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Aggregate Angularity Effect on Porous Asphalt Engineering Properties and Performance

Nadhir Ahmad Tarmuzi[a], Ramadhansyah Putra Jaya[a*], Haryati Yaacob [a], Norhidayah Abdul Hassan[a], Md. Maniruzzaman A. Aziz[b]

[a]*Department of Geotechnics and Transportation, Faculty of Civil Engineering, Universiti Teknologi Malaysia, 81310 UTM Johor Bahru, Johor Malaysia*
[b]*Construction Research Centre, Faculty of Civil Engineering, Universiti Teknologi Malaysia, 81310 UTM Johor Bahru, Johor Malaysia*

*Corresponding author: ramadhansyah@utm.my

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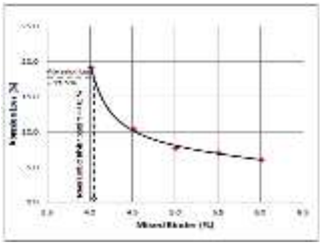
Graphical abstract



Abstract

Porous asphalt is a flexible pavement layer with highly interconnected air voids constructed using an open-graded type of aggregate. The aggregate shape and surface texture serve a vital function in determining the engineering properties and performance of porous asphalt. The angular aggregates with clearly defined fracture faces and sharp edges encourage better interlocking between the aggregates' skeleton structures, which makes them preferable to use in asphalt mixtures. This study evaluates the effect of aggregate angularity on the engineering properties and performance of porous asphalt using both conventional and empirical particle index test methods. The term "engineering properties" refers to the experimental works determining resilient modulus and stability, whereas "performance" deals with the porosity and durability characteristics of porous asphalt caused by variations in the particle index number (Ia). A laboratory data analysis shows that angular particles provide a larger Ia number than non-angular particles. Furthermore, resilient modulus and stability properties significantly improve when angular aggregates are applied. The angular particles provide high mixture porosity but cause poor durability performance of porous asphalt against abrasion loss. Some improvements are suggested to enhance the strength properties and performance of porous asphalt on the basis of engineering applications.

Keywords: Porous asphalt; aggregate shape; angularity aggregate; particle index; properties

■1.0 INTRODUCTION

Porous flexible asphalt is known for its advantages in terms of improving the skid resistance of pavements during rains, reducing splashing effects, and producing low riding noise [1]. These criteria have been developed because of the high porosity of pavement layers, which allows for the high drainage capability of surface run-off. According to Malaysia Public Works Department [2], porous asphalt generally has a total void percentage between 20% and 25%. This value is relatively higher than that of conventional hot mix asphalt. The highly interconnected void content of porous asphalt is achieved by applying an open-graded type of aggregate. Moreover, porous asphalt is a non-structural layer of flexible pavement that should possess sufficient strength to bear traffic-imposed external loads. Some engineering properties of the conventional asphalt layer (e.g., resilient modulus and stability) should also be evaluated in the case of porous asphalt. This evaluation is essential because porous asphalt forms the uppermost layer of a flexible pavement, thereby making it the direct recipient of loads from moving traffic [3]. The engineering properties of porous asphalt depend on several factors. One factor is related to aggregate shape angularity. Aggregate angularity is described in terms of how many fracture faces have to be produced to improve interlocking, which increases resistance against rutting and crack formations [4]. Accordingly, an early assumption states that porous asphalt with high angular aggregate constituent possesses enhanced engineering properties. Moreover, particle shape variation is estimated to affect the void ratio of porous asphalt, thereby influencing its performance in terms of porosity and durability.

Porous asphalt is a non-structural layer in a flexible pavement that is frequently exposed to defects caused by the imposed traffic loadings. The high porosity of porous asphalt has perhaps contributed to the severity of damage. Porosity is closely related to the amount of air voids within a mixture [5]. However, Liu and Cao [1] stated that the porosity effectiveness greatly depends on the air void type (i.e., open and closed). The porosity performance is rather small, and vice versa, if a closed air void in a structure constitutes a large portion of the total void volume [6, 7]. Pavement engineering properties, such as resilient modulus and stability, serve a vital function in ensuring porous asphalt resistance against permanent deformations and functional failure. Porous asphalt resistance is closely related to the physical shape of the aggregate, which mainly constitutes the materials used in forming asphalt layers. Using the aggregate particles with an undesirable shape might significantly influence the porous asphalt resistance against physical and functional defects. Therefore, porous asphalt should have adequate particle interlocking properties to maintain its porosity and durability characteristics. Balancing these two criteria is challenging because aggregate shape is a subjective parameter that influences the engineering properties and performance of porous asphalt. Janoo et al. [8] conducted a standard and large-scale test, which successfully proved that resilient modulus was a function of the crushed aggregate constituent in asphalt mixture. Resilient modulus was the least affected by the high crushed aggregate constituent (i.e., more than 75%) in mixture but was severely influenced if the crushed aggregate was less than the given percentage [8]. Furthermore, the increase in the crushed aggregate constituent reduced the asphalt layer deformation because a tougher mix was created [9]. Stability is another parameter used to predict the asphalt mixture stiffness against deformation. Correspondingly, Tutumluer et al. [10] conducted laboratory studies on the basis of the Marshall mixed design procedure. They found that the application of angular particles produced strong aggregate structures and high hot mix asphalt stability. A similar result was found by Singh et al. [11], who stated that the angularity resulted in improved interlock between the particles, thereby resulting in improved asphalt mix stability.

■2.0 MATERIALS AND METHODS

2.1 Binder and Aggregate

This study used a styrene butadiene styrene (SBS) modified binder supplied by Shell Malaysia. The manufacturer specification states that the relative density and ductility values of the SBS modified binder were 1.010 and 100 cm, respectively. The softening point and the penetration were 93°C and 84 dmm, respectively. The granite aggregates supplied by the Ulu Choh quarry were used throughout the experiment. The basic aggregate tests (i.e., aggregate impact value, specific gravity, particle index number, and water absorption test) were conducted to control the aggregate quality. The gradation test was used to isolate the aggregates from the stockpile to the designated sizes used in the mix design. The gradation B used in this study is shown in Table 1.

Table 1 Aggregate gradation "B" used in this investigation [2]

Sieve size (mm)	Percentage Passing (%)
20	100
14	85 – 100
10	55 – 75
5	10 – 25
2.36	5 – 10
0.075	2 – 4

2.2 Design Binder Content

The Cantabro and the binder drain-down tests were employed to determine the optimum binder content. The tested samples had varying mixed binder amount (i.e., 4% to 6% by total weight). The sample under the Cantabro test was subjected to 300 revolutions at room temperature in the Los Angeles Abrasion machine. The analysis on the percentage of mass loss against the binder content revealed the lower limit of the binder content. A wire basket, which enabled the binder to drain, was used for the loose porous asphalt mixture in the binder drain-down test. The upper limit value was measured based on the amount of the binder retained against the mixed binder content of the sample.

2.3 Particle Index Number

The effect of the aggregate angularity was evaluated through the particle index test following the ASTM C1252-06 [12] standard. This test was performed only for the particle size of more than 10% fraction by average with reference to gradation B (i.e., 10.0, 5.0, and 2.36 mm). The particle index number (Ia) was determined based on the following equations:

$$V_{10} = [1 - (M_{10} / sv)] \times 100 \tag{1}$$

$$V_{50} = [1 - (M_{50} / sv)] \times 100 \tag{2}$$

$$Ia = 1.25V_{10} - 0.25V_{50} - 32.0 \tag{3}$$

where V_{10} and V_{50} represent the voids in the aggregate compacted at 10 and 50 drops/layer, respectively; M_{10} and M_{50} denote the average mass of the aggregate in the mold compacted at 10 and 50 drops/layer, respectively; s is the bulk-dry specific gravity (SG) of the aggregate size fraction; v is the volume of the cylindrical mold in mL; and Ia is the particle index number.

2.4 Engineering Properties Of Porous Asphalt

Resilient modulus and stability were the engineering properties of porous asphalt used in this study. The resilient modulus test was conducted by measuring the sample elasticity behavior under standard repetitive loads of 1000 N at five loading pulses. The test was carried out according to the ASTM D4123-82 [13] test method. Furthermore, this test was performed using the universal testing machine (UTM) at 25°C. The UTM was capable of measuring the recoverable sample deformation after applying the load pulses. The stability and flow value of porous asphalt samples were determined using the Marshall testing apparatus at a sample temperature of 60°C.

2.5 Performance of Porous Asphalt

This study tested porosity and durability to evaluate the performance of porous asphalt. The SG and theoretical maximum density (TMD) tests were among the experiments conducted to measure the porous asphalt porosity on the basis of the percentage of air voids within the sample. Porous asphalt durability was evaluated in terms of resistance against abrasion loss. The compacted porous asphalt samples in this test were subjected to 300 revolutions in the Los Angeles Abrasion machine. The mass loss percent was used to determine the abrasion resistance of the porous asphalt samples.

■3.0 RESULTS AND DISCUSSIONS

3.1 Optimum Binder Content Determination

The results of the lower and upper limits of the binder content from the Cantabro and the binder drain-down tests are shown in Figure 1 and Figure 2. The lower-limit value obtained from the Cantabro test was 4.05%, whereas that from the binder drain-down test was 5.15%. Summing these two values and calculating the average for mixing purposes provided the optimum binder content as ~4.60%.

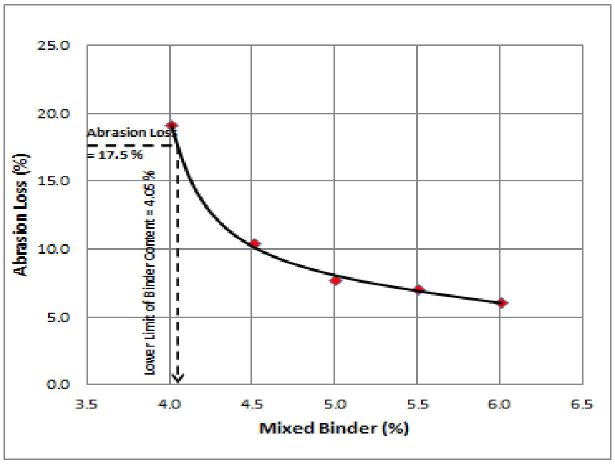


Figure 1 Abrasion Loss vs. mixed binder

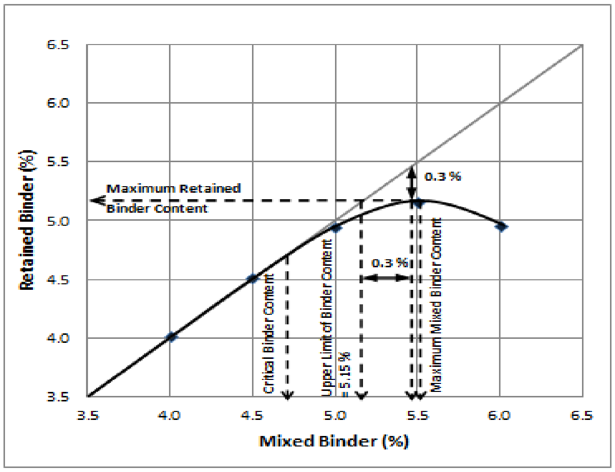


Figure 2 Binder drain-down vs. mixed binder

3.2 Aggregate Ia

The weighted Ia numbers are summarized in Tables 2 and 3. The fraction of the 14.0 and 0.075 mm aggregate sizes in the gradation was less than 10%. Hence, the Ia numbers were considerably similar to 10.0 and 2.36 mm. The aggregates from the particle index test with larger Ia numbers had higher degrees of angularity than those with smaller Ia numbers. The spherical and rounded aggregates generally had Ia numbers of 10 to 11, whereas the angular aggregates possessed Ia numbers of 13 to 15 for the 10.0 mm size. A larger Ia number in angular aggregates can be attributed to the high void content between the particles after the tamping process. However, the comparison of different aggregate sizes showed that the 2.36 mm size had the largest Ia number, followed by the 5.0 and 10.0 mm sizes. The smaller particles created a higher amount of air voids than the larger-sized particles after the tamping process. Hence, a smaller particle size resulted in a larger Ia number.

Table 2 Weighted I_a number based on particle size fractions (for Resilient Modulus and Stability Test)

Sample Set	I_a Value (*based on aggregate size and fraction in Gradation B*) :					Weighted I_a Number
	14.0 mm *(7.5 %)*	10.0 mm *(27.5 %)*	5.0 mm *(47.5 %)*	2.36 mm *(10.0 %)*	0.075 mm *(4.5 %)*	
A1	14.692	14.692	16.026	16.999	16.999	15.690
B1	13.840	13.840	15.997	16.877	16.877	15.350
C1	13.211	13.211	15.593	16.578	16.578	14.881
D1	12.650	12.650	15.518	16.520	16.520	14.633
E1	12.267	12.267	15.502	16.415	16.415	14.471
F1	11.755	11.755	15.171	16.336	16.336	14.113
G1	10.968	10.968	15.104	15.951	15.951	13.738

Table 3 Weighted I_a number based on particle size fractions (for Porosity and Durability Test)

Sample Set	I_a Value (*based on aggregate size and fraction in Gradation B*) :					Weighted I_a Number
	14.0 mm *(7.5 %)*	10.0 mm *(27.5 %)*	5.0 mm *(47.5 %)*	2.36 mm *(10.0 %)*	0.075 mm *(4.5 %)*	
A2	15.021	15.021	15.766	16.865	16.865	15.355
B2	13.866	13.866	15.731	16.669	16.669	14.892
C2	13.238	13.238	15.596	16.607	16.607	14.592
D2	12.662	12.662	15.399	16.526	16.526	14.280
E2	12.111	12.111	15.241	16.284	16.284	13.971
F2	11.342	11.342	15.182	16.185	16.185	13.650
G2	10.669	10.669	14.745	16.144	16.144	13.194

3.3 Resilient Modulus

The laboratory test conducted for the porous asphalt samples with different Ia numbers proved that the sample with the larger Ia number possessed a better resilient performance than the sample with the smaller Ia number. The resilient modulus value obtained for the porous asphalt sample with the Ia number of more than 15 reached 2000 MPa. The sample with the high constituent of angular aggregates created a better stone-to-stone contact among the particles, thereby forming a stiffer mixture. This rationale was proved using the total recoverable horizontal deformation (δ) generated by the resilient modulus test. The porous asphalt sample with the larger Ia number in the resilient modulus test produced a lesser amount of deformation than the sample with smaller Ia value. The relationships among the Ia number, Mr, and δ of porous asphalt are shown in Figures 3 and 4. The Mr value significantly decreased for Ia number more than 15. On one hand, the Mr value began to decrease slightly as the Ia number decreased in the range of less than 15. The Mr value finally turned constant, thereafter. On the other hand, the δ value began to increase drastically as the Ia number decreased. This value turned constant after the Ia number reached 14. The Mr and δ values exhibited an inverse relationship toward each other. The result of this study was supported by the research of Janoo et al. [8]. Their result demonstrated that the Mr value was least affected by the high constituent of angular aggregates (i.e., more than 75%) in the mixture but severely influenced if the crushed aggregate was less than the given percentage.

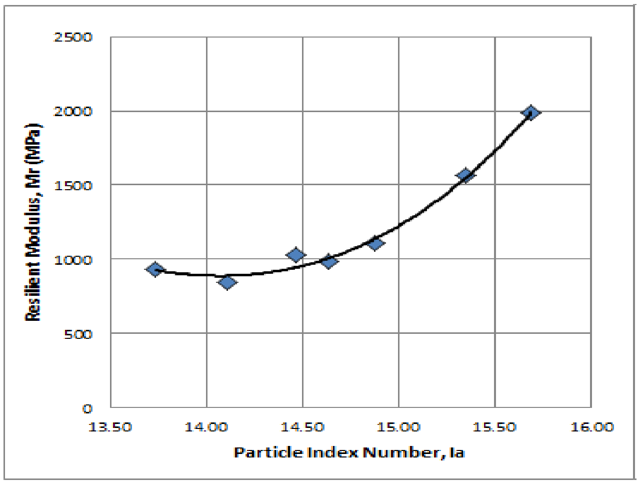


Figure 3 Relationship between Mr and Ia

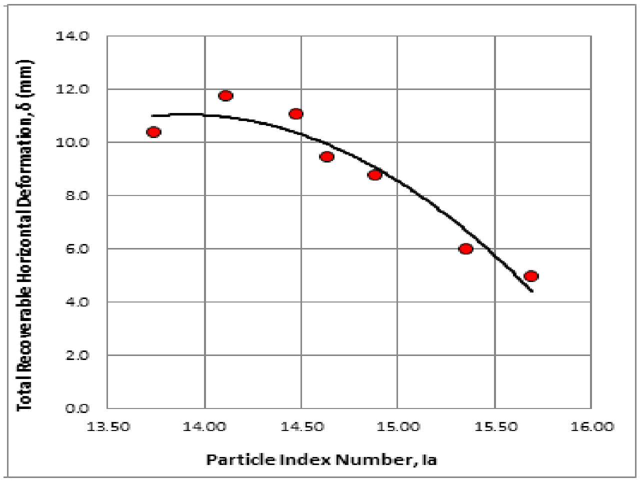


Figure 4 Relationship between δ and Ia

3.4 Stability And Flow

Based on the Marshall Stability test for the porous asphalt sample, the highest stability value occurred for the largest Ia number. The sample with a high constituent of angular aggregates exhibited improved performance against permanent deformation. The result obtained coincided with the research conducted by Tutumluer et al. [10] and Singh et al. [11]. Both studies stated that the angular aggregates formed stronger skeleton structures with better interlocking, which enhanced the asphalt mixture stability. The relationships between the stability and flow of the porous asphalt sample and its Ia number are shown in Figures 5 and 6. The plotted graphs showed the significant drops in the stability value of the porous asphalt sample when the Ia number decreased. Furthermore, the reduction amount in the stability value declined and almost turned constant when the Ia number became smaller. The values were less varied in terms of flow. However, a slight reduction in the porous asphalt flow occurred when the Ia number increased. Accordingly, the angular aggregates reduced the workability of the porous asphalt sample. The porous asphalt resistance against permanent deformation greatly depended on the coarse aggregate angularity, which provided a stiffer and stronger mixture.

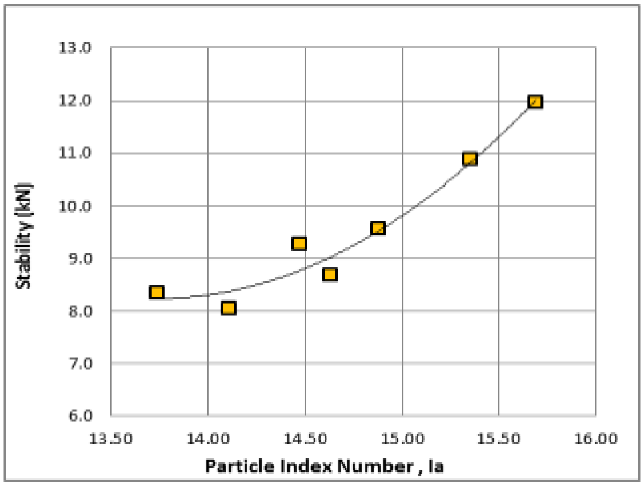


Figure 5 Relationship between stability and Ia Number

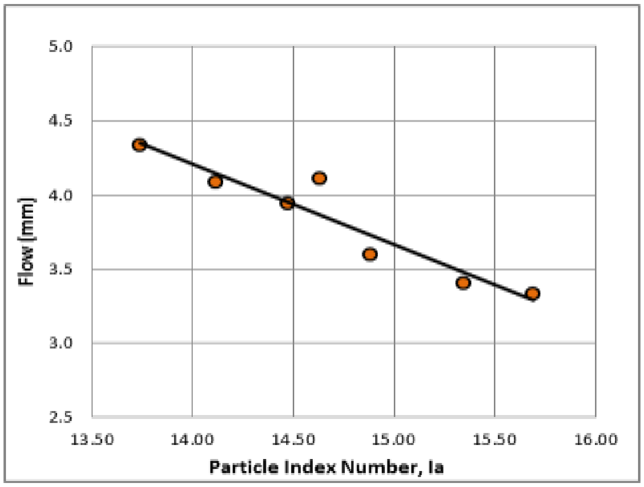


Figure 6 Relationship between flow and Ia Number

3.5 Porosity

The porous asphalt porosity was measured on the basis of the percentage of air voids (Va) within a sample [14]. The SG and TMD tests performed on samples with different Ia numbers showed that the sample with larger Ia number delivered a higher percentage of air voids than that with the smaller Ia number. Hence, applying the angular aggregates in porous asphalt enhanced porosity performance. The relationship between the air voids and the Ia number is demonstrated in Figure 7. Both parameters formed a linear relationship, in which air void percentage proportionally decreased with the reduction in Ia number. However, the air void amount for each of the porous asphalt sample obtained through laboratory compaction was insufficient compared with the criteria in the 18% to 25% range. This insufficiency was attributed to the compaction effort imposed on porous asphalt during the sample making. A previous study on the influence of the Marshall compaction efforts on the porous mixture revealed that a higher compaction level significantly reduced the air void percentage [15]. The compaction efforts were applied with 35, 50, and 75 blows.

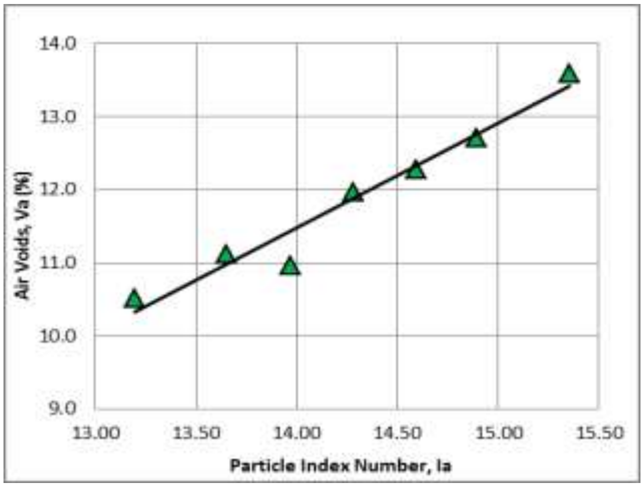


Figure 7 Relationship between air voids and Ia number

3.6 Abrasion Loss

Porous asphalt durability was measured on the basis of resistance against abrasion effect. The laboratory test found that the high percentage of abrasion loss occurred both at the largest and smallest Ia numbers. The amount of abrasion loss significantly decreased when the Ia number was reduced up to the value of 14.1, in which abrasion loss became constant. The percentage of abrasion began to increase steadily beyond this point. The relationship between the percent of abrasion loss and the Ia number is illustrated in Figure 8. The high abrasion loss occurred at the maximum Ia number because of the breaking of the angular aggregate (Figure 8). One sample was subjected to sudden impact force when it fell inside the steel drum while being lifted. The angular facets on the aggregates tended to break-off from the sample. The abrasion on porous asphalt in this case dealt with the resistance of the individual aggregate particles against the impact loads. Moreover, the abrasion easily occurred at the larger Ia number because of the high air voids within a porous asphalt sample. This result was supported by Suresha et al. [15], who found that abrasion loss decreased with the increment of the sample density (i.e., smaller air void percentage) because it was influenced by the laboratory compaction effort. Meanwhile, the high abrasion loss at a small Ia number was mainly caused by the insufficient particle-to-particle contact between the round aggregates. Consequently, the interlocking characteristics of the angular aggregates were proven to serve a vital function in enhancing the durability of porous asphalt sample against abrasion loss [16,17,18].

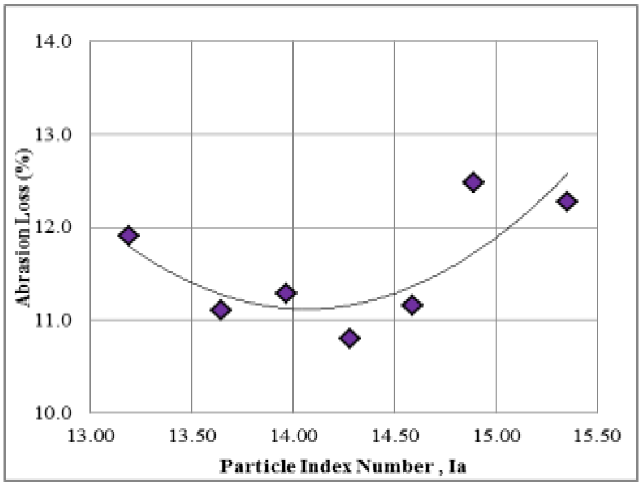


Figure 8 Relationship between abrasion loss and Ia number

■4.0 CONCLUSION

From the analysis of laboratory data, the following conclusions can be drawn as regards the effect of aggregate angularity on the engineering properties and performance of porous asphalt:

a. A correlation is found between the aggregate angularity and I_a. The increase in the number of angular particles within a porous asphalt sample provides a larger I_a number using the particle index test. The angular aggregate generally has an I_a number between 13 and 16, whereas the spherical and rounded particles tend to have I_a numbers less than 12.

b. The high constituent of angular aggregates (i.e., larger I_a number) enhances the resilient modulus (M_r) and stability of porous asphalt in terms of engineering properties. That is, the coarse aggregate with a high degree of angularity improves the interlocking bonds between the particles. This improvement further creates a stiffer mixture, which can resist the permanent deformation imposed by traffic loads. A smaller value of the total recoverable horizontal deformation (δ) and mixture flow is obtained by porous asphalt with the larger I_a number.

c. Porous asphalt with the high constituent of angular aggregates (i.e., larger I_a number) produces a high air void percentage. This result exhibits better characteristics of porous asphalt porosity. However, an insufficient amount of air voids is found within the samples formed through the laboratory compaction effort.

d. The excessive compaction effort mainly caused the lower air void percentage in terms of specification (i.e., 18% to 25%). A lower level of compaction is suggested to improve the air void percentage within the porous asphalt sample.

e. Porous asphalt durability at a larger I_a number is mainly affected by the mechanical properties of the aggregate used. Furthermore, performance at a smaller I_a number is influenced by the adequate interlocking between the particles. The aggregate with high angularity performs more appropriately because it provides better stone-to-stone contact for the larger I_a number than other aggregates. Therefore, aggregate types with sufficient mechanical properties should be selected to form a porous asphalt mixture that can resist the particle break-off effect from sudden impact forces.

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