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A Comparative Study on Performance of Malaysian Porous Asphalt Mixes Incorporating Conventional and Modified Binders

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Abstract: The Malaysian Public Works Department (PWD) has recently launched its new specifications and gradations on specialty mixes which includes porous asphalts. Two porous asphalt mix gradations, designated as A and B, were given in the PWD specifications. The aim of this study is to compare the performance of mixes prepared with the two gradations using two bitumen types, namely conventional binder 60/70 and PG-76 modified bitumen. Cylindrical specimens were prepared using the standard Marshall compactor by applying 50 blows on each face. The properties of the mixes were quantified and compared in terms of permeability, air voids, abrasion loss and indirect tensile strength through the water permeability test, determination of air voids, Cantabrian test, and indirect tensile strength test respectively. The results showed the volumetric and mechanical properties of the new Malaysian porous asphalt, as well as provide a better understanding of the effects of aggregate gradations, binder types, and binder contents on mix properties. It was found that Mix B exhibits better hydraulic conductivity and resistance to abrasion loss compared to Mix A, but lower indirect tensile strength. However, the use of modified binder has significantly increased the resistance to abrasion loss and strength of the mixes.

Key words: Aggregate grading, permeability, air voids, abrasion loss, indirect tensile strength

INTRODUCTION

Porous asphalt is described as a bituminous bound mix with selected grading and high-quality aggregates to provide an asphalt mix with 20% air voids. The presence of continuous air voids in the wearing course allows water to pass through the mix laterally and eliminates ponding water (Alvarez *et al*., 2006). Other benefits include elimination of glare, splash and spray, improvement in visibility, increased skid resistance of the road surface and improved traffic safety especially in wet conditions (Moore *et al*., 2001; Cooley *et al*., 2000; Poulikakos *et al*., 2004).

Porous asphalt also offers vast benefits to the environment. The good sound absorption potential has led to the application of porous asphalt on the expressway close to residential areas to attenuate noise. Alvarez *et al*. (2006) mentioned that by using porous asphalt, noise level can be reduced by approximately 3 dB (A) compared to dense asphalt. Higher reduction of 14 dB (A) was recorded on roads in Texas when asphalt-rubber open grade friction course was used to overlay an existing continuous reinforced concrete pavement (CRCP). Pagotto *et al*. (2000) pointed out that porous asphalt had also improved the quality of water runoff where heavy metal loads discharged into the environment were reduced with approximately 20% cuprum (Cu), up to 74% plumbum (Pb); solids were detained at a rate of 87% and hydrocarbons were intercepted at an even higher rate of 90%. It was reported that higher percentage of pollutants were found filtrated through porous asphalt from storm water which contained 99% of suspended solids, 38% phosphorus, 96% zinc and 99% of petroleum hydrocarbons from diesels (Roseen *et al*., 2007).

In Malaysia, porous asphalt was laid primarily to improve traffic safety. In general, Malaysia experience wet and humid tropical climate and subjected to high rainfall intensity throughout the year. Poor drainage system can result in hydroplaning especially for fast moving traffic. Under such circumstances, contact between tire and pavement can be eliminated. This hazardous situation leads to loss of control for braking and steering while driving. According to Hamzah *et al*. (2004), porous asphalt was first initiated on Malaysian road along the

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Cheras-Beranang Road in 1991. Subsequently, numerous patchy applications of the material were currently laid along the North-South Expressway and elsewhere. The use of porous asphalt pavement in Malaysia had resulted in a reduction of the number of accidents and promotes safety to the road users especially during wet weather. However, its service life is somewhat limited due to poor durability compared to conventional dense mix. Clogging is also a major problem that occurred throughout the service life of porous asphalt due to the open nature of the mix itself. Various types of clogging agent that may adversely affect the permeability of mix include tyre wear by-products, dirt, road dust, residual soils deposited from dirty wheels and lorries transporting earth. According to Hamzah *et al.* (2010), the abrasive action of vehicle wheel on pavement surfacing, especially on high stressed areas, can initiate particle loss while the action of water results in stripping. This leads to a pavement distress type known as ravelling and is more predominant in porous asphalt compared to conventional mix.

The national specifications for porous asphalt first appeared in Malaysia in the year 2008 when the Public Works Department (PWD) launched the specifications on specialty mixes that includes porous asphalt. Two porous asphalt gradations, designated as Grading A and Grading B in this study, are specified and they differ in terms of their nominal maximum aggregate sizes, which is 10 mm and 14 mm, respectively. The Malaysian PWD also suggests the use of modified bitumen and polymer additive in 70/100 pen grade bitumen to improve durability. Based on the new specifications, this study was carried out to evaluate the performance of both porous asphalt in the laboratory. In addition, a limiting value on the resistance to disintegration was set to suit typical ambient temperature in Malaysia using a Curve Estimation Regression based on established literature reviews. For precise experimental data interpretation, the General Linear Model (GLM) Univariate through Analysis of Variance (ANOVA) was used to identify whether there was any substantial effects of aggregate grading, bitumen type and bitumen content on the properties of porous asphalt mix. Subsequently, two types of bitumen were incorporated in the preparation of both mixes. Mix performance was quantified in terms of permeability, air voids, abrasion loss, and Indirect Tensile Strength (ITS). From statistical analysis, gradation, binder type, binder contents and the interactions between the factors has a significant effect on the properties of porous asphalt mixes tested.

MATERIALS AND METHODS

Materials: The experimental work involved used of crushed granite aggregates produced by Kuad Quarry Sdn. Bhd in Penang on December 2008. Crushed granites were washed, dried, and sieved into the selected range of sizes according to the Malaysian porous asphalt gradations as shown in Fig. 1. Table 1 shows the basic properties of crushed granite aggregate. The result shows that all aggregate properties satisfy the PWD specifications. Conventional bitumen 60/70 pen grade and PG-76 modified bitumen were used for the whole specimen preparations as well as hydrated lime and ordinary Portland cement as the fillers. The properties of binders are presented in Table 2. Characterization of the materials properties were conducted in the Highway Engineering Laboratory, Universiti Sains Malaysia.

Mixing and compaction temperatures: The mixing and compaction temperatures are dependent on binder viscosity as determined from a Brookfield Viscometer. According to the Asphalt Institute (2007), the ideal mixing and compaction temperatures correspond to conventional binder viscosities of 0.17±0.02 and 0.28±0.03 Pa.s, respectively. However, Yildrim *et al.* (2006) reported that from his study, the ideal mixing and compaction temperatures for modified binder are optimal at viscosity of 0.275±0.03 Pa.s and 0.550±0.06 Pa.s. Figure 2a and b display the viscosity-temperature relationships for both binders. The solid line indicates the graphical plot between viscosity versus temperature, while the

Table 1: Properties of crushed granite aggregate used in this study

Properties	JKR specification requirement	Result	Conform
Abrasion loss	Less than 25%	23.6%	Yes
Aggregate crushing value	Less than 25%	21.5%	Yes
Flakiness index	Less than 25%	21.8%	Yes
Water absorption	Less than 2%	0.7%	Yes
Polished stone value	Not less than 50	51.8	Yes

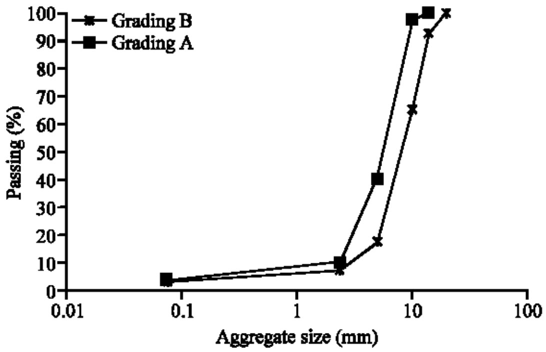

Fig. 1: Aggregate gradations

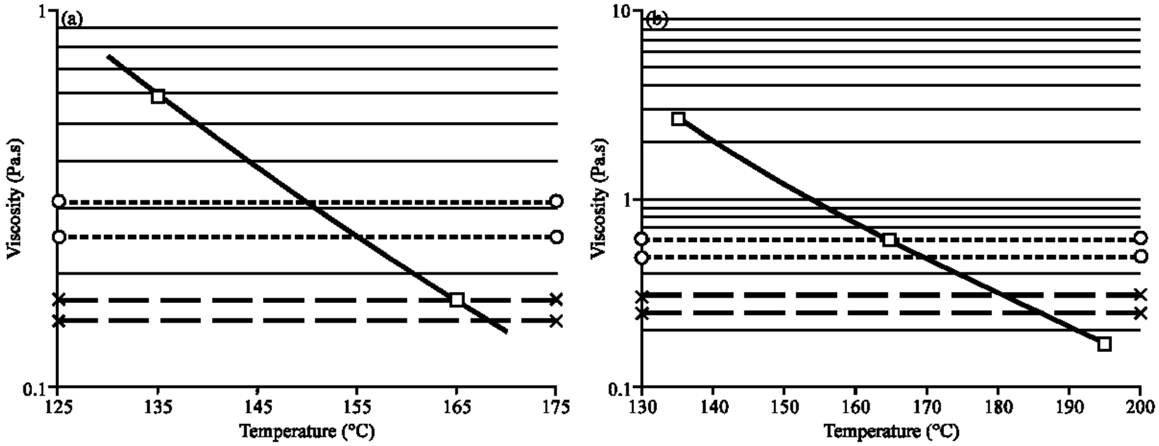

Fig. 2: Temperature and viscosity relationship. (a) 60/70 and (b) PG-76

Table 2: Properties of asphalt binder

	Bitumen	
Basic properties	60/70	PG-76
Specific gravity (g cm^{-3})	1.030	1.024
Penetration at 25°C (x0.1 mm)	63	45
Softening Point (°C)	49	64
Ductility at 25°C (cm)	>100	88.8

Table 3: Mixing and compaction temperatures adopted

	Temperature (°C)	
Type of binder	Mixing	Compaction
60/70	165	155
PG-76	180	170

Table 4: Specimen designation

Gradation type	Binder type	Mix designation
Grading A	60/70	A6
	PG-76	AP
Grading B	60/70	B6
	PG-76	BP

temperature ranges adopted for mixing and compaction are represented by the dashed and dotted line respectively and abbreviated in Table 3.

Specimen preparation: Each specimen comprised of about 1100 g of aggregate batches in addition to asphalt binder. The aggregates and asphalt binder were blended at their corresponding mixing temperatures. The loose hot mixes were conditioned at the compaction temperature for 2 h as recommended by the Asphalt Institute (2007). Compaction followed subsequently by applying 50 blows on each face of the specimen using the standard Marshall hammer. The compacted specimens were then subjected to a series of performance tests. Specimens were designated based on their gradations as shown in Table 4 for ease of reference.

Air voids determination: Prior to the air voids determination, the bulk specific gravity of a compacted mix (G_{mb}) was ascertained using the Specimen Geometry Method (SGM) by measuring its diameter (d), thickness (H) and the mass of the specimen in air (M_a). The theoretical maximum density (G_{mm}) of the loose mix was determined according to ASTM D2041 procedure (ASTM, 2000). Air voids (V_a) in the compacted specimen was calculated by using equations derived from the Asphalt Institute (2007). To ensure the porous asphalt has sufficient permeability, the air voids contents should be greater than 18% (JKR, 2008).

Water permeability test: Hydraulic conductivity is an important property of porous asphalt. The hydraulic conductivity of the compacted specimens was expressed in terms of the coefficient of permeability (k), and determined using a falling head water permeameter. A typical test on asphalt sample cured at ambient temperature involved pouring water into the perspex tube and sealing the orifice with the rubber bung. Once steady state conditions have been reached, the rubber stopper was then removed and the time taken for water to fall between two designated points on the perspex tube was noted. According to Mallick *et al.* (2000), permeability greater than 0.116 cm sec^{-1} (100 m day^{-1}) is recommended to ensure a permeable mix.

Cantabrian test: The Cantabrian test was conducted to determine the abrasion loss property of the mix using the Los Angeles drum without steel balls. A specimen was placed in the drum and rotated for 300 revolutions at 30-33 rpm. The specimen was subjected to abrasion and impact forces during the rotation of the drum. The masses of the specimens before and after the test were recorded. According to Herrington *et al.* (2005), the Cantabrian test

Table 5: Overview on limiting value of abrasion loss at various temperatures

Author	Paper title	Abrasion loss criteria
Colonna (1996)	Design and performance of porous asphalt in the puglia region of Southern Italy	The recommended permitted abrasion loss value for specimens tested at 18, 20, 25°C are 30, 25 and 20% respectively
Huber (2000)	Performance of open graded friction course mixes	A maximum weight loss of 25% is allowed at 20°C
Watson *et al.* (2004)	Laboratory performance of open graded friction course mixtures	A maximum weight loss of 20% is allowed at 25°C

is usually carried out at 25°C in many countries worldwide. This may be particularly true for temperate countries during the hot season. However, for countries in the tropics, the ambient temperature is higher than 25°C and this includes Malaysia. Maintaining the specimen temperature at 25°C throughout the Cantabrian test under local conditions would be an arduous task. Therefore, some adjustments were made and the abrasion loss criteria were carried out to determine the limiting abrasion loss value at a typical Malaysian ambient temperature of about 30°C. Prior to the test, the specimen was conditioned at 30°C for 4 h. To predict the limiting abrasion loss at 30°C, an extrapolation of permitted abrasion loss from the values given in Table 5 was necessary.

Determination of curve model: The best fit model of abrasion loss was established using the Curve Estimation Regression in SPSS 11.5 software. Four basic models have been chosen for comparison, namely linear, logarithmic, power and exponential.

Indirect tensile strength test: The Indirect Tensile Strength (ITS) was used to determine the splitting strength and serves as an indicator of the tensile strength of the mix. In the test, the specimens were subjected to compression load which acted parallel to the vertical diameter plane by using the Marshall testing machine. Kok and Yilmaz (2009) described the failure of the specimen by cracking along a loaded plane where tensile stress loading acts perpendicular to the specimen. Preceding the test, specimens were cured at 25°C in an incubator for 4 h. The test was done in accordance with ASTM D4123 procedure (ASTM, 2005).

RESULTS

Best fit curve model: Table 6 indicates the result of Curve Estimation Regression on linear, logarithmic, power and exponential models. From the graphs plotted, the power model gives the highest coefficient of determination (R squared) with an accuracy of 0.979. Therefore, it was selected as the best curve to determine the limiting abrasion loss value at 30°C.

Figure 3 shows the selected power model relationship of permitted abrasion loss at various temperatures obtained from Colonna (1996). The permitting abrasion loss value at 30°C extrapolated from this curve equals to 16%. Therefore, this value was adopted as the reference point to determine the minimum permissible abrasion loss. The solid line indicates the relationship between abrasion loss and test temperatures. The dashed line represents the reference point for the limiting abrasion loss at 30°C.

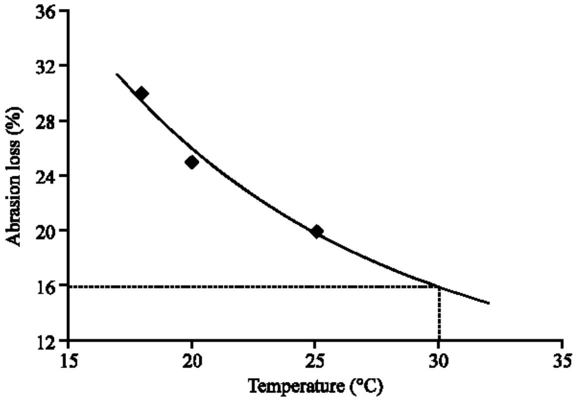

Fig. 3: Abrasion loss limiting value

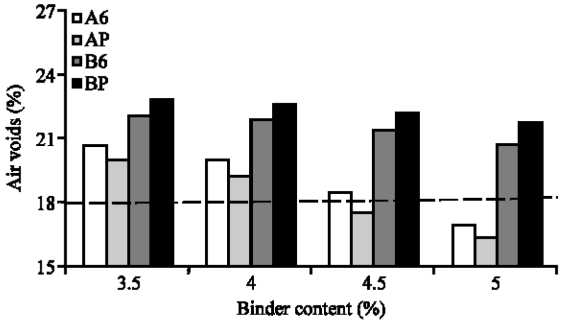

Fig. 4: Air voids results

Air voids: The air voids of both mixes and four different binder contents are estimated based on the bulk specific gravity (G_{mb}) and maximum theoretical density (G_{mm}). Figure 4 shows the typical trend of decrement in air voids as the binder content increases. The air voids of Mix B is higher than Mix A. The air voids for Mix B vary between 20.7 to 22.8% compared to 16.4 to 20.7 % for Mix A.

This is due to the fact that Mix B contains higher Nominal Maximum Aggregate Size (NMAS) which is 14 mm compared to 10 mm in Mix A. Mix A contained almost 20% higher aggregate size passing the 5 mm sieve

Table 6: Curve estimation of abrasion loss values from literature review

Dependent	Model	R^2	d.f	F	Sig.	b0	b1
Abrasion loss	Linear	0.942	1	16.33	0.154	53.2692	-1.3462
Abrasion loss	Logarithmic	0.959	1	23.34	0.130	113.592	-29.1900
Abrasion loss	Power	0.979	1	46.21	0.093	935.039	-1.1978
Abrasion loss	Exponential	0.966	1	28.71	0.117	78.8836	-0.0554

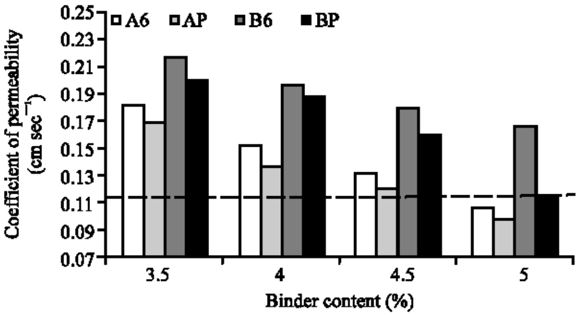

Fig. 5: Permeability test results

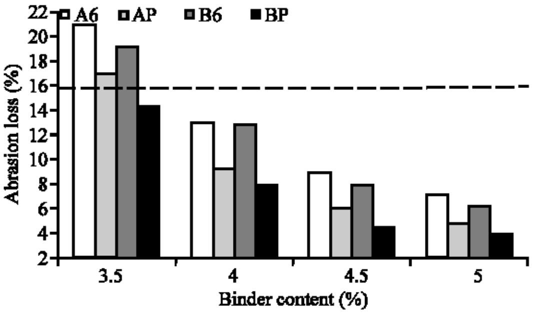

Fig. 6: Abrasion loss results

size compared to Mix B. Air voids is also influenced by the fine aggregate content in the gradation. The minimum recommended air voids is 18% as shown by the horizontal dashed line. Based on this criterion, only Mix B satisfies the criteria for all bitumen contents.

Coefficient of permeability: The effects of permeability on porous asphalt were evaluated for both mixes. The test results are shown in Fig. 5 and the dashed line indicates the recommended coefficient of permeability to ensure good drainage capacity. The result implies that there is a reduction in the coefficient of permeability for both mixes as the binder content increases. Similar pattern of air voids are found for both mixes, whereby Mix B exhibits higher coefficient of permeability compared to Mix A because the former has higher air voids. However, all mixes satisfy the recommended minimum value except for the A6 and AP mixes prepared at 5% binder content.

Abrasion loss: Figure 6 illustrates the results of the Cantabrian test. The recommended permitted abrasion loss at 30°C is indicated by the dashed line. All mixes are found to satisfy the limiting value stipulated in the specifications except for Mix A6, AP and B6 at 3.5% binder content. By comparing the results of both mixes, the results reveal that the abrasion loss of Mix A is higher than Mix B. The use of modified binder increases mix resistance to abrasion loss for both mixes, the corresponding values are 35.2 and 51%, respectively. In addition, the abrasion loss of both mixes reduces as the binder content increases.

Indirect tensile strength: Figure 7 shows the mean ITS of the mixes at different gradings, binder types and bitumen contents. When gradation is taken as the variable, it is clearly seen that the ITS of Mix A is 85.6% higher compared to Mix B. This implies that the higher air voids in Mix B result in reduced contact area between aggregate particles, hence leading to its lowered ITS. However, the use of modified bitumen increases the mean ITS values of both mixes by 18.1%.

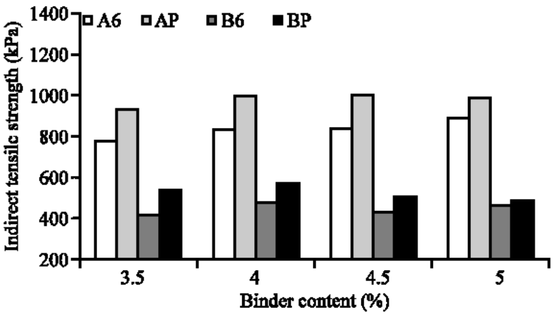

Fig. 7: Indirect tensile strength results

DISCUSSION

General Linear Model (GLM) Univariate analysis was used to identify whether there was any substantial effects of aggregate grading, bitumen types and contents on the properties of porous asphalt mix. GLM Type III Sum of Squares for the range of binder contents from 3.5 to 5% with a confidence level of 95% ($\alpha = 0.05$) was adopted.

Air voids: Table 7 presents the results of GLM analysis which shows the effects of Agregate Grading (GT), Bitumen Type (BT), Binder Contents (BC), and interactions between the factors on the air voids. However, not all factors have significant effects on the air

Table 7: Single and interaction effects on the air voids

Source	Sum of square	df	Mean square	F	p-value
Corrected model	124.685[a]	15	8.312	49.357	<0.001
Intercept	13145.501	1	13145.501	78055.373	<0.001
GT	83.657	1	83.657	496.739	<0.001
BT	0.002	1	0.002	0.013	0.912
BC	28.586	3	9.529	56.580	<0.001
GT×BT	4.852	1	4.852	28.808	<0.001
GT×BC	7.376	3	2.459	14.600	<0.001
BT×BC	0.166	3	0.055	0.328	0.805
GT×BT×BC	0.046	3	0.015	0.091	0.964

[a]R Squared = 0.979; Adjusted R Squared = 0.959

Table 8: Single and interaction effects on the coefficient of permeability

Source	Sum of squares	df	Mean square	F	p-value
Corrected model	0.040[a]	15	0.003	21.572	<0.001
Intercept	0.782	1	0.782	6330.973	<0.001
GT	0.013	1	0.013	108.228	<0.001
BT	0.003	1	0.003	23.078	<0.001
BC	0.022	3	0.007	59.839	<0.001
GT×BT	0.000	1	0.000	2.430	0.139
GT×BC	0.000	3	9.246E-05	0.749	0.539
BT×BC	0.000	3	0.000	0.916	0.455
GT×BT×BC	0.001	3	0.000	1.780	0.192

[a]R Squared = 0.953; Adjusted R Squared = 0.909

Table 9: Single and interaction effects on the abrasion loss

Source	Sum of square	df	Mean square	F	p-value
Corrected model	928.915[a]	15	61.928	35.140	<0.001
Intercept	3208.005	1	3208.005	1820.313	<0.001
GT	5.445	1	5.445	3.090	0.098
BT	75.645	1	75.645	42.923	<0.001
BC	820.785	3	273.595	155.246	<0.001
GT×BT	5.445	1	5.445	3.090	0.098
GT×BC	6.545	3	2.182	1.238	0.329
BT×BC	13.825	3	4.608	2.615	0.087
GT×BT×BC	1.225	3	.408	.232	0.873

[a]R Squared = 0.971; Adjusted R Squared = 0.943

Table 10: Single and interaction effects on the indirect tensile strength

Source	Sum of squares	df	Mean square	F	p-value
Corrected model	1563556.979[a]	15	104237.132	167.647	<0.001
Intercept	15791919.001	1	15791919.001	25398.439	<0.001
GT	1418685.901	1	1418685.901	2281.699	<0.001
BT	106560.361	1	106560.361	171.383	<0.001
BC	12961.904	3	4320.635	6.949	0.003
GT×BT	7756.351	1	7756.351	12.475	0.003
GT×BC	10251.404	3	3417.135	5.496	0.009
BT×BC	6740.984	3	2246.995	3.614	0.036
GT×BT×BC	600.074	3	200.025	.322	0.810

[a]R Squared = 0.994; Adjusted R Squared = 0.988

voids. The factors that seems to have no effects at all on the air voids of porous asphalt are single factor (BT) and interaction factors (BT*BC and GT*BT*BC) which exhibit a p-value greater than 0.05. This implies that the application of different binder types is not significant to improve the air voids of porous mix. The results of this study showed that incorporationg different binder content influence the air voids of porous asphalt mixes. This is similar to the findings of Faghri and Sadd (2002) but there was no statement of statistical significance. Mogawer *et al*. (2002) found that gradation have a significant effect on the air voids of asphalt mixes.

Coefficient of permeability: Table 8 shows the analysis of results corresponding to GT, BT and BC effects on the coefficient of permeability. The results indicate that all the single factors have significant effects but the combination factor shows otherwise. However, there is a strong correlation on the analysis due to higher R squared value of 0.953. It implies that the model fits the data very well. From a study done by Mogawer *et al.* (2002), it was indicated that gradations have significant effects on the permeability of hot mix asphalt mixes. Another study by Faghri and Sadd (2002), reported that the use of different types of binder had increased the permeability of porous asphalt mixes.

Abrasion loss: The GLM analysis was performed on the abrasion loss results as shown in Table 9. The results indicate that the gradation (GT) does not contribute to any substantial effects on the reduction of abrasion loss value for each binder contents. Furthermore, all interaction factors do not give any significant effects on the changes in abrasion loss of porous asphalt mixes tested. However, Nielsen *et al.* (2004) and Watson *et al.* (2003) reported that the use of modified binder had improved the resistance of porous asphalt to particle loss. Suresha *et al.* (2009) states, that binder content has significant effect on the abrasion loss of porous friction courses.

Indirect tensile strength: Table 10 presents the results for the GLM on the ITS results. The results indicate that all the factors are significant in affecting the ITS values, except for the interaction factor of GT×BT×BC which has a p-value (0.81) higher than 0.05. A study done by other researchers had also found that the use of polymer modified bitumen has increased by nearly doubled the strength of open-graded mixes (Faghri and Sadd, 2002).

CONCLUSIONS

This study presents the result of the new Malaysian porous asphalt mixes prepared according to gradations A and B. Generally, Mix B exhibits better performance in terms of permeability, and resistance to abrasion loss compared to Mix A, but the ITS results shows otherwise. The use of modified binder significantly increases the resistance to abrasion loss and ITS of the mixes. The GLM analysis provides a better understanding on which factors that have a significant influence on the performance of porous asphalt. This model can be used as a guide to improve the properties of porous asphalt with consideration to the related factors.

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