CHARACTERISATION OF FOAMED BITUMEN

KJ Jenkins* ,   MFC van de Ven,   JLA de Groot*****

* PhD Researcher
Institute for Transport Technology (ITT)
University of Stellenbosch
South Africa
Email: kjenkins@ing.sun.ac.za

** Professor in Civil Engineering
SABITA Chair
University of Stellenbosch
South Africa
Email: mfcvdven@maties.sun.ac.za

*** QA/QC Manager
G. van Hees en zonen bv
Tilburg
Netherlands
Email: jacgroot@euronet.nl

Abstract

Foamed bitumen stabilisation is experiencing a global renaissance and the variety and variability of bitumens available for use in this process, is prolific. In this dynamic environment the methods of foamed bitumen characterisation require scrutiny. Currently, the expansion ratio (volume increase ratio) and the half-life (stability with time) are utilised. Although these empirical indices are useful, they do not provide a complete fingerprint of a bitumen's "foamability". This paper explores new, more relevant measures and indices for characterising the foamed bitumen based on the physics of the foam and the composition of the bitumen. Research has included bitumen from various crude sources with different compositions, as well as a variety of additives. Recommendations are given for the standardisation of the foamed bitumen characterisation testing with due consideration given to the entire mix.

1. INTRODUCTION

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. In this manner, bitumen can be mixed whilst it is foaming (in a temporary state of low viscosity) with mineral aggregates at ambient temperatures and at in situ moisture contents. The foamed bitumen process is analogous to a baker beating an egg, which is viscous, into a foam of low viscosity before mixing it with flour. This step is required in order to produce a mix of acceptable quality and consistency. Mineral aggregates and sands stabilised with foamed bitumen have been found to be very useful in road construction. Applications for the process include road rehabilitation with recycling, labour intensive construction and new construction.

As with most pavement engineering processes, a degree of variability is inherent to foamed bitumen stabilisation. In particular, the quality of the foam produced can vary markedly for different bitumens and different foaming apparatuses (other factors such as mixing plant type, mixing moisture content etc are not considered in this paper). This in turn, can influence the performance of a mix. In order to control the quality of the foamed bitumen and consequently the foam stabilised mix, the correct characteristics of the foam require analysis and monitoring.

At present, the properties of the foam are characterised by means of the expansion ratio and the half-life values. These values are calculated as follows:

- Expansion Ratio = Maximum volume of foamed bitumen/Volume of bitumen
- Half-life = Time measured in seconds for the foamed bitumen to subside from the maximum volume to half of the maximum volume

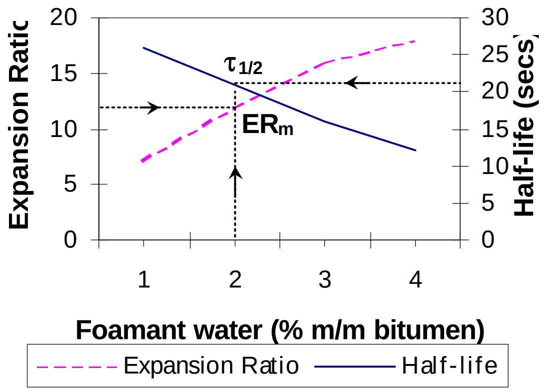


Figure 1a: Foam characteristics for a typical Penetration Grade bitumen in South Africa.

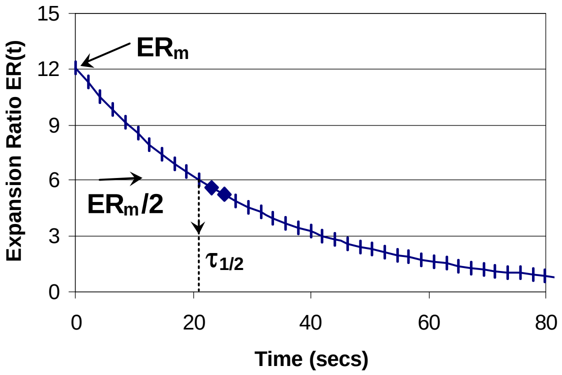


Figure 1b: Foam decay curve for same bitumen as Fig 1a, with 2% foamant water

Laboratory analysis of a given bitumen, heated and foamed into a vessel with a determined application rate of foamant water, currently requires only two points to be recorded viz. the measured maximum Expansion Ratio (ER_m) and the Half-life ($\tau_{1/2}$). By varying the application rate of the foamant water, a plot such as Figure 1a may be obtained. From such a plot, an application rate of foamant water is selected at present, for which the trade-off between ER_m and $\tau_{1/2}$ is considered acceptable. No standard specifications exist in South Africa, although recommended values of $ER_m > 10x$ and $\tau_{1/2}>12$ seconds have been published (CSIR, 1998).

After an intensive study of foaming characteristics, it has become evident that these two parameters and the manner in which they are currently determined are insufficient for adequate characterisation of foam properties. The rest of the curve outlining the collapse of the foam with time, is ignored at present (see Figure 1b). Improved or new parameters that utilise the decay curve, are necessary for the characterisation of the foam and the prediction of performance of foamed bitumen in mixing and coating applications. To this end, a new protocol has been established to standardise the investigation and testing of the "foamability" of different bitumens.

It should be noted that this investigation has been restricted to the use of the Wirtgen laboratory foaming plant. Further investigation into the characterisation of foamed bitumen using other laboratory apparatus is desirable and should receive attention.

2. WHAT MAKES BITUMEN FOAM?

The fundamentals of the foaming process require consideration before the factors influencing the characteristics of foamed bitumen can be analysed. The laws governing the behaviour of the bitumen during foaming are primarily physical, although chemistry does also play a role.

The moment that a cold water droplet (at ambient temperature) makes contact with the bitumen at 170°C to 180°C, the following chain of events occur:

- The bitumen exchanges energy with the surface of the water droplet heating the droplet to a temperature of 100°C and cooling the bitumen.
- The transferred energy of the bitumen exceeds the latent heat of steam resulting in explosive expansion and the generation of steam. Steam bubbles are forced into the continuous phase of bitumen under pressure, in the expansion chamber.
- With emission from the spray nozzle the encapsulated steam expands until a thin film of slightly cooler bitumen holds the bubble intact through its surface tension.
- During expansion, the surface tension of the bitumen film counteracts the ever-diminishing steam pressure until a state of equilibrium is reached.
- Due to the low thermal conductivity of bitumen and water, the bubble can remain stable for a period of time, usually measurable in seconds.

This process occurs for a multitude of bitumen bubbles that live contemporary meta-stable lives, providing foamed bitumen. As the colloidal mass cools at ambient temperature, the steam in the bubbles condenses causing bubbles to collapse and the foam to "decay".

3. THE PHYSICS OF FOAMED BITUMEN

The physics of foamed bitumen requires exploration in order to identify some of the pertinent factors influencing foam characteristics.

3.1 Conservation of Energy

Energy, predominantly in the form of heat, is probably the dominant factor that influences the physics of foamed bitumen. Extending the background work of Acott

(1980) and considering the production of foamed bitumen in the laboratory, the equilibrium temperature of the system can be calculated.

If foamed bitumen is discharged into a mild steel vessel in the laboratory, heat is transferred from the bitumen to the vessel and the foamant water. If the equilibrium state of the system is considered only in terms of heat transfer i.e. ignoring work required to overcome the surface tension of the bitumen, and all of the foamant water is converted to steam, the conservation of energy law may be simply applied. This implies that the energy gained by the water and the vessel is equal to the energy lost by the bitumen.

The energy may be expressed in terms of the specific heat capacity of the various components and a theoretical equilibrium temperature T °C achieved by the system. For example, the heat gained by the foamant water will comprise:

- The energy required to increase the water temperature from ambient to boiling point,
- The latent heat of steam, and
- The heat required to increase the steam temperature to T°C.

In such a way, one can develop a sensitivity analysis of the equilibrium temperature based on the temperatures of the main components, see Table 1 (for 500g bitumen foamed with 2,5% foamant water into a vessel of mass 1500g).

Table 1: Theoretical Equilibrium Temperature T (°C) for Foamed Bitumen System in the Laboratory

	Bitumen Temperature T_b			
Vessel Temp T_v	**150°C**	**160°C**	**170°C**	**180°C**
10°C	75.4	81.3	87.2	93.1
28°C	82.6	88.4	94.3	100.2
50°C	91.3	97.2	103.1	108.9
100°C	111.1	117.0	122.9	128.7

It is obvious from the range of theoretical equilibrium temperatures in Table 1 and the fact that foam stability is dependent on the steam temperature, that T_v and T_b require consideration in the determination of foam characteristics. The fact that some of the equilibrium temperatures are below 100°C does not preclude the possibility of foam production, as time is required for thermal conductivity before the theoretical equilibrium temperature may be achieved.

In order to eliminate misleading influences such as the vessel temperature, the laboratory testing procedures for characterising foamed bitumen should utilise either:

1. A vessel of known mass, material and temperature or
2. At least two trials before quality control tests commence, in order to establish an equilibrium temperature for the vessel.

In addition, a sensitivity analysis of the foam properties versus the bitumen temperature is imperative.

The energy considerations become important in the application of the Boyle-Charles-Gay-Lussac Law to the foam system. The Universal Gas Law (Hutchinson, 1959) is given in Equation1.

$$P\ .\ V = n\ .\ R\ .\ T \qquad \text{…………………………(Eq.1)}$$

Where,
P = Pressure in Atmospheres (atm)
V = Volume in litres (l)
n = Number of moles = mass/atomic mass of compound
R = Universal Constant = 22.414/273.16 (atm.l/mole.°Kelvin)
T = Temperature (°Kelvin)

Using the same laboratory application of 500g of foamed bitumen discharged into a vessel, the Universal Gas Law yields a volume of 21,2 litres of steam from the foamant water as it undergoes a phase change. This would yield an expansion ratio of 42,4 times for bitumen, which is some 2,5 times higher than the normal values measured in the laboratory. Explanations for the discrepancy include:

- Steam is not encapsulated and is lost during the foaming of bitumen i.e. it escapes. This can be observed in many cases.
- Not all of the water is utilised to generate steam i.e. a small water droplet remains insulated by steam in the bitumen bubble.
- The pressure inside the bitumen bubble is higher than atmospheric pressure.

3.2 The foamed bitumen bubble

In order to analyse the mechanical interaction of the steam and bitumen, a bubble in isolation should be considered before the complex colloidal system can be understood. Figure 2 below shows the changing parameters in an expanding bubble.

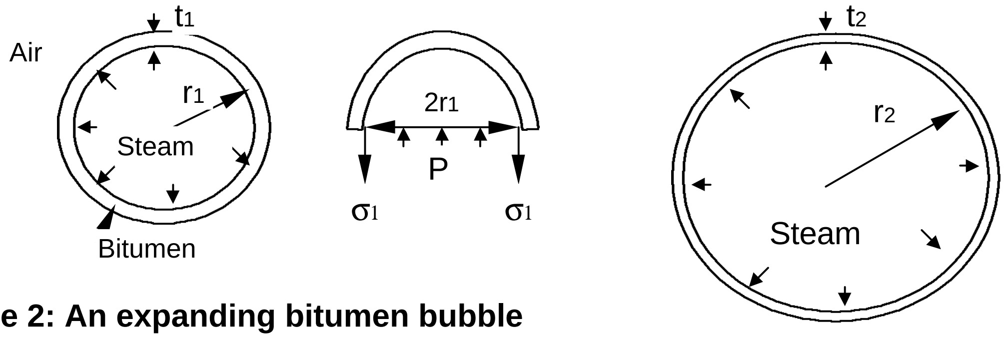


Figure 2: An expanding bitumen bubble

Using the geometry of a sphere, it may be proven that the tensile stresses remain constant as the bubble expands (Jenkins, For 1999). Other phenomena limit the expansion of the individual bubbles and ultimately the foam mass, therefore, as outlined below.

3.2.1 Free surface energy considerations

Schramm (1994) states that energy needs to be added to a system in order to achieve dispersion of .As was stated by Acott (1980) the free energy of the bitumen film forming the bubble needs to remain positive for a stable foam to exist with the separate phases of steam, bitumen and air. If this were not the case, then any mechanical or thermal fluctuations would expand the surface region continuously, leading to dispersion of the phases. Free surface energy is the work required to expand the surface area and is measured in erg/cm^2, where 1erg = 10^{-7} Joules. The value of the surface tension for bitumen is given in Table 2.

Table 2: Surface Tension of Bitumen (Lubbers, 1985)

Temperature (°C)	Surface Tension (erg/cm^2)
25	33
100	29
150	26

The free surface energy (G_b) of the foam bubble is the product of the energy per unit area or surface tension (γ) and the surface area (A).

$$G_b = \gamma.A = \gamma.8\pi r^2 \qquad \text{……………………….(Eq.2)}$$

The surface energy required to increase the radius of a bubble from r_1 to r_2 (see Figure 1) is given by :

$$\Delta G_b = \gamma.8\pi(r_2^2 - r_1^2) \qquad \text{……………………..(Eq.3)}$$

This energy may be equated with the energy lost by the steam (ΔG_S) during expansion of the bubble. This may be calculated from the integral of the force on the film (F_r) over the distance it has been expanded (r_2-r_1), see Equation2.

$$\Delta G_s = \int_{r1}^{r2} F_r.r.dr = P_1.4\pi r_1^3(r_2 - r_1) \qquad \text{…………………….(Eq.4)}$$

According to (Jenkins, For 1999), using Equations 2 and 3, for a bubble to expand from r_1=5mm to r_2=10mm at equilibrium, the final pressure in the bubble would be 830Pa. The Law of Boyle-Charles-Gay-Lassac indicates that a water droplet of 170µm would be required to produce such a foam bubble. Although the entire colloid mass has not been considered as yet, the bubble sizes in this example are representative of critical sizes observed in foamed bitumen mass that burst or collapse first.

3.1.2 Elongation at break criteria

Heukelom *et al* (1973) established a relationship between elongation at break and the stiffness modulus at break of bitumens with different penetration indices. Using this relationship, an indication of the elongation of the bitumen film of a foamed bubble that is produced in an explosive reaction, can be estimated. The following typical values have been utilised for foamed bitumen:

- Breaking time = 0.001 seconds,
- Temperature above $T_{r\&b}$ = 100 – 44 = 56°C
- Penetration Index = -0.5

From the Nomograph of Heukelom *et al*, the elongation at break will be 100x. This implies that a water droplet of 0.1mm radius and circumference 0.628mm, which is encapsulated in bitumen as it is entirely vaporised, will expand to 62.8mm circumference before breaking i.e. a bubble radius of 10mm. This concurs with observations that have shown bubble radii of 10 to 15mm to be the critical radii at which breaking occurs. The corollary is that water droplet sizes of approximately 100 to 150µm create the critical foamed bubbles which break, which correlates well with free surface energy considerations.

4. FOAMED BITUMEN DECAY

Having established some of the factors influencing the behaviour of foam bitumen, the pertinent parameters for characterisation can be developed. The collapse of foamed bitumen with time, which is referred to as “decay” in this paper and is also known as “breaking”, is considered to hold the key.

4.1 Factors influencing foamed bitumen decay

Several causes of the collapse of foamed bitumen bubbles with time, in the laboratory, may be noted:

- *Reduction in the temperature of the steam due to contact of the bitumen films with ambient air (and vessel) at lower temperature.* This occurs mainly with the bubbles at the frontier of the colloid mass. If rate of temperature and pressure reduction within a bubble exceeds the recovery rate of the bitumen film that is experiencing surface tension, the bubble will collapse. Larger bubbles, although possessing theoretically the same surface tension as their smaller counterparts, have a greater exposed surface area and will experience a higher rate of reduction in temperature and will therefore collapse first!
- *Exceedance of the elongation limit of the bitumen film.* Where the water droplet initiating the formation of the foamed bitumen bubble is too large, the steam pressure inside the bubble could extend the bitumen film beyond its ductile limit, resulting in failure. Larger bubbles will fail first allowing steam to escape. If a small water droplet was still present in the bubble, it could generate another bubble but less energy is available for this process as the bitumen temperature reduces.
- *Polydiverse colloidal mass.* It is apparent from literature (Adamson, 1990) that a bubble pattern in which the septums of the bubbles (dividing walls) meet at 120° will provide the most mechanically stable configuration. The inverse of this theory is also true i.e. foams of a polydiverse nature, with a variety of bubble sizes, will be unstable with bubbles riding over each other until an equilibrium is reached.

4.2 Modelling of foam decay

Research on a variety of bitumens using the Wirtgen Laboratory Foam Plant ® has shown that the decay of their foam can be successfully modelled by adapting equations for isotope decay. Jenkins (For 1999) developed the following relationship to describe the decay of unmodified bitumen foam:

$$ER(t) = ER_m . e^{\frac{-\ln 2}{\tau_{1/2}} * t} \qquad \text{…………………(Eq. 5)}$$

Where,

ER(t) = Expansion Ratio with respect to time after foam discharge
ER_m = Maximum Measured Expansion Ratio (immediately after discharge)
$\tau_{1/2}$ = half-life (seconds)
t = time measured from the moment all foam is discharged (sec)

The asymptotic theoretical decay line as defined in Equation 5, is plotted relative to an example of an actual foamed bitumen with ER_m=11 and $\tau_{1/2}$=6secs in Figure 3a below. The expansion ratio and half-life, as currently used in practise, are two points on this curve. The correlation coefficient of R^2 = 0.927 is a typical value for unmodified bitumens, but is dependent on repeated measurements for statistical reliability, and attention being paid to standard testing procedures.

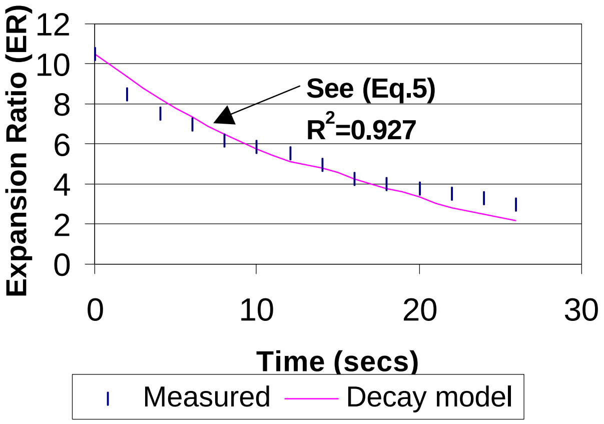


Figure 3a: Theoretical versus Actual Foam Decay

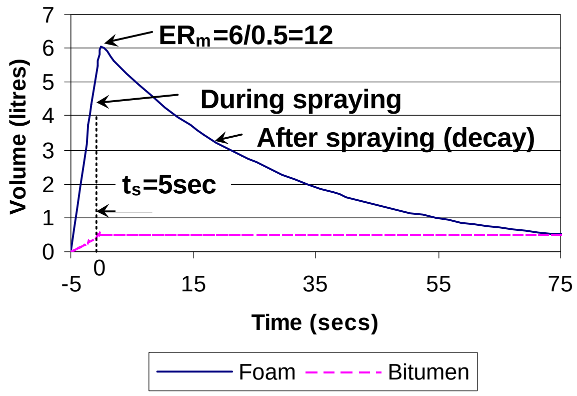


Figure 3b: Life cycle of foamed bitumen

To date, an important feature of the laboratory foaming process has been ignored i.e. the decay of the foam during spraying but before the volume is measured. This is one of the weaknesses of the currently used techniques for foamed bitumen characterisation and has an especially significant influence on bitumens with a low half-life. In most cases, the bitumen has been decaying for up to 5 seconds before the expansion ratio is measured, see Figure 3b i.e. the maximum expansion ratio measured ER_m is not the actual max. expansion ratio ER_a of the foam or $ER_m \neq ER_a$.

This difference has been accounted for by (Jenkins, For 1999). Using the foam decay relationship incrementally on foamed bitumen during discharge from the spray nozzle, the actual maximum expansion ratio ER_a required to yield the measured maximum expansion ratio ER_m in the laboratory can be back-calculated. It is not possible to measure the actual expansion ratio due to the decay during discharge; but it is possible to back-calculate it. Table 3 provides a sensitivity analysis of ER_a versus ER_m for different half-lives and spraying (discharge) times. It is therefore imperative to take account of this factor for bitumen with relatively short half-lives.

Table 3: Relationship between actual and measured Expansion Ratio

		ER_a				
Spray time (t_s)	**ER_m**	**$\tau_{1/2}$=2 (secs)**	**$\tau_{1/2}$=5 (secs)**	**$\tau_{1/2}$=15 (secs)**	**$\tau_{1/2}$=30 (secs)**	**$\tau_{1/2}$=60 (secs)**
1 sec	5	6.02	5.39	5.13	5.06	5.03
	15	18.05	16.17	15.38	15.19	15.10
	25	30.05	26.95	25.64	25.32	25.15
5 secs	5	11.50	7.20	5.66	5.30	5.20
	15	34.40	21.48	16.98	16.00	15.50
	25	57.20	35.80	28.30	26.60	25.80
10 secs	5	21.34	9.88	6.38	5.66	5.33
	15	63.98	29.64	19.14	16.98	15.97
	25	106.63	49.39	31.89	28.30	26.61

A more extensive relationship between ER_a and ER_m is shown graphically in Figure 4. Given t_s (time of spraying of the foamed bitumen) and $\tau_{1/2}$ (half-life), the correction factor c (=ER_m/ER_a) can be used to obtain the actual expansion ratio (ER_a) from the measured expansion ratio (ER_m).

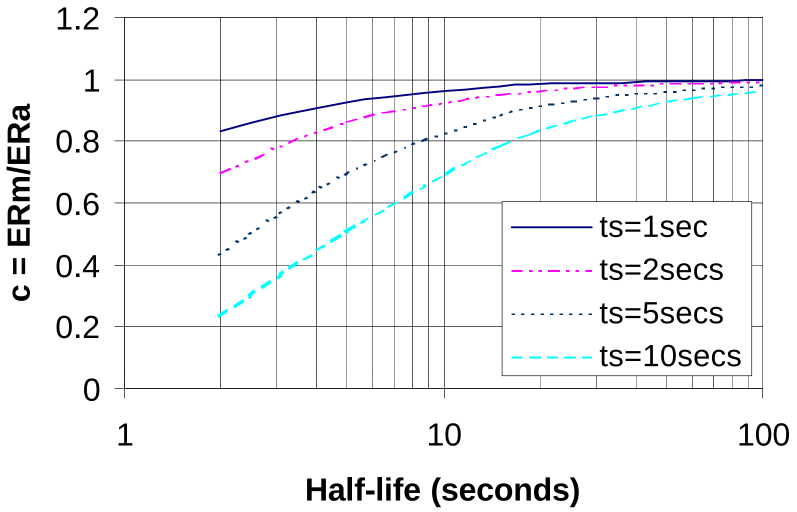


Figure 4: Relationship between Actual and Measured Max. Expansion Ratio

4.3 The Foam Index for measuring “foamability”

4.3.1 Unmodified foamed bitumen (no foamants)

An appropriate parameter for characterising foamed bitumen is one that reflects the ability of the foam to be mixed with mineral aggregate. The expansion ratio is a measure of the viscosity of the foam whilst the rate at which the foam collapses is defined by the decay curve, which is an indication the time available for mixing. The area under the decay curve for a particular foamed bitumen will therefore be the desired characteristic. This area has been defined as the Foam Index (Jenkins, For 1999).

In identifying the limits within which the foam’s “stored energy” (area under the curve) should be analysed, the viscosity of the foam with time requires consideration. In order to determine the trend of foam viscosity with time, a hand held viscometer was utilised with spindle immersed in decaying foam. In this way, various foams for a variety of bitumens and additives could be compared, see Figure 5.

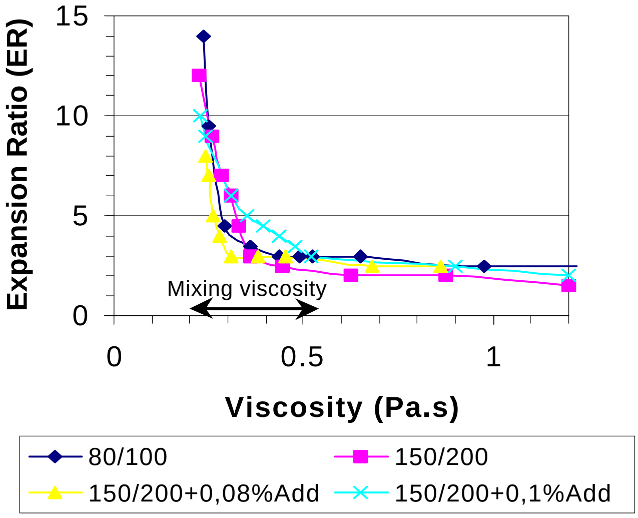


Figure 5: Relationship between viscosity and expansion ratio for foamed bitumen with and without additives (foamants)

Considering that acceptable mixing takes place at viscosities between 0.2 and 0.55 Pa.s (Shell Bitumen, 1990), the expansion ratio of the foam should at least be ER = 4 for adequate mixing of all foamed bitumens. This value is then utilised as the minimum value for calculating the area under the curve (Foam Index value), see Figure 6.

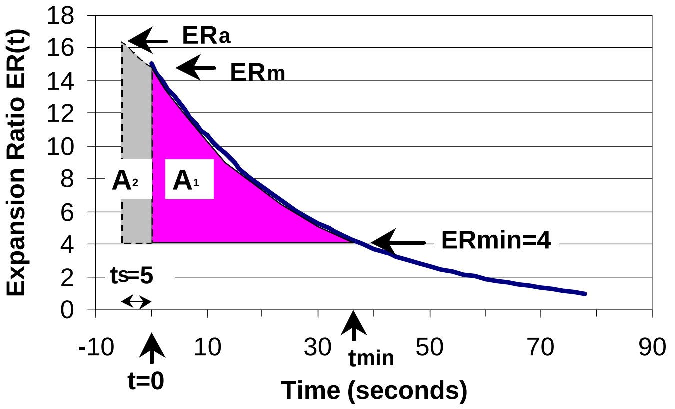


Figure 6 : The Foam Index FI for characterising the "foamability" of a bitumen for a given foamant water application rate, where FI = A_1+A_2

It should be noted that in this analysis no cognisance is taken of the fact that, during the mixing process, the aggregate will curtail the steady foam decay by drastically reducing the foam temperature upon contact. This is considered in the establishment of a recommended lower limit for FI. The characterisation of the foam in this manner has been developed in order to obtain an empirical parameter that is an appropriate performance index for the foams' suitability for mixing and dispersion in the mineral aggregate.

Integrating the decay equation to obtain area A1 and calculating area A2 geometrically, provides the following expression for the Foam Index (using the symbols as previously defined):

$$\mathrm{FI} = \frac{-\tau_{1/2}}{\ln 2}\left(4 - \mathrm{ER}_m - 4\ln\left(\frac{4}{\mathrm{ER}_m}\right)\right) + \left(\frac{1+c}{2c}\right) * \mathrm{ER}_m * t_s \qquad \text{………..(Eq.6)}$$

Example : Consider a bitumen with the following properties measured in the laboratory,

t_s = 5 seconds
ER_m = 15
$\tau_{1/2}$ = 10 seconds

From Figure 4, c = ER_m/ER_a = 0.83 and from Equation 6 FI = 165.1

Current recommended values (CSIR, 1998), using the old approach, are individually set at:

ER_m (min) = 10 and
$\tau_{1/2}$ (min) = 12 seconds

From Figure 4, c=0.86 and from Equation 6 FI = 94.5

The new “FI approach” does not result in bitumen in the example above being discarded because, for example, $\tau_{1/2}$ = 10 seconds (< 12 recommended). This bitumen would have an FI = 165.1 (>94.5) which shows a better foaming performance than the standard bitumen! A bitumen with a higher FI is able to store more energy in the foam whilst temporarily in the mixing viscosity range, than a bitumen with a lower Foam Index.

4.3.2 Bitumen with foamants

Not all bitumens possess the desired foaming characteristics for use in the foam process in their straight-run form. The minimum expansion ratio and half-life (or a minimum FI) is not always achievable. The reasons for the poor foamability is not always clear; bitumen composition is complex and anti-foamants such as silicones may be added in a refining process. However, what is clear is that the addition of appropriate foamants to the bitumen can improve the foaming characteristics significantly.

Where additives have been used in bitumens and the quality of foam that an apparatus produces is variable i.e. deviating from the decay curve model, a manual calculation of the Foam Index needs to be followed. This entails the following procedure:

- Measurement and plotting of the maximum ER_m and decaying expansion ratio ER(t) of the given bitumen with time, using the standard foam testing procedures. This should be done in steps with the highest frequency for:
    - expansion ratio, graduations of 3, and
    - time intervals of 10 seconds.
- This procedure should be repeated at least three times.
- Calculation of A_1 = the area under the decay curve between point ($t=0, ER_m$) and (t_{min}, ER_{min}) above the $ER_{min}=4$ line using an area by co-ordinates or similar routine,

- Calculation of A_2 from time $t=-t_s$ to $t=0$ using (see Figure 4),

$$A_2 = \left(\frac{1+c}{2c}\right) * ER_m * t_s \qquad \text{……………………(Eq.7)}$$

- Calculation of the Foam Index $FI = A_1 + A_2$.

This procedure is useful for the optimisation of the application rate of an additive to bitumen. The FI can be calculated for a range of application rates and the optimum additive content is then selected from a curve plotted from the results as shown in the example of a South African bitumen in Figure 7, which shows the average of three tests for each point.

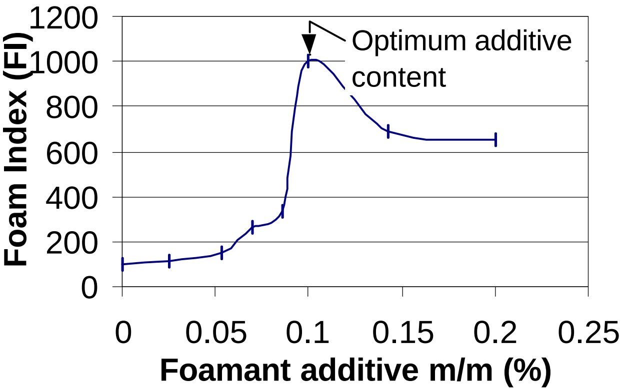


Figure 7 : Influence of foamant additive content (m/m bitumen) on Foam Index (for Calref 150/200 with 2,2% foamant water)

In the same manner, the Foam Index can be utilised to determine the optimum foamant water content for a specific bitumen (with or without additive). The decay curve of a foamed bitumen can be recorded for varying foamant water applications and the FI obtained for each curve. As shown in Figure 8a, the form of FI vs water content curve does not necessarily yield a definitive optimum point, but rather a range of foamant water contents to produced optimal foamed bitumen characteristics. The most likely reason for this is that :

- the lower water contents do not convert to sufficient volume of steam to produce the requisite expansion of the bitumen foam, whereas
- the higher water contents result in more steam being generated than the bitumen bubbles can accommodate, causing steam to escape and a loss of energy.

A margin between these scenarios exists for a given bitumen, which will produce optimal stored energy in the foamed bitumen and a relatively constant Foam Index.

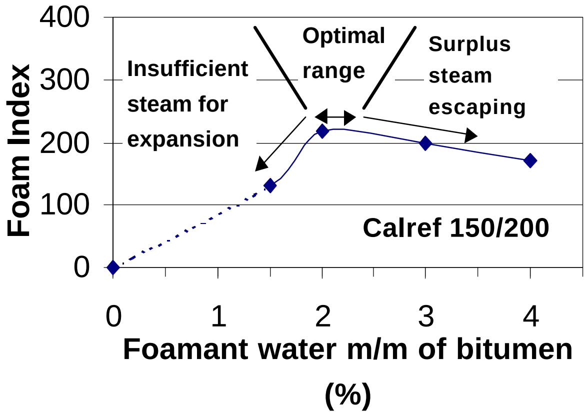


Figure 8a : Influence of foamant water content on foam bitumen characteristics

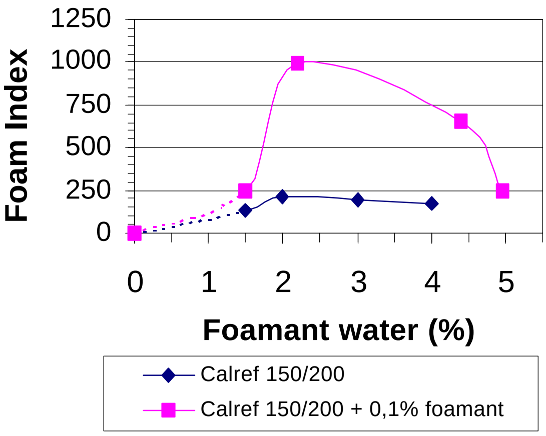
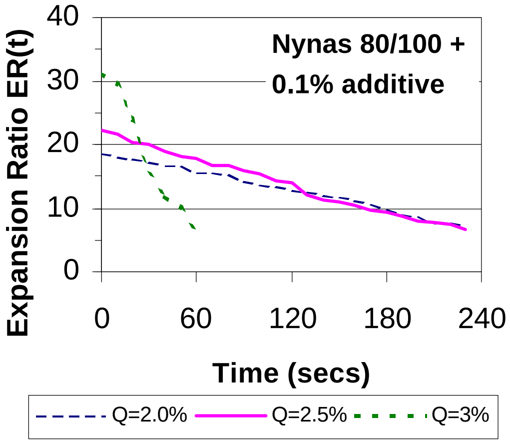


Figure 8b: Influence of foamant water and bitumen additive on Foam Index

The optimal range of foamant water contents appears to be of the same order for a specific bitumen with and without an additive, as shown in Figure 8b. The figure, which includes three tests for each point, also shows the potential improvements in the Foam Index of the Calref 150/200 with a specific foamant additive.

In the same manner, the FI can be compared for two different bitumens using the same additive. From tests carried out, one of the best Dutch bitumens with respect to foam characteristics has been selected for comparison with a typical South African bitumen. Figure 9a below shows the foamed bitumen decay curves (average of three tests) for a Dutch bitumen with the same additive as used with the Calref bitumen.



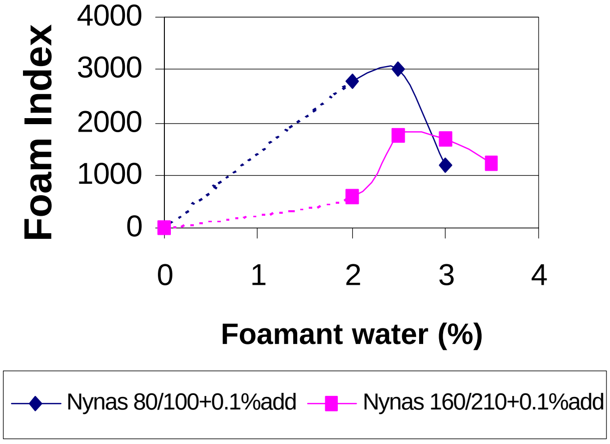


Figure 9a : Foamed bitumen decay curves for a Dutch bitumen with foamant

Figure 9b : Influence of foamant water content on FI for Dutch bitumen

Note : Q = Foamant water content (% m/m bitumen)

The following comments are relevant to these results:

- The optimal range of foamant water application is evident for the Dutch bitumen using the Foam Index procedure.
- It is interesting to note that the decay curves are linear for foamed bitumen produced with foamant water in the optimal range.

- It is evident that the expansion ratio for this bitumen can be boosted to in excess of ER_m = 30 by increasing the water application rate, at the expense of the Foam Index. This may be useful for specialist applications such as encapsulation of contaminants e.g tars, or where fine coating of particles is required in a foamed bitumen mix.

In comparing the results of the two bitumens, the following points are of interest:

- There is a marked difference in foaming characteristics between the two bitumens. The same foamant additive was utilised and it boosted the FI for both bitumens. However, the Nynas 80/100 bitumen had intrinsically better foam qualities that could not be met by the Calref 150/200, hence Nynas' three-fold higher foam index.
- The foamant has a significant contribution in the correction of the measured expansion ratio ER_m. By extending the half-life of the foamed bitumen, the foamant has the simultaneous effect of correcting ER_m so that it approaches the actual expansion ratio ER_a. This is evident in Table 5 and Figure 10 below. The correction factor c approaches unity as the Half Life increases, see Figure 4. The improvement in half-life by adding foamant "M" in this case is pronounced due to the extremely low initial values.

Table 5: Influence of Foamant "M" on Nynas 160/210 Bitumen

Foamant water	**Add "M" (%)**	**ER_m**	**ER_a**	**C (ER_m/ER_a)**	**$\tau_{1/2}$**	**FI**
1	0.0	8.3	9.7	0.86	11.7	68
1.5	0.0	12.7	19.4	0.65	4.2	105
2	0.0	13.3	21.4	0.62	3.7	111
3	0.0	18.7	29.1	0.64	4.0	169
2.0	0.1	18.7	19.6	0.95	41.7	611
2.5	0.1	24.5	25.1	0.98	84.3	1740
3	0.1	30.9	31.9	0.97	57.3	1702
3.5	0.1	36.7	39.1	0.94	29.7	1211

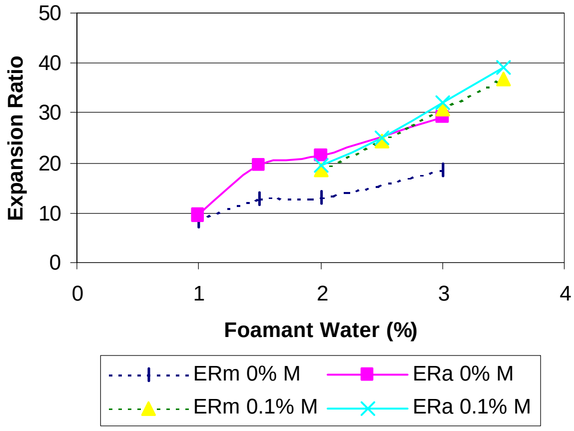


Figure 10a : The Influence of Foamant Water on ER for Nynas 160/210 Bitumen with and without Foamant "M".

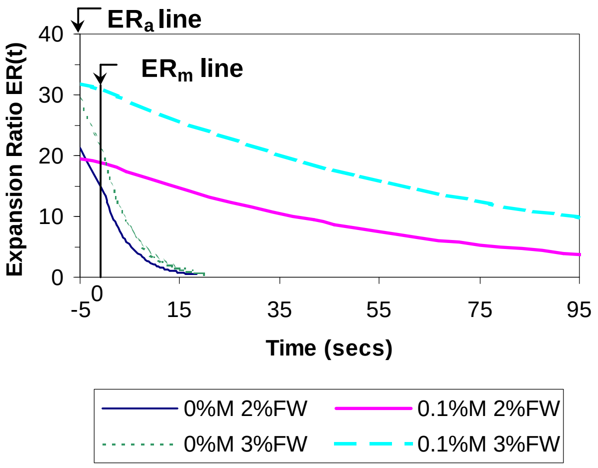


Figure 10b : Decay curves for Nynas 160/210 with and without Foamant (M) at different Foamant Water (FW) application rates

If the ER_a's are compared for the Nynas 160/210 with and without additive"M", as shown in Figure 10a, it is apparent that the additive has a negligible influence on the Expansion Ratio of a bitumen. The dangers in applying the old standard technique of measuring ER_m for a foam are evident in Figure 10b i.e. the actual and measured expansion ratios can vary considerably in reality. Although the expansion characteristics of foamed bitumen appear to be improved through application of the additive, it is apparent that this is not the case.

4.3.3 Additives in the foamant water

It has been shown in this paper that the droplet sizes of the moleculised foamant water have a significant influence on the characteristics of the foamed bitumen. The mist of foamant water produced in the process is not only apparatus dependent, but also water quality dependent. In addition, additives can be added to the foamant water as well as the bitumen to influence the characteristics of the foam.

For this reason, an investigation was carried out into the use of a super-plasticizer in the foamant water to reduce the surface tension of the water. This resulted in finer water droplets being produced during moleculisation of the water and therefore a greater number of droplets being injected into the expansion chamber.

The use of the super-plasticizer resulted in an increase of up to 60% in the expansion ratio of the bitumen and a slightly longer half-life. The problem with this particular plasticizer was that it negated the effects of another additive applied to the bitumen. Only limited research has been carried out in this direction and additional work is in progress on a diversity of bitumens, plasticizers and additives.

5. INFLUENCE OF BITUMEN TYPE AND COMPOSITION

Engineers have been aware of the differences in the foaming properties of different types of bitumen for several decades. (Acott,1985) stated that " *the crude type and/or method of bitumen manufacture also affects the foam characteristics*.

To date, no correlation has been noted between the foam characteristics and the bitumen composition in terms of SARA (Saturates Aromatics Resins and Asphaltenes) by the authors. Additives such as silicone anti-foamants used in the refining process, which are difficult to monitor, are more likely to result in differences in the foam characteristics than the crude-source of the bitumen.

From the limited literature, it is apparent that, where bitumens have originated from the same refining process, the softer bitumens have marginally lower surface energy (at the same temperature) for the steam pressure to overcome in the colloidal mass, yielding higher expansion ratios. Brennen *et al* (1983) stated that "*viscosity alone is not sufficient to explain the variations in expansion ratio and half-life*". Provided that the PI of two bitumens is the same, the half-life should remain constant. The Foam Index, however, does not necessarily increase for higher penetration bitumens, see Figure 9b.

6. CONCLUSIONS

Analysis of current practise with regard to the characterisation of foamed bitumen and research carried out on bitumen from various origins, the following conclusions have been drawn.

6.1 Modelling of foam decay

- The currently used expansion ratio (ER_m) and half-life ($\tau_{1/2}$) characteristics, although useful, are incomplete parameters for describing the attributes of foamed bitumen. In order to build on the existing system rather than to replace it, a correction factor has been established for ER_m in order to convert it into a more useful parameter ER_a (the actual expansion ratio). This may be done taking account of half-life and the spray time of the foam in the laboratory.
- The ER_a is an intrinsic measure of a bitumen's ability to expand during foaming at a fixed application of foamant water. Many foamants that are added to bitumen will increase ER_m and $\tau_{1/2}$, without changing ER_a.

6.2 The Foam Index

- Current practise does not provide the tools for optimisation of the foaming qualities of a bitumen. A new characteristic, the "Foam Index" (FI) is a useful tool for optimising the application rate of both the foamant water and proposed additives, for a given bitumen and foaming system. The Foam Index is a measure of the area under the decay curve i.e. the change in expansion ratio with time, which reflects the stored energy in the foam for a specific bitumen foamed at a known temperature with foamant water at a determined application rate.
- The FI may be determined using a standard decay equation for unmodified bitumen. Where foamants are utilised, a plot of the decay curve and manual calculation should be carried out to obtain the Foam Index.
- Research into the viscosity of various bitumens during foaming has shown that the expansion ratio ER_m should be a minimum of 4 in order to ensure that the foamed bitumen is at a sufficiently low viscosity to allow mixing.
- Although the environment and life-cycle of foamed bitumen for laboratory measurements and plant mixing differ significantly, the ER_a and FI obtained in the laboratory are important parameters for the comparison of different bitumens for a specific task. These characteristics can provide the basis for the selection of the appropriate bitumen.

6.3 Bitumen composition

- As with the performance properties of penetration grade bitumen used for asphalt production, the composition of the bitumen does not provide a reliable measure for prediction of performance properties of foamed bitumen.

6.4 Foam testing procedure

- The temperature and specific heat of the vessel into which a bitumen is foamed, as well as the bitumen temperature, has a significant influence on the results. To this end, either a vessel temperature and mass should be specified for testing or at least two trials should be carried out in a vessel to achieve equilibrium temperature, before quality control tests commence. In addition, a sensitivity analysis of FI and ER_a needs to be carried out for different bitumen temperatures.

- Due to the inherent variability of the measurement of foamed bitumen characteristics, a total of at least 3 tests should be carried out for each laboratory trial, in order to obtain an acceptable level of statistical reliability for the results.

7. RECOMMENDATIONS

The potential for practical application of the Foam Index (FI) and Actual Expansion Ratio (ER_a) as properties for the characterisation of foamed bitumen, appears promising. Additional work needs to be done on the following aspects of foamed stabilised mixes before these parameters should be used for specification purposes:

- The influence of FI and aggregate properties on the characteristics of a foamed bitumen stabilised mix, and
- The correlation of FI and plant mixing method/energy, on mix characteristics.

These aspects and others are currently receiving attention at the University of Stellenbosch.

ACKNOWLEDGEMENTS

The authors wish to extend their grateful appreciation to SABITA for funding the purchase of the Wirtgen laboratory foam apparatus that was an integral part of the research.

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