designers by;

- Recommending practices which are intended to enhance the Austroads guide
- Offering materials and practices which are intended to complement the Austroads guide
- Identify where practices depart from the Austroads guide.

The closest to a specific foamed bitumen pavement design process was an "interim design method" in the appendix of "Review of structural design procedures for foamed bitumen pavements" Austroads (2011b) Austroads (2011b) Austroads (2011b) Austroads (2011b) Austroads (2011b) Austroads (2011b) Austroads (2011b) Austroads (2011b) Austroads (2011b) Austroads (2011b) which is based on the Austroads 2012 method. Most Australian Road Authorities use the design procedure outlined in 2012 Austroads Pavement Design Guide Part 2.

Step	**Activity**
1	Set pavement profile and project reliability
2	Determine insitu subgrade elastic properties $E_v;\ E_h = 0.5E_v;\ \nu_v = \nu_h; f = E_v/(1+\nu_v)$
3	Determine the elastic properties of the top sublayer of subgrade
4	Determine the elastic parameters and thickness of the other granular sub-layers
5	Determine the elastic parameters for cemented materials, pre and post fatigue cracking
6	Determine elastic parameters of asphalt
7	Adopt the subgrade strain criteria
8	Determine fatigue criteria for cemented materials
9	Determine fatigue criteria for asphalt
10	Determine design number of Standard Axle Repetitions (SAR) for each distress mode

Table 2-3: Mechanistic design procedure: input requirements (Austroads, 2012)

11	Approximate the Standard Axle wheel Loadings as four uniformly loaded areas at centre-to-centre spacing of 330mm, 1470mm and 330mm; vertical load of 20kN is applied to each circular area at a vertical stress of 750kPa. Radius for each load is 92.1mm for highway traffic. $R = 2523p^{-0.5}$, where R=radius (mm) and p=vertical stress (kPa)
12	Determine critical locations in the pavement for the calculation of strains as follows: • Bottom of each asphalt or cemented layer, and • Top of in situ subgrade and the top of selected subgrade materials For load configurations see
13	Input the above values into the linear elastic model (i.e. CIRCLY) and determine maximum critical strains at each location

Table 2-4: Mechanistic design procedure: analysis (Austroads, 2012)

14	Determine the allowable number of Standard Axle Repartitions for each distress mode. If post-cracking phase of cemented material life is being considered, calculate the total allowable loading of the pre-cracking and post-cracking phase of life. In this case the total allowable loading is expressed in terms of ESA rather than Standard Axle Repartitions.
15	For each distress mode, compare allowable number of Standard Axle Repartitions with the design number of Standard Axles
16	If, for all distress modes, the allowable number of Standard Axle Repartitions exceeds the design number of Standard Axle Repartitions, the pavement is acceptable. If not, it is unacceptable.
17	If the pavement is unacceptable or additional pavement configurations are required, select a new trial pavement, return to Step 1 and repeat Steps 1 to 16
18	Compare alternate acceptable design

Table 2-5: Mechanistic design procedure: interpertation of results (Austroads, 2012)

Austroads (2012) describes two design procedures for designing a flexible pavement. These procedures are by;

- Empirical Design – This procedure is based around a design chart figure 8.4 in Austroads (2012) "Part 2: Structural Pavement Design". This design procedure allows for rutting and shape loss but does not take into account fatigue of the asphalt surfacing and is only intended for use on unbound granular pavements with up to 40mm asphalt or bituminous seal. This design method is inappropriate for this type of pavement.

- Mechanistic Design – The Mechanistic design uses structural analysis of the various pavement layers under standard road loadings. Critical strains are determined at so the life of the pavement can be determined for the various failure modes. Figure 2-11 illustrates the locations where the critical strains are determined in the pavement. Due to the complexity of the calculations computer programs like CIRCLY are used.

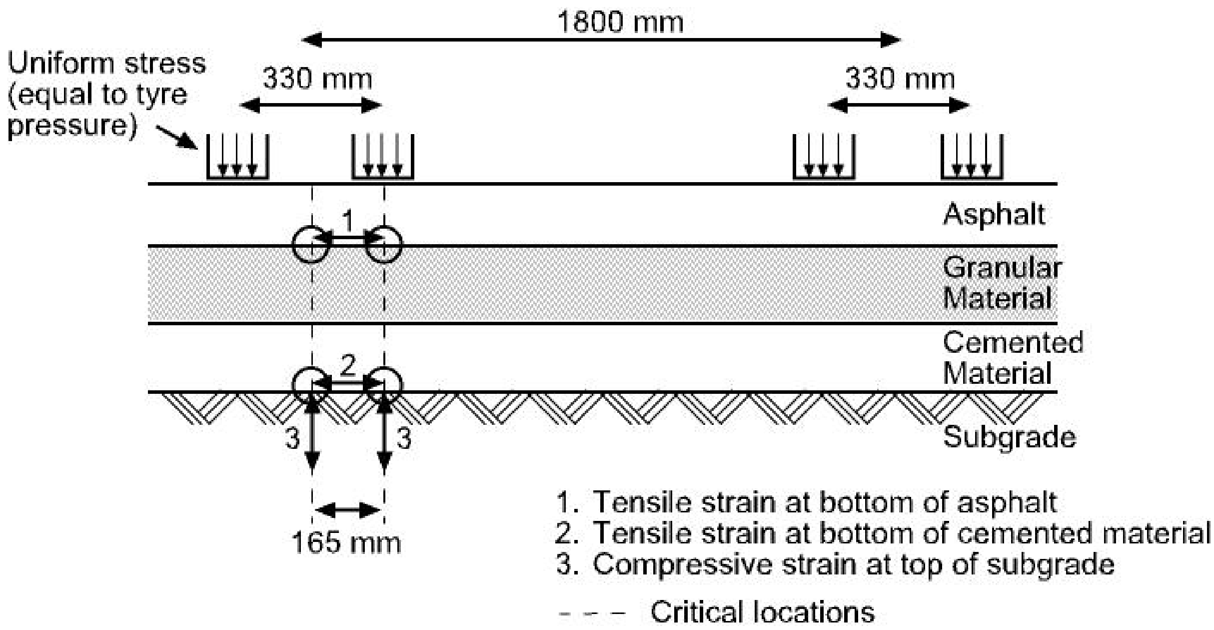

Figure 2-11: Mechanistic pavement design model (Austroads 2012)

2.6.1 Pavement Design Specifications

Various road authorities around the world have different design specifications for foamed bitumen stabilisation. In Australia the different state authorities have their own specifications which are based on the Austroads specification. The Austroads specification is part of the Austroads Pavement Technology Series, the Guide to Pavement Technology Part 4D: Stabilised Materials (2006).

In Australia, the design specifications are based on initial, unsoaked (dry) and soaked resilient modulus of the pavement and the retained modulus ratio. These values are based on the average daily ESA's in the year of opening.

The TMR mix design limits are;

Average daily ESA's in the year of opening	Minimum initial modulus (MPa)
<100	500
≥100	700

Table 2-6: Foamed bitumen - Initial modulus design limits (TMR 2012)

Average daily ESA's in the year of opening	Minimum Unsoaked 'Dry' cured MATTA modulus (MPa)	Minimum Soaked 'Wet' cured MATTA modulus (MPa)	Minimum retained modulus ratio
<100	2,500	1,500	0.4
100 – 1,000	3,000	1,800	0.45
>1,000	4,00	2,000	0.5

Table 2-7: Foamed bitumen pavement cured design limits (TMR 2012)

These different amounts of curing relate to different life stages of the pavement (Austroads 2011a).

- Initial Modulus – The modulus obtained within 3 hours of mixing. This is the modulus relating to the pavement strength for when the road is initially reopened to traffic.

- Unsoaked or 'Dry' Modulus – the modulus obtained after the test specimens have been cured for 72 hours at 40°C. This dry cured condition is indicative of the strength of the pavement 6 months after stabilisation.

- Soaked or 'Wet' Modulus – The modulus obtained after the test specimens have been cured for the dry modulus and then soaked for 24 hours at 20°C. The results of the wet modulus give an indication to the materials moisture sensitivity.

- Retained Modulus Ratio – This is the ratio of the 'Wet' modulus to the 'Dry' modulus. The purpose of this is to relate the effects of soaking on the strength of the pavement, and demonstrate how much strength is retained after the effect of moisture on the cured pavement.

TMR (2012) suggests that the modulus of the pavement should be determined over a range of additive contents (Table 2-10), of both the bitumen and secondary binder, to determine the optimum proportions for the additives. This should be conducted for both the bitumen and the lime or cement as small variations in the additives can result in variations in the properties of the material. Figure 2-12 demonstrated how the optimum bitumen content can be determined. This optimum bitumen content should be used providing it meets the modulus limits as shown in Table 2-6 and Table 2-7.

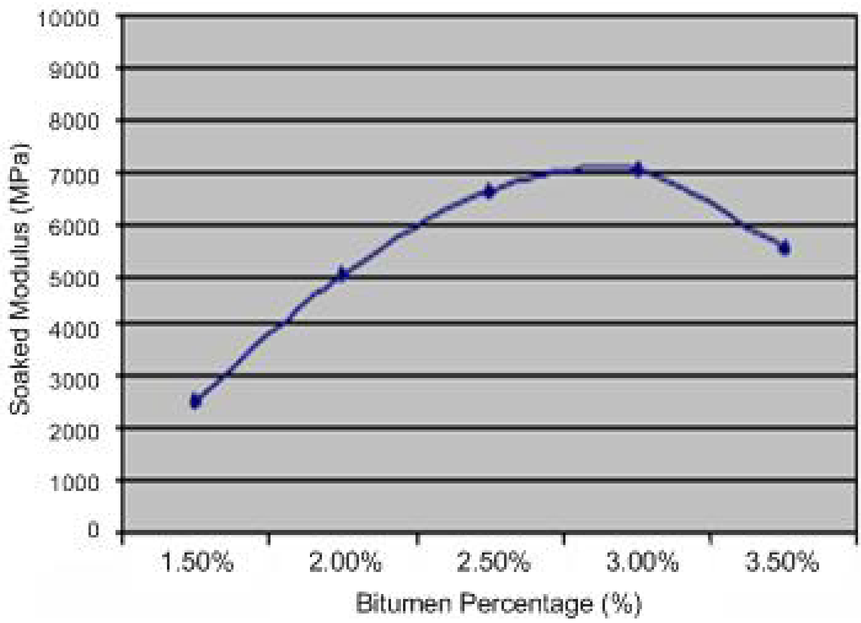

Figure 2-12: Optimum bitumen content determination (TMR 2012)

Soil Type	Binder (%)	Further Additives
Well graded clean sand	2.0 – 2.5%	
Well graded marginally clayey/silty gravel	2.0 – 2.5%	
Poorly graded marginally clayey/silty gravel	2.0 – 2.5%	
Clayey gravel	4.0 – 6.0%	Lime modification
Well graded clean sand	4.0 – 5.0%	Filler
Well graded marginally silty sand	2.5 – 4.0%	
Poorly graded marginally silty sand	3.0 – 4.5%	Low penetration of bitumen and filler
Poorly graded clean sand	2.5 – 5.0%	Filler
Silty sand	2.5 – 4.5%	
Silty clayey sand	4.0%	Possibly lime
Clayey sand	3.0 – 4.0%	Lime modification

Table 2-8: Optimal bitumen content ranges (Kendall et al. 2001)

Bowering and Martin (cited in Kendall et al. 2001), Table 2-8, give some guidance on what percentage bitumen binder should be used based on the different material classifications. Also guidance is given relating to pre-treatment that may be required to make the material suitable for the foamed bitumen process. Muthen (1998) offers a series of bitumen contents based on the material grading,

Table 2-9. It is also noted that these bitumen content proposed is suitable for most materials, depending on the parent material. TMR (2012) suggests similar bitumen contents based on the grading of the material, but also recommends testing the material with bitumen contents ±0.5% of the target bitumen content.

% passing 4,75 mm sieve	% passing 0,075 mm sieve	% Foamed bitumen
< 50 (gravels)	3 - 5	3
	5 - 7,5	3,5
	7,5 - 10	4
	> 10	4,5
> 50 (sands)	3 - 5	3,5
	5 - 7,5	4
	7,5 - 10	4,5
	> 10	5

Table 2-9: Bitumen content by particle size (Muthen 1998)

Percent passing 4.75 mm sieve	Percent passing 0.075 mm sieve	Bitumen content (% mass)	Plasticity Index (%)	Hydrated lime[(1)] (% mass)
<50	5–7.5	3.0	6–10	2.0
	7.5–15	3.5		
	15–20	4.0	3–6	1.5
>50	5–7.5	3.5		
	7.5–15	4.0	<3	1.0
	15–20	4.0		

Table 2-10: Bitumen content and secondary binder by particle size and plasticity index (Leek and Jameson (2011))

2.6.2 Pavement Service Life

The pavement service life can be determined by the procedure outlined in Austroads (2011b) and shown in Table 2-3, Table 2-4 and Table 2-5 above. This procedure is based on the asphalt fatigue relationship (Equation 2-1).

Once a pavement profile has been selected the required parameters can be entered in to CIRCLY (Wardle 2004) to determine the critical strains. The critical strains can then be entered into the fatigue equation and the allowable repetitions calculated. This is then converted into Equivalent Standard Axles using the relationship;

$$SAR5/ESA = 1.1$$

Equation 2-3: Damage Index (Austroads 2012)

$$\begin{aligned} &Where: \\ &SAR5/ESA = Damage\ index\ for\ the\ fatigue\ of\ asphalt \\ &SAR5 = Standard\ Axle\ Repetitions\ for\ asphalt\ fatigue \\ &ESA = Equivalent\ Standard\ Axles \end{aligned}$$

2.7 Testing Program and Data Analysis

2.7.1 Testing Methods

As a part of this project some testing and analysis is required. The following testing has been planned to be undertaken.

- AS1289.3.6.1, Particle Size Distribution – Mechanical analysis of a variety of different materials from around New South Wales, Queensland and Victoria to determine suitability for foamed bitumen stabilisation

- AS1289.3.1.1, 3.2.1, 3.3.1, Liquid Limit, Plastic Limit and Plasticity Index – Determination of the plasticity of materials from around New South Wales, Queensland and Victoria, where foamed bitumen testing has been performed to see the effect plasticity has on the modulus of the stabilised material.

- AS1289.5.1.1, Proctor compaction (Standard compactive effort) – For the determination of Maximum Dry Density (MDD) determination and Optimum Moisture Content (OMC) of the material before and after the addition of lime and foamed bitumen

- RMS T150, Density-Moisture relationship for mixtures of road materials and bituminous materials -

- RMS T153, The half-life and expansion ratio of foamed bitumen – To determine the bitumen moisture content to give a half-life of 20-40 seconds and minimum expansion ratio of 10 to ensure satisfactory foaming for mixing in to the pavement materials for testing

- RMS T154, Resilient modulus of road construction materials stabilised by foamed bitumen - Including the foaming, mixing and manufacture of test briquettes for the determination of the resilient modulus

2.7.2 Equipment Requirements

To complete the practical component of this project I will need to use an amount of testing equipment. The following items have been identified and permission to use this equipment with suitable guidance has been given.

- Nest of sieves – Sieves for sample preparation and sample analysis.
    - 37.5mm, 26.5mm, 19mm and 13.2mm sieves used bulk sample preparation, 2.36mm and 4.35µm sieves used for plasticity index sample preparation
    - AS sizes nest of sieves ranging from 37.5mm to 75µm for particle size distribution of the sample.

- Compaction Moulds – a variety of different mould sizes may be required for this project. The following sizes are expected to be used;
    - 1L/2L/2.4L mould – These moulds will be used for maximum dry density and optimum moisture content determination.
    - Foam Bitumen Briquette mould – a custom made mould with a diameter of 150mm and height of 85mm for the manufacture of the MATTA test specimens.

- Compaction hammers – Two different compaction hammers will be used.
    - Standard Proctor hammer – A drop hammer with a 2.7kg falling weight and a 300mm drop, where the energy is passes directly into the sample.
    - Marshall hammer – A drop hammer consisting of a sliding 4.5 kg weigh on to a tamping foot with a drop of 450mm, typically used for compacting asphalt samples

- Thermostatically Controlled Oven with a temperature range up to 110°C
    - Drying Oven – An oven thermostatically controlled for the range of 105°C to 110°C
    - Curing Oven – An oven thermostatically controlled for the range of 40°C to 45°C

- Casagrande Cup and grooving tool

- MATTA (MATerials Testing Apparatus) Universal Testing Machine – The MATTA is used to test the resilient modulus of the cured briquettes.

- Expansion Ratio Apparatus – A calibrated bucket and dip stick

- Stop watch

- Wirtgen WLB10 Laboratory scale foamed bitumen machine and Hobart mixer

I will have access to most of this equipment through the Coffey Testing laboratory located in Concord West. I will be able to access a MATTA universal testing machine through the RMS laboratory located in Russell Vale. The equipment for the void content testing will be accessed from the STS laboratory in Macquarie Park. I have a private arrangement with each of these testing facilities to access the equipment required to complete the necessary testing.

2.7.3 Proposed Data Analysis

As a part of this project I will be performing analysis on data obtained from testing performed by myself and from historical data obtained over the last 15 years. As a part of this analysis I will perform the following analysis on the data;

- Particle Size Distribution data – from the PSD data, materials will be grouped into ideal, marginal and unsuitable. This will categorise materials by physical properties. At present the PSD is the predominant method used for determining the suitability of the material for foamed bitumen stabilisation.

- Plasticity – Data on the plasticity of the materials will be used to help categorise the material and determine the influence of

- MATTA Testing data – Modulus data obtained from the MATTA test will determine the strength of the stabilised material and the compliance with published minimum design requirements. This data in conjunction with the PSD data will be analysed to determine the effect of PSD and plasticity on the modulus of the pavement material. If possible

2.8 Sustainable

Foamed bitumen stabilisation, like other forms of pavement stabilisation, is a sustainable pavement construction process resulting in social, environmental and direct cost benefit. Being an insitu stabilisation process the existing pavement is reused needing little or no material required to be brought to site and very little waste material needing disposal. This in turn speeds up the construction by shortening the duration of road closures, decreasing the number of heavy vehicle movements and the reducing amount of greenhouse emissions produces.

Foamed bitumen stabilisation is an insitu stabilisation process and consequentially reduces the time of road closures. The reconstruction of a road pavement can be complete within a day and the road can be reopened to traffic after the final compaction is complete with no detrimental effects on the pavement. The speed of the reconstruction means that work on the pavement can begin at the completion of the morning peak and be complete for the afternoon peak meaning less inconvenience to road users and residents.

Foamed bitumen is predominantly an insitu stabilisation process, as such, less heavy vehicles are required during the construction process as little or no material requires disposal off site and the only materials coming onto site is the binders which is about 2% to 3% of the quantity of the material to be stabilised. With less heavy vehicles movements the roads around the construction are less congested making the surrounding roads safer. The environment benefits from less noise and exhaust emissions being produces.

Old pavement materials are recycled in to a new revitalised pavement makes the process sustainable for the future by reducing the amount of waste going to landfill normally required for the construction of the new pavement and reduces the reliance on imported quarry materials. The existing pavement can be used as a linear quarry so material does not need to be imported making construction suitable for remote areas where importing a quarried material is financially prohibitive and reduces the environmental impact of opening sites to find new material sources. Less waste and import material reduces the cost of constructing the pavement and less waste material goes into landfill sites putting less strain on these facilities.

By recycling the existing pavement foamed bitumen stabilisation is a greener option when compared to full reconstruction of the pavement. With the pavement material is being recycled little to no material is required to be brought on to site and material is not being sent to landfill so less trucks hauling material to and from site reduced carbon footprint comes of the construction. Also material is not being sourced from quarry sites so quarrying works are not required for the construction, because of this work is not required to locate and quarry quality road base gravel further reducing the environmental impact and cost of the construction.

The ability to use marginal recycled materials for foamed bitumen stabilisation is a sustainable and ethical decision for road construction and rehabilitation. The use of recycled and marginal material has all of the social, environmental and cost benefits listed above.

2.9 Safety and Risk Assessment

With this project there are a number of inherent safety risks. These have been identified as;

- Working with hot materials
- Working with lime
- Exposure to dust
- Working with moving parts
- Exposure to potentially hazardous materials.

The most obvious hazard is working with hot materials. To be able to use the bitumen I will need to soften the solid bitumen to get into the kettle of the foamed bitumen machine, during this process the bitumen needs to be heated to about 130 - 140°C. While decanting the bitumen in to the kettle on the WLB10 extreme care must be taken as there is a risk of spilling or splashing the bitumen which may result in serious burns. While determining the bitumen flow rate, the half-life and the expansion ratio of the bitumen hot bitumen is expelled from the foaming chamber of the WLB10. At this time the bitumen is at about 180°C and any contact will cause serious burns. Protective gloves, long sheaves and face shield are required while handling hot bitumen or then there is a chance of exposure to protect against any bitumen splash or spills that may occur.

Lime is used as a secondary binder in the foamed bitumen process. In insitu stabilisation quicklime is used for economic reasons, however quicklime is too hazardous to use in a laboratory situation so hydrated lime is used. Hydrated lime, while not as hazardous as quick lime, is a potentially hazardous material. While working with lime there is a chance of exposure by direct contact while mixing the lime into the samples and by contact and inhalation of airborne lime resulting from the mixing process. Exposure to hydrated lime can cause skin and respiratory irritation.

Generally working there should not be too much dust, except for the lime, encountered as the materials for testing are kept in a moist state. The only occasions where dust may be an issue are in preparation of the Plasticity Index test as the material needs to be air dried and ground to pass through a 425µm sieve and any waste materials not cleaned up while working. This dust can be a slip hazard if it is left on the ground in walkways. It can also be a respiratory hazard if breathed in. Breathing in dust can result in respiratory irritation and, if silicon is present in the dust, silicosis. To prevent this, spills should be cleaned up and not left, where the chance of dust becoming airborne is present then dust masks or other respiratory protection should be used.

When mixing the lime and bitumen into the bulk sample a Hobart mixer is used. This has a planetary mixer which can move at variable speeds. While using this piece of equipment care should be taken to ensure hands and all loose items are clear of the mixing bowl prior to operation. If it is necessary to check the consistency or moisture content of the mixed material during the mixing process the mixer should be turned off and unplugged until the inspection of the material is complete.

Some potentially hazardous materials and additives are used in the foamed bitumen process. Some of the materials and additives are bitumen, lime, cement and foaming agents. Prior to using these substances, Material Safety Data Sheets (MSDS) should be sourced from the relevant manufactures. The MSDS has details about any potential hazards, toxicology and methods of disposal.

3 Testing Methodology

3.1 Standards and Specifications

- AS 1289.3.1.1
- AS 1289.3.2.1
- AS 1289.3.3.1
- AS 1289.3.6.1
- AS 2891.13.1 – Determination of the resilient modulus of asphalt – Indirect tensile method
- RMS T111 – Dry density/moisture relationship of road construction materials
- RMS T153 – The half-life and expansion ratio of foamed bitumen
- RMS T154 – Resilient modulus of road construction materials stabilised by foamed bitumen (blended in the laboratory)

3.2 Sample Preparation

Representative samples were submitted for testing from a number of different locations in each of the areas. The samples consisted of materials representing the of a profile pavement of the existing granular base and bituminous/asphaltic seal layers of the pavement, in some samples a granular material was added to improve deficiencies in the material to assist in making it suitable for stabilisation. These samples were prepared for testing by combining different the different layers of the pavement proportional to the thickness of the layers. Conglomerations of granular material were broken down to discreet particles or 19mm size. The bituminous seal or asphaltic concrete it be incorporated was broken down to 19.0mm size to simulate the effects of milling and mixing on the material. The combined composite samples were sieved on a 26.5mm sieve and particles retained on this sized sieve were broken down to simulate the action of the milling and mixing encounter in the stabilisation process. Samples were than mixed and subsampled for testing.

Some samples were not suitable for testing and had to have quality imported gravel blended to improve the material. Some of these samples had too much fines or not enough coarse material for to produce a satisfactory pavement.

3.3 Testing

3.3.1 Particle size Distribution

An AS1289.3.6.1 washed soil grading was conducted to determine the suitability of the material for testing. Samples were washed, dried and sieved on a standard set of AS sieves. The results of these grading were plotted on to the preferred grading envelope. The grading was performed on the material passing 26.5mm

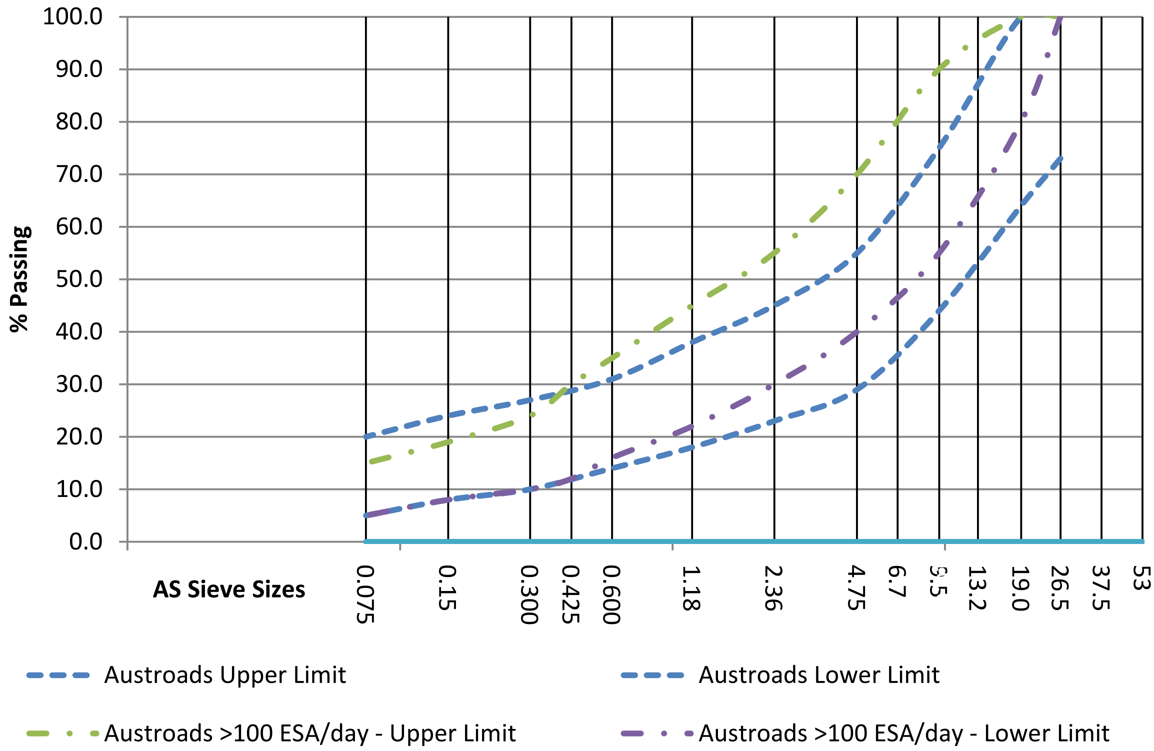

Figure 3-1: Preferred Grading Envelope

3.3.2 Plasticity Index

Each material was tested to AS1289.3.1.1, 3.2.1, and 3.3.1 to determine the plasticity index of the material. A subsample from each location was air dried and ground in a mortar and pestle to break particles down into discreet particles. The material was then sieved on a $425\mu m$ sieve. A portion of the material was wet up to test for the plastic limit, while the rest wet up to be able to be used to determine the liquid limit. Once the liquid limit and plastic limit portions had been prepared they were left of a minimum of 24 hours to cure and allow the moisture in the respective portions to fully penetrate the material. After the curing was completed, the material was tested for the plastic limit (PL), the moisture content where a material enters a plastic phase, and liquid limit (LL), the moisture content where a material enters the liquid phase.

The Plastic Limit (PL) is determined by rolling the material to be tested into a thread, the moisture content of the material when this thread just starts to crumble at a diameter of 3mm id the plastic limit. The Liquid Limit (LL) is determined by determined using a Casagrande Cup and grooving tool. The Plasticity Index is the difference in moisture content between the Liquid Limit and the Plastic Limit

$$Plasticity\ Index = LL - PL$$

Equation 3-1: Plasticity Index

3.3.3 Moisture Content

Secondary binders are added on a dry mass basis so the moisture content of the material is required to determine the dry mass of the material to be tested. By using this moisture content and the optimum moisture content of the material we were able to adjust the moisture in the material ready for the foaming process, as the ideal moisture ratio for the material for foaming is 70 -80% of the optimum moisture content. The method used was AS1289.1.2.1

$$\%\ Moisture\ Content = \frac{Wet\ mass - Dry\ mass}{Dry\ mass} \times 100\%$$

Equation 3-2: Moisture Content

3.3.4 Maximum Dry Density and Optimum Moisture Content

The Maximum Dry Density and Optimum Moisture Content of the material were determined by either a “Standard” Proctor Compaction, RMS T111. In the standard compaction the material is compacted into a mould using a drop hammer, the number of blows is proportional to the size of the mould. 25 blows for a 1L mould and 50 blows for a 2L mould. The mould size is determined by the size of the larger particles in the material being testes, a 1L mould is used for material less the 19mm and a 2L mould for material where there is material retained on the 19mm sieve and all material passing the 26.5mm sieve is included. The optimum moisture content determination was conducted on the unstabilised material, the material prior to any modification by the secondary binders; this was to assist the contractor with the moisture content they should use in the field.

The maximum dry density is required to assist in moulding the test specimens. The briquettes are usually moulded at 100%-102% of the maximum dry density. The maximum dry density for moulding the briquettes has been conducted on the material after the foaming process has been completed.

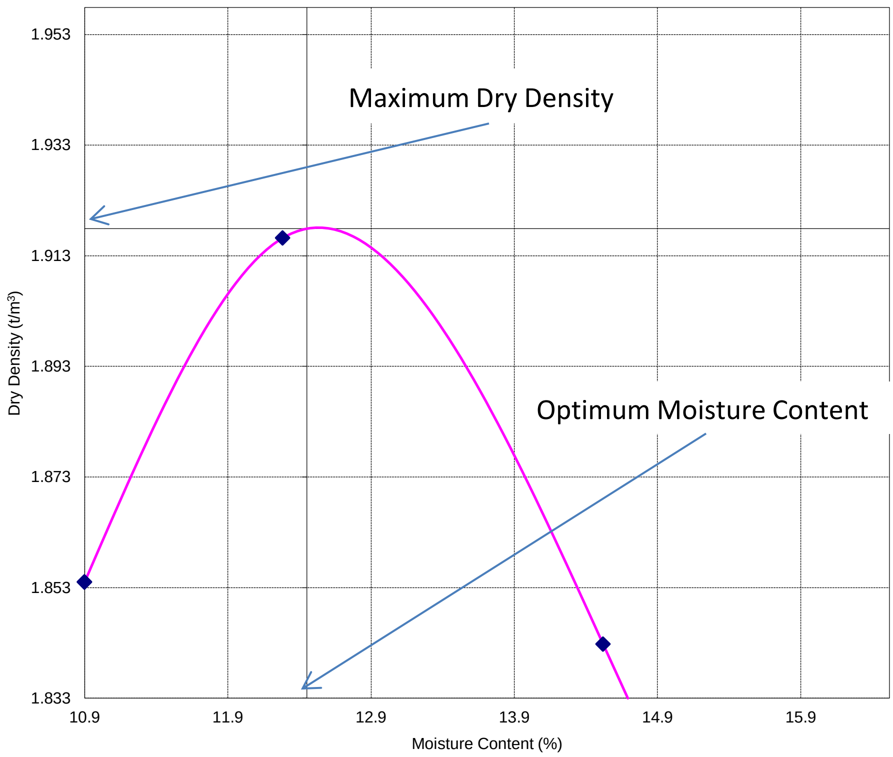

Figure 3-2: Maximum Dry Density and Optimum Moisture Content

3.3.5 Foamed Bitumen Mix and Briquette Manufacture

Mixing the foamed bitumen into the roadbase gravel we had to use some specialised equipment. To create the foamed bitumen we used a Wirtgen WLB10 Laboratory scale foamed bitumen machine. This machine is of one of the foaming jets the stabiliser used for stabilising in the field and consists of a;

- Heating kettle – used for heating the bitumen to 170-185°C

- Pressure vessel – for supplying pressure to the water used in the foaming, injecting air into the foaming process and operating the pneumatic solenoids for releasing the bitumen and water

- Bitumen pump – for supplying the bitumen for foaming and to keep the bitumen in the kettle moving

- Expansion chamber and foaming jet – where the air and water is injected into the hot bitumen

Prior to mixing the foamed bitumen into the roadbase material, the flow rate of the bitumen, the half-life and expansion ratio had to be determined. When the bitumen is released for foaming it is controlled by an automated timer so the flow rate of the bitumen was determined to enable accurate timing for the addition of the bitumen to be mixed into the roadbase. Next the half-life and expansion of the foam needed to be determined. This is because a half-life of 20 to 40 seconds is required and an expansion of 10 to 15 times. The half-life and expansion is checked at a number of different water addition rates to achieve the required half-life and expansion of the foamed bitumen, typically a foaming agent is added to the bitumen to assist in the foaming. The half-life and expansion was conducted as per the RMS T153 method.

Figure 3-3: WLB10 Laboratory scale foamed bitumen machine (Kendall et al. 2001)

The briquettes of the road material after the foaming process were compacted using an internal testing method for most of the testing due to the lack of any standardised compaction method. This compaction method involved the material being compacted in two layers using a modified compaction hammer, scarifying the first layer first layer prior to placing the second layer. More recently, with the publication of RMS T154, the method of compaction changed to the use of a Marshall Compaction hammer, where the briquettes have been moulded in one layer and compacted from either end. Typically three briquettes were produced for testing, an additional three briquettes may be produced if the initial modulus of the mix was required but this was not commonly required.

The briquettes were typically moulded into a mould 150mm diameter, or 100mm for samples where all the material is passing the 19mm sieve, and compacted to give the briquettes a height of 80mm±5mm.

3.3.6 Resilient Modulus Testing

The resilient modulus of the briquettes was tested by the RMS laboratory in Russel Vale. In testing the resilient modulus the briquettes were tested after 'dry' and 'wet' curing. The dry curing consisted of sealing the briquettes in a plastic bag and curing in an oven at 40°C for 72 hours prior to testing. The 'Wet' curing is then conducted where the briquettes are immersed in water at 23°C for 24 hours and towel dried prior to testing. The resilient modulus was determined by RMS T154 and AS 2891.13.1. The average of the modulus after each conditioning was taken as the modulus for the mix.

Figure 3-4: Roadbase material before (left) and after (right) addition of foamed bitumen.

Figure 3-5: Foamed bitumen briquette

4 Test Samples

4.1 Sample Locations

Material has been test from locations across New South Wales, Queensland and Victoria. The test samples have been grouped into geographic regions for comparison, these regions are:

- North Queensland – encompassing Townsville, Mackay and Gladstone
- The Sunshine Coast – including Maroochydore and Slippy Downs
- Southern Queensland – Logan City and Surrounds
- New South Wales Mid-North Coast – Tamworth, Port Macquarie and Mulbring
- Sydney – Greater Sydney Region
- Central and Western New South Wales – Bathurst and Parks areas
- Southern New South Wales – Bega district
- ACT
- Victoria

4.2 Summary of Samples

For all samples there was a grading, plasticity index, moisture content and maximum dry density/optimum moisture content tests were performed to classify the materials, assist in determining the required bitumen content and any adjustments that may be required to the sample prior to foaming. Following is a summary of the foamed bitumen mix testing conducted on the samples from each of the different sampling locations.

4.2.1 North Queensland

Samples were taken from 9 locations around Townsville, Gladstone, Mackay and the Whitsunday Coast. Of these samples there was;

- 2 samples tested with one bitumen content and one lime content
- 1 sample tested where the lime content was varied and the bitumen content was kept constant, 1 bitumen content and 2 different lime contents
- 2 sample tested where the bitumen content was varied, 2 different bitumen contents and 1 lime content, and 3 different bitumen contents and 1 lime content
- 4 samples tested where the bitumen content was varied and cement was added, 3 different bitumen contents and 1 cement content including one of these samples tested with 1 bitumen content and 1 lime content

4.2.1.1 Material Descriptions

The material from the samples around Townsville and Mackay were typically well graded sandy gravels with some plasticity predominantly existing roadbase gravels with some asphaltic concrete included. The samples from the Whitsunday Coast were quality existing roadbase gravel with no plasticity. The Gladstone sample was an imported roadbase gravel classified as a 2.1 roadbase as per the TMR specifications.

4.2.2 The Sunshine Coast

Samples were tested from 13 from locations around the Sunshine Coast Region. From these samples the following mixes were tested;

- 13 samples tested with one bitumen content and one lime content

4.2.2.1 Material Descriptions

The Sunshine Coast samples were all existing roadbase gravel samples, they mostly clayey gravels and well graded. Being existing roadbase samples they all had some asphalt seal in them. While most of the samples had some plasticity, three of the samples had little or no plasticity at all.

4.2.3 Southern Queensland

Samples were tested from 3 from locations around Southern Queensland southwest of Brisbane. From these samples the following mixes were tested;

- 2 samples were tested with one bitumen content and one lime content
- 1 sample was tested where the bitumen content was varied, 2 different bitumen contents and 1 lime content

4.2.3.1 Material Description

The Southern Queensland samples were all existing roadbase and all but one had an imported quarry gravel blended with it to improve the grading of the materials. One sample was tested as two different blends on the imported roadbase. The original roadbase materials were all silty roadbase gravels.

4.2.4 New South Wales Mid-North Coast

Samples were tested from 3 from locations around the New South Wales mid-North Coast/Hunter. From these samples the following mixes were tested;

- 2 samples were tested with one bitumen content and one lime content

- 1 sample was tested where the bitumen content was varied, 2 different bitumen contents and 1 lime content

4.2.4.1 Material Description

The sample from the Tamworth region was silty sandy gravel with some bituminous seal, this sample was well graded with no too may fines and non-plastic, this sample showed signs of previous cementitious stabilisation, a CBR test was performed on this material prior to foaming and was found to be CBR 50. The sample from the Hunter region was a blended sample of 60% decomposed granite and 40% 20/5mm concrete aggregate. The Port Macquarie sample was clayey roadbase gravel with some asphalt seal.

4.2.5 Sydney

Samples were tested from 6 from locations around the greater Sydney region. From these samples the following mixes were tested;

- samples were tested with one bitumen content and one lime content

4.2.5.1 Material Description

The samples taken from Sydney were all existing roadbase samples. Sample #4 from Sydney consisted of 80% existing roadbase gravel and asphaltic concrete and 20% crusher dust, Samples #5 & #6 were a blend of the existing pavement. Sample #5 was 22% Asphalt, 52% roadbase which had been previously cementitiously stabilised and 26% unmodified roadbase gravel. Sample #6 was 52% Asphalt, 22% roadbase which had been previously cementitiously stabilised and 26% unmodified roadbase gravel.

4.2.6 Central Western New South Wales

Samples were tested from 12 from locations around Central Western New South Wales. From these samples the following mixes were tested;

- 12 samples were tested with one bitumen content and one lime content

4.2.6.1 Material Description

The Central Western New South Wales samples were all existing roadbase samples. The material was silty sandy gravel and well graded with varying degrees of plasticity.

4.2.7 South Coast New South Wales

Samples were tested from 6 from locations around the South Coast of New South Wales. From these samples the following mixes were tested;

- 6 samples were tested with one bitumen content and one lime content

4.2.7.1 Material Description

The samples from the South Coast of New South Wales were all existing roadbase samples, all showed signs of previous stabilisation, some cementitious others with Polyroad. Sample #4, #5 and #6 are all gravelly silty sands which show signs of previous cementitious stabilisation. Samples #1 and #2 are graded roadbase gravels which had been previously treated with Polyroad.

4.2.8 Australian Capital Territory

Samples were tested from 2 from locations around the South Coast of New South Wales. From these samples the following mixes were tested

- 2 samples were tested with one bitumen content and one lime content

4.2.8.1 Material Description

The samples from the ACT were all existing roadbase samples. These samples were blended with 7% recycled Asphalt Pavement.

4.2.9 Victoria

Samples were tested from 8 from locations around the South Coast of New South Wales. From these samples the following mixes were tested

- 8 samples were tested with one bitumen content and one lime content, of this two samples were tested which had near identical grading profiles and as could be treated as the same material and were tested at different bitumen content

4.2.9.1 Material Description

The samples from Victoria were existing roadbase and blends of existing roadbase and imported materials. Sample #1 and 2 were a 60/40 composite of Sandstone gravel and 20mm imported quarries aggregate. Sample #3 and #4 were a composite blend of the existing road pavement with a fine crushed rock. Sample #4 was a composite blend of the existing roadbase gravel.

5 Data Analysis

5.1 Analysis Parameters

The data gained from the testing is to be analysed with the following parameters,

- Particle Size Distribution – Compared with the Austroads preferred grading and the >100 ESA's/day grading envelope for suitability

- Modulus – 'Dry' cured, 'Wet' cured and retained

	Austroads Limits			
AS Sieve Sizes (mm)	<100 ESA's /day		>100 ESA's /day	
26.5	73	100	100	100
19.0	64	100	80	100
9.5	44	75	55	90
4.75	29	55	40	70
2.36	23	45	30	55
1.18	18	38	22	45
0.600	14	31	16	35
0.425	--	--	12	30
0.300	10	27	10	24
0.150	8	24	8	19
0.075	5	20	5	15

Table 5-1: Preferred grading limits

Average Daily ESA	Minimum Dry Modulus (MPa)	Minimum Soaked Modulus (MPa)	Maximum Soaked Modulus (MPa)	Minimum retained modulus Ratio (%)
<100	2500	1500	2500	40%
100 – 1000	3000	1800	2500	45%
>1000	4000	2000	2500	50%

Table 5-2: Design modulus limits

Due to the nature of the material some variability is to be expected in the modulus results. As a result of this an average of the modulus results for comparison and determination of the retained modulus ratio, on occasion outliers have been experienced and Vorobieff

(2005) notes that when a result varies from the average by more than 30% it should be discarded and the average of the remaining results used.

5.2 Test Results Data

The results of the particle size distribution and resilient modulus testing can be found in Appendix A.

5.3 Effects of Particle Size Distribution on a Foamed Bitumen Stabilised Pavement

The particle size distribution, or grading, of pavement material is a key factor in foam bitumen stabilisation. The grading of the material is used to determine the suitability of the material for foam bitumen stabilisation and as an indicator of the percentage of bitumen to use in the mix design. Materials with different particle size distribution will affect the resulting stabilised pavement in different ways.

5.3.1 Particle Size Distribution

The Particle Size Distribution is a means by which a soil or aggregate can be classified by the sizes of the discreet and cemented particles. The material is passed through a set of sieves of decreasing mesh sizes, the percentage of the material retained on each sieve, by dry mass, is determined, from this a grading profile or particle size distribution is determined.

5.3.1.1 Effects of Particle Size Distribution on Resilient Modulus

When examining the results of the resilient modulus for the samples tested there is a trend relating the particle size distribution to the modulus. This trend can be found in both the wet cured and the dry cured modulus results.

When the results for the resilient modulus, for fixed bitumen content, are compared to the percentages of material finer than 75µm, a distinct trend was found as shown in Figure 5-1. As the percentage of material finer than 75µm increased so did the modulus until a maximum was reached. After this point the modulus tended to decrease.

On samples where there is a lower percentage of material passing the 75µm sieve the resilient modulus is relatively low. As this percentage of material passing increases so does the modulus. This increases to a point where a maximum occurs and there appears insufficient bitumen to bind the particles together.

This effect is seen in both the dry cured and the wet cured results; however the rate the modulus peaks for each of the curing conditions is different. The curve for the modulus of the wet conditioned specimens is much flatter than that of the dry conditioned specimens. As the percentage of material finer than 75µm increases, or decreases, away from the maximum the difference in the wet and the dry conditioned modulus becomes less.

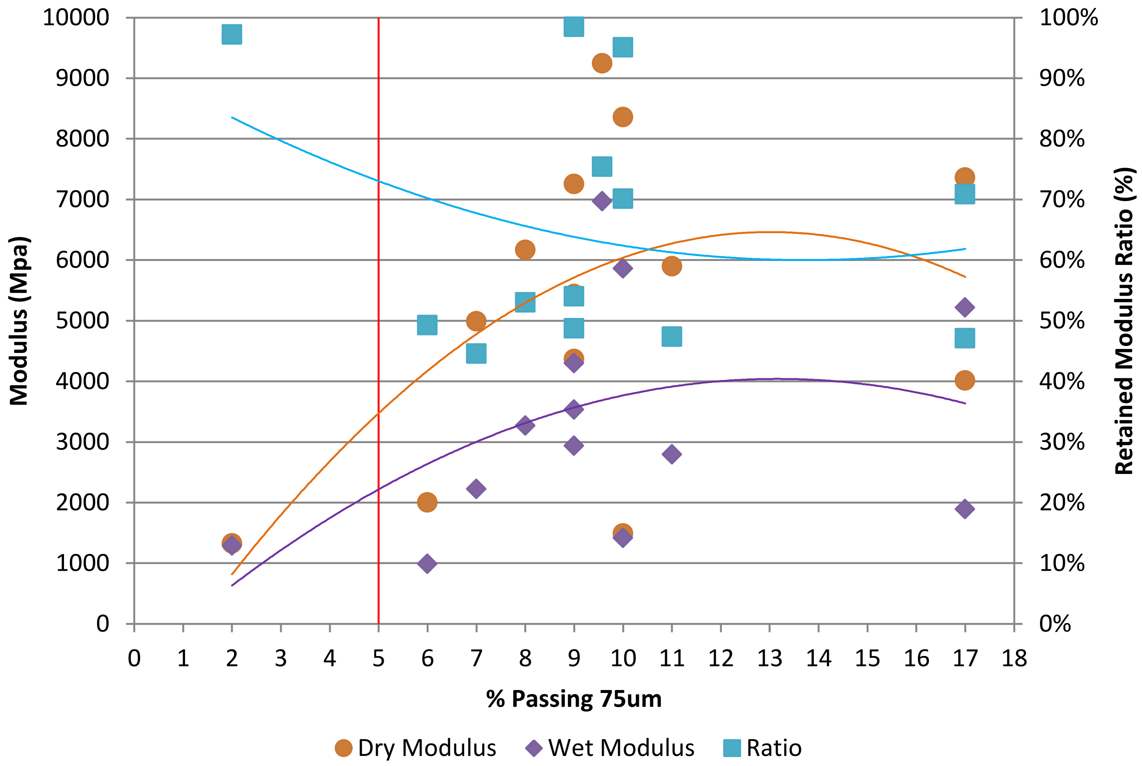

Figure 5-1: Effect of % material finer than 75µm on resilient modulus – 3% Bitumen with 2% Lime

In specimens with low percentages of fines, there is more bitumen coating the fine particles, the modulus tends to be lower because the bitumen will provide some lubrication between the particles. The retained modulus of these materials with low percentages of fines tends to be high, 80% or higher, this is due to the lubrication of the particles and in the wet cured specimens the bitumen coats more of the particles, waterproofing the material to some extent so the soaking has less of an effect.

Design specifications use the percentage of material passing 4.75mm as a significant in determining bitumen content. When the modulus results are split into results with <50% material finer than 4.75mm and >50% material finer than 4.75mm and plotted against the percentage of material finer than 75µm the same trends are observed as before. As the percentage of material finer than 4.75mm increases the peek modulus shifts to a higher percentage of material finer than 75µm (Figure 5-2).

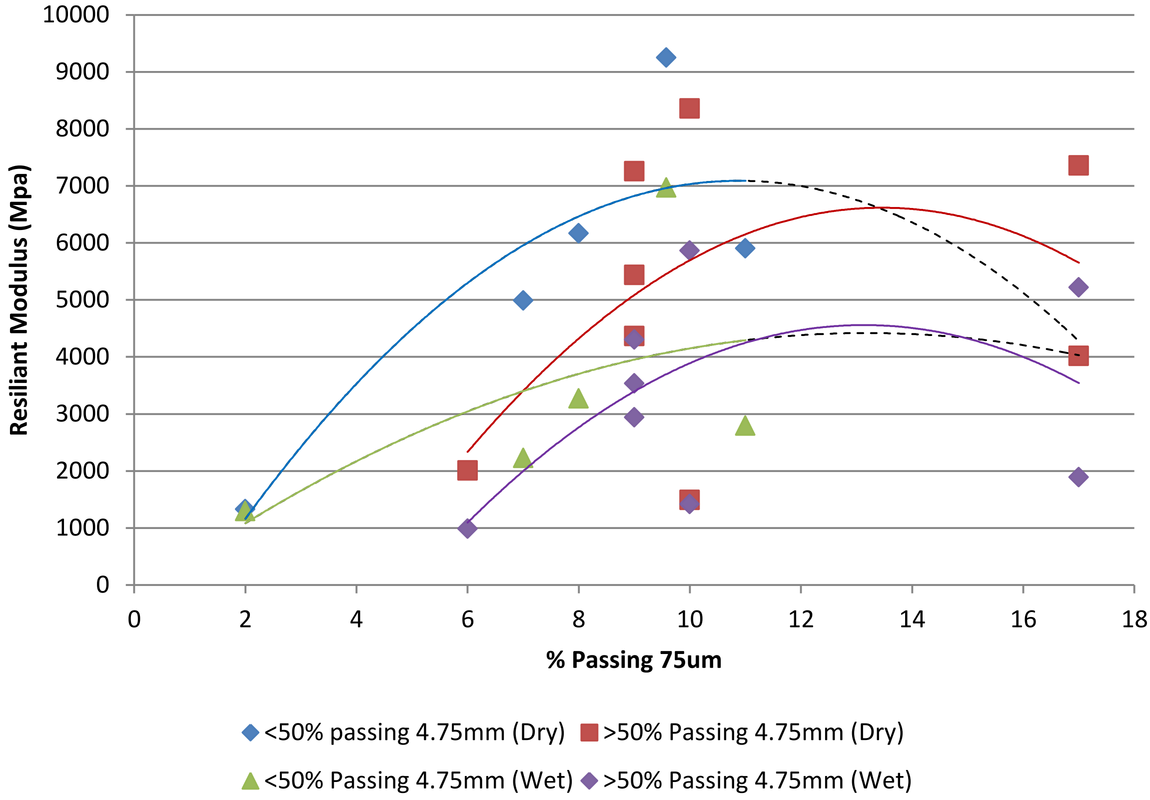

Figure 5-2: Effect of the percentage passing 4.75mm on resilient modulus - 3% Bitumen 2% Lime

5.4 Effects of Varying the Binders in a Foamed Bitumen Trial Mix

5.4.1 What the Bitumen does

The bitumen is used in the foamed bitumen stabilisation process as the primary binder; typically Class C170 bitumen is used. The bitumen is used to bind the granular particles of the roadbase gravel together to improve the strength of the stabilised pavement. The bitumen enables the pavement to gain strength while retaining a flexible pavement.

5.4.2 Bitumen Content

The bitumen content for foamed bitumen is the percentage of bitumen based on the amount of bitumen to be used as a percentage of the dry aggregate in the pavement.

$$\% \, Bitumen = \frac{\text{Mass of bitumen}}{\text{Mass of dry aggregate}} \times 100\%$$

Equation 5-1: Bitumen Content

5.4.2.1 How is the Bitumen Content Determined for a Mix?

The bitumen content for a design mix is based on design specification guidelines. Table 5-3 illustrates recommendations for the starting percentage of bitumen and Jones and Ramanujam (2008) suggests conducting trials at 0.5% either side of the starting content to determine the optimum bitumen content for the resulting pavement.

Passing 4.75mm Sieve (%)	Passing 0.075mm Sieve (%)	Foamed Bitumen Content (% of Dry Aggregate)
<50	5.0 – 7.5	3.0
	7.5 – 15.0	3.5
	15.0 – 20.0	4.0
>50	5.0 – 7.5	3.5
	7.5 – 15.0	4.0
	15.0 – 20.0	4.0

Table 5-3: Trial design Content (Jones & Ramanujam 2008)

The percentage of bitumen is typically dependant on the grading of the pavement material. The higher the percentage of the fine material the more bitumen is required to sufficiently coat these fine particles.

5.4.2.2 The effect of Varying the Bitumen Content

As a part of the testing conducted different samples were tested to different percentages of bitumen.

One sample was tested with three different percentages of bitumen. This sample has 46% passing 4.75mm and 10% passing 75µm and a plasticity index of 5%, the sample was tested with 2.0%, 3.0% and 4.0%, and 2.0% hydrated lime. Figure 5-3 indicates that the bitumen content was past the optimum bitumen content for the material tested. The dashed lines are extrapolations of the curves based on the three points tested. This extrapolation indicates optimum bitumen content at the maximum modulus is achieved.

Figure 5-4 illustrates how the maximum modulus varies with different bitumen contents. As the bitumen content increases the percentage of material finer than 75µm where the maximum modulus increases and the maximum modulus decreases.

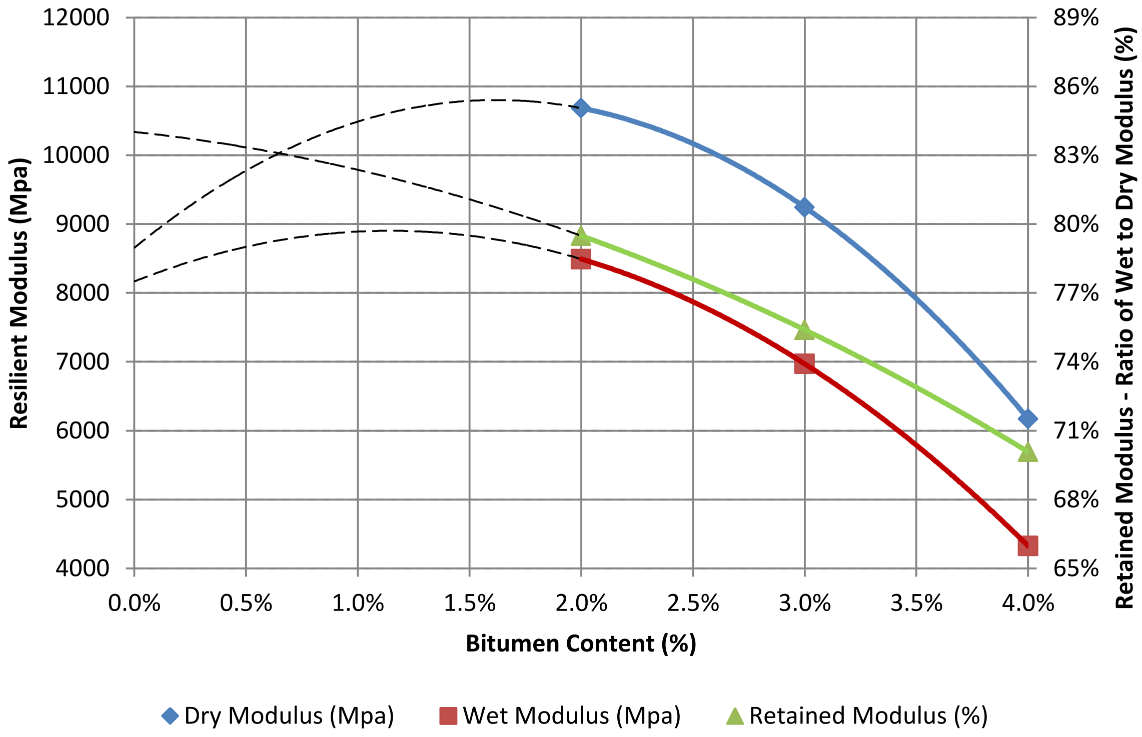

Figure 5-3: Bitumen Content vs. Resilient Modulus and Ratio of Retained Modulus

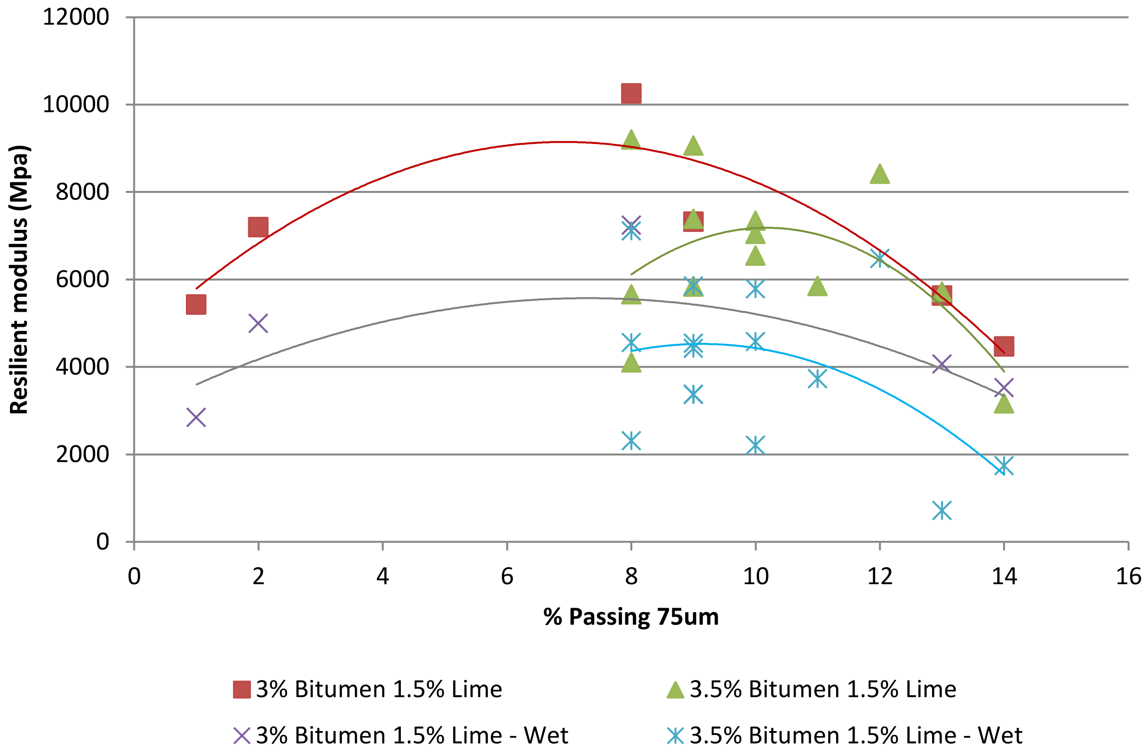

Figure 5-4: Effect on modulus from variations in bitumen content

5.5 Effects of Particle Size Distribution on the Bitumen Content of a Foamed Bitumen Stabilised Pavement

5.5.1 Particle Size Distribution and Bitumen Content

The particle size distribution of the material is used to determine the suitability of the material for foam bitumen stabilisation and as an indicator of the percentage of bitumen to use in the mix design. Materials with different percentages of fine material will be affected by the resulting stabilised pavement in different ways.

5.5.1.1 Effect of Particle Size Distribution of Bitumen Content

In all the design guides there is a sliding scale for the percentage of bitumen to use in design trial mixes. Typically the design guides indicate increasing bitumen content with increasing material passing. The data collected from the testing conducted appears to support this information. As the percentage of material finer than 75µm increases the pavement material is able to take a greater bitumen content.

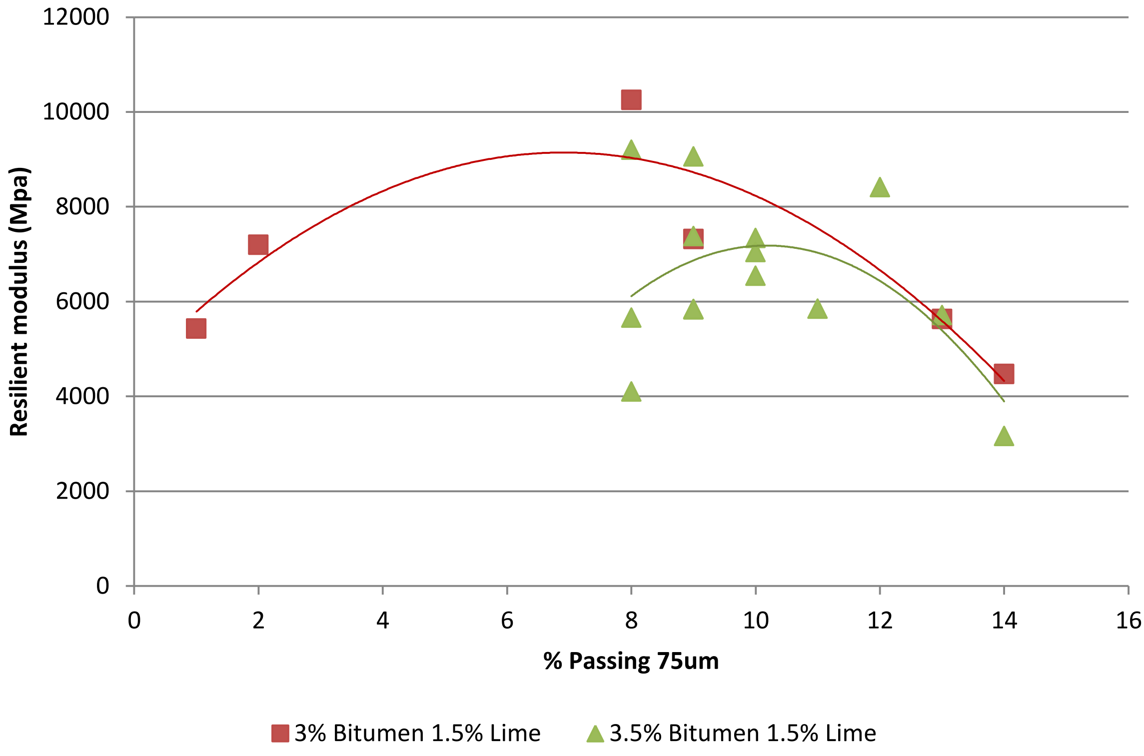

Figure 5-5 Effect of particle size distribution on Bitumen Content

5.6 Effects of Marginal Materials on a Foamed Bitumen Stabilised Pavement

A material can be defined as marginal based on the particle size distribution of the material, the type and quality of the material in the pavement, and if the pavement has been previously stabilised. Material which are considered marginal or unsuitable for use in foam bitumen stabilisation are usually discarded prior to testing as these materials are commonly thought to be unusable. The effect of these materials on the pavement can vary from an unsatisfactory to a successful pavement.

5.6.1 Marginal Materials

5.6.1.1 Particle Size Distribution

If the particle size distribution of the pavement material is at the edge, or outside, the preferred grading envelopes for foamed bitumen than it may be considered a marginal material (Figure 2-7). Some specifications give actual limits where the material is considered unsuitable and marginal. As previously discussed I am using the preferred grading envelope from Austroads (2012) and considering material at the outer edge of the grading envelope marginal

5.6.1.2 *Material Quality*

The quality of the material can make a pavement a marginal material. If the material is has too much clayey material or particles which will breakdown under compaction. Materials which breakdown under compaction will make excess fines and these will not be coated in bitumen making pockets of unstabilised material in the pavement. This is likely to occur in materials containing excess amounts of sandstone, RAP, or highly weathered aggregates.

5.6.1.3 *Previously Stabilised Pavement*

As discussed earlier there are four different methods of stabilisation, mechanical, cementitious, bituminous, and chemical. A road pavement in need of rehabilitation may have been previously stabilised by any one of these methods. A pavement previously stabilised by mechanical means may be difficult to identify, and due to the fact that foam bitumen stabilised pavements have not reached the repair and rehabilitation phase of their life cycle these two types of previously stabilised pavements are beyond the scope of this report.

5.6.2 Marginal Materials by Particle Size Distribution

Most of the materials tested fall outside the preferred grading envelope at some point, while very few samples were mostly or completely out of the grading envelope.

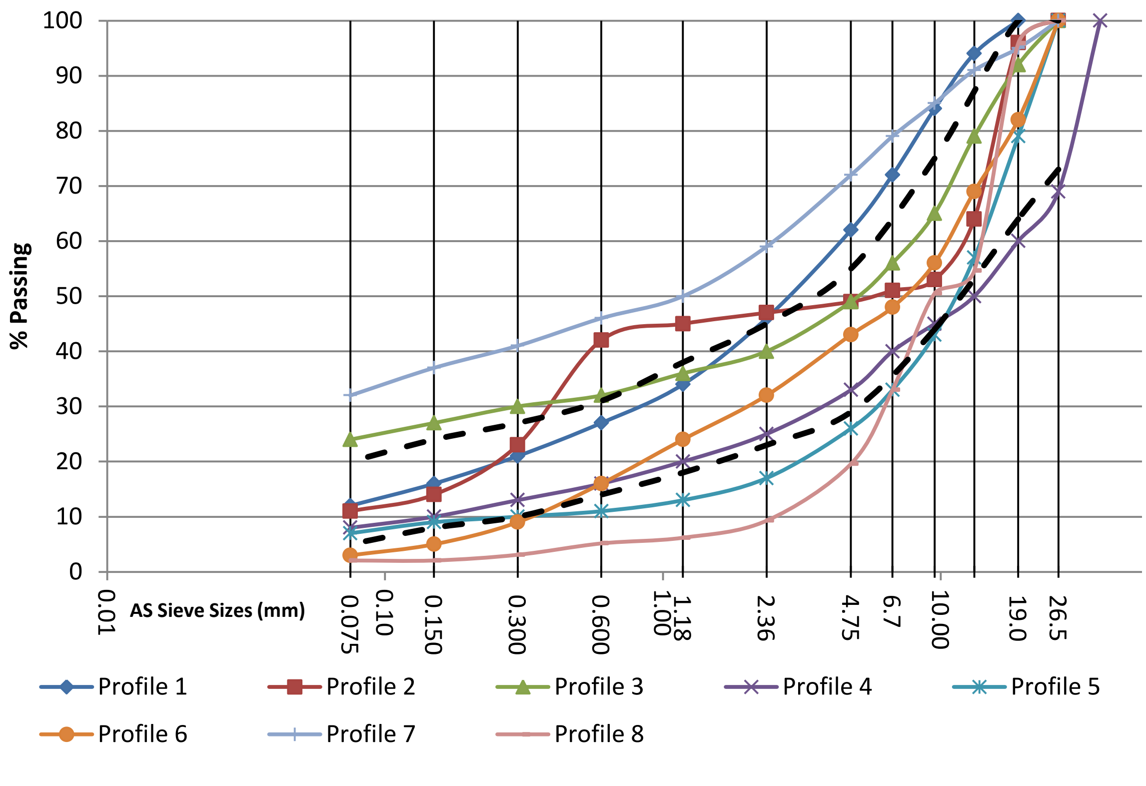

Figure 5-6: Marginal materials by Particle Size Distribution

Materials where the grading goes above and to the left the grading envelope are too fine.

Sample ID	Bitumen Content	Lime Content	Dry Cured Modulus (MPa)	Wet Cure Modulus (MPa)
Mackay 4	3.5%	2.0%	5385	2016
	4.5%	2.0%	4525	2090
Southern Queensland 1	3.5%	1.5%	8413	6479
Sydney 1	3.5%	1.5%	2389	1561
Bega 3	3.5%	1.5%	5867	3254
Bega 4	3.5%	1.5%	4089	2275
Victoria 3	3.5%	1.5%	3164	1738
Victoria 6	3.0%	1.5%	4469	3525
Victoria 7	3.0%	1.5%	5631	4063
Victoria 8	3.5%	1.5%	5657	4553

Table 5-4: Material for Grading Profile 1

Material like Grading Profile 1, are deficient in coarse and medium gravel sizes, material greater than 4.75mm; this material will not benefit from the mechanical interlock of the coarse aggregate. Most of the materials tested achieved sufficient resilient modulus to for a high traffic road (>1000 ESA/day). These samples are mostly silty or sandy gravels, where there is and excess amount of material in the sandy or silty sizes. While the results for the testing conducted on the sample Sydney 1 indicate will not produce a pavement suitable to carry low traffic counts (<100 ESA/day). This sample contained a high percentage of R.A.P. and is further explored in section 5.6.3.1.

In profile 2 the material has an excess amount of medium/fine gravel to coarse sand sizes, material sized from 4.75mm to 600µm size; this type of material is gap graded in one size in this range. Most of the samples tested have resilient modulus results to indicate a satisfactory pavement can be produced. A number of the samples have high dry modulus and low wet modulus results. This indicates that the pavement materials are susceptible to loss of strength resulting from the ingress of moisture. Most of the samples consisted of silty or sandy gravels, and being gap or poorly graded had the potential to have an increased amount of voids for the moisture to get in. The samples Victoria 1 & 2 had high quantities of sandstone and will be discussed in section later in section 5.6.3.2 .

Sample ID	Bitumen Content	Lime Content	Dry Cured Modulus (MPa)	Wet Cure Modulus (MPa)
Mackay 4	3.5%	2.0%	5385	4525
	4.5%	2.0%	2016	2090
Sunshine Coast 12	3.0%	2.0%	1490	1417
Sunshine Coast 13	3.0%	2.0%	4367	1300
Byron Regional Council	3.0%	2.0%	4014	1890
Parkes 2	3.5%	1.5%	5270	1388
Parkes 3	3.5%	1.5%	4153	2676
Parkes 4	3.5%	1.5%	5647	3446
Parkes 5	3.5%	1.5%	4326	1489
Parkes 6	3.5%	1.5%	7030	3882
Bathurst 1	3.5%	1.5%	2749	1381
Bathurst 5	3.5%	1.5%	5847	3730
Bega 5	3.5%	1.5%	4524	2835
ACT 2	3.5%	2.0%	7604	7044
Victoria 1	3.0%	1.5%	5629	301
Victoria 2	3.5%	1.5%	5715	718

Table 5-5: Material for Grading Profile 2

In profile 3 the material has excess silty or clay materials. This material will require more bitumen to coat all the fine material. The sample Mackay 3 consisted of silty gravel and the fine end of the grading is on the upper grading limit. Increases in the bitumen content indicate some improvement, however the bitumen content required to improve the material may make the process too expensive to be a viable option.

Sample ID	Bitumen Content	Lime Content	Dry Cured Modulus (MPa)	Wet Cure Modulus (MPa)
Mackay 3	3.5%	2.0%	2955	1088
	4.0%	2.0%	2792	1141

Table 5-6: Material for Grading Profile 3

On the underside of the grading envelope the grading profiles are too coarse in size. Material in profile 4, tend to be very bony, with an excess amount of coarse gravel. No samples were tested with this grading.

Profile 5 is material where there is an excess in the medium and coarse gravel size and deficiency in the sand and silt sizes. While there may be sufficient material passing the

75µm size to indicate a successful foam bitumen mix there may not be sufficient material in the fractions above to bind the material properly. The sample Bega 4 was a material which had been previously stabilised and this may account for the high modulus results.

Sample ID	Bitumen Content	Lime Content	Dry Cured Modulus (MPa)	Wet Cure Modulus (MPa)
Bega 1	3.5%	1.5%	3984	2932

Table 5-7: Material for Grading Profile 5

Profile 6 is material with insufficient fine material especially the passing 75µm. Material like this will, when mixed with foam bitumen, most probably result in bitumen stringers or dags and lumps of bitumen encrusted in coarse aggregate; to prevent this reduced bitumen contents may be required. This material will benefit from bending in another material with fine material prior to stabilisation. While the samples Sydney 5 & 6 and Victoria 4 & 5 both have insufficient material finer than 75µm to be considered for treatment with foamed bitumen the modulus results were satisfactory to produce pavements for moderate to high traffic counts. This may be the result of the samples 'Sydney 5' and 'Sydney 6' being previously stabilised, (see section 5.6.3.3.1) and in the case of the Victoria samples, sufficient material finer than 4.75mm to improve the material.

Sample ID	Bitumen Content	Lime Content	Cement Content	Dry Cured Modulus (MPa)	Wet Cure Modulus (MPa)
Whitsunday Coast 3	2.0%	0.0%	1.0%	1689	1140
	3.0%	0.0%	1.0%	1648	1117
	4.0%	0.0%	1.0%	1420	1008
Sydney 5	3.5%	2.5%	0.0%	3762	2759
Sydney 6	3.5%	2.5%	0.0%	3892	3314
Victoria 4	3.0%	1.5%	0.0%	5427	2842
Victoria 5	3.0%	1.5%	0.0%	7194	4995

Table 5-8: Material for Grading Profile 6

Profile 7 consists of materials which are deficient in the coarse fractions and have an excess amount of fine fractions. These materials are generally too fine and tend to have high clay and silt contents and are more likely to be gravelly clays. An example of this type of material is 'Mackay 5'.

Sample ID	Bitumen Content	Lime Content	Dry Cured Modulus (MPa)	Wet Cure Modulus (MPa)
Mackay 5	3.5%	2.0%	4624	892
	4.5%	2.0%	4028	1107

Table 5-9: Material for Grading Profile 7

This material had a high dry modulus and a very low wet modulus. This shows the materials highly sensitive to loss of strength due to moisture, this is probably due to the excess amount of fine material. The effect of moisture is reduced with increased bitumen however the dry modulus is seen to decrease more rapidly. While higher bitumen content may improve the wet modulus, higher bitumen content may result in making the treatment too expensive to be serviceable.

Sample ID	Bitumen Content	Lime Content	Dry Cured Modulus (MPa)	Wet Cure Modulus (MPa)
Mackay 2	2.0%	2.0%	3191	2270

Table 5-10: Grading Profile 8 Material

Grading Profile 8 is representative of a material which is deficient in fine material and considered to be "bony". This material poorly graded containing and excess amount of coarse material. 'Mackay 2' is a material fitting this profile. The stabilised material indicated it may make a suitable pavement and may be suitable for traffic loading of up to 1000 ESA's/day.

5.6.3 Marginal Material by Material Quality

Most specifications identify a number of material qualities as indications on marginal or unsuitable materials. Excessive bitumen in the pavement material, materials prone to breakdown and previously stabilised materials are all seen as being undesirable.

5.6.3.1 Recycled Asphalt Pavement (RAP) Blend

Sample: Sydney 1

The sample 'Sydney 1' was a good example of a material with a high percentage of RAP, with the sample containing a blend 55% RAP. The modulus for this material was poor with the cured modulus not making the minimum requirement for a road with less than 100 ESA's /day while the soaked and the retained were satisfactory for this category of traffic.

In the sample 'Sydney 1' the pavement material contained 55% Recycled asphaltic pavement and 45% crusher dust. This material blend was tested with 3.0% bitumen and 2% lime. A summary of the results of the modulus testing is shown in Table 5-11.

Sample ID	'Dry' Cured Modulus (MPa)	'Wet' Cured Modulus (MPa)	Retained Modulus Ratio (%)
Sydney 1	2389	1561	65%

Table 5-11: Summary of "Sydney 1" Modulus Testing

This shows that the pavement may have too much total bitumen in the mix. The bitumen content of the RAP has an effect of the bitumen content of the stabilised material. This sample has a low dry cured modulus and a relatively high wet cured modulus as indicated by the retained modulus ratio. This may suggest that the bitumen is causing some lubrication of the particles allowing movement in the pavement material, while decreasing the susceptibility of the material to moisture.

Sample: ACT 1 & ACT 2

The samples 'ACT 1' and 'ACT 2' both had a low percentage of RAP in the blend; the sample consisted of a blend on 93% existing pavement and 7% RAP. These modulus results exceeded the minimum design requirements of a road to carry more than 1000 ESA'a/day in the year of opening.

Sample ID	'Dry' Cured Modulus (MPa)	'Wet' Cured Modulus (MPa)	Retained Modulus Ratio (%)
ACT 1	8357	5861	70%
ACT 2	7604	7044	93%

Table 5-12: Summary of Modulus testing for "ACT 1" and "ACT 2"

The ACT samples had considerable less RAP blended into the material than the Sydney sample. This suggests that increasing percentage of RAP blended into pavement material results in a decrease in the resilient modulus of the test specimens. There may be an optimum percentage of RAP which can be blended in to the pavement material before the modulus of the test specimens is effected, this may be an area for consideration for future study.

5.6.3.2 Material Prone to Breakdown during Compaction

Sample: Victoria 1 & Victoria 2

In samples Victoria 1 & 2, the pavement consisted of 60% sandstone and 40% 20mm aggregate. The blended material was tested with 3.0 and 3.5% bitumen and 1.5% lime. A summary of the results of the modulus testing is shown in

Sample ID	'Dry' Cured Modulus (MPa)	'Wet' Cured Modulus (MPa)	Retained Modulus Ratio (%)
Victoria 1	5629	301	5%
Victoria 2	5715	718	13%

Table 5-13: Summary of Modulus testing for "Victoria 1" and "Victoria 2"

Both of the these samples show a high dry cured modulus indicating that there is the material has good dry strength while the wet strength is very low which suggests that the bulk of the material in the pavement has a relatively low wet strength of the pavement will be prone to breakdown with increased moisture.

5.6.3.3 Previously Stabilised Materials

5.6.3.3.1 Pavements previously treated with cementitious binders

Previously stabilised materials are considered unsuitable for foamed bitumen stabilisation. This is because pavement materials previously treated by cementitious stabilisation have a tendency not to produce many fines. This is due to the binder cementing the fine particles together and the pavement shattering during milling which does not produce fine material. Another problem that occurs is that the particles produced are not likely be to be discreet particles but cemented conglomerations of coarse medium and fine sizes. These particles may be prone to breakdown during stabilisation, compaction and or service. As these particles breakdown they will produce fine material which will in turn make for weak treated pockets in the pavement which may result in the pavement blowing out or washing out.

Sample: Sydney 6 & Sydney 7

The samples taken from the locations 'Sydney 6' and 'Sydney 7' contained examples of heavy bound pavement which, when prepared for testing, still had very high strength bound aggregation and as such most of the fine particles were still bound together. From the particle size distributions of these samples it can be seen that both of these materials have 4% less than 75µm size and 30% and 26% respectively less than 4.25mm size. These aggregations, at the time of testing, were not prone to breakdown and with the previous cementitious stabilisation and the foamed bitumen restricting the ingress of moisture the material was able to retain a higher wet cured modulus. The modulus results for these materials would indicate design traffic of 100-1000 ESA/day

Sample ID	'Dry' Cured Modulus (MPa)	'Wet' Cured Modulus (MPa)	Retained Modulus Ratio (%)
Sydney 5	3762	2754	73%
Sydney 6	3892	3314	85%

Table 5-14: Summary of Modulus testing for "Sydney 5" and "Sydney 6"

Sample: Bega 4, Bega 5 & Bega 6

The samples 'Bega 4' and 'Bega 5' both show results suitable for design traffic of greater than 1000 ESA/day. More fines were present in these materials with 11% and 12% materials less than 75µm size and 77% and 78% less than 4.75mm respectively. These samples have shown some potential for breakdown during milling, producing enough fine material for successful foamed bitumen stabilisation. The retained modulus ratio of 'Bega 4' and 'Bega 5' were not as high as that of 'Sydney 5' and 'Sydney 6', but the dry strength was higher indicating that 'Bega 4' and 'Bega 5' were more susceptible to the effects of moisture

The results for 'Bega 6' show a pavement suited to less than 100 ESA/day. This material had more coarse material produced during milling and similar percentages of material finer than 75µm as 'Bega 4' and 'Bega 5' and less material finer than 4.75mm. The dry modulus is considerably lower than 'Bega 4' and 'Bega 5' and the wet modulus is similar to 'Bega 4'. This indicates that some breakdown of the coarse particles may have occurred during compaction resulting in the lower dry modulus.

Sample ID	'Dry' Cured Modulus (MPa)	'Wet' Cured Modulus (MPa)	Retained Modulus Ratio (%)
Bega 4	4089	2275	56%
Bega 5	4524	2835	63%
Bega 6	2849	2162	76%

Table 5-15: Summary of Modulus testing for "Bega 4", "Bega 5" and "Bega 6"

Sample: Tamworth

The particle size distribution for the 'Tamworth' sample is within the ideal grading envelope, this suggests that this material should be suited to foamed bitumen stabilisation. The materials description indicating that the material has been previously stabilised indicates that it is not suited to foamed bitumen stabilisation. The modulus results indicate that the pavement material should not be used for foamed bitumen stabilisation. This results for this sample show that some of the coarse particles may be breaking down during compaction leaving pockets of unstabilised material.

Sample ID	'Dry' Cured Modulus (MPa)	'Wet' Cured Modulus (MPa)	Retained Modulus Ratio (%)
Tamworth	2147	1058	49%

Table 5-16: Summary of Modulus testing for "Tamworth"

5.6.3.3.2 Pavements Previously Treated with Polyroad

Polyroad is a polymer based stabilising agent which preserves the dry strength of the pavement material. Polyroad works by having an insoluble polymer coating an inert carrier which coats the particles in the pavement material, Polyroad also uses lime to cause clay particles to flocculate aiding the coating process.

Sample: Bega 1 & Bega 2

The sample 'Bega 1' and 'Bega 2' are samples which were previously treated with a Polyroad stabilising agent. The test specimens for these locations performed quite well. Both samples achieved the minimum wet cured requirements for a road to carry more than 1000 ESA's/day in the year of opening. The 'Bega 1' sample was only just low of this minimum dry cured requirement for while the Bega 2 sample achieved the minimum requirement. The retained modulus for these samples was 74% and 55% respectively; this indicated that the 'Bega 1' sample has potentially received greater residual benefits from the previous application of the Polyroad product.

Sample ID	'Dry' Cured Modulus (MPa)	'Wet' Cured Modulus (MPa)	Retained Modulus Ratio (%)
Bega 1	3984	2932	74%
Bega 2	5867	3254	55%

Table 5-17: Summary of Modulus testing for "Bega 1" and "Bega 2"

Road pavements previously treated with Polyroad may have some residual effects of the treatment. Polyroad preserves the strength of the pavement material by waterproofing the particles. Waterproofing the fine particles of the pavement material is a secondary effect of the foam bitumen process. As a result pavements previously treated by Polyroad may have wet cured modulus much higher than usual for the bitumen content.

6 Conclusions

In the process of conducting this project, I have assessed materials from a number of locations across Eastern Australia through Queensland, New South Wales and Victoria. Materials were tested to determine their properties prior to stabilisation and the resilient modulus of the post stabilised material. The material properties tested prior to stabilisation were particle size distribution and plasticity. Via visual assessment the material description and quality was ascertained to assist in categorising the pavement material. The materials were subjected to foamed bitumen stabilisation and tested for the resulting resilient modulus after a period of dry curing and then retested after wet curing. From this, data was assessed to determine the effects of the particle size distribution, percentage of bitumen and material quality on the modulus and how the service life of the resultant pavement may be affected.

When examining the pavement materials, it was found, that the particle size distribution had an influence on the post stabilised materials. Due to the complexity of the particle size distributions the percentage of material finer than 75µm and 4.75mm were used when determining the influence of the particle size distribution on the resilient modulus and bitumen content of the stabilised pavement. The resilient modulus of the stabilised materials was initially found to increase as the percentage of material finer than 75µm increased, for a given bitumen content. This continued till a maximum modulus was achieved, after this point increasing amounts of material finer than 75µm results in decreasing modulus, as the amount of fine material exceeds the point where the bitumen can satisfactorily bind the particles in the pavement. When examining the effect of the percentage of material finer than 4.75mm, it was found that when the material had less than 50% finer than 4.75mm there was a higher peak modulus coinciding with a lower percentage of material finer than 75µm when compared to a material with more than 50% finer than 4.75mm. This demonstrates that there is an optimum percentage of material finer than 75µm the percentage of bitumen used in stabilisation process.

Similar results were obtained when different percentages of bitumen were used. When the bitumen content was increased while the optimum percentage of material finer than 75µm increased. The rate the resilient modulus increased and decreased was less severe, reducing the how sensitive the modulus is to changes in the particle size distribution. This indicates that there is an optimum percentage of material finer than 75µm for each different percentage of bitumen used. The amount of bitumen used in the foamed bitumen stabilisation process was found to affect the service life of the pavement. As the modulus of the pavement increases so does the service life of the pavement. When the bitumen content is increased, the service life increases more rapidly with smaller increments in the resilient modulus.

The effect of the roadbase material quality was assessed with mixed results. Roadbase materials where the particle size distribution was marginal or non-compliant with respect to the Austroads preferred limits indicated that the main contributing factor was the percentage of material finer than 75µm and 4.75mm. The resilient modulus of pavements with very low percentages (less than 5% finer than 75µm) of fine material required small quantities of foamed bitumen and are very sensitive to fluctuations in the amount of bitumen used. While pavements, with high to very high percentages (more than 20% finer than 75µm) of fine material, require high quantities of foamed bitumen and the resilient modulus is less sensitive to small variations in the amount of bitumen added. These materials do not have a tendency to to achieve the prescribed modulus limits. Blending with other materials to improve the particle size distribution may be required for successful foamed bitumen stabilisation. Pavements where the percentage of material finer than 4.75mm is satisfactory yet the coarse fractions are marginal or non-compliant, the modulus has the tendency to be satisfactory however foamed bitumen mix testing to confirm the materials suitability still be conducted on a case by case basis.

Roadbase materials which were considered marginal because of material quality were tested. The testing included materials containing Recycled Asphaltic Pavement (RAP), materials likely to breakdown during compaction, and material from previously stabilised pavements. When a high proportion of RAP was blended into the pavement material it was found to be detrimental to the resilient modulus of the stabilised pavement. However, small quantities of RAP in the pavement material had little effect on the modulus of the pavement. Further testing is needed to determine the upper limiting content of RAP which can be blended into a pavement material for foamed bitumen stabilisation.

Pavements containing material prone to breakdown were tested, these pavement typically contained sandstone. When a material is mixed with the foamed bitumen the fine particles are coated with the bitumen. With these materials, during compaction some of the larger particles and aggregations may breakdown, producing more fine material. This newly produced fine material has had little or no exposure to the foamed bitumen so pockets of untreated material form. Testing on these samples showed high dry cured resilient modulus while the wet cured resilient modulus was very low showing high sensitivity to moisture. This indicates that while dry these pockets of untreated materials can maintain some strength however when wet these untreated particles are allowed to slide over each other resulting in a lower resilient modulus. From this it should be recommended that roadbase materials prone to break down during compaction are unsuitable for foamed bitumen stabilisation.

The suitability for, foamed bitumen stabilisation, of pavement materials that were previously stabilised was inconclusive. Pavements which were previously stabilised using cementitious binders cement the particles together. When the pavement is milled a reduced amount of fine material may be produced as the cemented pavement tends to shatter and the fine particles remain bound together. Some previously stabilised pavement material, due to fatigue or loss of strength, may breaks down during compaction. As a result the material will not be suitable for foamed bitumen stabilisation. If enough fine materials is produced and the previously stabilised material has a high residual strength it may prove satisfactory. Pavements previously treated with products like PolyRoad may have a higher retained modulus ratio than the material would normally have. This is due to the PolyRoad product waterproofing the material. If the previous PolyRoad treatment is still serviceable in the pavement it may help increase the wet cured modulus of an otherwise unsuitable material.

When looking at the service life of a foamed bitumen stabilised pavement with respect to the particle size distribution, similar trends were found. Maximum service life coincided with the optimum percentage of material finer than 75µm for maximum modulus and the service life dropped off on either side of this point. The service life of the pavement was found to be very sensitive to increases in the amount of material finer than 75µm and the percentage of bitumen used in the pavement. As a result of this sensitivity care must be taken to ensure accuracy in the delivery and the quantity of bitumen added to stabilise the pavement. Accuracy in sampling and testing is also important as variations in the particle size distribution can result in significant differences in strength and service life impacting on the design of the pavement.

In conclusion, particle size distribution and bitumen content does have a significant effect on a foamed bitumen stabilised roadbase material, influencing both the modulus and service life of the resulting pavement. Some marginal materials may be used in foamed bitumen stabilisation. Materials with insufficient or excess fine materials typically will not be suited. Where the quality of the material is poor, the material again may not be suited. Where material quality is in question testing should be conducted to determine if the material can be used.

7 Further Research

From this study, a number of areas of further exploration can be identified.

- The sensitivity of the modulus of foamed bitumen stabilised roadbase materials to changes in the particle size distribution can be a critical issue for foamed bitumen stabilisation pavement design. From this, examination of the effects of different field sampling methods for collecting laboratory test samples and heavy plant used in pavement stabilisation on the particle size distribution of a road pavement material.

- Blending RAP into a pavement to improve it for foamed bitumen stabilisation may become an environmentally beneficial way to dispose of a waste product resulting from road pavement rehabilitation and remediation. This study has indicated that the ratio of RAP to roadbase material may have an influence on the resulting pavement. Assessment of the quantity of RAP which can be blended into a roadbase pavement for to produce serviceable foamed bitumen stabilised pavements.

- The briquettes for this work was conducted using Marshall hammer, an alternate method of compaction is using a servopac gyratory compactor. These compaction methods compact the material in completely different way, and the method of compaction for the foamed bitumen specimens may have an effect on the modulus. How do these compaction methods affect the modulus and how will the compaction method affect the pavement design. This is issue is currently up for debate in the industry.

- Another area for further research could be focused around the debate of whether foamed bitumen stabilisation should be treated as asphalt. The void content of asphalt is critical in the design of an asphalt pavement. Does the void content of a foamed bitumen stabilised pavement affect the resilient modulus and serviceability of the pavement.

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Appendix A. Project Specification

PROJECT SPECIFICATION

FOR:	Adam O'Callaghan (0050049644)
TOPIC:	AN ANALYSIS OF ROAD PAVEMENT MATERIALS USED IN FOAMED BITUMEN STABILISATION
SUPERVISORS:	Soma Somasundaraswaran Peter Sheen, Coffey Pty. Ltd.
PROJECT AIMS:	This project seeks to examine the material properties of road base materials used in foamed bitumen stabilisation and the effect on the pavements strength and serviceability
SPONSORSHIP:	Coffey Pty. Ltd.

PROGRAM:

1. Research the,
   a. background of foamed bitumen stabilisation,
   b. ideal material properties,
   c. design requirements for foamed bitumen stabilisation.

2. Analysis the properties of materials used in foamed bitumen stabilisation from sites in New South Wales, Queensland and Victoria.

3. Evaluate the influence of material properties on pavement strength and expected design life in ESAs

4. Analyse the effects of changes in the material properties of road base materials on resilient modulus through laboratory testing.

5. Analysis the effect of bitumen content in marginal road base materials used in foamed bitumen.

If Time Permits

6. Evaluate the effects of air voids on pavement strength

7. The influence of varying the bitumen content on air voids and pavement strength.

<u>Note: A Preliminary plan for material testing (proposed by the student)</u>

Elements of this project will involve a variety of laboratory testing. I will need to learn and perform a number of standard and specialised test methods. Some of the specialised testing equipment I will need to use including a Wirtgen WLB10 laboratory scale foamed bitumen plant, located at the Coffey materials testing laboratory in Concord West NSW, and MATTA testing equipment at the RMS laboratory in Bellambi NSW. I have access, through my employer, to all the laboratory testing equipment I may require. I have been in contact with trained and experienced technicians who are willing to guide me through the testing I will need to perform.

Appendix B. Test Data

B.1. Test Data Location: Northern Queensland

Sample ID		Townsville	Mackay 1			Mackay 2	Mackay 3	
Material Description		Existing Roadbase Gravel	Existing Roadbase Gravel			Existing Roadbase Gravel	Existing Roadbase Gravel	
% Material Passing AS Sieve Size (mm)	26.5	100	100			100	100	
	19.0	90	91			96	98	
	13.2	78	77			55	81	
	9.5	68	63			51	72	
	6.7	58	53			33	63	
	4.75	49	46			20	54	
	2.36	35	37			9	40	
	1.18	26	31			6	32	
	0.600	20	24			5	29	
	0.300	15	19			3	27	
	0.150	12	14			2	24	
	0.075	10	10			2	20	
Binders								
Bitumen		3.5%	3.5%	3.5%	3.5%	3.0%	3.0%	3.0%
Hyd. Lime		2.0%	1.5%	1.5%	1.5%	2.0%	2.0%	2.0%
Resilient Modulus (MPa)								
		7020	10755	9050	6365	3421	3409	2820
		6630	10241	9206	6729	3511	2970	3041
		7466	11053	9480	5427	2640	2485	2514
Dry Cured		7039	10683	9245	6174	3191	2955	2792
		4819	8761	7185	4500	2279	1195	963
		4100	8727	7452	4625	2569	1232	1335
		4811	7987	6274	3854	1963	837	1125
Wet Cured		4577	8492	6970	4326	2270	1088	1141
Retained Modulus Ratio		65%	79%	75%	70%	71%	37%	41%

Table B-1: Northern Queensland roadbase test data Table (A)

Sample ID		Mackay 4		Mackay 5		Mackay 6	
Material Description		Existing Roadbase Gravel		Existing Roadbase Gravel		Existing Roadbase Gravel	
% Material Passing AS Sieve Size (mm)	26.5	100		100		100	
	19.0	98		95		87	
	13.2	92		91		71	
	9.5	85		85		60	
	6.7	76		79		54	
	4.75	63		72		49	
	2.36	42		59		40	
	1.18	31		50		32	
	0.600	27		46		25	
	0.300	24		41		19	
	0.150	21		37		15	
	0.075	16		32		11	
Binders							
Bitumen		3.5%	4.5%	3.5%	4.5%	3.5%	4.0%
Hyd. Lime		2.0%	2.0%	2.0%	2.0%	2.0%	2.0%
Resilient Modulus (MPa)							
		5439	4690	4657	4209	--	3963
		5234	4135	4427	3770	6256	3462
		5482	4750	4789	4106	4744	3916
Dry Cured		5385	4525	4624	4028	5500	3780
		2231	1963	1025	1208	--	2319
		2039	2088	855	1033	4936	2367
		1777	2219	796	1079	3274	2661
Wet Cured		2016	2090	892	1107	4105	2449
Retained Modulus Ratio		37%	46%	19%	27%	75%	65%

Table B-2: Northern Queensland roadbase test data Table (B)

Sample ID		Mackay 7		Mackay 8		Mackay 9	
Material Description		Existing Roadbase Gravel		20mm Roadbase Gravel		Existing Roadbase Gravel	
% Material Passing AS Sieve Size (mm)	26.5	100		100		100	
	19.0	96		95		83	
	13.2	81		83		73	
	9.5	70		71		64	
	6.7	60		61		56	
	4.75	51		53		49	
	2.36	37		38		38	
	1.18	27		29		30	
	0.600	21		23		23	
	0.300	17		18		17	
	0.150	14		14		13	
	0.075	9		11		10	
Binders							
Bitumen		3.5%	4.5%	3.5%	4.0%	3.5%	4.5%
Hyd. Lime		2.0%	2.0%	2.0%	2.0%	2.0%	2.0%
Resilient Modulus (MPa)							
		7512	5631	5898	4586	3292	3316
		7315	4093	5804	5125	3419	4290
		6552	7045	3915	3305	3932	3081
Dry Cured		7126	5590	5206	4339	3548	3562
		5186	4832	4222	3161	1042	2108
		5859	3178	3769	3211	1093	2102
		6037	5851	2923	1692	2108	3687
Wet Cured		5694	4620	3638	2688	1414	2632
Retained Modulus Ratio		80%	83%	70%	62%	40%	74%

Table B-3: Northern Queensland roadbase test data Table (C)

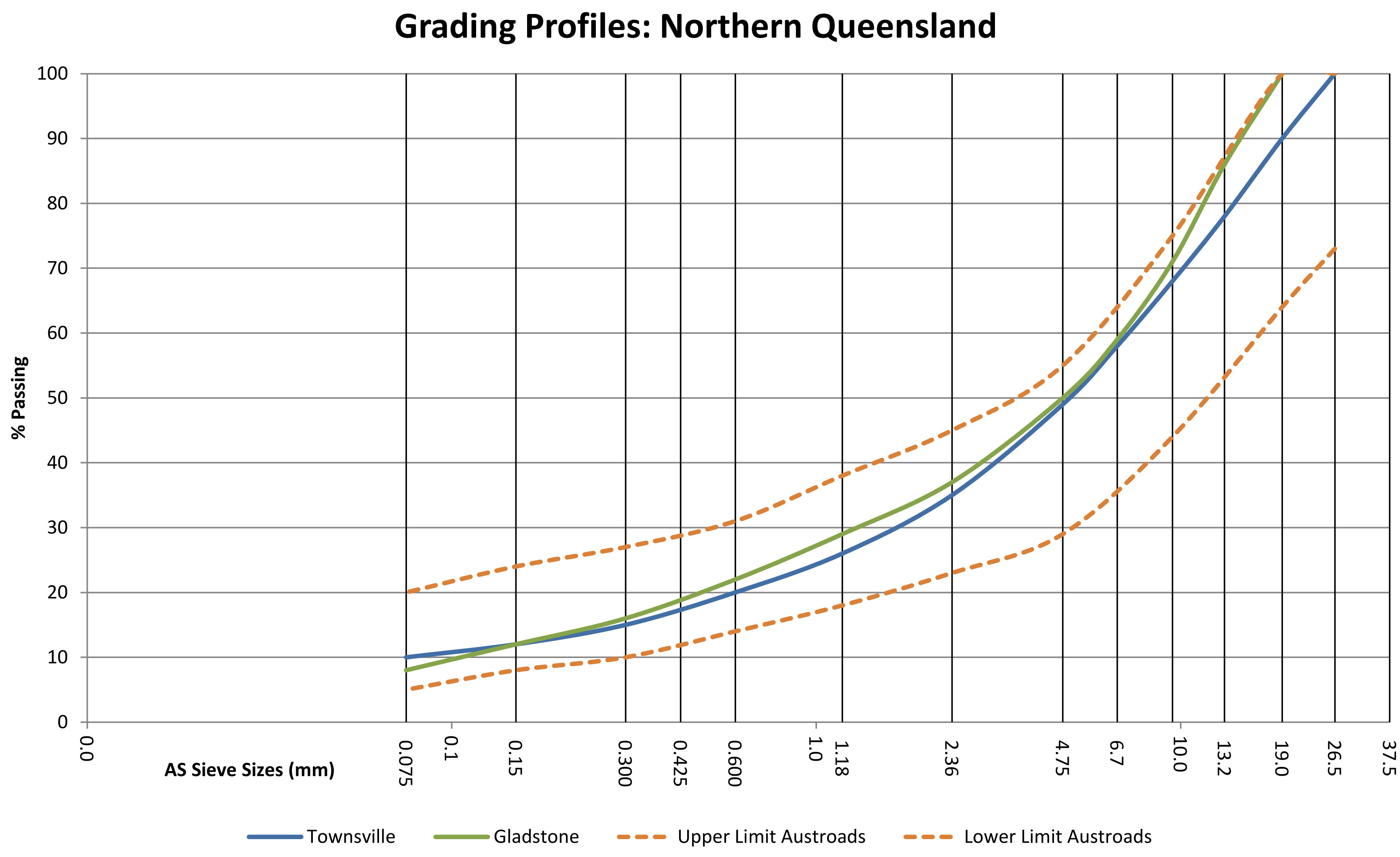

Figure B-1: North Queensland grading profiles - Townsville and Gladstone

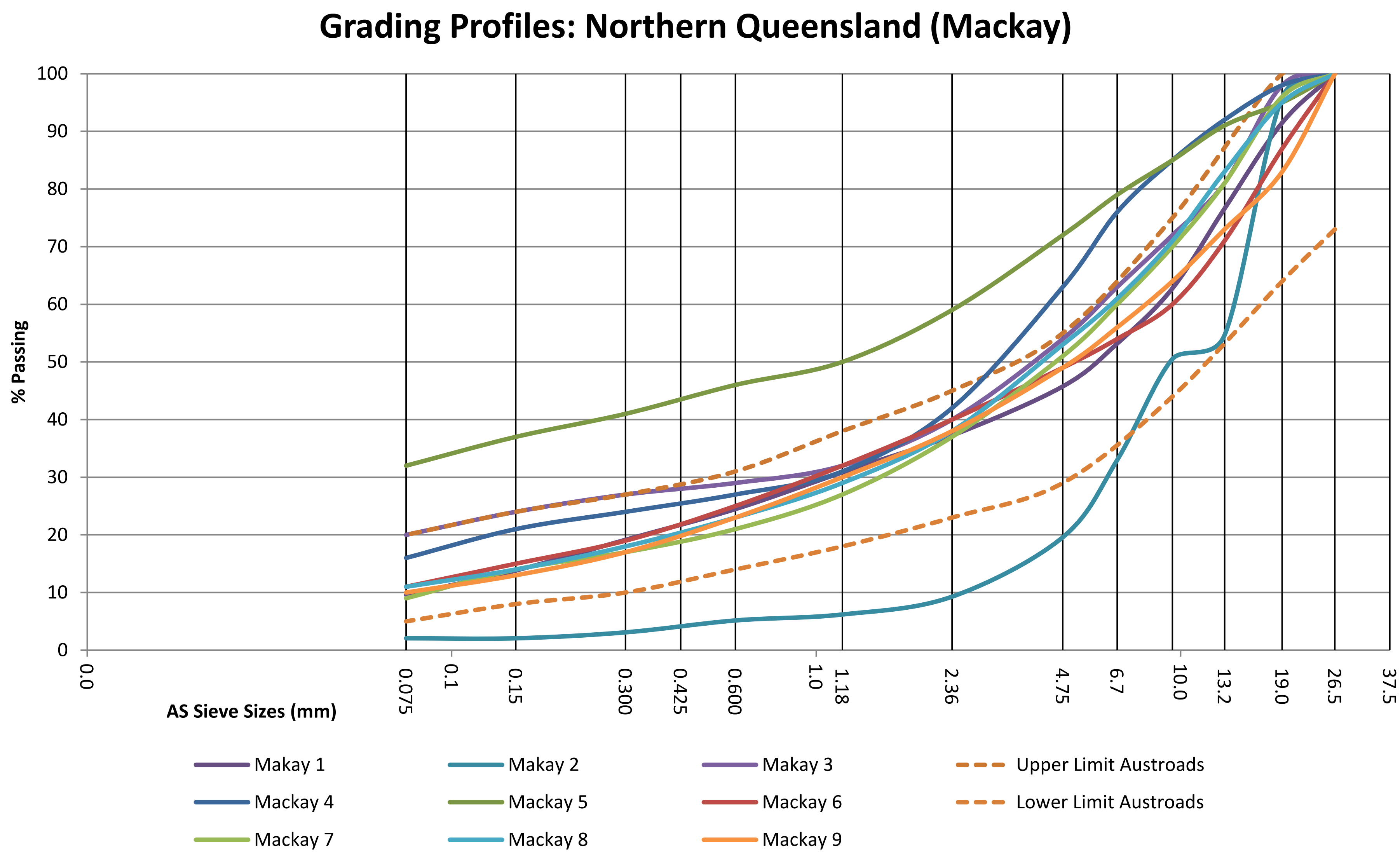

Figure B-2: North Queensland grading profiles - Mackay

B.2. Northern Queensland (Whitsunday Coast)

Sample ID		Whitsunday Coast 1				Whitsunday Coast 2		
Material Description		Existing AC & Roadbase				Existing AC & Roadbase		
% Material Passing AS Sieve Size (mm)	26.5	100				100		
	19.0	98				98		
	13.2	83				84		
	9.5	68				70		
	6.7	55				58		
	4.75	46				49		
	2.36	33				35		
	1.18	23				26		
	0.600	15				18		
	0.300	10				13		
	0.150	7				9		
	0.075	6				7		
Binders								
Bitumen		2.0%	3.0%	4.0%	3.0%	2.0%	3.0%	4.0%
GP Cement		1.0%	1.0%	1.0%	0.0%	1.0%	1.0%	1.0%
Hyd. Lime		0.0%	0.0%	0.0%	1.0%	0.0%	0.0%	0.0%
Resilient Modulus (MPa)								
		2358	1621	1448	2193	3314	2047	897
		2093	1761	1196	1915	4156	1838	1231
		1997	1518	933	2463	3486	1695	920
Dry Cured		2149	1633	1192	2190	3652	1860	1016
		1475	1134	1217	1985	1545	969	1021
		1422	1214	853	1649	1912	923	931
		1300	1041	783	1916	1684	964	497
Wet Cured		1399	1130	951	1850	1714	952	816
Retained Modulus Ratio		65%	69%	80%	84%	47%	51%	80%

Table B-4: Northern Queensland (Whitsunday Coast) roadbase test data Table (A)

Sample ID		Whitsunday Coast 3			Whitsunday Coast 4		
Material Description		Existing AC & Roadbase			Existing AC & Roadbase		
% Material Passing AS Sieve Size (mm)	26.5	100			100		
	19.0	97			97		
	13.2	78			84		
	9.5	62			71		
	6.7	47			61		
	4.75	38			52		
	2.36	27			40		
	1.18	19			29		
	0.600	13			19		
	0.300	8			12		
	0.150	6			8		
	0.075	4			6		
Binders							
Bitumen		3.5%	3.5%	3.5%	3.5%	3.5%	3.5%
GP Cement		1.0%	1.0%	1.0%	1.0%	1.0%	1.0%
Resilient Modulus (MPa)							
		1832	1832	1637	1999	1687	1264
		1883	1453	1290	2297	1489	1419
		1353	1660	1332	1858	1625	1228
Dry Cured		1689	1648	1420	2051	1600	1304
		1200	1167	1246	1630	1038	967
		1324	949	796	1183	1009	1060
		896	1234	983	1450	1001	874
Wet Cured		1140	1117	1008	1421	1016	967
Retained Modulus Ratio		67%	68%	71%	69%	63%	74%

Table B-5: Northern Queensland (Whitsunday Coast) roadbase test data Table (B)

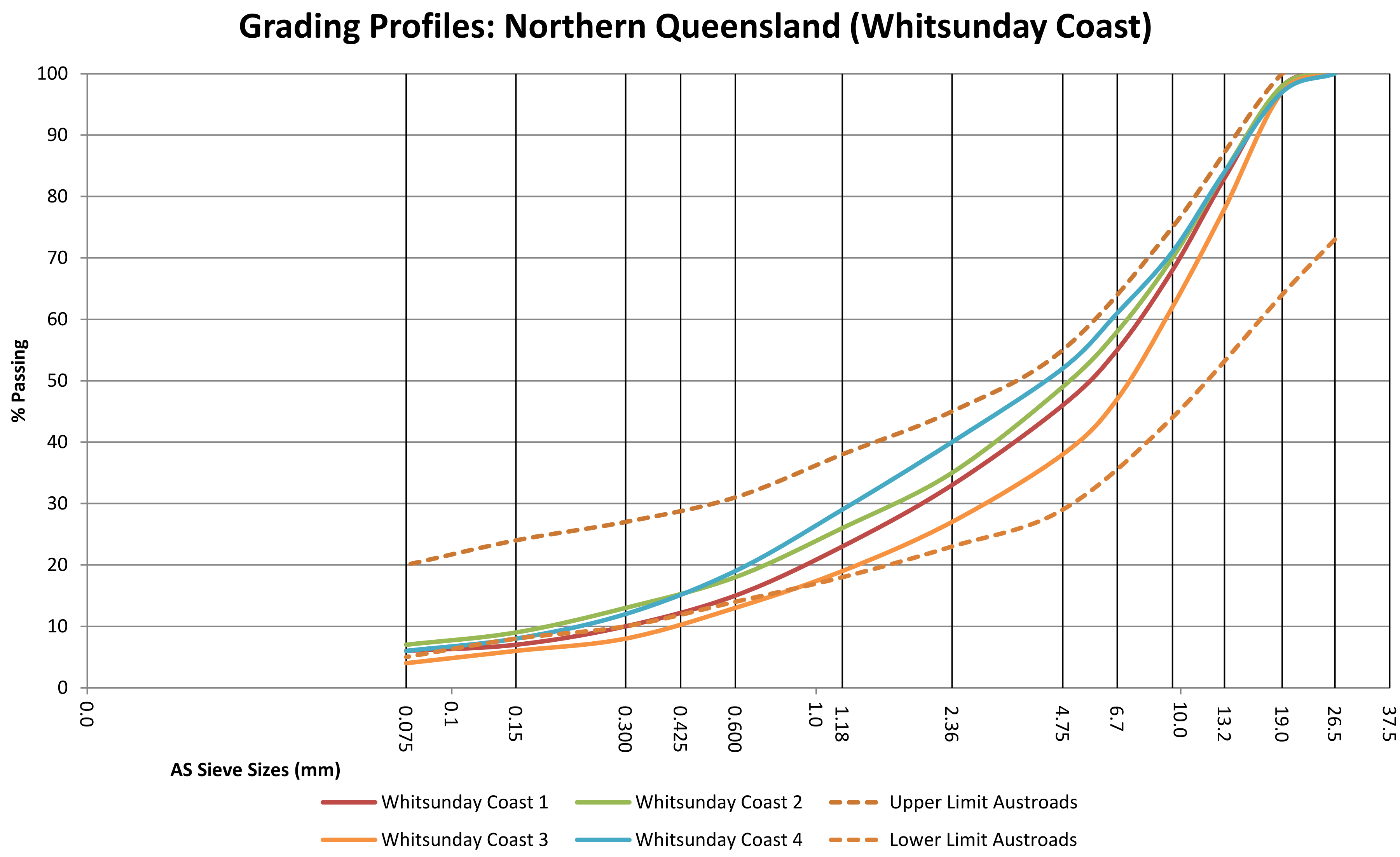

Figure B-3: North Queensland grading profiles - Whitsunday Coast

B.3. Sunshine Coast

Sample ID		Sunshine Coast 1	Sunshine Coast 2	Sunshine Coast 3	Sunshine Coast 4	Sunshine Coast 5	Sunshine Coast 6	Sunshine Coast 7
Material Description		Clayey gravel with Bitumen seal	Clayey gravel with Bitumen seal	Sandy Clayey gravel with Bitumen seal	Clayey Gravel with Bitumen Seal	Clayey Gravel with Bitumen Seal	Clayey Gravel with Bitumen Seal	Clayey Gravel with Bitumen Seal
% Material Passing AS Sieve Size (mm)	26.5	100	100	100	100	100	100	
	19.0	84	96	82	91	86	95	100
	13.2	70	81	65	79	68	81	89
	9.5	60	68	56	64	52	67	74
	6.7	52	57	47	52	39	56	61
	4.75	44	49	41	45	32	47	52
	2.36	34	37	30	34	23	34	39
	1.18	28	26	26	27	18	25	31
	0.600	24	20	21	22	14	18	25
	0.300	19	15	16	18	11	13	18
	0.150	13	12	12	14	7	10	13
	0.075	10	9	10	12	6	8	11
Binders								
Bitumen		3.5%	3.0%	3.5%	3.5%	3.5%	3.0%	3.5%
Hyd. Lime		1.5%	1.5%	1.5%	2.0%	2.0%	2.0%	1.5%
Resilient Modulus (MPa)								
		--	--	6367	6139	5992	4949	2642
		--	--	5602	7001	7114	4802	3481
		--	--	6103	6403	5960	4738	2993
Dry Cured		7339	5836	6024	6514	6355	4830	3039
		--	--	3749	4919	--	2031	1687
		--	--	3194	5583	--	2225	1669
		--	--	3310	5309	--	2528	1571
Wet Cured		5786	3372	3418	5270	3889	2261	1642
Retained Modulus Ratio		79%	58%	57%	81%	61%	47%	54%

Table B-6: Sunshine Coast roadbase test data (Table A)

Sample ID		Sunshine Coast 8	Sunshine Coast 9	Sunshine Coast 10	Sunshine Coast 11	Sunshine Coast 12	Sunshine Coast 13	Sunshine Coast 14
Material Description		Clayey Gravel with Bitumen Seal	Clayey gravel with some Bituminous seal	Clayey gravel with some Bituminous seal	Clayey Gravel with Bituminous seal	Existing Roadbase Gravel	Existing Roadbase Gravel	Roadbase Gravel
% Material Passing AS Sieve Size (mm)	26.5	100	100	100	100	100	100	100
	19.0	91	96	93	84	97	95	97
	13.2	79	81	79	72	85	84	86
	9.5	64	68	65	62	76	74	77
	6.7	53	57	51	51	71	66	63
	4.75	45	49	41	45	65	60	51
	2.36	33	37	30	36	50	47	38
	1.18	24	26	23	26	37	35	31
	0.600	17	20	19	21	27	26	25
	0.300	12	15	15	16	18	19	19
	0.150	9	12	11	13	13	12	12
	0.075	7	9	9	10	10	9	6
Binders								
Bitumen		3.5%	3.5%	3.5%	3.5%	3.0%	3.0%	3.0%
Hyd. Lime		2.0%	1.5%	1.5%	1.5%	2.0%	2.0%	2.0%
Resilient Modulus (MPa)								
		2453	5611	7338	9829	1050	4220	1510
		2795	6061	6930	4691	1860	4060	2311
		2876	--	7879	5116	1560	4820	2194
Dry Cured		2708	5836	7382	6545	1490	4367	2005
		1091	3742	5903	2492	520	4870	714
		1411	3001	5331	2092	1850	3770	1200
		1248	--	6322	2037	1880	4260	1049
Wet Cured		1250	3372	5852	2207	1417	4300	988
Retained Modulus Ratio		46%	58%	79%	34%	95%	98%	49%

Table B-7: Sunshine Coast roadbase test data Table B

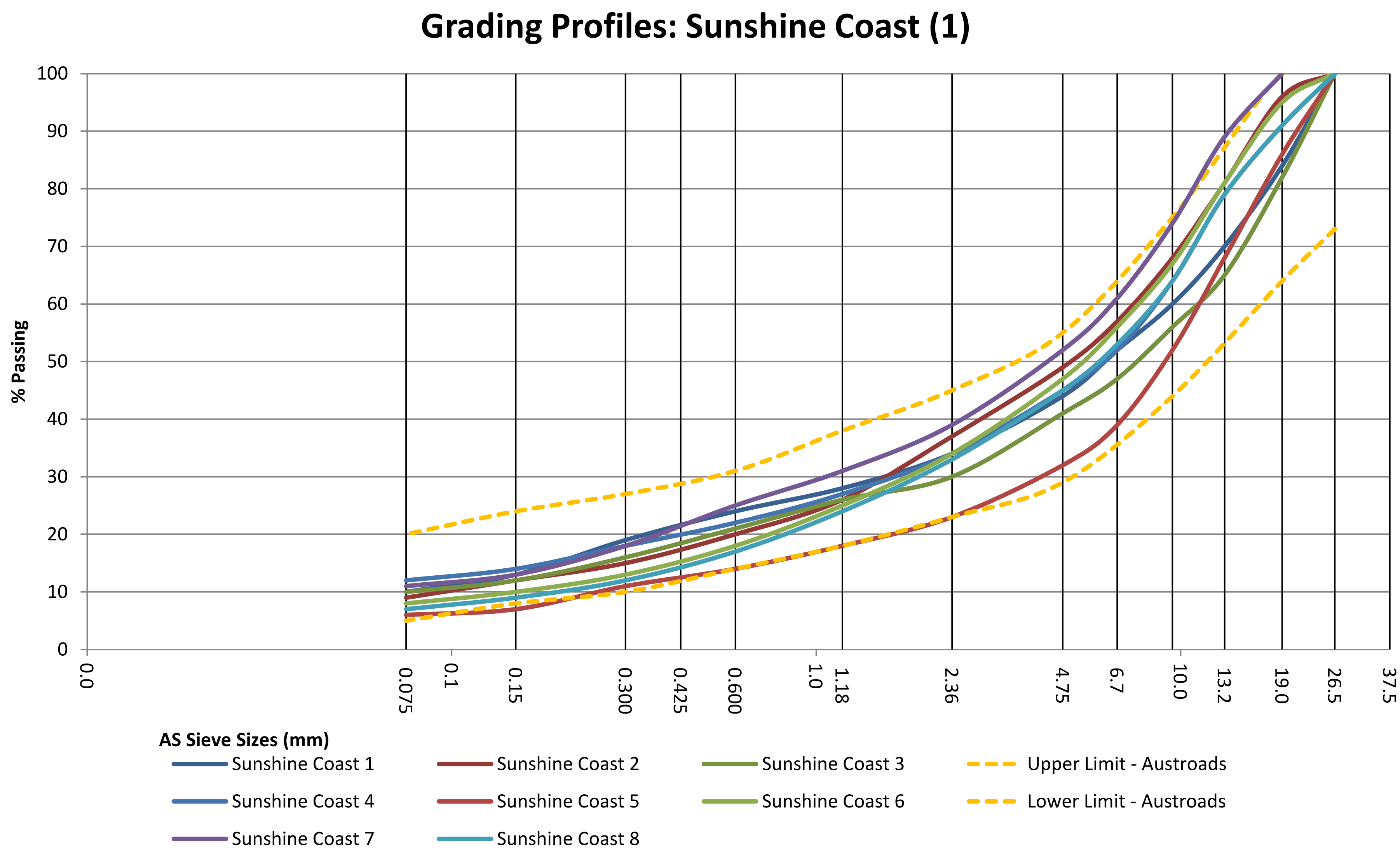

Figure B-4: Sunshine Coast grading profiles (1-8)

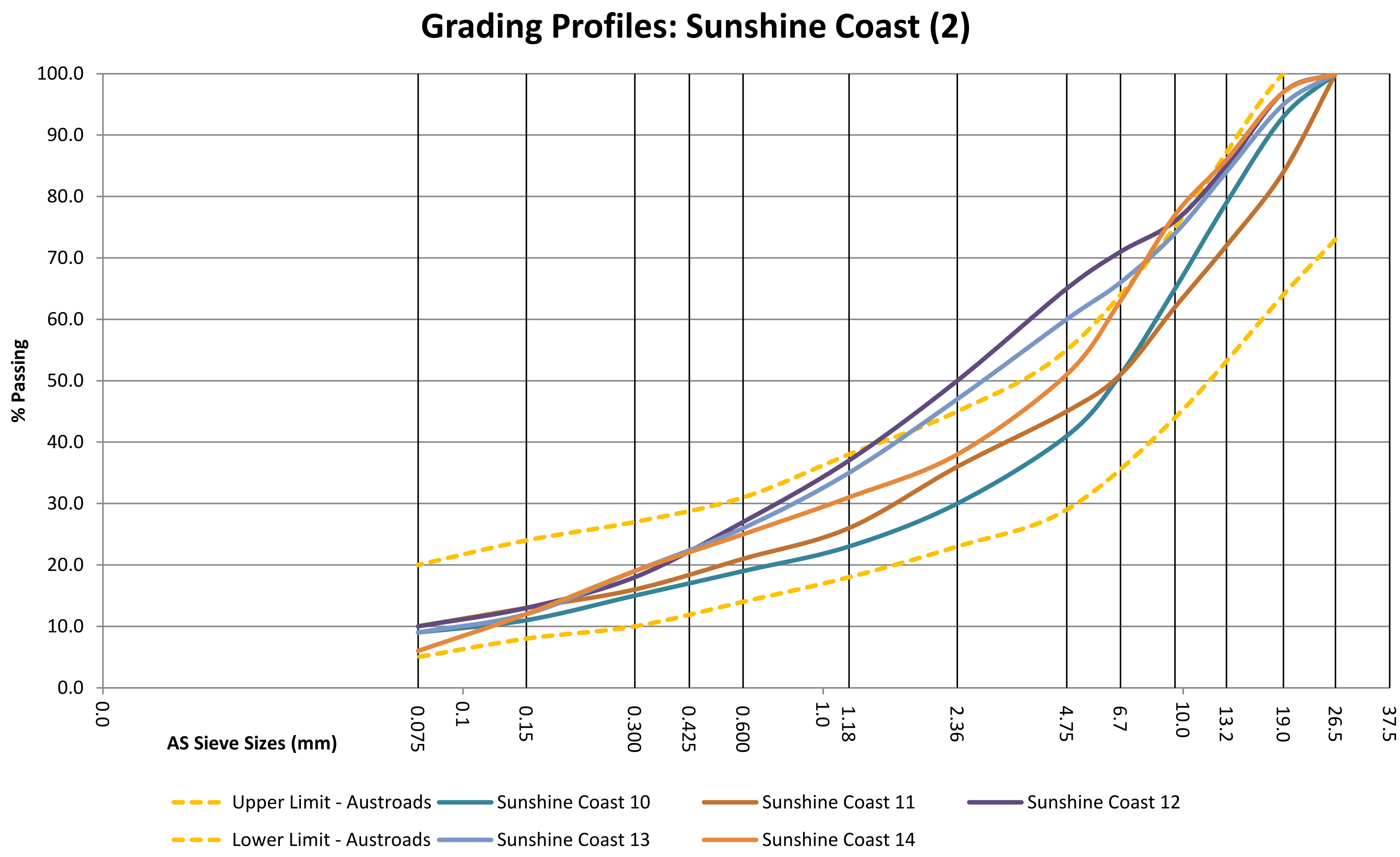

Figure B-5: Sunshine Coast grading profiles (10-14)

B.4. Southern Queensland

Sample ID		Southern Queensland 1	Southern Queensland 2	Southern Queensland 3	Southern Queensland 4	Southern Queensland 5
Material Description		Silty Roadbase Gravel	Roadbase Gravel + 10% FH2.3	Roadbase Gravel + 10% FH2.3	Blended Roadbase Gravel	Roadbase Gravel - imported
% Material Passing AS Sieve Size	26.5		100	100	100	100
	19.0	100	95	95	95	97
	13.2	94	76	85	87	86
	9.5	84	62	74	76	73
	6.7	72	52	63	68	61
	4.75	62	46	54	60	50
	2.36	46	38	41	49	35
	1.18	34	30	31	41	26
	0.600	27	21	25	35	20
	0.300	21	15	20	28	16
	0.150	16	12	18	21	12
	0.075	12	11	17	17	9
Binders						
Bitumen		3.5	3.5	3.5	3	3.5
Hyd. Lime		1.5	1.5	1.5	2	2.5
Resilient Modulus (MPa)						
		8214	6166	7078	7333	7256
		7872	5549	--	6888	--
		9154	5986	7640	7383	--
Dry Cured		8413	5900	7359	7201	7256
		6770	3124	5140	2599	3686
		6436	2674	2163	3604	--
		6231	2586	5292	2883	3385
Wet Cured		6479	2795	5216	2741	3536
Retained Modulus Ratio		77%	47%	71%	38%	49%

Table B-8: Southern Queensland roadbase test data

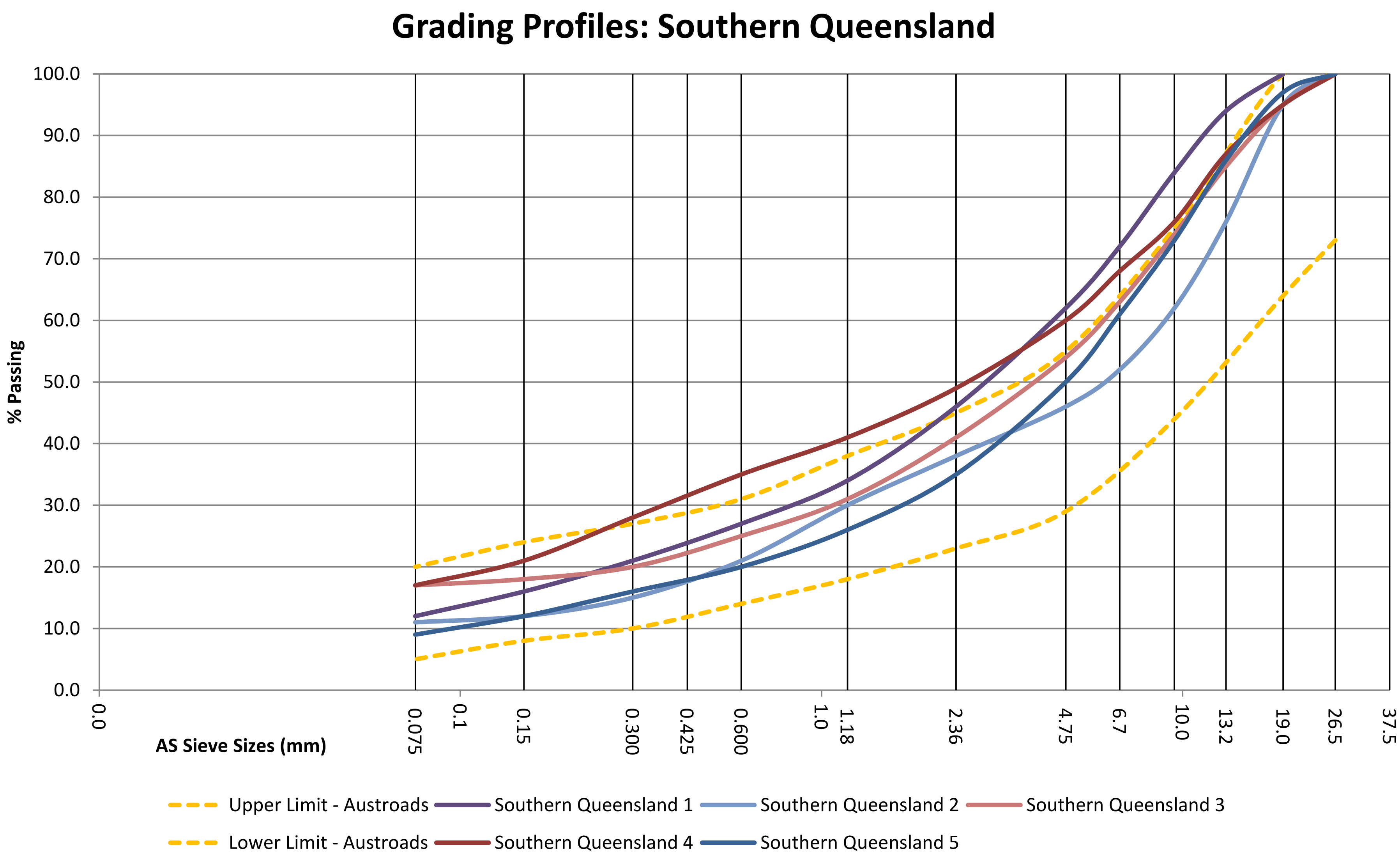

Figure B-6: Southern Queensland grading profiles

B.5. NSW Mid North Coast

Sample ID		Tamworth	Mulbring 1	Mulbring 2	Port Macquarie	Richmond River	Byron Region	Byron Region
Material Description		Sandy Silty gravel with some bituminous seal - Cemented lumps Polyroad	60% Decomposed Granite 40% 20/5mm Concrete aggregate	60% Decomposed Granite 40% 20/5mm Concrete aggregate	Clayey Roadbase Gravel	Existing Roadbase Gravel	Roadbase Gravel, Sandy Silty with some AC	Existing Roadbase Gravel
% Material Passing AS Sieve Size (mm)	26.5	100	100	100	100	100	100	100
	19.0	89	89	89	99	84	90	94
	13.2	81	68	68	89	71	88	82
	9.5	71	60	60	76	59	84	73
	6.7	58	56	56	54	51	73	63
	4.75	46	52	52	52	43	61	55
	2.36	31	44	44	37	34	50	43
	1.18	21	37	37	29	29	43	34
	0.600	15	29	29	22	24	37	26
	0.300	11	18	18	17	22	30	15
	0.150	8	12	12	14	19	24	10
	0.075	6	9	9	11	12	17	8
Binders								
Bitumen		3.5%	3.0%	3.5%	3.5%	3.5%	3.0%	3.5%
Hyd. Lime		1.5%	1.5%	1.5%	2.0%	2.0%	2.0%	1.5%
Resilient Modulus (MPa)								
		2194	7469	8567	5190	2926	--	4125
		1687	7802	9521	5224	3317	3897	4199
		2560	6690	9093	4843	2650	4131	3978
Dry Cured		2147	7320	9060	5086	2964	4014	4101
		1070	2819	4721	3446	1850	2365	2300
		863	3284	4855	2496	2005	1476	2263
		1241	2733	4034	2651	1547	1829	2357
Wet Cured		1058	2945	4537	2864	1801	1890	2307
Retained Modulus Ratio		49%	40%	50%	56%	61%	47%	56%

Table B-9: NSW Mid North Coast roadbase test data

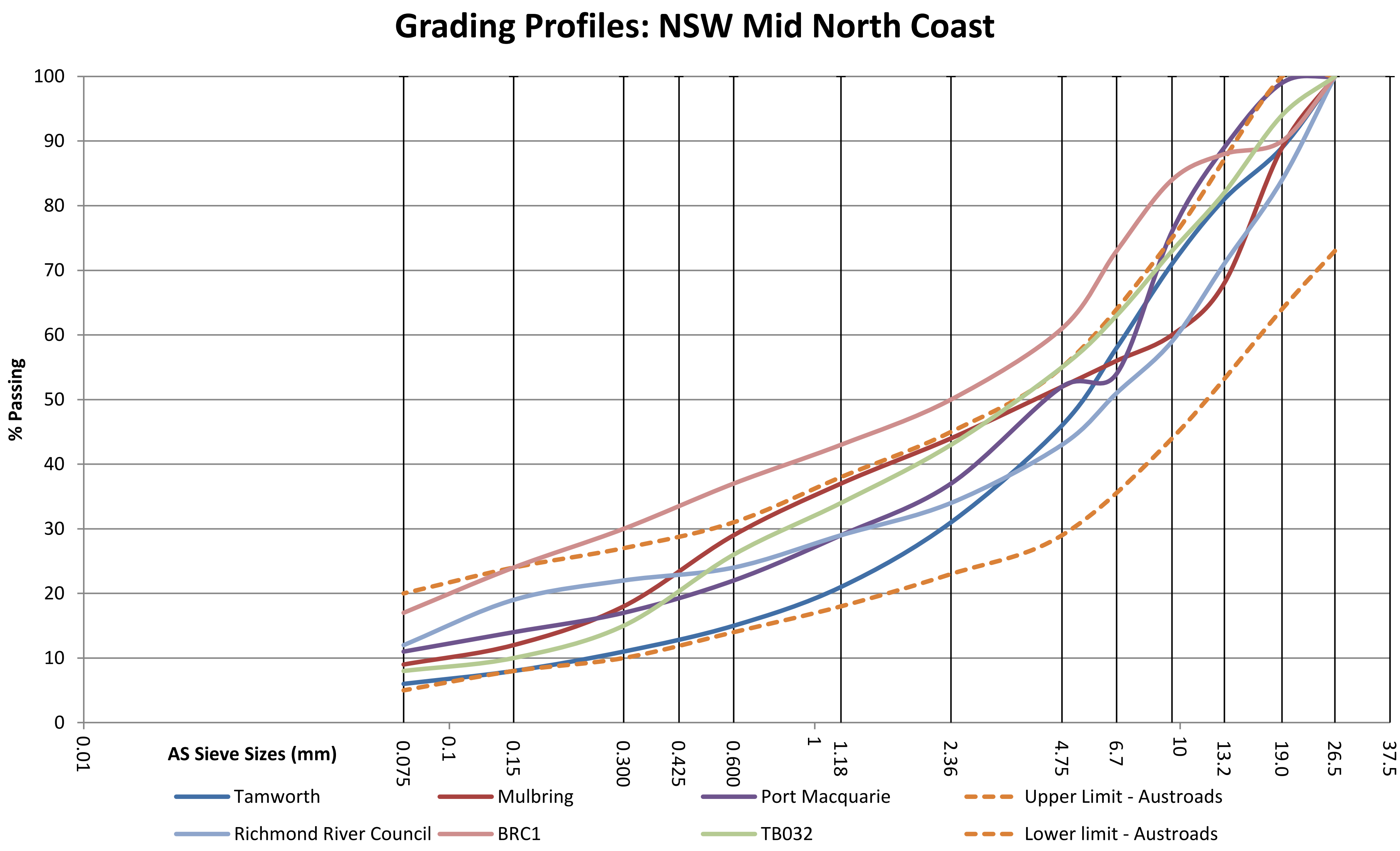

Figure B-7: NSW Mid North Coast grading profiles

B.6. Sydney

Sample ID		Sydney 1	Sydney 2	Sydney 3	Sydney 4	Sydney 5	Sydney 6
Material Description		55%RAP 43% Crusher Dust	Roadbase Gravel and Asphalt seal	Roadbase Gravel and Asphalt seal	80% Roadbase Gravel & AC 20% Crusher Dust	22% AC 52% Red Stabilised Roadbase 26% Roadbase Gravel	52% AC 22% Red Stabilised Roadbase 26% Roadbase Gravel
% Material Passing AS Sieve Size	26.5	100		100	100	100	100
	19.0	99	100	97	87	71	79
	13.2	99	91	84	74	56	57
	9.5	96	79	69	58	44	43
	6.7	85	65	54	46	35	33
	4.75	80	52	44	36	30	26
	2.36	53	35	31	21	21	17
	1.18	31	23	22	12	15	13
	0.600	19	16	15	7	11	11
	0.300	11	11	11	4	8	9
	0.150	7	8	8	3	5	6
	0.075	5	7	6	2	4	4
Binders							
Bitumen		3.5%	3.5%	3.5%	3.0%	3.5%	3.5%
Hyd. Lime		1.5%	1.5%	1.5%	2.0%	2.5%	2.5%
Resilient Modulus (MPa)							
		2941	2125	1915	--	4358	3814
		2057	2654	1816	1299	3682	3710
		2170	2663	1679	1357	3245	4153
Dry Cured		2389	2481	1803	1328	3762	3892
		2011	1054	902	1729	2992	3433
		1396	1142	984	1280	2796	2745
		1276	1142	1090	1302	2488	3763
Wet Cured		1561	1272	992	1291	2759	3314
Retained Modulus Ratio		65%	51%	55%	97%	73%	85%

Table B-10: Sydney roadbase samples testing data

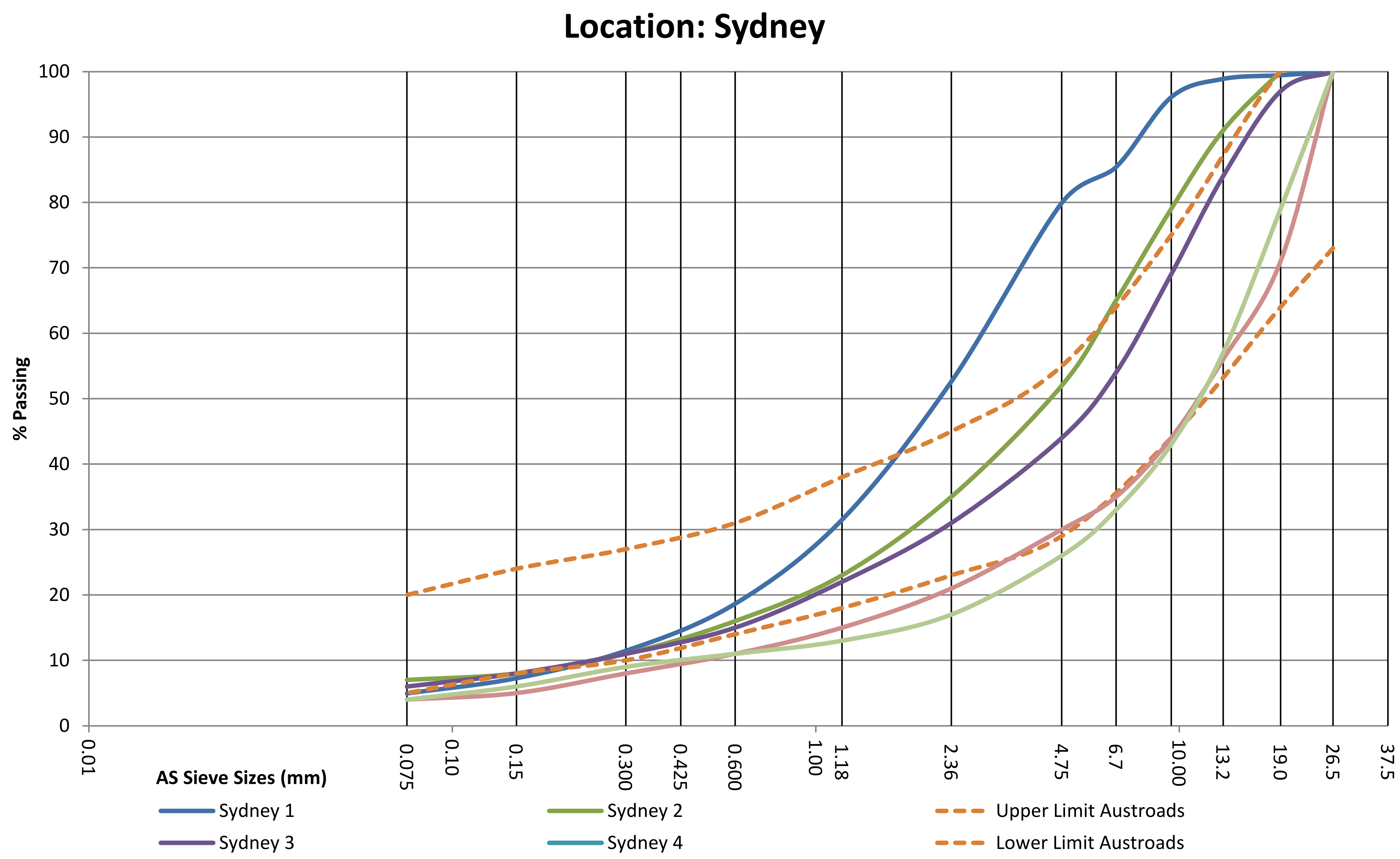

Figure B-8: Sydney grading profiles

B.7. Western NSW

Sample ID		Parkes 1	Parkes 2	Parkes 3	Parkes 4	Parkes 5	Parkes 6
Material Description		Silty Sandy Gravel	Silty Sandy Gravel	Silty Sandy Gravel	Silty Sandy Gravel	Silty Sandy Gravel	Silty Sandy Gravel
% Material Passing AS Sieve Size (mm)	26.5	100	100	100	100		
	19.0	98	97	98	99	100	100
	13.2	92	91	97	96	98	98
	9.5	83	84	91	91	94	95
	6.7	71	78	83	83	86	89
	4.75	59	71	72	74	77	82
	2.36	42	57	52	57	61	66
	1.18	31	43	37	43	48	51
	0.600	21	33	24	30	37	37
	0.300	14	24	15	20	28	27
	0.150	11	19	10	14	21	20
	0.075	9	15	7	10	16	16
Binders							
Bitumen		3.5%	3.5%	3.5%	3.5%	3.5%	3.5%
Hyd. Lime		1.5%	1.5%	1.5%	1.5%	1.5%	1.5%
Resilient Modulus (MPa)							
		7673	5219	4284	5220	4071	5916
		6627	5417	4223	5880	4599	8344
		7835	5174	3951	5871	4309	6830
Dry Cured		7378	5270	4153	5657	4326	7030
		4171	1369	2711	3220	1353	3559
		3387	1380	2683	3360	1551	4238
		4242	1415	2633	3759	1564	3848
Wet Cured		3933	1388	2676	3446	1489	3882
Retained Modulus Ratio		53%	26%	64%	61%	34%	55%

Table B-11: Western NSW roadbase test data

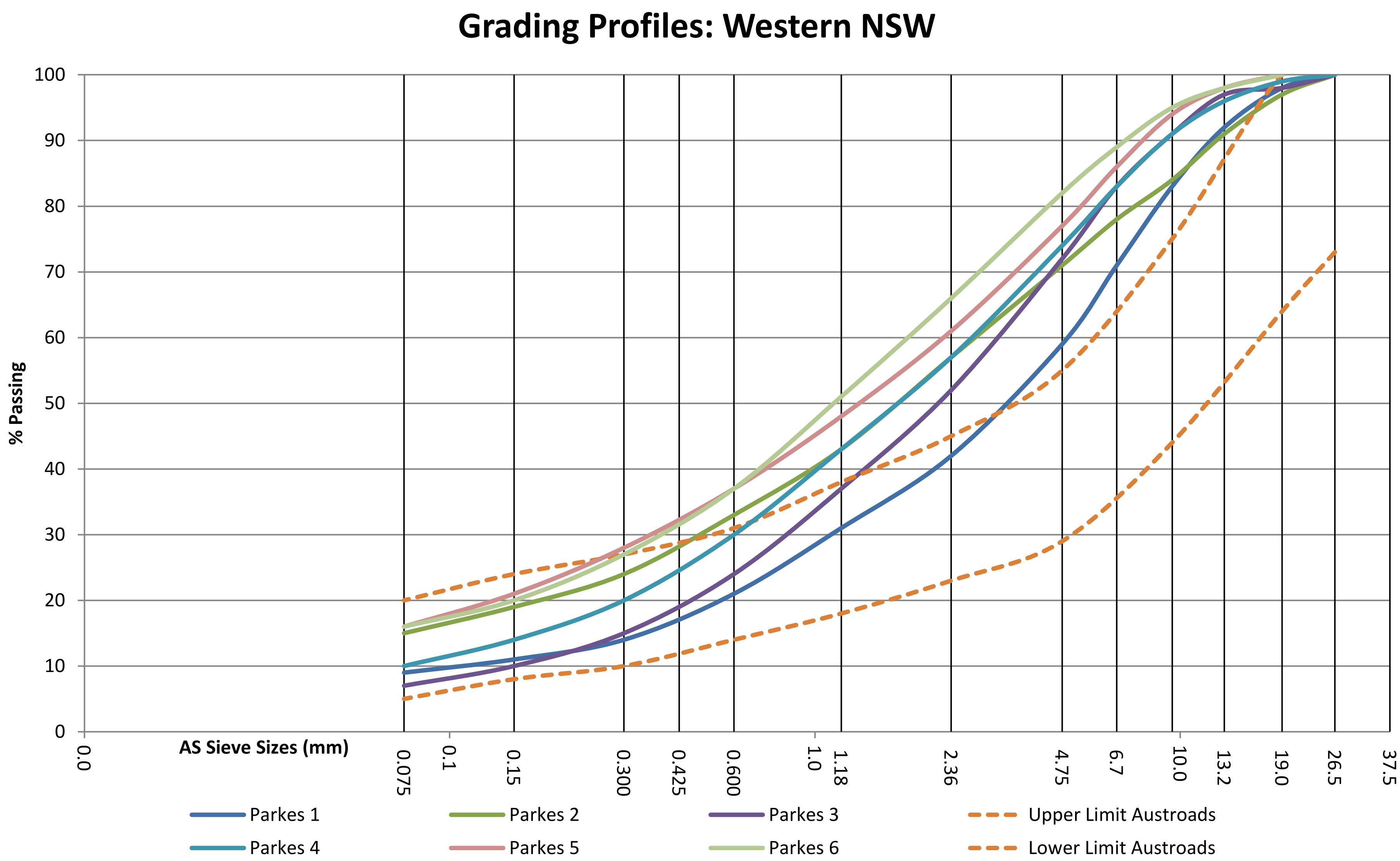

Figure B-9: Western NSW grading profiles

B.8. Central NSW

Sample ID		Bathurst 1	Bathurst 2	Bathurst 3	Bathurst 4	Bathurst 5	Bathurst 6
Material Description		Silty Sandy Gravel	Silty Sandy Gravel	Silty Sandy Gravel	Silty Sandy Gravel	Silty Sandy Gravel	Silty Sandy Gravel
% Material Passing AS Sieve Size (mm)	26.5	100	100	100	100	100	100
	19.0	97	96	99	99	99	96
	13.2	90	90	89	89	97	86
	9.5	83	83	76	76	92	77
	6.7	77	72	64	64	83	65
	4.75	72	63	52	52	73	56
	2.36	65	47	37	37	58	42
	1.18	53	36	29	29	45	33
	0.600	42	27	22	22	32	23
	0.300	33	20	17	17	23	16
	0.150	26	15	14	14	16	12
	0.075	20	11	11	11	11	9
Binders							
Bitumen		3.5%	3.5%	3.5%	3.5%	3.5%	3.5%
Hyd. Lime		1.5%	1.5%	1.5%	1.5%	1.5%	1.5%
Resilient Modulus (MPa)							
		2659	4466	3584	3642	5915	5386
		2891	4059	2862	3227	6239	6188
		2696	3863	2612	2718	5388	5949
Dry Cured		2749	4129	3019	3196	5847	5841
		1350	3124	1463	2122	3746	2264
		1508	2861	1970	2017	4117	4412
		1284	2893	1970	2035	3328	4426
Wet Cured		1381	2959	1801	2058	3730	4419
Retained Modulus Ratio		50%	72%	60%	64%	64%	76%

Table B-12: Central NSW roadbase test data

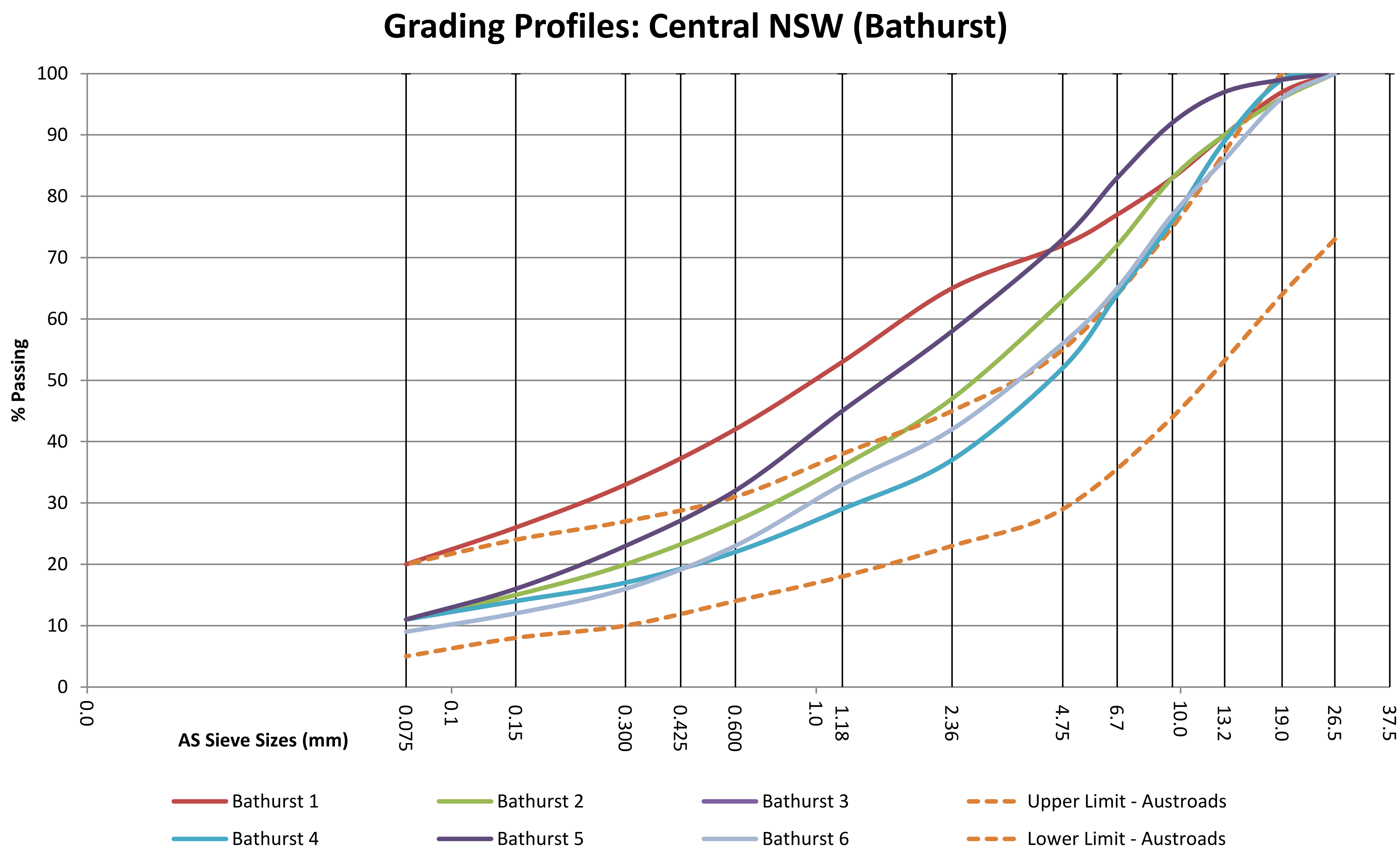

Figure B-10: Central NSW grading profiles

B.9. Southern NSW

Sample ID		Bega 1	Bega 2	Bega 3	Bega 4	Bega 5	Bega 6
Material Description		Gravelly Silty Sand with Bituminous Seal	Gravelly Silty Sand with Bituminous Seal	Roadbase Gravel previously stabilised with Polyroad	Gravelly Silty Sand with Bituminous Seal	Gravelly Silty Sand with Bituminous Seal	Roadbase Gravel previously stabilised with Polyroad
% Material Passing AS Sieve Size (mm)	26.5	100	100	100	100	100	100
	19.0	93	97	87	94	95	96
	13.2	77	90	62	90	91	89
	9.5	67	80	48	88	87	81
	6.7	57	68	37	83	84	75
	4.75	51	59	30	77	78	69
	2.36	41	45	21	64	66	55
	1.18	39	33	15	33	50	39
	0.600	36	26	11	25	35	26
	0.300	25	20	8	18	24	17
	0.150	17	15	6	14	17	11
	0.075	10	11	5	11	12	7
Binders							
Bitumen		3.5%	3.5%	3.5%	3.5%	3.5%	3.5%
Hyd. Lime		1.5%	1.5%	1.5%	1.5%	1.5%	1.5%
Resilient Modulus (MPa)							
		2717	--	3553	3652	3943	5439
		2888	--	4216	4031	4518	6364
		2942	--	4184	4584	5111	5799
Dry Cured		2849	5875	3984	4089	4524	5867
		2200	--	3165	1969	2549	2735
		2159	--	2826	2370	2929	3485
		2127	--	2804	2487	3027	3543
Wet Cured		2162	4586	2932	2275	2835	3254
Retained Modulus Ratio		76%	78%	74%	56%	63%	55%

Table B-13: Southern NSW roadbase test data

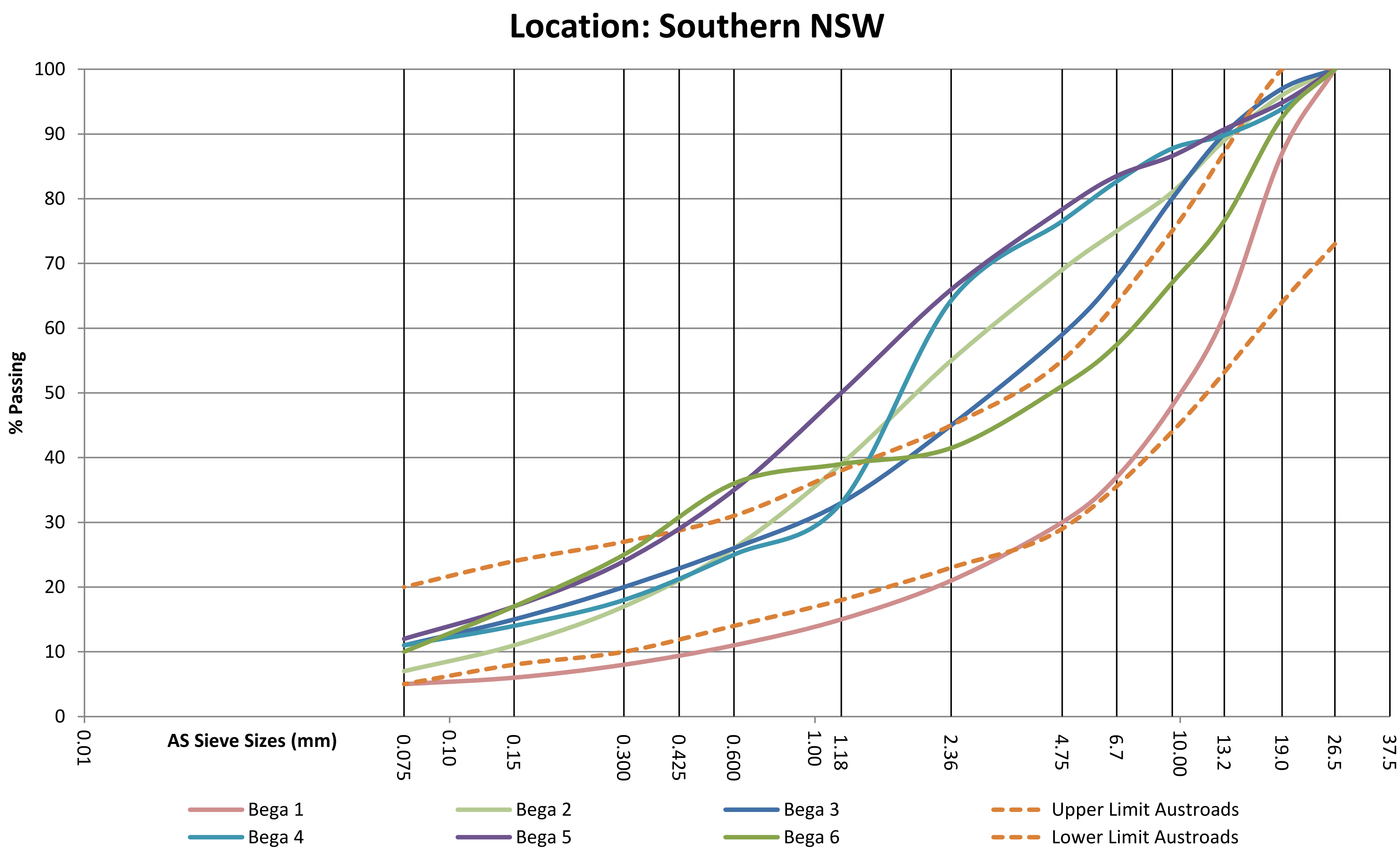

Figure B-11: Southern NSW grading profiles

B.10. ACT

Sample ID		ACT 1	ACT 2
Material Description		93% Roadbase 7% RAP	93% Roadbase 7% RAP
% Material Passing AS Sieve Size (mm)	26.5	100	100
	19.0	99	96
	13.2	88	90
	9.5	76	83
	6.7	67	75
	4.75	59	66
	2.36	45	52
	1.18	32	42
	0.600	23	34
	0.300	17	28
	0.150	13	24
	0.075	10	20
Binders			
Bitumen		3.0%	3.5%
Hyd. Lime		2.0%	2.0%
Resilient Modulus (MPa)			
		7662	7735
		8862	7366
		8547	7710
Dry Cured		8357	7604
		4304	7215
		6485	7051
		6794	6866
Wet Cured		5861	7044
Retained Modulus Ratio		70%	93%

Table B-14: ACT roadbase test data

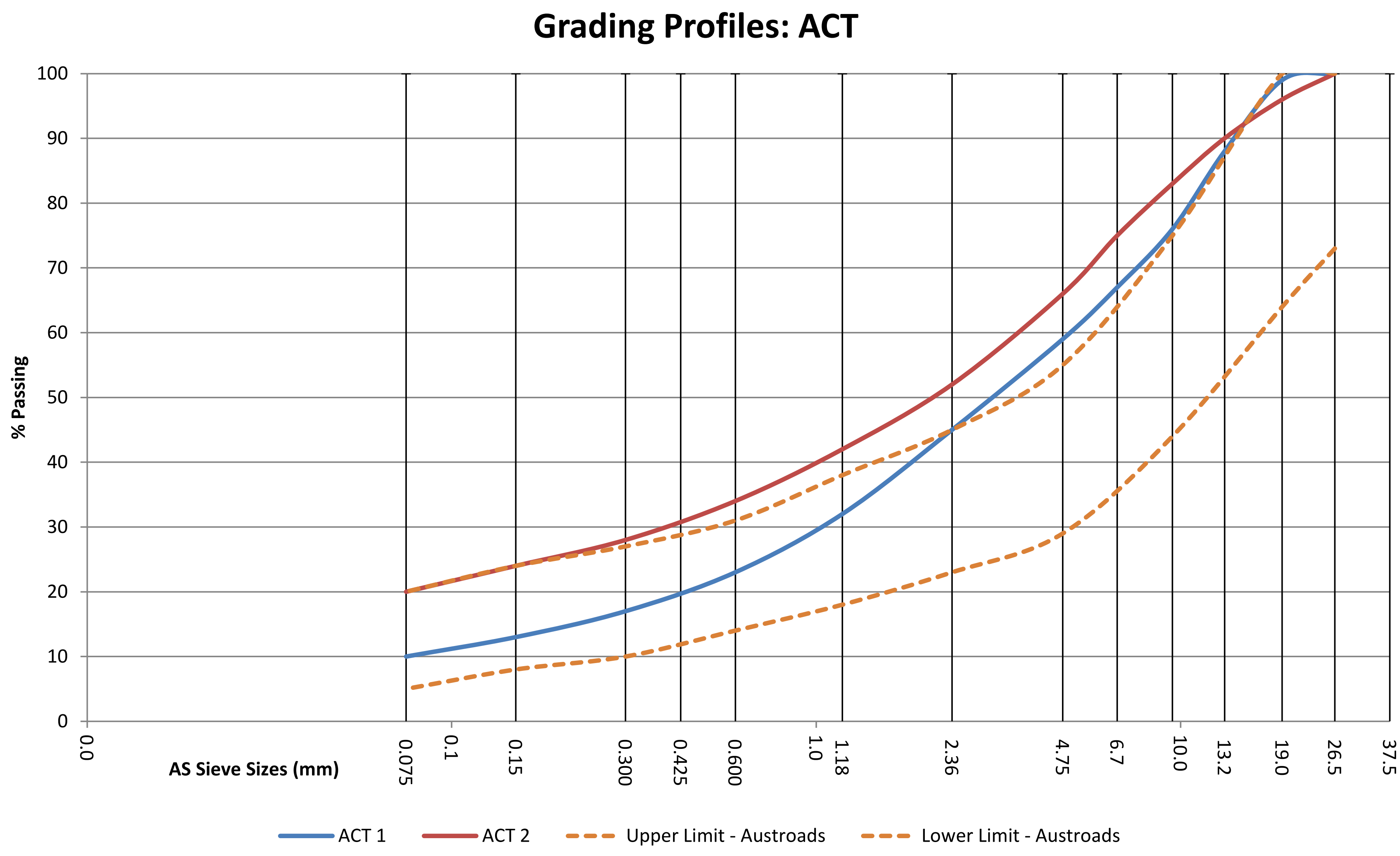

Figure B-12: ACT grading profiles

B.11. Victoria

Sample ID		Victoria 1	Victoria 2	Victoria 3	Victoria 4	Victoria 5	Victoria 6
Material Description		60% Sandstone 40% 20mm aggregate	60% Sandstone 40% 20mm aggregate	57% Composite 43% Hillview Class 2 FCR	Composite Roadbase Gravel	50% Composite 50% Hillview Class 1 FCR	Roadbase Gravel and Bitumen seal
% Material Passing AS Sieve Size (mm)	26.5	100	100		100	100	
	19.0	96	96	100	98	91	100
	13.2	64	64	94	86	82	98
	9.5	53	55	89	77	71	92
	6.7	51	52	85	65	62	78
	4.75	49	50	80	56	52	63
	2.36	47	47	67	42	39	50
	1.18	45	44	47	27	27	41
	0.600	42	40	34	16	17	35
	0.300	23	25	24	8	11	30
	0.150	14	17	18	3	8	23
	0.075	11	13	14	1	2	14
Binders							
Bitumen		3.0%	3.5%	3.5%	3.0%	3.0%	3.0%
Hyd. Lime		1.5%	1.5%	1.5%	1.5%	1.5%	1.5%
Resilient Modulus (MPa)							
		6548	6738	3263	4455	7291	4830
		5630	5220	2941	5646	8507	3900
		4709	5187	3289	6179	5785	4676
Dry Cured		5629	5715	3164	5427	7194	4469
		336	803	1776	2286	5687	4016
		313	752	1684	3140	5926	3259
		255	598	1754	3100	3373	3299
Wet Cured		301	718	1738	2842	4995	3525
Retained Modulus Ratio		5%	13%	55%	52%	69%	79%

Table B-15: Victoria roadbase test data Table (A)

Sample ID		Victoria 7	Victoria 8	Victoria 9	Victoria 10	Victoria 11
Material Description		Roadbase Gravel and Bitumen seal	Roadbase Gravel	Roadbase Gravel	Roadbase Gravel	Roadbase Gravel
% Material Passing AS Sieve Size (mm)	26.5	100	100	100		100
	19.0	99	97	89	100	96
	13.2	91	88	75	86	86
	9.5	81	80	61	68	73
	6.7	71	72	49	56	61
	4.75	62	56	41	48	53
	2.36	51	41	32	35	41
	1.18	40	29	26	24	30
	0.600	31	21	21	17	23
	0.300	25	14	17	13	17
	0.150	18	10	12	10	13
	0.075	13	8	8	7	9
Binders						
Bitumen		3.0%	3.5%	3.0%	3.0%	3.0%
Hyd. Lime		1.5%	1.5%	2.0%	2.0%	2.0%
Resilient Modulus (MPa)						
		5258	5248	6139	5236	5454
		6262	5455	6845	--	5753
		5372	6268	5521	4744	5104
Dry Cured		5631	5657	6168	4990	5437
		4248	4244	3365	2697	3196
		3511	4490	3667	1720	2496
		4431	4924	2782	2256	3117
Wet Cured		4063	4553	3271	2224	2936
Retained Modulus Ratio		72%	80%	53%	45%	54%

Table B-16: Victoria roadbase test data Table (B)

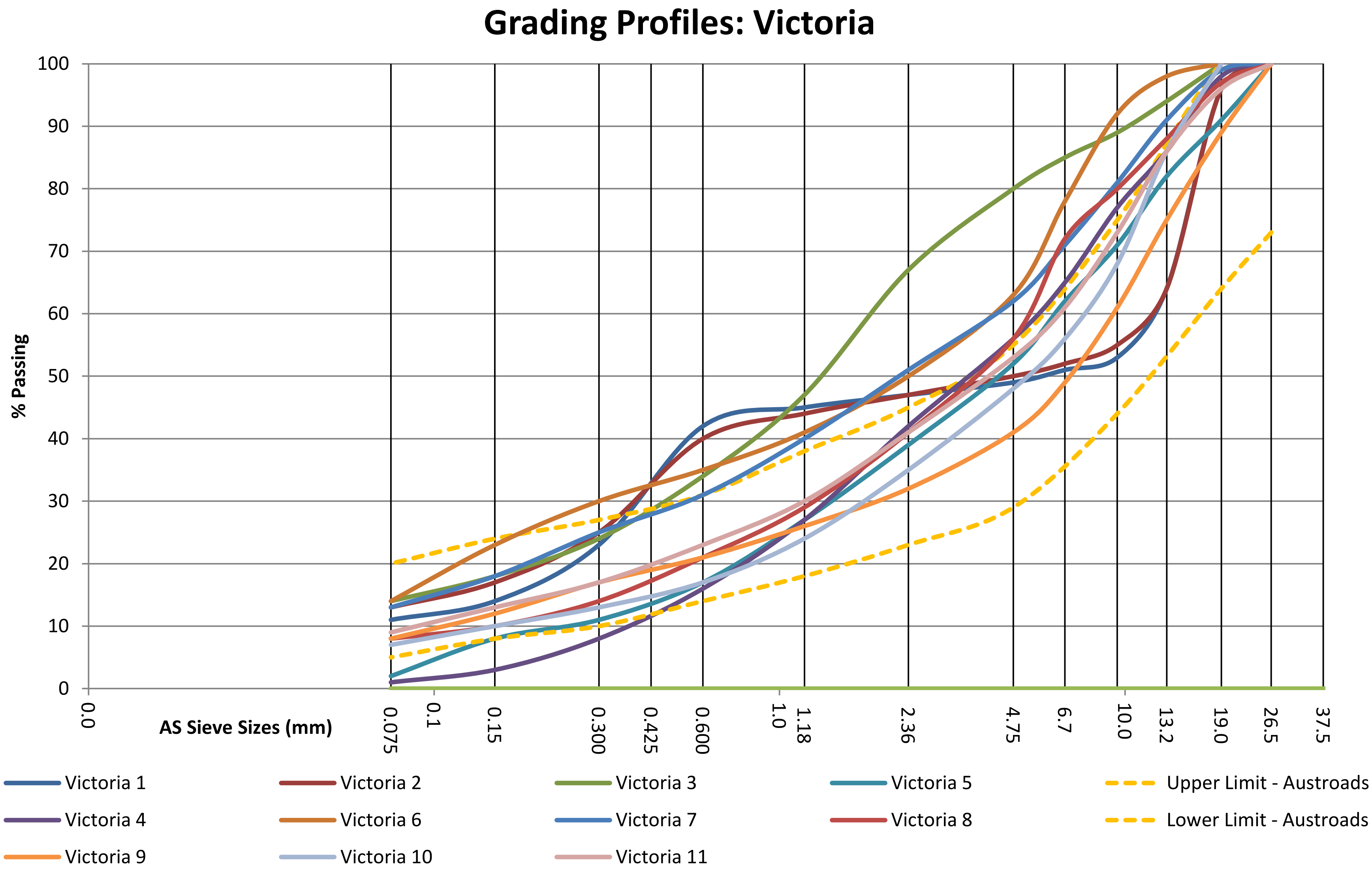

Figure B-13: Victoria grading profiles

Appendix C. CIRCLY Output

C.1. 3% Bitumen 1% Lime 6% finer than 75µm

Service Life

3% Bitumen 1% Lime 6% Passing 0.075mm
Maximum damage values for each vehicle type

Vehicle Type	Damage Factor	Critical Strain
ESA750-Full	.20476E+00	-0.19022E-03

Maximum of total damage= 0.2047636

Subgrade, CBR=5,Aniso
Maximum damage values for each vehicle type

Vehicle Type	Damage Factor	Critical Strain
ESA750-Full	.72427E-04	0.46000E-03

Maximum of total damage= 7.2427443E-05

C.2. 3% Bitumen 1.5% Lime 2% finer than 75µm

Service Life

3% Bitumen 1.5% Lime 2% Passing 0.075mm
Maximum damage values for each vehicle type

Vehicle Type	Damage Factor	Critical Strain
ESA750-Full	.20783E-01	-0.79627E-04

Maximum of total damage= 2.0782905E-02

Subgrade, CBR=5,Aniso
Maximum damage values for each vehicle type

Vehicle Type	Damage Factor	Critical Strain
ESA750-Full	.60702E-06	0.23232E-03

Maximum of total damage= 6.0702411E-07

C.3. 3% Bitumen 1.5% Lime 6% finer than 75μm

Service Life

3% Bitumen 1.5% Lime 6% Passing 0.075mm
Maximum damage values for each vehicle type

Vehicle Type	Damage Factor	Critical Strain
ESA750-Full	.11443E-01	-0.63723E-04

Maximum of total damage= 1.1442849E-02

Subgrade, CBR=5,Aniso
Maximum damage values for each vehicle type

Vehicle Type	Damage Factor	Critical Strain
ESA750-Full	.18672E-06	0.19631E-03

Maximum of total damage= 1.8671868E-07

C.4. 3% Bitumen 1.5% Lime 10% finer than 75μm

Service Life

3% Bitumen 1.5% Lime 10% Passing 0.075mm
Maximum damage values for each vehicle type

Vehicle Type	Damage Factor	Critical Strain
ESA750-Full	.14074E-01	-0.69564E-04

Maximum of total damage= 1.4074348E-02

Subgrade, CBR=5,Aniso
Maximum damage values for each vehicle type

Vehicle Type	Damage Factor	Critical Strain
ESA750-Full	.29638E-06	0.20970E-03

Maximum of total damage= 2.9637530E-07

C.5. 3% Bitumen 1.5% Lime 13% finer than 75µm

Service Life

```
3% Bitumen 1.5% Lime 13% Passing 0.075mm
Maximum damage values for each vehicle type
------------------------------------------
Vehicle Type    Damage Factor    Critical Strain
------------    -------------    ---------------
ESA750-Full       .35343E-01      -0.97110E-04

Maximum of total damage=             3.5343062E-02

Subgrade, CBR=5,Aniso
Maximum damage values for each vehicle type
------------------------------------------
Vehicle Type    Damage Factor    Critical Strain
------------    -------------    ---------------
ESA750-Full       .17611E-05       0.27050E-03

Maximum of total damage=             1.7611352E-06
```

C.6. 3% Bitumen 1.5% Lime 15% finer than 75µm

Service Life

```
3% Bitumen 1.5% Lime 15% Passing 0.075mm
Maximum damage values for each vehicle type
------------------------------------------
Vehicle Type    Damage Factor    Critical Strain
------------    -------------    ---------------
ESA750-Full       .17260E+00      -0.17792E-03

Maximum of total damage=             0.1725960

Subgrade, CBR=5,Aniso
Maximum damage values for each vehicle type
------------------------------------------
Vehicle Type    Damage Factor    Critical Strain
------------    -------------    ---------------
ESA750-Full       .49719E-04       0.43593E-03

Maximum of total damage=             4.9719143E-05
```

C.7. 3.5% Bitumen 1.5% Lime 2% finer than 75µm

Service Life

3.5% Bitumen 1.5% Lime 2% Passing 0.075mm
Maximum damage values for each vehicle type

Vehicle Type	Damage Factor	Critical Strain
ESA750-Full	.39097E+00	-0.31540E-03

Maximum of total damage= 0.3909675

Subgrade, CBR=5,Aniso
Maximum damage values for each vehicle type

Vehicle Type	Damage Factor	Critical Strain
ESA750-Full	.12974E-02	0.69467E-03

Maximum of total damage= 1.2974023E-03

C.8. 3.5% Bitumen 1.5% Lime 6% finer than 75µm

Service Life

3.5% Bitumen 1.5% Lime 6% Passing 0.075mm
Maximum damage values for each vehicle type

Vehicle Type	Damage Factor	Critical Strain
ESA750-Full	.30711E-01	-0.11659E-03

Maximum of total damage= 3.0711215E-02

Subgrade, CBR=5,Aniso
Maximum damage values for each vehicle type

Vehicle Type	Damage Factor	Critical Strain
ESA750-Full	.47595E-05	0.31178E-03

Maximum of total damage= 4.7594940E-06

C.9. 3.5% Bitumen 1.5% Lime 10% finer than 75µm

Service Life

3.5% Bitumen 1.5% Lime 10% Passing 0.075mm
Maximum damage values for each vehicle type

Vehicle Type	Damage Factor	Critical Strain
ESA750-Full	.16530E-01	-0.92316E-04

Maximum of total damage= 1.6529826E-02

Subgrade, CBR=5,Aniso
Maximum damage values for each vehicle type

Vehicle Type	Damage Factor	Critical Strain
ESA750-Full	.13402E-05	0.26015E-03

Maximum of total damage= 1.3402429E-06

C.10. 3.5% Bitumen 1.5% Lime 15% finer than 75µm

Service Life

3.5% Bitumen 1.5% Lime 15% Passing 0.075mm
Maximum damage values for each vehicle type

Vehicle Type	Damage Factor	Critical Strain
ESA750-Full	.19165E-01	-0.97599E-04

Maximum of total damage= 1.9164797E-02

Subgrade, CBR=5,Aniso
Maximum damage values for each vehicle type

Vehicle Type	Damage Factor	Critical Strain
ESA750-Full	.18096E-05	0.27155E-03

Maximum of total damage= 1.8095545E-06

C.11. 3.5% Bitumen 1.5% Lime 20% finer than 75µm

Service Life

3.5% Bitumen 1.5% Lime 20% Passing 0.075mm
Maximum damage values for each vehicle type

Vehicle Type	Damage Factor	Critical Strain
ESA750-Full	.93744E-01	-0.17891E-03

Maximum of total damage= 9.3743533E-02

Subgrade, CBR=5,Aniso
Maximum damage values for each vehicle type

Vehicle Type	Damage Factor	Critical Strain
ESA750-Full	.51306E-04	0.43789E-03

Maximum of total damage= 5.1305753E-05

C.12. 2% Bitumen 2% Lime 2% finer than 75µm

Service Life

2% Bitumen 2% Lime 2% Passing 0.075mm
Maximum damage values for each vehicle type

Vehicle Type	Damage Factor	Critical Strain
ESA750-Full	.47720E+00	-0.14361E-03

Maximum of total damage= 0.4772003

Subgrade, CBR=5,Aniso
Maximum damage values for each vehicle type

Vehicle Type	Damage Factor	Critical Strain
ESA750-Full	.15025E-04	0.36743E-03

Maximum of total damage= 1.5025473E-05

C.13. 2% Bitumen 2% Lime 10% finer than 75µm

Service Life

2% Bitumen 2% Lime 10% Passing 0.075mm
Maximum damage values for each vehicle type

Vehicle Type	Damage Factor	Critical Strain
ESA750-Full	.40097E-01	-0.56660E-04

Maximum of total damage= 4.0096771E-02

Subgrade, CBR=5,Aniso
Maximum damage values for each vehicle type

Vehicle Type	Damage Factor	Critical Strain
ESA750-Full	.10095E-06	0.17980E-03

Maximum of total damage= 1.0094633E-07

C.14. 3% Bitumen 2% Lime 2% finer than 75µm

Service Life

3% Bitumen 2% Lime 2% Passing 0.075mm
Maximum damage values for each vehicle type

Vehicle Type	Damage Factor	Critical Strain
ESA750-Full	.11782E+01	-0.38477E-03

Maximum of total damage= 1.178222

Subgrade, CBR=5,Aniso
Maximum damage values for each vehicle type

Vehicle Type	Damage Factor	Critical Strain
ESA750-Full	.40893E-02	0.81847E-03

Maximum of total damage= 4.0893313E-03

C.15. 3% Bitumen 2% Lime 6% finer than 75μm

Service Life

3% Bitumen 2% Lime 6% Passing 0.075mm
Maximum damage values for each vehicle type

Vehicle Type	Damage Factor	Critical Strain
ESA750-Full	.58090E-01	-0.11718E-03

Maximum of total damage= 5.8090344E-02

Subgrade, CBR=5,Aniso
Maximum damage values for each vehicle type

Vehicle Type	Damage Factor	Critical Strain
ESA750-Full	.48941E-05	0.31302E-03

Maximum of total damage= 4.8940792E-06

C.16. 3% Bitumen 2% Lime 10% finer than 75μm

Service Life

3% Bitumen 2% Lime 10% Passing 0.075mm
Maximum damage values for each vehicle type

Vehicle Type	Damage Factor	Critical Strain
ESA750-Full	.27400E-01	-0.88289E-04

Maximum of total damage= 2.7399695E-02

Subgrade, CBR=5,Aniso
Maximum damage values for each vehicle type

Vehicle Type	Damage Factor	Critical Strain
ESA750-Full	.10545E-05	0.25139E-03

Maximum of total damage= 1.0545166E-06

C.17. 3% Bitumen 2% Lime 15% finer than 75µm

Service Life

3% Bitumen 2% Lime 15% Passing 0.075mm
Maximum damage values for each vehicle type

Vehicle Type	Damage Factor	Critical Strain
ESA750-Full	.25283E-01	-0.85686E-04

Maximum of total damage= 2.5282897E-02

Subgrade, CBR=5,Aniso
Maximum damage values for each vehicle type

Vehicle Type	Damage Factor	Critical Strain
ESA750-Full	.89820E-06	0.24569E-03

Maximum of total damage= 8.9819582E-07

C.18. 3% Bitumen 2% Lime 20% finer than 75µm

Service Life

3% Bitumen 2% Lime 20% Passing 0.075mm
Maximum damage values for each vehicle type

Vehicle Type	Damage Factor	Critical Strain
ESA750-Full	.57651E-01	-0.11685E-03

Maximum of total damage= 5.7651374E-02

Subgrade, CBR=5,Aniso
Maximum damage values for each vehicle type

Vehicle Type	Damage Factor	Critical Strain
ESA750-Full	.48182E-05	0.31233E-03

Maximum of total damage= 4.8181951E-06

C.19. 3% Bitumen 2% Lime 24% finer than 75µm

Service Life

3% Bitumen 2% Lime 24% Passing 0.075mm
Maximum damage values for each vehicle type

Vehicle Type	Damage Factor	Critical Strain
ESA750-Full	.11192E+01	-0.37668E-03

Maximum of total damage= 1.119193

Subgrade, CBR=5,Aniso
Maximum damage values for each vehicle type

Vehicle Type	Damage Factor	Critical Strain
ESA750-Full	.36164E-02	0.80423E-03

Maximum of total damage= 3.6164462E-03

C.20. 3.5% Bitumen 2% Lime 2% finer than 75µm

Service Life

3.5% Bitumen 2% Lime 2% Passing 0.075mm
Maximum damage values for each vehicle type

Vehicle Type	Damage Factor	Critical Strain
ESA750-Full	.32453E-01	-0.11914E-03

Maximum of total damage= 3.2452766E-02

Subgrade, CBR=5,Aniso
Maximum damage values for each vehicle type

Vehicle Type	Damage Factor	Critical Strain
ESA750-Full	.53582E-05	0.31710E-03

Maximum of total damage= 5.3582157E-06

C.21. 3.5% Bitumen 2% Lime 6% finer than 75µm

Service Life

3.5% Bitumen 2% Lime 6% Passing 0.075mm
Maximum damage values for each vehicle type

Vehicle Type	Damage Factor	Critical Strain
ESA750-Full	.25167E-01	-0.10815E-03

Maximum of total damage= 2.5167475E-02

Subgrade, CBR=5,Aniso
Maximum damage values for each vehicle type

Vehicle Type	Damage Factor	Critical Strain
ESA750-Full	.31577E-05	0.29403E-03

Maximum of total damage= 3.1577397E-06

C.22. 3.5% Bitumen 2% Lime 10% finer than 75µm

Service Life

3.5% Bitumen 2% Lime 10% Passing 0.075mm
Maximum damage values for each vehicle type

Vehicle Type	Damage Factor	Critical Strain
ESA750-Full	.21213E-01	-0.10135E-03

Maximum of total damage= 2.1213247E-02

Subgrade, CBR=5,Aniso
Maximum damage values for each vehicle type

Vehicle Type	Damage Factor	Critical Strain
ESA750-Full	.22196E-05	0.27959E-03

Maximum of total damage= 2.2196064E-06

C.23. 3.5% Bitumen 2% Lime 15% finer than 75µm

Service Life

3.5% Bitumen 2% Lime 15% Passing 0.075mm
Maximum damage values for each vehicle type

Vehicle Type	Damage Factor	Critical Strain
ESA750-Full	.18766E-01	-0.96814E-04

Maximum of total damage= 1.8765554E-02

Subgrade, CBR=5,Aniso
Maximum damage values for each vehicle type

Vehicle Type	Damage Factor	Critical Strain
ESA750-Full	.17323E-05	0.26986E-03

Maximum of total damage= 1.7322736E-06

C.24. 3.5% Bitumen 2% Lime 20% finer than 75µm

Service Life

3.5% Bitumen 2% Lime 20% Passing 0.075mm
Maximum damage values for each vehicle type

Vehicle Type	Damage Factor	Critical Strain
ESA750-Full	.18161E-01	-0.95602E-04

Maximum of total damage= 1.8160792E-02

Subgrade, CBR=5,Aniso
Maximum damage values for each vehicle type

Vehicle Type	Damage Factor	Critical Strain
ESA750-Full	.16184E-05	0.26725E-03

Maximum of total damage= 1.6183669E-06

C.25. 3.5% Bitumen 2% Lime 25% finer than 75µm

Service Life

3.5% Bitumen 2% Lime 25% Passing 0.075mm
Maximum damage values for each vehicle type

Vehicle Type	Damage Factor	Critical Strain
ESA750-Full	.19123E-01	-0.97472E-04

Maximum of total damage= 1.9122604E-02

Subgrade, CBR=5,Aniso
Maximum damage values for each vehicle type

Vehicle Type	Damage Factor	Critical Strain
ESA750-Full	.17969E-05	0.27128E-03

Maximum of total damage= 1.7969185E-06

C.26. 3.5% Bitumen 2% Lime 30% finer than 75µm

Service Life

3.5% Bitumen 2% Lime 25% Passing 0.075mm
Maximum damage values for each vehicle type

Vehicle Type	Damage Factor	Critical Strain
ESA750-Full	.19123E-01	-0.97472E-04

Maximum of total damage= 1.9122604E-02

Subgrade, CBR=5,Aniso
Maximum damage values for each vehicle type

Vehicle Type	Damage Factor	Critical Strain
ESA750-Full	.17969E-05	0.27128E-03

Maximum of total damage= 1.7969185E-06

C.27. Mackay 1 (2%)

Service Life

Foam Bitumen Stabilised 2% Bitumen (Mackay 1)
Maximum damage values for each vehicle type

Vehicle Type	Damage Factor	Critical Strain
ESA750-Full	.40097E-01	-0.56660E-04

Maximum of total damage= 4.0096771E-02

Subgrade, CBR=5,Aniso
Maximum damage values for each vehicle type

Vehicle Type	Damage Factor	Critical Strain
ESA750-Full	.10095E-06	0.17980E-03

Maximum of total damage= 1.0094633E-07

C.28. Mackay 1 (3%)

Service Life

Foam Bitumen Stabilised - 3% Bitumen (Mackay 1)
Maximum damage values for each vehicle type

Vehicle Type	Damage Factor	Critical Strain
ESA750-Full	.24968E-02	-0.63451E-04

Maximum of total damage= 2.4968218E-03

Subgrade, CBR=5,Aniso
Maximum damage values for each vehicle type

Vehicle Type	Damage Factor	Critical Strain
ESA750-Full	.18257E-06	0.19568E-03

Maximum of total damage= 1.8257163E-07

C.29. Mackay 1 (4%)

Service Life

Foamed Bitumen Stabilised - 4% Bitumen (Mackay 1)
Maximum damage values for each vehicle type

Vehicle Type	Damage Factor	Critical Strain
ESA750-Full	.58860E-03	-0.86813E-04

Maximum of total damage= 5.8859552E-04

Subgrade, CBR=5,Aniso
Maximum damage values for each vehicle type

Vehicle Type	Damage Factor	Critical Strain
ESA750-Full	.96334E-06	0.24816E-03

Maximum of total damage= 9.6334134E-07

C.30. Marginal Material – Sandstone

3% Bitumen 1.5% Lime

Dry Modulus

Service Life

Marginal Materials Sandstone (5629MPa)
Maximum damage values for each vehicle type

Vehicle Type	Damage Factor	Critical Strain
ESA750-Full	.15255E+00	-0.93220E-04

Maximum of total damage= 0.1525498

Subgrade, CBR=5,Aniso
Maximum damage values for each vehicle type

Vehicle Type	Damage Factor	Critical Strain
ESA750-Full	.14125E-05	0.26211E-03

Maximum of total damage= 1.4125047E-06

Wet Modulus

Service Life

Marginal Material SS (301 MPa)
Maximum damage values for each vehicle type

Vehicle Type	Damage Factor	Critical Strain
ESA750-Full	.45613E+02	-0.83646E-03

Maximum of total damage= 45.61252

Subgrade, CBR=5,Aniso
Maximum damage values for each vehicle type

Vehicle Type	Damage Factor	Critical Strain
ESA750-Full	.36311E+00	0.15536E-02

Maximum of total damage= 0.3631113

4% Bitumen 1.5% Lime

Dry Modulus

Service Life

Marginal Material SS (5715 MPa)
Maximum damage values for each vehicle type

Vehicle Type	Damage Factor	Critical Strain
ESA750-Full	.67795E-02	-0.92135E-04

Maximum of total damage= 6.7794663E-03

Subgrade, CBR=5,Aniso
Maximum damage values for each vehicle type

Vehicle Type	Damage Factor	Critical Strain
ESA750-Full	.13262E-05	0.25976E-03

Maximum of total damage= 1.3261762E-06

Wet Modulus

Service Life

Marginal Material SS (301 MPa)
Maximum damage values for each vehicle type

Vehicle Type	Damage Factor	Critical Strain
ESA750-Full	.45613E+02	-0.83646E-03

Maximum of total damage= 45.61252

Subgrade, CBR=5,Aniso
Maximum damage values for each vehicle type

Vehicle Type	Damage Factor	Critical Strain
ESA750-Full	.36311E+00	0.15536E-02

Maximum of total damage= 0.3631113

Appendix D. Typical Service Life Calculations

Step 1

Layer	Material Type	Thickness (mm)
Sealing Layer	Spray Seal Surface	--
Basecourse	Foamed Bitumen Stabilised Material	260
Subgrade	Existing Subgrade $CBR = 5\%$	Semi-Infinite

For Foamed bitumen stabilisation the project reliability is

$K = 1.0$

Step 2

$Subgrade\ CBR = 5\%$

$E_v = 50,$

$E_h = 25;$

$v_v = v_h = 0.45;$

$f = E_v/(1 + v_v) = 50/1.45 = 34.5$

Step 3

Not relevant – No granular subgrade layers

Step 4

Not relevant – No granular subgrade layers

Step 5

Not relevant – No granular subgrade layers

Step 6

No sublayering

$Poisson's\ Ratio = 0.40$

Resilient modulus = 2190MPa

Heavy Vehicle traffic speed = 100km/hr

$In\ service\ temperature\ =\ 28℃$

$$\frac{Modulas\ at\ WMAPT}{Modulus\ at\ test\ temperature\ (T)} = \exp\left(-0.025(28-25)\right)$$

$Temperature\ ratio = 0.93$

$$\frac{Modulus\ at\ speed\ V}{Modulus\ at\ test\ load\ rate} = 0.46 \times 90^{0.16}$$

$Load\ rate\ ratio = 0.96$

$Modulus\ correction = 2190 \times 0.93 \times 0.96 = 1953MPa$

Elastic properties of all materials

Material Type	Material Thickness (mm)	Elastic Modulus		Poisson's Ratio		f Value
		E_v	E_h	v_v	v_h	
Spray Seal	-	-	-	-	-	-
Foamed bitumen	260	1953	1953	0.40	0.40	1395
Subgrade	Semi infinint	50	25	0.45	0.45	34.5

Step 7

$$Allowable\ permanent\ deformation\ loading = \left(\frac{9300}{\mu\varepsilon}\right)^7$$

Step 8

Not relevant

Step 9

Foamed bitumen fatigue

$$N = \left(\frac{6918(1.08 + 0.856V_b)}{E_v^{0.36}\mu\varepsilon}\right)^5$$

$V_b = 6.1\%$

Step 10

Not relevant

Step 11

Standard axle load represented as

Tyre-pavement contact stress=750kPa

Load radius=92.1mm

Four circular area separated centre-to-centre 330mm, 1470mm and 330mm

Step 12

Critical location of calculated strains

- Bottom of Foamed Bitumen layer
- Top of Subgrade layer

The strains are calculated beneath one of the loaded wheels and mid-way between the loaded wheels

Step 13

Critical strains from CIRCLY

$Foamed\ Bitumen\ = 190\mu\varepsilon$

$Subgrade = 460\mu\varepsilon$

Step 14

Calculated Allowable Traffic Loading

- Foamed Bitumen

$$N = \left(\frac{6918(1.08 + 0.856 \times 6.1)}{(1953)^{0.36} \times 190}\right)^5 = 7.3 \times 10^5 SAR5$$

Converting Standard Axle Repartitions to ESA using $SAR5/ESA = 1.1$

$$N = \frac{7.3 \times 10^5}{1.1} = 6.6 \times 10^5\ ESA$$

- Subgrade

$$N = \left(\frac{9300}{460}\right)^7 = 3.4 \times 10^9\ SAR7$$

Converting Standard Axle Repartitions to ESA using $SAR7/ESA = 1.6$

$$N = \frac{3.4 \times 10^9}{1.6} = 8.6 \times 10^8\ ESA$$

Step 15

Allowable Traffic Loading = Service Life

- Foamed Bitumen $= 6.6 \times 10^5\ ESA$
- Subgrade $= 8.6 \times 10^8\ ESA$

Step 16

Not relevant – No design traffic

Step 17

Not relevant – No design traffic

Step 18

Not relevant – No design traffic

Appendix E. Summary of Service Life Data

Bitumen Content (%)		Lime Content (%)	% Finer than $75\mu m$	Dry Modulus (MPa)	Corrected Dry Modulus (MPa)	Critical Strain $(\mu\varepsilon)$	Service Life (ESA)
by dry weight	By Volume						
2.0	4.0%	2.0	2	3191	2845	143.6	2.9×10^5
2.0	4.0%	2.0	10	10683	9535	56.66	3.4×10^6
3.0	6.0%	1.0	6	2190	1953	190.2	6.6×10^5
3.0	6.0%	1.5	2	6905	6156	79.6	6.5×10^6
3.0	6.0%	1.5	6	9195	8198	63.7	1.2×10^7
3.0	6.0%	1.5	10	8217	7326	63.6	9.4×10^6
3.0	6.0%	1.5	13	5338	4759	97.1	3.8×10^8
3.0	6.0%	1.5	15	2397	2137	177.9	7.9×10^5
3.0	6.0%	2.0	2	818	729	384.8	1.2×10^5
3.0	6.0%	2.0	6	4174	3722	117.2	2.3×10^6
3.0	6.0%	2.0	10	6041	5386	88.3	5.0×10^6
3.0	6.0%	2.0	15	6279	5599	85.7	5.3×10^6
3.0	6.0%	2.0	20	4190	3736	116.9	2.4×10^6
3.0	6.0%	2.0	24	843	753	376.7	2.1×10^5
3.5	7.0%	1.5	2	1089	971	315.4	3.5×10^5
3.5	7.0%	1.5	6	4203	3747	116.6	4.4×10^6
3.5	7.0%	1.5	10	5701	5083	92.3	8.2×10^6
3.5	7.0%	1.5	15	5302	4728	97.6	7.1×10^6
3.5	7.0%	1.5	20	2379	2121	178.9	1.5×10^6

Table E-1: Service life data - Variations in Grading, Bitumen content and lime content (1)

Bitumen Content (%)		Lime Content (%)	% Finer than $75\mu m$	Dry Modulus (MPa)	Corrected Dry Modulus (MPa)	Critical Strain $(\mu\varepsilon)$	Service Life (ESA)
by dry weight	By Volume						
3.5	7.0%	2.0	2	4084	3642	119.1	4.2×10^5
3.5	7.0%	2.0	6	4637	4135	108.2	5.4×10^6
3.5	7.0%	2.0	10	5047	4501	101.4	6.4×10^6
3.5	7.0%	2.0	15	5359	4778	96.8	7.2×10^6
3.5	7.0%	2.0	20	5447	4857	95.6	7.5×10^6
3.5	7.0%	2.0	25	5412	4736	97.5	7.1×10^6
3.5	7.0%	2.0	30	4953	4416	102.8	6.2×10^6

Table E-2: Service life data - Variations in Grading, Bitumen content and lime content (2)

Bitumen Content (%)		Lime Content (%)	Dry Modulus (MPa)	Corrected Dry Modulus (MPa)	Critical Strain $(\mu\varepsilon)$	Service Life (ESA)
by dry weight	By Volume					
2.0	4.0%	2.0	10683	9525	56.7	3.4×10^6
3.0	6.0%	2.0	9245	8243	63.5	5.4×10^7
4.0	8.0%	2.0	6174	5505	86.8	2.3×10^8

Table E-3: Service life data - Variations in bitumen content

Bitumen Content (%)		Lime Content (%)	% Finer than $75\mu m$	Curing Condition	Dry Modulus (MPa)	Corrected Dry Modulus (MPa)	Critical Strain $(\mu\varepsilon)$	Service Life (ESA)
by dry weight	By Volume							
3.0	6.0%	1.5	11	Dry	5629	5019	93.2	8.9×10^5
				Wet	301	268	836.5	1.4×10^4
4.0	8.0%	1.5	13	Dry	5715	5096	92.1	4.2×10^6
				Wet	718	640	420.3	1.7×10^5

Table E-4: Service life data - Marginal material (Sandstone)