GUIDELINES FOR THE MIX DESIGN AND PERFORMANCE PREDICTION OF FOAMED BITUMEN MIXES

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ABSTRACT

As the use of foamed bitumen mixtures in the road pavements of the Southern African region continues to grow, so the need for sound mix design procedures and performance criteria for these mixes becomes paramount.

Four years of fundamental and developmental research into foamed bitumen mixes has been combined with practical experience obtained from laboratory and field application of foamed mixes, as well as previous publications on these mixes, to provide guidelines for their usage. This paper proposes:

- methods for the optimisation of the foamed bitumen properties and the setting of suitable limits for its characteristics dependent on type of application,
- guidelines for the selection of the ideal aggregate structure for cold foamed mixes including separate filler, sand and large aggregate considerations,
- procedures for carrying out cold mix design in the laboratory (including mixing, compaction and curing),
- procedures for manufacturing half-warm foamed mixes in the laboratory,
- pavement design methods for road structures incorporating foamed mix layers.

In particular, the spatial composition of the aggregate plays an important role in determining the behaviour of a foamed mix. To this end, procedures are provided that enable the interaction of moist filler and foamed bitumen to be modelled in terms mastic stiffness as well as optimal blending of aggregate fractions for most suitable foamed mix properties.

The proposed guidelines of this paper are pertinent to the Southern African region. They are intended to provide a means of foamed mix selection with improved reliability that is based on sound pavement engineering principles.

1 Background to Foamed Bitumen

Foamed bitumen can be produced through the injection of small quantities of cold moleculised water, as a fine mist, into hot penetration grade bitumen in an expansion chamber. Whilst it is foaming (which may last about 20 seconds), the bitumen is in a temporary state of low viscosity and can be mixed with mineral aggregates at ambient temperatures and at in situ moisture contents.

The production of foamed bitumen is not reliant on mechanical energy but rather on heat transfer, as illustrated in Figure 1. The cold water droplets are heated above the latent heat of steam as they make contact with the hot bitumen (at about 170ºC) and expand within bitumen bubbles to form foam. This foam is mixed with mineral aggregates to form a bitumen bound mixture.

With the growing global application of the foamed bitumen process in recent years, it has become increasingly necessary to more clearly understand the properties of the foam and the mix itself. The objective should be to appreciate the interaction of the foamed bitumen with the mineral aggregate at the various stages of the manufacture and construction process. In so doing, the optimisation of both the foam and the mix is made possible.

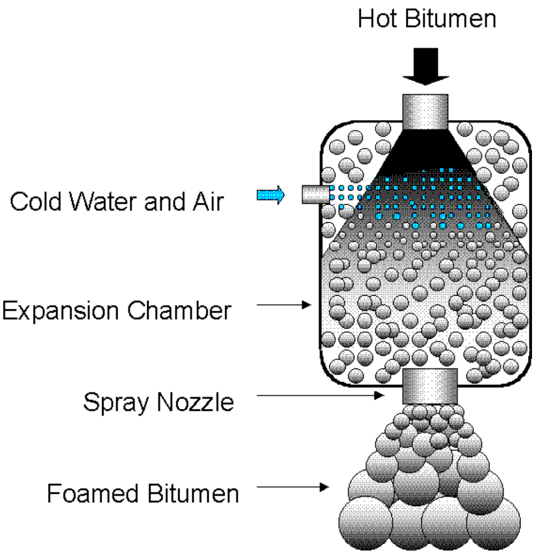


Figure 1. Foamed Bitumen Production

As the use of foamed bitumen has increased, so have the different areas of application. Back in 1957 Csanyi[1] perceived foamed bitumen as a means of improving the quality of marginal aggregates such as loess, to enable them to be used in road pavements. Subsequently, foamed bitumen has been found to produce good quality cold mixtures when added to mineral aggregates of varying qualities, where the mix can be placed and compacted at ambient temperatures. These improvements in quality have encouraged the use of foamed bitumen for rehabilitation of road pavements through the use of cold in place recycling.

Some of the main applications of foamed bitumen include use as a binder for:

a) conventional cold mixes with good quality or marginal aggregates,
b) cold mixes with Reclaimed Asphalt Pavement (RAP) material,
c) half-warm (higher quality) foamed bitumen mixes,
d) encapsulation or immobilisation of contaminants such as asbestos or tar in mineral aggregates (where permitted), and
e) specialist surface dressings.

Each of the various applications of foamed bitumen requires different characteristics from the foam for optimal performance of the mixture as is outlined later. These requirements not only influence the choice of the bitumen type, but also the preferred temperature of the bitumen for foaming, the selection of foam-enhancing agents or foamants (if any) and the application rate of the foamant water (the cold water added in Figure 1)

2 The Foam Index *as a new parameter* for Optimisation

Two parameters are important when considering the suitability of foamed bitumen for use in binding mineral aggregate together i.e. Expansion Ratio (ER) and Half-life ($\tau_{½}$). Although practical experience of working with foamed mixes has helped to identify desired values for the ER and $\tau_{½}$ to obtain a suitable quality mix, these two variables are inter-dependent and their optimisation is not simple. Both variables are dependent for example on the foamant water application rate.

The Foam Index, which is a measure of a combination of expansion ratio and half-life, has been shown to be useful for identifying the optimal properties, Jenkins *et al* [2,3]. Instead of using merely these two points that define the decay of the foam (ER and $\tau_{½}$), the Foam Index is calculated using the entire curve of foam expansion versus time, as measured in a bucket in the laboratory, for example.

In order to calculate the Foam Index, cognisance needs to be taken of the types of decay curves that are produced by different types of foamed bitumen. Extensive investigation into the foam characteristics of various types of bitumen with variation in factors such as temperature, foamant water content, air pressure and additive content has provided an insight into the types of foam that are produced[2,3]. These can be summarised by asymptotic decay (Figure 2) and non-asymptotic decay (Figure 3).

For a given set of conditions i.e. bitumen type and temperature, water application rate, etc. the area under a decay curve for foamed bitumen is defined as the Foam Index[2,3]. The area is calculated for the purpose of optimising the foamant water application rate and that of a foamant, if used. A value of 4 for the expansion ratio has been defined as the minimum for appropriate mixing viscosity of the foam[3]. In order to account for different spraying (discharge) times used in testing foam under laboratory conditions, the decay curve is extrapolated back over the duration of the spraying. In this way the actual expansion ratio (ER_a) may be obtained from the measured expansion ratio (ER_m), see Figure 2 and Figure 3.

Foam Index = $A_1 + A_2$ …….Equation 1

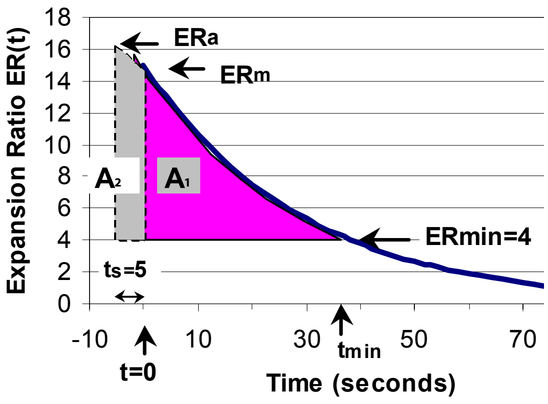


Figure 2. Foam Index calculation for Asymptotic Decay at one Foamant Water Application Rate

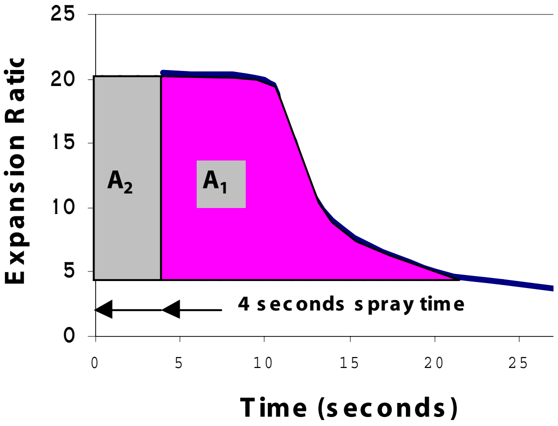


Figure 3. Foam Index for Non-Asymptotic Foam at one Foamant Water Application Rate

A sensitivity analysis of the foam characteristics is necessary to determine the optimum conditions for foam production. The foamant water (or foamant) application rate is varied and the Foam Index determined (see individual points in Figure 4).

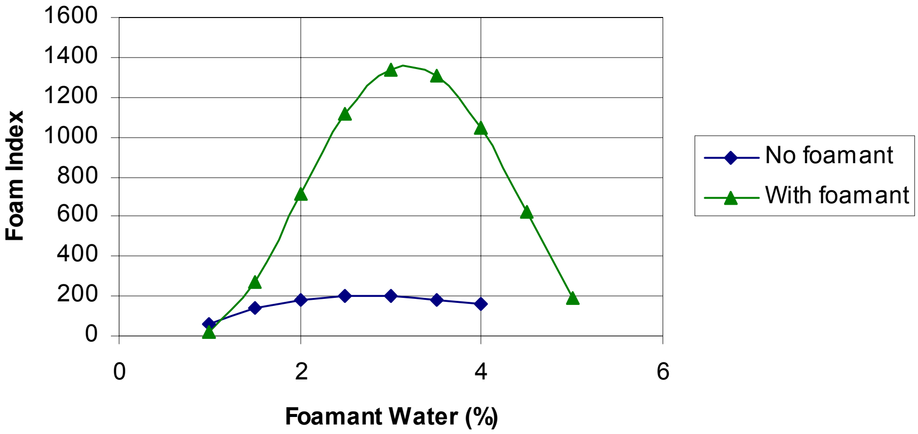


Figure 4. Optimisation of the "Foamability" of Bitumen (integrated viscosity and stability) for a Typical Bitumen (Calref 150/200) using the Foam Index

The shift in Foam Index value for bitumen with the addition of a foamant, is significant. This is a result of the proportionate increase in the FI to the increase in half-life. Consider, for example, the formula [2,3] for the calculation of the FI for foam with *asymptotic decay* where the influence of half-life is apparent:

$$FI = \frac{-\tau_{1/2}}{\ln 2}\left(4 - ER_m - 4\ln\left(\frac{4}{ER_m}\right)\right) + \left(\frac{1+c}{2c}\right) * ER_m * t_s \qquad \text{......Equation 2}$$

Where,

ER_m = Maximum Measured Expansion Ratio (immediately after discharge, where net expansion of foam is considered, excluding the bitumen volume)
ER_a = Actual Maximum Expansion Ratio (back-calculated)
$c = ER_m/ER_a$
$\tau_{1/2}$ = half-life (seconds)
t_s = time of spraying to discharge all foam (sec)

Application of the Foam Index as a guide for foamed bitumen selection should take account of the type of application. Encapsulation, for example, requires higher expansion than surface dressings, which require higher foam stability ($\tau_{1/2}$). Foam should be produced at optimal conditions for both of these applications i.e. highest integrated expansion and stability or FI.

Figure 5 provides suggested guidelines for the limits of foamed bitumen properties, taking account of ER, $\tau_{1/2}$ and FI (based on asymptotic decay).

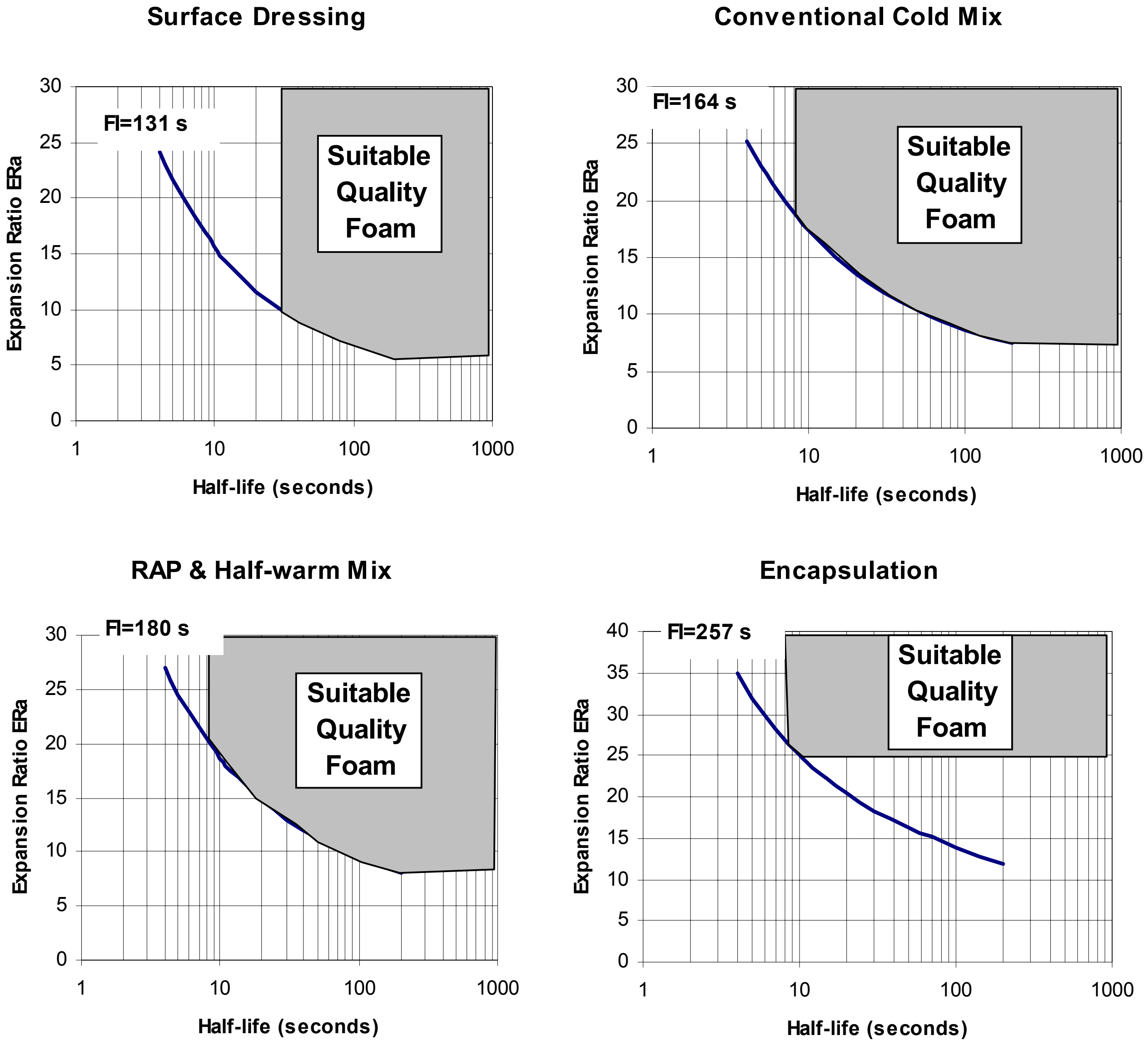
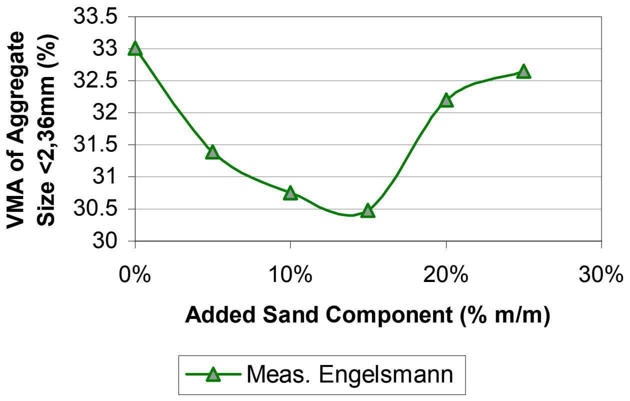


Figure 5. Interaction of Expansion Ratio and Half-life *(and FI)* to Provide Acceptable Quality Foamed Bitumen for Different Applications in Mix Production (Half-warm Aggregate Temperature > 65ºC; other mixes Aggregate Temperature > 15ºC)

3 Selection of Aggregate Structure

It is generally accepted that the filler fraction of the mineral aggregate is necessary to ensure adequate dispersion of foamed bitumen in a mix. Insufficient filler (generally less than 5% by mass) results in bitumen droplets coalescing rather than coating the very fine aggregate.

Filler is by no means the only important fraction in foamed mixes. The significance of the sand fraction and its Voids in the Mineral Aggregate (VMA) has been shown through research[3,4]. By minimizing the VMA in the sand fraction using, for example, an Engelsmann apparatus[5] which compacts the dry sand fraction through vibration (free fall impact), mix properties can be measured and enhanced. Figure 6 and Figure 7 show the increase in mix tensile strength as finer (Philippi) sand is added to a mix to reduce the VMA.



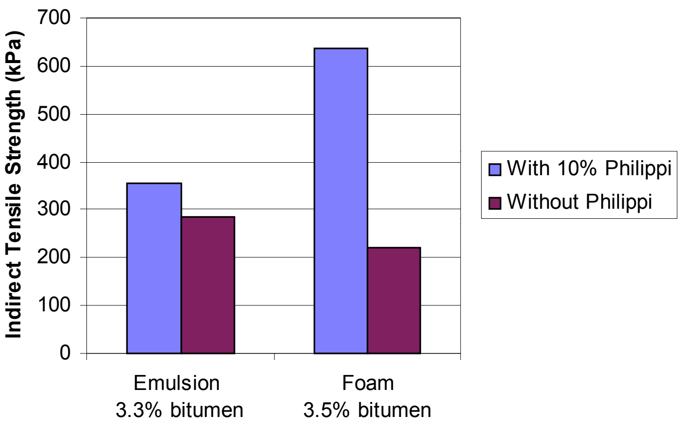


Figure 6. Minimizing VMA through Blending of Two Sand Fractions (*or sand and filler)*

Figure 7. Influence of VMA on ITS at 25ºC (material without Philippi Sand has higher VMA)

The reason for this phenomenon becomes more apparent when the influence of the spatial composition of the sand fraction on the mechanical properties of the mix are considered. As the VMA in particularly the sand fraction reduces, so the inter-particle contacts increase and mastic carrying the foamed bitumen can be forced between sand particles during compaction. This enhances adhesion of binder and mineral aggregate as well as binder dispersion. As observed in Figure 7, bitumen emulsion is not as dependent on VMA of the sand fraction as foamed mix, primarily due to the different mode of binder dispersion to foamed bitumen. Bitumen emulsion is not as selective in particle size coating and generally coats large aggregates too.

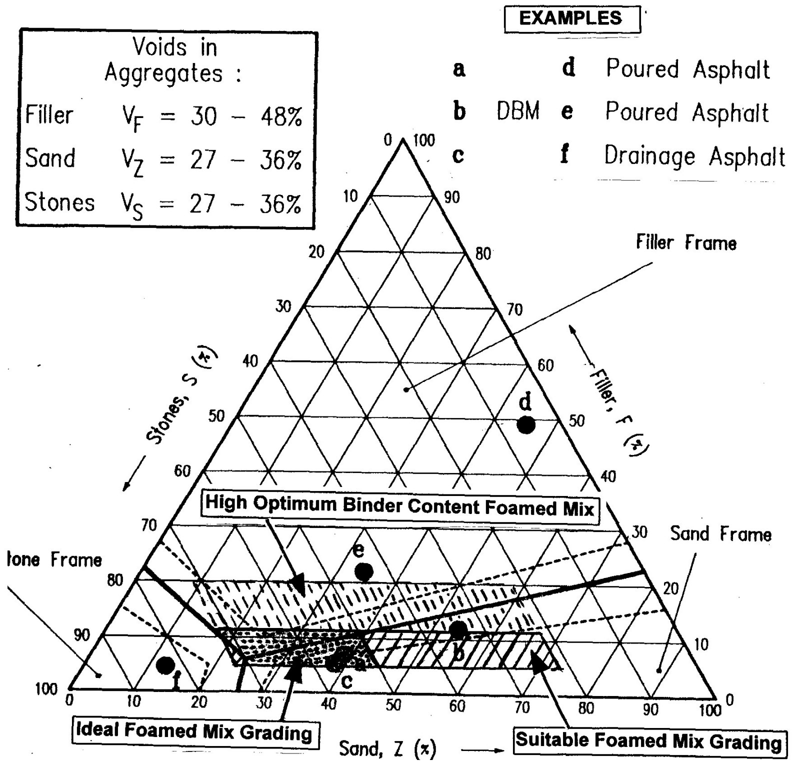


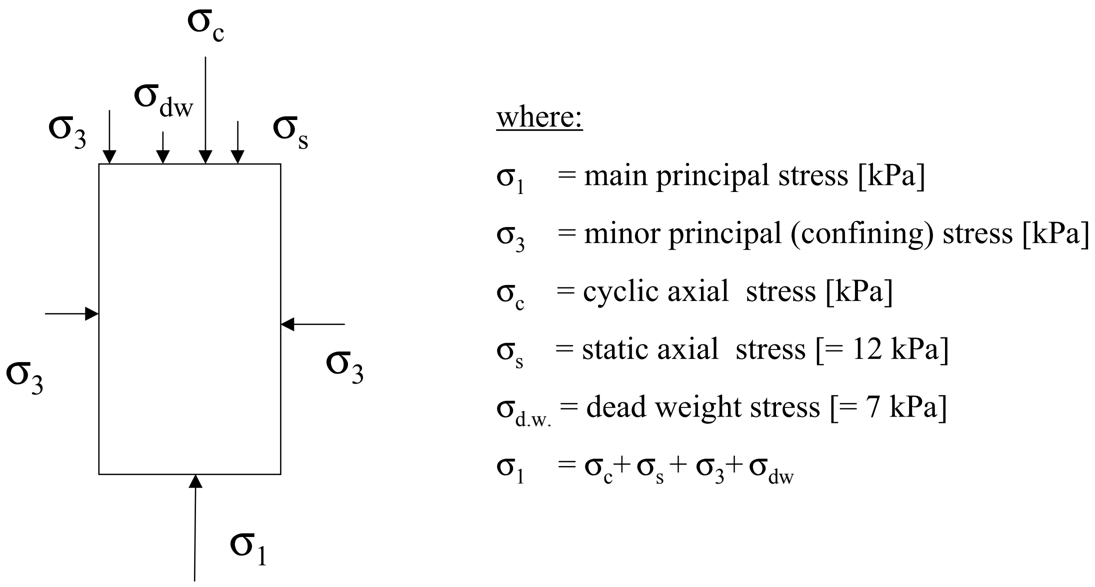
Figure 8. Suitability of Aggregate Gradations for Treatment with Foamed Bitumen, utilising the “Magic Triangle” after Francken and Vanelstraete[6]

The principle of minimum VMA improving the engineering properties of foamed mix can be extended beyond the sand fraction to the entire mixture. The “magic triangle” in Figure 8 gives a ranking of suitability levels of different aggregate structures in terms of the combination of coarse aggregate, sand and filler fractions. In this case the 2,36mm and 0,075mm sieves are used to define the boundaries between the aggregate sizes. Such an analysis tool can provide a useful insight into causes of segregation, particularly for coarse grained and gap graded mixes.

4. Pavement Design Considerations for Lightly Bound Cold Foamed Mixes (BC<2.5%)

4.1. Resilient Modulus

Foamed mix can range from lower binder content cold mix that resembles weakly bound granular material, to higher binder content half-warm mix that resembles hot mix asphalt. Development of a unified performance prediction model that satisfies this range of mixes is ambitious and probably unrealistic. The focus of this section is on the modelling of lightly bound cold foamed mixes.



where:

σ_1 = main principal stress [kPa]

σ_3 = minor principal (confining) stress [kPa]

σ_c = cyclic axial stress [kPa]

σ_s = static axial stress [= 12 kPa]

$\sigma_{d.w.}$ = dead weight stress [= 7 kPa]

$\sigma_1 = \sigma_c + \sigma_s + \sigma_3 + \sigma_{dw}$

Figure 9. Stresses Applied in Triaxial Test on Foamed Mixes

Triaxial testing, which is an effective way of simulating loading conditions in a pavement layer, has shown that foamed mixes with less than 4% foam and up to 1% cement, exhibit a granular nature in terms of stress dependency[3]. From 3% and above, the stress dependency declines. Figure 9 provides a graphical layout of stresses applied in the triaxial test used in the research. Implementation of such tests on lightly bound foamed mixes yields Figure 10, which shows how the resilient stiffness of a foamed mix doubles as the total principal stresses increase from 100kPa to 900 kPa.

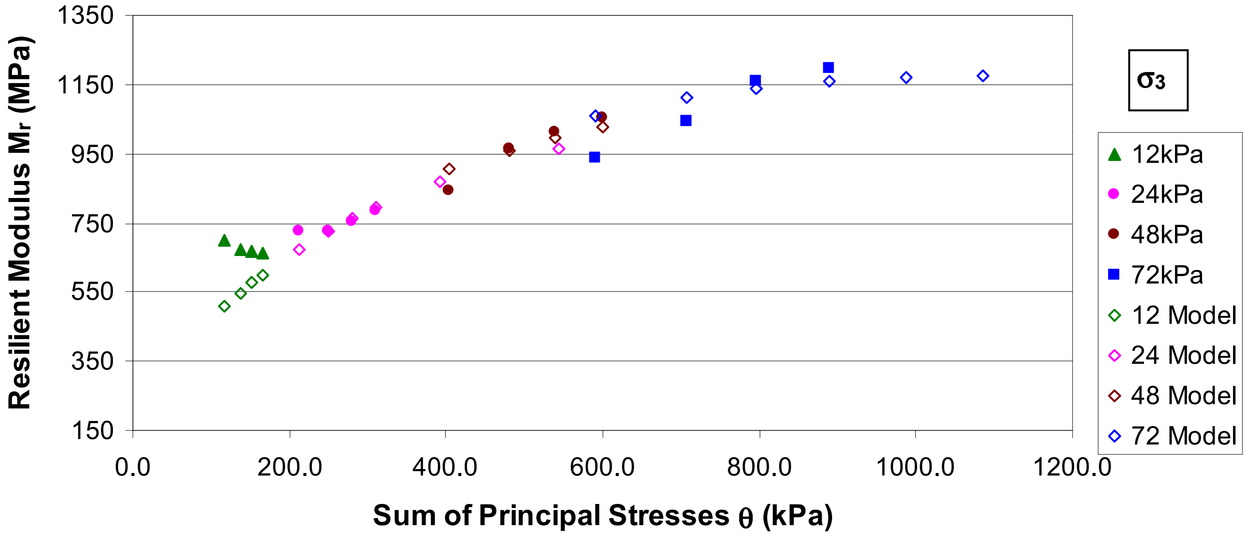


Figure 10. Resilient Modulus as a Function of Total Stress from Triaxial Tests on Foamed Mix with 2% Binder after Conditioning with 10 000 Load Pulses at $\sigma_d/\sigma_{d,f}$ of 40% (testing temperature 20°C)

The **M_r- θ-$\sigma_1/\sigma_{1,f}$ Model**, effectively expresses the resilient modulus as a function of the total stress of a granular (or foamed) material, see Equation 3.

$$M_r = k_5 \left(\frac{\theta}{\theta_0}\right)^{k_6} \left(1 - k_7 \left(\frac{\sigma_1}{\sigma_{1,f}}\right)^{k_8}\right) \qquad \text{.....Equation 3}$$

Where,

M_r = Resilient Modulus (MPa)

θ = sum of principal stresses (kPa)

= $\sigma_1 + 2.\sigma_3 = \sigma_c + \sigma_s + 3.\sigma_3 + \sigma_{d.w.}$

σ_3 = minor principal stress (kPa)

σ_1 = major principal stress (kPa)

$\sigma_{1,f}$ = major principal stress at monotonic failure(kPa)

θ_0, $\sigma_{3,0}$,$\sigma_{d,0}$ = reference values (= 1 kPa)

k_5 = regression coefficients (MPa)

k_6, k_7, k_8 = regression coefficients (-)

The $\sigma_1/\sigma_{1,f}$ term in this equation is necessary to account for the decrease in stiffness that can result in triaxial testing as σ_1 approaches $\sigma_{1,f}$ whilst σ_3 remains constant. It is important to include such a term in models of stress-dependent materials otherwise iterative pavement analysis using, for example, finite elements, can converge at very high stiffness values. This occurs when the foamed bitumen layer attracts stresses high in a pavement structure that in turn, result in higher material stiffness, which then attracts more stresses in the next iteration etc. In such an analysis, the foamed bitumen layer should be divided into sub-layers of 15 to 25mm to more accurately model the stress distribution and hence stiffness distribution with depth.

4.2. Shear parameters

The granular nature of lower binder content cold foamed mixtures implies that shear parameters are important measures of characterizing such materials. These parameters can be determined using monotonic failure tests in the triaxial mode. Mohr-Coloumb analysis of the results of the monotonic triaxial tests conducted on the granular materials and their equivalent cold foamed bitumen mixes provides a clearer insight into the function of the foamed bitumen binder. According to the summary of the monotonic triaxial test results in Table 1 and as shown in Figure 11, the friction angle ϕ decreases whilst the cohesion of the mix increases with the inclusion of foamed bitumen in a cold mix.

Table 1. Typical Shear Failure Parameters C and ϕ for Granular and Equivalent Foamed Mixes (subscript indicates binder content)

Material	Type	C (MPa)	ϕ (°)	R^2
G1gau	Granular	0.082	53.0	*
G1gau$_2$	Foamed	0.166	44.7	0.99
G1eer$_1$	Foamed	0.162	45.8	0.95
G1eer$_2$	Foamed	0.156	45.9	0.92

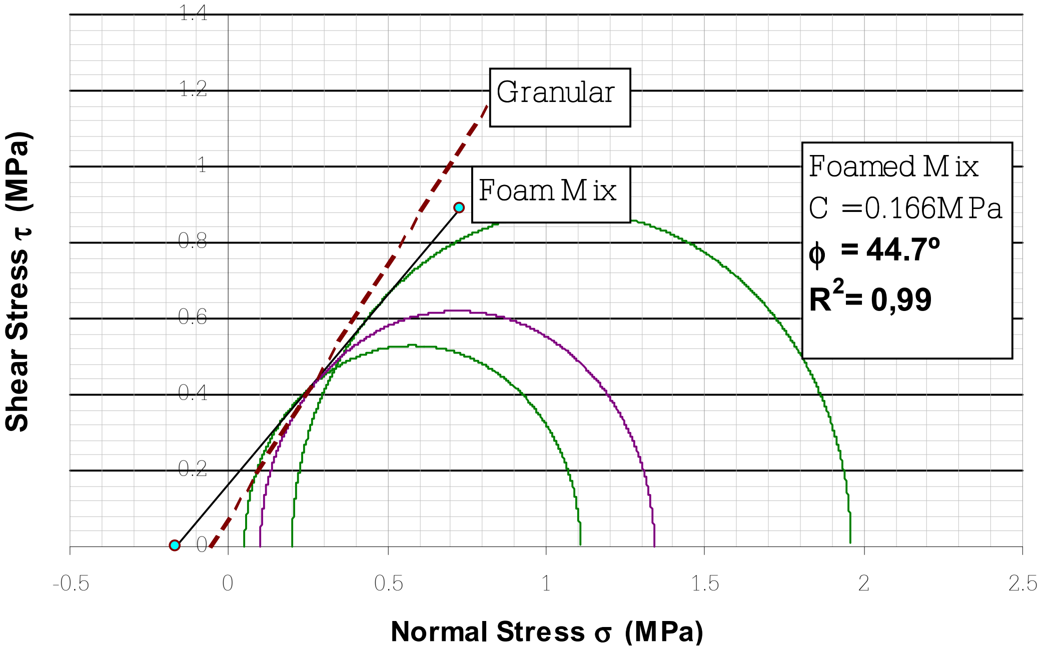


Figure 11. Mohr-Coloumb Circles for G1gau$_2$ Foamed Mix with Failure Envelopes for G1gau Superimposed *(temperature)*

Shear parameters also provide a useful means of measuring the moisture susceptibility of foamed bitumen mixes. Research into materials exposed to moisture using a technique where the laboratory specimen is exposed to water under 100mm of Hg vacuum for 1 hour at 25°C, followed by a further 1hour under water without vacuum, showed the shift in the Mohr-Coloumb failure envelope due to moisture damage. Although the moisture effects can increase the friction angle ϕ by up to 7% (probably through ensuring clean inter-particle contacts), it is the reduction in the cohesion value C that provides the yardstick for moisture susceptibility assessment of a particular material. The cohesion can decrease from insignificant amounts to almost total cohesion loss. This goes towards assessing a material's durability and needs to be investigated for each particular material during the mix design phase. Currently the Indirect Tensile Strength (ITS) test is used for this purpose by some designers.

4.3. Permanent Deformation ε_p under Repeated Loads

Cumulative axial permanent strain ($\varepsilon_{p,axial}$) analysed as a function of load repetitions (N) provides insight into performance of different foamed bitumen mixes. Variability in the ultimate shear strength and hence failure envelope of triaxial specimens is inherent and therefore forms an intrinsic factor in ε_p analysis. The use of ultimate shear strength as an intrinsic factor is very useful for material modelling, as it incorporates factors such as compaction, moisture content, curing and even moisture susceptibility effects e.g. shear strengths after vacuum saturation. In this way a template for permanent deformation behaviour can be developed. The ultimate deviator stress $\sigma_{d,f}$ has been selected as it is a more representative factor than $\sigma_{1,f}$ by incorporating the influence of the confining stress σ_3 on the ultimate strength.

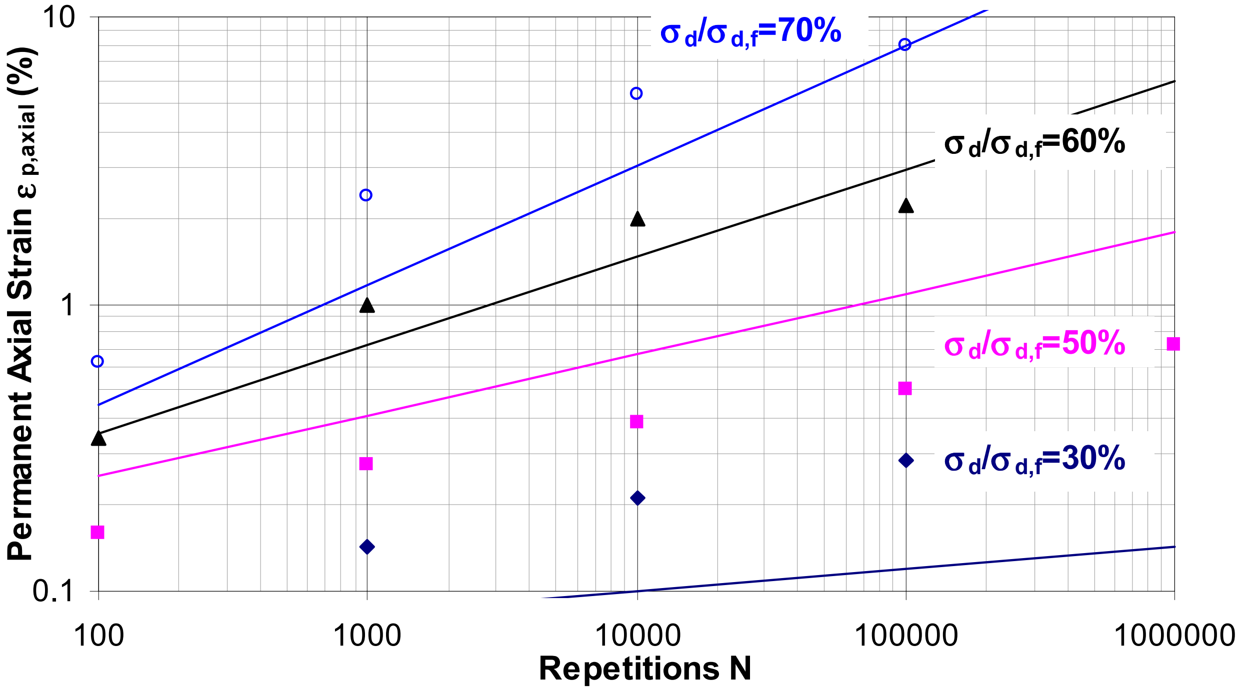


Figure 12. Template for Permanent Deformation Modelling of Foamed Mixes with <4% Foamed Binder and Without Cement based on Averaged Triaxial Results *(*at 20ºC test temperature and OMC*)*

It is apparent from the results of the permanent deformation tests on foamed treated materials that, as with granular materials, a critical stress ratio defines the boundary between stable ε_p growth and accelerated ε_p growth under repeated loading up to 10^6 cycles. Although it is possible to model the permanent deformation under axle loads of different magnitudes[3], these performance tests need to be extended to include a greater variety of materials before a comprehensively tested template is available. Nevertheless, using the present results it is possible to define a ratio of $\sigma_d/\sigma_{d,f}$ = 55% as the critical boundary for permanent deformation failure of foamed treated materials with 4% or less binder and without cement. The ratio of 55% has been selected as a boundary value between steady permanent deformation development and explosive ε_p growth from numerous tests. Pavement designs incorporating foamed bitumen treated layers should therefore be designed with this limit as a guide to ensure satisfactory performance.

5. Conclusions & Remarks

Some general comments may be made with regard to foamed bitumen mixes:

- The Foam Index is a useful function for the optimisation of foamed bitumen production taking account of factors such as binder type and temperature.
- The characteristics of the foam should be optimised for specific bitumen according to the type of application e.g. cold mix or half-warm mix.
- The VMA of the sand fraction (<2,36mm) can be used as a parameter for the selection of suitable aggregate gradation for foamed bitumen treatment. The VMA should be optimised through blending to obtain a minimum value in order to achieve the best mix properties.
- The overall aggregate skeleton can be defined in terms of the “Magic triangle” comprising a mix of three different fractions viz, filler, sand and coarse aggregate. Boundaries have been identified that define the optimal ratios within which these fractions should be combined in foamed mixes.
- Foamed bitumen mixes with less than 4% binder have been found to exhibit stress-dependent behaviour. Binder contents of 2% behave similarly to granular materials. Such materials can experience a 100% increase in stiffness as the total stress-state increases from 100kPa to 900kPa under dynamic triaxial testing. Monotonic triaxial testing provides a reliable measure of characterising such mixes with granular type behaviour, yielding values for cohesion and friction angle.
- The permanent deformation behaviour of a range of cold foamed mixes has shown that a critical stress ratio for $\sigma_d/\sigma_{d,f}$ defines the boundary between stable ε_p growth and accelerated ε_p growth under repeated loading up to 10^6 cycles. For foamed mixes with up to 4% bitumen and no cement, this critical ratio of $\sigma_d/\sigma_{d,f}$ = 55% and should not be exceeded if sound pavement performance is to be achieved .

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Kim Jenkins is currently the incumbent of the SANRAL Chair in Pavement Engineering at the University of Stellenbosch. He comes originally from Natal where he studied and worked for more than ten years as a consultant in geotechnical engineering and pavement materials. Thereafter he made a career shift, choosing to become involved in research and academics in the field of road pavements. This led Kim down to Stellenbosch as well as more than a year in Delft in the Netherlands.