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Effects of flat and elongated aggregates on the performance of porous asphalt mixture

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Abstract: Four flat and elongated (F&E) contents (0%, original, 30%, and 40%) were investigated to evaluate the effects of F&E particles on the performance of porous asphalt mixture (PA). Laboratory tests including volumetric determination, two-dimensional image analysis, Cantabro loss tests, breakdown tests, and permeability tests were conducted to evaluate the volumetric properties, the state of stone-on-stone contact, durability, skeleton stability and permeability of PA, respectively. The test results indicate that the F&E content was a significant factor for total air voids, aggregate skeleton break down, and permeability. The functionality, rutting resistance, long-term durability, and skeleton stability decrease with the increase of F&E content since F&E aggregates in porous asphalt mixtures have a tendency to breakdown. Compared with traditional dense graded mixtures, PA is more sensitive to the F&E content due to an open graded aggregate structure. Therefore, the stricter requirement for F&E content should be met for porous asphalt mixtures than the one for traditional dense graded mixture.

Key words: porous asphalt mixture; flat and elongated aggregate; skeleton stability; durability; permeability

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Porous asphalt mixture (PA) is an open graded mixture. It has a high air void (AV) (18% to 23%) and a coarse aggregate skeleton with stone-on-stone contact[1]. PA was designed to infiltrate storm water, reduce the risk of hydroplaning and wet skidding, decrease splash and spray, and lower noise[2]. High AV and a coarse granular skeleton bring these advantages, but result in some disadvantages, such as reduced performance, high construction costs, and low durability[3]. Aggregate properties play the most important role in the performance of PA since it consists of more than 80% coarse aggregates (retain on the 2.36 mm)[4]. Fine aggregate angularity and coarse aggregate shape are the two of the aggregate properties which have the most important influence on mixture performance[5].

According to the ratio of the length to the minimum thickness or width, coarse aggregates can be classified into flat, elongated, flat and elongated (F&E), and neither flat nor elongated (non-F&E) particles[6]. In this study, F&E particles include flat, elongated, flat and elongated particles. Superpave mix design system specifies that an aggregate is determined to be F&E particles if the ratio is greater than five and requires that the F&E content in the aggregate shall not exceed 10% for mixture[7]. The standard of F&E particles with the ratio of 5∶1 cannot distinguish different aggregates, and most coarse aggregate sources satisfy the current specification of a maximum limit of 10% content of F&E with the ratio of 5∶1. Therefore, many researchers recommend that F&E particles should be changed from the ratio of 5∶1 to 3∶1[8-9]. In China, specifications have the same requirement that the F&E content must not exceed 15% for all types of mixtures, even though PA has larger coarse aggregate proportion.

Huber et al.[5] found that the dense graded mixtures with 19.4% and 9.0% F&E (ratio 3∶1) contents have no significant difference in volumetric properties. Other studies conducted by Buchanan[9] revealed that F&E (ratio is 3∶1) contents of 29.5%, 21.8% and 16.2% show no significant differences in volumetric properties, rutting resistance, fatigue resistance, and breakdown for traditional dense graded mixture. However, regarding granite with F&E contents of 57%, 14.4%, and 2.1%, significant changes were found in the voids in mineral aggregate (VMA) and gradation. Brown et al.[8] evaluated various F&E contents (0%, 25%, 50%, 75% and 100%) for stone matrix asphalt (SMA) mixtures. The results also indicated that the change in percent passing the 4.75 mm sieve shows an increase with the increase in F&E content. Airey et al.[10] stated that gap graded asphalt mixtures have a greater amount of aggregate degradation after compaction compared with dense graded asphalt mixtures.

PA has a larger proportion of coarse aggregates and higher requirements on the quality of coarse aggregates than that of dense graded mixture. The skeleton of coarse aggregate of PA is potentially more sensitive to the F&E content. However, most agencies required the same F&E

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content limitation for both dense and open graded mixtures. Only limited research was conducted to evaluate the effects of F&E aggregates on the performance of PA. Therefore, it is of great significance to investigate the effects of F&E contents on the physical and mechanical properties of PA. The role of F&E particles can be evaluated by evaluating the effects of different F&E contents on the performance of PA through laboratory tests. The laboratory tests including volumetric determination, two-dimensional image analysis, Cantabro tests, breakdown tests, and permeability tests, were conducted to evaluate the volumetric properties, the state of stone-on-stone contact, durability, skeleton stability and permeability of PA, respectively.

1 Objectives and Scope

The main objective of this paper is to investigate the influence of the F&E content on the volumetric properties, stone-on-stone contact, durability, aggregate breakdown and permeability of PA. Since every F&E particle was manually picked from different groups of coarse aggregates, four F&E contents (0% (control), original, 30%, and 40%) were considered. Statistical analysis was then conducted to determine whether the F&E content has a significant influence on the performance of PA. In the statistical analysis, the null hypothesis H_0: F&E aggregates will not have a significant influence on the volumetric properties, durability, stability and permeability of PA.

2 Materials and Mixture Design

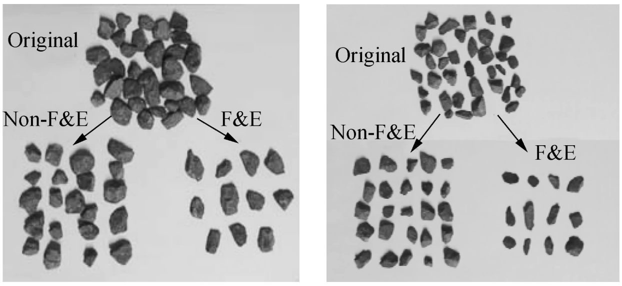
2.1 Materials

High viscosity polymer-modified asphalt is commonly used in Asian countries to improve the anti-ravelling and high-and-low temperature performance. Compared with traditional modified asphalt, high viscosity polymer-modified asphalt has an extremely high dynamic viscosity and soft point. The dynamic viscosity at 60 ℃ is 143 202 Pa · s, and the soft point is 90 ℃

Basalt coarse aggregate is used in the mixture. The properties of aggregate are summarized in Tab. 1. In this paper, an aggregate is determined to be F&E particles if the ratio of the length to the minimum thickness or width is greater than 3. In order to design a mixture with different F&E contents, F&E and non-F&E particles were manually picked up from the original aggregates one by one, as shown in Fig. 1. The original aggregates were divided into F&E and non-F&E particles by comparing the ratio of the length to minimum thickness or width. Two groups of original 10-15 mm and 5-10 mm coarse aggregates were prepared. As shown in Tab. 1, the F&E content of original 10-15 mm and 5-10 mm are 11.2% and 14.0%, respectively. A large amount of aggregates was processed in this study to fabricate a total of 64 specimens.

Tab. 1 Summary of the properties of original aggregates

Property	Aggregate type	
	10-15 mm	5-10 mm
Bulk specific gravity	2.848	2.785
Apparent specific gravity	2.948	2.971
Percentage of F&E particles (3:1)/%	14.0	11.2
LA abrasion loss (C grading)/%	10.78	
Crushing value/%	10.5	



(a) (b)

Fig. 1 Different particle shapes of two groups of coarse aggregates. (a) 10-15 mm; (b) 5-10 mm

2.2 Mixture design

PA with 13.2 mm nominal aggregate size, mostly used in the drainage pavement wearing course, was used as the control mixture. The mixture design process contains aggregate gradation selection and asphalt content determination. The selection of the PA gradation was mainly based on an evaluation of AV combined with the evaluation of stone-on-stone contact[1]. AV should satisfy the minimum requirement of 18% to ensure adequate functionality[11]. The state of stone-on-stone contact is required to provide sufficient resistance to permanent deformation and is determined by comparing the AV in the coarse aggregate (VCA) evaluated in the dry-rodded condition (VCA_{DRC}) and the compacted PA mixture (VCA_{mix}). The breaking-sieve size is 2.36 mm and the stone-on-stone contact was verified by using a maximum VCA_{mix}/VCA_{DRC} ratio (VCA ratio) of 1.0[12]. The selected gradation of PA is shown in Tab. 2. The mass percent of four aggregate groups of 10-15 mm, 5-10 mm, 0-3 mm, and filler in a specimen are 39%, 43%, 13%, and 5%, respectively. The asphalt content is 4.8% and the VCA ratio is 0.989. A superpave gyratory compactor (SGC) with 50 gyrations was used to fabricate two groups of cylindrical samples with a diameter of 100 mm and approximate height of 63.5 mm, and a diameter of 100 mm and approximate height of 100 mm. Specimens with a length of 300 mm, width of 300 mm, and height of 50mm were fabricated for the permeability test with the same gradation. All of the specimens produced and studied in this

Tab. 2 The selected gradation of PA

Sieve/mm	16	13.2	9.5	4.75	2.36	1.18	0.6	0.075
Percentage passing/%	100	90.3	64.3	19.3	14.0	11.0	9.1	4.6

paper had the same gradation and asphalt content regardless of the F&E content.

2.3 F&E content design for mixture

To evaluate the influence of different F&E contents on the performance of PA, four different F&E contents (0%, original, 30% and 40%) reference to the selected gradation were considered. Each F&E content mix was made by blending original aggregates, non F&E and F&E particles in various proportions. Assuming that one specimen contains a total mass of 1 100 g aggregates, the composition of each specimen is shown in Tab. 3.

Tab. 3 Composition of mixtures with different F&E contents

F&E content	Mass of 10-15 mm group/g			Mass of 5-10 mm group/g			Mass of 0-3 mm group/g	Mass of filler/g
	Original	Non-F&E	F&E	Original	Non-F&E	F&E		
0%	0	429.0	0	0	473.0	0	143	55
Original	429.0	0	0	473.0	0	0	143	55
30%	349.2	0	79.8	372.9	0	100.1	143	55
40%	299.3	0	129.7	319.6	0	153.4	143	55

3 Laboratory Tests

3.1 Volumetric determination

Volumetric parameters depend on the bulk specific gravity (G_{mb}) and the theoretical maximum specific gravity of the mixtures (G_{mm}). Total AV (A_{total}) and water-accessible AV ($A_{water\text{-}accessible}$) are calculated as[13]

$$G_{mb} = \frac{m}{V} \times \rho_{\omega} \tag{1}$$

$$G_{mm} = \frac{100}{\dfrac{100 - P_b}{G_{se}} + \dfrac{P_b}{G_b}} \tag{2}$$

$$A_{total} = \left(1 - \frac{G_{mb}}{G_{mm}}\right) \times 100\% \tag{3}$$

$$A_{water\text{-}accessible} = \frac{V - \dfrac{m - m_w}{\rho_w}}{V} \times 100\% \tag{4}$$

where m is the mass of the specimen in air, g; V is the total volume of the specimen which is calculated by average height and diameter; ρ_{ω} is the density of water, g/cm^3; P_b is the asphalt content based on mass of mixture; G_{se} is the average effective specific gravity of the aggregate; m_w is the saturated sample mass in water, g.

3.2 Two-dimensional (2-D) image analysis

Volumetric and gradation information can be processed using 2-D image analysis to characterize the internal structure of asphalt mixtures[14]. Furthermore, aggregate interaction information, such as the number of aggregate contacts, contact length, normal to contact plane orientation, can also be captured from 2-D image analysis to define the state of stone-on-stone contact[15]. The influence of F&E contents on the state of stone-on-stone contact was evaluated using 2-D image analysis. 2-D image analysis was conducted on MATLAB software by programming a series of algorithms. Adjacent aggregates are defined as contacted if the distance of two aggregates is less than 0.2 mm for PA[16], and the contact length can be obtained. Testing specimens with a diameter of 100 mm and height of 100 mm were fabricated at 50 gyrations of SGC. The specimens were cut into three sections to attain six 2-D images, with one cutting section at the middle of the specimen and two in a distance of 2.5 cm from the middle section (see Fig. 2)[15]. Image analysis processes are shown in Fig. 3.

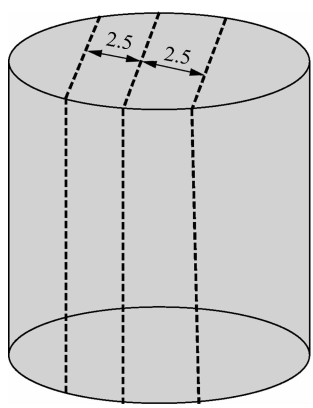


Fig. 2 Cutting sections (unit: cm)

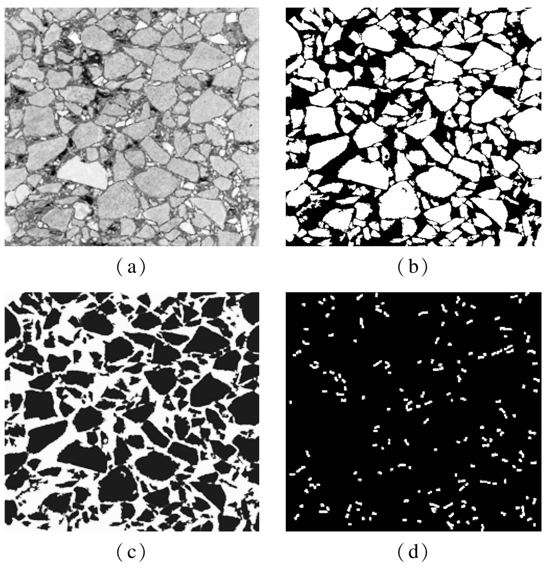


Fig. 3 Image analysis processes. (a) Scanned images of mixtures; (b) Coarse aggregates; (c) Thresholding; (d) Aggregate contact line

3.3 Cantabro loss test

The Cantabro loss test can provide an indirect evaluation of mixture cohesion and adhesion. Alvarez et al. [17] compared the Cantabro loss test, Hamburg wheel-tracking test, and overlay test to evaluate the durability of the permeable friction course, and the result recommended the Cantabro loss test as the most appropriate for durability evaluation. The Cantabro loss test was performed by placing a compacted specimen into the Los Angeles (LA) abrasion machine and used the percent of weight loss (Cantabro loss) to evaluate the durability of mixtures. Three different conditioning scenarios (dry, wet, and 7 d aging) were prepared to evaluate the moisture susceptibility and long-term durability of PA. The dry conditioning was performed at room temperature (25 ℃). The wet conditioning involves soaking the specimen in a water bath for 48 h at 60 ℃ and then drying the specimen for 24 h using a fan at room temperature. 7 d aging was used to investigate the long-term durability of PA which involved aging the specimens at 60 ℃ in an oven for 7 d and then cooling them at room temperature for 24 h. Cantabro loss was obtained after applying 300 revolutions in the LA abrasion machine and was calculated by

$$\Delta S = \frac{m_0 - m_1}{m_0} \times 100\% \tag{5}$$

where m is the initial weight; m_1 is the retained weight; S is the Cantabro loss, %. For wet specimens, the Cantabro loss was calculated by

$$\Delta S = \frac{m_0 - (m_1 - (m_d - m_0))}{m_0} \times 100\% \tag{6}$$

where m_d is the weight after drying to eliminate the water trapped during immersion in water.

3.4 Breakdown test

It is believed that mixtures which contain high F&E content have a tendency to break down during compaction. According to Jiang et al. [18], changes in geometrical parameters of aggregate will affect the transmission of load in the asphalt mixture. F&E particles have a tendency to break down during compaction and will affect the overall stress-strain distribution in the asphalt mixture. Aggregate breakdown was tested after compaction with SGC. Each specimen was put into the oven at (538 ± 5)℃ until the mass was fixed. Gradation after ignition oven burn was determined by a sieve analysis, then compared to the design gradation and the percent breakdown calculated[19].

3.5 Permeability test

A permeability test[20] was performed to evaluate the influence of F&E contents on the permeability of PA. The permeameter was placed on the specimen, and the bottom of the permeameter was sealed with putty to ensure that no water would drain around the outer edges of the specimen (see Fig. 4). The test result was reported as the amount of water (mL) penetrating into the specimen within 15 s on average[21].

Fig. 4 Permeability test

4 Results and Discussion

This section presents the results of four groups (the control, original, 30% F&E content, and 40% F&E content) in terms of volumetric properties, the state of stone-on-stone contact, durability, skeleton stability and permeability. Test results are compared by statistical analysis with a 5% level of significance.

4.1 Volumetric properties

The volumetric properties of the four groups (the control, original, 30% F&E content, and 40% F&E content) are evaluated in this study and shown in Fig. 5. Fig. 5(a) shows the total AV of PA versus different F&E contents, and Fig. 5(b) shows the water-accessible AV versus the four F&E contents. The total AV with four F&E contents all satisfied the requirement of 18% minimum total AV. Statistical analysis results as shown in Tab. 4 indicate that no significant difference was found in total AV values among the control, original, and 30% groups. Meanwhile, no significant differences in water-accessible AV were found for all of the four groups. However, significantly different total AV can be found while F&E content changes up to 40%. This is different from the traditional dense graded mixtures. Mahboub et al. [22] conducted research to evaluate three groups (0%, 15% F&E content and 40% F&E content) on the volumetric properties of traditional dense graded mixtures. No significant difference was found in volumetric properties of 40% F&E content. In this study, the 40% F&E group

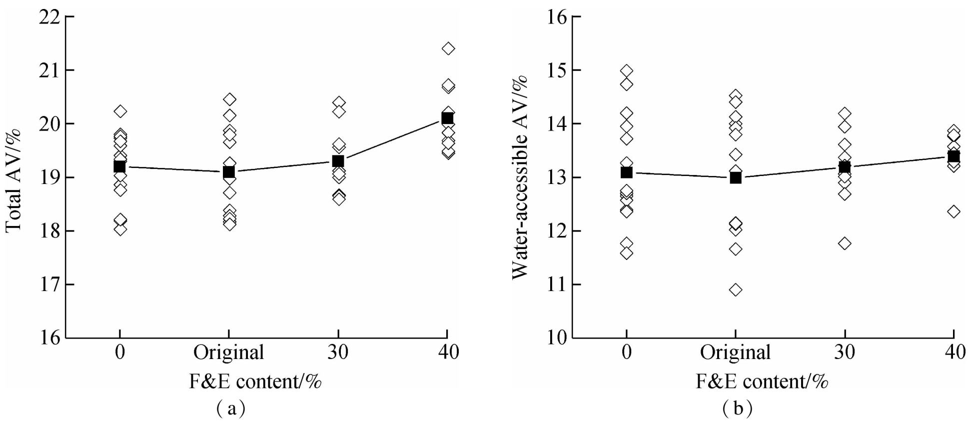


Fig. 5 Volumetric properties versus change in F&E contents. (a) Total AV; (b) Water-accessible AV

Tab. 4 Statistical analysis of various F& E contents ($\alpha = 0.05$)

F& E content/%	Total AV				Water-accessible AV			
	0	Original	30	40	0	Original	30	40
0		NS	NS	S		NS	NS	NS
Original	NS		NS	S	NS		NS	NS
30	NS	NS		S	NS	NS		NS
40	S	S	S		NS	NS	NS	

Note: S represents significant difference; NS represents no significant difference.

has the largest total AV and water-accessible AV. However, previous research concluded that the increased AV is false AV created by the fracture of coarse aggregate[23]. This can be verified by the later permeability test.

4.2 Stone-on-stone contact

The number of contact points (NCP) and total contact length (TCL) were chosen to define the state of stone-on-stone contact[15]. The area of the analytical image for all specimen sections is 6 500 mm^2. The average values of two replicate images for each F&E content are shown in Fig. 6. NCP represents the connectivity of the internal aggregate structure. Higher NCP can lead to a better stress distribution with fewer stress concentrations. Longer contact length can increase the friction and interlocking between aggregates[15]. TCL and NCP show a good susceptibility to the change of F&E contents. The original group has the largest value of NCP and TCL, while 40% F&E content mixture is the smallest. The PA of 40% F&E content has the weakest resistance to permanent deformation. Statistical analysis results are presented in Tab. 5 and a significant difference was observed in NCP among the four F&E groups. Oduroh et al. [24] concluded that up to 40% of F&E (3:1) particles could be permitted in a mixture without negative effects on its performance. Apparently, the PA does not agree with this conclusion.

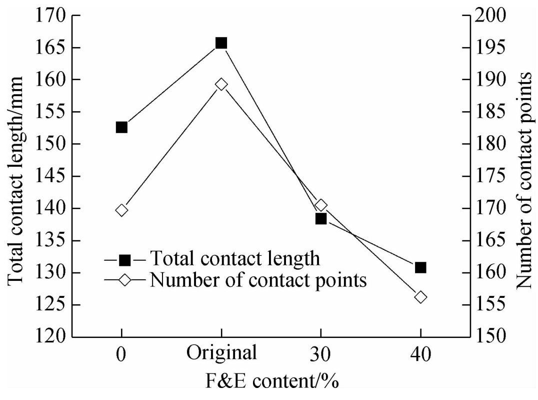


Fig. 6 Average image analysis results versus change in F&E content

Tab. 5 Statistical analysis of image analysis results ($\alpha = 0.05$)

F& E content/%	Total contact length				Number of contact points			
	0	Original	30	40	0	Original	30	40
0		S	NS	S		S	S	S
Original	S		NS	NS	S		S	S
30	NS	NS		NS	S	S		NS
40	S	NS	NS		S	S	NS	

4.3 Durability

The Cantabro loss test results at different conditions and F&E contents are presented in Fig. 7. To guarantee the durability of PA, it is recommended that Cantabro loss should not exceed 20% for unaged specimen and 30% for aged specimen[17]. Fig. 7 indicates that the four F&E groups all satisfied this requirement. Statistical analysis presented in Tab. 6 indicates that there are no significant differences in Cantabro loss for dry, wet, and 7 d aging conditions among the control, original, and 30% groups. When the F&E content is up to 40%, significant difference is found under wet and 7 d aging conditions. Compared with the control group, the Cantabro loss of the 40% group is increased by 77.9%, 128.2% and 97.8% under wet, 7 d aging, and dry conditions, respectively. Therefore, the long-term durability and moisture susceptibility of PA will be deteriorated when the F&E content is high.

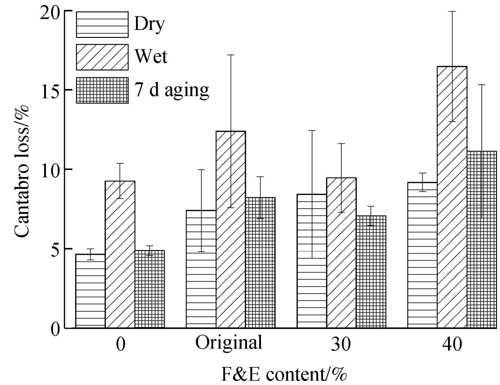


Fig. 7 Average cantabro loss for different F&E contents

Tab. 6 Statistical analysis of various F& E contents (α = 0.05)

F& E content/%	Dry condition				Wet condition				7 d aging condition			
	40	0	Original	30	40	0	Original	30	40	0	Original	30
0		NS	NS	NS		NS	NS	S		NS	NS	S
Original	NS		NS	NS	NS		NS	NS	NS		NS	NS
30	NS	NS		NS	NS	NS		NS	NS	NS		NS
40	NS	NS	NS		S	NS	NS		S	NS	NS	

4.4 Breakdown

The results of the breakdown test are presented in Fig. 8, in which strong linear relationships between F&E contents and percent breakdown are observed on the 2.36 mm sieve and 4.75 mm for the PA mixture. The percent breakdown increased significantly with the increase of the F&E content and this trend was reported in previous research[9]. As reported by previous research, the percent of aggregate breakdown was 3.0% on the 4.75 mm sieve for dense graded mixture with 30% F&E content[9]. In this research, the percent of aggregate breakdown is 6.8% with the same F&E content for the PA mixture. Greater breakdown of 9.1% and 6.3% on 4.75 mm and 2.36 mm are observed for 40% F&E content. Therefore, PA mixture has greater risk of breakdown than dense graded mixture because it has an open graded aggregate structure. High F&E content has a significant influence on the percent breakdown, and this may induce the failure

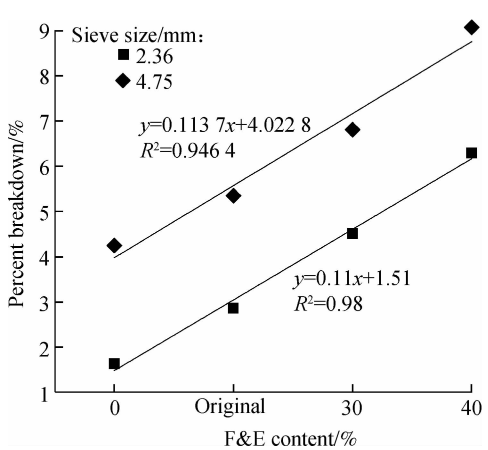


Fig. 8 Aggregates percent breakdown versus change in F&E content

of the aggregate structure. Based on previous studies, F&E contents did not have significant influence on the performance of traditional dense graded mixtures even though they are up to 40%[22, 24]. However, the F&E contents have a significant influence on the performance of the PA, and 40% F&E content seriously reduced the performance of the PA. It can be concluded that the PA is more sensitive to the F&E content than traditional dense graded mixtures.

4.5 Permeability

The permeability of PA for the four F&E contents of 0%, original, 30%, and 40% is 74.9, 81.8, 68.6, and 62.3 mL/s, respectively. The lowest permeability satisfies the requirements of minimum 60 mL/s[21]. Fig. 5 (a) shows that the 40% F&E group has the largest total AV and water-accessible AV. Based on the previous research, permeability increased with the increase of total AV and water-accessible AV[4]. However, the 40% F&E group had the lowest permeability in this study. Permeability decreased with the increase of the F&E content because the breakdown greatly increased false voids. As shown in Tab. 7, a significant difference can be found for the four F&E groups. F&E content has a significant influence on the permeability, and permeability may constantly deteriorate during long-term operations.

Tab. 7 Statistical analysis with different F&E contents (α = 0.05)

F& E content/%	0	Original	30	40
0		S	S	S
Original	S		S	S
30	S	S		S
40	S	S	S	

5 Conclusions

1) A significant difference in total AV is found as the F&E content reaches up to 40% and the F&E content has no significant influence on the water-accessible AV. However, a significant difference in permeability is found among the four F&E groups. The 40% F&E group has the lowest permeability even though total AV and water-accessible AV are the largest. This phenomenon can be attributed to the fact that the increased AV created by breakdown is false AV. Therefore, the F&E content has a significant influence on the functionality of the PA.

2) 2-D image analysis, the Cantabro loss test, and breakdown test were conducted in this study. Results indicate that F&E particles have negative effects on the rutting resistance, long-term durability and skeleton stability. At the same F&E content, the PA was observed to have significant negative effects on the performance while traditional dense graded mixtures did not. PA has greater breakdown than dense graded mixtures, and breakdown exacerbates negative effects.

3) From what was discussed above, the PA is more sensitive to F&E particles due to an open graded aggregate skeleton with a larger proportion of coarse aggregates. Specifications should recommend different F&E limitations for PA and traditional dense graded mixtures instead of having the same.

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粗集料针片状对多孔沥青混合料性能的影响

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摘要: 研究了4种粗集料针片状颗粒含量(0%, 原状, 30%, 40%)对多孔沥青混合料骨架结构和性能的影响. 分别采用二维数字图像处理、飞散试验、混合料破碎试验以及渗透试验, 评价针片状对多孔沥青混合料的体积指标、骨架接触特性、耐久性、骨架稳定性和渗透性能的影响. 试验结果表明: 针片状含量对多孔沥青混合料的空隙率、骨架接触线长度、骨架接触点个数、集料破碎率和渗透系数具有显著的影响. 由于粗集料针片状的破碎, 多孔沥青混合料的有效空隙率、高温性能、长期耐久性以及骨架稳定性随着针片状含量的增大而衰减. 与传统密级配沥青混合料相比, 由于多孔沥青混合料具有开级配骨架, 从而对针片状含量更加敏感, 多孔沥青混合料应采用更严格的针片状含量要求.

关键词: 多孔沥青混合料; 针片状; 骨架稳定性; 耐久性; 渗透性

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