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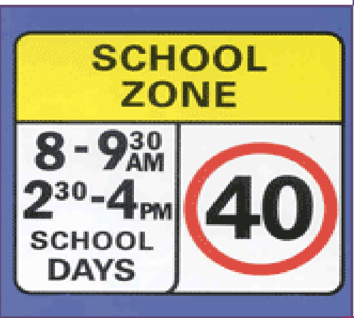
AUSTROADS TECHNICAL REPORT

Review of Foamed Bitumen Stabilisation Mix Design Methods



Austroads

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Review of Foamed Bitumen Stabilisation Mix Design Methods

Austroads

Sydney 2011

Austroads profile

Austroads' purpose is to contribute to improved Australian and New Zealand transport outcomes by:

- providing expert advice to SCOT and ATC on road and road transport issues
- facilitating collaboration between road agencies
- promoting harmonisation, consistency and uniformity in road and related operations
- undertaking strategic research on behalf of road agencies and communicating outcomes
- promoting improved and consistent practice by road agencies.

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- Roads and Traffic Authority New South Wales
- Roads Corporation Victoria
- Department of Transport and Main Roads Queensland
- Main Roads Western Australia
- Department for Transport, Energy and Infrastructure South Australia
- Department of Infrastructure, Energy and Resources Tasmania
- Department of Lands and Planning Northern Territory
- Department of Territory and Municipal Services Australian Capital Territory
- Commonwealth Department of Infrastructure and Transport
- Australian Local Government Association
- New Zealand Transport Agency.

The success of Austroads is derived from the collaboration of member organisations and others in the road industry. It aims to be the Australasian leader in providing high quality information, advice and fostering research in the road sector.

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SUMMARY

Foamed bitumen stabilisation is a road construction technique whereby bitumen is used to bind the existing or imported granular material to produce a flexible pavement material for use in base and subbase pavement layers, and in particular for road rehabilitation.

Foamed bitumen is a mixture of hot bitumen, water and air. For instance, in Queensland typical quantities are 97.5% bitumen, 2% water and 0.5% foaming agent. The foaming agent is added to improve the quality of the foam. When hot bitumen (160 to 200 °C) comes in contact with cold water (15 to 25 °C) the mixture expands to greater than 10 times its original volume and forms a fine mist or foam.

The foamed bitumen is sprayed into the mixing drum where it coats the surface of the some fine particles (typically less than 0.075 mm in diameter), making agglomerations of loosely packed mortar that adhere to the larger particles. Foamed bitumen mixes are generally regarded as cold-mixes, as they are placed and compacted at ambient temperatures.

Austroads Project No: TT1358: *Review of Structural Design Procedures for Foamed Bitumen Pavements* proposed a method for the thickness design of foamed bitumen to be adopted in principle by Austroads.

Appropriate foamed bitumen mix design method is an essential element in this technology which is increasing being used to rehabilitate Australian pavements.

The Austroads *Guide to Pavement Technology Part 4D Stabilised Materials* provides on the selection and mix design of foamed bitumen stabilisation treatments.

The aim of this report is review international and Australian methods used to determine mix properties and design optimum bitumen and secondary binder contents for the construction of foamed bitumen pavements to identify areas to improve and enhance Part 4D.

The mix design methods used in South Africa and Australia were examined.

South African mix design methods are very well represented in papers and guidelines pertaining to foamed bitumen. Whilst the research undertaken in South Africa is highly commendable, its relevance to Australia is currently limited. South Africa tends to use lower bitumen contents and models the foamed bitumen pavements as unbound granular pavements with enhanced performance.

In Australia higher binder application rates are the norm, and the stabilised material is considered susceptible to fatigue cracking. The mix design and structural thickness design methodologies used in South Africa and Australia are therefore different.

Based on the review of current practice, it is recommended that the Austroads *Guide to Pavement Technology Part 4D Stabilised Materials* be amended and updated to reflect the current state-of-the-art in Australian foamed bitumen mix design. Appendix A contains text for consideration in the Part 4D revision.

1 INTRODUCTION

1.1 General

Foamed bitumen stabilisation is a road construction technique whereby hot bitumen is used to bind the existing or imported granular material to produce a flexible pavement material for use in base and subbase pavement layers, and in particular for road rehabilitation.

Foamed bitumen is a mixture of hot bitumen, water and air. For instance, in Queensland typical quantities are 97.5% bitumen, 2% water and 0.5% foaming agent. The foaming agent is added to improve the quality of the foam. When hot bitumen (160 to 200 °C) comes in contact with cold water (15 to 25 °C) the mixture expands to greater than 10 times its original volume and forms a fine mist or foam.

The foamed bitumen is sprayed into the mixing drum where it coats the surface of the some fine particles (typically less than 0.075 mm in diameter), making agglomerations of loosely packed mortar that adhere to the larger particles. Consequently, these coated fines together with the secondary binder (i.e. cement of lime) improve the performance of the parent material. Foamed bitumen mixes are generally regarded as cold-mixes, as they are placed and compacted at ambient temperatures.

Austroads Project No: TT1358: *Review of Structural Design Procedures for Foamed Bitumen Pavements* (Austroads 2009) proposed an interim Austroads method for the structural thickness design of foamed bitumen stabilised pavements.

The aim of this report is to investigate international and Australian methods used to determine mix properties and design optimum bitumen and secondary binder contents for the construction of foamed bitumen pavements and to provide the necessary input values in the pavement design process.

The following documents were reviewed for consideration and information:

- *Foamed Asphalt Mixes Mix Design Procedure* (CSIR Transportek 1998)
- *Guide to Pavement Technology Part 4D: Stabilised Materials* (Austroads 2006)
- *Design of Foam Stabilised Pavements* (Ramanujam & Jones 2008)
- *Mix Design of Bitumen Stabilised Materials: Best practice and considerations for classification* (Ebels & Jenkins 2007)
- *Technical Guideline: Bitumen Stabilised Materials: A Guideline for the Design and Construction of Bitumen Emulsion and Foamed Bitumen Stabilised Materials* (Asphalt Academy 2009a).

Other sources were also consulted and referenced.

Based on this review an interim mix design method developed from the Queensland Department of Transport and Main Roads method is proposed for adoption by Australian road agencies.

1.2 Selected Mix Design Methods

1.2.1 South African Methods

Extensive research and development of methods and specifications for foamed bitumen stabilisation has been undertaken in South Africa.

CSIR Transportek (1998) details the method used in South Africa until the release in 2002 of the *Asphalt Academy Interim Technical Guideline TG2* (Asphalt Academy 2002), and formed the basis of many specifications for foamed bitumen pavements elsewhere in the world. The Asphalt Academy is a southern African centre for the coordination and development of knowledge transfer programmes and skills development in bituminous product technology in pavements. The Asphalt Academy Trust is operated on a non-profit basis, funded by the trustees Sabita (Southern Africa Bitumen Association) and the CSIR Built Environment.

In 2009, following research by Ebels and Jenkins (2007), a project was undertaken to update and revised *Interim Technical Guideline TG2*. The revised TG2 is titled *Technical Guideline: Bitumen Stabilised Material: A Guideline for the Design and Construction of Bitumen Emulsion and Foamed Bitumen Stabilised Materials*. This Guideline covers the classification, design and construction of Bitumen Stabilised Materials (BSMs), specifically bitumen emulsion and foamed bitumen treated materials.

The mix design of BSMs involves three levels of testing, which depend on the design traffic level. For Levels 1 and 2, this mix design method characterises mixes using indirect tensile strength (ITS) testing in dry and soaked states. For Level 3, applicable to heavily trafficked roads (design traffic exceeding 6×10^6 Equivalent Standard Axles (ESA)), it is recommended that ITS testing is supplemented by triaxial testing.

1.2.2 Queensland Department of Transport and Main Roads Method

Queensland Department of Transport and Main Roads (TMR) recommended design methodology for foamed bitumen stabilised pavements is contained in the Departmental manual *Design of Foam Stabilised Pavements* (Ramanujam & Jones 2008).

This mix design method, which was developed from the South African Asphalt *Academy Interim Technical Guideline* (Asphalt Academy 2002), is currently the most developed Australian method. Note that the design binder content is selected on the basis of indirect tensile modulus results rather than strength as used in the South African methods.

1.2.3 Austroads Pavement Technology Series

In 2006 Austroads published the *Guide to Pavement Technology Part 4D: Stabilised Materials*, which was developed from a complete revision of the Austroads Guide to Stabilisation in Roadworks (1998).

Aspects of Part 4D have now been superseded by information made available from Queensland Department of Transport and Main Roads (TMR) and Asphalt Academy. It is anticipated that the review undertaken in this report will result in Part 4D being updated.

1.3 Purpose for Characterisation of Materials

There are several reasons why laboratory characterisation of materials is undertaken. These include:

- to optimise material performance and to ensure the material meets minimum service requirements
- to provide material parameters for the thickness design method
- to minimise costs and to save non-renewable resources by optimising use of materials and additives

- to ensure the pavement when constructed according to the specification lasts a minimum design period
- research to determine fundamental pavement properties, to refine design methods and to generally extend knowledge that may be applied to pavements in material selection, material performance, pavement performance, application of pavement processes in various climatic conditions, and the effect of different axle loads and configurations on pavements.

For all but the first point above, a laboratory method and mix design procedure needs to meet the following criteria:

- cost-effective
- relatively quick
- repeatable
- reproducible by any competent technician
- provide realistic design inputs that match field performance
- ensure that the material and binders perform for the design period and withstand the traffic load applied.

Another important factor is that, generally pavements are not uniform, there are often significant variations within a pavement section, and during construction, there will be variations in moisture content, compaction input and mixing.

In selecting densities for preparation of laboratory test specimens consideration should be given to the minimum specified relative compaction levels and the variation in field compaction with depth below the surface. In some cases in urban areas, the presence of sensitive services such as old water mains and gas mains, and proximity to structures, mean that vibratory compaction may not always be possible and this may affect the level of compaction achieved.

In addition, the action of mechanical stabilisers on softer aggregate may change the particle size distribution during construction, and laboratory mixing may not reflect this change.

It is therefore important that any mix design process:

- recognise construction limitations
- consider variations in grading
- recognise that pavements are rarely consistent.

It is essential to recognise that laboratory characterisation should be used as a guide. Judgement and past experience should not be overlooked.

2 MATERIAL PROPERTIES

2.1 Bitumen Foaming Properties

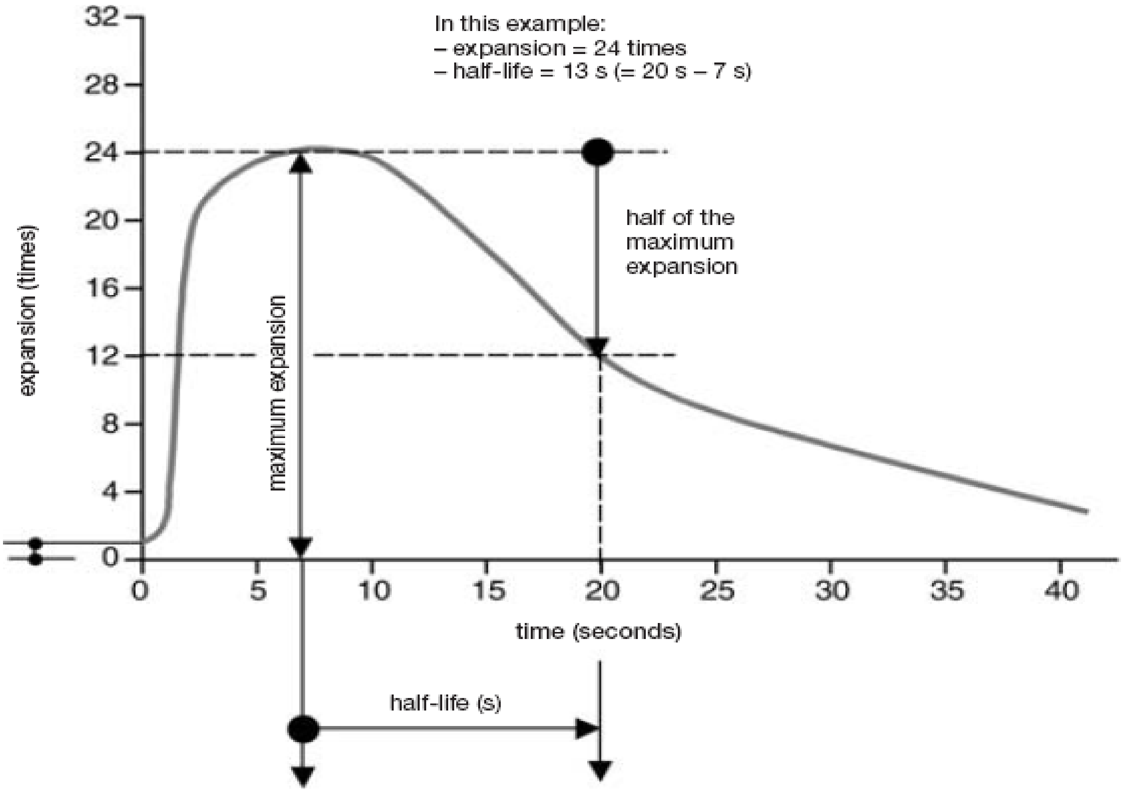
Foamed bitumen is a mixture of air, water and hot bitumen. Injecting a small quantity of cold water into hot bitumen produces an instantaneous expansion of the bitumen – forming foam with up to 15 times the original bitumen volume.

When the bitumen is in a foamed state it is ideal for mixing with fine materials because its large surface area bonds to fine particles. As the foam collapses very quickly, rapid mixing is required to adequately disperse the bitumen throughout the material.

The foam characteristics have been shown by Bowering and Martin (1976) to influence cohesion, stability and compressive strength. Foamed bitumen is normally characterised by:

- The **expansion ratio** of the foam which is defined as the ratio between the maximum volume achieved in the foam state and the final volume of the binder once the foam has dissipated.
- The **half-life** is the time, in seconds, between the moment the foam achieves maximum volume and the time it dissipates to half of the maximum volume.

These properties are shown schematically in Figure 2.1.



Source: Wirtgen (2004).

Figure 2.1: Foaming properties

These test properties can only be undertaken using specially-designed laboratory apparatus (Figure 2.1) and experienced technicians. In this test, bitumen is heated in a storage chamber to the desired temperature and a small quantity is discharged into a vertical sided receiving drum. As the bitumen is discharged to the drum, a known percentage of water is injected into the bitumen stream.

A calibrated ruler is used to measure the height of the foamed bitumen in the drum, and a stop watch is used to time the collapse of the foam. From these measurements the expansion ratio and half-life is calculated. The time taken to reach half of the difference between the maximum height and the minimum height is the half-life, and the expansion ratio is the ratio between the fully expanded and fully collapsed height of foam. Should the half-life or expansion ratio be unsatisfactory, the test is repeated with differing percentages of water and or the addition of foaming agents until the desired foam properties are achieved.

Source: Austroads (2006).

Figure 2.2: Example of laboratory foamed bitumen apparatus

Any bitumen may be foamed given the appropriate combination of nozzle type, water and air injection pressure; however it is noted that (adapted from CSIR Transportek 1998):

- bitumen containing silicones could have reduced foaming ability
- bitumen with low viscosity has superior foaming properties
- bitumen with low viscosity has superior aggregate coating ability
- anti-stripping agents intensify foaming ability
- acceptable foaming requires binder temperatures above 160 °C

- higher water contents and temperatures typically increased expansion ratios and decreased half-life
- certain foaming agents can produce expansion ratios of greater than 15 and a half-life greater than 60 seconds
- cohesion and compressive strength of mixes are generally greater when expansion ratios are high (15:1).

Abel and Hines (1978) found that bitumens of lower viscosity foamed more readily than those of higher viscosity, providing foams with higher expansion ratios and half-lives, but that higher viscosity bitumens produced an improved coating of aggregates. Clearly, consideration needs to be given to the type of bitumen used.

Note that the application of foaming agents to the bitumen or foaming water can extend the half-life of the bitumen by an order of magnitude (Jenkins 2000).

It should be noted that no published information has been available in Australia on the properties of the foaming agents used with bitumen supplied to AS 2008. The effectiveness of foaming agent is judged by their influence on expansion ratio and half life.

2.1.1 Austroads

The Austroads *Guide to Pavement Technology Part 4D: Stabilised Materials* does not describe the required properties of the virgin bitumen. Instead the suitability of the bitumen is assessed in terms of its measured foaming characteristics: the expansion ratio of not less than 15 times and a half-life of 30 to 45 seconds.

2.1.2 Queensland Department of Transport and Main Roads

The Queensland Department of Transport and Main Roads (TMR) recommended design methodology for foamed bitumen stabilised pavements is contained in the departmental manual *Design of Foam Stabilised Pavements* (Ramanujam & Jones 2008) and Ramanujam et al.2009.

In Queensland Class 170 bitumen is commonly used for stabilisation modified with 0.5% or more foaming additive to achieve the following foaming characteristics:

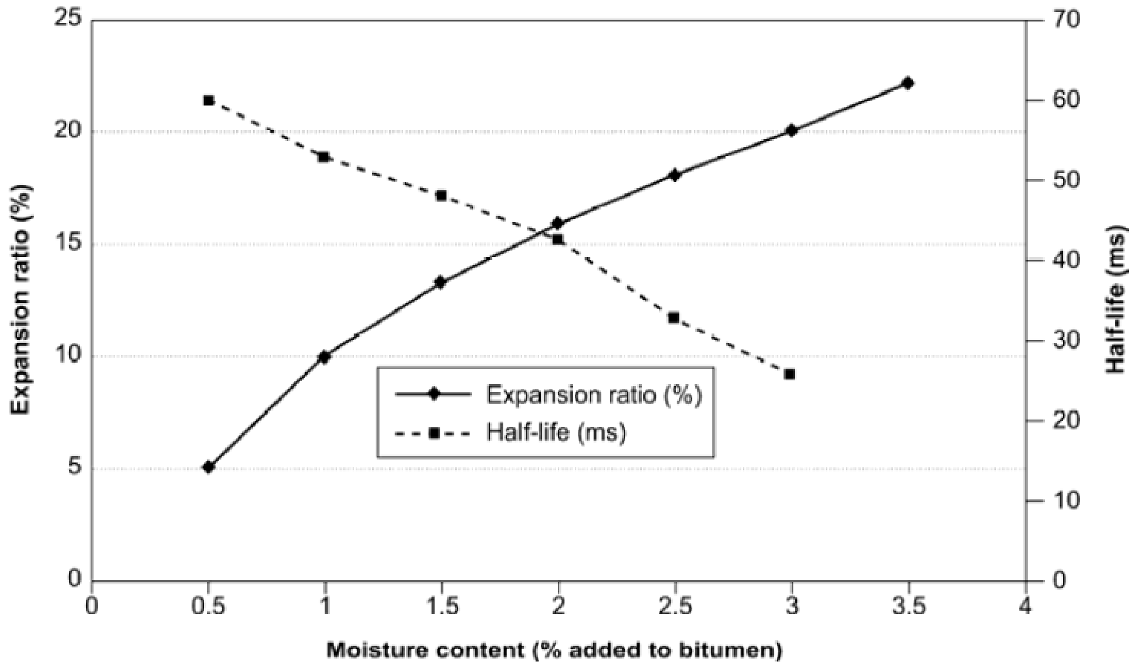
- recommended minimum expansion ratio of 12 times, with an absolute limit of 10 times
- recommended half-life of 45 seconds, with an absolute half-life of 20 seconds.

The foaming moisture content is 2.5%, unless the minimum expansion ratio of half-life requirements cannot be achieved.

2.1.3 Asphalt Academy

The Asphalt Academy method is the latest method for foamed bitumen mix design adopted in South Africa. This mix design method recommends minimum expansion ratios of 8 and 10 when the parent material is at temperatures of greater than 25 °C and 10−25 °C, respectively. A minimum half-life of 6 seconds is recommended irrespective of aggregate temperature (Asphalt Academy 2009a).

The method for determining the optimum water bitumen ratio for foaming is illustrated in Figure 2.3.



Source: Austroads Part 4D.

Figure 2.3: Determination of optimum foamant water content

2.2 Aggregate Properties

2.2.1 Particle Size Distribution

The recommended optimum particle size distributions of Austroads, TMR, and Asphalt Academy are shown in Figure 2.4. CSIR Transportek states that whilst materials outside the grading envelope may be stabilised, this should be treated with extreme caution (CSIR Transportek 1998).

The TMR recommended grading envelopes are slightly finer than those recommended by Austroads and Asphalt Academy.

The fines content is a critical property and all methods require a minimum 5% passing the 0.075 mm sieve. The resultant mastic of bitumen and fines has a significantly higher viscosity than the raw bitumen that acts as a mortar between the coarse aggregate particles.

For very low trafficked roads, TG2 has a grading limit approximating a coarse sand (Figure 2.4).

Materials that fall outside the recommended grading envelopes, whether coarse or fine can be rectified through the addition of the deficient fractions.

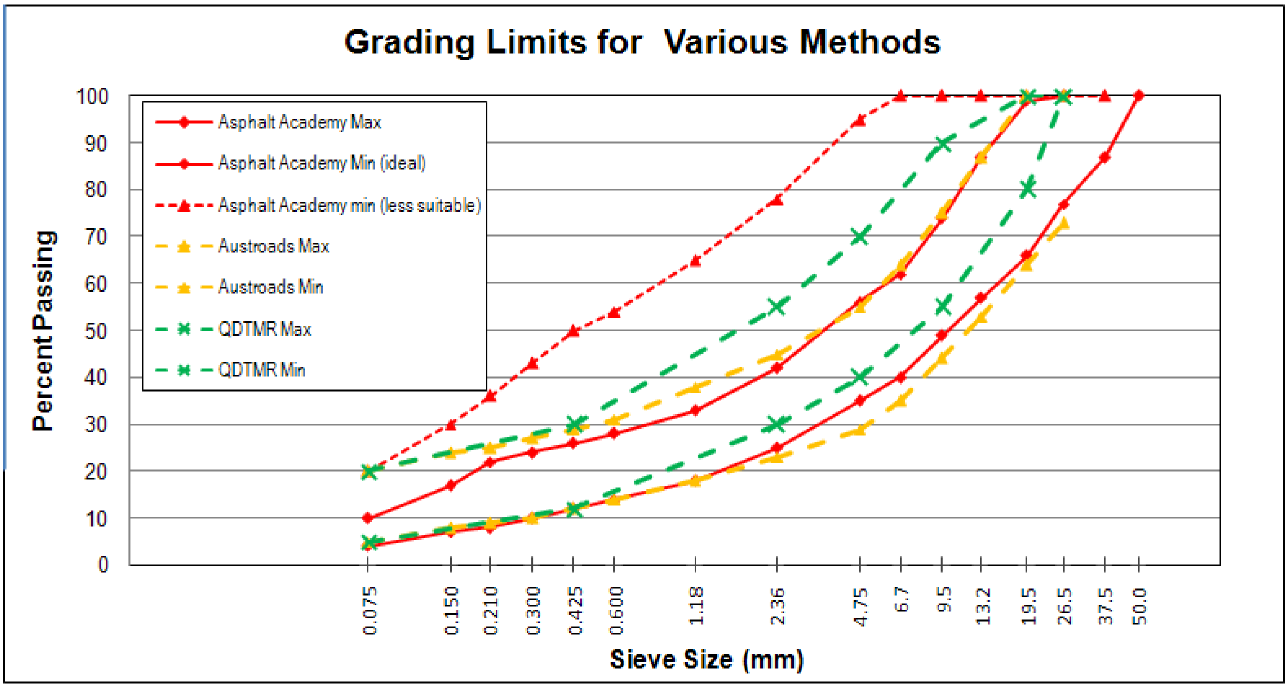


Figure 2.4: Grading envelope for foamed bitumen

2.2.2 *Aggregate Plasticity*

Plasticity limits assist in determining the suitability of an aggregate for stabilisation, and may be used to determine the application rate and type of secondary binder (lime and/or cement).

TMR recommends a maximum Plasticity Index (PI) of 10, but also states that lime is used for the following purposes (Ramanujam & Jones 2008):

- to flocculate and agglomerate the clay fines in the material
- stiffen the bitumen binder
- act as an anti-stripping agent
- assist in bitumen dispersion throughout the mix
- improve initial stiffness and early rut resistance.

TMR commonly uses 1.5 to 2.0% hydrated lime in their mixes (Ramanujam et al. 2009).

Austroads states that materials with a PI of 10 or less are usually suitable for stabilisation; above this level they are usually unsuitable unless pre-treated with lime (Austroads 2006).

Asphalt Academy (2009a) also recommends a maximum PI of 10, above which the material should be treated with lime. However, an upper limit of 1.5% hydrated lime is recommended by the Academy.

2.2.3 *Secondary Binders*

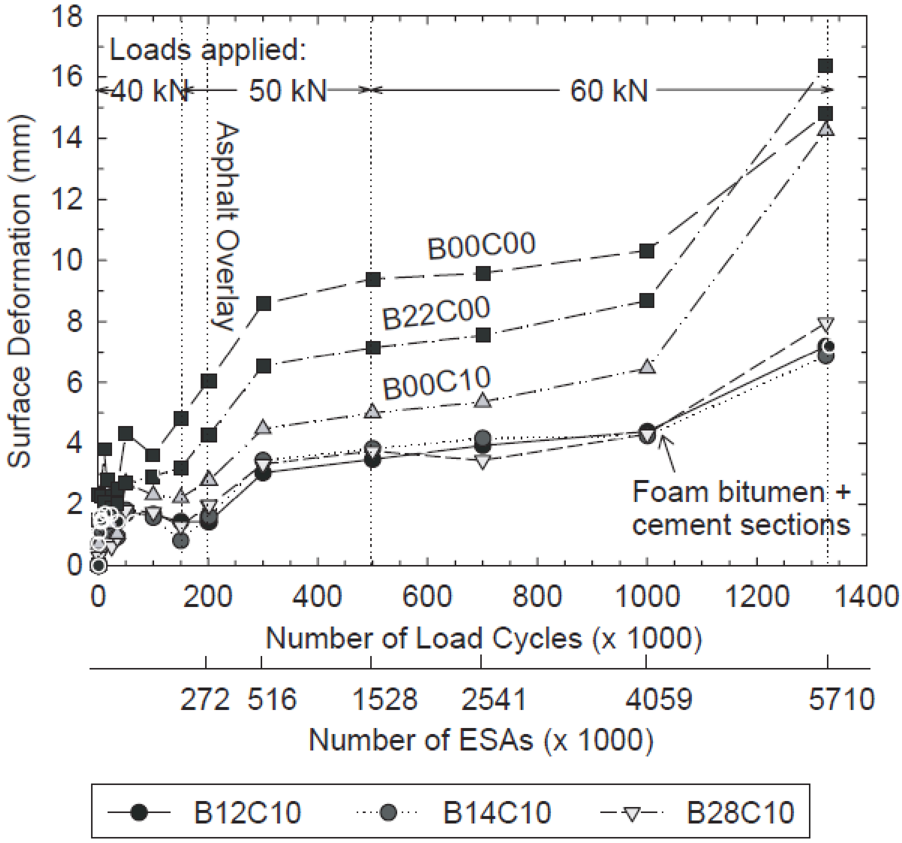
The strength characteristics of foamed asphalt mixes are highly moisture-dependent. Certain material types found in the existing pavement may require lime treatment to enable them to perform satisfactorily. This is because of the relatively low binder contents and high void contents of foamed asphalt mixes. Additives such as lime reduced the moisture susceptibility of the mixes.

Cement was also found to be as effective as lime, and cheaper (CSIR Transportek 1998). In Australia, hydrated lime is commonly used as a secondary binder and to a lesser extent cement.

The secondary binder, is said to serve the following purposes: (Jenkins 2008)

- stabilising binder for early strengths and cementitious bonds
- modifier to reduce plasticity
- dispersive binder for foamed bitumen
- anti-stripping agent.

An accelerated full-scale experiment was conducted in New Zealand (Gonzalez et al. 2009) to study the effects of foamed bitumen and cement in the performance of pavements (Figure 2.5). Six pavement sections were tested. Three were constructed with foamed bitumen contents of 1.2%, 1.4%, and 2.8% and with a common secondary binder content of 1.0% cement (pavement Sections B12C10, B14C10 and B28C10 in Figure 2.5).



Source: Gonzalez et al. (2009).

Figure 2.5: Surface deformation versus number of load cycles for CAPTIF test

Two more pavements were constructed with 1.0% cement only (B00C10) and 2.2% foamed bitumen only (B22C00). In addition, one control section with the untreated unbound granular material was tested (B00C00). The experiment showed that the surface deformation of section B22C00 was twice as much as that of sections stabilised with foamed bitumen and 1% cement.

At the end of the experiment section B22C00 failed (showing severe rutting and heaving) while the surface deformation of the sections stabilised with foamed bitumen and cement was between 7−8 mm. These results indicate that cement improves pavement performance for the materials tested and 1% cement should be added in foamed bitumen mixes for early-life performance. However, some Australian road agencies have observed shrinkage cracking when more than 1% cement has been used as the secondary binder.

Trials undertaken in the City of Canning in Western Australia (Leek 2010) have shown that cement is more effective in rapid strength gains in very early life, but the stiffness of lime or cement stabilised pavements appear little different after a month, and rutting under early traffic was not an issue for pavements constructed of predominantly crushed materials. However, bitumen contents are higher than that of the New Zealand trial above, ranging from 3.5% to 4.0% by mass.

The percentages of secondary binder specified by different agencies vary but are listed as follows:

- Asphalt Academy – zero to 1.5% hydrated lime, zero to 1% cement.
- TMR – between 1% and 2% hydrated lime is recommended, with 1.5% used where PI < 6% and 2% where PI > 6%.
- City of Canning – initially 1.5% quicklime resulted in significant transverse cracking, but no further cracking was observed when 0.8% quicklime was used. Trials have been undertaken without lime and no apparent difference in pavement performance has been noted.

More information regarding secondary binders is given in Section 3.3.

2.2.4 Aggregate Angularity

Stability of foamed asphalt mixes is influenced greatly by the aggregate interlock and angularity rather than binder viscosity, which is different to asphalt and implies lower temperature sensitivity for foamed bitumen compared to asphalt. The angularity of fine aggregate is an excellent indicator of suitability for foamed stabilisation.

In a limited study, Sakr and Manke (1985) showed that the stability of foamed asphalt mixes is affected to a greater extent by the aggregate interlock than by the viscosity of the binder, different from the behaviour of hot-mix asphalt. They also found that the angularity of fine aggregates is an excellent indicator of suitability for foam stabilisation. A minimum particle index of 10 was suggested in order to achieve good stabilities.

Early-life shear failure of some pavements stabilised using foamed bitumen in Western Australia has been attributed to low aggregate angularity (Leek 2010). Further research is required to establish whether such shear failure can be identified from laboratory measured aggregate angularity.

The angularity of fine aggregate is an excellent indicator of suitability for foamed stabilisation. A minimum particle index (ASTM D3398 2006) of 10 is recommended (CSIR Transportek 1998). Aggregate angularity is mentioned as an important property in TG2, but no guidance is given.

TMR recommends wheel tracker tests for pavements subject to over 1000 ESA/day in the first year after opening. In this test, a slab 300 mm x 300 mm is compacted to a density of 100% standard compaction. To check early performance, the slabs are cured for four hours at 40 °C and then tested with the wheel tracker at 25 °C. To assess the long-term rutting performance, the slabs are cured for 24 hours at 25 °C. The measurements of rut depth are recorded at 2000 cycles and 10 000 cycles.

2.2.5 Aggregate Durability

Durability is considered to be one of the most important aspects of the untreated aggregate, as this will determine the likely breakdown of particles resulting in generation of possible excess fines both in service and during stabilisation (Asphalt Academy 2009a).

Refer to Austroads *Guide to Pavement Technology Part 4J Aggregates and Source Rocks* for guidance on assessment of durability.

3 MIX DESIGN

3.1 Aggregate Preparation

There are various methods for preparing aggregate for trial specimens used in optimising bitumen content and secondary binder. The current methods are outlined in the following sections.

3.1.1 Queensland Department of Transport and Main Roads

The TMR method requires samples representative of the pavement profile and collected from that part of the pavement that is to be stabilised to the depth of stabilisation. Materials may be collected by mechanical excavation only where pavement material is sound and durable. Where aggregate quality is suspect (i.e. likely to break down further during mechanical mixing) sampling by skidsteer equipment with a profiler attachment is recommended.

3.1.2 CSIR Transportek and Asphalt Academy

The CSIR Transportek design method requires that the aggregates should be oven dried to a constant mass. The dried aggregates are riffled into five batches of 10 kg each. These are used to produce five batches of foamed asphalt samples at various binder contents. Whilst not stated in some other documents, this principle is a common requirement, the only difference being the number of batches.

The following points need to be addressed in sample preparation (Asphalt Academy 2009a):

- The grading that will be generated by a recycling machine needs to be replicated in the laboratory testing, and this is best achieved by sampling each layer separately in the pavement using a milling machine.
- The blending of reclaimed asphalt pavement (RAP) and pavement layers needs to be in the same proportion as existing in the pavement.
- The variability of material type over the length and depth of the existing pavement, so that adjustments can be made to the mix design where necessary. Where variability is encountered, the individual layers should be sieved into the respective fractions and recombined in the required ratios. In this way a consistent blend can be achieved and the influence of variations in grading on the mix properties can be investigated.
- On-site milling is the most suitable method for achieving representative samples.

As many particles in an existing pavement are greater than 25 mm, 150 mm specimens should be prepared rather than 100 mm specimens.

Recycled granular layers should have a stone size limited to 75 mm, with a minimum layer thickness three times the largest stone size and less than 20% by mass of any stone larger than 50 mm. Up 75% reclaimed asphalt (RA) is acceptable, and in areas with moderate climate and well regulated axle loading this may be increased to 100%. In a warm climate or high axle loads, then the composition of the RA needs to be modified by blending with 15−25% crusher dust to improve the required shear resistance.

3.2 Bitumen Content for Trial Mixes

Bitumen content is limited in range by loss of stability at high bitumen contents and water susceptibility at lower end. Some practitioners (CSIR Transportek 1998, Ruckel et al. 1982) consider the ratio of bitumen to fines is a significant parameter in the optimum binder content.

3.2.1 Austroads

Part 4D recommends testing at three bitumen contents, 2%, 3% and 4% bitumen by mass.

3.2.2 Queensland Department of Transport and Main Roads

A trial bitumen content is selected based on the material particle size distribution as shown in Table 3.1. The trial bitumen content is commonly 3%. Three test cylinders are then prepared at each of the following bitumen contents:

- trial content -0.5%
- trial content
- trial content +0.5%.

Table 3.1: Bitumen content versus particle size

Passing 4.75 mm sieve (%)	Passing 0.075 mm sieve (%)	Bitumen content (% of dry aggregate)
< 50	5.0−7.5	3.0
	7.5−15	3.5
	15−20	4.0
> 50	5.0−7.5	3.5
	7.5−15	4.0
	15−20	4.0

Source: Ramanujam and Jones (2008).

3.2.3 Asphalt Academy

The new South African method states that for foamed bitumen pavements, the bitumen content is usually between 1.7% and 2.5% (Asphalt Academy 2009a). There are no guidelines as to the determination of an optimum binder content.

The test method refers to a grading modulus but fails to define what this term means. Note grading modulus is not referred to in TG2.

The grading modulus is defined as: (Paige-Green 2006)

> Grading Modulus (GM) = (P2+P425+P075)/100 where P2, P425 and P075 are the percentages retained on the 2.0, 0.425 and 0.075 mm sieves, respectively.

Test Method 8(1) (Asphalt Academy 2009b) gives a target bitumen content as detailed in Table 3.2.

Table 3.2: Target percentage bitumen content

Material type	100% Reclaimed asphalt pavement (RAP)	Granular materials or blends grading modulus > 2	Granular materials or blends grading modulus < 2
Recommended percentage of residual bitumen (%)	2.0	2.5	3.0

Source: Asphalt Academy (2009b).

3.3 Secondary Binder Contents

TMR states (Ramanujam & Jones 2008) that the secondary binder content is dependent on grading and plasticity of the parent material. For in situ stabilisation works, the following hydrated lime contents are generally used:

- 2.0% lime for PI ≥ 6% up to the maximum PI of 10
- 1.5% lime for PI < 6%.

The Austroads method recommends 1−2% supplementary binder (lime or cement); the 2% upper limit being a practical limit based on field experience. The Guide notes that the lime may not be required for lightly-trafficked roads if the PI of the parent material is very low (Austroads 2006).

The new South African TG2 method states that for foamed bitumen pavements, the PI should not exceed 10 unless lime is added (Asphalt Academy 2009a). There are no guidelines as to the determination of a target secondary binder content, but does state that where cement is used, it should not exceed 1% by mass. Secondary binder is generally hydrated lime or cement. Any cement type apart from rapid setting cement may be used. When cement is used, the maximum addition rate should not exceed 1%. The optimum secondary binder cannot be predicted without laboratory characterisation. When lime is used, 1.5% or more can be added to modify plasticity. When existing materials are plastic, in the laboratory testing should consider the time required for the lime react with the plastic fines before the addition of bitumen.

3.4 Moisture Content for Trial Mixes

The moisture content of the mineral aggregate at the time of mixing with the foamed bitumen needs particular consideration. Whilst insufficient water reduces workability, bitumen dispersion and compaction, too much water reduces strength, increases curing time and affects aggregate coating (CSIR Transportek 1998).

Note that the moisture content for mixing and compaction is different from the moisture content required to foam the bitumen (Section 2.1).

3.4.1 Queensland Department of Transport and Main Roads

TMR method requires that the moisture content is determined from the PI or field moisture contents as follows:

- PI < 6% – prepare test samples at 70% Optimum Moisture Content (OMC) of the untreated material using Standard compaction
- PI 6−10% – prepare test samples at 70% OMC of the untreated material using Standard compaction or higher
- where field moisture content are greater than 70% OMC (Standard compaction), prepare test samples at field moisture content.

3.4.2 Asphalt Academy

Sample moisture contents vary through the mix preparation process. The mixing moisture content is 65% to 85% of OMC as determined by modified AASHTO compaction of the untreated material. The minimum mixing moisture content is the aggregate ‘fluff point’, the point at which maximum bulk volume of the loose aggregate is obtained.

A vibratory hammer is used for laboratory mix characterisation, and the OMC for the material is determined using this form of compaction. The method is detailed in Test Method 8(1) (Asphalt Academy 2009b). Due to compaction with heavy vibratory rollers, the appropriate moisture for field compaction may be 1.5% lower than the OMC by laboratory vibratory compaction.

Briefly, the method requires the following steps:

- determine the OMC of the untreated material
- add 60% of OMC as compaction water to the mix and inject the target bitumen content into the mix
- sample the mix
- add increments of 1% water to the mix, sampling at each increment
- compact samples using a vibratory hammer and construct density-moisture curve
- determine OMC where maximum density is achieved.

3.5 Mixing and Compaction

3.5.1 Austroads

The method of mixing the binders with the aggregate is important as only a finite mixing time is available before the foam collapses and returns to a highly viscous state, with no affinity for particle coating. In general, the foamed bitumen is applied directly from the laboratory foam plant (Figure 2.2) to the aggregate as it is being agitated in the mixer (Figure 3.1).

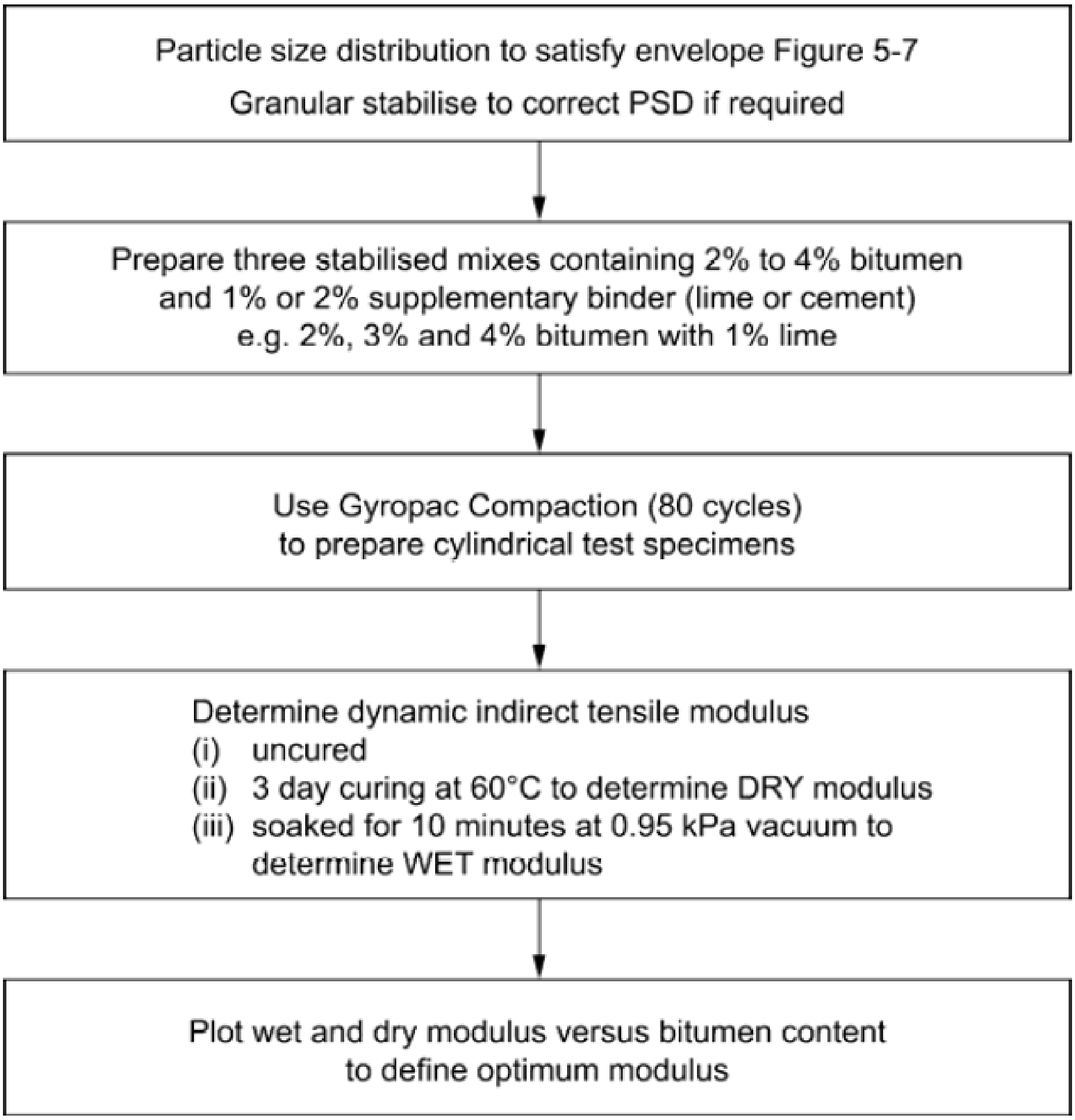
Source: Gonzalez personal communication (2010).

Figure 3.1: Sample mixing prior to addition of foamed bitumen

An appropriate laboratory compaction technique should not only achieve the voids content expected in the field but also, as far as possible, emulate the particle orientation after field rolling.

Austroads (2006) recommends compaction of test cylinders is undertaken using gyratory compaction (80 cycles) or Marshall (50 blows) compaction. The gyratory method is a refinement of that developed by Maccarrone et al. (1994). It should be noted research by Jones et al. (2000) showed that pavement materials may be sensitive to the type of compaction.

The Austroads mix design procedure is summarised in Figure 3.2.



Source: Austroads (2006).

Figure 3.2: Procedure for the design of bituminous stabilised materials

3.5.2 Queensland Department of Transport and Main Roads

The TMR method specifies the following steps to mix samples for characterisation for each trial binder content:

- wet the dried sample to design moisture content
- place a 10−12 kg sample in the mixing bowl
- mix in the required quantity of secondary binder, lime is commonly used but for some projects cement is used
- commence mixing and add desired weight of foamed bitumen, allowing for losses in containers and foaming apparatus

- determine the actual bitumen content of the mix
- ensure bitumen source and type is the similar to that to be used for the works, with a minimum 0.5% bitumen foaming binder
- ensure bitumen temperature range is 170 °C to 190 °C
- add the foaming water to produce foam optimised to meet both the half-life and expansion ratio requirements (Section 2.1.2).

After mixing, cylindrical test specimens are compacted using the Marshall hammer (50 blows/layer) as follows:

- riffle stabilised material into four samples of 2.5 kg
- compact in 150 mm diameter Marshall moulds (not heated) using 50 blows/face.

3.5.3 Asphalt Academy

Problems associated with Marshall and modified AASHTO compaction methods are identified as (Ebels & Jenkins 2007):

- lack of simulation of kneading action of rollers resulting in mortar failing to occupy voids on outer annulus
- variability in target densities for on-site quality control purposes
- delamination of specimens during modified AASHTO compaction.

Whilst gyratory compaction may overcome some of these issues, there is considerable variability in results.

The Asphalt Academy considers vibratory hammer compaction emulates the field density and particle orientation achieved in the field. Where a vibratory hammer is not available, Marshall compaction may be used, but it is the less preferred option. The OMC must be relative to the compaction method used, and is based on the untreated material.

The method calls for the production of 150 mm diameter 300 mm high specimens using the vibratory hammer method. The moisture content recommended is the OMC of the untreated material determined using modified AASHTO compaction. Compaction is undertaken at 25 ± 2 °C.

3.6 Laboratory Curing Conditions

Curing is the process whereby the mixed and compacted material discharges water through evaporation, particle charge repulsion or pore pressure induced flow paths (Jenkins 2000). The reduction in moisture content leads to an increase in strength and rut resistance of the mix.

In the field, curing may take many months. The laboratory process needs to simulate field conditions of curing, but as it is impractical to cure for months, an accelerated method is required to emulate field conditions.

According to Maccarrone et al. (1994), oven curing for three days at a temperature of 60 °C appears appropriate. From a United Kingdom study (Durkin 1993), both the resilient modulus and creep properties of laboratory specimens cured in this manner were similar to those of field cores taken 12 months after construction. However, as discussed below, more recently the accelerated curing temperature has been lowered to 40 °C.

3.6.1 Austroads

Austroads recommends the following approach to sample curing:

- Immediately after compaction the cylinders are tested for modulus without curing. The uncured modulus needs to exceed 700 MPa to ensure that the pavement can be opened to traffic after trimming.
- The cylinders are then oven cured at 60 °C for three days and then tested dry for indirect tensile modulus (M_{dry}).
- The cylinders are then soaked in water prior to testing for their soaked modulus (M_{wet}). Two methods may be used for soaking the cylinders: submerged under water for 24 hours, or in a vacuum chamber for 10 minutes.
- The wet and dry modulus results are then plotted versus bitumen content to define the optimum modulus.
- Note samples should be prepared with moisture contents such that M_{wet}/M_{dry} is 0.5 or more, because bituminous binders will not cure at excessive moisture contents.

On large projects, additional testing may be undertaken including unconfined compressive strength, flexural fatigue and creep.

3.6.2 Queensland Department of Transport and Main Roads

In the TMR method, the prepared samples are tested for modulus in three states as follows:

- Initial modulus after three hours curing at 25±5 °C is determined to provide an indication of susceptibility to permanent deformation early in pavement life. Where the initial daily traffic on opening is 1000 ESA or more, TMR recommends that this three hour curing time be confirmed by wheel tracker testing.
- Cured modulus where the sample is oven cured at 40 °C for three days to provide an indication of medium term stiffness 3−6 months after construction.
- Soaked modulus where the sample is submerged under water for 10 minutes under a 95 kPa vacuum to provide an indication of the moisture sensitivity of the material.

Based on TMR experience, laboratory cured samples compacted to 50 blow Marshall compaction achieve similar resilient modulus values to the upper half of field cores after 12−24 months field curing.

TMR practice is not to seal the samples during curing.

3.6.3 Asphalt Academy

In the new South African method, the shortcomings of several curing methods in use were discussed as follows (Asphalt Academy 2009a):

- Curing at 60 °C in an oven results in lower moisture contents than field equilibrium.
- Characterising materials with secondary binders where curing for 7 days or 28 days resulting in time delays.
- Sealing specimens in plastic bags and curing for 72 hours in an oven at 40 °C retains excessive moisture and gives conservative results.

- Curing for 24 hours at 25 °C (unsealed) followed by 48 hours sealed in a bag and cured in an oven at 40 °C more closely reflects equilibrium moisture content but does not provide evidence that the laboratory stiffness truly reflects field stiffness.
- Interpretation of stiffness from tangent modulus derived from modified Californian Bearing Ratio (CBR) compression tests and determination of curing time at ambient temperature yields modulus values comparable to that used in the mechanistic design – but results in time delays and requires more research.
- Field testing in southern Africa to re-evaluate prediction models for equilibrium moisture content has provided more robust predictions based of optimum moisture content, bitumen content and climate and showed that the 24 hours at 25 °C unsealed and then 48 hours sealed at 40 °C provided the most accurate prediction.

Whilst research is currently underway in southern Africa, as an interim, the current recommended method is to cure for 24 hours at 25 °C unsealed and then seal and cure for a further 48 hours at a temperature of 40 °C (Asphalt Academy 2009a).

3.7 Design Binder Content Determination

3.7.1 Austroads

In the Austroads method, the resilient modulus of three samples both wet and dry is plotted to determine the binder content at the maximum resilient modulus. Note that the maximum modulus is not the only criteria used to establish the 'optimum' binder content: maximum modulus, wet to dry modulus ratio and local experience are used to establish the most effective bitumen binder content along with the addition of a supplementary binder.

3.7.2 Queensland Department of Transport and Main Roads

In the TMR method, the design binder content is determined from the indirect tensile modulus results of the trial mixes. The indirect tensile modulus is determined in accordance with AS2891.13.1 using the following parameters:

- condition pulse period 2000 ms
- test pulse period 3000 ms
- rise time 40 ms
- target resilient strain 50 $\mu\varepsilon$
- Poisson's ratio 0.40.

The minimum limits for mix design are detailed in Table 3.3 . Note these values are only appropriate for:

- test cylinders mixed, compacted and cured using the TMR method
- pavements surfaced with up to 100 mm hot mix asphalt.

The modulus is not the only criteria used to establish the 'optimum' binder content and it should be emphasised that modulus, wet to dry modulus ratio and local experience are used to establish the most effective bitumen binder content along with the addition of a supplementary binder.

Table 3.3: TMR minimum mix design modulus values

Average daily traffic at year of opening to traffic (ESA)	Base and subbase	Base course			Subbase course		
	Initial modulus(1) (MPa)	Min cured modulus(3) (MPa)	Min soaked modulus (MPa)(4)	Min retained modulus ratio(5)	Min cured modulus (MPa)(3)	Min soaked modulus (MPa)(4)	Min retained modulus ratio(5)
< 100	500	2500	1500	0.40	2500	1500	0.40
100−1000	700	3000	1800	0.45	2500	1500	0.45
> 1000	700(2)	4000	2000	0.50	2500	1500	0.50

1 Samples initially cured at 25 °C for 3 hours prior to initial modulus testing.
2 Recommended supplementary wheel tracking testing to confirm curing time.
3 Samples cure at 40 °C for 3 days prior to cured modulus testing.
4 Cured modulus test samples conditioned in a water bath under vacuum of 95 kPa for 10 minutes prior to testing.
5 Retained modulus ratio = soaked modulus/cured modulus.

Source: Ramanujam et al. (2009).

To minimise the risk of rutting after early-life curing, wheel tracking testing is recommended by TMR, particularly for project with daily traffic of 1000 ESA or more on opening to traffic. The test procedure for long-term rut resistance assessment is as follows (adapted from the Deformation Resistance of Asphalt Mixtures by the Wheel Tracking Test (Austroads 2006) used for hot mix asphalt):

- prepare three slabs 300 mm x 300 mm x 100 mm in segmented wheel compaction device at a density of 100% standard compaction
- the slabs are cured for 3 days at 40 °C
- apply wheel load of 700 N
- test for 10 000 cycles in wheel tracking device at a test temperature is 25 °C
- measure rut depth at 2000 cycles and 10 000 cycles.

Acceptable limits are:

- maximum rut depth at 2000 cycles: 5 mm
- maximum rate of rut progression: 0.1 mm/kilocycle.

3.7.3 Asphalt Academy

The Asphalt Academy method is very detailed, and as such requires more detailed discussion under the headings below.

Mix characterisation tests

The limitations of the current unconfined compressive strength (UCS) and indirect tensile strength (ITS) tests for mix design were noted as:

- UCS test is similar to triaxial test without confinement and the height to diameter ratio of 0.85 is considered too low to provide realistic shear values.
- The ITS test is simple but the interpretation of results is complex. The assumption that plane stress is achieved is not correct for the specified cylinder dimensions.

Despite these drawbacks, the UCS and ITS tests are considered suitable for **first stage** of mix design. These tests assist in optimising the following properties:

- aggregate grading – UCS
- blend proportions of pavement materials – UCS
- use of secondary binder – ITS
- use of cement or lime as secondary binder – ITS
- moisture susceptibility – ITS
- type of binder – UCS and ITS
- binder content – UCS and ITS.

Material incompatibility is highlighted in these strength tests and their use reduces the number of subsequent of more fundamental performance related tests which include:

- shear resistance as measured with the triaxial test
- permanent deformation resistance measured with the triaxial test
- the Texas triaxial test.

Material classifications

The 2009 TG2 defines three grades of bitumen stabilised materials, BSM1, BSM2 and BSM3 depending on the quality of the parent material and the design traffic. The three classes are:

- BSM1: This material has a high shear strength, and is typically used as a base layer for design traffic of more than 6 million ESA. For this class of material, the source material is typically a well graded crushed stone or reclaimed asphalt (RA).
- BSM2: This material has moderately high shear strength, and is typically used as a base layer for design traffic applications of less than 6 million SA. For this class of material, the source material would typically be a graded natural gravel or RA.
- BSM3: This material typically consists of soil-gravel and/or sand, stabilised with higher bitumen contents. As a base layer, this material is only suitable for design traffic applications of less than 1 million ESA.

Outline of procedure

Preliminary tests are always undertaken and include:

- particle size distribution
- Atterberg limits
- moisture/density relationships (OMC and maximum dry density).

There are three levels of mix design with specific requirements as follows:

- Level 1 mix design for design traffic less than 3 million ESA
  - compact 100 mm Marshall blocks and cure for indirect tensile strength (ITS) testing
  - identify preferred bitumen stabilising binder
  - determine optimum bitumen content
  - identify need for and type and content of secondary binder.

- Level 2 mix design for design traffic 3 to 6 million ESA
  - prepare 150 mm diameter 127 mm high (Proctor) specimens using vibrating hammer and cure for ITS testing
  - determine optimum bitumen content determined.
- Level 3 mix design for design traffic greater than 6 million ESA
  - 150 mm diameter 300 mm high specimens are prepared as per Level 2
  - undertake triaxial testing for higher level of confidence.

Laboratory mixing equipment

A pugmill type with a mixing time of 20 to 30 seconds is recommended to simulate the energy input during construction.

Curing of specimens

The curing method is dependent on the level of mix design as follows:

- Level 1 – cure 3 days at 40 °C unsealed. After the dry ITS (ITS_{dry}) is measured, the specimens are soaked in water for 24 hours then the soaked ITS (ITS_{soaked}) is measured.
- Level 2 and 3 – the objective of the curing is to produce moisture contents of 43−50% of OMC, which represents the long-term equilibrium moisture content of the material in the field. A two-stage approach to curing is used: cure for 20 hours at 30 °C unsealed and then cure for 48 hours at 40 °C sealed.

Mechanical tests

This South African method does not specifically detail the number of samples to be tested at each binder content, nor does it specify the binder content range for the determination of a target binder content. It would be assumed that specimens at and either side of a target bitumen content would be prepared and three samples tested both soaked and unsoaked, implying the preparation of 6 specimens at each binder content.

Indirect tensile strength (ITS)

For Level 1, 100 mm diameter Marshall blocks are prepared and ITS_{dry} and ITS_{soaked} are determined at 25 °C. This test is used to optimise bitumen content. The ratio of ITS_{dry} and ITS_{soaked} is determined and expressed as a percentage. This is called tensile strength retained (TSR).

For Level 2 testing, the curing is to simulate equilibrium moisture content, and the ITS value unsoaked but cured is termed ITS_{equil}. Again the soaked value is termed ITS_{soaked}.

The TSR is useful to identify problem materials. If the TSR is less than 50%, it is recommended that secondary binder be used. Where a material has a TSR less than 50%, and the ITS_{dry} exceeds 400 kPa, the material is likely to contain clays and the bitumen is ineffective. In this situation, the material probably requires pre-treatment.

The limits for interpreting the various ITS tests, and the purpose of the tests are provide in Table 3.4 .

Table 3.4: Interpretation of ITS tests

Test	Specimen diameter (mm)	BSM1	BSM2	BSM3	Purpose
		ITS (kPa)			
ITS_{dry}	100	> 225	175−225	125−175	Indicates optimum bitumen content
ITS_{wet}	100	> 100	75−100	50−75	Indicates need for secondary binder
TSR	100	N/A			Indicates problem material where TSR < 50 and ITS_{dry} > 400 kPa
ITS_{equil}	150	> 175	135−175	95−135	Optimise bitumen content
ITS_{soaked}	150	> 150	100−150	60−100	Check value on ITS_{wet}

Source: Asphalt Academy (2009a).

Triaxial test

A simple triaxial test (STT) is used to obtain cohesion and friction angle values. The monotonic stiffness of the material, tangent modulus (Etan), provides an indication of resilient response of the material and may be used to track trends in stiffness of different mix compositions.

The tangent modulus is, however, not a direct measure of the resilient modulus. Advanced triaxial setups may also be used for testing. The cohesion, friction angle and tangent modulus are used in the classification of BSMs. The limits used to interpret the data for the three material classes are shown in Table 3.5.

Moisture induced sensitivity test

Triaxial specimens are conditioned with moisture exposure using the moisture induced sensitivity test (MIST) apparatus which applies cyclic moisture ingress at realistic pore pressures. The cohesion values are compared for specimens with and without moisture exposure, to provide the retained cohesion percentage for the particular BSM. These values assist in the classification of the mix. The values are shown in Table 3.5.

Table 3.5: Interpretation of triaxial tests

Test or indicator	BSM1	BSM2	BSM3
Cohesion (kPa)	> 250	100−250	50−100
Friction angle (°)	> 40	30−40	< 30
Retained cohesion (MIST)	> 75%	60−75%	50−60%

Source: Asphalt Academy (2009a).

4 DISCUSSION

In the proposed Austroads interim thickness design method, foamed bitumen stabilised materials are considered to be susceptible to fatigue cracking. This interim Austroads method is applicable to bitumen contents of 3% or more commonly used in Australia (Austroads 2009). In contrast, in New Zealand and South Africa the lower bituminous binder contents used are considered to result in a material which is considered to be a modified granular material not susceptible to fatigue cracking. Accordingly the mix design methods and specification are different.

In recommending an interim mix design process for use by Australian road agencies, it is essential the method is compatible with the interim Austroads thickness design method. Accordingly, the TMR mix design method, rather than New Zealand and South Africa methods, is the most relevant as it reflect current Australian foamed bitumen stabilisation practice.

The various design methods have many common elements and differences. These are highlighted below.

4.1 Foaming Water Content

The foaming characteristics of the bitumen is assessed by heating the bitumen to between 170 °C and 190 °C and measuring foam expansion and half-life at five moisture contents between 1% and 3% at 0.5% increments.

The water content for bitumen foaming is selected such that both the minimum specified foam half life and expansion ratio values are met. Table 4.1 summarises the current specified values against which the laboratory measured values are compared.

It is proposed that Austroads Guide to Pavement Technology Part 4D expansion ratio and half-live values be amended to the TMR values.

Table 4.1: Minimum expansion ratio and half-life

Source	Minimum expansion ratio	Minimum half-life
Austroads Guide to Pavement Technology Part 4D (2006)	15	30−45 seconds
TMR Ramanujam and Jones (2008), Ramanujam et al. (2009)	Recommended limit: 12 Absolute limit: 10	Recommended limit: 45 Absolute limit: 20
South African Asphalt Academy TG2 (2009)	Temp 10−25 °C: 10 Temp > 25 °C: 8	6

4.2 Materials Suitable for Foamed Bitumen Stabilisation

4.2.1 Varying Requirements with Traffic Loading

The new South African guidelines define three grades of bitumen stabilised materials, BSM1, BSM2 and BSM3 (refer Section 3.7.3) depending on the quality of the parent material and the design traffic.

Although TMR varies modulus and wheel tracker deformation requirements with traffic loading, the TMR guidelines do not vary the quality of the untreated material. Nevertheless, the concept of increasing material quality level with traffic loading is widely used for unbound granular materials to ensure adequate performance rather than relying on modulus and wheel tracker deformation tests as measures of performance.

Until such time as performance tests such as wheel tracking are established, consideration should be given to varying the quality of the untreated material with traffic loading.

TMR currently uses three classes of traffic loading:

- average daily traffic on opening to traffic less than 100 ESA
- average daily traffic on opening to traffic less than 100−1000 ESA
- average daily traffic on opening to traffic greater than 1000 ESA.

It is proposed that these traffic categories be adopted in future revisions of Part 4D and are used in the following sections.

4.2.2 Aggregate Grading

Table 4.2 compares the recommended grading envelope of Part 4D of the Austroads Guide, TMR and the South African TG2.

For daily traffic loading greater than 1000 ESA, stabilised base should be limited to a size 20 mm to ensure a high standard ride quality, consistent with the TMR envelope. However, both the Austroads and TMR envelopes allow much finer gradings below the 0.300 mm sieve than the recommended TG2 envelope.

In addition Table 4.6 of TG2 indicates that bitumen stabilisation of materials with more than 25% passing 0.425 mm sieve is ‘doubtful or supplementary binder required’. This suggests that for heavily trafficked roads at least, the grading envelope for 0.425 mm sieve should be similar to TG2.

In summary, consideration should be given to amending Part 4D to provide a different grading envelope for heavily trafficked bases as shown in Table 4.2.

Table 4.2: Comparison of recommended particle size distribution of untreated material

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

4.2.3 Plasticity

Austroads Part 4D currently states that materials usually suitable for stabilisation have a PI less than or equal to 10. Between PI of 10 and 20 the material is suitable only if there is more than 25% passing the 0.425 mm sieve. Above PI of 20, the parent material is unsuitable.

It is noted that TMR limits the parent material to a maximum PI of 10, irrespective of the percentage passing the 0.425 mm sieve.

It is recommended that Part 4D remain unchanged, except to highlight that materials with PI between 10 and 20 may be pre-treated with lime to reduce the PI to a maximum of 10.

4.2.4 Aggregate Durability

Durability is that property of a rock which enables its particles to retain their dimensions and mechanical properties in service. Durability is the abrasion and weathering resistance of a material. It describes the changes in the performance of a material under repeated loading and long-term weathering.

Components of durability may be measured by physical test procedures (e.g. wet/dry strength variation, Los Angeles value and degradation factor tests). The purpose of specifying these individual durability test limits is to ensure that materials will not significantly break down, resulting in a change to the particle size and shape and increases in the fines-content and fines-plasticity during construction and throughout the life of the pavement. These factors strongly affect the engineering properties of unbound materials (shear strength, stiffness and permanent deformation) and hence their long-term performance.

No mention is made in the TMR Guidelines about assessment of aggregate durability, however the South African TG2 has adopted the same Durability Mill test as used for unstabilised materials.

Given the source rocks for the production of unbound granular pavements commonly have durability limits to ensure long-term performance, consideration should be given to the durability of the material proposed to be stabilised, particularly in the construction of heavily trafficked pavements. Austroads *Guide to Pavement Technology Part 4J Aggregates and Source Rocks* (Austroads 2008) describes durability tests in common use.

4.2.5 Aggregate Angularity

CSIR Transportek (1998) suggests that fine aggregate angularity is a good indicator for rutting resistance, and that a minimum particle index of 10 is recommended. Leek (2010) also reports rutting failure in pavements subject to heavy traffic when the parent aggregate was natural rounded aggregate, although the specifics of the fine aggregate were not investigated.

It is suggested that angularity characteristics of the fine and coarse aggregate should be included in the investigation, and that should materials be of low angularity, additional tests for rutting potential, such as wheel tracking, should be undertaken.

4.3 Quantity and Type of Secondary Binder

In South Africa and New Zealand it is common to use up to 1% cement as secondary binder, and if necessary lime is added to reduce plasticity. This is different from TMR practice of only using 1.5 to 2.0% lime as shrinkage cracking has been observed on some projects where cement has been used.

Currently, the Austroads Guide Part 4D states that 1 or 2% lime or cement may be required. No change to this text is required, other than to state that most Australian experience relates to the use of lime.

4.4 Test Sample Compaction

There are differing standards of compaction and mould sizes used in various methods.

Austroads Guide Part 4D describes two possible methods of sample compaction:

- Marshall hammer (50 blows)
- gyratory compaction (80 cycles).

However, the Marshall compaction method is used extensively for asphalt and is used for the preparation of foamed bitumen stabilised materials in the TMR method.

In South Africa for Level 1 design specimens are compacted with the Marshall hammer, whereas for Levels 2 and 3 a vibratory hammer is used.

As an interim measure, pending further research, it is recommended that no change be made to Part 4D.

4.5 Sample Curing

Austroads Part 4D provides for modulus testing:

- uncured, tested just after compaction
- oven cured at 60 °C for three days and tested dry
- then testing the materials after either submerged under water for 24 hours or in a vacuum chamber for 10 minutes.

This is similar to the TMR method, except that the TMR oven curing temperature is 40 °C.

The TG2 provides a similar approach in its Level 1 method. However, in Levels 2 and 3, applicable to moderate to heavily trafficked roads, the objective of the curing is to test the materials at their long-term equilibrium moisture contents in the field.

As an interim measure, it is proposed to amend Part 4D to make it consistent with the current TMR method. Further research is recommended to assess whether the samples should be cured to their long-term equilibrium moisture contents, as well the extremes of dry and soaked.

4.6 Strength/Stiffness Characterisation Tests

Characterisation tests follow two different paths:

- Method 1: Samples are cured according to a specified regime, and the Indirect Tensile Strength (ITS) and Unconfined Compressive Strength (UCS) is used to determine the optimum binder content. Samples are tested in both dry and soaked conditions.
- Method 2: Samples are cured according to a specified regime and the indirect tensile modulus (ITM) is determined and used to optimise binder content. Again samples are tested in both soaked and unsoaked conditions.

The first method is that applied primarily in South Africa and may be supplemented by triaxial tests and or indirect tensile modulus testing, but the optimisation of binder content is based primarily on maximising ITS and the ratio of ICS (soaked) to ITS (dry). The triaxial tests which measure friction angle and cohesion are used to characterise shear resistance for heavily trafficked pavements.

The second method based on modulus rather than strength is that used by TMR. The agencies that have adopted modulus consider the higher binder content (3−4% bitumen) typically used, results in flexible bound material with propensity for fatigue cracking. Given that modulus rather than strength is used for asphalt, another flexible bound material, they consider modulus more appropriate than strength for bitumen stabilised materials. The wheel tracking tester is used to characterise rut resistance of mixes proposed for heavily trafficked roads.

As it is proposed to base the Austroads mix design procedure around TMR practice, it is recommended that the Austroads procedure uses modulus rather than strength.

5 SUMMARY AND RECOMMENDATIONS

Foamed bitumen stabilisation is a road construction technique whereby bitumen is used to bind the existing or imported granular material to produce a flexible pavement material for use in base and subbase pavement layers, and in particular for road rehabilitation.

Appropriate foamed bitumen mix design method is an essential element in this technology which is increasing being used to rehabilitate Australian pavements.

The Austroads *Guide to Pavement Technology Part 4D Stabilised Materials* provides guidance on the selection and mix design of foamed bitumen stabilisation treatments.

The aim of this report is review international and Australian methods used to determine mix properties and design optimum bitumen and secondary binder contents for the construction of foamed bitumen pavements to identify areas to improve and enhance Part 4D.

The following documents were reviewed for consideration and information:

- *Foamed Asphalt Mixes Mix Design Procedure* (CSIR Transportek 1998)
- *Guide to Pavement Technology Part 4D: Stabilised Materials* (Austroads 2006)
- *Design of Foam Stabilised Pavements* (Ramanujam & Jones 2008)
- *Mix Design of Bitumen Stabilised Materials: Best practice and considerations for classification* (Ebels & Jenkins 2007)
- *Technical Guideline: Bitumen Stabilised Materials: A Guideline for the Design and Construction of Bitumen Emulsion and Foamed Bitumen Stabilised Materials* (Asphalt Academy 2009a).

The review highlighted significant areas of agreement in mix design methods, but also significant areas where the methods being developed in South Africa and increasingly New Zealand differed from those emerging in Australia.

Amendments to Part 4D were identified that would update the Guide to more closely reflect the current state-of-the-art in Australian foamed bitumen mix design. Appendix A contains text for consideration in the Part 4D revision.

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APPENDIX A PROPOSED REVISION TO AUSTROADS GUIDE TO PAVEMENT TECHNOLOGY

The Austroads *Guide to Pavement Technology Part 4D Stabilised Materials* includes guidance on the selection and design of pavement stabilisation treatments. Based on the review of current practice described in this research report a number of areas have been highlighted for updating and improving Part 4D text in relation to foamed bitumen stabilisation.

In revising Part 4D it is recommended that consideration be given to incorporating the text of this Appendix.

A.1 Preliminary Thickness Design

In order to correctly characterise the mix of pavement layers within a section or subsection of stabilised pavement, it is necessary to first determine a pavement design based on the subgrade strength, design traffic and characteristics of the climate under which the pavement will operate. An interim thickness design method has been published (Austroads 2009).

This preliminary thickness design is necessary to determine the range and percentage of each existing pavement material that will be incorporated into the mix. The ratios of each material type will rarely be constant throughout a pavement, and it is possible that in cases, some subgrade will be incorporated into the mix.

A.2 Sample Collection and Preparation

The pavement section selected for rehabilitation should be sampled at regular intervals by coring of asphalt layers and test pits.

Asphalt coring should be undertaken wherever any visual indication of past pavement repairs, rehabilitation or extension is noted. The spacing of cores should be relevant to the length of rehabilitation, but at no greater interval than 100 m.

The pavement should be subdivided into subsections where differing pavement materials are noted.

On identification of subsections, where subsections are less than 200 m in length, one test pit should be excavated using a skid steer profiler for any asphalt or bound layers, but mechanical means of pick and shovel or backhoe may be used for unbound layers. The details of each pavement layer should be noted and samples taken for laboratory testing, including in situ moisture content. The top layer of subgrade should also be sampled and the in situ strength measured with a dynamic cone penetrometer.

Where subsections are greater than 200 m in length, two test pits should be sampled as above.

Where pavement sections of significantly differing profiles are identified, the boundaries of any longitudinal and transverse joints should be determined as accurately as possible.

Boundaries should be clearly noted on plans, and also on the pavement for reference during rehabilitation operations.

A.3 Determination of Bitumen Foaming Properties

A.3.1 Bitumen Type

Bitumen is usually Class 170 complying with AS2008−1997. Most bitumen will foam, but bitumen containing silicones could have reduced foaming abilities. Polymer modified bitumen is not suitable as it does not foam.

A.3.2 Determination of Bitumen Water Ratio

The foaming properties of bitumen are characterised by:

- Expansion Ratio. A measure of the viscosity of the foamed bitumen, calculated as the ratio of the maximum volume of the foam relative to the original volume of bitumen.
- Half-life. A measure of the stability of the foamed bitumen, calculated as the time taken in seconds for the foam to collapse to half of its maximum volume.

The objective is to determine the temperature of bitumen and percentage of water addition that is required to produce the best foam properties (maximum expansion ratio and half-life) for a particular source of bitumen.

The testing should be undertaken over a range of temperatures, at least 160 °C, 170 °C and 180 °C, and at 2%, 3% and 4% water content by mass to determine the temperature and water content at which a foam with a target expansion ratio of 12 (minimum 10) and a target half-life of 45 seconds (minimum 20) is achieved.

Each test should be undertaken three times to ensure reliable results are obtained.

A.3.3 Additives

Some bitumens will not provide the required foam characteristics. When this occurs, foaming agents will be required, alternatively anti-stripping agents may be added. The bitumen foaming properties should be determined with any proposed additives to ensure good foaming characteristics are maintained.

A.4 Aggregate Characterisation

A.4.1 Particle Size Distribution

A particle size distribution (PSD) should be determined for each pavement material, and a spreadsheet used to determine the PSD of every combination of material ratios in each individual pavement core in each subsection. Where two samples are collected from a single pavement section, the PSD of each combination of material ratios in each individual pavement core in each subsection should be determined at the PSD extremes of each test pit.

Having determined the combined PSD that would result at each location in the pavement, samples should be prepared using the combination of materials that would generate the finest, the coarsest and the median grading so determined.

Where the grading curves are similar and do not vary by more than 10% for any sieve size over 2.36 mm, or by 5% for any sieve size less than 2.36 mm, the mean combination percentage values of all pavement layers should be combined.

A minimum of 10 kg of each trial material should be prepared, but an additional sample is recommended to be prepared should additional testing be required.

Materials suitable for foamed bitumen stabilisation have PSD within the envelopes shown in Table A 1.

Table A 1: Material Suitable for Foamed Bitumen Stabilisation

Sieve size (mm)	Percentage passing	
	Initial daily traffic on opening ≤ 1000 ESA	Initial daily traffic on opening > 1000 ESA/day
26.5	73–100	100
19.5	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	12–29	12–30
0.300	10–27	10–24
0.150	8–24	8–19
0.075	5–20	5–15

A.4.2 Plasticity

The Plasticity Index (PI) should be determined for each pavement material. Materials suitable for foamed bitumen stabilisation usually have a maximum PI of 10. Materials with PI of 10−20 may be used if they are pre-treated with lime to reduce their PI to a maximum of 10. However, there is limited Australian experience with such materials, including knowledge the mellowing period between the pre-treatment with lime and the stabilisation with foamed bitumen.

A.5 Mix Design

A.5.1 Mixing Equipment

The laboratory mixing method should as near as possible be selected to replicate the mixing process in the field. Asphalt mixers do not replicate the harsh conditions imposed on aggregate by a mechanical stabiliser, which may break down some aggregate particles and alter the particle size distribution of the pavement materials.

It is recommended that the laboratory characterisation of foamed bitumen pavements be undertaken with a purpose-designed machine incorporating a pugmill.

A.5.2 Trial Mixes

To determine the optimum combination of bitumen and secondary binder contents a number of trial mixes need to be tested with various additive combinations. Table A 2 provides guidance to commence this testing. In some cases, it may be necessary to prepare four trial mixes ±0.5% bitumen and ±0.5% secondary binder from the target value.

Table A 2: Suggested bitumen and secondary binder contents to commence mix design

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		

1 Cement may also be used as a secondary binder, but appropriate percentages may vary from values listed for hydrated lime.

For each trial mix, firstly the untreated material and the secondary binder are placed in the mixing chamber and mixed. Water is then added to bring moisture content to:

- material with PI < 6%, 70% of the untreated material OMC
- material with PI 6 −10%, 75% of the untreated material OMC
- field moisture content, for projects where field moisture content is less than 70% OMC and site conditions are such that the material will not dry back.

Finally the foamed bitumen is added into the mixing chamber from the laboratory foam bitumen apparatus (Figure 2.2).

A.5.3 Preparation of Test Cylinders

Samples should be transferred immediately and compacted into Marshall moulds (63.5 mm height) using 50 blows of the Marshall hammer per face or using by gyratory compaction (Gyropac 80 cycles). Moulds do not require pre heating. Four specimens should be prepared for each bitumen and secondary binder content combination.

A.5.4 Determination of Indirect Tensile Modulus

Indirect tensile modulus shall be determined at three conditions on each of the four specimens as follows using AS2891.13.1−1995, *Methods of sampling and testing asphalt – Determination of the resilient modulus of asphalt – Indirect tensile method*:

- samples tested after 3 hours after compaction, cured (unsealed) at 25 °C
- after 3 days of oven curing (unsealed) at 40 °C
- after 3 days of oven curing (unsealed) at 40 °C and then soaked in water for 10 minutes under 95 kPa vacuum.

The indirect tensile modulus is determined in accordance with AS2891.13.1 using a MATTA machine using the following parameters:

- condition pulse period 2000 ms
- test pulse period 3000 ms
- rise time 40 ms
- target resilient strain 50 microstrain
- Poisson's ratio 0.40

- test temperature 25 °C.

From the test results of the four specimens, three of the four indirect tensile modulus values which are closest in value are selected. Where the individual result of any of the three results is outside the range of ±30% of the mean, the tests should be repeated. The 90th percentile value of the selected three results shall be the characteristic modulus value at the particular bitumen and secondary binder content combination.

A.5.5 Adoption of Design Bitumen Content

To determine the optimum bitumen and secondary binder combination, the characteristic modulus values need to be compared against specification requirement.

For instance, Table A 3 illustrates the TMR specification requirements for mixes prepared, compacted and tested using their methods, including compacting specimens into 150 mm diameter moulds with the Marshall hammer. These specification values may not be appropriate if:

- different processes (e.g. gyratory compaction) are used to prepare test specimens
- for environments and traffic loadings different from which the TMR experience is based
- the thickness of asphalt surfacing exceeds 100 mm

Table A 3: TMR minimum indirect tensile modulus values for design traffic conditions

Average daily traffic at year of opening to traffic (ESA)	Base and subbase	Base course			Subbase course		
	Initial modulus(1) (MPa)	Min cured modulus(3) (MPa)	Min soaked modulus (MPa)(4)	Min retained modulus ratio(5)	Min cured modulus (MPa)(3)	Min soaked modulus (MPa)(4)	Min retained modulus ratio(5)
< 100	500	2500	1500	0.40	2500	1500	0.40
100−1000	700	3000	1800	0.45	2500	1500	0.45
> 1000	700(2)	4000	2000	0.50	2500	1500	0.50

1 Samples initially cured at 25 °C for 3 hours prior to initial modulus testing.
2 Recommended supplementary wheel tracking testing to confirm curing time.
3 Samples cure at 40 °C for 3 days prior to cured modulus testing.
4 Cured modulus test samples conditioned in a water bath under vacuum of 95 kPa for 10 minutes prior to testing.
5 Retained modulus ratio = soaked modulus/cured modulus.

Source: Ramanujam et al. (2009).

Modulus is not the only criteria used to establish the 'optimum' binder content, it should be emphasised that results of other tests (e.g. wheel tracking) and local experience are used to establish the most effective bitumen binder content along with the addition of a supplementary binder.

A.6 Determination of Rut Resistance

Having selected a bitumen and secondary binder combination from the modulus testing, rut resistance should be determined when the design traffic during the first year of service exceeds 1000 ESA/day, or where identified by aggregate angularity requirements.

Rut resistance is determined by the wheel tracking test where equipment is available. Samples are tested in accordance with deformation resistance of asphalt mixtures by the wheel tracking test (Austroads 2006).

The method to assess the long-term rut resistance is as follows:

- prepare three slabs 300 mm x 300 mm x 100 mm in segmented wheel compaction device at a density of 100% standard compaction
- the slabs are cured for 3 days at 40 °C
- apply wheel load of 700 N
- test for 10 000 cycles in wheel tracking device at a test temperature is 25 °C
- measure rut depth at 2000 cycles and 10 000 cycles.

The measure rut depth is then compared against the specification requirement.

For instance, Table A 4 illustrates the TMR specification requirements for mixes prepared, compacted and tested using their methods, including compacting specimens with Marshall hammer. These specification values may not be appropriate if:

- different processes (e.g. gyratory compaction) are used to prepare test specimens
- for environments and traffic loadings different from which the TMR experience is based
- for pavements with more than 100 mm thickness of asphalt surfacing.

Table A 4: Recommended limits for rut progression

Design traffic in first year of service (ESA/day)	Max rut depth at 2000 cycles (mm)	Max rate if rut progression (mm/kilocycle)
< 100	10	0.20
100−1000	7	0.15
> 1000	5	0.10

INFORMATION RETRIEVAL

Austroads, 2011, **Review of Foamed Bitumen Stabilisation Mix Design Methods**, Sydney, A4, pp. 37.
Keywords: foamed bitumen, stabilisation, mix design, recycling, **Abstract:** This report investigates international and Australian methods used to determine mix properties and design optimum bitumen and secondary binder contents for the construction of foamed bitumen stabilised pavements. Based on the review, it is recommended that the Austroads *Guide to Pavement Technology Part 4D Stabilised Materials* be amended and updated to reflect the current state of the art in foamed bitumen mix design.