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APPLICATION OF PACKING THEORY ON GRADING DESIGN FOR POROUS ASPHALT MIXTURES

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ABSTRACT

The design life of porous asphalt is shorter than dense mix as a consequence of permeability loss due to clogging and poor resistance to disintegration. To mitigate problems associated with clogging, double layer porous asphalt has been constructed in the Netherlands. This paper investigated a development of a new grading design for porous asphalt by varying percentage of aggregate with maximum sizes of 20, 14 and 10mm; a theory of packing was used. The most common method used for grading design is based on empirical, which does not relate the packing behaviour of the aggregate mass. The packing theory used in this study was facilitated by a vibratory compactor. It was found that mixtures containing aggregate sizes 14 and 10mm have a good permeability and stability, when vibrated for 65 second with a frequency of 40Hz, while for aggregates containing 20mm, to achieve the requirement for Marshall stability, the gradation needs to be modified. Properties of porous asphalt based on packing theory are better from the empirical grading from Spain (P-12).

Keywords: Grading design, porous asphalt, porosity, permeability, stability.

INTRODUCTION

Porous asphalt is an innovative road surfacing technology, which allows water to enter into the asphalt mix through its continuous air voids. It is used in wearing course and always laid on an impervious base course. It is promising and proofs effective in enhancing traffic safety in rainy weather, reducing hydroplaning tendencies and having good skid resistance properties at higher speed. Porous asphalt is also used to reduce noises and glare at night and on wet surfaces. In addition it also has good resistance to permanent deformation.

Two prime factors affecting the performance of porous asphalt are permeability loss and poor resistance to disintegration. Apart from traffic loading, those factors appear to be affected by the maximum aggregate size, aggregate gradation, binder type and content. In general, higher coarse aggregate content implicates higher porosity and permeability but a reduction in strength and durability.

According to investigation of actual condition about porous asphalt pavement in Japan [1], and also some other countries, it has many problems, such as drainage and scattering.

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The biggest problem facing the existing single layer porous asphalt (conventional porous pavement) is a drainage function falls. This phenomenon is caused by clogging of road dust, coming-flying dust and by consolidation of air void. To mitigate problems associated with clogging, double layer porous asphalt has been constructed in the Netherlands [2]. The structure of conventional and double layers porous asphalt is shown in Figure 1.

Figure 1. The difference between conventional and double layer porous asphalt

This research focuses on the development of porous asphalt aggregate gradation with varying maximum aggregate sizes by determining the proportion of aggregate fractions that gives rise to minimum dry aggregate porosity using a dry aggregate vibratory compactor. Modification from this minimum void gradation will be made if it does not meet the target mix porosity and permeability.

The main objective of this research is to develop suitable combinations of aggregate gradation for porous asphalt based on packing theory.

Empirical grading for porous asphalt from Spain (P-12) is used in this investigation as comparison.

AGGREGATE GRADING DESIGN BY PACKING METHODS

Packing can be defined as the arrangement of the particles which fit together to fill voids. The shape of particles, which in turn influence porosity of the mix, influences the mode of packing. Grading of aggregate is also an important factor, which controls the void content in the mixture.

Many experimental studies have been made with mixtures of two or more particle sizes to obtain minimum void, mainly by using smaller particles. Curves showing minimum voids in the system against percentage of the larger size fraction for a number of size ratio is produced [3].

A porous asphalt aggregate grading consists predominantly of coarse aggregate. The fine aggregate fractions are added so as not to bulk or interfere with the interlock of the coarse aggregate matrix but to leave enough voids to maintain a pervious structure. Aljarallah et al. [3], developed the packing volume concept (Vp) which defined packing volume as the volume which a rock particle occupies in mass of one-size (mono-volume) particles. The packing volume encompasses not only the surface capillaries (micro surface voids) but also the volume of surface macro dips and valleys (macro surface voids).

POROUS ASPHALT

Porous asphalt surface course is distinguished by the fact that there is hardly any aquaplaning, the formation of spraying water and the danger of glaring is essentially reduced, and driving on porous asphalt is sensed as comfortable. In the United States of America (USA), the Federal Highway Administration (FHWA) prefers to use the term “open-graded asphalt friction course” (OGFC), while the Federal Aviation Administration used the term “porous friction course" when referring to pavement surfacing made from this material.

The Spanish gradation limits designed as P-12 is given in Table 1. When prepared at binder contents ranging 4 to 5%, the mix porosity of the PA mixes is in excess of 20% [4].

Table 1. The Spanish gradation limits

Gradations	Cumulative percentage passing on sieve sizes (mm)						
	20	12.5	10	5.0	2.5	0.63	0.075
P-12	100	75-100	60-90	32-50	10-18	6-12	3-6

Properties of porous asphalt

Properties commonly measured include voids in mix, Marshall stability and permeability. These properties are influenced by gradation; maximum aggregate particle and bitumen content.

1) Porosity

To a large extent, porosity or void content determines the mix permeability. In porous asphalt, the quantity and gradation of coarse aggregate determines porosity, hence permeability. In general, increasing the proportion of the coarse mineral aggregate and reducing the amount of fine aggregate fraction can increase porosity [5]. An initial porosity suggested by Kandhal et al [6] was at least 25%, Van Heystraten [7] and Jimenes [8] both suggested 20%.

2) Permeability

Permeability is an important engineering property of a bituminous mix. It indicates the degree of void interconnection to form capillary channels that allows the passage of a permeate. The coefficients of permeability (k), in units of cm/s, reported by a number of researchers differ greatly. Average k values of 0.16-0.41cm/s are reported in references [9-11]. Permeability loss is imminent when voids close up. Increasing the binder content reduces permeability since the excess binder replaced the air voids.

3) Marshall stability

In porous asphalt, the source of stability is aggregate interlock enhanced by the coarse aggregate. Generally, Marshall stability values for porous asphalt are significantly lower than that of dense asphalt. Marshall stability increases, as the gradation becomes less open graded by incorporating more fines [5].

METHODOLOGY

There are three stages of gradation selection, namely; determination of material properties; minimum dry porosity of aggregate, and porous asphalt mixture properties (porosity, permeability and Marshall stability). The mixtures are made with various maximum aggregate sizes, 20, 14 and 10mm. Empirical grading for porous asphalt from Spain (P-12) was used in this investigation as comparison.

Bitumen penetration grade 60/70 supplied by Shell Malaysia is used as a binder. Crushed aggregates supplied by Kuad Bhd Quarry are used in this investigation. The aggregates are washed, dried and sieved in to their respective size range or "fractions" as shown in Table 2. Coarse aggregate is defined as material retained on the 3.35mm sieve. The combination of hydrated lime and Portland cement is used as filler.

Table 2. Aggregate sizes ranges and fractions used

Sieve (mm)	20-14	14-10	10-5	5-3.35	3.35-0.425	0.425-0.075
Fractions (%)	A	B	C	D	E	F

Dry aggregate compaction

To assess the packing behavior of the aggregates used, a vibratory compaction is utilized. The vibratory compactor is a vibrating table. A 4kg steel cylinder surcharge was placed on top of the sample to achieve a uniform compacted surface. After preliminary trials, a compaction time of 65 second and frequency 40 Hz are chosen as an optimum time and vibrating frequency.

The laboratory process consisted of weighing the blend of fractions A plus xB (x varied in steps of 10%) aggregate fraction, mixing the aggregates in a bowl and pouring them into the Marshall mould from constant height. After placing the surcharge on top of the aggregate specimen in mould, the compactor is switched on for 65 second and frequency 40 Hz, after which the height of the sample at three equally spaced points is recorded to the nearest 0.01mm. The results used for the design are the average of two tests. The total weight of aggregate used in this investigation is 1000 grams. The proportion between A and B is determined by minimum dry aggregate porosity. The blend AB is the balanced proportion between aggregate fractions A and B for the next step, blend AB then becomes a new coarser component into which the next finer component C is added incrementally to result in a new minimum dry aggregate porosity mix AB, C. Next, fraction D is added to ABC as the above steps.

Mix ABC,D represents the blend that gives the minimum dry aggregate porosity of the ABCD aggregate matrix. If this matrix is then considered to be a stable matrix which will provide strength and resistance to deformation, the next step is to vary the fine aggregate grading in order to achieve a target porosity that is considered suitable for pervious mix. The final fine aggregate size E is obtained by combining mix ABCD starting with 0%, 5%, 10%, and 15% of fraction E. Knowing the target porosity, the various aggregate grading can be obtained. The method enables the design of grading with any desired porosity when the dry aggregate porosity of the coarse aggregate matrix is at its minimum, as shown in Figure 2.

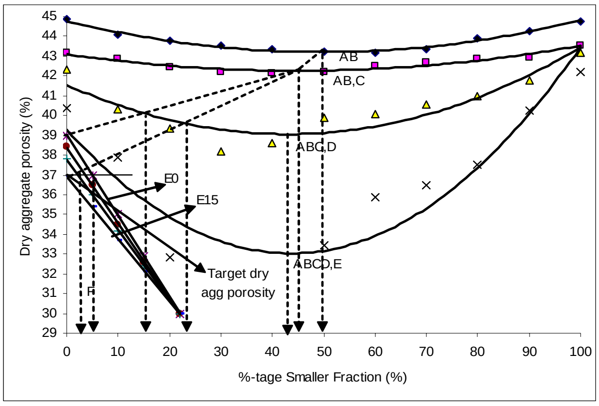

Figure 2. The relationship between dry aggregate porosity and percentage smaller fraction

The porosity P is determined from Equation 1.

$$P = 100\,((1-(D/Dr)) \quad (1)$$

Where,
P : porosity (%)
D : compacted density of dry aggregate
Dr : relative density of mixed aggregate (gr/cm^3)

Dr is obtained from Equation 2.

$$Drn = 100/(\Sigma Pwi/Dri) \quad (2)$$

Where
Drn : relative density of the mixture of n aggregates
Pwi : percentages of aggregate from fraction i
Dri : relative density of aggregates from fraction i

Modified gradation can be done when the values of porosity, permeability and Marshall stability are not fulfilled. Modified gradation will create the higher void in coarse aggregate by reducing the fraction of D. This reduction of fraction D is determined by fine aggregate fraction to fill the void in coarse aggregate. The maximum total fine aggregate in porous asphalt is 15%. The various fine aggregate fraction is added to coarse aggregate to achieve the requirement for porosity, permeability and Marshall stability. The minimum requirement for porosity is above 20%, permeability for porous asphalt made with maximum aggregate size 20 mm is about

0.20cm/s, for maximum aggregate sizes 14 and 10mm is above 0.15cm/s; and for requirement for stability is higher than 5.0kN.

Specimen preparation and test on asphalt mixtures

1) Experimental design

Marshall specimens are prepared after having determined the appropriate aggregate grading to achieve the target porosity. A 4.5% binder content is chosen for all mixtures and 4% for filler. Aggregate is mixed with binder at 140 °C and compacted 130 °C. Specimen is compacted at 2x50 blows.

2) Test on asphalt mixtures

a) Permeability

After compaction, specimens are cooled in their mould. The specimens are then tested for permeability before extrusion to take advantage of the tight bond between the bituminous mix and the mould. The permeability coefficients as all other results are the average of three results.

The coefficient of permeability of the specimen k is computed from Equation 3.

$$k = 2.3\ [a.L/At]\ [\log (h1/h2)] \qquad (3)$$

Where:

k = coefficient of permeability (cm/s)

a = the cross sectional area of standpipe (cm^2)

h1, h2 = water in the standpipe fall from h1 to h2 (cm)

A = cross sectional area of specimens (cm^2)

L = height of specimens (cm)

b) Marshall stability

Specimens are extruded and the density by measuring the height and diameter. This is followed by Marshall stability tests at 60°C for 40 minutes. The stability as all other results is the average of three specimens.

RESULTS AND DISCUSSION

The minimum void of coarse aggregate

The results of vibratory compaction of coarse aggregate for maximum aggregate sizes 20, 14 and 10mm are shown in Table 3. It is found that the blending made with maximum aggregate size 20 mm has higher dry-aggregate porosity from the other blending.

Table 3. Dry aggregate porosity for maximum aggregate sizes 20, 14 and 10mm

Aggregate	Proportions (%)				Total	Porosity
	A	B	C	D	(%)	(%)
Max. size 20mm	15.7	15.7	25.6	43	100	39.0
Max. size 14mm		28.5	28.5	43	100	38.3
Max. size 10mm			46	54	100	38.4

Aggregate grading design

1) Aggregate gradation for maximum aggregate sizes 14 and 10mm

The porosity values of compacted dry aggregates for coarse aggregates used in this investigation are tabulated in Table 3. The dry aggregate porosity values resulting after mixing and compacting various proportions of aggregates from fractions B and C are plotted as a curve. Minimum porosity is achieved when B and C are blended in the ratio of 50:50, in which the minimum dry aggregate porosity is found 41%. Combining fraction D aggregates with the optimum of B + C (50:50) resulted in the minimum dry aggregate porosity of three-component system and is found to occur at 43% D, as shown in Figure 3. This blend gives the most stable coarse aggregate matrix. Therefore, adjusting the proportion to express this blend as a combination of B:C:D gives 28.5%:28.5%: 43%. The results of investigation show that the minimum dry aggregate porosity of a system composed of several components is always smaller than that of a single component.

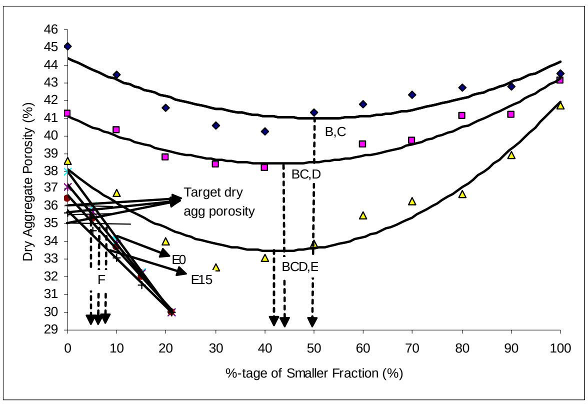

Figure 3. Dry aggregate porosity for maximum aggregate size 14mm

Using fractions of various fine aggregates in mixtures made of maximum aggregate size 14mm resulted in a decrease in the permeability coefficient when the amount of fine aggregate is increased. The mixtures made of fine aggregate 10.5-15% results in the permeability 0.11–0.19cm/s and stability 4.5–6.1kN. Based on the relationship between permeability and various fine aggregates as shown Figure 4, it is found that the amount of fine aggregate at permeability 0.15cm/s is 11.75%. At this condition, the values of stability are found to be 5.7kN, as shown in Figure 5. Based on the requirements of stability and permeability, amount of fine aggregate 11.5% can be used for porous asphalt mixtures made with maximum aggregate size 14mm.

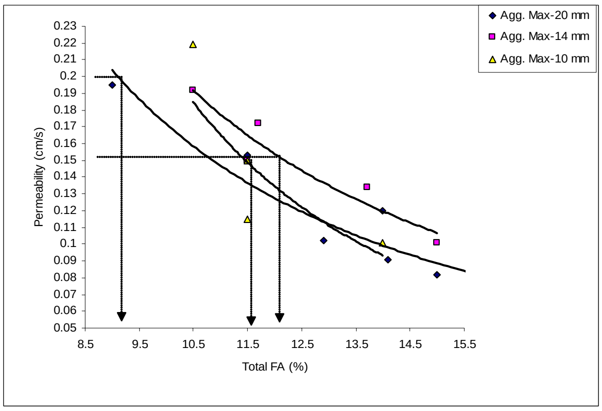

Figure 4. Relationship between permeability and total fine aggregate (FA) for maximum aggregate sizes 20, 14 and 10mm

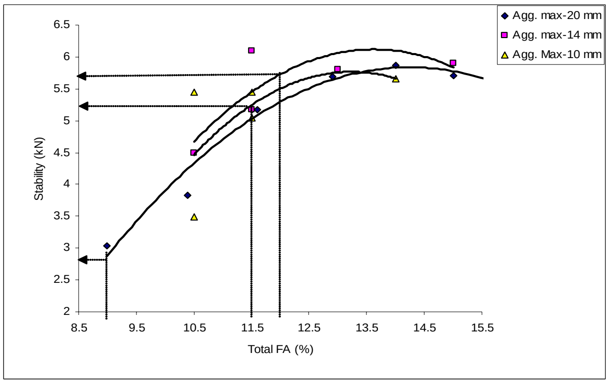

Figure 5. Relationship between Marshall stability and total fine aggregate (FA) for maximum aggregate size 20, 14 and 10mm

The procedure of combining between fractions C and D for maximum aggregate size 10mm is similar with procedure for the combination of fractions B and C of maximum aggregate size 14mm. The optimum composition C and D for achieving the minimum dry aggregate porosity is at comparison 46%: 54%.

The use of various fine aggregates to mixtures made of maximum aggregate size of 10mm results in mix the porosity above 20%. The porosity of mixtures made of maximum aggregate size 10mm is higher than that made of maximum size aggregate 14mm. This indicates that the smaller diameter particle has more surface area of aggregate for bitumen coverage.

The mixtures are made of fine aggregate in the range of 10.5-14%. The maximum aggregate size 10mm results in the Marshall stability ranging from 3.5kN to 5.7kN and coefficient of permeability 0.10-0.22cm/s. The highest permeability is achieved with the fine aggregate of 10.5%, but with lowest stability of 3.5kN. As shown in Figure 4, the amount of fine aggregate is found as 11.5% at permeability 0.15cm/s. At this condition, the value of stability is 5.2kN, as shown in Figure 5.

2) Aggregate gradation for maximum aggregate size 20mm

The porosity of mixtures made of maximum aggregate size 20mm is found to be above 20%. The fine aggregate used is in range of 9.0% to 15% resulting in the permeability of 0.08cm/s to 0.19cm/s and Marshall stability between 3.0kN to 5.9kN. Based on this result, it can be seen that the mixture at maximum permeability 0.19cm/s results in the lowest stability of 3kN, as shown in Figures 4 and 5. This stability is under minimum value for Marshall stability. Marshall stability is achieved >5.0kN after modified gradation with the fraction D 15-26% and fine aggregate 10% as shown in Table 4.

Table 4. Permeability, Marshall stability, and porosity values of mixtures made of modified gradation maximum aggregate size 20mm

Proportions		Porosity (%)	Stability (kN)	Permeability (cm/s)
Fraction D in coarse agg (CA) (%)	Fine agg. (FA) (%)			
19	10	22.0	5.30	0.20
23	10	20.7	5.35	0.16
25	10	23.0	5.57	0.13

Table 4 shows that the mixture made of fraction D 19% has permeability of 0.20cm/s and Marshall stability of 5.3kN. The permeability coefficient for mixture made with fraction D 19% is higher than the mixture made of fraction D 23%. On the contrary for stability, the mixture made of fraction D 23% is higher than the mixture made of fraction D 19%. Thus, mixture made of lower fraction D results the higher permeability. However, the values of permeability have to be controlled by Marshall stability value. In over all for mixtures made with maximum aggregate size 20mm, the modified gradation meet the requirement of porosity, permeability and Marshall stability.

3) Selected gradations for porous asphalt and their properties

Based on the stability and permeability, the best grading for porous asphalt made with maximum aggregate sizes 20, 14 and 10mm are found as shown Figure 6. The average values of porosity, coefficients of permeability and Marshall stability for selected gradation of maximum aggregate sizes 20, 14 and 10mm are shown in Table 5. It can be seen that all mixtures can fulfill the requirements of porosity, permeability and Marshall stability for porous asphalt mixtures. It is also shown that properties based on packing theory is better than the empirical grading from Spain (P-12).

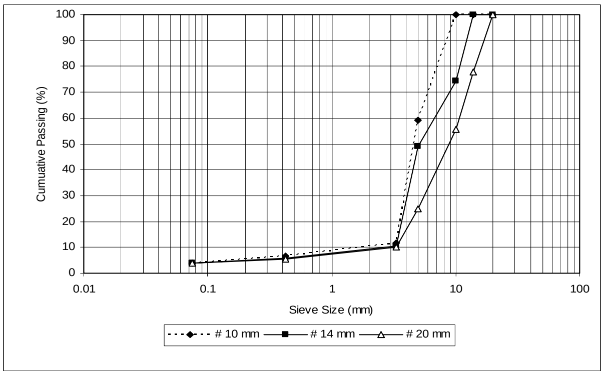

Figure 6. Selected gradations for porous mixtures of maximum aggregate sizes 20, 14 and 10mm

Table 5. Average values of porosity, permeability and stability for selected gradations

Gradation	Result			Specification	
	Porosity (%)	Permeability (cm/s)	Stability (kN)	Porosity (%)	Stability (kN)
Max. size 20mm	22.0	0.20	5.3	>20.0	>5.0
Max. size 14mm	23.0	0.16	5.2		
Max. size 10mm	26.7	0.15	5.4		
P-12	22.1	0.11	5.1		

CONCLUSIONS

1) The addition of fine aggregate to coarse aggregate matrix at minimum porosity results in mixtures that do not fulfill the minimum requirement for permeability for some porous aggregate gradations. In this investigation, the aggregate grading consisting of 20mm maximum aggregate size requires modification.
2) Properties of porous asphalt based on packing theory are better from the empirical grading than Spain (P-12).

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