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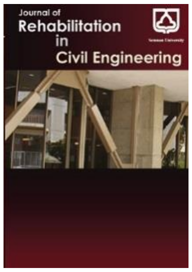

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An Investigation on the Mix Design of Double Layer Porous Asphalts

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ABSTRACT

Porous asphalt (PA) are used to drain water from the surface of the asphalt pavements. It reduces aquaplaning and subsequently decreases splash and spray. Clogging reduces the permeability of PA over the years. The double layer PA are used to mitigate this problem. Different aggregate gradations and binder types can alter the performance of double layer PA. The objective of this research is to evaluate the effects of these parameters on the performance of double layer PA. For this purpose, different samples were fabricated using various aggregate gradations based on Malaysian asphalt mixture standards. Indirect tensile strength, permeability and air voids of the samples were determined. The proposed aggregate gradation for top and bottom layers were mixed with two different asphalt binders. Cantabro and binder drainage tests were later carried out on these samples. The results were then compared with the corresponding results from the Dutch double layer PA gradations. Laboratory test results showed that aggregate gradation significantly affect the indirect tensile strength, permeability and air voids of both top and bottom layer of PA. The design binder content for the bottom layer is also lower than that for the top layer. However, the binder type did not significantly change the design binder content.

1. Introduction

Double layer porous asphalt (DLPA) has two layers with different aggregate gradations. The top layer contain fine aggregates and the bottom layer contains coarse aggregates. The top layer is thinner than the bottom layer. According to the Kandhal (2004), the size

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range of aggregates for the bottom layer is from 16 to 22 mm, while, for the top layer, it is from 5 to 8 mm [1]. This arrangement prepares a condition for preventing clogging during the service life of the porous asphalt. The top layer acts as a barrier to prevent dirt and debris to enter the bottom layer. Hence, this top layer is prone to clogging and it needs a cleaning technique to prevent clogging. The most common type of cleansing machines that exist today operates by spraying high-pressure water into the overlay and then vacuuming out the resulting sludge. Another method is a machine using a high pressure air to loosen the clogging particles and the particles are then vacuumed up. This machine has two air blowers attached on both sides of the pavement and a vacuum in the middle that collects dust and dirt from the pavement. In DLPA, the top layer reduces the tire noise and the bottom layer provides damping mechanism for the sounds. The discharge capacity of bottom layer is higher than that of conventional porous asphalt.

Over the years, different aspects of the performance of DLPA have been studied [2–4]. Some of these researches have focused on the clogging of DLPA. Hamzah et al. (2013) simulated the clogging performance of DLPA and single layer porous asphalts (SLPA) in the laboratory [5]. The clogging resistance of the samples was investigated by different clogging and cleansing cycles. Their results showed that the DLPA have better clogging performance compared to SLPA. Afonso et al. (2020) evaluated the hydraulic properties of DLPA and its clogging behavior [6]. It was found that the clogging materials significantly affect hydraulic performance of PA. Hu et al. (2021) used discrete element method and computational fluid dynamics model to evaluate the clogging development in DLPA [4]. Their results showed significant effects of the climate, air voids, amount of clogging materials and pavement structure on the clogging of DLPA. Xu et al. (2022) studied on the influence of distribution regularity and deposition states of clogging substances on the behaviors of DLPA [7]. The particle gradation of clogging substances showed a significant effect on pore clogging.

In some other researches, the relationship between the DLPA and noise pollution has been studied. Jung et al. (2016) evaluated the influence of DLPA on the noise reduction through site measurement and computer simulation [8]. The result indicated that the DLPA is more useful than noise barriers in reducing the noise for the urban areas. Yuan et al. (2021) reported the highest amount of noise reduction is from DLPA [9]. Kuijpers and van Blokland (2010) modeled the performance of DLPA with a theoretical model and plane wave transfer [10]. It was found that the thinner top layer improves the acoustic performance of roads. Sandberg and Mioduszewski (2018) evaluated the noise properties of a constructed DLPA in Sweden. It was reported that DLPA after 7 years, reached its acoustical end of life [11].

The evaluation of physical and mechanical performance of DLPA fabricated with different materials is another area of research for DLPA. Zhang et al. (2012) used rejuvenation approach to improve the self-healing capability of DLPA and SLPA during their service life [12]. After treatments, SLPA showed higher bending stiffness when compared to DLPA based on the 3-point bending test. Hu et al. (2021) used modified asphalt binders with high viscosity for the design of DLPA [13]. Moisture sensitivity, low temperature properties, air voids content, high temperature properties and permeability coefficient of the samples were evaluated. The binder incorporating 8% crumb rubber showed the best performance for DLPA. Golchin et al. (2022) evaluated the fracture properties of DLPA due to clogging [14]. It was observed that asphalt binder type has significant effects on the fracture resistance of DLPA. Meanwhile, Chen et al. (2023) studied the optimum binder content for DLPA containing styrene butadiene styrene and high viscosity modifiers [15]. The results met the standard requirements for low temperature performance, moisture sensitivity and permeability.

Aggregate gradation plays an important role in the performance of DLPA. Hence, in this study, different aggregate gradations were used to fabricate the top and bottom layer of double layer PA. The properties of these samples were then determined and compared with the samples fabricated by the Dutch aggregate gradation of DLPA. The effects of binder type were also evaluated. This study aims to find the appropriate aggregate gradation and binder type for the fabrication of DLPA.

2. Materials and methods

Figure 1 shows the flow of the research plan implemented in this study. For this purpose, a conventional 60/70 asphalt binder with high-temperature performance grade of 70°C and a polymer modified asphalt binder with high-temperature performance grade of 76°C were used in this study. Table 1 exhibits the properties of the binders used. The aggregate used was locally crushed granite supplied by Kuad Quarry Sdn. Bhd, Malaysia. Physical properties of the aggregate were presented in Table 2. The specific gravity and water absorption of aggregates are shown in Table 3. The absorption of water for each aggregate fraction does not exceed 2% which conforms to the Malaysian PWD specification (2008). The Malaysian PWD is an abbreviation for Public Works Department which is responsible for the construction and maintenance of public infrastructures in Malaysia.

Initially, the Dutch double layer gradations were used to fabricate samples. The Dutch gradations are shown in Figure 2. The top and bottom layer of samples were prepared using 60/70 penetration binder at 6.0% and 4.2% binder contents by weight of total mix, respectively. These samples were then tested for their air voids, permeability and Indirect Tensile Strength. Table 4 shows the properties for top and bottom layer of Dutch double layer PA. These values were used for comparison between Dutch double layer PA and trial gradations.

In the next stage, different gradations were selected for top and bottom layers as shown in Tables 5 and 6. These gradations were divided into sets A, B, C, and D. Each set differed in terms of the percentage of aggregate sizes used. Each set consisted of 3 different gradations. The filler content was restricted to 2% following the PWD standard.

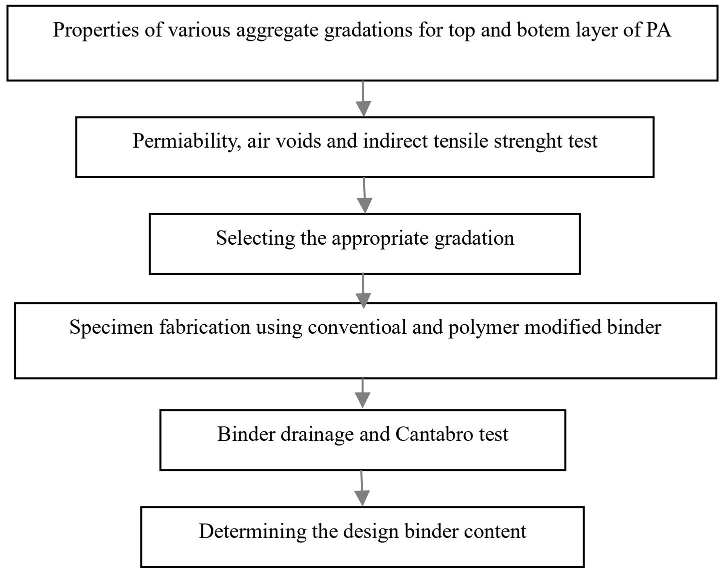

Fig. 1. Research plan used in this study.

Table 1. Properties of binders used according to Malaysian PWD specifications.

Properties	**Binder**			
	Conventional	**Requirement**	**Modified**	**Requirement**
Viscosity (Pa.s) at 135°C	0.594	-	2.65	-
Penetration	63	60-70	48	Not stated
Softening Point (°C)	52	48-56	66	>60
Ductility (cm)	>100	>100	83	Not stated
Specific gravity (gr/cm^3)	1.03	Not stated	1.055	Not stated

Table 2. Physical properties of aggregate used according to Malaysian PWD specifications.

Properties	Value (%)	Requirement
Flakiness Index	18.1	<25
Elongation Index	18.4	Not stated
Aggregate Crushing Value	17.9	<25
Los Angeles Abrasion Value	20.1	<25

Table 3. Water absorption aggregate and specific gravity of aggregate.

Aggregate Size (mm)	Specific Gravity			Water Absorption (%)
	Bulk	SSD	Apparent	
20 – 14	2.623	2.636	2.658	0.504
14 – 10	2.627	2.641	2.664	0.524
10 – 6.3	2.629	2.643	2.667	0.537
6.3 – 3.35	2.633	2.650	2.678	0.643
3.35–1.18	2.639	2.658	2.689	0.706
1.18-0.3	2.649	2.672	2.711	0.872
0.3–0.075	2.679	2.704	2.746	0.918

Table 4. Dutch double layer PA properties.

Mix Properties	Results	
	Top Layer	Under Layer
Air Voids (%)	16.7	24.7
Coefficient of Permeability (cm/s)	0.0971	0.5774
Indirect Tensile Strength (kPa)	746.46	461.83

Table 5. Mix trials (top layer).

Aggregate Size (mm)	% Passing											
	SET A			SET B			SET C			SET D		
	I	II	III	I	II	III	I	II	III	I	II	III
20-14	100	100	100	100	100	100	100	100	100	100	100	100
14 -10	98	98	98	98	98	98	98	98	98	98	98	98
10 – 6.3	-	-	-	-	-	-	60	48	36	60	60	60
10 – 5.0	33	26.4	19.8	33	33	33	-	-	-	-	-	-
6.3 – 3.35	-	-	-	-	-	-	14	14	14	11.2	8.4	5.6
5.0 – 3.35	14	14	14	11.2	8.4	5.6	-	-	-	-	-	-
3.35 – 1.18	12.5	12.5	12.5	10	7.5	5	12.5	12.5	12.5	10	7.5	5.0
1.18 – 0.3	11	11	11	8.8	6.6	4.4	11	11	11	8.8	6.6	4.4
0.3 – 0.075	2	2	2	2	2	2	2	2	2	2	2	2

Table 6. Mix trials (bottom layer).

Aggregate Size (mm)	% Passing					
	SET C			SET D		
	I	II	III	I	II	III
24-20	100	100	100	100	100	100
20 -14	65	65	65	65	65	65
14 -10	17	13.6	20.4	17	17	17
10 – 6.3	12.5	12.5	12.5	10	7.5	15
6.3 – 3.35	11.8	11.8	11.8	9.4	7.1	14.2
3.35 – 1.18	9.5	9.5	9.5	7.6	5.7	11.4
1.18 – 0.3	6.0	6.0	6.0	4.8	3.6	7.2
0.3 – 0.075	2	2	2	2	2	2

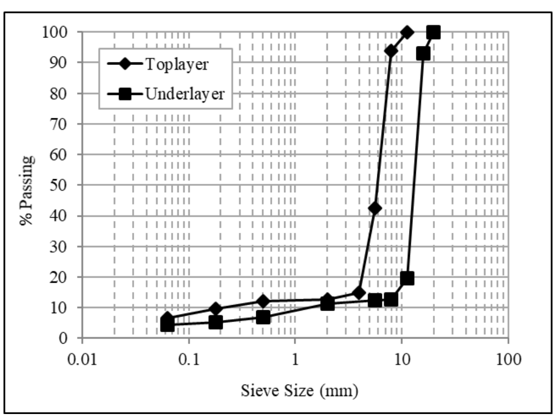

Fig. 2. Dutch double layer PA Gradation [16].

The indirect tensile strength (ITS) and air voids of the samples were determined. The permeability of porous asphalt prepares an environment for water to flow through the pores. A permeability test was used to evaluate this property. There is no standard laboratory equipment for measuring the water permeability of porous asphalt. A new water permeameter was developed in the Laboratory of Universiti Sains Malaysia. The concept of the permeability test involved a perspex tube filled with water and allowing water to flow from one designated point to another point. Meanwhile, the time is recorded. The coefficient of permeability was calculated using the time taken for the water to flow out of the specimen (while still in its compacting mould) from the designated points based on Equation 1. The falling-head permeameter is shown in Figure 3.

$$k = 2.3\frac{\mathrm{aL}}{\mathrm{At}}\log_{10}\left(\frac{h_1}{h_2}\right) \quad (1)$$

Where, a is tube cross sectional area (cm^2) and k is the coefficient of permeability (cm/s). A is the specimen's cross-sectional area (cm^2) and L is the height of samples (cm). While, t is time (s) and h_1, h_2 are initial and final levels (cm).

Fig. 3. Falling-head permeameter.

A hydraulic gradient was created across the specimen that allowed water to flow through the specimen from h_1 to h_2 marked on the stand pipe. The time taken in seconds was recorded as t and corrected to the nearest 0.1s. An average of three readings was taken as the final time to determine the permeability of the specimen. After determining the permeability, the specimen was left to drain out the excess water overnight and extruded to measure the physical dimensions of the specimen.

The ITS test determines the ability of the sample to withstand tensile forces until failure. This test was conducted according to ASTM D4123. Conditioning of the specimens was done at 20°C prior to the test.

The binder drainage test was carried out to ensure that the mixture is not over-filled with bitumen. This test involved placing the loose mixture inside a perforated basket with 3 mm diameter holes inside a heated oven. The empty perforated basket was weighted before hanging it loosely over a metal hook secured in the heated oven for two hours prior to testing. A drainage tray wrapped with pre-weighted aluminum foil, was placed underneath the drainage basket to collect any drained binder during the test. The loose specimens were prepared by mixing the aggregates and bitumen at a temperature that is 10°C higher than the actual mixing temperature. Table 7 shows the adopted temperatures.

Table 7. Binder drainage test and mixing temperatures [17].

Binder	Temperature (˚C)	
	Mixing	Binder drainage test
Conventional	155	165
Modified	170	180

After completing the mixing process, the loose mixture was then transferred to the perforated basket and weighted before hanging it back in the oven. The perforated basket and tray were then taken out of the oven after three hours. The drainage tray was left to cool before recording the mass of binder that had drained on the tray. The drained binder on the tray contained bitumen and filler. The percentage of retained binder (RB) was then calculated using Equation 2.

$$RB = \frac{100B\left[1-\frac{D}{B+F}\right]}{1100+B} \quad (2)$$

Where, D, B and F are mass of binder and filler drained (g), initial mass of binder in the mix (g) and initial mass of filler in the mix (g), respectively. The test results were compared to the PWD specifications (JKR, 2008) to ensure that the maximum allowable binder drainage does not exceed 0.3%.

The abrasion loss was determined by the Cantabro test using the Los Angeles abrasion drum in the absence of steel balls. Sample were placed in the drum and they were rotated for 300 revolutions at 30 to 33 rpm. The samples were conditioned at 25 ℃ (4 hours prior to test). Abrasion and impact forces were subjected to the specimens during the rotation of the drum. As the drum rotated, the steel plate picked up the specimen and dropped it down when it reached the top of the drum thus subjecting the specimen to impact forces. The specimen then rolled within the drum with an abrading action until the steel bar picked up the specimen again and the cycle repeated [18]. The final and initial masses of the samples were recorded. The percentage of abrasion loss is calculated according to Equation 3.

$$AL = \frac{M_1 - M_2}{M_1} \times 100 \quad (3)$$

Where, AL, M_1 and M_2 are abrasion loss (%), initial mass of specimen (g) and final mass of specimen (g), respectively.

3. Results and discussion

Figures 4 to 6 present the average coefficient of permeability, air voids and ITS of the samples. The highest permeability and air voids were obtained by mix Set DIII but it does not necessarily provide the highest ITS values. Therefore, the three properties should be viewed as a whole instead of evaluating the properties separately (see Table 5). Higher air voids can decrease the strength of the asphalt mixtures reflected by ITS values.

The coefficient of permeability, k, was taken as the main factor which determined the selection of the proposed gradation. The permeability of the mix was considered the main concern due to the heavy rainfall received throughout the year in Malaysia and also to provide sufficient permeability during the laboratory clogging test. The k value obtained for Dutch top layer is 0.097 cm/s. Mixes that exhibit higher k values compared to Dutch top layer were considered for the proposed gradation.

As shown in Figure 4, the mixes that exhibit higher k compared to top layer are BII, BIII, DI, DII and DIII with k values of 0.111, 0.149, 0.119, 0.185, and 0.207 cm/s, respectively. The next step was to evaluate the air voids. From Figure 5, the same mixes BII, BIII, DI, DII and DIII generally exhibits air voids comparable to Dutch top layer (16.7%) with 18, 20, 19.4, 21.4, and 23.5% air voids, respectively. As expected, higher air voids exhibit higher k values. Finally, the ITS values were assessed. The ITS values shown in Figure 6 for the Dutch double layer is 746.5 kPa while BII, BIII, DI, DII and DIII registers 688.5, 591.5, 704.1, 577.8, and 459.8 kPa, respectively. Based on the evaluation summarized in Table 8, the best mix for the top layer proposed gradation was DI with k equals to 0.119 cm/s, 19.4% air voids and ITS value 704.1 kPa. This gradation has the highest ITS between BII, BIII, DI, DII and DIII sets.

Even though the ITS of CI, CII and CIII samples are higher than that of DI sample, their k values are smaller than that of DI samples. That is why, they were not selected as a suitable gradation for top layer of DLPA.

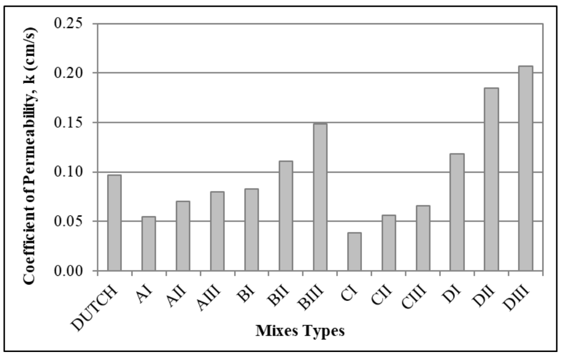

Fig. 4. Permeability of samples for top layer.

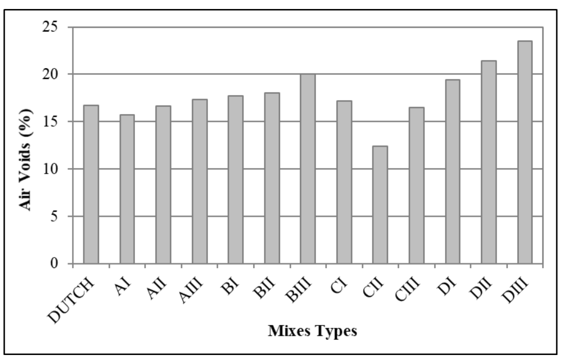

Fig. 5. Air voids of top layer.

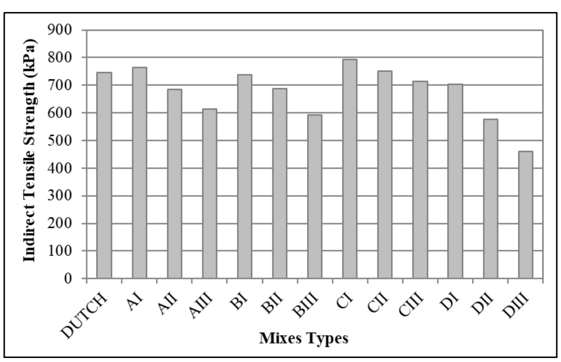

Fig. 6. ITS of top layer.

Table 8. Properties of top layer.

Mix Types (Top)	Coefficient of Permeability, k (cm/s)	Air Voids (%)	ITS (kPa)
DUTCH	0.097	16.7	746.5
AI	0.055	15.7	764.7
AII	0.070	16.6	683.9
AIII	0.080	17.3	613.4
BI	0.083	17.7	737.2
BII	0.111	18.0	688.5
BIII	0.149	20.0	591.5
CI	0.039	17.2	792.5
CII	0.056	12.4	752.0
CIII	0.066	16.5	715.3
DI	0.119	19.4	704.1
DII	0.185	21.4	577.8
DIII	0.207	23.5	459.8

Figures 7 to 9 show the coefficient of permeability, air voids, and ITS results of the bottom layer samples. The Dutch bottom layer recorded 0.577 cm/s, 24.7% and 461.8 kPa for k, air voids and ITS, respectively. Properties evaluation was carried out on SET C and SET D mixes due to the sieve's sizes selected for the top layer proposed gradation. The results show that generally all mixes exhibit lower coefficient of permeability compared to Dutch bottom layer. Similar results were found for air voids. From Table 9, mix DII was evaluated as the best mix for the proposed bottom layer with k, air voids and ITS registering 0.568 cm/s, 24.4% and 532.1 kPa, respectively. The k value is comparable to the Dutch bottom layer and the ITS value is higher than that of Dutch bottom layer.

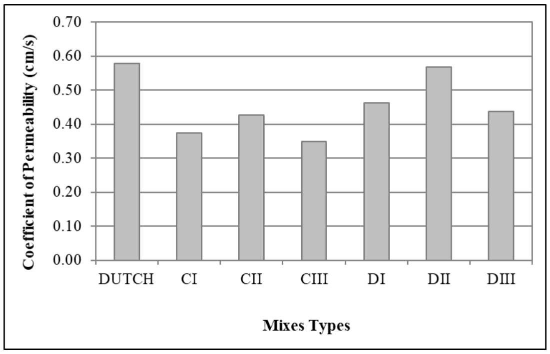

Fig. 7. Permeability of samples for bottom layer.

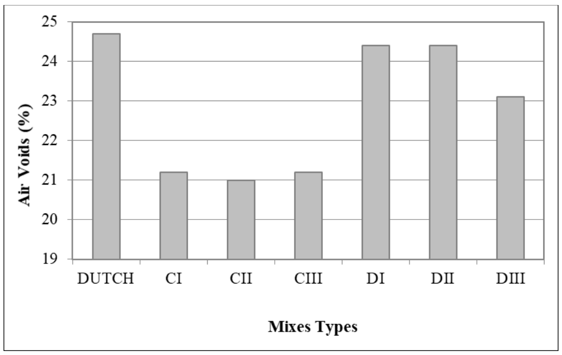

Fig. 8. Air voids of bottom layer.

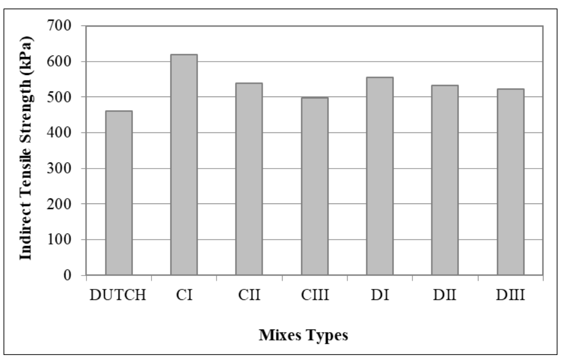

Fig. 9. ITS of bottom layer.

Table 9. Properties of bottom layer.

Mix Types (Bottom)	Coefficient of Permeability, k (cm/s)	Air Voids (%)	ITS (kPa)
DUTCH	0.577	24.7	461.8
CI	0.374	21.2	618.1
CII	0.427	21.0	539.0
CIII	0.350	21.2	498.6
DI	0.463	24.4	556.2
DII	0.568	24.4	532.1
DIII	0.438	23.1	522.4

Based on the evaluation made on the permeability, air voids and ITS of the samples, it was concluded that the proposed top and bottom layer would be DI and DII, respectively. The ITS of top layer is higher than that of bottom layer. Additionally, Golchin et al (2022) reported that the fracture toughness of DLPA for top layer is higher than that for bottom layer [14]. The top layer (DI) also exhibit higher air voids compared to the bottom layer (DII) gradation. This approach is similar to the approach used in previous research [5]. After the selection of the proposed top and bottom layer gradations, design binder content was determined by limiting the minimum and maximum amount of binder using the Cantabro and Binder Drainage Tests, respectively. The design binder content determinations was carried out on top and bottom layer gradations incorporating conventional and modified binders. The mixes are designated in Table 10 for ease of reference.

The relationships between binder drainage and binder content are presented in Figure 10. The data are presented for top and bottom layer that were produced with conventional and modified binders. The binder content that corresponds to the allowable binder drainage of 0.3% of the total mix was taken as the design binder content. T70 and T76 register 8.20% and 8.42%, respectively, while B70 and B76 recorded 4.70% and 4.78% binder drainage. In general, for the binder drainage test, the top layer produced with modified binder exhibits the highest design binder content.

The original Los Angeles Abrasion Loss test was carried out at ambient temperatures of either 18°C or 25°C. The suggested maximum value for abrasion loss was below

35% and it is generally lower than 30% when the test was conducted at 18°C and 25°C [19]. According to Hassan (2011), the ambient temperatures in the tropics, including Malaysia, is higher than 25°C [17]. Maintaining the specimen throughout the Cantabro test for 10 minutes under local conditions would be an arduous task. Therefore, Hassan (2011) carried out an investigation for limiting abrasion loss value at Malaysian ambient temperature (30°C) [17]. It was concluded that the permitting abrasion loss at this temperature is 16%. This value was used in this study as the abrasion loss limiting value for the design binder content criteria.

Figure 11 demonstrates the relationship between binder content and abrasion loss for top and bottom layer made with base and modified bitumen. Generally, the abrasion loss reduces when the binder content increases. The lower limit of binder content that is required to resist 16% abrasion loss are 4.30%, 4.2%, 4.40%, and 4.35% for T70, T76, B70, and B76 mixes, respectively. These values are almost similar to each other. The binder drainage test establishes the upper limit and the abrasion loss test ascertains the lower limit required for the design of the binder content. Conventionally, the design binder content is the average of the minimum and maximum values from the two tests, but for this study, various binder contents within the limiting values were used. The results are shown in Table 11. From the table, the design binder content for the top layer is higher than that for the bottom layer. This is because of the higher amount of fine aggregate (higher surface area) in the top layer compared to the bottom layer. Therefore, more binder is needed to fully coat the finer aggregates.

Table 10. Mix Designations.

Layer type	Asphalt binder	
	Conventional	Modified
Top	T70	T76
Bottom	B70	B76

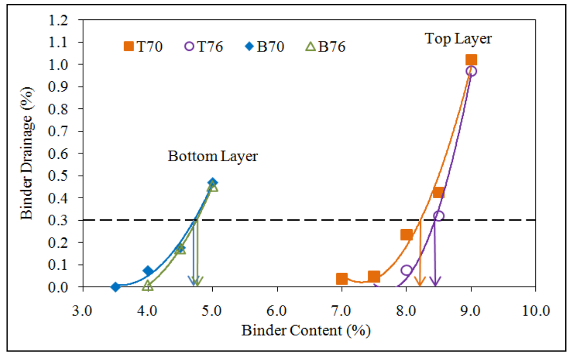

Fig. 10. Binder Drainage versus Binder Content.

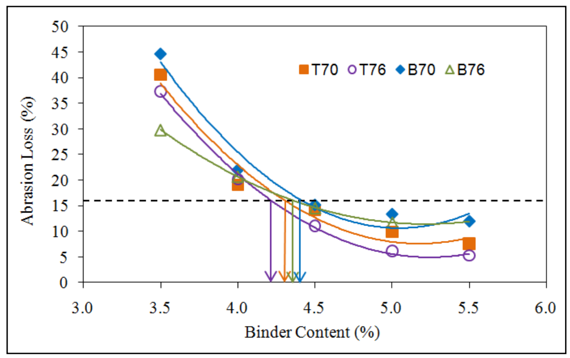

Fig. 11. Abrasion Loss versus Binder Content.

Table 11. Design Binder Content.

Mix type	Conventional binder		Modified binder	
	Min	Max	Min	Max
Top	4.30	8.20	4.21	8.42
Bottom	4.40	4.70	4.35	4.78

4. Conclusion and recommendations

This paper proposed a new gradation, following the Malaysian PWD sieve sizes, for the bottom and top layer of DLPA based on the permeability, ITS and air voids tests. The new gradations were compared with the properties of Dutch double layer PA. According to these evaluations:

- Air voids and coefficient of permeability for mixtures with new proposed aggregate gradation are higher than those with Dutch aggregate gradation.
- The ITS of mixtures for bottom layer with new proposed aggregate gradation is 15.2% higher than that with Dutch aggregate gradation.
- Design binder content for the top layer is higher than that for the bottom layer. This is because of higher amount of fine aggregate in the top layer compared to the bottom layer
- The binder drainage for top layer samples are higher than that of bottom layer.

Since moisture damage is a common type of deterioration in asphalt mixtures [20,21], in future studies, it is recommended to evaluate the performance of DLPA from this view point.

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Conflict of Interest

The authors declare no conflict of interest.

Authors Contribution Statement

First Author: responsible for drafting the initial manuscript and supported the editing and formatting of the manuscript. Second author: conceived the study, designed the methodology, conducted the primary data analysis and was responsible for drafting the initial manuscript. Third and fourth authors: provided expertise in this field, critically revised the manuscript for important intellectual content. They also played a key role in ensuring the quality and consistency of the research data.

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