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LABORATORY SIMULATION OF POROUS ASPHALT PARKING LOT SYSTEM AND MIX DESIGN FOR STORM WATER MANAGEMENT

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Abstract

Porous asphalt pavement was initially developed for the purpose of improving road safety, best candidate material for quiet pavement and to avoid aquaplaning and skidding in wet weather. However, from previous studies, porous asphalt is able to mitigate surface runoff. Porous asphalt parking lots with underlying reservoir course perform as additional temporary water storage matrix that enables reduction of flash flood. This paper elaborates the development of a new porous asphalt aggregate grading design for storm water mitigation using the Nominal Maximum Aggregate Size (NMAS) 20 mm. The properties of the mixes were quantified and evaluated in terms of air voids, permeability, abrasion loss and indirect tensile strength. It was found that the proposed gradation has the best permeability and Indirect Tensile Strength (ITS) values when compacted at 50 blows per face with a standard *Marshal compactor*. The porous asphalt slab was prepared using a slab compactor to simulate porous parking lot paving at site. The porous asphalt slab was finally placed inside a locally fabricated water flow simulator to simulate a porous asphalt pavement system for parking lots.

Keywords: Impermeable surfaces, Parking lot, Mix design, Porous asphalt, Water flow simulator.

1. Introduction

Porous asphalt (PA) is an innovative road surfacing technology which allows water to percolate into the PA pavement. The inter-connected voids inside the PA allowed water to infiltrate through the pavement and is usually laid on an impervious compacted base course. Impervious surfaces, such as roadways, roof

Nomenclatures

A	Cross section area of specimen
a	Cross section area of permeameter tube
D	Specimen diameter
G_{mb}	Bulk specific gravity
G_{mm}	Theoretical maximum density
H	Specimen thickness
h_1	Initial water level marked on permeameter tube
h_2	Final water level marked on permeameter tube
k	Coefficient of permeability
L	Height of specimen
M_a	Mass of specimen in Air
P	Maximum applied load
T	Time taken for water to drop between two designated points
V_a	Air voids in compacted specimen

Abbreviations

ACV	Aggregate Crushing Value
AIV	Aggregate Impact Value
AL	Abrasion Loss
BMP	Best Management Practice
DBC	Design Binder Content
FI	Flakiness Index
ITS	Indirect Tensile Strength
LAAV	Los Angeles Abrasion Value
NMAS	Nominal Maximum Aggregate Size
PA	Porous Asphalt
PSV	Polish Stone Value
SGM	Specimen Geometry Method
TRL	Transportation research Laboratory
WFS	Water Flow Simulator

tops and parking lots resulting storm water runoff and deliver dirt and debris directly into the stream. In turn, the existing impervious surfaces caused ponding water which translates few hours of heavy rain into flash floods. Since the 19th century, most cities of the developed country rely on traditional pipe and open drain network system to mitigate storm water runoff. The captured storm water runoff afterwards distributed to nearby water course and sewer system [1]. Existing impervious surfaces due to urban constructions and implementation of concrete drainage system to provide fast solution for storm water runoff, unfortunately limits the dual purpose of PA. Despite providing spaces or parking and roads, it also served as a storm water storage and infiltration system [2]. Researcher described porous parking lot system as a system that consists of PA over an aggregate base, function as reservoir structure for temporary storm water detention which infiltrate into the existing ground [3]. PA parking lot system proved that the pavement certainly provides green solution to manage storm water runoff.

In the late 1960's, PA was proposed to provide environmentally-sound solution to increase soil percolation, reduce floods, raises water table, replenish aquifers and reduce storm water sewer loads [2]. Since the late 1970s, many additional porous pavement sites have been constructed. PA surfaces were able to capture the initial surface runoff of a rainstorm with high proportions of trash, dirt and debris from entering sewers, subsequently into streams and rivers [4]. Others defined PA as an invention that allows water drain all the way through the pavement structure [5]. A properly designed system will provide a best management practice (BMP) for storm water runoff problems as well as groundwater recharge. Based on the laboratory results from the mixes prepared using the modified gradation, the adopted gradation should fulfil the following criteria for storm water management purposes [2]:

- Air Voids

  Minimum air voids of 16% to 22 % (or greater) [2, 3] is acceptable to assure good permeability of the mix. The volume by dimension must be determined when computing the air voids of PA.

- Binder Content

  Adequate binder content is important for durability of the mix. For NMAS 9.5mm, 5.75% minimum by weight of total mix of binder content is required. For larger NMAS mixes, lower minimum asphalt content is acceptable.

- Draindown

  Generally, 0.3 percent maximum of draindown is permitted to quantify optimum amount of binder that suitable for mixing, transportation and laying process.

This paper highlights the determination of the design binder content (DBC) for porous asphalt slab which was placed in a specially fabricated 400×300 mm water flow simulator's body to simulate porous parking lot system.

2. Materials and Methods

Mineral aggregate constitutes approximately 96% of porous asphalt by weight. The mineral aggregate for porous parking lot is made up of higher percentage of coarse aggregate compared to fine aggregate. Flat and elongated aggregate particles tend to break during mixing, compaction and under traffic loading. Since interlocking of each coarse aggregate particle in porous asphalt is critical, only good quality aggregate with high abrasion value, crushing value and polish value was chosen.

2.1. Materials

Aggregate type granite supplied by Kuad Sdn. Bhd, sited in Bukit Mertajam, Pulau Pinang was used in this study. The aggregates were sieved, washed and dried into selected size fractions according to proposed gradation. Instead of being applied for PA, the aggregates were also set up for other layers in the PA parking lot system. The proposed gradation is shown in Fig. 1 meanwhile the basic properties of crushed granite aggregates are presented in Table 1. All results follow the requirements in Jabatan Kerja Raya (JKR) specifications [6]. Only conventional bitumen 60/70 penetration grade was used throughout the study as well as ordinary Portland cement and hydrated lime as the fillers. Table 2 provides the properties of binder used in this study.

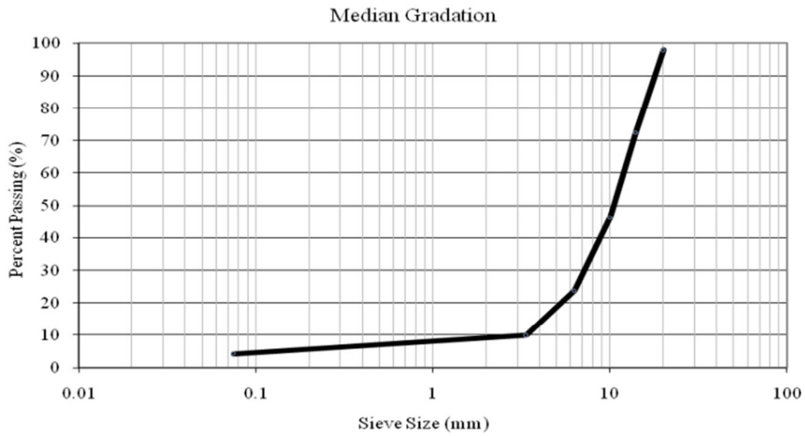

Fig. 1. Proposed Gradation.

Table 1. Properties of Crushed Granite Used in this Study.

Test Properties	Results
Impact Value (AIV)	21.6%
Crushing Value (ACV)	18.9%
Flakiness Index (FI)	19.0%
Polish Stone Value (PSV)	52.2%
Los Angeles Abrasion Value (LAAV)	23.0%

Table 2. Properties of Asphalt Binders (Penetration Grade 60/70 Bitumen).

Test Properties	Results
Penetration at 25°C (×0.1mm)	63
Softening Point (°C)	49
Ductility (cm)	> 100
Specific Gravity	1.035
Density (kg/m^3)	1032

2.2. Methods

2.2.1. Mixing and compaction temperature

Viscosity test was carried out using the Brookfield viscometer according to ASTM D4402 [7] designation at 135°C and 165°C. The temperature opted for viscosity measurements, 135°C and 165°C signify common mixing and compaction temperature range of asphalt mixtures [8]. Three viscosity measurements were made at each temperature. The mixing and compaction temperatures of asphalt mix rely on the viscosity of the asphalt binder used.

According to researcher, the ideal mixing and compaction temperatures correspond to conventional binder dynamic viscosities of 0.170±0.020 and 0.28±0.030 Pa.s respectively [8]. Figure 2 shows the viscosity-temperature relationship for the binder utilised in this study.

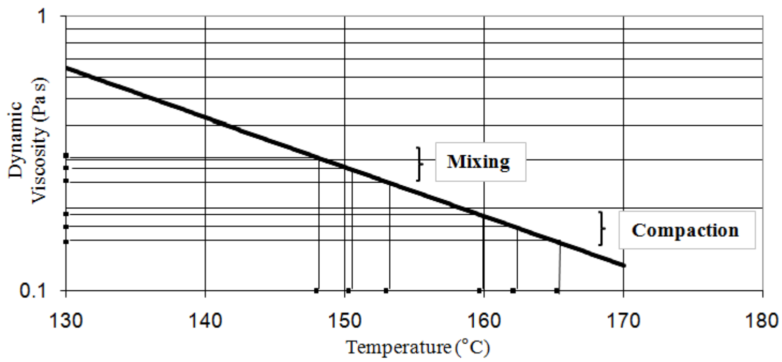

Fig. 2. The 60/70 Pen Bitumen Mixing and Compaction Temperature.

The line with linear correlation indicates the graphical plot between viscosity versus temperature, while the temperature ranges for mixing and compaction were extrapolated to binder viscosities equivalent to 0.170±0.020 and 0.28±0.030 Pa.s, respectively. By adopting current viscosity ranges, the 60/70 pen bitumen's mixing and compaction temperatures range from 160°C to 165°C and 148°C to 153°C.

2.2.2. Preparation of aggregate batch

Aggregates and filler were batched in a high capacity electrically heated vertical paddler mixer with large capacity. PA slab preparation required approximately 16 kg of aggregates and filler. While, each batch weighted 1100 gram was prepared for single Marshall sample preparation. The aggregates were batched according to the proposed gradation.

2.2.3. PA sample preparation

Two types of PA samples were prepared, namely cylindrical and slab. The cylindrical samples were prepared according to the Marshall method. The samples were used to determine the DBC and performance evaluation. The slab compactor was used to produce rectangular slab that was placed inside the WFS's body to simulate the uppermost layer of porous parking lot layers.

2.2.4. Mixing and compaction

Prior to the mixing process, the electrically heated vertical paddle mixer was first set to the required mixing temperature. The oven dried aggregates were fed into the mixture container and mixed dry for 30 seconds to ensure uniformity and homogeneity of the aggregate blend. Subsequently, the exact quantity of bitumen was poured onto the aggregate blended and the mixing was continued until the aggregate were uniformly coated with bitumen. The entire mixing process took approximately 2 minutes to accomplish. Next, the loose hot mix was placed onto a clean tray and conditioned in an oven at the compaction temperature (153°C) for 2 hours as recommended by Asphalt Institute [8]. After conditioning, the hot mix was transferred onto the hot Marshall moulds via a metal chute. Once the compaction temperature was reached, specimen was subjected to 50 blows per face. The compacted samples were allowed to cool at room temperature overnight and extruded for further testing except for those subjected to permeability test.

2.2.5. Air voids determination

Determination of air voids content requires bulk specific gravity of compacted mix (G_{mb}) which was determined based on specimen geometry in air (M_a). The G_{mb} of the mixture was determined using Specimen Geometry Method (SGM) based on Eq. (1)

$$G_{mb} = 4M_a/\pi d^2 h \tag{1}$$

where M_a: Mass of specimen in air (g), d: Diameter of specimen (cm), and h: Height of specimen (cm)

Meanwhile, the theoretical maximum density (G_{mm}) of the loose mix was determined using the Rice Method according to ASTM D2041/D2041M [9] procedure. The air voids in compacted specimen (V_a) calculated corresponds to the G_{mb} and G_{mm} as shown in Eq. (2)

$$V_a = 100\{1-(G_{mb}/G_{mm})\} \tag{2}$$

where V_a: Mass of specimen in air (g), G_{mb}: Bulk specific gravity, and G_{mm}: Theoretical maximum density (g/cm^3).

2.2.6. Water permeability test

Coefficient of permeability (k) of the mixes was determined using a falling head water permeameter. The k value represents the hydraulic conductivity of the compacted specimens. The asphalt sample was cured at ambient temperature. The water was poured into the acrylic perspex tube with two designated points after sealing the orifices with the rubber bung. The rubber lining prevented water from leaking through the base. The time taken for water to fall between two designated points on the acrylic perspex tube was recorded. Permeability greater than 0.116 cm sec^{-1} is recommended to ensure significant percolation of water through the PA [10]. The coefficient of permeability was computed using Eq. (3)

$$k = \frac{aL}{At} \ln \frac{h_1}{h_2} \tag{3}$$

where k: Coefficient of permeability (cm/s), A: Cross section area of specimen (cm^2), a: Cross section area of permeameter tube (cm^2), L: Height of specimens (cm), T: Time taken for water to drop between two designated points (s), h_1:

Initial water level marked on permeameter tube, and h_2: Final water level marked on permeameter tube.

2.2.7. Indirect tensile strength (ITS) test

The ITS test was carried out based on ASTM D6931 [11] procedure. The method was applied to develop tensile stresses along the diametral axis of a test specimen. When the test was conducted, the specimen between two diametrically opposed, arc shape rigid platen was subjected to a compressive load. The compacted specimens were loaded diametrically at the rate of 50.8 mm/min along and parallel to their vertical diametric planes which eventually force the specimens to split or crack as shown in Fig. 3. Prior to the test, the specimen was cured at 20°C in an incubator for 4 hours. The specimen dimensions and peak load (recorded load at failure, P) were used to calculate the indirect tensile strength (failure strength) of the specimen using Eq. (4)

$$\text{ITS} = 2000\, P/\, \pi\, h\, D \tag{4}$$

where P: Maximum applied load (N), H: Specimen thickness (mm), and D: Specimen diameter (mm)

Fig. 3. Crack Pattern on ITS Specimen.

2.2.8. Los Angeles abrasion value

The Cantabro test was carried out to determine the abrasion loss of the specimen. The sample inside Los Angeles abrasion drum was subjected to 300 drum rotations at a speed of 30 to 33 rotations per minute without the abrasive charge of steel spheres at ambient temperature. The abrasion loss was expressed in terms of the percentage mass loss compared to the original mass as illustrated in Eq. (5)

$$\text{AL} = \frac{M_1 - M_2}{M_1} \times 100 \tag{5}$$

where AL: Abrasion Loss (%), M_1: Initial specimen mass (g), M_2: Final specimen mass (g).

2.2.9. Binder drainage test

The binder drainage test was conducted following closely the Transportation Research Laboratory (TRL) procedure and used to determine the upper limit of the DBC for PA mix [12]. The perforated baskets with trays were initially heated in an oven for at least 2 hours before testing begun. A 1.1 kg of loose mix was transferred into a perforated basket without any loses. The perforated baskets contain loose mix were then conveniently being hung over a pre weighted tray (wrapped with aluminium foil) in an oven at the maximum mixing temperature for 3 hours. At the end of the test, the mass of the drained binder was determined after the tray had cooled down. The loose mix was prepared at 10°C lower than the normal mixing temperature. The binder drainage test temperature was carried out at 163°C. The Malaysian Public Works Department specifications [6] specified maximum allowable binder drainage at 0.3%.

3. Results and Discussion

3.1. Selection of porous asphalt gradation

In most porous asphalt pavements for stormwater management, a 9.5 mm NMAS is used for the surface layer [2]. However, it is reported that larger NMAS mixes have been utilised for the same objective. A new generation of mix designs used 12.5 and 16 mm NMAS instead of 9.5 mm [13]. New mix specifications are producing mixtures with higher level of air voids, larger pore sizes and longer durability [13]. The larger aggregate size was proposed since it resulted in higher air voids which are less susceptible to clogging and allowed rapid water percolation.

This study aimed to adapt NMAS 20 mm aggregate into a gradation used for porous asphalt pavement layer for storm water mitigation purpose. In addition, the Urban Stormwater Management Manual for Malaysia [14] also suggested NMAS 20 mm aggregate for storm water management purposes. This study proposed a new gradation; a median gradation of six different gradations which adapted NMAS larger than 9.5 mm. The gradation proposed was based on the median gradation of six randomly selected established PA gradations as shown in Fig. 4.

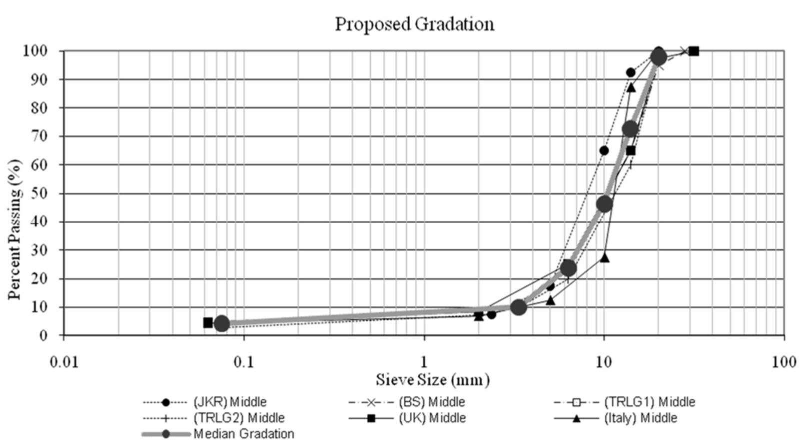

Fig. 4. The Proposed Gradation (Median Gradation).

Figure 4 illustrates selected gradations with the proposed median gradation. With proper design, porous asphalt which has larger open space between interlocking aggregate skeleton provides more air voids, thus enable shorter duration for water to percolate through the porous pavement. However, the drainage function only can be attained by the prevalence of interconnected air voids. Sufficient connected air voids in porous asphalt mixtures is vital to ensure the water can permeate through the air voids to achieve the drainage function. Other factors affecting air voids include bitumen content, aggregate shape and aggregate gradation.

3.2. Design binder content (DBC)

3.2.1. Binder drainage

One of the common set back related to porous asphalt mix is drainage of binder from the aggregate due to excessive bitumen content used during mixing or low viscosity of bitumen content. Bitumen content used must be just enough to prevent excessive binder drainage occurring during mixing process, transporting and laying. The coarser the aggregate gradation, the drain down probability of asphalt bitumen during mixture design and field production is greater [10]. Binder drain down causes binder content variations in an asphalt mix. Ravelling easily took place in areas deficient in bitumen content meanwhile too much bitumen content causes permeability loss. This result of this study should comply to requirements for draindown, which is 0.3% maximum draindown [2, 6]. The mixes were prepared at 155°C and tested at 10°C higher than the mixing temperature. The binder drainage test results are shown in Table 3 and correspond to the upper limit of the DBC. The results showed that more binder drainage took place as the binder content increase. Meanwhile, Fig. 5 shows the correlation between retained binder and mixed binder in determining the upper limit of the DBC.

The results show that the retain binder is linearly correlated to the mixed binder content at lower bitumen contents. However, at binder contents exceeding 4.5%, the relationship diverge from the linear line but the amount of retained binder continues to increase until 5.5% binder content, beyond which point the amount of retained binder reduces. The binder drainage test was carried out to determine the maximum permissible binder content for specimen. For design purposes, the upper limit of the DBC adopted the target binder content which is 0.3% less than the optimum mixed binder content. From Fig. 3, the target binder content is 5.2%.

Table 3. Binder Draindown Test Results.

Bitumen Content(%)	Binder Drained (g)	Retained Binder%
3	0	3
3.5	0	3.5
4	0.6	4
4.5	0.8	4.5
5	4.5	4.9
5.5	11.3	5.2
6	33.9	4.9
6.5	54.5	4.6

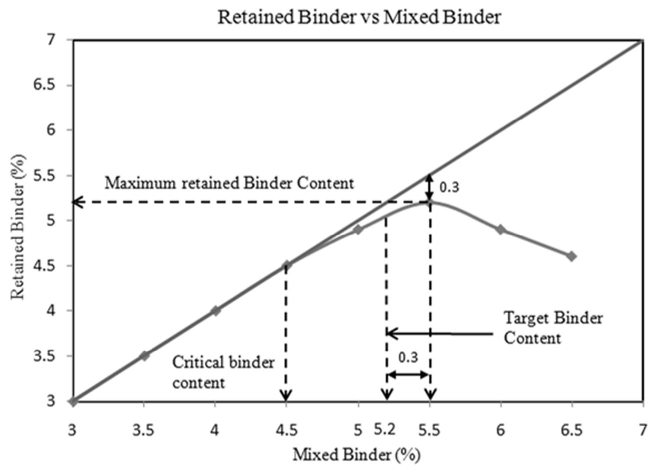

Fig. 5. Relationship between Retained Binder and Mix Binder Content.

3.2.2. Abrasion resistance

A previous study recommended maximum permitted abrasion loss value for compacted specimens tested at 18°C, 20°C, 25°C equal to 30%, 25% and 20%, respectively [15]. To determine the minimum permissible abrasion loss, the relationship between abrasion loss and temperature has been established. A power model relationship to correlate permitted abrasion loss at various temperatures was established [16]. The curve estimation regression using SPSS 11.5 proved that the power model was the best curve to determine limiting abrasion loss value at ambient temperature. The typical Malaysian ambient temperature was about 30°C [16]. The permitted abrasion loss value at 30°C was determined by extrapolating abrasion loss versus temperature curve. Figure 6 shows relationship between abrasion loss versus temperature as suggested by previous study [15]. From the graphical relationship shown, the permitting abrasion loss value at 30°C extrapolated from the graph equals to 16%. This value corresponds to the permitted abrasion loss adopted to determine the lower limit of the design binder content. The relationship between the abrasion loss and the binder content for mixes prepared with 60/70 penetration bitumen is shown in Fig. 7.

The specimen abrasion loss decreases from 61.1% to 10.6% when the binder content increases from 3% to 5%. The test results indicate that at lower range of bitumen content, the mixes are more prone to disintegration. At higher binder content, more cohesion is established between the aggregate particles, thus reducing mix disintegration. Generally, the resistance of disintegration is assessed in term of its abrasion loss. The graph shows that the aggregate particles disintegration gradually as the binder content increases. As presented in Fig. 7, more binder content shows less abrasion loss percentages, since there is more binder to strongly bind the aggregate particles together. By adopting 16 % abrasion loss, the lower limit of the DBC is set at 4.1%. Therefore, the DBC of the PA mix tested ranges from 4.1% to 5.2%.

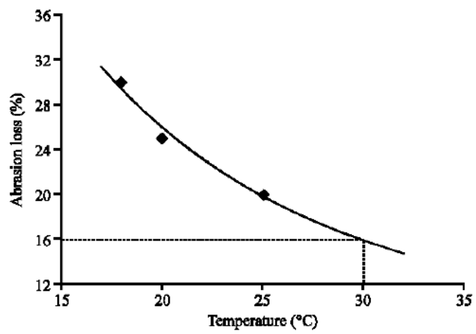

Fig. 6. Abrasion Loss Limiting Value [16].

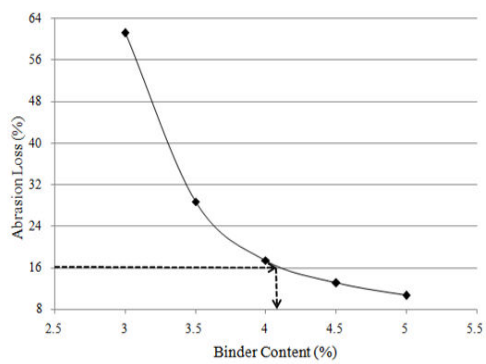

Fig. 7. Abrasion Loss and Binder Content Relationship.

3.3. Performance tests

The main purpose of PA mix design is to determine suitable binder content for PA slab preparation. The slab was prepared at median binder content using slab compactor to simulate PA parking lot system at site. The slab was finally placed inside the locally fabricated water flow simulator to simulate the system. However, a simple performance tests at minimum, median and maximum binder content were carried out using a Marshall sample to assess binder content relationship to air voids, coefficient of permeability and ITS values. Three binder contents were evaluated, 4.1%, 4.65% and 5.2%. Figs. 8 (a) to (c) show the results obtained.

The voids content of the mixes evaluated are shown in Fig. 8(a). It is found that the mixes made with NMAS 20 mm has air voids more than 16% at all binder contents. Higher binder content used allows more voids filled with asphalt, thus lower the voids content. This effect can be explained by the fact that the excess bitumen replaced the air voids and clogged some of the interconnected pores.

Figure 8(b) shows the permeability results of all mixes tested. The values computed show a reduction in coefficient of permeability as the binder content increases. At maximum binder content, the *k* reduces by 40.5% as compared to the k of mixes at the minimum binder content. When specimens were prepared at very high binder contents, the binder effectively seals off a greater percentage of interconnected air voids, which in turn produce sample with low permeability. The increased binder content has reduces the air voids, thus resulting in lower permeability. The size of the voids, whether or not the voids are interconnected, and the access of the voids to the surface of the pavement, affects the coefficient of permeability.

Theoretically, with increasing air voids, the ITS is expected to reduce. Despite, the ITS results varies for other reason such as binder content (refer to Fig. 8(c)). It is anticipated that with increasing binder content, the ITS values will increase. Commonly, the cohesion of the mix increases with increasing binder content, up to a certain point. The relationship shows that ITS values increase from 4.10% to 4.65% binder content. However, at 5.2% binder content, the value decreases due to too thick bitumen film coating aggregate particles resulting in loss on inter-particle friction.

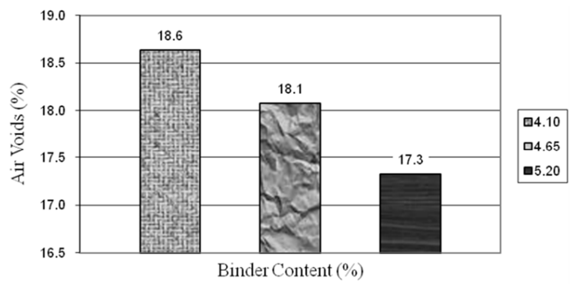

Fig. 8 (a). Air Voids and Binder Content Relationship.

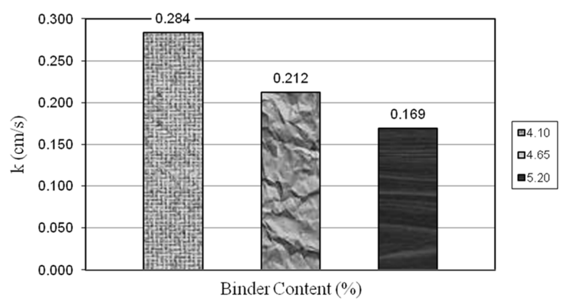

Fig. 8 (b). Coefficient of Permeability, *k* and Binder Content Relationship.

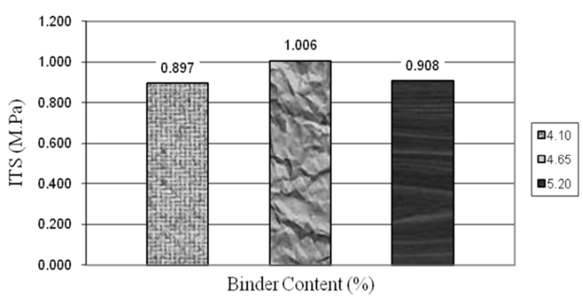

Fig. 8 (c). The ITS and Binder Content Relationship.

It indicates that more binder content increases the roll of binder to sustain loading capacity of the sample. Asphalt binder contributes to approximately 15% of the structural bearing capacity. Therefore, more binder content can increase the structural bearing capacity of the sample. In this regard, by increasing binder content, ITS values as a parameter to evaluate a structural capacity of the mixes increase because more cementitious material present to bind aggregate particles together. Thicker bitumen film thickness will prolong mix service life as the binder do not age and harden as rapid as thin ones do.

The ITS value and stability of the specimen depends mainly on the aggregate interlock and the cohesion of the binding agent. Internal friction of aggregate particles depends on aggregate shape and surface texture. The more angular the shape of the particle, the higher stability of the mix since rough surface texture provides stronger internal friction between the aggregate matrix.

4. Simulation of Porous Asphalt Parking Lot System

The study also aimed at simulating PA parking lot system into a laboratory scale approach using locally fabricated WFS. The top layer was simulated by introducing a 75 mm thick slab. A total mass of 16.4 kg of aggregates and filler was required to prepare the medium. The slab was prepared with 4.65% binder content. The thickness of the slab complied to the minimum compacted PA thickness (63.5 mm) suggested by the guideline [2]. The length and width (395×295 mm) of the slab were slightly smaller than the WFS' body inner dimensions to facilitate proper placing of the slab. Figure 9 depicts the slab that was laid just above the choker course. The installation of the slab can be seen clearly in Fig. 10.

Fig. 9. Porous Asphalt Slab.

Fig. 10. Assembly of the Slab inside Water Flow Simulator's Body.

Slab properties

To simulate the action of a field roller compactor, the slab was compacted using a locally fabricated slab compactor. The slab compactor was able to simulate the action of a field roller compactor. A field permeameter as shown in Fig. 11 was used to determine slab permeability, fabricated according to the pioneering design by previous study [17].

Fig. 11. Field Permeameter.

The results showed that the porous asphalt slab (75×400×300 mm) prepared with 4.65% binder content has 20.6% air voids and coefficient of permeability, k equals to 2.633 cm/s. The results recorded were higher in comparison with the air void contents and k value obtained from Marshall samples with the same binder content which is 0.212 cm/s and 18.1% respectively. The higher air voids is due to different compaction mode used, kneading versus impact mode for slab and Marshall samples respectively. In addition, the slab permits water to flow both horizontal and vertical. Meanwhile, the Marshall sample is confined so water permeates through the sample unidirectional. At 4.65% binder content, the properties of the Marshall samples using median gradation comprises of 7.5% abrasion loss and Indirect Tensile stress (ITS) value of 1006 kPa. The stability and flow of marshal sample at mean binder content were 5810 kN (with 0.83 correction factor) and 3.55 mm respectively. The stability value recorded exceed the minimum stability of 5340 N, meanwhile the flow obtained fall within 2.0 to 4.0 mm range [18].

5. Conclusions

This paper presented the method adopted for PA mix design. A new gradation with NMAS 20 mm was proposed for storm water runoff mitigation measure. The design procedures included the determination of the gradations from a few established gradations. The simple performance tests for the proposed gradation were carried out at various binder contents. The design binder content for median gradation ranges from 4.1% to 5.2%. The PA slab was prepared at mean binder content to simulate PA porous parking lot systems in laboratory scale inside a water flow simulator. The stability and flow of PA are in accordance with the proposed guidelines by UNHSC [18]. Detailed elaboration on the advantages of this technique and maintenance required can be referred to previous publications on water flow simulator [19, 20].

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