TENSILE STRENGTH AND STIFFNESS MODULUS OF FOAMED ASPHALT APPLIED TO A GRADING REPRESENTATIVE OF INDONESIAN ROAD RECYCLED PAVEMENT MATERIALS

Sri Sunarjono [1)]
[1)] Ph.D Candidate of University of Nottingham, UK
e-mail: irssmt_ums2002@yahoo.com

ABSTRACT

Saving energy and sustainable construction are becoming important issues in pavement engineering. These issues constitute a strong incentive towards the use of foamed asphalt technology worldwide. Unfortunately, there is no current research attempting implementation of foamed asphalt technology in Indonesia. Therefore, this paper contributes an important figure of cold recycling construction in which a deteriorated pavement with a grading representative of Indonesian road was stabilised using foamed bitumen. The specimens containing 2% foamed bitumen were fabricated with diameter 100mm and height 50mm. The specimens were cured at ambient temperature prior to tensile strength and stiffness modulus testing at various curing period. The results have provided preliminary indication of foamed asphalt characteristics. During curing period, the properties can be identified into 3 stages; (1) moisture dependent region in which the tensile strength and stiffness modulus increase with time due to loss of moisture, (2) critical region in which the correlation between moisture and properties is not clear and affected by temperature regime, and (3) ageing or loss of latent moisture region in which the properties is predicted increase with longer curing time. The correlation between tensile strength and stiffness modulus has been established in which its stiffness (MPa) is about 4 times of its strength (kPa).

Keywords: *foamed asphalt, stiffness modulus, tensile strength, moisture content, recycling, Indonesian road.*

INTRODUCTION

Foamed asphalt is an asphalt mix using foamed bitumen as its binder. Foamed bitumen is composed of gas and continuous hot bitumen liquid phase, produced by injecting a small amount of air and cold water into hot bitumen. During the foaming process, the gas content increases rapidly causing the bitumen

The increasing application of pavement construction using foamed bitumen in many countries is driver by saving energy and sustainable construction issues, as foamed bitumen enables coating of wet aggregates and therefore can be applied as a cold mix system. Foamed bitumen can be used with a wide range of aggregat in Dahlan et al. (1997). In 1992, a new specification for AC mixes with high minimum binder content to improve mix durability was launched. Recently on parts of the national road network, Split Mastic Asphalt (SMA) was also e types from conventional high quality graded materials, reclaimed asphalt and granular materials to marginal materials such as those having a high plasticity index (Muthen, 1999).

Foamed bitumen technology known over 50 years ago; nevertheless this material has not yet been applied in Indonesia. Also, as far as is known, there is no current research attempting implementation of foamed bitumen technology in Indonesia. Therefore this investigation of foamed bitumen will be a very important research especially concerning an attempt to implement this binder in Indonesian road construction.

Regarding historical road pavements in Indonesia (described in Part 2), it should be understood that Indonesian roads have mainly been constructed using Asphalt Concrete (AC) or Hot Rolled Sheet (HRS) as a surface layer, and are often found to have failed prematurely due to cracking and plastic deformation. Any new layer overlaid on to that layer will deteriorate due to a lack of structural support. Therefore, recycling technology is one interesting alternative solution to overcome these problems.

This paper presents an experimental work on foamed asphalt applied to a grading representative of Indonesian road recycled pavement materials. Indirect Tensile Stiffness Modulus (ITSM) and Indirect Tensile Strength (ITS) testing were used in order to assess the foamed asphalt properties.

INDONESIAN ROAD DEVELOPMENT AND ITS PROBLEMS

In general, the pavement typical of Indonesian roads is Penetration Macadam as a surface layer, Telford construction as base, River Sandy Gravel as sub-base and compacted in situ material as sub-grade. Telford construction consists of big stones with size 15/20 cm that is arranged manually and then it is locked by stones with size 3/5 cm. Since

1975, many of Java's roads were overlaid with asphalt concrete (AC) and many others (especially outside Java island) were built as new road constructions with AC material.

Unfortunately, these constructions often failed prematurely by cracking. There may be a need to improve the flexibility and durability of mixtures. Then in 1986, Hot Rolled Sheet (HRS) began to be applied to overcome the weakness of AC material. HRS is a material adapted from Britain, namely Rolled Asphalt. However, actually HRS was applied as a fine AC with high bitumen content and faileprematurely by plastic deformation. The weakness of Indonesian roads in associate with cracking and deformation described above can be found implemented. Figure 1 shows the common pavement structures applied in Indonesia. Road surface uses AC (and also HRS) material, whereas Asphalt Treated Base (ATB) and unbound granular base Class A and B were commonly used as base material and unbound granular sub-base Class A, B and C were commonly used for sub-base material.

Asphalt concrete	40mm	Marshall Stability > 750 kg
Asphalt Treated base	70mm	Marshall Stability > 750 kg
Unbound granular base	200mm	Aggregate class A CBR 80%
Unbound granular sub-base	500mm	200mm Aggregate class B CBR 60% 300mm Aggregate class C CBR 30%
Compacted sub-grade	varies	Selected materials

Figure 1. Indonesian road pavement structure

The main problem with the existing pavement layer materials that contain AC (or HRS) material is their bad condition, caused by cracking and plastic deformation. Any new layer overlaid on a deteriorated pavement section will fail prematurely. Furthermore, it is strongly predicted that base and sub-base layers have a lack of structural capacity. It can be understood that, in part, rutting indicates a base or sub-base layer problem. Therefore, recycling technology is one interesting alternative solution to overcome those problems. The cold recycling system using foamed bitumen is then evaluated to understand its properties.

A recycling system was first introduced in the mid 1990s. The project location was part of a section of main road between Bandung and Cikampek in West Java. The failed old pavement layer was recycled to full depth by a hot recycling system and produced a new base course layer. A cold recycling project has also been conducting in many Indonesian road sections e.g. in Kutai, East Kalimantan, starting in 2004 in which asphalt emulsion was used as a binder for the reclaimed material.

TENSILE STRENGTH AND STIFFNESS MODULUS TEST

Indirect Tensile Stiffness Modulus (ITSM)

Stiffness is one of the important mechanical properties, defined as uniaxial stress divided by the corresponding strain. A base layer behaving high stiffness can protect the soil foundation by decreasing soil shear stress; although this brings a risk that the base layer itself may crack (Brown, 1994).

The Nottingham Asphalt Tester (NAT) developed at the University of Nottingham enables measurement of stiffness properties, especially for bituminous materials, using simple practical methods provided by a simple closed-loop computer controlled pneumatic testing system.

Stiffness of bituminous material can be measured quickly and easily using the indirect tensile stiffness modulus (ITSM) test (BS DD 213, 1993) under the Nottingham Asphalt Tester (NAT), which is a non-destructive method and has been widely used for determination of stiffness modulus values (Cooper and Brown, 1989). This testing method uses cylindrical specimens that may be prepared in the laboratory or sampled from the field. The standard target parameters pertaining throughout testing are as follows:

- Test temperature : 20^oC
- Rise time : 124 ± 4 ms
- Horizontal deformation : 5±2μm (for ø 100mm)
7±2μm (for ø 150mm)
- Poisson's ratio : 0.35

Prior to testing, all specimens are stored in a conditioning cabinet at the test temperature of 20^oC for at least two hours. During testing, it is important to adjust the magnitude of peak load to result in a transient horizontal deformation value of 5 ± 2 μm for a specimen with nominal diameter 100 mm. Figure 2 shows the typical test configuration for ITSM. Based on the ITSM test, the stiffness modulus of bituminous mixtures, S_m, can be determined using Eq.1 below:

$$S_m = \frac{L(\nu + 0.27)}{Dt} \quad (1)$$

where:

S_m indirect tensile stiffness modulus (MPa)

L peak value of the applied vertical load in Newtons (N);

D mean amplitude of the horizontal deformation obtained from two or more applications of the load pulse in millimetres (mm)

t mean thickness of the test specimen in millimetres (mm)

ν Poisson's ratio which for bituminous mixtures is normally assumed to be 0.35

Figure 2. ITSM test configuration

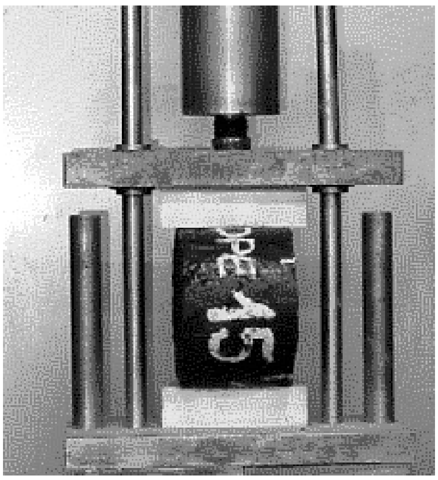

Figure 3. ITS test configuration

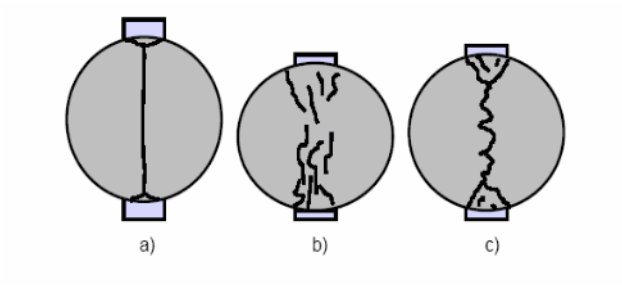

Figure 4. Type of failure on ITS specimens

a) Clear tensile break – Specimen clearly broken along a diametrical line, except perhaps for small triangular section close to the loading strips,
b) Deformation – Specimens without a clearly visible tensile break line,
c) Combination – Specimens with a limited tensile break line and larger deformed areas close to the loading strips.

Indirect Tensile Strength (ITS)

The Indirect Tensile Strength (ITS) test may very useful in understanding the tensile strength characteristics and in predicting the crack appearance in the mixture. The test method is also widely used to determine the water sensitivity of bituminous specimens once the volumetric design has been completed.

BS EN 12697-23: 2003 describes the procedure of determining the ITS value. The ITS test can also be used to obtain the fatigue life and water sensitivity using appropriate temperatures and deformation rates (Table 1).

Table 1. ITS test protocol

Application	Deformation rate (mm/min)	Temperature (^oC)
ITS	50	25
Water sensitivity	50	25
Fatigue cracking	50	-10, 4, 20

In the ITS test, a cylindrical sample is subjected to compressive loads between two loading strips, which creates tensile stress, along the vertical diametric plane causing a splitting failure. Diametral load is applied continuously at a constant rate of deformation until the peak load is reached, at which point the specimen fractures (Figure 3). The type of failure recorded may help the understanding of crack appearance in the mixture (Figure 4). The ITS is the maximum tensile stress calculated from the peak load applied at break and the dimensions of the specimen (Eq.2).

$$\text{ITS} = \frac{2000P}{\pi D t} \qquad (2)$$

where

ITS is the indirect tensile strength, expressed in kPa

P is the peak load, expressed in kN

D is the diameter of the specimen in mm

T is the thickness of the specimen in mm

PROPERTIES OF MATERIALS USED

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.

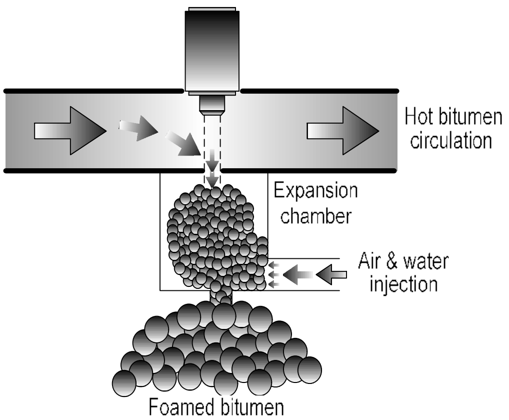

Figure 5. Foamed bitumen produced in an expansion chamber

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 5.

In this study, penetration grade bitumen pen 70/100 was selected for the production of foamed bitumen. Basic properties of the bitumen including penetration, softening point, and viscosity were determined and the results are presented in Table 2.

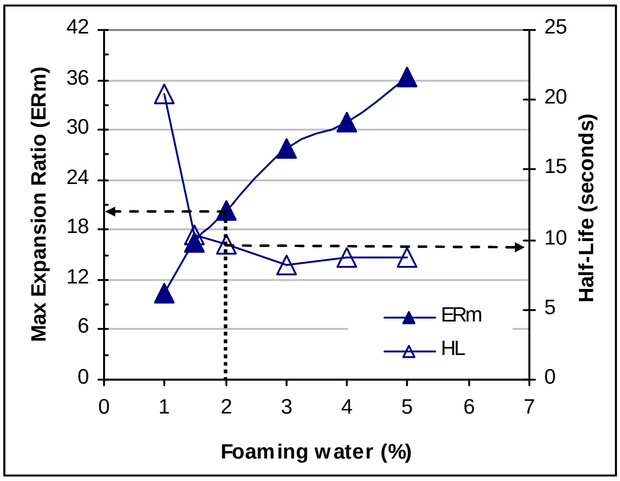

Figure 6. Foaming characteristics of bitumen pen 70/100 at foaming temperature 150 °C

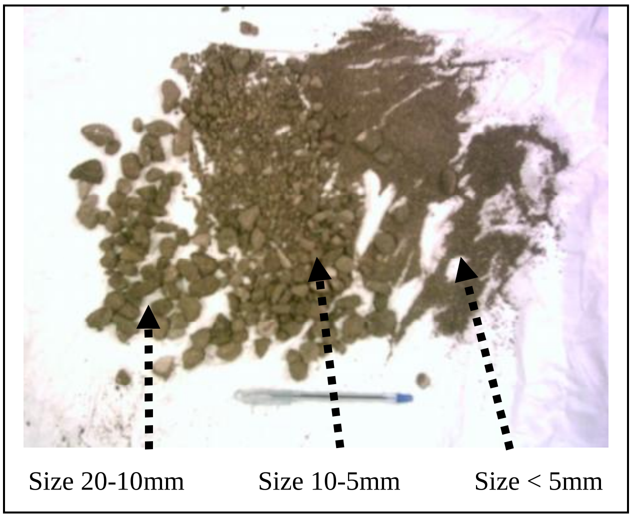

Figure 7. Profile of RAP material

Table 2. Basic properties of bitumen pen 70/100

Penetration (25 C, 100 g, 5 s)(0.01 mm)	76
Softening point (ring & ball) (˚C)	49.6
Viscosity @ 140 ˚C (mPa s)	262
Viscosity @ 160 ˚C (mPa s)	114
Viscosity @ 180 ˚C (mPa s)	57

Foamed bitumen is commonly characterised in terms of its Maximum Expansion ratio (ERm) 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. ERm 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. For a given temperature, there is an optimum percentage of added water by mass of bitumen (foaming water) that produces the most effective ERm and HL of the foamed bitumen.

Figure 6 presents the foamed bitumen characteristics at foaming temperature of 150 °C. It can be seen that if foaming water increase, the ERm increase and the HL tends to decrease. Wirtgen (2005) recommends a minimum expansion ratio of 8 times and half-life of 6 seconds. In this study, foaming water of 2.0% was selected to create the most stable foam. The corresponding maximum ER and HL values were 20 times and 10 seconds.

Reclaimed Asphalt Pavement (RAP)

Reclaimed asphalt pavement (RAP) was collected from an asphalt producer with an in-plant asphalt recycling facility. The RAP was originally milled from various asphalt roads and brought together into one stockpile. Composition analysis was performed to determine the properties of RAP and its extracted components. The results are shown in Table 3.

In this study, to avoid variability of RAP material, both in its gradation and other properties, the materials are separated into 3 portions i.e. coarse portion (10-20mm), medium portion (5-10mm) and dust (< 5mm). Stone with size bigger than 20mm was discarded since one or two big stones in a specimen (diameter 100mm) would have an effect inconsistent with specimen properties. RAP material used in this study can be seen in Figure 7.

DEVELOPING ARTIFICIAL GRADING

In this study, an artificial grading means a gradation of combined reclaimed pavement materials in which the materials are collected from United Kingdom sites but a grading was established closer to that for an Indonesian reclaimed pavement. The reason for this is that it is quite difficult to bring large quantities material from Indonesia. As described in Part 0, plenty of Indonesian roads suffer premature damage in the surface layer, and this situation is the main reason to reconstruct using a recycling system.

Because there is no detail available of the gradation of Indonesian reclaimed pavement, so reference is made to the material specification used generally in Indonesia (BM 1983 and DGH 1992).

This study investigated a scenario of 110 mm recycling depth that contains recycled Asphalt Concrete (AC) 40mm and Asphalt Treated Base (ATB) layer 70mm (see Figure 1).

The recycling depth will be simulated with 100% RAP material. The grading of AC and ATB was combined at a ratio of 40:70. The AC and ATB grading was set from the lower limit of their specifications. AC uses continuous grading whereas ATB uses gap grading in which there is little material size of 5 to 10 mm. The combined grading is considered to be the desired grading. The artificial grading for 100% RAP materials was then developed by consideration of the grading limit for foamed asphalt, the provided grading of RAP material and the desired grading (see Figure 8). Because the artificial grading has insufficient filler, so at least 5% filler should be added to the artificial graded material.

Table 3. Properties of RAP

Bulk properties			
Colour	Black/ brown		
Initial water content (%)	3 - 4		
Particle shape			
Flakiness index	13.4		
Shape index	8.2		
Elongation index	11.5		
Particle density (Mg/m3)	< 5mm	5-10mm	10-20mm
Oven dried	2.39	2.49	2.54
Saturated surface dry	2.45	2.52	2.56
Apparent	2.54	2.56	2.60
Water absorption (%)	2.55	1.01	0.93
Recovered bitumen			
Binder content (%)	4.1		
Penetration (25 °C, 100 g, 5 s) (0.01 mm)	25		
Softening point (ring & ball) (°C)	63.2		
Viscosity @ 120 °C (mPa s)	2530		
Gradation			
Sieve size	Cummulative percent Passing		
	Bulk RAP	Extracted RAP	
20 mm	93.7	99.1	
14 mm	80.6	87.9	
10 mm	64.8	74.4	
6.3 mm	44.8	60.5	
2.36 mm	24.6	44.3	
1.18 mm	14.3	35.2	
0.600 mm	8.4	28.7	
0.300 mm	3.5	20.0	
0.150 mm	1.1	13.2	
0.075 mm	0.4	9.7	

SPECIMEN PREPARATION

Mix design procedure

In this study, the mix design procedure used was adopted from Muthen, K.M. (1999), Lee, H.D and Kim, Y.J (2003), Wirtgen (2005) and preliminary study of Sunarjono (2006). Table 4 shows detail of the applied mix design procedure.

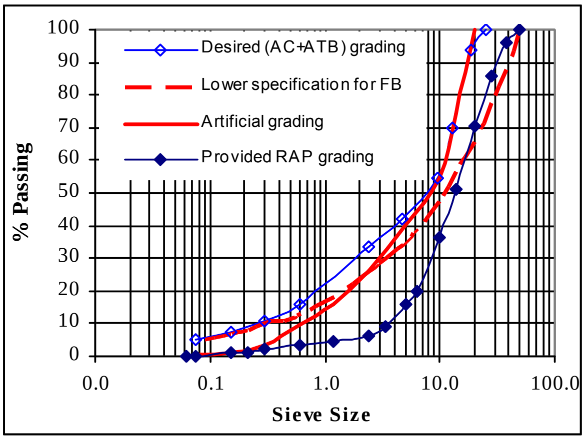

Figure 8. Developed artificial grading

Specimen preparation procedure

All information of specimen preparation procedure conducted in this study resulting briquettes for further testing can be seen in Table 5. As an example, a 100mm diameter of specimen compacted using Gyratory compactor is shown in Figure 9.

Table 4. Mix design procedure

STEP 1: Determine the best foam quality
- Investigate ERmax and HL of foam at various temperatures and foaming water content. - Select the best bitumen grade and temperature using the curve of ER vs HL - Select the best foaming water using the curve of ER-HL vs foaming water and selected foam specification
STEP 2: Prepare the aggregate
- Check the Plasticity Index (BS 1377-2: 1990), add lime 1% for high PI aggregate. - Check the gradation (BS EN 933-1:1997), ensure that gradation is located within the specification envelope for foamed asphalt (Akeroyd and Hicks ,1988). Minimum filler should be 5%. - Determine maximum dry density (MDD) and optimum moisture content (OMC) using modified Proctor (BS 13286-2: 2004). - Prepare 3 x 10 kg mass samples, check initial moisture content (MCintial) using duplicate sample. - If using cement or lime, it should replace the equivalent percentage of filler
STEP 3: Mixing process
- Calculate the amount of water (mass by percentage of total aggregate mass) using the equation OCC = OMC – MCreduc.- MCinitial. - Select 3 values of FBC. Calculate the amount of foamed bitumen by percentage of total aggregate mass. Add 25% to calculated foam mass. Set timer of foaming machine appropriate to foam mass. - Add water to the aggregates first and mix for about 1 minute, continuing with spraying foam and extend mixing for a further 1 minute. - Complete mixing the three 10 kg samples with selected FBCs.
STEP 4: Compaction process
- Compact the foamed blends using the Marshall hammer or Gyratory compactor. - If using the Marshall hammer, compact specimens 2 x 75 blows. - If using the Gyratory compactor, compact specimens with the superpave standard protocol. Investigate the number of gyrations to obtain MDD. - Produce a minimum of 6 specimens for each FBC.
STEP 5: Curing process
- Leave specimens in the mould for 1 day at ambient temperature. Do not open the top of the mould if using cement. - Oven dry specimens at 40 °C for 3 days. - Soak half the number of specimens at 25 °C for 24 hours.
STEP 6: Property testing
- Store the specimens in a temperature cabinet at 20°C for at least 2 hours before testing. - Test specimens using ITS test, ITSM test, Marshall Test or UCS test. These tests could be combined to obtain more accurate data.
STEP 7: Select the Optimum Foamed Bitumen Content (OFBC)
- Plot the data on a curve of FBC vs ITS/ stiffness/ stability & flow, UCS - Select OFBC according to the maximum values; it should be higher than the minimum values as follow: **ITS** : dry 200 kPa, wet 100 kPa (Bowering and Martin,1976) **UCS**: 1.8 MPa (Bowering and Martin ,1976)

Figure 9. Profile of a 100mm diameter specimen

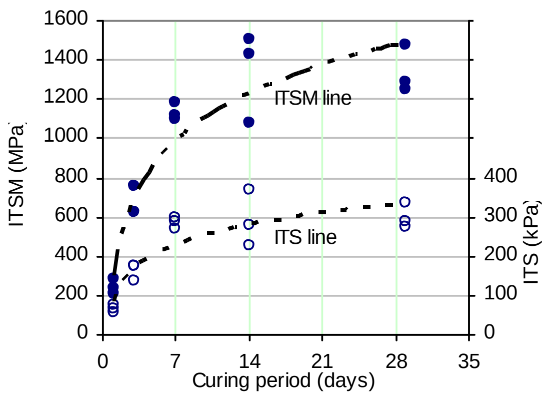

Figure 10. ITS and ITSM properties at various curing period

Table 5. Specimen preparation procedure

RAP composition	10-20mm = 45% 5-10mm = 15% Less than 5% = 35% Filler = 5% (limestone)
Foamed bitumen	Bitumen Pen 70/100 Foaming temperature 150 ^{o}C Foaming water 2% Foamed bitumen content 2%
Foaming machine setting	Air pressure= 5 bar Water pressure= 6 bar Setting calculation for FBC 2% (mass of aggregate 8000g) *Mass of foamed bitumen* *= 2% x 8000g = 160g* *FB used = 1.25 x 160 = 200g* *Setting timer = 200/100 = 2 seconds*
Moisture content calculation	OMC = 5.2 % MCreduc. = 1.28 % MCinitial = 0.3 % OCC = 3.62 %
Mixing	Using Hobart mixer 20 quarts *Mass of aggregate = 8000g* *Mass of water =3.62% x 8000g* *= 289.6g ~290g* *Water used = 1.05 x 290g* *= 305g (3.81%)*
Density	MDD = 2.145 Ton/m^3
Specimen preparation	Specimen size: diameter 100mm, height 50mm *Mass of dry material=MDD x Vol* *= 2.145 x 392.70 = 842.4g* *Mass of water = 3.81% x 842* *= 32.1 g* *Total mass of FA blending* *= 842.4 +32.1* *= 874.5 g ~ 875g* *Checked moisture content =* *4.46% (higher than calculation)*
Gyratory compaction	Force 600 kPa Compaction angle = 1.25 degree Setting = density control
Curing	At ambient temperature

Table 6. ITS and ITSM test Results

Samples	Age (days)	Moisture content (%)	ITS (kPa)	ITSM (MPa)
1	1	1.651	58	232
2	1	2.002	65	206.5
3	1	1.289	77	280
4	3	0.705	174	620.5
5	3	0.611	136	624
6	3	0.636	174	756
7	7	0.349	296	1114
8	7	0.295	271	1097
9	7	0.366	290	1180
10	14	0.207	367	1427
11	14	0.218	277	1502
12	14	0.217	225	1081
13	29	0.169	288	1248
14	29	0.218	335	1477
15	29	0.199	275	1285

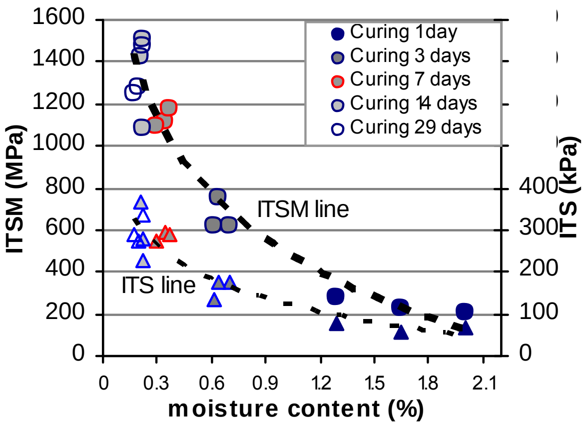

Figure 11. Effect of moisture content on ITS and ITSM

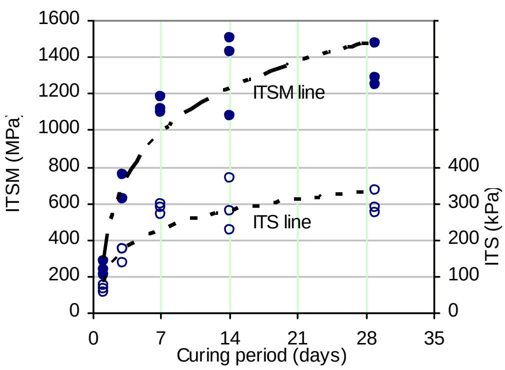

Figure 10. ITS and ITSM properties at various curing period

TEST RESULTS AND DISCUSSION

Table 6 shows the results of ITS and ITSM testing at different curing time.

All specimens were subjected to stiffness modulus investigation (ITSM test) prior to strength testing (ITS test). This procedure is allowed due to the ITSM testing is a non-destructive assessment. All tests were conducted at temperature of 20^{o}C in order to establish a correlation between stiffness modulus and strength properties.

The ITSM tests were carried out using a standard testing procedure, i.e. Poisson's ratio 0.35 and target rise time 124 m.seconds (DD 213:1993 clause 7, 8.2 and 4.9.3) at 5 microns target horizontal deformation.

The ITS tests were performed in an Instron machine. The apparatus is displacement controlled and both load and displacement can be recorded by load cell and LVDT respectively. In this test, the load was set at 10 kN and the maximum stroke 10mm. The tests were conducted using standard displacement speed i.e. 50 mm per minute.

Figure 10 shows the results of ITS and ITSM tests on all specimens. The specimens cured at ambient temperature were tested at 1 day, 3 days, 7 days, 14 days and 29 days age. It can be seen that an increased curing period significantly increased the tensile strength and stiffness of specimens. The initial properties is very low i.e. ITS and ITSM values are about 50 kPa and 200 MPa respectively and then its properties improve sharply during 7 days. This can be explained by Figure 1 that presents moisture content data during the curing period. It can be seen that during 7 days, the moisture content reduce significantly. It is clear that increasing strength and stiffness of specimens during the curing period is mostly caused by loss of moisture.

As shown in Figure 10 and 11, there is no significant different between ITS and ITSM trend data in relation to curing time and moisture content. Figure 12 gives strong support in that ITS and ITSM have approximately linear correlation with R^2 equal 0.9298. It is found that ITSM value (MPa) is about 4 times of ITS value (kPa). This correlation is very important in order to understand a relationship of fundamental and engineering properties of foamed asphalt materials. However, more data is still required to develop a valid equation of those properties.

Figure 13 explains the characteristics of material stiffness depending on the amount of moisture loss during curing time. The various data from specimens cured at ambient temperature from 1 day until 60 days and specimens cured with accelerated curing were collected together to construct this relationship. The logarithmic trend line was established to allow the possibility of forward forecasting.

As shown in Figure 13, it can be stated that the stiffness of specimens, during curing, are moisture dependent until this reach a critical region. In the critical region, the moisture appears very difficult to lose. It may be that this point is the latent moisture content of the specimen, hidden inside the aggregate or trapped by the foam. In other observation, it was also found that the latent moisture content both of covered and uncovered specimens reached around 0.2 to 0.3 %. In this study, as shown in

Figure Figure 4, the critical region was found to be around 0.2 to 0.4 % of moisture content. In the field, Batista (2005) found that the moisture content of pavements during 60 days varied between 0.25 and 1.5 % in the case of a study on emulsion mix.

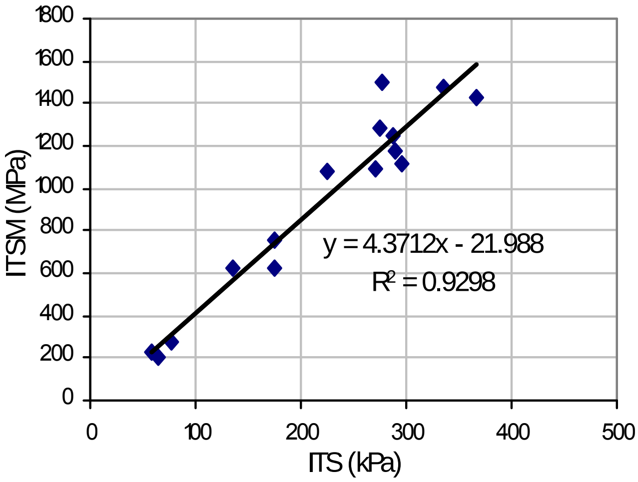

Figure 12. Relationship between ITS and ITSM values

After passing the critical region, it is unknown what will happen in term of change to specimen properties and moisture. This is because, in this study, the specimens still stand within the critical region at 60 days and no data is yet available after that. It is strongly predicted that stiffness will increase with longer curing time (Thom, 2005). However, it is as yet unanswered what might came such an increase in stiffness. In hot mix asphalt, ageing of asphalt, the tendency for bitumen to harder has been known as the cause of increasing stiffness during pavement life. But the increase is very small, around a quarter of the ageing index during mixing (Read and Whiteoak, 2003). In the case of emulsion asphalt, Batista (2005) found that during 2 to 4 months the stiffness increased significantly from 1000MPa to around 2000 MPa (uncovered specimens) and from 1500 MPa to 2000 MPa (covered specimens). In case of foamed asphalt, which only uses a small amount of bitumen and has imperfect coating of the aggregate particles, and also with the presence of low water content in the material, increasing stiffness after the critical region can not be explained directly?

In the critical region, the lower moisture content of specimens does not guarantee higher stiffness as shown in Figure 14. It is predicted that temperature plays important effect on the specimen properties. In order to understand of specimens properties at low moisture content with avoid temperature effect, the vacuum method is adopted.

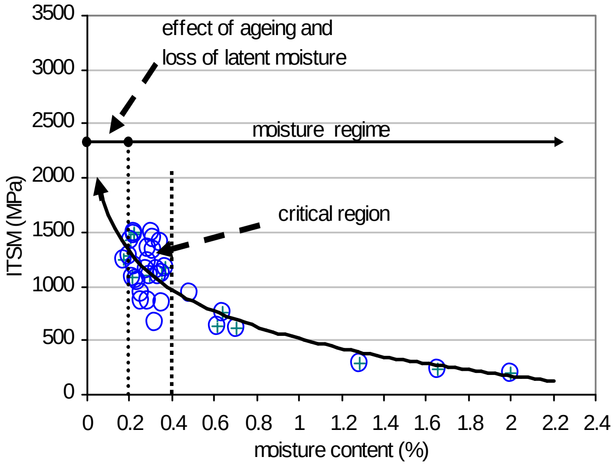

Figure 13. ITSM-moisture content relationship

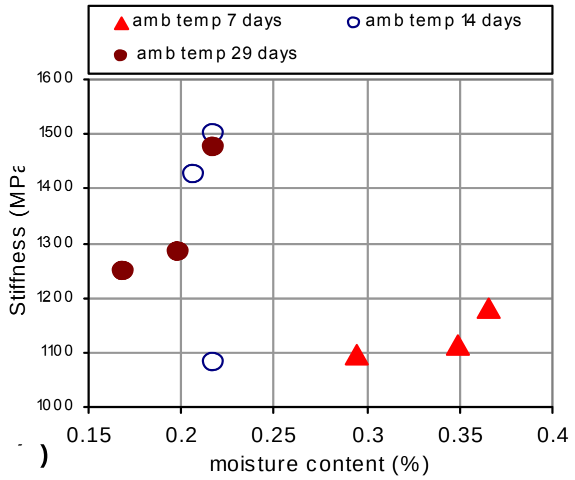

Figure 14. Foamed asphalt properties at critical region

The specimens were put in a vacuum cabinet at 30 mBar for 15 hours. Two temperatures were selected i.e. 20 °C and 30 °C. Figure 15 shows the results relative to the specimens cured at 40°C (3 days) and ambient temperature (29 days). It can be seen that the final moisture content of all specimens approached to the critical region (0.2-0.4%). The stiffness of specimens using vacuum method are found lower than specimens cured at 40°C and ambient temperature. This fact gives support that temperature applied during curing period affects to the stiffness of specimens.

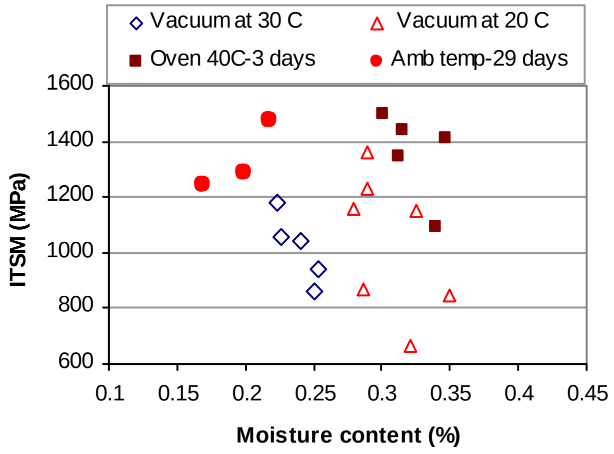

Figure 15. Effect of accelerated curing on ITSM

CONCLUSIONS

This paper summarizes a laboratory investigation on the strength and stiffness modulus properties of foamed asphalt in which the gradation of material used was established closer to that for an Indonesian reclaimed pavement. Based on the results, the following conclusions are drawn:

1) The initial strength and stiffness modulus of foamed asphalt material are low; however these properties improve significantly during curing period. The increasing strength and stiffness of specimens is mostly caused by loss of moisture.
2) The ITS and ITSM values have approximately linear correlation in which the ITSM value (MPa) is about 4 times of ITS value (kPa).
3) The curing time period of foamed asphalt can be divided into 3 stages: *first*, moisture dependent region in which the properties improve with reducing moisture content; *second*, critical region in which the correlation between moisture and properties is not clear; and *third*, ageing or loss of latent moisture region in which the properties is predicted increase with longer curing time.
4) Temperature during curing time plays important effect on the properties especially in the critical and ageing region.

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