INFLUENCE OF FOAMING WATER ON THE FOAMING PROCESS AND RESULTANT ASPHALT MIX STIFFNESS

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ABSTRACT

The energy saving and environmental aspects of pavement construction with foamed cold mix asphalt technology are gaining it worldwide popularity. Foamed bitumens are commonly characterised by two key parameters; i.e. maximum expansion ratio (ERm) and half-life (HL), and these are mainly affected by the quantity of foaming water. Unfortunately, the effect of foam characteristics on asphalt mix performance remains poorly understood. This paper presents data from a series of laboratory investigations with the aim of enhancing the understanding of the relationship between foam characteristics and resultant asphalt mix stiffness.

Thus foam properties have been investigated at various foaming water contents (FWC) at a temperature of 180^{o}C using a 70/100 pen. grade bitumen. The aggregates were mechanically mixed with the foamed bitumen at a range of FWC's using either an aluminium dough hook or a flat steel Hobart agitator. The resulting asphalt mixes were then compacted using a gyratory compactor. The indirect tensile stiffness modulus values of all specimens was measured at a temperature of 20^{o}C following a curing period of 3 days at 40°C. Selected specimens were also stiffness tested at other temperatures and following enhanced curing regimes.

Overall, better mixing was found to aid material properties thus enhancing mix stiffness, with the flat steel agitator performing better than the aluminium dough hook. Specimens mixed at different FWC using the aluminium dough hook exhibited no significant differences in mix stiffness; minor fluctuation of stiffness values were attributed to small variations in mix moisture content and density. However, when specimens were mixed using the flat steel agitator, their cured stiffness values increased significantly and the effect of FWC was clearly evident. Optimum performance was obtained with specimens prepared at 5% foaming water, and this became even more evident when the full range of testing temperatures and curing conditions were considered. In summary, the results indicate that foam properties play an important role in foamed asphalt performance.

Key words: foamed bitumen, foaming water, stiffness, cold mix asphalt.

1. INTRODUCTION

The aspects of energy saving, sustainability and the environment, when associated with pavement construction activities, are driving the popularity of foamed asphalt technology worldwide. Foamed bitumen can potentially be used as a stabilizing agent for a wide variety of materials, such as recycled asphalt, soil/granular aggregates and other marginal or waste materials.

Foam technology is a unique method for generating bitumen-aggregate mixtures. In its foamed state, which lasts only a few seconds, bitumen can be mixed with wet aggregates at ambient temperatures. It is therefore reasonable to assume that the foam characteristics during the mixing process play an important role in mix performance.

The relationship between these foam characteristics and mix properties has not been thoroughly investigated. This investigation was designed to explore the effects of foaming water content on foam characteristics and resultant mix stiffness.

2. LITERATURE REVIEW

Foaming technology was first introduced by Professor Ladis Csanyi (Csanyi 1957) and then further developed by Mobil Oil in the 1960s by creating an expansion chamber. In this laboratory investigation, foamed bitumen was produced by a Wirtgen Ltd. foaming machine (type WLB 10, 1996). In this machine, both air and water are injected together into hot bitumen in an expansion chamber and the resulting volumetric expansion (as water is vapourized) generates a jet of foam. This type of machine can be utilised to investigate foam characteristics and also to generate foamed asphalt mixes by attaching a mechanical mixer to the foaming unit.

Foamed bitumen is commonly characterised in terms of its maximum expansion ratio (ERm) and half-life (HL). ERm is defined as the ratio between maximum foam volume achieved and the volume of original bitumen, whereas the HL is the time that the foam takes to collapse to half of its maximum volume. Both depend critically on the foaming water content (FWC), as illustrated in Figure 1.

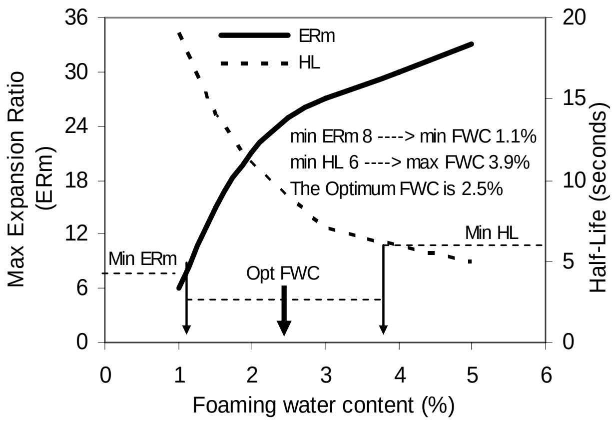

Figure 1- Typical foamed bitumen characteristics

It is necessary to select a particular FWC value prior to mixing with aggregate materials. This is achieved by investigating the foaming properties of the bitumen over the full FWC range. Both a high ERm and a long HL are currently understood to be desirable – which means that compromise has to be found. The guidance proposed by Wirtgen (2005) is that the minimum permissible values of ERm and HL should be 8 and 6 seconds respectively. Based on these, Figure 1 illustrates their proposed technique for deriving an optimum FWC value. In contrast, CSIR (1998) suggest minimum values of 10 and 12 seconds for ERm and HL. However, these methods, though useful for field applications, are not very rigorous, particularly since the relationships of both ERm and HL with FWC are non-linear.

As an alternative, Jenkins (2000) introduced Foam Index (FI) as a function of experimental parameters ERm and HL (see Figure 2). He introduced a new term ERa (actual expansion ratio) which assumes that during the foaming and foam growth process, no foam is collapsing and all the foam will achieve and retain its maximum volume.

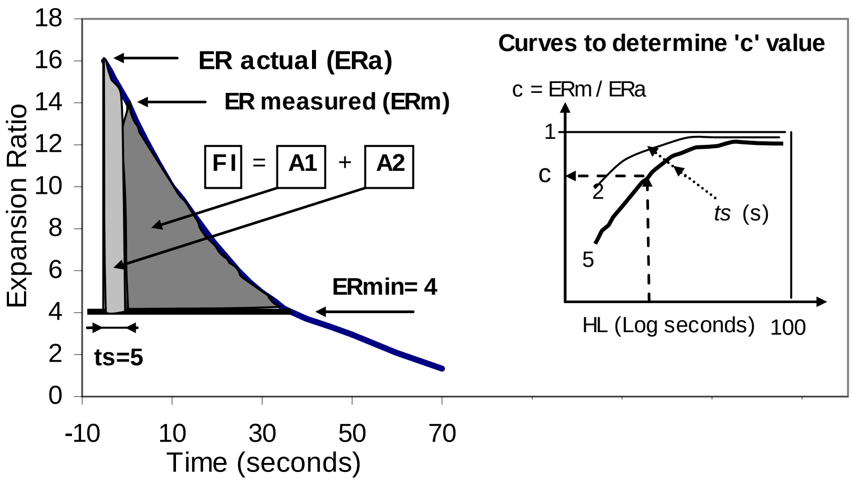

Figure 2- Foam Index calculation method (Jenkins, 2000)

The definition of FI is complex and is derived from an assumption that foam collapse follows the logarithmic decay equation. In effect it is the area under the ER v time plot but above the ER=4 line, and adjusted to take account of an assumed ERa value. Eq. 1 gives the formula for FI in terms of the measured properties. Jenkins suggested a minimum FI of 164 seconds for conventional cold mix applications.

$$FI = \frac{HL}{\ln 2}\left[4 - ERm - 4\ln\left(\frac{4}{ERm}\right)\right] + \left(\frac{1+c}{2c}\right) \times ERm \times ts \qquad \textbf{Eq. 1}$$

In general, it is expected that a maximum FI will occur at an optimum FWC giving optimised foam quality. On the other hand, some studies have found that with some bitumens, the increasing ERm values caused by higher FWC values, were not necessarily accompanied by decreasing HL values. Saleh (2006) and He & Wong

(2005) found that HL values decrease up to certain FWC and then remain constant. Such a trend results in FI values increasing continually with increasing FWC and hence an optimum FWC value becomes impossible to locate.

Saleh (2006) proposed an alternative method in which foam viscosity was measured using a Brookfield rotational viscometer at several times, and an average foam viscosity over the first 60 seconds was calculated. The relationship between FWC and average foam viscosity was plotted and the minimum viscosity value was selected as the best foam composition. Saleh also found that foams that were categorised as poor-performing, according to their FI values, can still be effectively mixed with aggregates. It was thus proposed that the ability of a foam to form a well coated asphalt mix was directly related to its viscosity.

However, most studies of general foam (not necessarily bitumen foam) agree that the apparent viscosity increases with the gas content and decreases with shear rate (Assar and Burley, 1986). For example, Marsden and Khan (1966) found that increasing gas content from 70% to 80% and 90% resulted in increasing the foam viscosity from 130cp to 210 and 280cp respectively (Heller and Kuntamukkula, 1987). If the same applies to foamed bitumens, then viscosity should increase with increasing FWC and hence ERm.

Crucially, neither Jenkins nor Saleh discuss the correlation between foam characteristics and asphalt mix properties, a very significant omission. Therefore, in this study it was decided to investigate the effect of FWC on both the foam properties and resultant mix performance.

3. MATERIALS AND TESTING

3.1. Materials used

Bitumen grade 70/100 pen. was selected for the production of foamed bitumen in this investigation. Basic properties of the bitumen including penetration, softening point, and viscosities were determined and the results are presented in Table 1.

In this study, crushed virgin limestone aggregate was used without the addition of any reclaimed asphalt pavement (RAP) materials as commonly used for foam asphalt mixes. The absence of old/aged binder is considered necessary to facilitate a clearer inspection of the effect of foam properties on the mix. The aggregates were divided into 6 fractions i.e. 20mm, 14mm, 10mm, 6mm, fines and filler. The selected composition was chosen to be close to the Fuller packing equation with a maximum aggregate size of 25mm and within the grading limits for foamed asphalt as recommended by Akeroyd and Hicks (1988) (Figure 3). Details of aggregate properties are shown in Table 2.

Table 1-Basic properties of bitumen Pen.70/100

Property	Value
Penetration (25°C, 100 g, 5 sec.)(0.01 mm)	85-93
Softening point (ring & ball) (ºC)	45-49
Viscosity @ 180 °C (mPa.s)	57

Table 2-Properties of crushed limestone aggregates

Property	Value					Method					
Liquid limit (Cone Penetrometer) (%)	17.9					BS 1377-2: 1990					
Plastic limit (%)	15.2										
Plastic index (%)	2.7										
Maximum dry density (kg/m^3)	2242					Modified Proctor					
Optimum moisture content (%)	6.4					BS EN 13286-2: 2004					
Gradation (BS 812-103.1: 1985)											
Size (mm)	25	20	14	10	6.3	2.36	1.18	0.6	0.30	0.15	0.075
% Pass	100	96.7	74.6	62.9	51.2	31.7	22.7	17.2	13.6	10.9	8.6

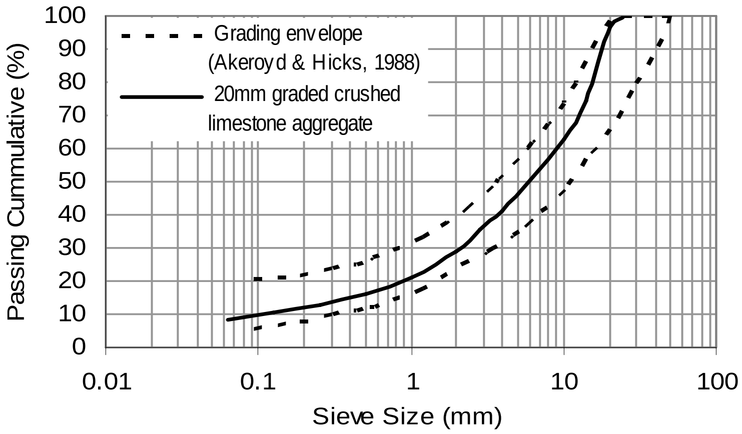

Figure 3- Gradation of crushed limestone aggregate

3.2. Foam characteristics investigation

Foam properties were investigated at a temperature of 180^{o}C and at various FWC values. At FWC up to 5%, the ERm and HL were determined using 500g bitumen for each test. Foam properties at FWC > 5% were investigated using a reduced mass of bitumen (250g) so that the expanded foam volume did not to exceed the capacity of the measuring cylinder.

Flow behaviour was also investigated at selected FWC values in order to evaluate the foam's ability to flow and coat the aggregate surfaces during the mixing process. These results can also be used to indicate the apparent foam viscosity which may complement Jenkins' (2000) and Saleh's (2006) investigations. The method used in this study was adapted from the standard tar viscometer technique, i.e. measurement of flow rate through an orifice to establish viscosity of the material (Read and Whiteoak, 2003). In this study, 200 grams of sprayed foam was collected in a container (Ø = 200mm and h = 300mm) and allowed to flow directly through a 9mm orifice created at the bottom of container. The foam collected through the orifice was then directly weighed with time. Using this method, the change in foam consistency with time was observed up to the point when flow values were too small to record.

3.3. Specimen preparation

The foam was produced using a Wirtgen WLB 10 foamer. The bitumen temperature was elevated to 180oC prior to starting the foaming process. The foam produced was directly mixed with pre-wet aggregates for 1 minute using a Hobart mixer. Two types of agitators i.e. a dough hook and a flat paddle were trialled. Foamed materials were then stored in sealed plastic bags and compacted the following day using a gyratory compactor. Each specimen required approximately 1200 grams of wet foamed material. In the first part of this investigation, specimens mixed with the dough hook agitator were compacted to a set bulk density (gyratory set at 800 kPa, gyratory angle of 2.0º and a target density setting of 2300 kg/m3). Later specimens were subsequently compacted to a target compaction effort (gyratory settings at 600 kPa, 1.25° and 200 gyrations). All compacted specimens were left in the mould for one day before demoulding and curing at 40oC for 3 days. Prior to testing, the cured specimens were conditioned at the required test temperature in an environmental conditioning cabinet. More details on specimen preparation are provided in Table 3.

Table 3-Data for specimen preparation

Crushed limestone aggregate	Composition: 20mm = 25% 6mm = 8% 14mm = 12% Dust = 39% 10mm = 13% Filler = 3%	Compaction data: Max dry density = 2242 kg/m^3 Opt. moisture content= 6.4%
Foamed bitumen	Bitumen temperature 180^{o}C Foamed bitumen content = 4% of total aggregate mass	
Foaming machine setting	Air pressure = 5 bar Water pressure = 6 bar Timer setting calculation Mass of aggregate for a batch = 4800g Mass of foamed bitumen = 4% × 4800g = 192g Bitumen used = 1.25 × 192 = 240g Setting timer = 240/100 = 2.40 seconds	
Moisture content calculation	Optimum Moisture Content (OMC) = 6.4% Moisture content used = 0.5×(65%+80%) * 6.4% = 4.6% Moisture used = 4.6% × 4800g = 221 g	
Mixing	Using Hobart mixer 20 quarts Mixing time = one minute after spraying foam	
Compaction	Using Gyratory compactor Force 600 kPa, angle = 1.25º, gyration number = 200 Force 800 kPa, angle = 2.0º, density = 2300 kg/m^3	
Specimen	Diameter 100mm, height 65-67mm Wet specimen mass = 1200 g	

3.4. Mix stiffness testing

The Indirect Tensile Stiffness Modulus (ITSM) determinations (BS DD 213: 1993) were carried out using the Nottingham Asphalt Tester (NAT) apparatus. The test parameters were as shown in Table 4.

Table 4-Parameters for ITSM testing

Test temperature	5°C, 20°C, 40°C
Rise time	124 ± 4 ms
Horizontal deformation	5 ± 2 μm
Assumed Poisson's ratio	0.35

4. RESULTS AND DISCUSSION

4.1. Effect of FWC on foam properties

4.1.1. Maximum expansion ratio and half-life

The results shown in Figure 4 indicate that the FWC influences the ERm and HL values significantly. The ERm values increase with increasing the amount of foaming water, whilst the HL values tend to behave in an opposite manner to ERm. Interestingly, increasing the FWC from 1 to 2% resulted a doubling of the ERm value but at higher FWC's the increase was more moderate. Similarly, increasing the FWC from 1 to 2% causes the HL to decrease sharply and beyond a FWC of 2%, the HL stabilises at an almost constant value. These findings are similar to those reported by Saleh (2006) and He & Wong (2005). The calculated FI, as shown in Figure 4, increases with increasing ERm. The results imply that, using the FI concept, the best foam properties should be at an unrealistic FWC of over 10%.

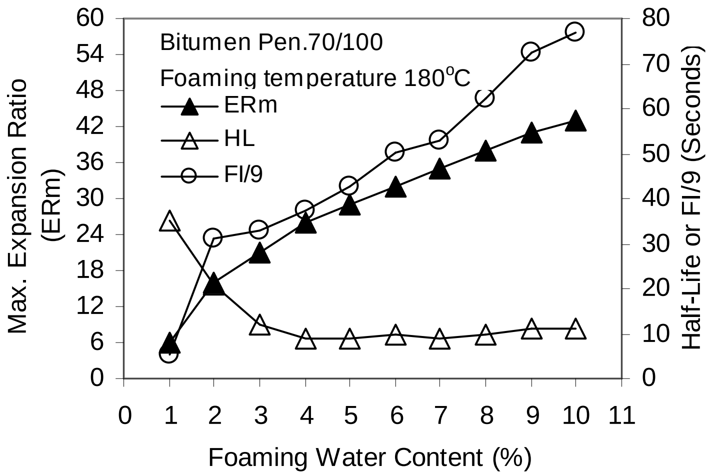

Figure 4- Effect of FWC on ERm and HL

4.1.2. Flow behavior

The flow behaviour of bitumen foams with FWC values of 1, 2 and 5% is shown in Figure 5. It must be noted at this stage that, in all cases, the foam was unable to flow out of the container completely. This was attributed to the bitumen/foam cooling down rapidly and becoming too stiff to flow within a reasonable experimental time. It was found that a foam with a higher FWC flows at a slower rate through the orifice with a reduced total amount flowing out of the container and a longer time required to terminate the experiment. This behaviour should be considered when foam behaviour is analysed in terms of viscosity measurements. For example, Figure 5 shows clearly that during the first 60 seconds, the foam with a FWC of 1% had a higher flow rate than the other two FWC's, whereas between 120 and 180 seconds, the foam with a FWC of 5% was found to have the highest flow rate. Thus, studying the flow behaviour in one time zone alone will not necessarily reflect on the viscosity of the foam at other times, and the appropriate time zone to consider for mixture performance is far from clear.

In general, the effects of FWC on flow behaviour can be clearly seen in which the rate of foam flow through a 9mm orifice tends to decrease with increasing FWC. A foam with a higher FWC contains by default a higher gas content thus resulting in larger sized bubbles which in turn promotes stronger interaction within the foam structure and retards flow. This phenomenon gives rise to non-Newtonian rheological effects (Kraynik, 1988). It is thus suggested that flow rate can be linked to viscosity as in the tar standard viscometer. It can thus be concluded that a foam with a higher FWC tends to have a decreased flow rate and hence higher viscosity, which is in line with the findings of Assar and Burley (1986).

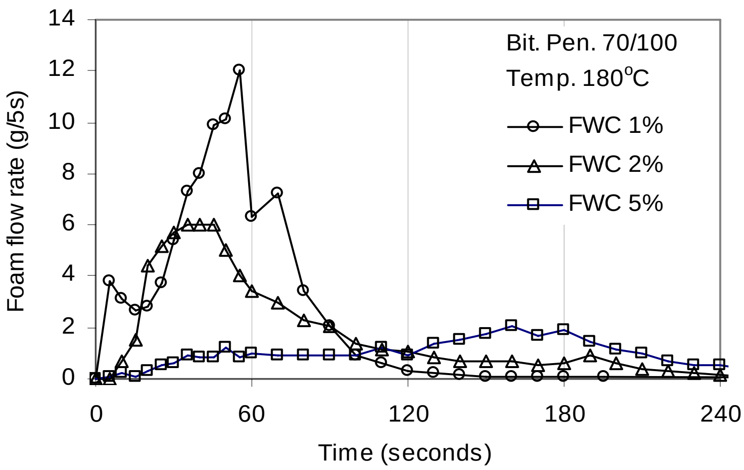

Figure 5- Effect of FWC on foam flow rate

4.2. Effect of FWC on mix stiffness

4.2.1. Using different mixing methods

Figure 6 shows the results from an investigation into the effect of FWC on mix stiffness. It was found that the mixing method is a very important variable in foamed asphalt performance. The mixing technique controls the efficiency of distribution of the expanded foam across the aggregates phase.

The results show that specimens mixed using a dough hook exhibited poorer binder distribution and lower stiffness values. Across the full range of FWC investigated (i.e. up to 10%), the effect of FWC on mix stiffness was not clear. The appearance of minor fluctuations in stiffness values were attributed to small variations in mix moisture content and density values. However, when specimens were mixed using the flat agitator, their cured stiffness values increased significantly and the effect of FWC was clearly evident. In this case optimum performance was clearly obtained with specimens prepared at 5% foaming water.

The trend-line of poorly mixed specimens (dashed line) has a slight negative slope with increasing FWC. This means that ERm has virtually no effect on the properties of poorly mixed specimens. It is hypothesised that the slightly higher stiffness values at low FWC values in the poor mixes was caused by the improved foam flow and hence coating ability during the mixing stage.

For the more efficiently mixed specimens, the FWC (which affects both the ERm and flow behaviour) seems to have a greater effect on mix properties. When considering the full range of FWC, it appears that the ERm effects were more dominant on the drier side of optimum FWC, whereas flow behaviour is more dominant on the wetter side. This implies that the minimum acceptable FWC is controlled by the ERm parameter and the maximum acceptable FWC is limited by flow behaviour.

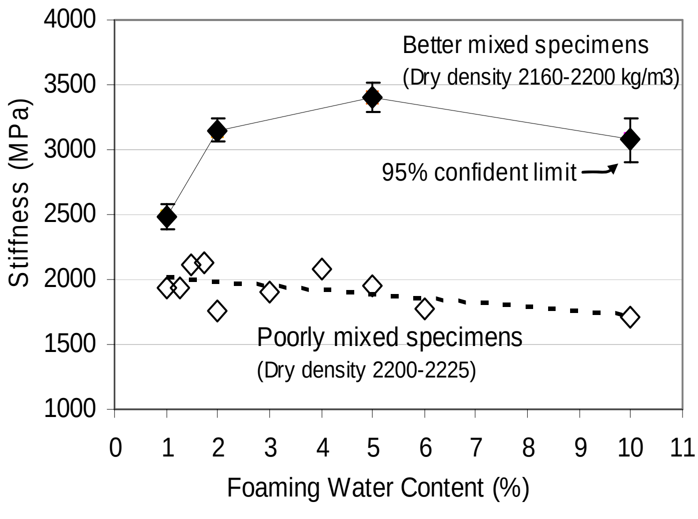

Figure 6- Effect of FWC on stiffness of well mixed asphalt (top line) and badly mixed specimens (lower line)

4.2.2. At different test temperatures

All the specimens presented in Figure 6 were tested at a standard temperature of 20°C. In order to evaluate the effect of test temperature on stiffness (temperature susceptibility), it was decided to conduct additional ITSM tests at 5°C and 40°C.

Figure 7 shows the effect of test temperature on mix stiffness at various FWC. It can be seen that at FWC 5%, the mix stiffness is generally slightly higher than at other FWC values, which indicates that at this FWC the bitumen component of the foam is more efficiently dispersed throughout the aggregate skeleton and can hence contribute more to the mix performance compared to other FWC values.

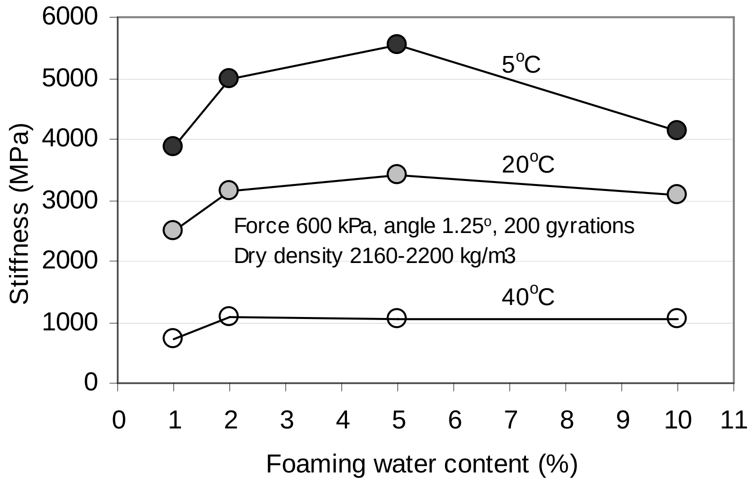

Figure 7- Effect of test temperature on foam asphalt stiffness

4.2.3. At different curing conditions

One of the key differences between foam cold mix asphalts and hot mix asphalts is in the rate at which they achieve their "peak stiffness" (not taking ageing into consideration) following laying and compaction in the field. Unlike hot mix asphalts, foamed asphalts demand a substantial curing time (to allow loss of water from the compacted mix) during which the mixes gradually gain stiffness.

Therefore, a typical foamed asphalt laboratory mix design procedure normally includes an accelerated curing regime. In this study, the specimens were cured at 40°C for 3 days to simulate approximately 6 months of field curing (Lee & Kim, 2003). The curing temperature of 40°C was selected to be lower than the softening point of the bitumen to ensure minimal damage to the specimens and to reduce binder ageing. By carefully weighing the specimens before and after curing, it was found in this study that following 3 days of curing at 40°C, the 100mm diameter specimens were not totally dry, with around 0.2 to 0.4% of moisture remaining trapped within the specimens. It was subsequently decided to subject selected specimens to additional curing at 30°C for a period of 6 days. The temperature of 30°C was considered as normal in hot climatic conditions.

Figure 8 shows the results of the effects of curing regime on the stiffness of the foam asphalt specimens, this time using only 100 gyrations. The results indicate a clearly defined optimum FWC. Interestingly, the extended curing regime seems to increase the stiffness at the optimum FWC significantly more than the modest increases at other FWC values.

It can thus be argued that peak performance from a foamed asphalt (assessed for example using stiffness criteria) can only be guaranteed when the mix is manufactured and compacted at optimum FWC.

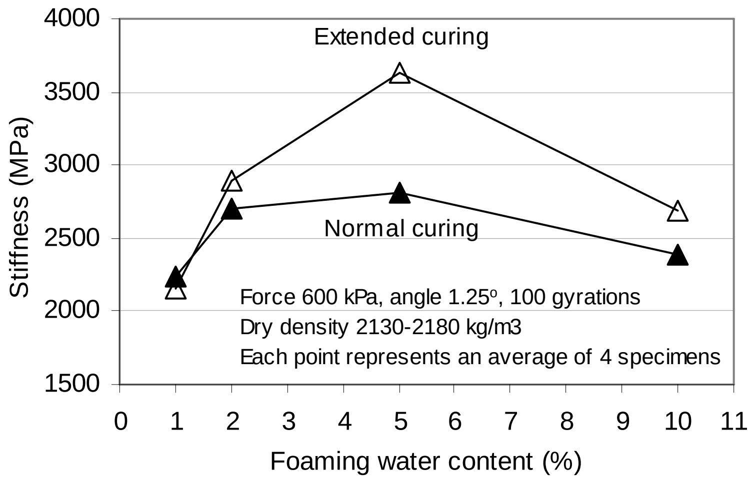

Figure 8- Effect of curing regime on stiffness of specimens

5. CONCLUSIONS

Based on the results discussed earlier, the following conclusions can be drawn:

- Selecting an efficient mixing method is crucial for ensuring adequate binder dispersion in foamed asphalts and this will enhance compacted mix stiffness.
- It has been demonstrated that the FWC does affect the foam properties extensively in terms of ERm, HL and flow behaviour. At higher FWC values, the ERm increases, the HL decreases up to a constant value and the flow rate decreases.
- For poorly mixed materials, the mix stiffness tends to decrease with increasing FWC due to a combination of decreased foam flow rate and/or increased foam viscosity. However, for well mixed materials, the effect of FWC was clearly evident. In this study, optimum performance was obtained with specimens prepared at 5% foaming water content. This point represents a compromise between the two variables of ERm and flow rate.

REFERENCES

AKEROYD, F.M.L. & HICKS, B. J. (1988)- “Foamed Bitumen Road Recycling”- *Highways*, Volume 56, Number1933, pp 42, 43, 45.

ASSAR, G. R. and BURLEY, R. W. (1986)- “Hydrodynamics of foam flow in pipes, capillary tubes, and porous media” – in *Encyclopedia of Fluid Mechanics*, edited by N.P. Cheremisinoff, Vol. 3, pp. 26-42.

BRITISH STANDARD (1993)- *Method for determination of indirect tensile modulus stiffness of bituminous mixtures* – Draft for Development, DD 213: 1993.

CSANYI, L.H. (1957)- “Foamed Asphalt in Bituminous Paving Mixes” - *Highway Research Board Bulletin*, Vol.10, No.160, pp 108-122.

HE, G. & WONG, W. (2005) - “Decay Properties of the Foamed Bitumens**”** - *Construction and Building Materials, Elsevier*.

HELLER, J.P. and KUNTAMUKKULA, M.S. (1987)-“Critical Review of the Foam Rheology Literature”- *Ind. Eng. Chem. Res.*, Vol. 26, No. 2, 1987, pp. 318-325, © 1987 American Chemical Society.

JENKINS, K.J. (2000)- *Characterisation of Foamed Bitumen*- Chapter 3, Mix Design Considerations for Cold and Half-warm Bituminous Mixes with Emphasis on Foamed Bitumen, PhD Dissertation, University of Stellenbosch, South Africa.

KRAYNIK, A.M. (1988)-“Foam Flows”- *Ann. Rev. Fluid Mech.*, 20: 325-57.

LEE, H.D. AND KIM, Y.J. (2003). *Developing of a mix design process for cold-in-place rehabilitation using foamed asphalt.* Final Report for TR-474 Phase I. Report on Research Sponsored by Iowa Department Transportation, Public Policy Center, Civil and Environment Engineering, The University of Iowa, Desember 2003.

READ, J. AND WHITEOAK, D. (2003) -*The Shell Bitumen Handbook*- Fifth edition, ISBN: 0 7277 3220 X, Shell UK Oil Products Limited.

SALEH, M. (2006)-“Characteristisation of Foam Bitumen Quality and the Mechanical Properties of Foam Stabilised Mixed”- *10th International Conference on Asphalt Pavements*, Quebec, Canada.

WIRTGEN, (2005)-Foamed bitumen mix design procedure using the Wirtgen WLB 10 # 147 236.0001-Wirtgen GmbH, Hohner Strasse 2, 53578 Windhagen, Germany.

WIRTGEN, *Foamed bitumen - The innovative Binding Agent for Road Construction*- Wirtgen GmbH, Hohner Strasse 2, 53578 Windhagen, Germany.

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