Hindawi
Journal of Engineering
Volume 2020, Article ID 1261368, 7 pages
https://doi.org/10.1155/2020/1261368

Research Article

Standard of Crushing Value of Coarse Aggregates for Permeable Asphalt Mixture Based on Contact Stress between Aggregates

Tian Xiaoge,[1,2] **Wang Xiaofei**,[2] **and Yuan Huitong**[2]

[1]*State Engineering Laboratory of Highway Maintenance Technology, Changsha University of Science and Technology, Changsha, Hunan 410114, China*
[2]*School of Traffic and Transportation Engineering, Changsha University of Science and Technology, Changsha, Hunan 410114, China*

Correspondence should be addressed to Tian Xiaoge; tianxiaoge@126.com

Received 7 October 2019; Revised 20 December 2019; Accepted 2 January 2020; Published 20 January 2020

Academic Editor: Xing Ma

Crushing resistance of coarse aggregate is the key to the stability and durability of the skeleton structure of permeable asphalt (PA) mixture. To determine the technical requirements of crushing value of coarse aggregate used in PA mixture, step-loading compression tests were conducted on the mixtures of PA-13 and a control asphalt mixture AC-13, respectively. Virtual compression tests under the same loading conditions were simulated on the corresponding digital specimens with PFC2D®. By comparing the load-deformation curves obtained from the actual tests and virtual simulation, the values of the microscopic parameters of the two graded mixtures were obtained through trial calculation and adjustment. Then, the states of contact stress between aggregates in PA-13 and AC-13 mixtures under the standard crushing pressure (400 kN) were analyzed with PFC2D®. It was found that the average normal contact stress and the maximum normal contact stress between aggregates in PA-13 were 1.71 times and 1.28 times larger than those in AC-13, respectively. The crushing values of two different lithologic coarse aggregates were measured under different pressures, 400 kN or 600 kN, respectively. The crushing value criterion of coarse aggregates used in the PA mixture was suggested to be no greater than 16% after comparative analysis.

1. Introduction

Permeable asphalt (PA) mixture is a kind of skeleton-void mixture, and the vehicle load is mainly borne by the stone-stone contacting skeleton structure formed by coarse aggregates. So, the stability and durability of the skeleton are very important for PA mixture. If the compressive capacity of coarse aggregate is poor, some of the coarse aggregates will be crushed under the action of vehicle load, which will destroy the stability of the skeleton structure. As a result, the deformation resistance of PA mixture will be weakened, the voids in pavement will be reduced, and the drainage capacity will be gradually weakened. A stable skeleton structure is the key to ensure durable drainage of the PA pavement. The crushing of coarse aggregate in PA mixture is caused by the excessive contact pressure between aggregates, so the coarse aggregates are more easily crushed by vehicle load. So, the crushing value of coarse aggregate is very important for the durability of PA mixture [1–3].

Yan et al. proposed that the requirement for the crushing value should be no more than 20% [4]. Huang proposed that the crushing value of coarse aggregates for OGFC mixture should be no more than 25% [5]. Wu et al. proposed that the aggregate used for OGFC should meet the standard of SMA, and the crushing value of coarse aggregates should not be more than 24% [6]. Guo believed that the skeleton-void structure formed in the PA mixture reduced the contact area between the aggregates by about 25% compared with the ordinary dense graded asphalt mixture, resulting in an increase in stress magnitude between the contacting aggregates. Therefore, the properties of aggregates have a great influence on the properties of PA mixtures. It was proposed that the crushing value of the coarse aggregate used in PA mixture should be no more than 20% [7]. Liu et al. suggested that the crushing value of coarse aggregate for the OGFC-13 mixture should not exceed 15% [8]. Dang et al. proposed that the crushing value of coarse aggregate was not more than 15% [9]. Cao et al. suggested that it should be no more than 16% [10]. Wang et al. studied the effect of the change of the passing rates of aggregates with different particle sizes on the stability of the skeleton structure of PA mixture [11]. It can be seen that the researchers had realized the importance of the skeleton structure and stability of the PA mixture and proposed improving the crushing value technical requirements of the coarse aggregate for PA mixture. However, the proposed crushing values differed greatly, from 15% to 25%. This may be due to the lack of theoretical analysis and further research.

The authors suggested that the technical requirements for the crushing value of the coarse aggregate should be corresponding to the maximum value of contact pressure between the coarse aggregates in the asphalt mixture. So, the difference of the contact stress between coarse aggregate particles in the mixtures of PA-13 and AC-13 was analyzed through the discrete element method program, PFC2D®. Then, the crushing value tests were conducted on two kinds of coarse aggregates under two different pressures to obtain the effect of pressure to the crushing values. Finally, the technical requirement for the crushing value of coarse aggregate in the PA mixture was proposed according to the relationship between the crushing value of different lithologic aggregates and pressure.

2. Raw Materials

2.1. Coarse Aggregates. The coarse aggregates used in this paper were crushed from two different rocks, basalt aggregates produced by Shucheng Stone factory, and diabase aggregates produced by Dawang stone factory. Their technical indexes are shown in Table 1.

2.2. Fine Aggregates. The fine aggregates used in this paper are the machine-made sand, crushed with basalt stone. Its technical indexes are shown in Table 2.

2.3. Densities of Basalt Aggregates. The apparent densities of basalt aggregates of different sieve sizes are shown in Table 3.

3. Gradation of the Mixtures

Asphalt concrete AC-13 is commonly used for surface course of asphalt pavement. PA mixture used for surface course of permeable asphalt pavement is usually PA-13. And, in Chinese technical specifications of asphalt pavement construction, the criterion for crushing value of coarse aggregate in PA mixture is the same as that in AC mixtures, no greater than 26%. So, the state of contact stress between coarse aggregates in PA-13 mixture and that in AC-13 mixture was compared. Both of their gradations are the median gradations recommended by the Chinese specification [3], as shown in Table 4.

4. Digital Specimens of the Graded Mixtures

4.1. Mold. Because both of the molds used in step-loading compression test and crushing value test are cylindrical steel models, a closed rectangle generated by the built-in command “wall” in PFC2D® was used to simulate the mold. The width of the mold, D, is 150 mm and its height, h, is 100 mm. Four walls were used to constrain the particle elements in the mold, and the external pressure is simulated by moving the wall 3 down. Wall 1, wall 2, and wall 4 were fixed constraints [12], as shown in Figure 1.

4.2. Particle Size and Number. According to the gradations of the mixtures (Table 4) and the apparent densities of different sizes of aggregates (Table 3), the mass ratios of aggregates were converted into area ratios under the two-dimensional plane state.

The numbers of aggregates at every sieve size can be calculated through equation (1) assuming that aggregates of particle size i were evenly distributed between the maximum particle diameter r_{h} and the minimum particle diameter r_{l}:

$$n_i = \frac{A_i}{\pi\left[\left(r_{\mathrm{h}} + r_{\mathrm{l}}\right)/2\right]^2}, \tag{1}$$

where n_i is the number of aggregates remains on the sieve size i, A_i is the total area of aggregates with size i, and r_{h} and r_{l} are the maximum and minimum radii of aggregates with size i.

4.3. Method of Particle Placement. The expansion coefficient method [12–14] was utilized to generate the digital specimens of graded mixtures. To avoid excessive overlap between the randomly generated particles, the expected final particle sizes were firstly divided by the specified constant coefficient, m, to reduce their sizes (equation (2)). After the specified number of particles was generated, all of the particles were expanded with the same expansion factor, m, to meet the desired void ratio:

$$m = \sqrt{\frac{1-n}{1-n_0}}, \tag{2}$$

where n_0 is the void ratio after particles’ radii were decreased and n is the void ratio after particles’ radii were expanded. ($m = 1.6$ was taken in this paper).

According to the gradations in Table 4, digital specimens of graded mixtures PA-13 and AC-13 were randomly generated with PFC2D through the expansion coefficient method, as shown in Figure 2.

5. Values of Microscopic Parameters of Graded Mixtures

PFC2D® is a system based on the discrete element method, and some microscopic parameters such as particle element and contact between particle elements are needed to simulate the flow and deformation of particles aggregation model under external load, for example, normal stiffness of particles

Table 1: Technical indexes of basalt coarse aggregates.

Items	Apparent density (g/cm^3)	Needle-like content (%)	Crushing value (%)	Water absorption rate (%)	Soundness (%)	Los angeles wear loss (%)
Specification	—	≤15	≤26	≤2.0	≤12	≤20
Basalt	2.737	3.9	13.4	1.08	—	10.3
Diabase	2.762	3.2	10.1	0.87	—	8.43

Table 2: Technical indexes of fine aggregates.

Items	Apparent density (g/cm^3)	Sand equivalent (%)	<0.075 mm content (%)	Methylene blue value (g/kg)	Angularity (s)
Specification	—	≥60	≤3.0	≤25	≥30
Measured	2.82	78	2.0	0.8	44.3

Table 3: Apparent densities of basalt aggregates.

Particle size (mm)	13.2~16	9.5~13.2	4.75~9.5	2.36~4.75	0~2.36
Apparent density (g/cm^3)	2.728	2.737	2.742	2.743	2.82

Table 4: Mineral gradations of AC-13 and PA-13 mixtures.

Mixtures	Passing rates through the following sieve sizes (mm) (%)									
	16	13.2	9.5	4.75	2.36	1.18	0.6	0.3	0.15	0.075
AC-13	100	96.5	71.8	41.9	28.3	20.5	15.2	11.0	8.6	5.6
PA-13	100.0	92.5	60.9	20.1	14.9	11.0	8.9	6.9	6.0	5.0

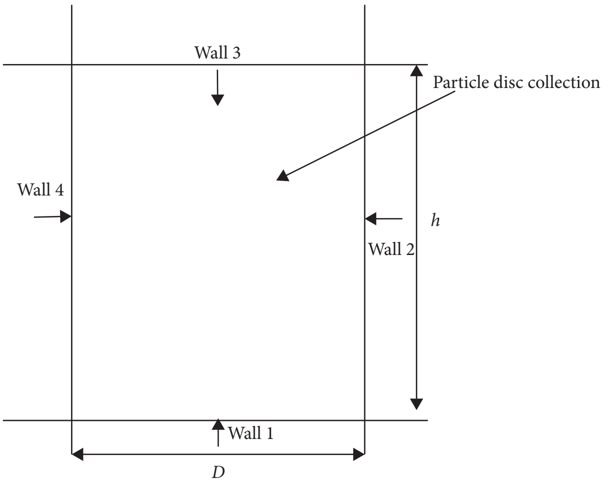

Figure 1: Digital mold and loading mode.

(K_n), tangential stiffness of particle (K_s), friction coefficient (μ), normal stiffness of the loaded walls (K_{jn}), and normal stiffness of restraint wall (K_{yn}). The values of these microscopic parameters have a great influence on the simulation results of PFC [15]. However, there is no suitable test method to determine the values of these microparameters so far. In this paper, the method and steps to determine the values of these related microscopic parameters are as follows.

5.1. Method. Determining the values of every microscopic parameters of the mixture is elaborate for virtual simulation with PFC2D® [13]. The method applied to obtain the values of every microscopic parameters of graded mixture was as follows:

(a) A set of initial values of the microscopic parameters was assumed, and then PFC2D® was used to simulate the step-loading compression process on the digital specimen (Figure 2) to obtain the simulated load-displacement relationship.

(b) Graded aggregates specimen was prepared according to the gradation and step-loading compression was exerted on it, and the actual load-displacement curve was measured.

(c) The simulated load-displacement curve was compared with the measured curve. If the deviation between the two curves exceeded allowance, the assumed values of the microscopic parameters should be adjusted and then simulated again until the deviation met the allowance.

In this way, the final fine-tuned values of the microscopic parameters can be taken as the actual values of the microscopic parameters of the gradation mixture. The specific process is shown in Figure 3.

5.2. Step-Loading Compression Test on Graded Mixture. Cylindrical steel mold, whose diameter is 150 mm and height is 100 mm, were filled with graded aggregates for the step-loading compression test. The aggregates at different sizes were weighed, respectively, according to its gradation (Table 1), mixed uniformly and poured into the mold by loose packing and stacking method. Then, the step-loading

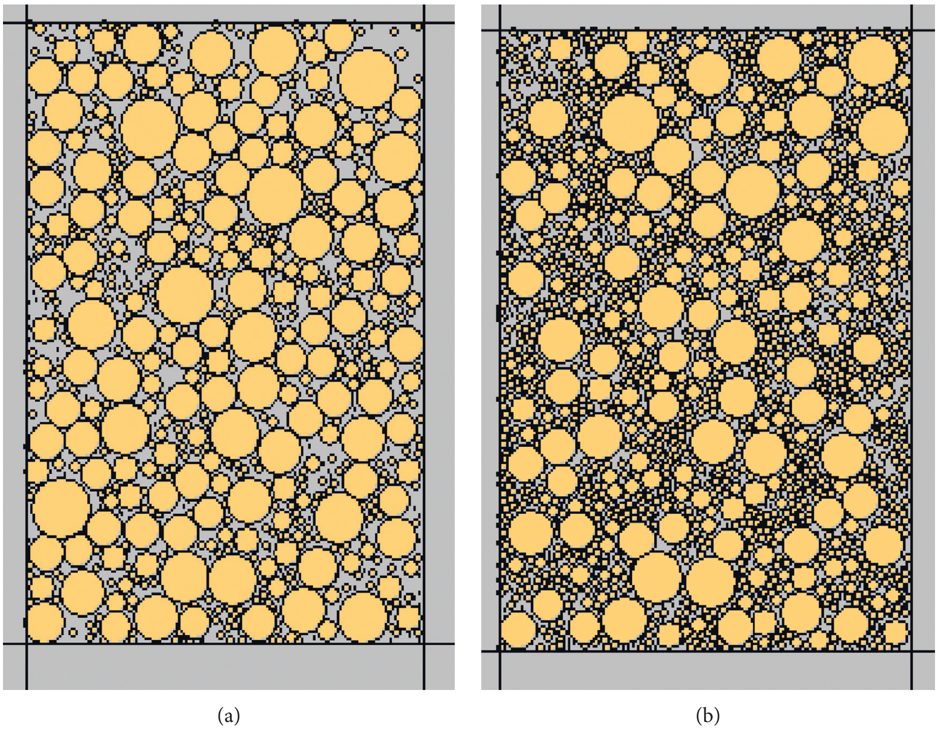

Figure 2: Digital specimens of the graded mixtures. (a) PA-13. (b) AC-13.

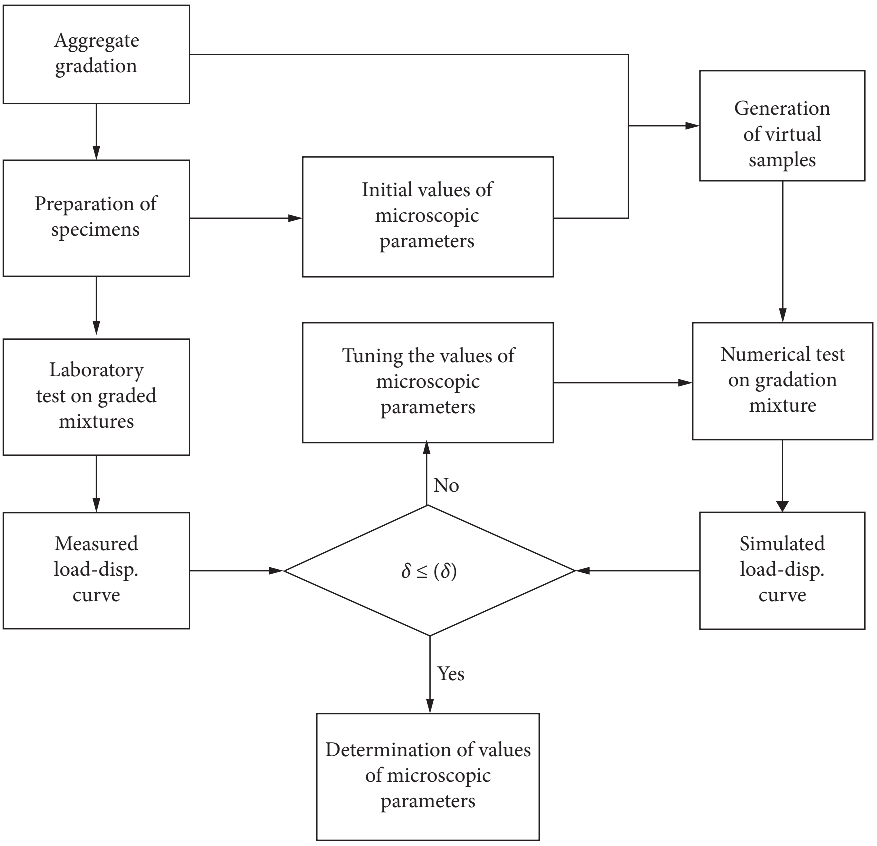

Figure 3: Method of determining the values of microscopic parameters of graded aggregates.

compression test [16] was carried out through the hydraulic servo material testing machine, MTS-810. The pressure was stepwise increased by 50 kN until it reached to 400 kN. The measured vertical deformation curves to pressure of the two graded mixtures are shown in Figure 4.

5.3. Microscopic Parameters of the Graded Mixture. According to the abovementioned method, the values of the microscopic parameters of the two graded mixtures were obtained, as shown in Table 5.

6. Contact Stress States between Aggregates in Graded Mixtures

The digital specimens of PA-13 and AC-13 mixtures (Figure 2) with the values of their microscopic parameters (Table 5) were step-loading compressed to 400 kN in PFC2D® system, respectively, which is called thevirtual crushing value test. The maximum pressure applied to the wall 3 is 2.26×10^7 Pa, which is equivalent to 400 kN exerted on the actual cylindrical specimen. The state of microscopic contact stress between aggregates in the digital specimens was obtained, as shown in Figure 5.

Figure 5 shows the transfer path of the maximum pressure (400 kN) in the two different graded mixtures under lateral restraint conditions. The thickness of the black mesh lines indicates the magnitude of the contact stress between aggregates or the contact stress between aggregate and inner wall of steel mold. The thicker the mesh line, the greater the contact stress. It can be clearly seen that the contact stresses in the PA-13 mixture is significantly greater than those in the AC-13 mixture.

Virtual crushing values tests were simulated three times as above with different aggregates distribution in specimens to take into account the effect of random distribution of aggregates in the actual specimens. The simulation results are shown in Table 6.

It can be seen from Table 6 that the normal contact stress between aggregates in the PA-13 mixture is significantly greater than that in the AC-13 mixture. The average value of the normal contact stress in the PA-13 mixture is 5.340/3.127 = 1.71 times greater than that in AC-13 mixture. The maximum value of the normal contact stress in the PA-13 mixture is 4.183/3.260 = 1.28 times greater than that in the AC-13 mixture.

7. Effect of Pressure on the Crushing Value of Coarse Aggregate

The greater the pressure on aggregate, the easier it will be crushed. When the crushing test of coarse aggregates is carried out, the contact stress between coarse aggregates should be consistent with the actual contact stress between coarse aggregates in actual pavement. Therefore, the maximum pressure applied on the coarse aggregate specimen should be varying with the gradation of the mixture. The value of maximum pressure in the crushing test of coarse aggregate should not be a fixed value, 400 kN, for all kinds of asphalt mixtures. According to the results of PFC2D® analysis, the contact stress between coarse aggregates in PA-13 mixture is higher than that in AC-13 mixture to reflect the difference of contact stress between coarse aggregates.

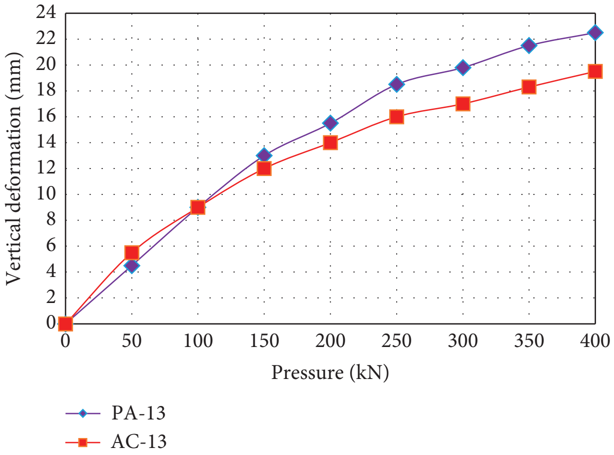

Figure 4: Measured vertical deformation to pressure of graded mixtures.

It can be seen from Table 6 that, under the same external pressure, the average contact stress and the maximum contact stress between coarse aggregates in the PA-13 mixture were 1.71 times and 1.28 times greater than those in the AC-13 mixture, respectively. A multiple factor of 1.5 was yielded through averaging these two ratios. So, it was proposed that the maximum pressure of the crushing value test for coarse aggregates used in PA mixture should be increased to 1.5 times of the maximum pressure in the standard crushing value test. That is, the maximum pressure should be increased from 400 kN to 600 kN. Meanwhile, if the loading rate remains unchanged, the loading time will be extended from 10 minutes to 15 minutes.

Coarse aggregates of two different lithologies, basalt and diabase, that can be used for PA mixture, were subjected to the crushing value test with different maximum pressures, 400 kN and 600 kN, respectively [16]. The results are shown in Table 7.

It can be seen from Table 7 that, when the maximum pressure was increased to 600 kN, the crushing values of the two lithologic aggregates were larger than those under the standard pressure, 400 kN. But, the increased ratio is different from the lithologic type of aggregates. For basalt aggregate, it increased by 1.48 times and it increased by 1.63 times for diabase aggregate. So, it can be derived that diabase aggregate is more sensitive to the pressure. Therefore, in order to ensure stability and durability of skeleton-void structure in PA mixture, the criteria of crushing value of coarse aggregate used in PA mixture should be improved.

8. Recommended Crushing Value Standard of Coarse Aggregate in PA Mixture

In current Chinese technical specification, the crushing value of the coarse aggregate for surface layer of asphalt pavement is no greater than 26% [1]. So, the crushing value standard of

Table 5: Values of the microscopic parameters of graded mixtures.

Gradation type	Normal stiffness of particles, K_n (N/m)	Tangential stiffness of particles, K_s (N/m)	Friction coefficient μ	Void ratio p	Normal stiffness of the loaded wall, K_{jn} (N/m)	Normal stiffness of the restraint walls, K_{yn} (N/m)
PA-13	7.6*e*8	7.5*e*8	0.5	0.28	7.6*e*9	7.6*e*7
AC-13	7.6*e*8	7.6*e*8	0.5	0.27	7.6*e*9	7.6*e*7

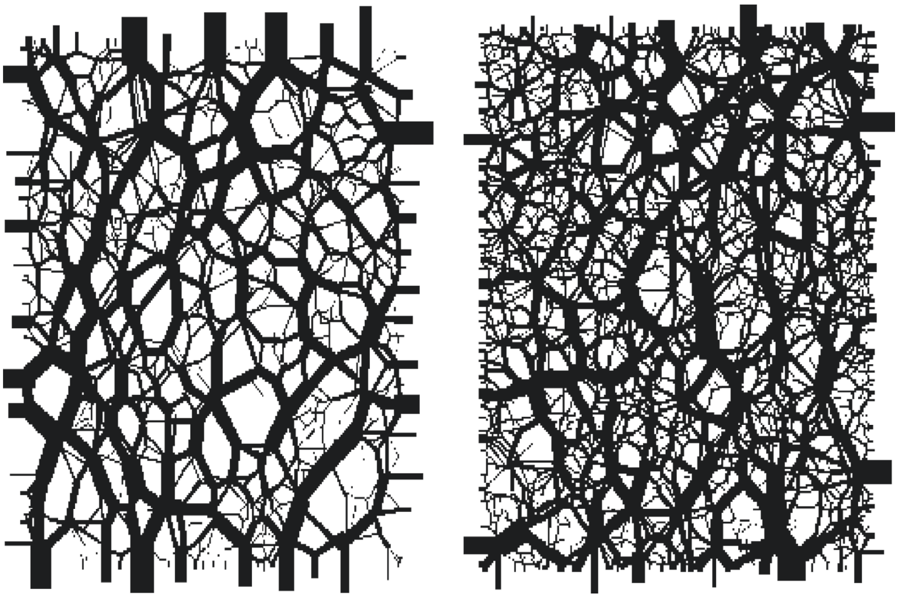
(a) (b)

Figure 5: Microscopic contact stresses between aggregates. (a) PA-13. (b) AC-13.

Table 6: Simulated microscopic normal contact stresses between aggregates.

Simulation No.	PA-13		AC-13	
	Average (10^4 Pa)	Maximum (10^5 Pa)	Average (10^4 Pa)	Maximum (10^5 Pa)
1	5.448	4.161	3.191	3.262
2	5.044	4.106	3.068	3.184
3	5.527	4.283	3.123	3.335
Average	5.340	4.183	3.127	3.260

Table 7: Measured crushing values of coarse aggregates under different maximum pressures.

Lithology of aggregate	Maximum load (kN)	Crushing value (%)					
		1	2	3	Average	Ratio	Average ratio
Basalt	400	13.6	12.8	13.2	13.2	—	1.56
	600	19.3	18.5	20.6	19.5	1.48	
Diabase	400	11.8	8.3	10.2	10.1	—	
	600	15.7	16.2	17.6	16.5	1.63	

basalt coarse aggregate used in PA mixture should be increased to not more than 26%/1.48 = 17.6%. As for diabase aggregate, it should be no more than 26%/1.63 = 16.0%.

Aggregates of different lithologies produced from different places have different mechanical properties, and their crushing values vary with pressure. Although only two kinds of aggregate were compared in this paper, considering the importance of improving the crushing value standard of coarse aggregate for improving the durability of PA pavement, it is suggested that the crushing value should be no greater than 16% to ensure the stability and durability of its skeleton-void structure in PA mixture.

9. Conclusions

In this paper, microscopic contact stresses between aggregates in PA-13 mixture and those in AC-13 mixture were compared through simulation with PFC2D®. The crushing value tests were physically conducted on two kinds of coarse aggregates under two different maximum pressures of 400 kN and 600 kN, respectively. Finally, the crushing value standard of coarse aggregates for PA mixtures was proposed. The following conclusions were obtained.

(1) The average and maximum values of contacting stresses between aggregates in the PA-13 mixture are 1.71 times and 1.28 times greater than those in the AC-13 mixture, respectively. The average of these two values is 1.5.

(2) It was proposed that the maximum pressure in the crushing value test for coarse aggregate used in PA mixture should be increased 1.5 times from 400 kN to 600 kN, according to the relationship between the contact stress of aggregates in the PA-13 and that in the AC-13 mixtures.

(3) It was found that the crushing value of coarse aggregate increased with the increases of the maximum pressure. The larger the maximum pressure was, the more the amount of aggregates was crushed. The increased multiple of crushing values of basalt and diabase aggregates were 1.48 and 1.63 times, respectively, when the maximum crushing load was increased from 400 kN to 600 kN.

(4) It was proposed that the crushing value of coarse aggregate used in PA mixture should be increased to no more than 16% according to current Chinese technical specifications.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

Acknowledgments

The authors appreciate the support of the National Natural Science Foundation of China (51978086).

References

[1] M. Razzaghmanesh and S. Beecham, "A review of permeable pavement clogging investigations and recommended maintenance regimes," *Water*, vol. 10, no. 3, p. 337, 2018.

[2] X. Tian, H. Han, Q. Zhang, X. Li, and Y. Li, "Design and performance of anticracking asphalt-treated base," *Advances in Materials Science and Engineering*, vol. 2017, Article ID 2394945, 9 pages, 2017.

[3] JTG F40–2004, *Technical Specifications for Construction of Highway Asphalt Pavements*, China Communications Press, Beijing, China, 2004.

[4] X. Yan and J. Liu, "Application of OGFC13 open grade surface layer in Xi'an-Xianyang airport expressway," in *Proceedings of Road Engineering Academic Exchange Conference*, Beijing, China, 2004.

[5] S. Huang, *Study on the Grade and Performance of Open-Graded Friction courses (OGFC)*, Wuhan University of Technology, Wuhan, China, 2004.

[6] W. Wu, Y. Gao, X. Huang et al., "Study on the application of open grade friction course," *Modern Transportation Technology*, vol. 2, no. 1, pp. 13–17, 2005.

[7] Y. Guo, *Application Study on Expressway Porous Asphalt Mixture*, Southeast University, Nanjing, China, 2006.

[8] J. Liu, D. Ma, G. Zhang et al., "Design of mix for OGFC-13 porous asphalt concrete pavement," *Highway*, vol. 2, no. 6, pp. 163–167, 2009.

[9] Y. Dang, A. Li, H. Li et al., "Optimization study on mix design of drainage asphalt mixture," *Highway*, vol. 6, no. 6, pp. 147–150, 2009.

[10] D. Cao, Q. Liu, and G. Tang, *Porous Asphalt Pavement*, China Communications Press, Beijing, China, 2010.

[11] X. Wang, X. Gu, J. Jiang, and H. Deng, "Experimental analysis of skeleton strength of porous asphalt mixtures," *Construction and Building Materials*, vol. 171, pp. 13–21, 2018.

[12] Itasca Consulting Group, Inc., *Particle Flow Code in 2 Dimensions, PFC2D® Version 3.0*, Itasca Consulting Group, Minneapolis, MN, USA, 2002.

[13] X. Tian, "Double side shear fatigue property of anti-cracking asphalt stabilized macadam," *Jianzhu Cailiao Xuebao/Journal of Building Materials*, vol. 21, no. 1, pp. 165–168, 2018.

[14] H.-N. Wang and P.-W. Hao, "Advances in microstructure study on asphalt mixture," *Journal of Changan University (Natural Science Edition)*, vol. 28, no. 3, pp. 11–15, 2008.

[15] J. Zhou, Y. Chi, Y-W. Chi et al., "The method of particle flow and PFC2D® code," *Rock and Soil Mechanics*, vol. 21, no. 3, pp. 271–274, 2000.

[16] JTJ058-2000, *Test Methods of Aggregate for Highway Engineering*, China Communications Press, Beijing, China, 2000.