

# LABORATORY STIFFNESS CHARACTERIZATION OF FOAMED COLD-MIX ASPHALT USING INDIRECT TENSILE STIFFNESS MODULUS TEST

## KARAKTERISASI *STIFFNESS* CAMPURAN DINGIN *FOAMED ASPHALT* DI LABORATORIUM DENGAN MENGGUNAKAN ALAT UJI *INDIRECT TENSILE STIFFNESS MODULUS*

Sri Sunarjono

Study Programme of Master of Civil Engineering, Department of Civil Engineering, Universitas Muhammadiyah Surakarta, Jl. A. Yani Pabelan Kartasura Tromol Pos 1 Surakarta Post Code 57102, e-mail: ssunarjono@gmail.com

### ABSTRACT

The use of foamed cold-mix asphalt (FCMA) can potentially save energy and fuel consumption and reduce greenhouse gas emission. For these reasons, FCMA has been gaining popularity worldwide. These benefits can be realized because foamed bitumen enables the coating of aggregate particles at ambient temperature. It should be understood that in FCMA not all aggregate particles are coated by binder. The sprayed foamed bitumen is seen distributing on the fine particles only and hence its physical performance is unlike the conventional asphalt. In order to gain better understanding about these unique characteristics, an investigation of the fundamental properties of FCMA is warranted. This paper presents the results from a stiffness investigation of FCMA in laboratory by using ITSM (Indirect Tensile Stiffness Modulus) test. The results show that the ITSM test is suitable to evaluate the stiffness characteristics of FCMA materials. It was found that mixing quality is an important aspect in developing stiffness characteristics. Using a better mixed specimens, parameter of foaming water content (FWC) can be clearly identified affecting the ITSM values. In the tensile mode, the ITSM values decrease with the increase in the applied horizontal deformation (stress) and test temperature. One of the interesting findings from this investigation was that binder distribution played a more important role than binder stiffness in developing the ITSM values at low temperature. At the end of investigation, the water resistance of FCMA specimens with 50/70 pen bitumen was found to be acceptable only when the specimens have FWC higher than 5%.

**Key words:** Foamed cold-mix asphalt, stiffness, tensile, mixing, water resistance

### ABSTRAK

Penggunaan foamed cold-mix asphalt (FCMA) untuk bahan perkerasan jalan dapat menghemat energi dan penggunaan bahan bakar, serta mengurangi emisi gas rumah kaca. Hal inilah yang menyebabkan penggunaan material FCMA menjadi semakin populer di dunia. Keuntungan tersebut dimungkinkan karena foamed bitumen mampu mengikat partikel agregat pada suhu kamar. Perlu dipahami bahwa untuk material FCMA, tidak semua partikel-partikel agregat dapat diikat oleh binder. Foamed bitumen dominan hanya terdistribusi pada partikel-partikel halus sehingga secara visual tidak tampak seperti campuran aspal konvensional. Dalam rangka mendapatkan pemahaman yang lebih baik terhadap karakteristik FCMA yang unik ini, maka diperlukan sebuah penyelidikan terhadap properties fundamental FCMA. Artikel ini mempresentasikan hasil-hasil investigasi stiffness FCMA di laboratorium dengan menggunakan pengujian ITSM (Indirect Tensile Stiffness Modulus). Hasil pengujian menunjukkan bahwa pengujian ITSM dapat digunakan untuk mengevaluasi karakteristik stiffness material FCMA. Dalam penyelidikan ini dapat diketahui bahwa kualitas pencampuran merupakan aspek penting dalam pembentukan karakteristik stiffness. Dengan menggunakan benda-benda uji hasil pencampuran yang lebih baik, parameter foaming water content (FWC) dapat secara jelas teridentifikasi pengaruhnya terhadap nilai stiffness. Pada sistem mode tarik, nilai ITSM berkurang dengan meningkatnya deformasi horizontal (tegangan) dan suhu pengujian. Salah satu temuan yang menarik dalam investigasi ini adalah bahwa distribusi binder memainkan peran yang lebih penting dari pada nilai stiffness binder dalam pembentukan nilai ITSM pada kondisi suhu rendah. Di akhir investigasi, ketahanan campuran FCMA yang menggunakan aspal pen 50/70 terhadap air ditemukan bahwa nilai yang masih dapat diterima hanyalah pada benda uji dengan FWC diatas 5%.

**Kata-kata kunci:** Foamed cold-mix asphalt, stiffness, tarik, pencampuran, ketahanan air

### INTRODUCTION

Foamed cold-mix asphalt (FCMA) is a friendly road material which has been successfully implemented in many roads across the world. The use of this mixture can potentially save energy and fuel consumption and reduce greenhouse gas emission. Discussion of this material can be found in Widyatmoko and Sunarjono (2007) and Sunarjono (2007) in terms of considerations to implement this technology for road construction in Indonesia.

FCMA is produced by mixing of sprayed foamed bitumen and homogenous wet aggregates. Foamed bitumen enables the coating of wet aggregates at ambient temperature to form foamed asphalt for road pavement material.

In FCMA, not all aggregate particles are coated by binder. The sprayed foamed bitumen is seen distributing on the fine particles only. If the predetermined aggregate moisture is incorrect

and the quantity of fine particles is insufficient, the resulting mixture becomes unworkable (see Brennen et al, 1983). Moreover, if both moisture and fines have been prepared correctly, but this is not accompanied by proper design of selected foamed bitumen characteristics (see also Muthen, 1999) and suitable mixing (see also Long et al, 2004); the resultant mixture will be inconsistent and hence its performance will be unpredictable.

Due to the unique characteristics of FCMA as mentioned above, it is very demanding to investigate the fundamental properties of this mixture. This paper discusses the results of stiffness investigation of foamed cold-mix asphalt explored based upon laboratory experiment using Indirect Tensile Stiffness Modulus (ITSM) test. Stiffness modulus is an important property for bituminous base course layers. Increasing the elastic stiffness improves load-spreading ability, thus reducing the peak stress transmitted to the subgrade.

## LITERATURE REVIEW AND THEORY

### Foamed bitumen

Foamed bitumen is produced by injecting air and water droplets under high pressure into a pre-heated penetration grade bitumen. As the water turns into steam, bitumen changes from the liquid state into foam. This is mainly a physical rather than a chemical process. The life of the foam at ambient temperature is very short, measured in seconds. Soon after production, the foam bubbles quickly collapse thus reverting the bitumen back to its liquid state and gradually regaining its viscous condition.

Foaming technology was first introduced by Professor Ladis Csanyi (Csanyi 1957) and then developed by Mobil Oil in the 1960s by creating an expansion chamber. In the mid-1990s, the equipment manufacturers Wirtgen developed this system by creating the Wirtgen WLB-10 laboratory foaming plant in which both air and water are injected into the hot bitumen in an expansion chamber as shown in Figure 1.

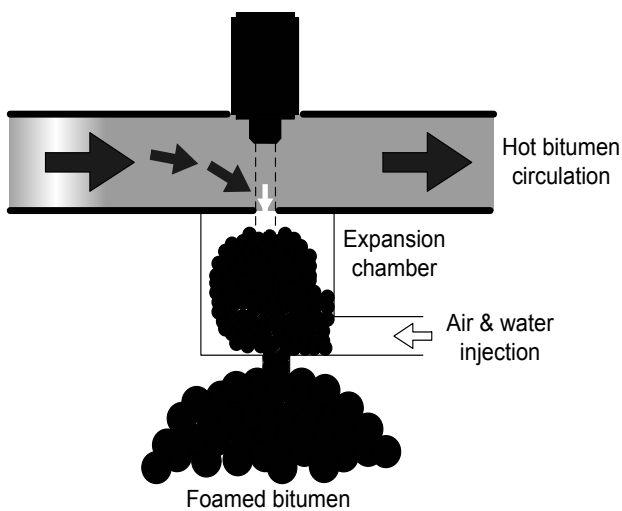


Figure 1. Foamed bitumen produced in an expansion chamber

Foamed bitumen is commonly characterised in terms of its Expansion ratio (ER) and Half-life (HL). During the bitumen foaming process, the foamed bitumen would expand to a maximum volume and then the bubbles would collapse completely. ER is defined as the ratio between maximum volume achieved in the foam state and the volume of bitumen after the foam has completely dissipated. HL is the time that the foam takes to collapse to half of its maximum volume. The ER and HL parameters were affected significantly by Foaming Water Content (FWC). FWC is an added water (by mass of bitumen) at foam production. Discussion and an example of foaming characteristics related to the relationship between FWC, ER, and HL can be seen in Jenkins et al (1999) and Sunarjono (2007).

### Foamed cold-mix asphalt (FCMA) properties

As is common for cold-mix asphalts, the strength of FCMA at early life develops with loss of moisture (Bowering, 1970; Jitarekul et al, 2007; and Sunarjono, 2007). In a pilot scale project (Nunn and Thom, 2002), FCMA at very early life exhibited stiffness typical of unbound material when their moduli were investigated using a Dynamic Plate tool. Based on Falling Weight Deflectometer (FWD) data, the stiffness at 20°C of the FCMA layer was found to increase from < 1000MPa (at early life) to 3500MPa (at one year). The mixture developed to gain satisfactorily high stiffness levels within 6 months.

Temperature sensitivity of FCMA has been investigated by Nataatmadja (2002) in terms of indirect tensile stiffness. The

temperature sensitivity of FCMA and HMA might be similar in that they are dependent upon the binder rheology, but their micro-structures and coating details are different. The results of both investigators are relatively similar: increasing the temperature by 10°C resulted in the tensile stiffness modulus reducing by 12-15% at binder contents around 1.5 – 4.5%, with the highest stiffness having a greater sensitivity. In addition, Nataatmadja found that the indirect tensile stiffness decreased with increasing strain level. The strain sensitivity was greatest at highest stiffness. Moreover, Acott (1979) reported that resilient modulus of foam treated sand mixtures (determined using the repeated load indirect tensile test) was affected not only by stress and temperature but also by loading rate. The moduli were found to increase in loading rate and decrease in stress and temperature. Merrill et al (2004) suggested that the choice of bitumen grade is a compromise between foaming ability and stiffness; higher grade bitumen foams easily but has lower stiffness.

Additionally, discussion of FCMA properties in terms of fatigue and rutting performance can be seen in Sunarjono (2006) and Sunarjono (2009) respectively.

### Stiffness modulus in indirect tensile mode

In the indirect tensile mode, the compression load is applied across the vertical diameter of a cylindrical specimen and it results a biaxial stress distribution in the specimen as shown in Figure 2. It can be seen that both a vertical compressive stress ( $\sigma_v$ ) and a horizontal tensile stress ( $\sigma_h$ ) are induced on the horizontal diameter of the specimen. The magnitudes of the stresses vary along the diameter and they reach a maximum value at the centre of the specimen. By measuring the horizontal deformation ( $\Delta h$ ), the maximum strain at the centre of the specimen and hence the stiffness modulus can be calculated. This calculation uses the following assumptions:

- The specimen is subjected to plane stress conditions ( $\sigma_z = 0$ ).
- The material is linear elastic.
- The material behaves in a homogeneous and isotropic manner.
- Poisson's ratio ( $\nu$ ) for the material is known.
- The vertical load ( $P$ ) is applied as a line loading.

When the above assumptions are met, then the stress conditions in the specimen agree with the theory of elasticity. This theory shows that when the width of the loading strip is less than or equal to 10% of the diameter of the specimen and the distance of the element of material from the centre is very small then Eq. 1 to Eq. 4 can be applied (Read, 1996).

$$\sigma_{,ix(\max)} = \frac{2P}{\pi \cdot t} \quad (1)$$

$$\sigma_{,vx(\max)} = \frac{-\nu P}{\pi \cdot t} \quad (2)$$

The average of horizontal and vertical stress can then be expressed as follows:

$$\sigma_{,ix} = \frac{0.273P}{d \cdot t} \quad (3)$$

$$\sigma_{,vx} = \frac{-\nu}{d \cdot t} \quad (4)$$

where:

d = specimen diameter

t = specimen thickness

- P = applied vertical compressive load
- $\sigma_{hx(max)}$  = maximum horizontal tensile stress at the centre of the specimen
- $\sigma_{vx(max)}$  = maximum vertical compressive stress at the centre of the specimen
- $\bar{\sigma}_{hx}$  = average horizontal tensile stress
- $\bar{\sigma}_{vx}$  = average vertical compressive stress

Considering the average principal stresses in a small element subjected to biaxial stress conditions, the horizontal tensile strain would be:

$$\bar{\epsilon}_{hx} = \frac{\bar{\sigma}_{hx}}{S_m} - \nu \frac{\bar{\sigma}_{vx}}{S_m} \quad (5)$$

$$\bar{\epsilon}_{hx} = \frac{0.273P}{S_m \cdot d \cdot t} + \frac{\nu P}{S_m \cdot d \cdot t} \quad (6)$$

Horizontal deformation can be calculated from:

$$\Delta = \bar{\epsilon}_{hx} \cdot d \quad (7)$$

$$\Delta = \frac{0.273P}{S_m \cdot t} + \frac{\nu P}{S_m \cdot t} \quad (8)$$

The stiffness modulus of the material can therefore be calculated from:

$$S_m = \frac{P(0.273 + \nu)}{\Delta \cdot t} \quad (9)$$

where:

- $\bar{\epsilon}_{hx}$  = average horizontal tensile strain
- $\nu$  = Poisson's ratio (assumed)
- $S_m$  = Stiffness modulus
- $\Delta h$  = horizontal deformation (measured)

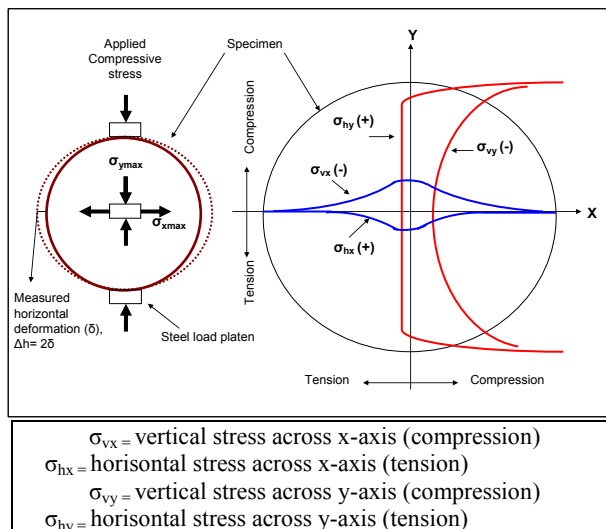


Figure 2. An induced biaxial stress distribution under compressive load in indirect tensile mode

### ITSM test

The ITSM test was carried out in accordance with BS DD 213:1993. The testing method uses cylindrical specimens either prepared from field cores or laboratory moulded, with a diameter of 100mm or 150mm and a thickness of between 30mm and

80mm. The standard target parameters pertaining throughout testing are as follows:

Test temperature	: 20°C
Rise time	: 124 ± 4 ms
Horizontal deformation	: 5 ± 2 μm (for diameter 100mm)
	: 7 ± 2 μm (for diameter 150mm)

Prior to testing, specimens should be stored in a conditioning cabinet at the test temperature of 20°C for at least two hours. The stiffness modulus of bituminous mixtures,  $S_m$ , can be determined using Eq. 9, in which  $\Delta h$  is the mean amplitude of the horizontal deformation obtained from two or more applications of the load pulse and the Poisson's ratio for bituminous mixtures is normally assumed to be 0.35.

The ITSM test configuration can be seen in Figure 3. The specimen is centrally positioned between the lower and upper platens. The deformation measuring devices should be located symmetrically about an axis through the centroid of the specimen and perpendicular to the direction of loading and the axis of symmetry of the specimen.

Input parameters required for testing are specimen temperature, specimen thickness and diameter, Poisson's ratio, load, rise time and target horizontal deformation. The rise time, a time needed by the load to achieve the peak value, is normally 124 ms. This value is generally slower than that associated with moving traffic for which a value of 20 to 30 ms would be more appropriate (depending on the vehicle speed and the depth below the surface), but this would be difficult for the pneumatic system to achieve (Needham, 1996).

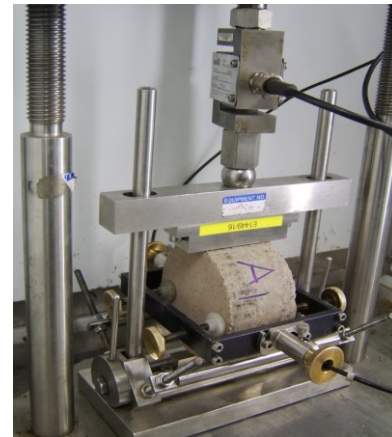


Figure 3. ITSM test configuration

## MATERIALS AND SPECIMEN PREPARATION

### Aggregate and bitumen used

The aggregate used in this study was virgin crushed limestone. Particle gradation as shown in Figure 4 was designed to be within the ideal grading envelope for foamed asphalt as recommended by Akeroyd and Hicks (1988). The maximum aggregate size was 20 mm with 51.20% fines (< 6 mm) and 8.60% filler. This aggregate has a low Plasticity Index (PI) i.e. 2.7%. The maximum dry density and optimum moisture content were found to be 2.242 Mg/m<sup>3</sup> and 6.4% respectively, determined in accordance with BS EN 13286-2: 2004 (modified Proctor).

Three bitumen grades were used in this study i.e. Pen 50/70, Pen 70/100 and Pen 160/220. The properties of these bitumens are shown in Table 1. The bitumen viscosities were mea-

sured using a Dynamic Shear Rheometer (DSR) at a frequency of 0.1 Hz for temperatures of 5, 20 and 40°C and a Brookfield rotary viscometer for temperatures of 140°C to 180°C. It can be seen that the differences in viscosity values of the 3 bitumen grades increase with decreasing temperature.

Foamed bitumen was generated using a laboratory mobile foaming plant type Wirtgen WLB 10 in which the three bitumen grades were foamed at a water pressure of 6 bars and an air pressure of 5 bars. The characteristics of foamed bitumen were varied by applying different foaming water contents (FWC) and temperatures.

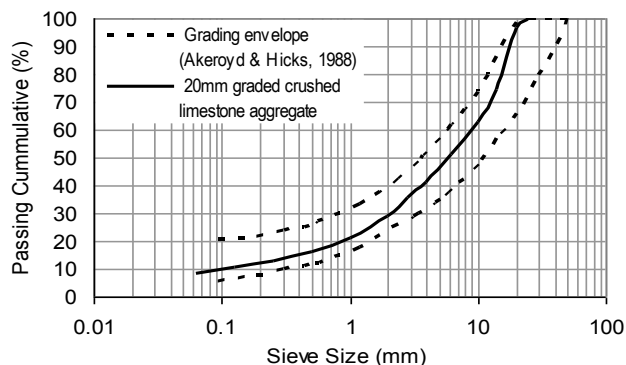


Figure 4. Gradation of Virgin Crushed Limestone aggregate

Table 1. Properties of bitumen grade 50/70, 70/100 and 160/220

Property	Bitumen Grade		
	50/70	70/100	160/220
Specific gravity	1.024	1.03	1.021
Penetration (0.1 mm)	54 - 56	85 - 93	180 - 198
Softening Point (°C)	52 - 53	45 - 49	37 - 38
Viscosity at 5°C (kPa.s)	8795	4322	1315
Viscosity at 20°C (kPa.s)	899	257	68
Viscosity at 40°C (kPa.s)	21.90	5.54	1.63
Viscosity at 140°C (mPa.s)	362	262	164
Viscosity at 160°C (mPa.s)	153	114	74
Viscosity at 180°C (mPa.s)	77	57	40

### Specimen preparation

The foam was produced using a Wirtgen WLB 10 foamer. The bitumen temperature was elevated to around 140°C-180°C prior to starting the foaming process. The foam produced (4% of the total aggregate mass) 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 using the dough hook agitator were compacted to a set bulk density (gyratory set at 800 kPa, gyratory angle of 2.0° and a target density setting of 2300 kg/m<sup>3</sup>). Later specimens (mixed using flat agitator) 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 40°C for 3 days. Prior to testing, the cured specimens were conditioned at the required test temperature in an environmental conditioning cabinet.

## RESULTS AND DISCUSSION

### Effect of mixing method

As shown in Figure 5, the effect investigation of mixing method in different foaming water content (FWC) on mix stiffness was conducted using two types of mixer agitator i.e. dough hook and flat agitator (see Figure 6). The dough hook mixed specimens (Figure 6 right, left picture) and the flat agitator mixed specimens (Figure 6 right, right picture) were prepared as described in the subsection of specimen preparation. The dry densities (after curing) of flat agitator mixed specimens were slightly lower than the that of dough hook mixed specimens. It was found that the mixing method is a very important variable in Foamed cold-mix asphalt (FCMA) performance. The mixing technique controls the efficiency of the expanded bitumen distribution across the aggregate phase.

The results show that specimens mixed using a dough hook exhibited poorer binder distribution (can be seen clearly as shown in Figure 6 right) and hence lower stiffness values (Figure 5). 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 was attributed to small variations in mix moisture content and density values. The linear trend-line for the poorly mixed specimens (dashed line) has a slight negative slope with increasing FWC. However, when specimens were mixed using the flat agitator, their cured ITSM 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 (Figure 5).

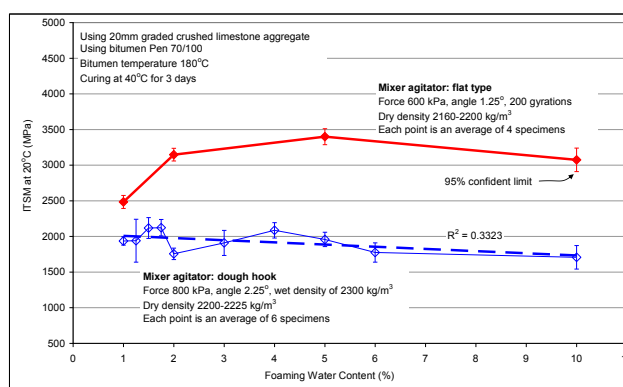


Figure 5. Effect of mixing method on the ITSM values in different foam properties



Figure 6. Spiral dough hook (left) and flat (middle) agitator type, and the produced specimens (right)

It should be noted that the flat agitator performs better but it causes degradation of aggregates. It was observed that the gradation of specimens mixed using the flat agitator was finer by about 3% at the smallest sieve size and 9% at the largest sieve size. For subsequent mixes, it was therefore decided to mix firstly foamed bitumen and 10mm graded aggregate; aggregate larger than 10mm (i.e. 14mm and 20mm) was added prior to the compaction process. This should not significantly affect the mixture

performance since foamed bitumen only coats effectively aggregates with a maximum size of 6.3mm (Sunarjono, 2008).

### Effect of applied horizontal deformation

Figure 7 shows the effect of applied horizontal deformation on the ITSM values. An aged specimen (with a diameter of 100mm) was used due to its strength being relatively high and this was expected to reduce the damage during testing. Detailed data from the specimens can be read in the figure.

It was noted that increasing horizontal deformation was always accompanied by an increasing horizontal stress value. Therefore the result can be used to assess the stress effect on mixture stiffness. The test was conducted over two days in order to evaluate any healing that occurred after an overnight rest. As shown in the figure, the specimen was tested with an applied horizontal deformation from 2  $\mu\text{m}$  to 25  $\mu\text{m}$ , directly returning to 5  $\mu\text{m}$ .

It can be seen that an increasing horizontal deformation significantly affected the stiffness of the specimen. On the first day, the ITSM value decreased about 1800 MPa, which means that the mean stiffness reduction is about 350 MPa for each increase in horizontal deformation of 1  $\mu\text{m}$ . However, in fact, the stiffness reductions decreased for higher deformations. On the second day, the rate of stiffness reduction was only about 100 MPa per 1  $\mu\text{m}$ . It was observed that some healing occurred since there was no significant reduction of ITSM value from 7  $\mu\text{m}$  to 9  $\mu\text{m}$  after an overnight storage. It was clear that after the series of tests with deformation up to 25  $\mu\text{m}$ , the specimen was damaged since when it was re-tested with a deformation of 5  $\mu\text{m}$ , its ITSM value was far lower than previously.

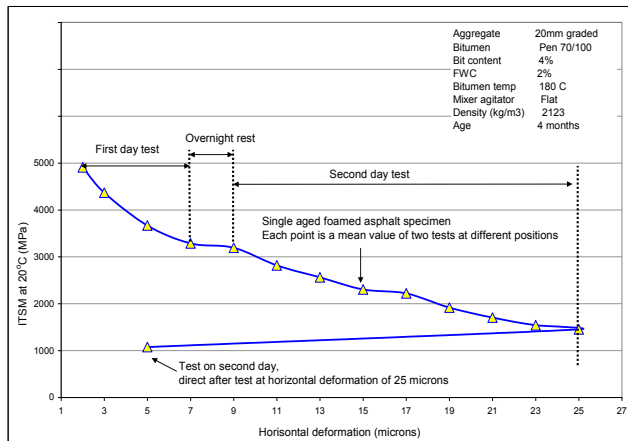


Figure 7. Effect of horizontal deformation on the ITSM values of FCMA specimen

Based upon this investigation, it can be stated that the applied stress significantly affects the stiffness of a FCMA specimen and high stress potentially damages the specimen. This can be understood since FCMA is not a fully bonded material since the binder does not coat all aggregate surfaces. This type of structure will tend to have a stress dependent behaviour and the uncoated surfaces in the mixture form the equivalent of cracks, which redistribute stress onto surrounding coated surfaces.

Figure 8 presents the effect of applied horizontal deformation on the ITSM values of three different mixture types i.e. a well mixed specimen (material mixed using the flat agitator), a poorly mixed specimen (material mixed using the dough hook agitator) and a HMA specimen. These three specimens contained approximately 4% of bitumen (% by aggregate mass) and the well mixed specimen had slightly higher density than the others. The aged foamed asphalt specimens exhibited higher ITSM values than the fresh specimens (at early age). Detailed data on the specimens can be read in the figure. All specimens were tes-

ted with applied horizontal deformations from 2  $\mu\text{m}$  to 13  $\mu\text{m}$  as shown in the figure.

The results show that the rate of ITSM reduction of the well mixed specimen was higher than that of the poorly mixed specimen due to its ITSM value being far higher than the ITSM value of the poorly mixed specimen. However, the rate of ITSM reduction of both these specimens was higher than that of the HMA specimen. It can therefore be deduced that the ITSM value of the foamed asphalt specimens is more sensitive to applied horizontal deformation (stress) than the HMA specimen. The foamed asphalt structure, which is not fully bonded, causes the mixture to be more stress dependent than fully bonded HMA materials.

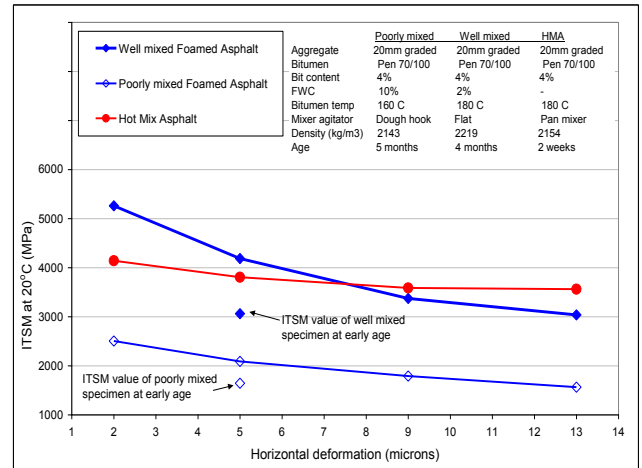


Figure 8. Effect of horizontal deformation on the ITSM values of well and poorly mixed foamed asphalt & HMA specimens

### Effect of test temperature

Figure 9 shows the effect of test temperature on stiffness values of aged FCMA and fresh hot mix asphalt specimens. It can be seen that these two specimens have a comparable ITSM value at a test temperature of 20°C. When the specimens were tested at 40°C, their stiffness reduced significantly to values lower than 1000 MPa. However, when they were tested at 5°C, the ITSM value of the HMA specimen was far higher than that of the FCMA specimen. This can be understood since HMA specimens have more uniformly distributed bitumen film coating the aggregates than those of FCMA specimens. This means that FCMA material is less sensitive to temperature than hot mix asphalt.

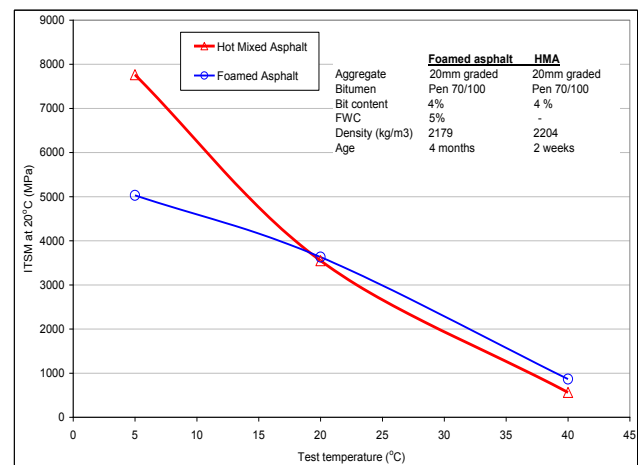


Figure 9. Effect of test temperature on the ITSM values of foamed asphalt & HMA specimens

## Effect of bitumen types and bitumen temperature

Figure 10 shows the ITSM values of specimens produced using three different types of binder in which the foamed bitumen was generated at different temperatures. All specimens were produced at a FWC of 5% and tested at temperature of 20°C. The results reveal that the effect of bitumen types are clearly identified. Specimens produced using harder bitumen type result in better ITSM values. This figure indicates that bitumen type affect significantly the FCMA material stiffness at ambient temperature.

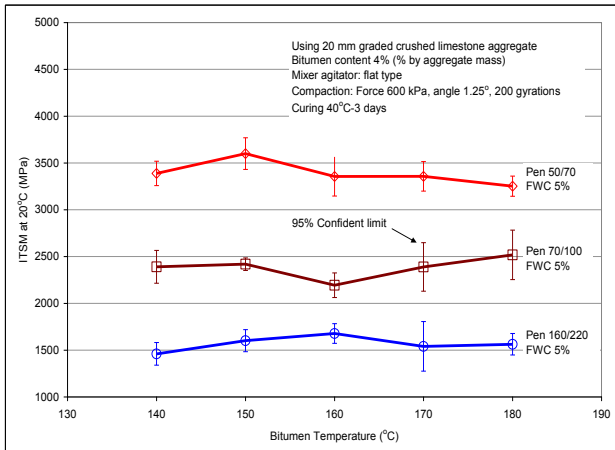


Figure 10. Effect of bitumen type on the ITSM values of foamed asphalt produced in different bitumen temperature

It is however the effect of bitumen temperature between 140°C and 180°C is not particularly significant for mixture properties. Based upon the 95% confidence limit, the ITSM values of specimens produced at different bitumen temperatures for one binder type are relatively similar.

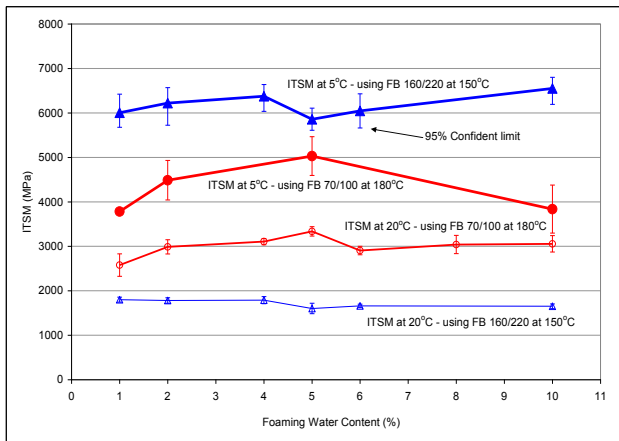


Figure 11. Effect of test temperature on the ITSM values of foamed asphalt generated at different binder type

## Effect of binder distribution

The case of specimens produced using bitumen Pen 160/220 is very interesting. As shown in Figure 11, at a test temperature of 20°C the ITSM values of these specimens were lower than the ITSM values of specimens produced using bitumen Pen 70/100, but at a test temperature of 5°C the result was the reverse. This may be explained as follows. Since bitumen Pen 160/220 is softer than bitumen Pen 70/100, specimens using Pen 160/220 are better mixed than specimens using bitumen Pen 70/100.

Therefore, it is likely that at a test temperature of 5°C binder distribution is more important than binder stiffness in developing the ITSM value.

## Water sensitivity test

Water sensitivity test was conducted by soaking the specimens in a water bath at a temperature of 40°C for 68 to 72 hours. This conditioning procedure was in accordance with BS EN 12697-12: 2003, which is a standard test for assessing water sensitivity of materials using the indirect tensile strength (ITS) test. However, this study applied the ITSM test for assessing water sensitivity of specimens produced at different FWC values. The results are intended to give an indication of the effect of FWC on the mixture stiffness after the soaking treatment.

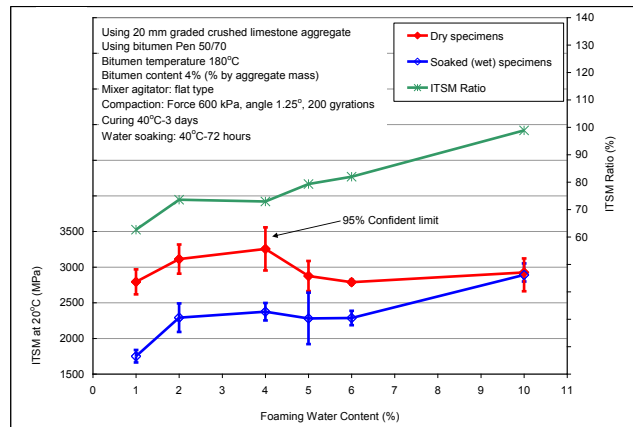


Figure 12. Effect of water soaking on the ITSM values for specimens generated using bitumen Pen 50/70

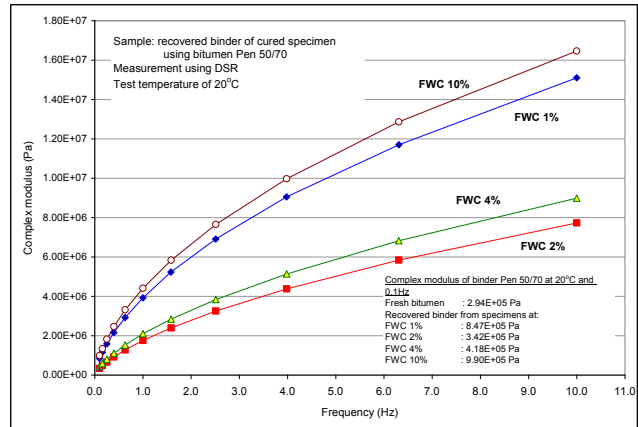


Figure 13. Complex modulus of binder at various frequencies measured using DSR of recovered binder of cured specimens produced using bitumen 50/70 at various FWC values

As shown in Figure 12, only the specimens with FWC higher than 5% have acceptable resistance to water damage (ITSM ratio > 80%). Interestingly, a higher FWC gives a higher ITSM ratio. The ITSM ratio was calculated from the wet ITSM divided the dry ITSM value. The specimens at a FWC of 10% demonstrated no stiffness reduction after water soaking. It should be noted that water soaking at a temperature of 40°C may affect both specimen damage (ITSM value decrease due to water infiltration) and ageing (ITSM value increase due to bitumen stiffness increase). The recovered binders of these specimens were therefore investigated using the DSR (Dynamic Shear Rheometer).

The DSR investigation results are presented in Figure 13. It can be seen that the binder stiffness of specimens produced at

FWC of 1% and 10% is higher than those at FWC of 2% and 4%. The complex moduli of the recovered binders were found to be higher than the complex modulus of fresh binder measured at a frequency of 0.1 Hz (see notes in the Figure 13). It means that the treatment of the specimens caused binder ageing. Therefore the high wet ITSM values at a FWC of 10% are probably due to binder ageing whereas the lower wet ITSM values at a FWC of 1% might be due to specimen damage.

## DISCUSSION OF THE OVERALL RESULTS

Due to FCMA not being a fully bound material and its binder not being as continuous as an HMA's binder, it is therefore interesting to understand its tensile stiffness characteristics. The trends of horizontal deformation/stress and test temperature effects on the ITSM value were found to be similar to those of HMA, the ITSM values decreasing with those two parameters. However, the ITSM values of FCMA were found to be more sensitive to applied horizontal deformation and less temperature susceptible than those of HMA (see Figure 7 and 8). These facts may indicate that the ITSM test is suitable to evaluate the stiffness of FCMA materials. It is supposed that binder distribution in the mixture controls the stiffness value of FCMA materials. Necessarily, well mixed specimens will tend to be more sensitive than poorly mixed specimens in terms of the effect of horizontal deformation and test temperature. This is seen in that the ITSM value reduction for the well mixed specimens was higher than for the poorly mixed specimens as shown in Figure 8, due to their ITSM values being so different.

As the focus of this study, the tensile stiffness characteristics of FCMA has been explored deeply. It was found that foam properties and mixing quality are two important aspects, influencing each other, in developing stiffness characteristics. Foam property variation was created by using different bitumen types, FWC values and bitumen temperatures, whereas mixing variation was created by different mixer agitators.

The flat agitator performed better at mixing than the dough hook and it aided material properties and enhanced the ITSM value (see Figure 5). Binder in the well mixed specimens was better distributed and hence more continuous than in the poorly mixed specimens. In the compacted specimen, the presence of this binder reduces the strain under loading and hence improves the ITSM value.

Specimens mixed at different FWC values using the dough hook exhibited no significant differences in ITSM (see Figure 5); minor fluctuations might be representative of small variations in mixture density and moisture content. It can be seen that, since the dough hook gives poor mixing, different foam properties do not have any effect on the binder distribution in the mixture. Interestingly, when specimens were mixed using the flat agitator their cured ITSM values increased dramatically and the effect of FWC was clearly evident.

Optimum performance was obtained at a FWC of 5% for specimens prepared using FB 70/100 at 180°C. It may be that the optimum performance is obtained with the best binder distribution in the mixture, in which state the mixture is more sensitive to testing temperature and curing condition (see Sunarjono et al, 2007). However, at a FWC of 5%, bitumen foaming temperature was found to be less significant than FWC in developing stiffness. This can be understood since foamed bitumen properties do not change significantly with bitumen temperature.

It was found that at a test temperature of 5°C the ITSM values of specimens using Pen 160/220 exhibited higher than specimens using Pen 70/100. It can be then deduced that binder distribution at low temperature is more important than binder stiffness in developing the ITSM value since specimens using

Pen 160/220 are better mixed than specimens using bitumen Pen 70/100.

The performance of FCMA materials under water soaking has been investigated. Specimen produced using bitumen Pen 50/70 were evaluated in terms of their ITSM values before and after water soaking at 40°C for 3 days. The test results as shown in Figure 12 are very interesting. It was found that the resistance to water damage of Pen 50/70's specimens was acceptable only on the specimens with FWC higher than 5%. The fact that the ITSM ratio increased with FWC might be due to binder ageing. It is known that the binder was ageing, since the recovered binder moduli were higher than those of the fresh binder (see Figure 13). It should be noted that binder ageing was not caused by the foaming process but it occurred in the compacted specimens. Since the binder is not continuously distributed in the mixture, the void content becomes higher and the bitumen film becomes thicker. High void content will make the mixture less durable due to oxidation but a thick binder film will reduce binder hardening (making it more durable). So, durability of foamed asphalt mixtures is an interesting topic requiring further research.

## CONCLUSIONS

Following the work described in this paper, it can be deduced that the stiffness characteristics of FCMA are as follows:

1. The ITSM test is suitable to evaluate the stiffness characteristics of FCMA materials.
2. Mixing quality is an important aspect in developing stiffness characteristics. The flat agitator performed better at mixing than the dough hook and it aided material properties and enhanced the ITSM value.
3. The ITSM values decrease with the increase of applied horizontal deformation and test temperature. However, the ITSM values of FCMA were found to be more sensitive to applied horizontal deformation and less temperature susceptible than those of HMA.
4. Optimum performance was obtained at a FWC of 5% for specimens prepared using FB 70/100 at 180°C.
5. Bitumen foaming temperature was found to be less significant than FWC in developing stiffness. This can be understood since foamed bitumen properties do not change significantly with bitumen temperature.
6. Binder distribution at low temperature is more important than binder stiffness in developing the ITSM values.
7. In the water sensitivity test, the FCMA resistance was found to be acceptable only on the specimens with FWC higher than 5%. The fact that the ITSM ratio increased with FWC might be due to binder ageing.

## ACKNOWLEDGEMENTS

The author is very grateful for the assistance and advice of Dr. N.H. Thom and Dr. S.E. Zoorob, and for many helpful discussions with Dr. M.H. Sutanto. This work was carried out with the financial support of TPSDP program SPMU-UMS unit Civil Engineering.

## REFERENCES

- Acott, S.M., 1979. Sand Stabilisation Using Foamed Bitumen. In: *3rd Conference on Asphalt Pavements for Southern Africa*, 3rd, 1979, Durban, pp.155-172.
- Akeroyd, F.M.L. & Hicks, B.J., 1988. *Foamed Bitumen Road Recycling*. Highways, Volume 56, Number 1933, pp 42, 43, 45.
- Bowering, R.H., 1970. Properties and Behaviour of Foamed Bitumen Mixtures for Road Building. In: *Proceedings of the 5th Australian Road Research Board Conference*, held in Canberra, Australia, 1970, pp. 38-57.

- Brennen, M., Tia, M., Altschaeffl, A.G. & Wood, L.E., 1983. Laboratory Investigation of The Use of Foamed Asphalt for Recycled Bituminous Pavements. In: *Asphalt materials, mixtures, construction, moisture effects and sulfur*. Washington, DC: Transportation Research Board. (Transportation Research Record; 911), pp 80-87.
- British Standard, 1993. *Method for Determination of Indirect Tensile Modulus Stiffness of Bituminous Mixtures*. Draft for development, DD 213: 1993.
- British Standard, 2003. *Bituminous Mixtures – Test Methods for Hot Mix Asphalt. Part 12: Determination of The Water Sensitivity of Bituminous Specimens*. BS EN 12697-12: 2003.
- British Standard, 2004. *Unbound and Hydraulically Bound Mixtures – Part 52: Method for the Manufacture of Test Specimens of Hydraulically Bound Mixtures Using Vibrocompaction*. BS EN 13286-52: 2004.
- Csanyi, L.H., 1959. Foamed Asphalt. *Technical bulletin No 204*, American Road Builders Association, Washington, D.C.
- Jenkins, K.J., de Ven, M.F.C. and de Groot, J.L.A., 1999. Characterisation of Foamed Bitumen. *7<sup>th</sup> Conference on Asphalt Pavements for Southern Africa (CAPSA)*.
- Jitarekul, P., Sunarjono, S., Zoorob, S.E., Thom, N.H., 2007. Early life performance of cement and foamed bitumen stabilised reclaimed asphalt pavement under simulated trafficking. *The International Conference on Sustainable Construction Materials and Technologies*, 11-13 June 2007, Coventry UK.
- Long, F.M., Theyse, H.L. and Ventura, D.F.C., 2004. *Characterisation of Foamed Bitumen Treated Material from HVS Test Section*. CSIR Transportek, PO Box 395, Pretoria, 0001, South Africa.
- Merrill, D., Nunn, M. and Carswell, I., 2004. *A Guide to The Use and Specification of Cold Recycled Materials for The Maintenance of Road Pavements*. TRL Report TRL 611. ISSN 0968-4107.
- Muthen, K.M., 1999. *Foamed Asphalt Mixes, Mix Design Procedure* Contract Report CR-98/077, June 1999. CSIR Transportek, South Africa.
- Nataatmaja, A., 2002. Some Foamed Bitumen Mix: Soil or Asphalt? *9<sup>th</sup> International Conference on Asphalt Pavements*, pp. 14-21, 2002.
- Needham, D., 1996. Developments in Bitumen Emulsion Mixture for Roads. *PhD thesis, Department of Civil Engineering, University of Nottingham*.
- Nunn, M.E. and Thom, N.H., 2002. *Foamix: Pilot Scale Trials and Design Considerations*. Viridis Report VR1. ISSN 1478-0143.
- Read, J.M., 1996. *Fatigue Cracking of Bituminous Paving Mixtures*. PhD thesis, Department of Civil Engineering, University of Nottingham.
- Sunarjono, S., 2006. A Study on Fatigue Performance of Reclaimed Asphalt Pavement Stabilised with Foamed Bitumen. *Seminar Nasional Teknik Sipil*, Universitas Muhammadiyah Malang, December 2006.
- Sunarjono, S., 2007. Tensile Strength And Stiffness Modulus of Foamed Asphalt Applied To A Grading Representative Of In-donesian Road Recycled Pavement Materials. *Jurnal Dina-mika Teknik Sipil*, Vol. 7, No. 1, Januari 2007, ISSN 1411-8904, Terakreditasi BAN DIKTI 55a/DIKTI/Kep/2006.
- Sunarjono, S., Zoorob, S.E. and Thom, N.H., 2007. Influence of Foaming Water on The Foaming Process and Resultant Asphalt Mix Stiffness, *4<sup>th</sup> International SIV Congress Palermo, Italy*, 12-14 September 2007.
- Sunarjono, S., 2008. The Mechanism Of Binder Distribution In Foamed Asphalt Mixture. *Jurnal Teknik Eco Rekayasa*, Vol. 4, No. 2, September 2008, ISSN 1907-4026. Program Studi Magister Teknik Sipil, Program Pascasarjana, Universitas Muhammadiyah Surakarta.
- Sunarjono, S. 2009. Investigating Rutting Performance of Foamed Cold-Mix Asphalt Under Simulated Trafficking, *Jurnal Dinamika Teknik Sipil*, Vol 9, No. 2, Juli 2009, ISSN 1411-8904, Terakreditasi BAN DIKTI 55a/DIKTI/Kep/2006.
- Widyatmoko, I. and Sunarjono, S., 2007. Some considerations to implement foamed bitumen technology for road construction in Indonesia. *The 1st International Conference of European Asian Civil Engineering Forum (EACEF)* at Universitas Pelita Harapan, 26 - 27 September 2007.