Design of foamed bitumen layers for roads

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ABSTRACT

This paper provides an overview of the current approach mechanistic design of foamed bitumen stabilised materials in Australia. The author has published several papers on this topic over the last two years and this paper outlines further refinement to the design method being proposed by the author

Some aspects of construction practices and specification compliance of insitu foamed bitumen works are included as the design model relies on a sound site investigation and appropriate compliance measures.

1 INTRODUCTION

The successful use of foamed bitumen stabilisation occurs if the laboratory mix design procedures match the design models, and the application of the binder to the appropriate pavement material specifications. This paper will outline how laboratory testing results are used to get a suitable pavement thickness using the information in the 2004 Austroads pavement design guide (Austroads, 2004a) and known performance data of foamed bitumen layers constructed in Australia.

Overseas design models have been examined by the author and are not considered appropriate in Australia. Some overseas design models are based on moisture of the pavement material and yet the insitu moisture content cannot be determined with any degree of certainty leading to irrelevant model characteristics. Other models use special compaction methods that are not used in Australia, and any relevance to the material design in the laboratory and field conditions become difficult to rationalise.

In Australia, most of the work in foamed bitumen stabilisation is at basecourse level for rehabilitation projects, however there is an increasing trend to consider foamed bitumen materials for subbase layers for new pavements. If foamed bitumen is used for subbase layers, it is not recommended to have granular base layers as water will be trapped at the top of the subbase layer leading to the potential for under performance in the granular material. However, asphalt or concrete would be suitable as a base layer over a foamed material (subbase layer).

The three distress modes for foamed bitumen materials have been identified and these are:

- Fatigue cracking from repetitive wheel loading
- Rutting of the surface
- Shrinkage cracking (not common)

All bound materials are likely to fail in fatigue distress from wheel loading and this paper outlines a fatigue based mechanistic design model with a post-fatigue cracking pavement life (with limitations).

Similar to granular and asphalt materials, rutting is also a distress mode and needs to be considered in the design model along with laboratory prediction test procedures.

Some prior foamed bitumen projects have been shown to form shrinkage cracking and reflection cracking from the subgrade, and this is also a form of distress that needs to be addressed in the design model. Investigations into these cracked pavements indicate either a lower bitumen content, the use of too much GP cement or the pavement material has high inherent shrinkage.

This paper covers:

- Key elements from laboratory results
- Design modulus for structural design
- Fatigue equations for pavement life
- Post cracking life
- Thickness determination
- Pavement design example

2 LABORATORY RESULTS

Three key elements in the laboratory mix design process are:

- to ensure the hot bitumen foams to the desired range of parameters
- to mix sufficient bitumen and lime to meet the target design modulus for early trafficking and long-term performance (including minimum M_w/M_d).
- the use of a wheel tracker test and to determine the rate of rutting for heavy duty roads

Modulus values should be determined from a minimum of 3 samples with the mean value taken as representing the material provided such that the upper and lower values remain within 30% of the mean value. Whilst pavement designers have been known to accept lower values of Mw for light trafficked roads, further work is required to assess the impact this lower value may have on performance.

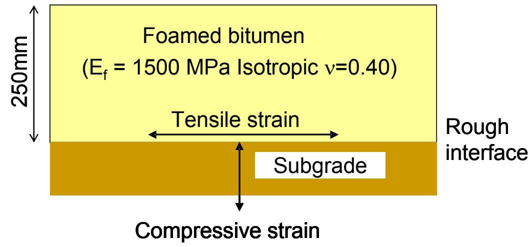
3 DESIGN MODULUS

The mechanistic design model in the Austroads design guide requires the designer to assign the elastic modulus of the material in each layer for the layered elastic analysis. For both asphalt and cemented materials, the elastic modulus refers to the flexural modulus derived from a beam test.

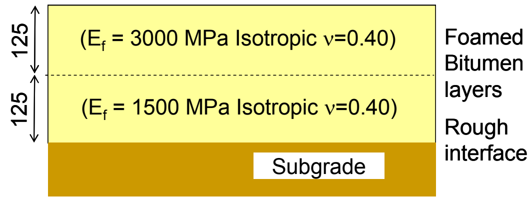
Colin Leek, a pavement engineer from the City of Canning, has engaged researchers to extract samples from the road after 5 months of age to assess density, UCS and resilient modulus of the extracted cores of three roads (Leek, 2001). The laboratory design modulus for all three roads was in the order of 1,300 to 1,800 MPa, and these results showed that on many occasions the modulus exceeded the design value by a factor of 2. These high modulus values after 5 months also confirms that the material becomes bound using the appropriate mix design protocols and construction procedures.

Modulus testing of cores extracted from existing roads indicates that the modulus in the lower half is about half that in the upper half of the core. The samples also indicated that after 12 months, the lower layer modulus was typically greater than the wet modulus from the laboratory mix design. The lower modulus values in the bottom area of the core indicates that greater voids, slower curing or less density is achieved during compaction.

Given the change in modulus with depth, it is considered conservative to use the lower modulus layer through the whole stabilised layer. For instance, if the assigned modulus for a foamed bitumen pavement base layer is 1,500 MPa and the layer is 250 mm in thickness supported on a subgrade of 7%, the number of repetitions to failure is 9.75×10^6 and 18.9×10^6 where the modulus is uniform or non-uniform respectively as shown in Figure 1. This example highlights that if the designer assumes the lower modulus through the foamed bitumen layer, the outcome will be conservative.



(a) single layer modulus on subgrade
$N = 9.75 \times 10^6$



(b) two layer modulus on subgrade
$N = 18.9 \times 10^6$

Figure 1 The number of repetitions to fatigue cracking for a single and double modulus layer using the design model in this paper.

In Chapter 8 of the Austroads Guide, the laboratory modulus is adjusted according to the operating temperature and vehicle speed (see Figure 2). The asphalt temperature factor (see equation 1) is significant when the layer is thin (Youdale, 1984) and when higher pavement temperatures (WMAPT[1]) are to occur as shown in Table 2. The factor in the Austroads guide is independent of depth and for foamed bitumen works where the critical stain is in the bottom layer, one would question the impact of temperature effects at depths of 250 to 300 mm.

$$\frac{\text{Modulus at WMAPT}}{\text{Modulus at Test Temperature}(T)} = \exp(-0.08[\text{WMAPT} - T]) \qquad \text{Equation 1}$$

The origins of the temperature factor are detailed in Austroads guide AP-T33 (2004b) and the factor is based on the Mulgrave ALF trial with full-depth asphalt at 120 to 150 mm in thickness. As noted previously, the asphalt at this trial is significantly different in thickness compared to foamed bitumen base layers.

QDMR have proposed lower temperature reduction factors for Queensland than the Austroads pavement design guide and these are listed in Table 1. Given the changes in modulus over time for foamed bitumen materials and the lime filler likely to reduce the temperature effects on the material, it would be reasonable at this stage to assume the reduction factors suggested by QDMR are satisfactory and extend them to temperatures below 25°C as shown in Table 2.

Where foamed bitumen materials are used in the subbase layer, it would be reasonable to use a factor of 1.0, whatever the WMAPT is for the site.

Table 1 Temperature reduction factor from Austroads and proposed by QDMR (Jones, 2003).

WMAPT (°C)	Austroads	QDMR
20	2.51	-
25	1.0	1.0
30	0.4	0.9
35	0.16	0.8
40	0.06	0.7

[1] WMAPT refers to Weighted Mean Annual Pavement Temperature, and data is available in Appendix 6.1 of the Austroads pavement design guide.

Table 2 Temperature reduction factor proposed by AustStab for foamed bitumen used as a base layer.

WMAPT (°C)	F_t
≤ 25	1.0
30	0.9
35	0.8
40	0.7

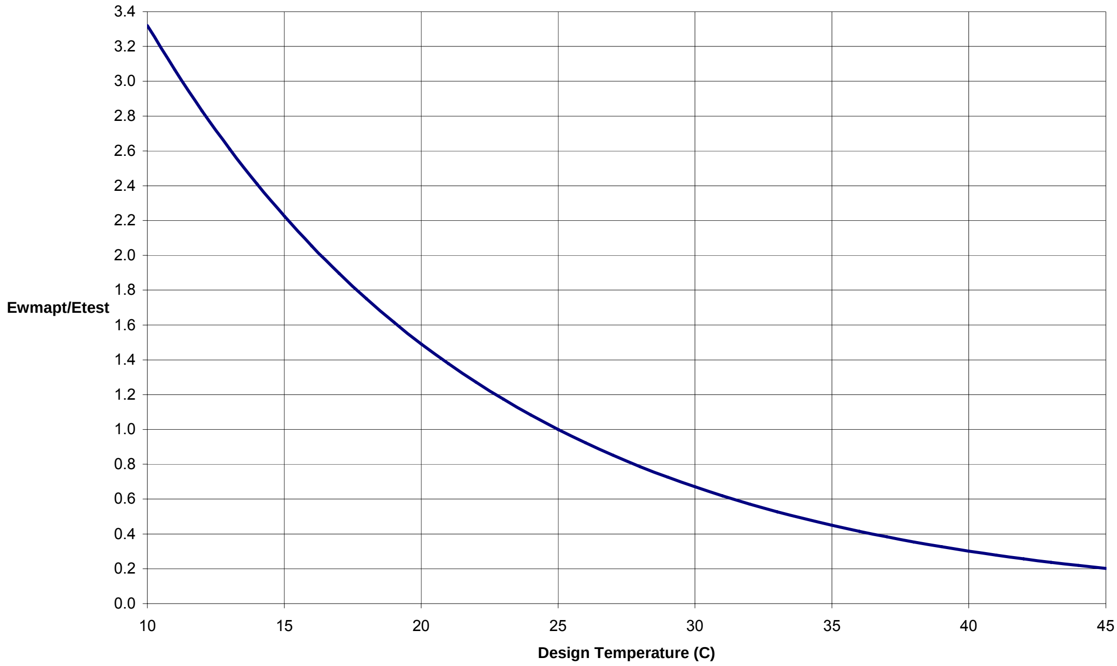


Figure 2 Ratio of modulus at WMAPT (E_{WMAPT}) to the modulus from Standard Indirect Tensile Test (E_{test}) for conventional asphalt mixes only. (Austroads, 2004a)

Vehicle speed is also an important factor to consider for asphalt. As noted in the material design section, the rise time for the MATTA test is 40 ms and the correction applied to conventional asphalt mixes varies from 0.92 to 0.3 as the design vehicle speed decreases. In foamed bitumen materials, the content of bitumen is decreased compared to asphalt and the depth of the critical strain layer is two to three times that of asphalt. It is therefore suggested that the vehicle speed factor is as per equation 2, based on the laboratory loading rate of 40 ms (Austroads, 2004b). Table 3 lists typical values for different heavy vehicle design speeds.

$$F_v = 0.36\ V^{0.21} \qquad \text{Equation 2}$$

Therefore, the design modulus (E_f) used for foamed bitumen materials subject to fatigue is:

$$E_f = F_t \times F_v \times M_w \qquad \text{Equation 3}$$

Where, F_t = Temperature correction factor from Table 2
. F_v = Vehicle speed correction factor taken from Equation 2 or 1.0 for subbase layers.
. M_w = Wet resilient modulus from test program (MPa)

Table 3 Velocity reduction factor for foamed bitumen used as a base layer.

Vehicle Speed (kph)	F_v
60	0.85
80	0.90
100	0.95
110	0.97

4 FATIGUE EQUATION

The current fatigue relationship for cemented materials and asphalt in Australian mechanistic design models (Austroads, 2004a) are:

$$N = RF\left[\frac{\left(113{,}000 / E^{0.804} + 191\right)}{\mu\varepsilon}\right]^{12}$$ for cemented materials Equation 4

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

where N = allowable number of repetitions of the load
$\mu\varepsilon$ = tensile strain produced by the load (microstrain)
E = modulus of cemented material modulus (MPa)
V_B = percentage by volume of bitumen in the asphalt (%)
S_{mix} = asphalt modulus (MPa), and
RF = reliability factor.

In the above equations:

- (tensile) strain is based on the static loading of an equivalent axle load of 80 kN using a dual tyre configuration with 750 kPa tyre pressure[2]
- modulus is either a presumptive value or taken from laboratory measurements
- reliability factors for new pavements are based on the importance of the road

As noted earlier in this paper, cores extracted from the existing foamed bitumen stabilised materials indicate that the material is 'fully' bound and not modified or granular as may have been considered about 5 years ago.

Research work carried out by Mobil Bitumen (Maccarrone, 1994), by ARRB Transport Research (Alderson, 2001) and QDMR (Jones, 2003) indicates that the asphalt fatigue equation with appropriate modulus and volume of bitumen, should provide reasonable estimates of fatigue life for foamed bitumen stabilised material with bitumen and hydrated lime contents in the range of 2 to 4% and 1 to 2% respectively.

Table 4 shows the difference between asphalt and foamed bitumen for three common material properties. The high air void content is indicative of the lower modulus of foamed bitumen materials compared to asphalt.

[2] A presumptive radius of 92.1 is adopted in CIRCLY and small changes to strain are likely if the radius is changed.

Table 4 Property differences between dense graded asphalt and foamed bitumen stabilised materials.

Property	Dense graded asphalt	Foamed bitumen stabilised
Volume of bitumen	11%	7%
Air voids	4 to 10%	10 to 15%
Resilient modulus (25°C, 4ms)	3,000 to 8,000 MPa	1,000 to 3,000 MPa

Since 1992, the Austroads pavement design guide has always allowed for reliability factors. These factors in the 2004 guide are now applied to the fatigue equation and for new pavements. For road rehabilitation, the reliability factor is taken as 1 (Austroads, 2002b).

5 POST CRACKING LIFE

VicRoads TB37 (VicRoads, 1993) and the current Austroads pavement design guide allows for a post cracking phase of life in cemented materials that have exceeded their fatigue life. Clause 6.4.3.6 notes that:

> For the purpose of mechanistic modelling in the post-fatigue phase, cemented materials may be assumed to have a presumptive vertical modulus of 500 MPa and a Poisson's Ratio of 0.35. The layer is not sublayered and is considered to be cross-anisotropic, with a degree of anisotropy of 2.

It is reasonable to assume a similar postcracked phase of life as per cemented materials using similar parameters provided there is the provision of hydrated lime in the mix, the surface is adequately sealed during the cracked phase of the pavement and the wet modulus from the laboratory test program exceeds 1,500 MPa. QDMR currently uses 500 MPa as the postcracking modulus (Jones, 2003) and this would be a reasonable modulus to assume.

In the 2004 Austroads guide, the equations which take account of the postcracking phase of the cemented material are as follows:

Asphalt Fatigue: $$N_A = N_{1stCT} + \left(1 - \frac{N_{1stCT}}{N_{1stAS}}\right) x\, N_{2nsAS}$$ Equation 6

where N_A = total allowable loading to asphalt fatigue (ESAs);

N_{1stCT} = allowable number of load repetitions (ESAs) to cemented material fatigue (1st Phase life);

N_{1stAS} = allowable number of load repetitions (ESAs) to asphalt fatigue during the cemented material 1st phase; and

N_{2ndAS} = allowable number of load repetitions (ESAs) to asphalt fatigue after cemented material fatigue (2nd phase life).

Permanent Deformation: $$N_S = N_{1stCT} + \left(1 - \frac{N_{1stCT}}{N_{1stS}}\right) x\, N_{2nsS}$$ Equation 7

where N_S = total allowable loading to unacceptable permanent deformation (ESAs);

N_{1stCT} = allowable number of load repetitions (ESAs) to cemented material fatigue (1st Phase life);

N_{1stS} = allowable number of load repetitions (ESAs) to unacceptable permanent deformation during the cemented material 1st phase; and

N_{2ndS} = allowable number of load repetitions (ESAs) to unacceptable permanent deformation after cemented material fatigue (2nd phase life).

Note that equation 6 is only applicable if N_{1stCT} exceeds N_{1stAS} and equation 6 is only applicable if N_{1stCT} exceeds N_{1stS}. Also, if there is no asphalt (ie $N_{2ndAS} = 0$) equation 6 provide no additional allowable traffic life (ie benefit).

At this stage, it is reasonable to assume that the above approach could be used with or without an asphalt base layer provided the appropriate interpretations to the above equations are considered - refer to Section 8.2.4 of the Austroads pavement design guide. In addition, the pavement wearing surface seals the foamed bitumen layer.

6 THICKNESS DETERMINATION

6.1 Traffic

The design traffic may be established using information in the Austroads guide or the analysis of traffic loading and composition from a local WIM[3] site. As previously discussed, the use of the asphalt fatigue curve results in the damage exponent (m) adopted for foamed bitumen layers as 5. If no traffic distribution loading is available, the presumptive rural and urban TLD[4] of 1.1 (ie SAR/ESA) may be used.

Once the design traffic is calculated, equation 8 may be used to compare the design traffic for the layer against the allowable repetitions for the material.

$$DSAR_m = SAR_m/ESA \times DESA \qquad \text{Equation 8}$$

where SAR_m / ESA = average number of Standard Axle Repetitions per Equivalent Standard Axle for damage type with an exponent of *m*

DESA = design traffic loading in ESAs.

6.2 Interim design model

The allowable repetitions from a foamed bitumen layer is based on the asphalt fatigue equation with appropriate inputs. The potential for a post cracking phase of life for the layer may be considered provided the requirements described in Section 4.4 are met.

The fatigue equation that is suggested for pavement design is:

$$N = RF\left[\frac{6918(0.856\,V_B + 1.08)}{E_f^{0.36}\,\mu\varepsilon}\right]^5 \qquad \text{Equation 9}$$

where
N = allowable number of repetitions of the load
$\mu\varepsilon$ = tensile strain produced by the load (microstrain)
E_f = corrected resilient modulus of foamed bitumen material (MPa)
V_B = percentage by volume of bitumen in the asphalt (%)
RF = reliability factor, taken as 1.0 for rehabilitation.

[3] WIM refer to Weigh in motion
[4] TLD refers to Traffic Load Distribution. Refer to Section 7.6.2 of the Austroads pavement design guide.

The proposed interim design model is outlined in Table 5 and limited to the following uses:

- Class 170 bitumen with foaming characteristics as described in this paper
- The particle size distribution limits being met
- Laboratory sample preparation and curing as described in this paper
- Normal road traffic loading conditions
- Foamed bitumen material constructed to AustStab model specifications.

There is insufficient data at this stage to apply this design approach for heavy wheel loads likely at container hardstands and major airports taking commercial jet aircraft. It is also important to ensure that the construction temperature limits specified in the AustStab model specifications are met. For instance, experience has shown that the foaming mechanism diminishes when the pavement material temperature is below 10°C. In addition, poor construction equipment will also lead to inefficient bitumen foaming resulting in less than desirable bitumen distribution.

Table 5 Interim design method for foamed bitumen stabilisation.

Step	Description
1	Design a laboratory mix program and report M_i, M_w and M_d.
2	Meet requirements for laboratory mix M_i and M_w/M_d for traffic volumes (this may include wheel tracking test)
3	Estimate the design traffic
4	Select trial pavement thickness
5	Determine tensile strain at underside of foamed bitumen layer using CIRCLY
6	Using the asphalt fatigue equation with appropriate input, determine allowable repetitions to failure
7	Compare allowable axle repetitions to design traffic
8	Allow for post cracking phase of life as appropriate
9	Check against allowable life for other layers in the pavement configuration
10	Revise layer thickness or modulus to optimise all material layers
11	Take into consideration details of joints, drainage and interlayer

6.3 Design example

A rural highway has a 20-year design traffic of 5 x 10^6 DESAs. The proposed pavement configuration for rehabilitation is a 280 mm deep foamed bitumen layer with a geotextile sprayed seal wearing surface. The design subgrade CBR is 7% and the WMAPT for the site is 24°C and the heavy traffic speed is 100 kph.

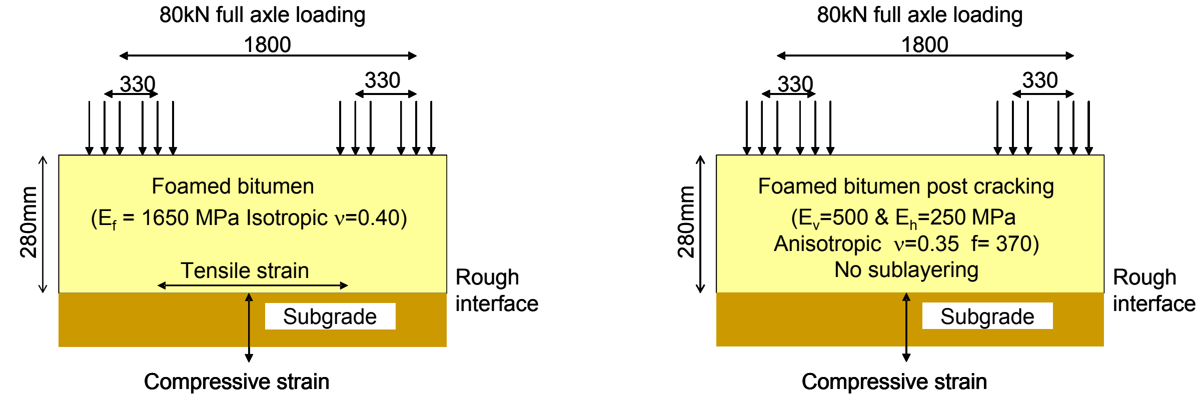
Using the presumptive TLDs from the guide, the DSAR is 1.1 x 5 x 10^6 = 5.5 x 10^6 and the reliability factor is chosen as 1.

The laboratory mix results are as follows:

Initial resilient modulus (M_d)	780 MPa
Dry resilient modulus (M_d)	2,540 MPa
Dry resilient modulus (M_w)	1,740 MPa
Ratio (M_w / M_d)	0.68

V_B	7%[5]

Figure 3 shows the layout of the pavement layers in the linear elastic model. The calculations follows two phases, namely the allowable traffic during the fatigue life followed by a cracked state. The second phase is only valid if the foamed bitumen layer is protected from the ingress of water, for example, by the use of a geotextile seal.



(a) precracking design phases (b) postcracking design phase

Figure 3 Design example as modelled in CIRCLY 5 for precracking and postcracking design phases.

In the calculations the total allowable number of standards axle repetitions is 2.3 times the precracking design phase. It would be prudent to add 20 mm for construction tolerance in the contract document specify the foamed bitumen layer as 300 mm.

Steps		**Calculations**
1	Design modulus	F_t = 1 from Table 2 with WMAPT = 24°C. Fv = 0.95 from equation 3, E_f = 1740 x 1 x 0.95 = 1650 MPa
2	Fatigue equation	V_B=7%, E_f = 1650 MPa and RF=1. $N = (3398/\mu\varepsilon)^5$
3	Allowable N from fatigue of foamed bitumen	Max. horizontal strain in foamed bitumen layer is 179με and this equates to $N = 2.47 \times 10^6$
4	Allowable N from subgrade	Max vertical strain in subgrade is 454με and this equates to $N = 1.51 \times 10^9$
5	Precracking life of pavement	$N = 2.47 \times 10^6$ ESAs
6	Design modulus in cracked state	E_v = 500 MPa, E_h = 250 MPa and Poisson's ratio = 0.35
7	Allowable N from subgrade	Max vertical strain in subgrade is 1098με and this equates to $N = 3.13 \times 10^6$ ESAs
8	Combined allowable N	Using equation 6, $N = 2.47 \times 10^6 + \left[1 - \frac{2.47 \times 10^6}{1.51 \times 10^9}\right] 3.13 \times 10^6$ $N = 5.59 \times 10^6$ ESAs
9	Compare design traffic to allowable	DSAR = 5.5×10^6 < Allowable N = 5.59×10^6 Trial pavement thickness OK

[5] V_B based on 3% of bitumen used in the laboratory.

7 CONCLUSIONS

This paper has provided an overview of a pavement design procedure for foamed bitumen materials within a pavement structure. The interim design model detailed in this paper is now being used by many road designers in Australia. The current limitations to the design model are important and with time there is likely to be additional fine tuning to the input parameters and laboratory values used to improve the prediction of performance.

Further work is required in the following areas:

- Refinement of the fatigue design model using resilient modulus
- Analysis of post-fatigue life of material
- Further refinement of the temperature and vehicle speed correction factors for modulus.

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