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A Comparative Study on Properties of Malaysian Porous Asphalt Mixes with Different Bitumen Contents

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Abstract: Inadequate bitumen content in porous pavement construction may result in incomplete coating of aggregates which a thin bitumen film can oxidize rapidly resulting in premature failure of the pavement. This and presents the effects of porous asphalt prepared with 4.0% and up to 6.0% binder content with 0.5% increments binder. Bitumen penetration grade 60/70 and crushed granite were used in preparing the porous asphalt specimen. The porous asphalt mixes were compacted by applying 50 blows on each face using a Marshall Impact compactor. The specimens were tested for air voids, indirect tensile strength and water permeability and abrasion loss. The moisture sensitivity was assessed according to the AASHTO T283 procedures. The result shows that the increasing of bitumen content has decreased the, bulk density air voids, coefficient of permeability and abrasion loss values However, the Indirect Tensile Strength (ITS) has significantly increased and this is a good indication to resistance against moisture sensitivity. It can be concluded that the increasing of bitumen content in porous asphalt has increased the thickness of binder coating around the aggregates. This results reduction in air voids and water permeability, on the other hands it increases resistance to disintegration and ITS value which give better resistance to moisture sensitivity of porous specimens.

Keywords: Bitumen content, moisture sensitivity, porous asphalt, resistance to disintegration

INTRODUCTION

Porous asphalt is described as a bituminous bound mix with selected grading and high-quality aggregates to provide asphalt mix typically in excess of 20% air voids. The open structure of porous asphalt allows quick drainage of water from the road surface during wet weather. Inefficient drainage system can result in hydroplaning which is dangerous to fast moving traffic. This can reduce contact between tyre and pavement, leading to the loss control of braking and steering during driving (Aman and Hamzah, 2014a). For this reason, the introduction of porous asphalt provides effective solution to address some of the engineering related setback experienced by road users.

Hanson *et al*. (2005) reported that the modification of pavement surface type using porous surfaces such as porous asphalt has succeeded to reduce noise. Nicholls *et al*. (2002) mentioned that the noise generated from vehicle tyres on a rigid pavement was 5 dB (A) to 7 dB (A) higher than on asphalt roads. According to Mo *et al*. (2011), 90% of highways in the Netherlands are made of porous asphalt. The quest for a comfortable driving experience, traffic noise reduction and improving road safety, encourage wider application of porous asphalt on road surfaces. In Malaysia, the earliest porous asphalt trial took place in 1991 on the Cheras-Beranang Road aimed at reducing traffic accident. In addition, roads along the Kerinchi Link, Kuala Lumpur also was laid with porous asphalt to reduce traffic noise (Aman and Hamzah, 2014b). In the United State, Open Graded Friction Course (OGFC) was generally applied to highways and airports to prevent skidding on wet pavements (Nielsen, 2006). In general, OGFC has lower air voids between 10 to 15% compared with porous asphalt mixes with higher air void between 18 to 22%. Watson *et al*. (2004) reported that the mix design OGFC air void is 18% based on Cantabro tests. According to Aman (2013), in 1980 in New Zealand, porous asphalt is widely used with an air void greater than 20%, but due to an observed poor effective life a research was conducted to maximize the void content (up to 30%) and applying modified bitumen to ensure adequate strength. However, porous asphalt is widely used for water drainage and noise reduction to improve traffic safety and driving comfort. The wet weather driving conditions have been improved since the water drained through the porous structure, avoiding standing water on the road surfaces.

Typically, the fundamental properties of bituminous mixture influence the stability and

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durability of porous asphalt pavement to withstand the destructive effects of dynamic wheel loading. A well-designed porous asphalt promoted good mix properties, more durable and caused minimum traffic induced damages during its service life (Aman, 2013). Porous asphalt mixture design includes the determination of minimum and maximum binder content required and modification of the aggregate grading. The larger maximum aggregate size and lower fine aggregate used, resulted in mixes that are prone to abrasion loss. Meanwhile, the adequate affinity between the binder and aggregate also improves resistance to disintegration (Hamzah *et al*., 2009). The distress of porous asphalt is normally due to loss of aggregate particles from the wearing course caused by the embrittlement of the bitumen after reaction with atmospheric oxygen. This form of distress involved aggregate loss through cohesive failure between the bitumen and aggregate interface (Hamzah *et al*., 2011). Hamzah *et al*. (2009) stated that the optimum binder content also has a significant effect on porous asphalt performance. Lower bitumen content caused the incomplete coating of aggregates. A rapid oxidation might occur due to thinner bitumen film and eventually caused ravelling. In contrast, excess bitumen content led to binder drainage (Aman and Hamzah, 2014b). According to Hamzah *et al*. (2010a), decreased binder content in porous asphalt mixes, increased air void and decreased the resistance to abrasion, which resulted in lesser adhesion between aggregate particles. A thin binder coating is inadequate to prevent particles from being dislodged by traffic. It also aged more rapidly, thus aggravating the ravelling problem. As reported by Huber (2000), the most critical factors in the performance of bituminous mixes are due to the tendency of the binder film on the surface of the aggregate to be continuously exposed to the effects of oxygen, sunlight and water. When the bitumen becomes too hard and brittle, the aggregate striped from the asphalt mix. On the other hand, the adoption of modified binder to counter the tendency to ravel has lengthens the life span of porous asphalt. The determining adequate binder content is of greatest importance in pavement construction. The lower bitumen content may result in incomplete coating of aggregates or a bitumen film, which is so thin that it oxidizes rapidly, resulting in premature failure of the surfacing. Subsequently, the higher the bitumen content may cause the excess bitumen to drain off from the aggregate during transportation, resulting in variation in bitumen content in the laid material. In extreme cases, bitumen has been running from the tailboards of delivery vehicles (D'Angelo *et al*., 2008). Aman *et al*. (2014c) stated that another drawback of porous asphalt is the low pavement strength. It is a known fact that the proportion of fines in an aggregate gradation affects mix stability. In order to achieve a high percentage of voids the fine aggregate content is lowered and the mortar content must be drastically reduced compared to dense asphalt mixes. Generally, mixtures with lower fine contents will exhibit lower stability and vice versa. Meanwhile, higher coarse aggregate content implicates higher permeability but reduction in strength and lacking in durability. Further, Hamzah *et al*. (2009) mentioned that in porous asphalt the source of stability is from aggregate interlock, enhanced by the stability of the coarser aggregate matrix. However, the stability value of porous asphalt is lower than that of dense asphalt, but increases as the gradation becomes less open by integrating more fines. In fact, porous asphalt wearing courses has a low structural strength compared to conventional pavement.

The main purpose of this study was to investigate the properties of porous asphalt mixes at different binder contents and to evaluate moisture damage resistance after water immersion and freeze-thaw conditioning.

MATERIALS AND METHODS

Material properties: Crushed granite aggregates were washed, dry and sieve into select size range according to a porous asphalt gradation. The gradation specification was adopted from the Public Works Department (PWD, 2008) specifications. The conventional 60/70 penetration grade bitumen in 25 L/container was heated and poured into a small container and left to cool at ambient temperature before storing for further laboratory testing. This step was adopted to prevent wastage and overheating of bitumen. Bitumen and Crushed granite were supplied by Shell Ltd and Hanson Quarry Sdn. Bhd., Batu Pahat, respectively. The material properties of asphalt binder and crush granite aggregate are shown in Table 1 and 2 correspondingly. The combined aggregate grading is shown in Table 3.

Table 1: Properties of asphalt binder

Test properties	Standard	PWD requirement	Test results
Specific gravity (g/cm^3)	ASTM D36 (2005)	Not stated	1.033
Softening point (ºC)	ASTM D36 (2005)	48-56	63
Penetration at 25ºC (dmm)	ASTM D5 (2005)	60-80	49

Table 2: Properties of crush granite aggregate

Test properties	Standard	PWD requirement (%)	Test results
Flakiness index	BS 812-105.1 (1989)	Less than 25	23.1
Abrasion loss at 25ºC (%)	ASTM D131 (2005)	Less than 25	24.1
Aggregate impact value (%)	BS 812-112 (1990)	Less than 25	21.9

Table 3: Combined aggregate gradation

Sieve size (mm)	20.0	14.0	10.0	5.0	2.36	0.075
Percentage passing	100	100	97.5	40.0	10.00	3.500

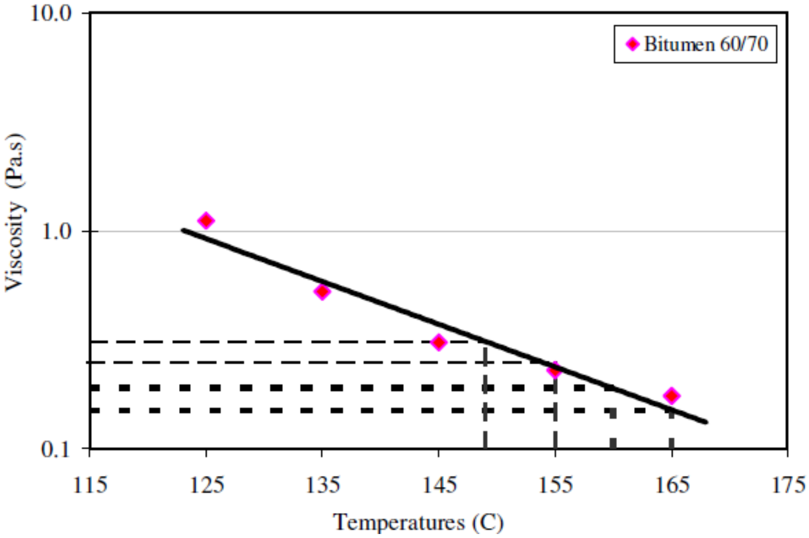

Fig. 1: Temperature-viscosity relationships

Mixing and compaction temperatures: The viscosity of asphalt pen grade 60/70 was determined using a Brookfield Rotational Viscometer and conducted according to ASTM D4402 (2005). The Asphalt Institute (2007) recommends ideal binder mixing and compaction viscosities corresponding to 0.17±0.02 and 0.28±0.03 Pa sec, respectively. Figure 1 displays the semi-logarithmic relationship between viscosity and temperature, while the temperatures range adopted for mixing and compaction are represented by the dashed and dotted lines, respectively. From the slope lines, the mixing and compaction temperatures were found to be in the range of 160 to 166°C and 149 to 155°C, correspondingly. Based on these results, the required mixing and compaction temperatures were 165 and 155°C which were used in the investigations.

Specimen preparation: The procedure adopted for the preparation porous asphalt specimens is similar to dense graded asphalt, as suggested in the Asphalt Institute (2007). Aggregates and fillers were batched in a metal container to produce the specimens of approximately 1100 g. The batched aggregates were then pre-heated in an oven for a period of at least 4 h at the desired mixing temperature. The porous asphalt mixes were prepared by blending aggregates with 5 different binder percentages (4, 4.5, 5, 5.5 and 6%, respectively) at mixing temperature. The loose mixes were conditioned in an oven for 2 h at the compaction temperature to allow the asphalt binder absorption to take place as recommended by The Asphalt Institute (2007). To prepare a cylindrical specimen, loose hot mix was compacted by applying 50 blows on each end of the specimen, using the standard Marshall hammer and left to cool down overnight at ambient temperature prior to subsequent testing.

Testing methods:

Air voids determination: The air voids for all mixes prepared with 4 to 6% bitumen content are estimated based on the bulk specific gravity of compacted specimens (G_{mb}) and the theoretical maximum density. For this study, an air voids analysis was conducted by using CoreLok vacuum-sealing and dimensional methods. According to Watson *et al*. (2004), the CoreLok vacuum-sealing method has been used for several years to determine the density of bituminous mixtures and was found to be more accurate for determining the density of specimens at relatively high air voids level such as porous asphalt specimens. Therefore, the bulk specific gravity of compacted specimens was evaluated using the CoreLok vacuum-sealing method according to ASTM D3203 (2005) procedure. The theoretical maximum density (G_{mm}) of the loose mix was carried out according to the ASTM D2041 (2005) procedure. Subsequently, the air voids in the compacted specimens were calculated using Eq. (1), derived from ASTM F3203 (2005) procedure. This test was conducted to ensure the porous asphalt containing varies bitumen percentage has sufficient permeability and the air voids should greater than 18% and conform to the Public Works Department (PWD, 2008) specification:

$$Va = 100\times\left(1-\frac{G_{mb}}{G_{mm}}\right) \tag{1}$$

where,

Va = The air void

G_{mb} = The bulk specific gravity of the compacted specimen

G_{mm} = The theoretical maximum density

Indirect tensile strength test: The Indirect Tensile Strength test (ITS) was used to determine the splitting strength and serves as an indicator of the tensile strength of the porous asphalt mix. In this study, the ITS test was conducted according to the ASTM D4123 (2005) procedures using the Marshall loading machine. This test was performed by loading the cylindrical specimens with single compressive load, which acted parallel to and along the vertical diametral plane. Kok and Yilzmaz (2008) reported that the failure specimen was observed by cracking along a loaded plane where tensile stress loading acts perpendicular to the specimens. Preceding the test, specimens were cured at 25ºC in an incubator for 4 h before tested.

Cantabro test: The Cantabro test was conducted to determine the abrasion loss of specimens prepared with 4 to 6% bitumen content using the Loss Angeles drum without steel balls charged and rotated 300 times at 30 rpm. As recommended by Herrington *et al*. (2005), the Cantabro test is carried out at 25ºC. Therefore, the porous asphalt specimens were conditioned in an incubator at 25ºC for 4 h before being assessed the cohesiveness of the porous asphalt mixes. The test result was expressed as percentage of the weight loss relative to the initial weight, indicating the cohesive properties of the mix. The test method adopted the procedures described by Jimenez and Perez (1990). The percentage of each abrasion loss was calculated based on Eq. (2):

$$P = \left(\frac{P_1 - P_2}{P_1}\right)\times(100) \tag{2}$$

where,

P = The abrasion loss (%)

P_1 = The mass before test (g)

P_2 = The mass after test (g)

Water permeability test: The permeability of porous asphalt mix is controlled by the shape and size distribution of aggregates and interconnection of the air void. According to Alvarez *et al*. (2006), the common approach to determine the drainage capability of porous asphalt is by measuring the time taken for the discharge of a specific water volume. The hydraulic conductivity of compacted specimens was expressed in terms of coefficient of permeability (k) and determined using a falling head water parameter at ambient temperature. The permeability of the porous specimen can be estimated when a hydraulic gradient is created across the porous specimen. Mallick *et al*. (2000) recommended that the permeability of porous asphalt should greater than 0.116 cm/sec to ensure a permeable mix. Therefore, the coefficient of permeability, (k) was computed from Eq. (3):

$$k = 2.3\left(\frac{aL}{At}\right)\log\left(\frac{h_1}{h_2}\right) \tag{3}$$

where,

k = The coefficient of permeability (cm/sec)

a = The tube cross sectional area (cm^2)

A = Specimen cross sectional area (cm)

L = Height of specimen (cm)

t = Time (sec)

h_1 and h_2 = Initial water level at t_1 (cm) and final water level at t_2 (cm)

Moisture conditioning: The moisture sensitivity conditioning was used to evaluate the effect of water saturation on porous asphalt specimens. The testing procedure described herein followed the AASHTO T283 (2007) procedures for the determination of water sensitivity of bituminous mixtures. Two subset compacted specimens were prepared for subsequent conditioning and the un-conditioning procedures. The conditioned specimens were exposing them to vacuum at 6.7 kPa for 10 min and submerged for another 10 min in a water bath. The dry specimens were conditioned at 25°C in an incubator for a similar period of time. To determine the effect of the freeze-thaw cycle, the specimens were wrapped with leak proof plastic bags containing 10 mL of distilled water. The plastic bag was placed in a freezer at -18°C for 16 h, followed by immersion of the specimens in a water bath at 60°C for 24 h. Then, the specimens were pre-conditioned for 4 hours at 25°C in an incubator before tested for the Indirect Tensile Strength (ITS). This test was conducted according to the ASTM D4123 (2005) procedures and the ITS value was calculated based on Eq. (4):

$$ITS = \frac{2000F}{\pi hd} \tag{4}$$

where,

ITS = Indirect Tensile Strength (kPa)

F = Maximum applied load (N)

h = Specimen thickness (mm)

d = Specimen diameter (mm)

The results of ITS conditioned specimens were compared to those unconditioned (dry) specimens to evaluate the resistance to moisture damage. According to the BS ASSHTO T283 (2007) procedure, the moisture damage was targeted at least 80%. Resistance to moisture sensitivity was assessed based on the ITS Ratio (ITSR), calculated using Eq. (5):

$$\text{ITSR} = \left(\frac{ITS_{wet}}{ITS_{Dry}}\right)\times(100) \qquad (5)$$

where,

$ITSR$ = The indirect tensile strength ratio (%)
ITS_{Wet} = The average ITS of the wet group (kPa)
ITS_{Dry} = The average ITS of the dry group (kPa)

The laboratory test results of this study were further analyzed by using statistical analysis. The data analysis focused on the effects of increasing bitumen content on bulk specific gravity and air voids, coefficient of permeability, abrasion loss and strength of porous asphalt to resist to moisture damage at 95% confidence level (α = 0.05).

RESULTS AND DISCUSSION

Volumetric properties: Figure 2 shows the relationship between bulk specific gravity (G_{mb}) and air avoids of the porous specimens. The individual bar chart indicates a general trend which the G_{mb} increase as the bitumen percentage increases. On the contrary, increasing the bitumen percentage resulted decreasing in air voids. The individual bar chart exhibits that the average G_{mb} and air voids of the porous specimens are in ranges from 1.852 to 1.864 g/cm^3 and 14.5 to 25.8%, respectively. Specimens prepared with 4.0% bitumen content exhibit lower G_{mb} compared specimens prepared with 6.0% bitumen content. By increasing the bitumen content from 4 to 6%, the G_{mb} of the porous specimen are increased by 0.7%, in contrast the air voids decreased by 40.1%, respectively. This might due to the higher binder content contributes to thicker binder films, this leads to increase in densification of the mix and consequently increases the air voids values. As shown in Fig. 2, it can be seen that the increasing of bitumen percentage increases the G_{mb} results decreases the air voids. However, the specimens prepared with 6.0% bitumen content show lower air voids compared with the specimens prepared with 4.0% bitumen content because of the presence of a large quantity of binders. The results are similar to that of Hamzah *et al*. (2010b), which indicated that increasing the binder content decreased the air voids in asphalt mixtures. According to Public Works Department (2008), the minimum allowable air voids is 18%. However, Huber (2000) and Mallick *et al*. (2000) suggested that to additional resistance to clogging and to ensure good drainage capacity, the minimum air voids of porous asphalt is 20%. In general, the results indicate that porous specimens prepared with 4.0, 4.5 and 5.0% are exhibits highest air voids value which are 25.4, 24.2 and 22.1%, respectively and conform to Huber (2000) and Mallick *et al*. (2000) recommendations, while specimens prepared with 6% bitumen show less than 18% air voids and not conform to the PWD (2008) specifications.

Table 4 summarizes the correlation among bitumen content used, increment on bulk specific gravity (G_{mb}) and increment air voids values of the porous asphalt mixes. The results analyzed using statistical analysis show that the correlation between bitumen content, G_{mb} and air voids values, which are 0.915, 0.961 and 0.829, respectively.

The experimental data obtained were further analysed using General Linear Model (GLM) multivariate Type III analysis between the effect of bitumen content of air void and bulk specific gravity at 95% confidence level (α = 0.05). Table 5 shows the results of a GLM analysis the effect of bitumen content on bulk specific gravity and air voids which the bitumen content has a significant effect on the bulk specific gravity and air voids.

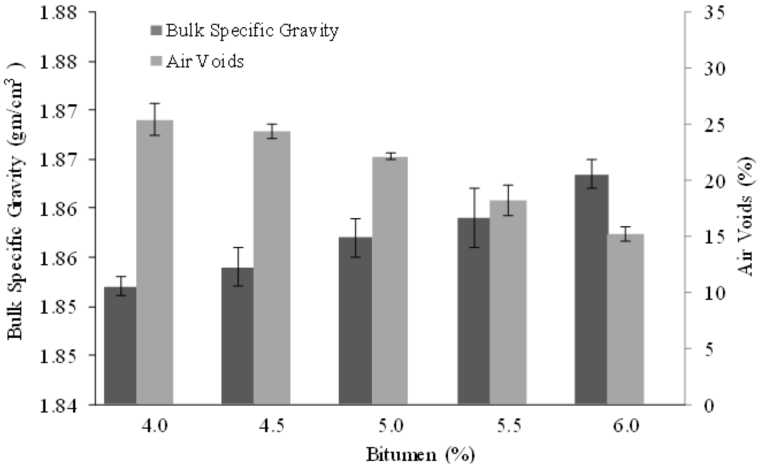

Fig. 2: Relationship between bitumen content (%) and bulk specific gravity (G_{mb})

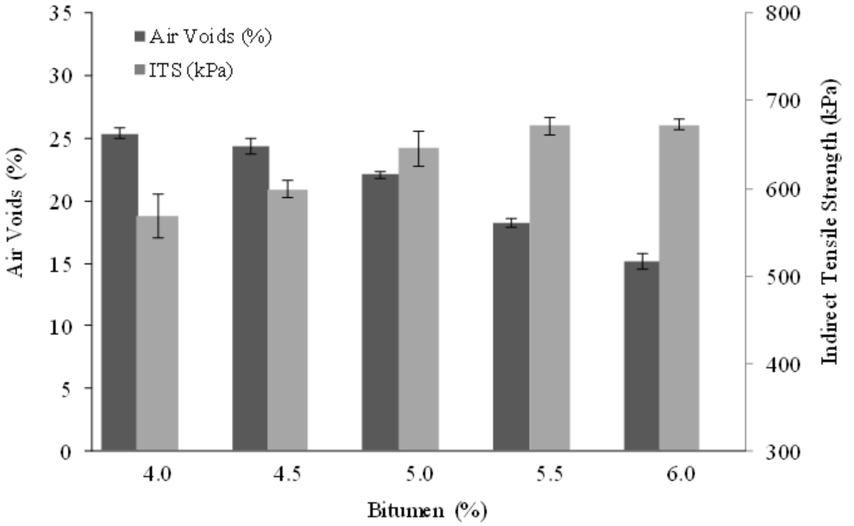

Fig. 3: Effects on air void and ITS

Table 4: Correlation between bitumen content and G_{mb} on air voids

		Bitumen	Increment of G_{mb}	Increment of air voids
Bitumen	Pearson correlation	1	0.915**	-0.961**
	Sig. (2-tailed)		0.001	0.001
	N	15.000	15.000	15.000
Increment of G_{mb}	Pearson correlation	0.915**	1.000	-0.829**
	Sig. (2-tailed)	0.001		0.001
	N	15.000	15.000	15.000
Increment of air voids	Pearson correlation	-0.961**	-0.829**	1.000
	Sig. (2-tailed)	0.001	0.001	
	N	15.000	15.000	15.000

**: Correlation is significant at the 0.01 level (2-tailed)

Table 5: GLM analysis on bulk specific gravity and air voids

Source	Dependent variable	Type III S.S.	df	M.S.	F	p-value
Corrected model	G_{mb}	0.000[a]	4	6.177E-5	15.189	0.001
	Air voids	223.924[b]	4	55.981	8.164	0.003
Intercept	G_{mb}	51.734	1	51.734	1.272E7	0.001
	Air voids	6270.993	1	6270.993	914.494	0.001
Bitumen content	G_{mb}	0.000	4	6.177E-5	15.189	0.001
	Air voids	223.924	4	55.981	8.164	0.003
Error	G_{mb}	4.067E-5	10	4.067E-6		
	Air voids	68.573	10	6.857		
Total	G_{mb}	51.734	15			
	Air voids	6563.490	15			
Corrected total	G_{mb}	0.000	14			
	Air voids	292.497	14			

[a]: R squared = 0.859 (adjusted R squared = 0.802); [b]: R squared = 0.766 (adjusted R squared = 0.672); S.S.: Sum of square; M.S.: Mean square

Table 6: One-way ANOVA effects of air void on ITS

Source	df	S.S.	M.S.	F	p-value
Voids	23	47928.20	2083.83	4167.67	0.012
Error	1	0.50	0.50		
Total	24	47928.70			

R-Sq = 99.99%; R-Sq (adj) = 99.97%; S.S.: Sum of square; M.S.: Mean square

Effect on air void and indirect tensile strength: Figure 3 shows the effects of air voids on Indirect Tensile Strength (ITS) for compacted specimens prepared with 4 to 6% of bitumen percentage tested at 25°C. Based on the results, it can be seen that the porous specimens prepared with 6% bitumen content exhibit higher ITS values than the specimens prepared with 4% of bitumen content. The result shows a general increasing trend of the ITS values as air voids decrease. The ITS values for porous specimens prepared with 4 to 6% bitumen content are between 567.4 to 672.7 kPa, respectively.

As shown in Fig. 3, by adding with 6% bitumen, the air voids correspondingly decrease by 40.1%, resulting increase of ITS by 15.7%. At higher binder content, the aggregates in the mixes were fully coated with a thick asphalt film and filled up the spaces between aggregates in the mix which led to air voids reduction. Therefore, the finding show that the to improve the ITS values. According to Hamzah *et al*. (2014a), increasing the bitumen content in asphalt mixes enhance the cementation to bind aggregate particles together results increase the ITS values. Further Yang and Ning (2011) mentioned that increasing the air voids in porous mixes produces low tensile strength. This results can be supported by finding from Aman and Hamzah (2014b), which porous specimen prepared with higher binder content reduced the air voids due to the aggregates in the mixes were fully coated with a thicker asphalt film.

One-way Analysis of Variance (ANOVA) was adopted to ascertain the statements on the effects of air voids on increasing of ITS values at 95% confidence level ($\alpha = 0.05$). The One-way ANOVA results are shown in Table 6. It can be seen from the results that air voids have a significant effect on the increasing of ITS value.

Effect of air void on dry abrasion loss: The abrasion action of vehicle wheels on a pavement wearing course specimens mixed with 6% bitumen has higher potential can initiate particle loss especially a high stress area results in ravelling. In the laboratory, resistance to ravelling was evaluated via the Cantabro test. The abrasion loss test results after 300 revolutions at 25ºC for all specimens prepared with varying bitumen content are shown in Fig. 4. The result depicts that that abrasion loss for all mixes exhibit decrease as the air voids decreasing due to increasing of binder content percentage. The mean air voids values for 4 to 6% bitumen content were found to be in the range of 14.5 to 25.8% having abrasion loss ranging from 3.2 to 17.5%, respectively. By adding 6% of bitumen content, the air voids and abrasion loss reduced by 40.1 and 80.8%, correspondingly.

Based on the Fig. 4, specimens prepared with 6% bitumen exhibit lower abrasion loss compared to the specimens prepared with 4% bitumen content. This may due to excessive binder content fully coated the aggregates thus increase the strength of the

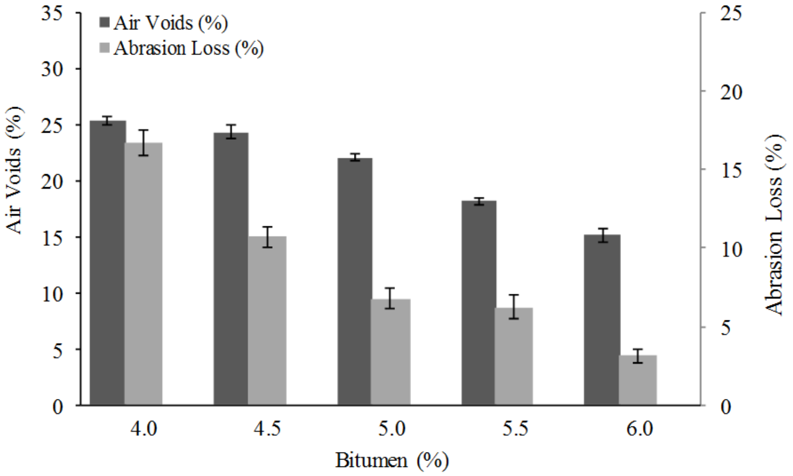

Fig. 4: Effect of air void on abrasion loss

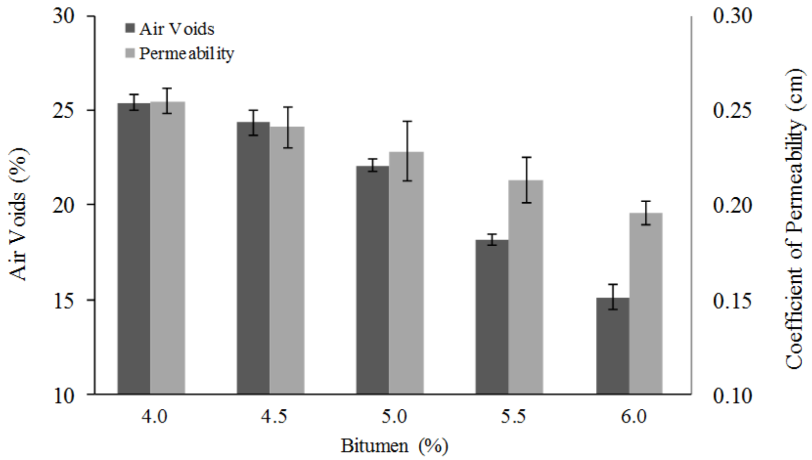

Fig. 5: Effect of air void on coefficient of permeability

Table 7: One-way ANOVA effects of air void on abrasion loss

Source	df	S.S.	M.S.	F	p-value
Air voids	24	564.50	23.52	6.96	0.02
Error	5	16.89	3.38		
Total	29	581.39			

R-Sq = 97.09%; R-Sq (adj) = 83.15%; S.S.: Sum of square; M.S.: Mean square

binder-aggregate bonding results greater resistance to surface disintegration. This finding is similar to Hamzah *et al*. (2010b), which the presence of high binder content in porous asphalt mixes decreases air voids and contributes to increase in resistance against abrasion loss. As reported by Aman (2013), a high amount of binder improves the mix cohesion and the resistance to porous asphalt disintegration. Watson *et al*. (2004) and Hamzah *et al*. (2010b) stated that the dry abrasion loss for un-aged specimens tested at 25°C does not exceed 25%. Therefore, the dry abrasion loss of specimens prepared with 4 to 6% bitumen content met the requirement stipulated by Watson *et al*. (2004) and Hamzah *et al*. (2010b). It can be concluded that increasing the binder content decrease the air voids and abrasion loss values. Specimens prepared with 4 to 6% bitumen content were found to be less than the predicted maximum limit of abrasion loss.

Further analysis was performed using a One-way Analysis of Variance (ANOVA) to determine the effects of air voids on abrasion loss at 95% confidence level. Table 7 summarizes the analysis results on the abrasion loss. It can be seen that the air voids has significantly affected the abrasion loss values.

Effect of air void on coefficient of permeability: Figure 5 shows the effects of air voids on coefficient of permeability for specimens prepared with 4 to 6% bitumen content. The mean bar chart indicates that the general trend in which as bitumen content increases, the air voids decreases. This is followed by decreasing in coefficient of permeability. The air voids are in the range of 25.8 to 14.5% while the coefficient of permeability is in the range of 0.265 to 0.191 cm/sec. It can be seen that by adding 6% bitumen the coefficient of permeability has decreased by 27.9%. This is due to excessive of binder content in porous mixes. According to Hamzah *et al*. (2011), a higher binder content used allows more voids filled with asphalt, thus lower the air void. This effect can illustrate by the fact the excess bitumen replaced the air voids and clogged some of the interconnected pores. In contrast, specimens prepared with 4% bitumen content show the slightly higher coefficient of permeability values compare to specimens prepared with 6% bitumen. However, low bitumen content may result in incomplete coating of aggregates or thin coating film results high air voids; consequently it oxidizes rapidly and leads to premature failure of the pavement surface.

From Fig. 5, the resulting coefficient of permeability values depends on the air voids continuity and which is highly prevalent in a porous mixture. Liu and Cao (2009) reported that there are two types of air voids in porous asphalt. Connected air voids provide most efficient drainage for porous asphalt while isolated air voids are a result of no opening to the air voids. Mallick *et al*. (2000) recommended a minimum coefficient of permeability for porous asphalt at least 0.116 cm/sec to provide sufficient drainage. Based on the test result, it can be seen that all mixes in this study exhibit higher the coefficient of permeability values and complies with the Mallick *et al*. (2000) recommendation.

The effects of air voids on coefficient of permeability was analysed using a One-way Analysis of Variance (ANOVA) at the 95% confidence level (α = 0.05). Table 8 shows the effects of the air voids on increasing of coefficient of permeability values. The result indicates that the air voids have a significant effect on increasing of coefficient of permeability values.

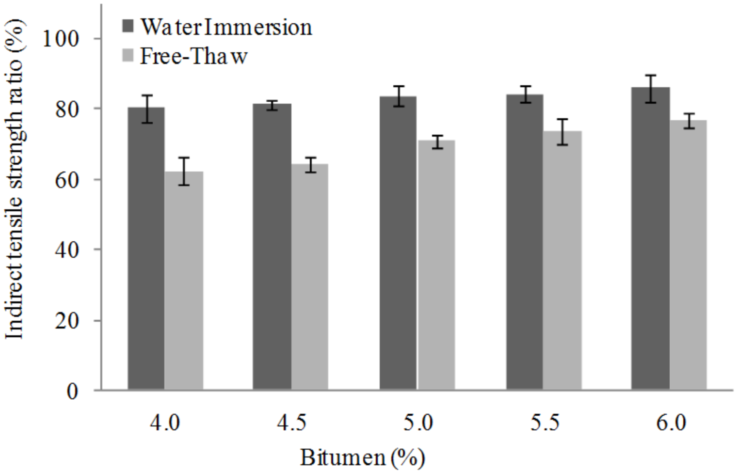

Fig. 6: Comparison of ITS ratio of water sensitivity methods

Table 8: One-way ANOVA effects of air void on coefficient of permeability

Source	df	S.S.	M.S.	F	p-value
Voids	21	0.0126113	0.0006005	24.18	0.012
Error	3	0.0000745	0.0000248		
Total	24	0.0126858			

R-Sq = 99.41%; R-Sq (adj) = 95.30%; S.S.: Sum of square; M.S.: Mean square

Effect of bitumen content on moisture sensitivity: Figure 6 shows the mean bar chart of Indirect Tensile Strength (ITS) ratio for porous asphalt prepared with 4 to 6% bitumen content via water immersing and freeze-thaw methods. The result indicates a general trend where the ITS ratio increases as the bitumen content increases for both of conditioned methods. Based on the test results, specimens prepared with 6% bitumen exhibit higher ITS ratio compared to 4% bitumen for all type of conditions. The ITS ratio value of specimens prepared with 4 to 6% bitumen conditioned by immersion in water were found to be in the range of 76.3 to 90.1%. While specimens conditioned by freeze-thaw, the ITS values are in the range of 58.4 to 78.7%. When specimens blended with 6% bitumen and conditioned with water immersion and freeze-thaw separately, the ITS ratio increases by 6.8 and 18.6%, respectively. This is due to excessive bitumen increases the thickness of binder coating. Subsequently it increases the adhesion between aggregate and bitumen and reduces the attraction between water and aggregate.

Figure 6 shows the increasing trend for all mixes specimens under freeze-thaw compared to water immersion, which may possibility due to the bitumen turns out to be stiff and increases the surface tension of the aggregate-bitumen bonding and weakening the mixture bonding. According to Mo *et al*. (2009), bitumen films between aggregates is decreasing in strength at frost condition, resulting in cohesion failure through the bitumen interlayer or adhesion failure through the aggregate-bitumen interface and easily prone to water damage due to fracture of the thin asphalt-cement film bonding the aggregate particles caused by the formation of ice crystals. It can be seen that all specimens with water immersion conditioned have ITS value more than 80%. The results conform to AASHTO T283 minimum requirement on resistance against moisture sensitivity.

CONCLUSION

The bulk density and ITS value are increased as binder content increases. However this binder increases has caused decreasing in air void which resulted decreasing in coefficient of permeability and abrasion loss. It is also found that all freeze-thaw specimens exhibit lower ITS ratio compared to water immersion specimens. We can be concluded that increasing of bitumen content significantly decreases the air voids and abrasion loss, but increases the ITS which indicates better resistance to water sensitivity.

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