Effect of Gradation Variability on Volume Parameter and Key Performances of HMA

Shutang Liu[1], Lin Zhu[1], Huiqin Zhang[2]*, Tao Liu[2], Ping Ji[2] and Weidong Cao[1]*

[1]School of Qilu Transportation, Shandong University, Jinan, China, [2]Shandong Hi-Speed Technology Development Group Co., Ltd., Jinan, China

The graded mineral aggregate composed of coarse aggregate, fine aggregate, and mineral powder is the main component of hot asphalt mixture (HMA), and it occupies a mass ratio of more than 95% in HMA. The gradation variability of mineral aggregate is frequently an unavoidable problem in the construction of asphalt pavement engineering. In order to investigate the effect of gradation variability on the volume parameters and key performances of HMA, the asphalt concrete with a nominal maximum particle size of 20 mm (AC20) was selected as the research carrier. Firstly, a benchmark mineral aggregate gradation (BMAG) was designed based on the theory of dense skeleton gradation presented in the paper. Secondly, six types of HMA (that is, AC20) with variable gradations were also determined and all the specimens were prepared by rotary compaction process with the same optimum asphalt content (gradation varies but asphalt content remains the same), and finally based on asphalt pavement analyzer, the performances of all the specimens of each gradation were tested. The results show that, compared with the BMAG-HMA, the volume parameters such as air voids, voids in mineral aggregate, and voids filled with asphalt of the variable-graded HMA change in different directions, but the water stability and high-temperature performance both degrade greatly. The experimental results also show the feasibility and effectiveness of the dense skeleton gradation design theory adopted in this study.

Keywords: water stability, high-temperature performance, volume parameter, gradation variability, hot mix asphalt mixture

INTRODUCTION

Hot mix asphalt mixture (HMA) has become the main material of flexible pavement because of its good performance. However, due to the aggregate particles with different sizes and the inevitable variability of aggregate sources in actual engineering, HMA often has a certain degree of gradation variability in the construction process. Gradation variability can take many forms. For example, compared with the design gradation at the beginning, the overall gradation curve deviates upward causing the mixture to become finer or deviates downward causing the mixture to become coarser, or coarse aggregate and fine aggregate separate producing segregation and so on. The varying of mineral aggregate gradation must have some influence on the volume parameter and performance of HMA. Cominsky et al. (1994) have shown that the air voids (AV) and voids in mineral aggregate (VMA) are the two most important volume parameters of HMA. Therefore, people often use AV and VMA as the volume parameter for evaluation in research on HMA. By the rank-sum test method, Tan et al.

(2012), Xu (2007) analyzed the law between the AV and the trend of the gradation curve through the study of 11 gradation curves, and the results show that the change of fine aggregate has the greatest influence on the *AV* under the condition that the content of asphalt and the amount of mineral powder remain unchanged. Liu et al. (2005) studied the influence of gradation curve on AV based on the principle of gray correlation analysis and believed that the greater the correlation between the gradation curve and the theoretical maximum density line, the smaller the *AV*. Wang et al. (2002) found a good correlation between *VMA* and the pass rate of 2.36 mm sieve size through statistical analysis for 150 groups of HMA. Lin (2005) studied the influence of gradation change on *VMA* and gave an equation to estimate its value. Praticò and Vaiana (2013) also showed that gradation is the internal factor that affects the *VMA* of HMA. By Bailey method Vavrik et al. (2002a), Vavrik et al. (2002b) indirectly showed the effect of gradation changes on the volume parameters, and gradation variability also affects the high-temperature performance, water stability, low-temperature performance, and fatigue performance of HMA. Yan (2007) showed that the effect of gradation on HMA accounts for 60–70%. Li (2016) conducted rutting tests on six gradations at 60°C under the condition of the optimum asphalt content and concluded that the dynamic stability is larger when the percentage passing the sieve of 2.36, 4.75, and 9.5 mm approaches the median gradation. Vavrik et al. (2004) analyzed the influence of the coarse aggregate ratio above the 4.75 mm sieve size on the high-temperature performance of the stone matrix asphalt (SMA), and the results show that the increase of larger particle size in the coarse aggregate can improve the high-temperature performance to a certain extent. Chen (2003) showed that increasing the amount of aggregate of 4.75–9.5 mm is conducive to improving high-temperature performance. Golalipour et al. (2012) divided the gradation range into upper, middle, and lower regions, analyzed the effects of gradation changes on rutting through Marshall Tests and dynamic creep tests, and found that the permanent deformation decreases when the gradation curve is close to the upper limit of the gradation. Matthews and Monismith (1992) studied, respectively, the effects of four kinds of temperature, two kinds of gradation and two kinds of asphalt on rutting, and found that when the gradation curve is close to the median gradation, the high-temperature performance is better than that of the coarse gradation. Using asphalt pavement analyzer (APA) as a test method, Kim et al. (2009) studied the high-temperature performance of four gradations, located, respectively, in the upper areas and lower areas beyond the control zone and the control zone. And the results show that the coarser gradation is more likely to produce ruts and the factor that affects the gradation performance is the degree of roughness and fineness of the gradation rather than the restricted area. Cheng et al. (2006) carried out the immersion Marshall test and freeze-thaw splitting test on four graded HMA with their respective optimal asphalt content (OAC), and the results show that the closer the gradation curve is to the theoretical maximum density line, the better the water stability is. Peng et al. (2013) selected five different gradations for the immersion Marshall test and

found that the water stability of HMA near the middle gradation is the best and the water stability of HMA with fine gradation is better than that of the coarse gradation. Xie (2011) showed that the best water stability of rubber HMA belongs to gap gradation. Huang et al. (2011) studied the effect of gradation on the water stability of AC13 (asphalt concrete with a nominal maximum diameter of 13 mm) using fractal theory and found that, in order to meet the freeze-thaw splitting strength ratio (>75%) of HMA, the fractal dimension value should not be < 2.432.

Zheng et al. (2012) showed that low-temperature damage is closely related to the gradation of HMA. Zhang et al. (2016) selected five kinds of rubber HMA for low-temperature bending test through the comprehensive parameters of bending strength, failure strain, and bending stiffness modulus, and the results show that the intermediate gradation has the best low-temperature performance. Ma et al. (2017) showed that increasing the fine aggregate content of HMA will reduce the resistance to low-temperature cracking. Garcia-Gil et al. (2019) discussed the effect of gradation of HMA overlay on the crack resistance at low temperature and concluded that the smaller the content of fine aggregate is, the smaller the nominal maximum particle size is and the stronger the crack resistance tends to be and concluded that the influence of fine aggregate content on the ductility of the mixture is greater than that of the nominal maximum particle size.

Kasu et al. (2019) evaluated the impact of nominal maximum particle size on the fatigue performance of the mixture at three stress levels and three loading frequencies, and the results show that a smaller nominal maximum particle size is beneficial to the fatigue performance. Valdes-Vidal et al. (2019) showed that fine aggregates could affect the energy dissipating in the process of HMA fatigue damage. Lv et al. (2020) showed that open-graded HMA has a better fatigue life than dense-graded HMA. Liu et al. (2019) used a uniaxial penetration test to study the fatigue performance of five kinds of HMA, and the results show that the fatigue performance of HMA with more fine aggregates and less coarse aggregates is better.

In summary, the above researches show that the aggregate gradation is directly related to the volume parameter, high-temperature performance, water stability, low-temperature performance, and fatigue performance of HMA, or it can be inferred that the change in gradation will bring changes to the volume parameters and performance parameters of HMA. However, firstly, these studies often focus on the direct comparison of HMA with different gradation, rather than specifically designing an aggregate gradation as the benchmark mineral aggregate gradation (BMAG) for comparison; therefore, in the strict sense, they are not studies on the influence of gradation variability on the performance of HMA. Secondly, these studies about the HMA were carried out with OAC of each aggregate gradation. However, in practical engineering, when the gradation variability occurs, the OAC designed for BMAG is often unchanged. Third, some of the conclusions of the above studies, such as the high-temperature performance, are inconsistent with each other. Therefore, it is still worth studying how the aggregate gradation variability

TABLE 1 | Specific gravity and water absorption test results of aggregates with different particle sizes and mineral powder.

Technical parameter	10–20 (mm)	5–10 (mm)	0–5 (mm)	Mineral powder	Technical requirements
Bulk specific gravity	2.642	2.627	—	—	—
Apparent specific gravity	2.716	2.720	2.719	2.771	≥2.5
Water absorption (%)	1.05	1.30	1.14	—	≤2.0

TABLE 2 | Particle composition of each grade of aggregate.

Size (mm)	Pass rate (%) of each sieve size (mm)											
	26.5	19	16	13.2	9.5	4.75	2.36	1.18	0.6	0.3	0.15	0.075
10–20	100	86.9	77.7	60.1	27.8	3.8	0	0	0	0	0	0
5–10	100	100	100	99.9	97.2	34.7	1.8	0.5	0.3	0.2	0.1	0
0–5	100	100	100	100	100	99.9	74	53.3	38	22.7	15.6	12.8
Mineral powder	100	100	100	100	100	100	100	100	100	99	90	75

TABLE 3 | Pass rate of 4.75 mm sieve size for each gradation and *VMA* of HMA (%).

Parameter	Gradation number		
	Gradation 3 (λ = 1.20)	Gradation 4 (λ = 1.27)	Gradation 5 (λ = 1.46)
Pass rate of 4.75 mm sieve size (%)	36.6	39.2	46.5
VMA (%)	13.2	12.7	13.4

quantitatively affects the volume parameters and performance parameters of HMA.

Taking into consideration the fact that the OAC in practical engineering is always strictly controlled and will not change, the gradation inevitably changes due to the instability of the particle composition of aggregates. Hence, the objective of this paper is to study the change of volume parameters, water stability, and high-temperature performance of HMA (the other performances are not discussed in the limited space) when the OAC of BMAG remains unchanged and the gradation of aggregate varies and to provide an important reference for controlling construction quality of asphalt pavement. It should be pointed out that the BMAG, which is used to compare the gradation variability, is designed by using the optimal design theory of mineral aggregate gradation established by the first author.

MATERIALS AND EXPERIMENTAL PROGRAM

Experimental Material
Mineral Aggregate and Its Technical Parameters
The HMA used in the study was determined as AC20, and the maximum size of aggregate was selected accordingly. Limestone aggregate with the size of 0~5, 5–10, and 10–20 mm was used, and the filler was limestone powder.

The specific gravity and water absorption of the aggregate and mineral powder were tested in accordance with the Chinese test method, and the test results were shown in **Table 1**.

The results of the sieving tests for aggregates of various particle sizes were shown in **Table 2**.

Asphalt and Its Properties
SBS-modified asphalt was used. The penetration (25°C, 100 g, 5 s) is 58 (0.1 mm), the ductility at 15°C is greater than 100 cm, and the softening point is 74.5°C, which were all measured according to the stand test method (JTG E20-2011, 2011).

Mineral Gradation Design and Asphalt Content Determination
Design of BMAG
To study the gradation variability problem, there needs a BMAG as the basis for judging the gradation variability. According to the optimal design theory of mineral aggregate gradation (Liu et al., 2015), the research intends to design a dense skeleton gradation (it should be pointed out that the skeleton density gradation here has a relative meaning and is different from SMA) as the basic gradation.

The design idea of the dense skeleton gradation of the literature is three steps (Zhang et al., 2016): firstly, a gradation curve (gradation no. 1) is drawn within the gradation range given in the specification, as shown in **Figure 1**. Secondly, according to the proportion of the determined mineral aggregate, the bulk specific gravity of composite coarse aggregate and apparent specific gravity of composite fine material (which is made up of fine aggregate and mineral powder) are calculated, and the voids of coarse aggregate as well as fine aggregates (4.75 mm is used as the boundary sieve size of coarse and fine aggregate in the
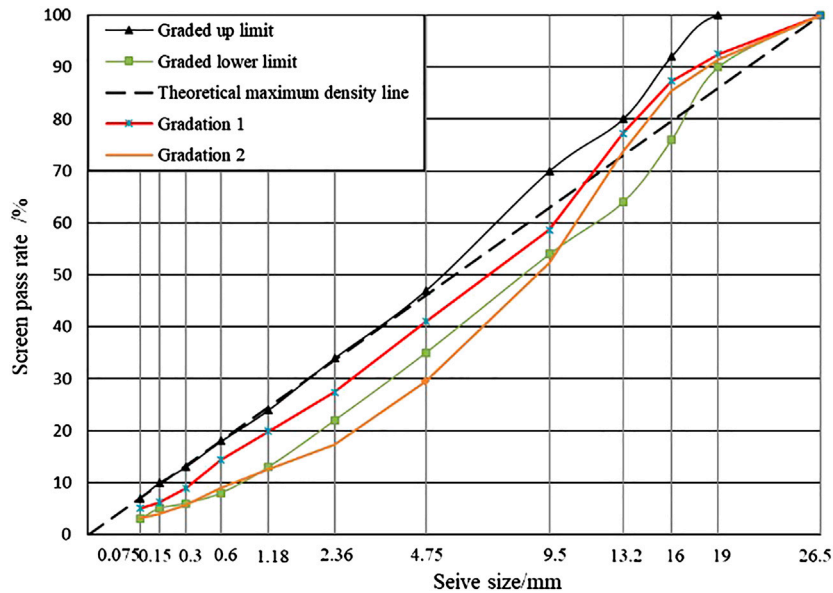
FIGURE 1 | Preliminary proposed gradation curve and theoretical dense skeleton gradation.

TABLE 4 | Average volume parameters of HMA for each gradation.

Gradation type	Volume parameter (%)		
	AV	VMA	VFA
BMAG	4.2	12.7	66.9
BMAG-F1	3.2	11.7	72.6
BMAG-F2	1.3	10.0	87.0
BMAG-C1	6.8	15.0	54.7
BMAG-C2	5.8	14.2	59.2
BMAG-D	5.5	13.7	59.9
BMAG-U	5.0	13.4	62.7

research for AC20; that is, aggregate with particle size greater than 4.75 mm is called coarse aggregate) are measured, respectively. Then, according to **Eq. (1)**, the pass rate of 4.75 mm sieve size of the skeleton density gradation can be calculated.

$$x_0 = \frac{1}{1 + \frac{\gamma_{ca}}{\gamma_{fa}} \frac{1-V_{CA}}{1-v_{fa}} \frac{1}{V_{CA}}} \qquad (1)$$

where x_0 is the pass rate of 4.75 mm sieve size of the skeleton density gradation; γ_{ca} is the bulk specific gravity of composite coarse aggregates, which is calculated by the bulk specific gravities of coarse aggregates with different particle size; γ_{fa} is the apparent specific gravity of composite fine material, and it is calculated by the apparent specific gravity of fine aggregate and mineral powder; V_{CA} is the void of coarse aggregate, which is obtained through the vibration test; v_{fa} is the void of composite fine material, and it is recommended that the void value should be for the natural stacking state without any external force being applied. In this research, V_{CA} and v_{fa} tested are 39.2 and 36.9%,

respectively; γ_{ca} and γ_{fa} calculated are 2.640 and 2.720, respectively.

Substituting the above four parameters into **Eq. (1)**, the pass rate of 4.75 mm sieve size can be calculated as 29.5%, and further calculation can give the dense skeleton gradation (gradation no. 2), as shown in **Figure 1**.

Note that gradation 2 has broken the lower limit of the gradation range. At the same time, it should be pointed out that **Eq. (1)** is established for graded mineral aggregate without asphalt and based on certain assumptions (such as ignoring the interference of fine aggregates on the arrangement of coarse aggregates). Therefore, the calculated gradation 2 is theoretically a dense skeleton gradation without any asphalt and formed by the vibration test (because the void of coarse aggregate is obtained by the vibration test). Actually, when the coarse aggregates and fine materials are mixed and gradually become dense under a certain compaction process, the fine aggregates inevitably have a certain interference effect on the coarse aggregate arrangement. Therefore, V_{CA} in the actual dense skeleton gradation will certainly be larger than that of the simple coarse aggregate vibration test. The practical dense skeleton gradation curve is necessarily located above the gradation curve 2, and its specific location could be obtained tentatively based on gradation 2.

Assume that the interference of fine aggregate increases the void of coarse aggregate in dense skeleton gradation to λV_{CA}. Here, λ is the coefficient, let λ be 1.20, 1.27, and 1.46, respectively, the corresponding x_0 is recalculated according to **Eq. (1)**, and three gradation curves are further calculated (the numbers are gradation 3, gradation 4, and gradation 5, respectively), which are shown in **Table 3** and **Figure 2**.

The rotary compactor was employed to make the specimens of HMA; and the bulk specific gravities of the
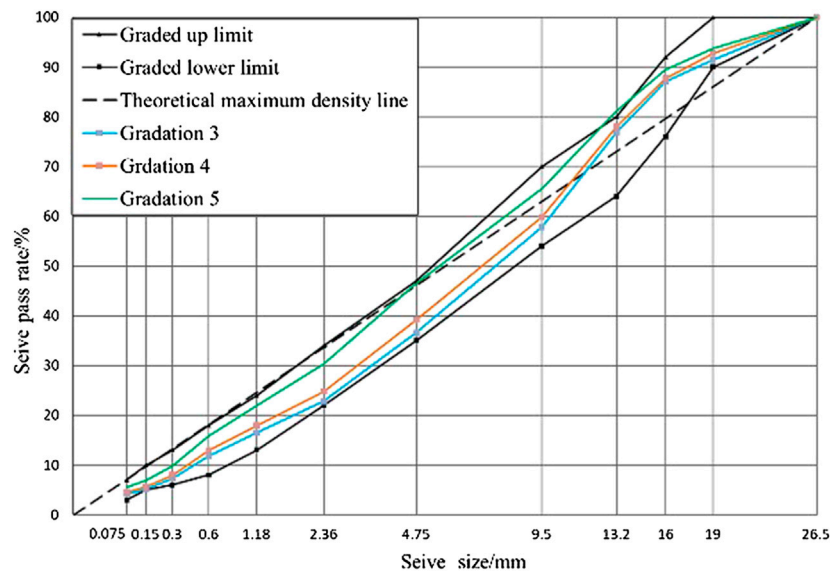
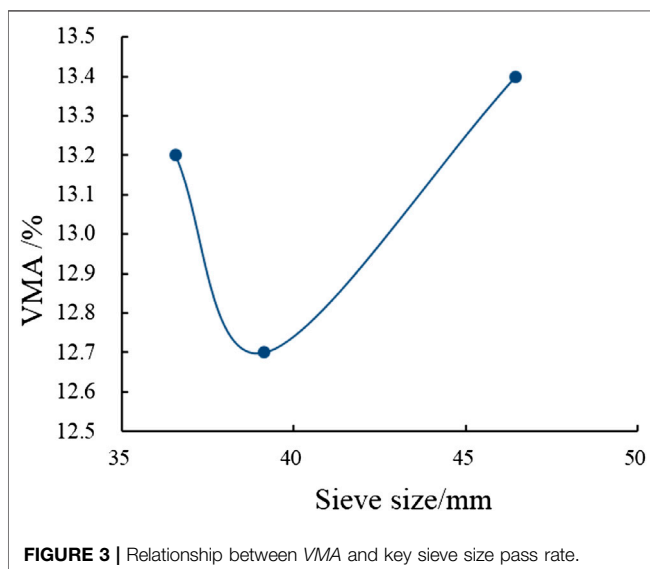**FIGURE 2 |** Possible actual curves of dense skeleton gradation.

FIGURE 3 | Relationship between *VMA* and key sieve size pass rate.

specimens were measured and *VMA* were calculated, as shown in **Figure 3**.

It can be seen from **Figure 3** that the *VMA* curve presents an asymmetric concave curve shape and gets the valley value when λ is 1.3. The smaller *VMA* is a typical feature of dense skeleton gradation and a criterion for determining whether a gradation is a dense skeleton gradation. Therefore, it can be determined that gradation 4 is the skeleton dense type gradation, and it should be taken as the BMAG.

Design of Variability Gradation

There are many possible situations of gradation variability. As an experimental study, this research designs the following three types of gradation variability based on BMAG: 1) Keep the shape of the gradation curve of the coarse aggregate section of the BMAG unchanged and change the gradation curve of the fine material section, and two variable gradations BMAG-F1 and BMAG-F2 are obtained (the two variability gradation curves are both above the BMAG curve. Because of the gradation characteristics of fine material employed in the research, it was not possible to design a variable gradation below the BMAG curve). 2) Keep the shape of the gradation curve of the fine material section of the BMAG unchanged and change the gradation curve of the coarse aggregate section, and two variable gradations BMAG-C1 and BMAG-C2 are obtained. 3) By deviating the whole gradation curve from the BMAG, two variability gradation curves BMAG-U and BMAG-D located, respectively, above and below the BMAG curve are obtained. The above six variability gradation curves are shown in **Figures 4–6**, respectively.

Determination of Asphalt Content

The asphalt-aggregate ratio (P_a) for the BMAG should be designed firstly. In order to reduce the test workload and improve the efficiency of the study, P_a was estimated according to **Eq. (2)** and then verified by tests.
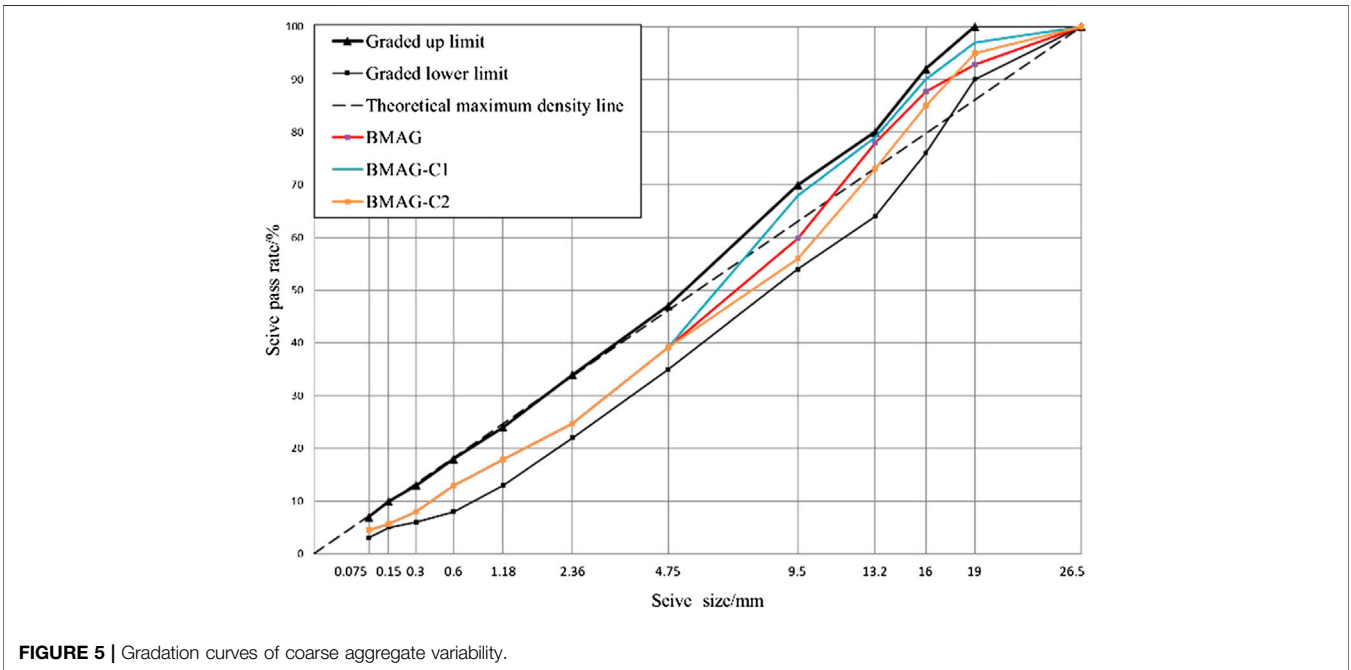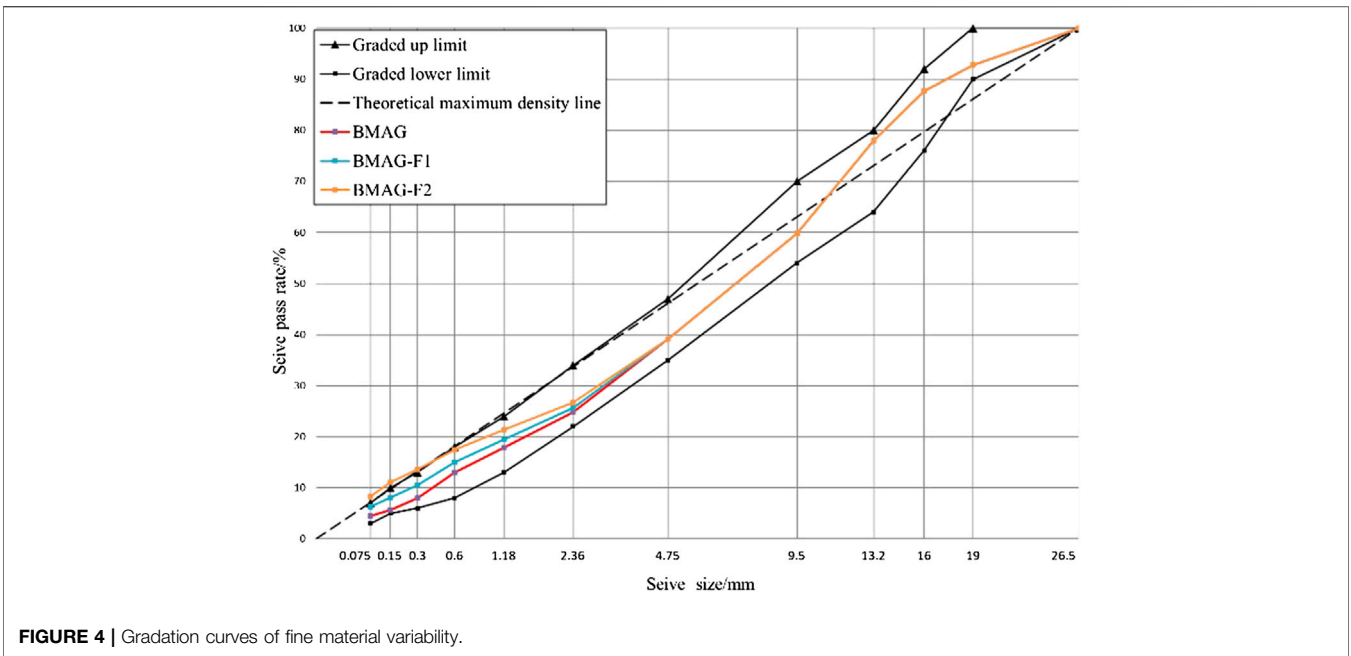
$$P_a = \left(\frac{100 - AV}{100 - VMA} \cdot \frac{1}{\gamma_{sb}} - \frac{1}{\gamma_{se}} \right) \cdot \gamma_a \tag{2}$$

where P_a is the asphalt-aggregate ratio, %; AV and VMA are the air voids and voids in mineral aggregate of compacted HMA specimens, respectively, %; γ_{sb} and γ_{se} are bulk specific gravity and effective specific gravity of the composite mineral aggregates, respectively.

According to **Eq. (2)**, the estimated asphalt-aggregate ratio is 4.3%, and the OAC is 4.1%.

Two specimens were prepared for each gradation through the rotary compaction process, and the bulk specific gravities of

FIGURE 4 | Gradation curves of fine material variability.

FIGURE 5 | Gradation curves of coarse aggregate variability.

specimens were measured according to the test procedures. The *AV*, *VMA*, and *VFA* (void filled with asphalt) were further calculated, which were shown in **Table 4**.

Since this paper studies the situation of gradation variability and the *OAC* remains unchanged, therefore, the asphalt content used in each variability gradation is still 4.1%.

By transforming **Eq. (2)**, **Eq. (3)** is obtained.

$$AV = 100 - (100 - VMA) \times \left(\frac{P_a}{\gamma_a} + \frac{1}{\gamma_{se}} \right) \times \gamma_{sb} \qquad (3)$$

It can be seen from **Eq. (3)** that when the asphalt-aggregate ratio remains unchanged, if the *VMA* changes due to the
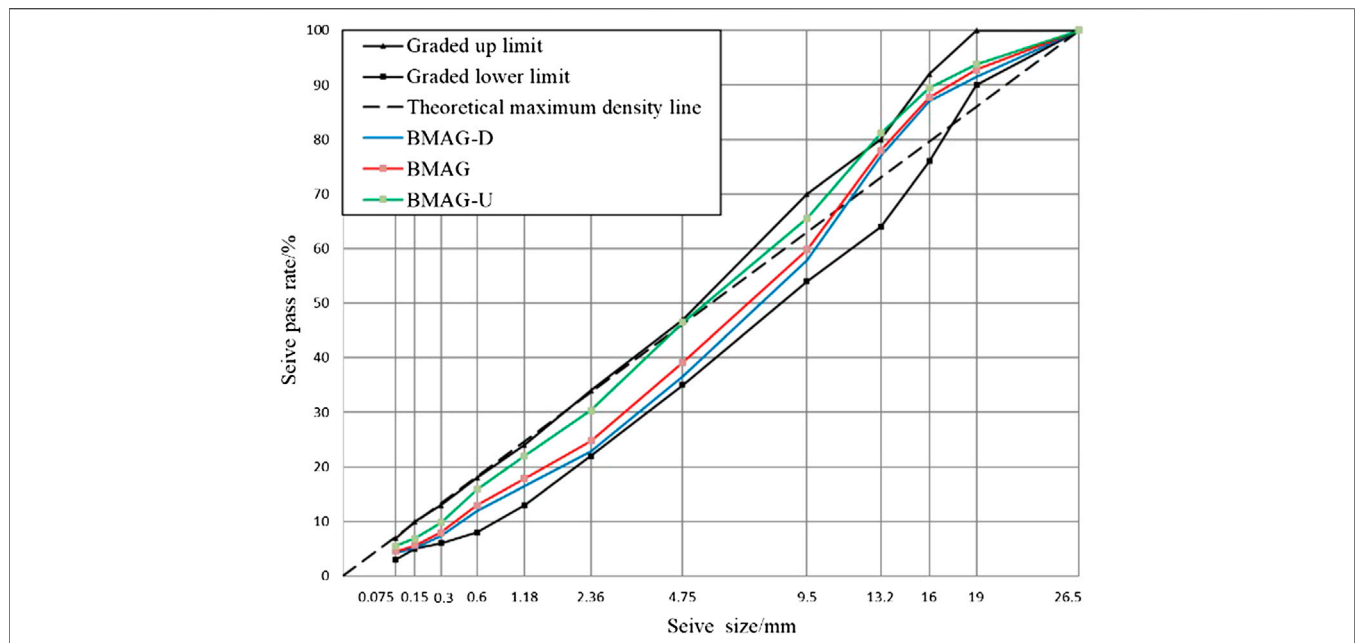
FIGURE 6 | Gradation curves of coarse aggregate and fine material variability.

TABLE 5 | Coefficient values of regression equations for load cycle times and rut depth of BMAG and variability gradation HMA.

Coefficient	HMA of different gradations						
	BMAG	**BMAG-F1**	**BMAG-F2**	**BMAG-C1**	**BMAG-C2**	**BMAG-D**	**BMAG-U**
A	2,704.972	13.458	12.476	4.589	8.899	5.629	18.538
B	2,003,032.707	41,977.638	80,354.096	23,359.513	30,509.256	30,929.143	52,791.121
C	0.26047	0.72223	0.78893	1.39741	1.49947	0.80762	0.46848
x_{SN}	15,851	3,867	8,322	4,201	5,761	3,299	2,297
Δx_{SN} (%)	0	−75.6	−47.5	−73.5	−63.7	−79.2	−85.5

Δx_{SN} (%) stands for relative deviation.

gradation variability, the AV will change in the same direction.

RESULTS AND ANALYSIS

Influence of Gradation Variability on Volume Parameters

AV, VMA, and VFA were selected as the assessment indicators. The volume parameter results of each HMA can be seen in **Table 4**.

Influence of Fine Material Variability on Volume Parameters

According to **Table 4**, compared with the volume parameters of BMAG-HMA, the AV and VMA of the BMAG-F1 and BMAG-F2 mixtures became smaller. This is because the composition and dosage of the coarse aggregate remain unchanged, the V_{CA} remains unchanged. When the amount of fine material increases, the extent to which the fine material fills the gap between the coarse aggregate particles increases, so the VMA

decreases. Moreover, the variability of density parameter of mineral aggregate gradation is very small and can be ignored; therefore, according to **Eq. (3)**, when the asphalt-aggregate ratio is constant, the decrease in VMA will inevitably lead to a decrease in AV. Compared with BMAG-F1, BMAG-F2 has finer materials, so its ability to fill the gaps of coarse aggregate is stronger, and AV and VMA of it are both smaller. The VFA values of the BMAG-F1 and BMAG-F2 mixtures are larger than those of BMAG. It can be inferred that when the fine material becomes finer than BMAG, the general rule is that the AV and VMA of HMA decrease and VFA increases.

Influence of Variability of Coarse Aggregate on Volume Parameter

As can be seen from **Table 4**, compared with the BMAG, AV and VMA of BMAG-C1 and BMAG-C2 mixtures are increased. When analyzing the reasons for the increase of AV and VMA, it should be noted that BMAG mixture is a dense skeleton gradation and its VMA and AV are smaller. With the variability of coarse aggregate, its V_{CA} must change greatly or little. Because the amount of fine material is not changed, the

HMA with variable gradation becomes a skeleton void structure or suspension dense structure. According to the law of asymmetric concave shape change of the *VMA* revealed in the literature (Zhang et al., 2016), it can be inferred that the *VMA* with variable gradation will inevitably increase. As mentioned above, the density parameters of mineral aggregate gradation after variability can be considered to be approximately constant, so according to **Eq. (3)**, when the asphalt-aggregate ratio is constant, the increase of *VMA* will lead to *AV* increasing. As for *VFA*, the values of BMAG-C1 and BMAG-C2 mixtures are smaller than that of BMAG. It can be speculated that, compared to BMAG gradation, after variability of coarse aggregate, the general rule is that both *VMA* and *AV* of the HMA increase, while *VFA* decreases.

Influences of Variability of Coarse Aggregate and Fine Material on Volume Parameter

It can be seen from **Table 4** that when coarse and fine aggregates have simultaneously variabilities, the *VMA* and *AV* of the two gradations of BMAG-D and BMAG-U compacted HMA both increase. The reason is the same as the situation that fine material gradation is basically unchanged but the coarse aggregate is changed visibly.

Effects of Gradation Variability on Water Stability and High-Temperature Performance
Test Instruments and Conditions

APA was employed to test the water stability and high-temperature performance of HMA. Because of the modified asphalt, the Hamburger wheel tracking test (HWTT) was conducted with cylindrical specimens under the condition of 60°C water in a bath (Izzo, 1999; Li et al., 2011; Zhang et al. 2018).

Evaluation Parameter and Analysis Method

Wheel load times and rutting depth are the basic test data of HWTT, regarding the processing of experimental data, the traditional method provided by AASHT0T324 is curve fitting based on data. Then, the postcompaction stage, creep stage, and spalling stage were artificially distinguished to obtain spalling inflection point (SIP) and creep slope, which were used as the evaluation methodology of water stability and high-temperature performance, respectively. Obviously, the traditional method has many subjective factors and lacks a mathematical basis. In order to avoid this defect, Tsai and Harvey (2003) put forward the three-stage Weibull approach to fit rut curve. Based on this, Yin et al. (2014) proposed a new method to evaluate the performance of water stability and high-temperature performance by fitting the whole rutting process and proved the reliability of evaluation parameters. In this paper, the Yin fitting method is used to analyze the test results. The basic steps of the analysis are as follows:

(1) The function of **Eq. (4)** is used for curve fitting.

$$RD(x) = A \times \left[\ln\left(\frac{B}{x}\right) \right]^{-1/C} \qquad (4)$$

where x is the load cycle times; $RD(x)$ is the rutting depth corresponding to x; A, B, and C are model parameters.

The fitting curve includes two parts of negative curvature and positive curvature, and the connection point between the two parts is defined as the critical point.

(1) Calculate the load cycle times x_{SN} corresponding to the critical point.

Take the second derivative of both sides of **Eq. (4)** with respect to x and set the derivative equal to zero to obtain x_{SN}, as shown in **Eq. (5)**. The water stability of HMA is evaluated by x_{SN}, and the larger x_{SN} indicates that the water stability of HMA is better.

$$x_{SN} = B \times \exp\left(\frac{1 + C}{C}\right) \qquad (5)$$

(1) Obtain the viscoplastic strain function before the critical point and taking the derivative.

Rutting before the critical point is mainly the viscoplastic deformation of the HMA specimen under load, and **Eq. (6)** can be used to fit the viscoplastic strain of the deformation stage.

$$\varepsilon^{vp} = \varepsilon_{\infty}^{vp} \exp\left[-\left(\frac{a}{x}\right)^b \right] \qquad (6)$$

where ε^{vp} is viscoplastic strain; $\varepsilon_{\infty}^{vp}$ is saturated viscoplastic strain; a and b are model coefficients; $\varepsilon_{\infty}^{vp}$, a, and b are obtained by nonlinear regression analysis.

Take the derivative of both sides of **Eq. (6)** with respect to x and set $x = 10,000$ obtaining **Eq. (7)**. The viscoplastic strain rate $\dot{\varepsilon}_{10000}^{vp}$ can be used to evaluate the high-temperature performance of HMA. A smaller $\dot{\varepsilon}_{10000}^{vp}$ indicates that the HMA has a better high-temperature performance.

$$\dot{\varepsilon}_{10000}^{vp} = a^b b \varepsilon_{\infty}^{vp} \exp\left[-\left(\frac{a}{10,000}\right)^b \right] \times 10,000^{-(b+1)} \qquad (7)$$

Influence of Gradation Variability on Water Stability

The load cycle times of each gradated HMA and the corresponding rut depth data were fitted with curves as shown in **Eq. (4)**. To save space, for example, only the fitting curves of BMAG, BMAG-F1, BMAG-C1, and BMAG-D are given, as shown in **Figure 7**. The fitting parameters of all graded HMA are shown in **Table 5**; x_{SN} is calculated according to **Eq. (5)**; and the analysis of the x_{SN} deviation percentage of each graded HMA from the BMAG-HMA is also listed in **Table 5**.

The parameters that affect water stability include the *AV*, *VFA*, and asphalt film thickness of HMA. It can be seen from **Table 5** that, compared with the HMA of BMAG, the load cycle times of all variable-graded HMA decrease greatly, indicating that the water stabilities all decrease significantly, but the degree of decrease is quite different. As can be seen from **Table 4**, *AV*s of HMA of BMAG-F1and BMAG-F2 are both smaller, but BMAG-F1 has more fine materials and smaller asphalt film thickness, so the reduction of x_{SN} of its HMA is larger. The
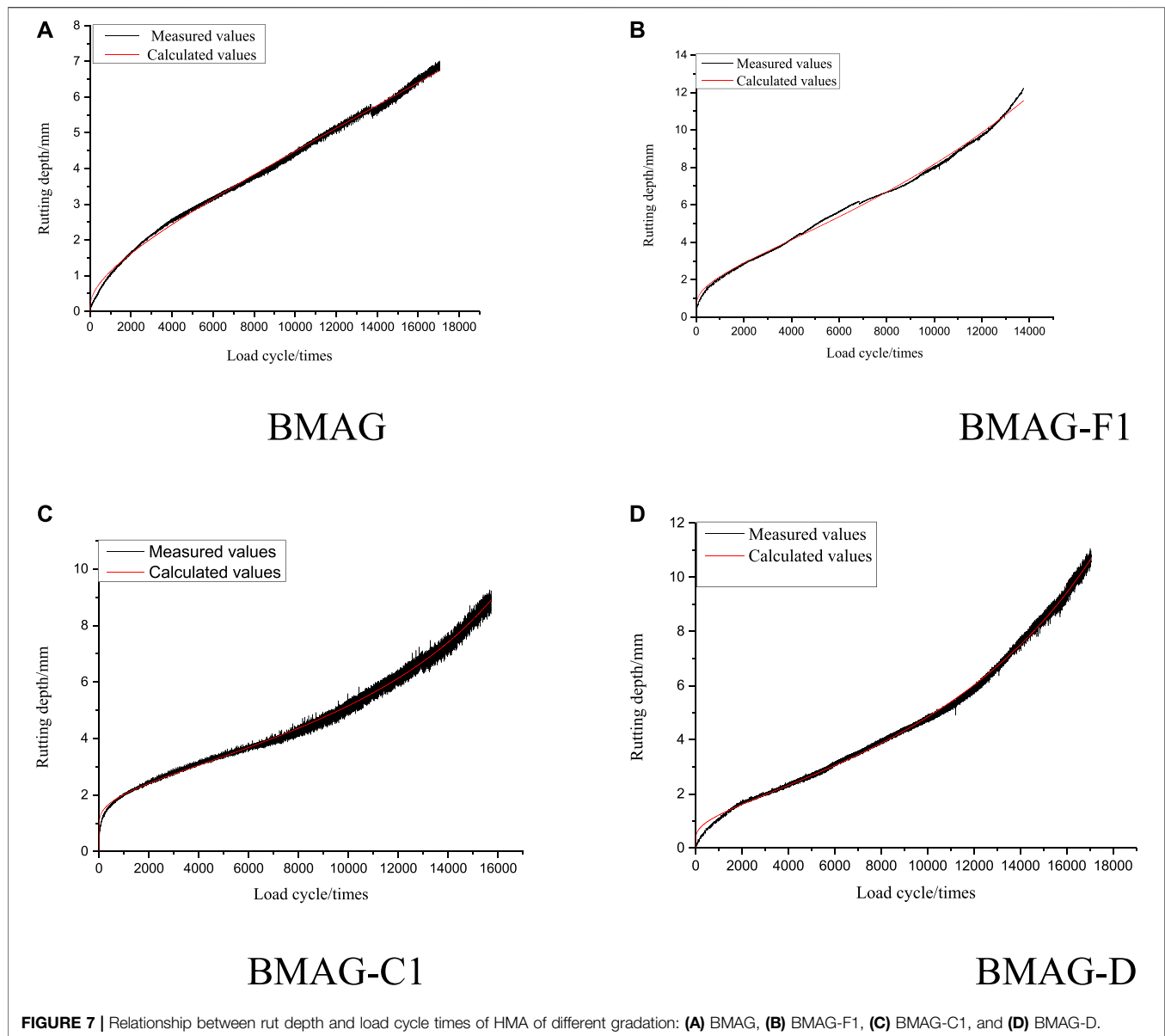
FIGURE 7 | Relationship between rut depth and load cycle times of HMA of different gradation: **(A)** BMAG, **(B)** BMAG-F1, **(C)** BMAG-C1, and **(D)** BMAG-D.

TABLE 6 | Viscoplastic strain parameters and high-temperature performance parameters of each gradated HMA.

Parameters	BMAG	BMAG-F1	BMAG-F2	BMAG-C1	BMAG-C2	BMAG-D	BMAG-U
$\varepsilon_{\infty}^{VP}$	13.650	54.860	61.820	434.459	0.827	0.591	90.436
a	3.359E+18	1.250E+18	1.726E+17	1.077E+17	4.196E+06	1.735E+06	6.783E+14
b	0.050	0.058	0.062	0.075	0.115	0.169	0.079
$\dot{\varepsilon}_{10000}^{vp}$ (10−6)	1.77	2.93	3.39	2.33	2.57	2.19	3.93
Relative deviation of $\dot{\varepsilon}_{10000}^{vp}$ (%)	0.0	65.5	91.5	31.6	45.2	23.7	122.0

asphalt film thicknesses of BMAG-C1 and BMAG-C2 HMA are close to each other, but it can be seen from **Table 4** that AV of the former is larger, so the water stability of the HMA decreases more. The volume parameters of BMAG-U and BMAG-D HMA, such as AV, differ little, but the former's asphalt film thickness is small, so the decrease of water stability is more obvious.

Effect of Gradation Variability on High-Temperature Performance

The rutting before the critical point is mainly the viscoplastic deformation of HMA under load, and **Eq. (6)** can be used to fit the viscoplastic strain of the deformation stage. For water damage of HMA, the strain before the critical point is fitted by the

Tseng-Lytton model (6). After obtaining the model parameters, the viscoplastic strain rate $\dot{\varepsilon}_{10,000}^{vp}$ is calculated according to **Eq. (7)**, as shown in **Table 6**. The calculated and analyzed increase of $\dot{\varepsilon}_{10,000}^{vp}$ value of variability gradation compared with the reference gradation is also listed in **Table 6**.

It has been pointed out earlier that a smaller $\dot{\varepsilon}_{10,000}^{vp}$ indicates that the HMA is getting a better high-temperature performance. It can be seen from **Table 6** that the viscoplastic strain rate increased by 24–122% when the number of cyclic loadings was 10,000. Therefore, the high-temperature performance of the mixture of BMAG is the best, and the high-temperature performances of the variably graded mixtures have been significantly reduced in varying degrees.

Compared with BMAG-F1, the fine material of BMAG-F2 is finer, resulting in a more obvious viscoplastic strain rate and indicating that even though the HMA is a dense skeleton gradation, its high-temperature performance is very sensitive to the change of fine material. In comparison, the high-temperature performance of BMAG-C1 and BMAG-C2 mixture decreases relatively little, indicating that the high-temperature performance of HMA is less sensitive to the change of coarse aggregate. Compared with BMAG-C2, the high-temperature performance of BMAG-C1 mixture is slightly higher, which should be caused by more stone-stone contact points of the aggregates. Compared with BMAG-U, the overall BMAG-D gradation curve deviates a little bit from BMAG, while the former deviates farther from BMAG. The HMA of BMAG-U is a typical suspended dense structure, being with coarse aggregate particles far away from each other and no stone-stone contact, so its high-temperature performance degradation is more serious.

CONCLUSION

In practical asphalt pavement engineering, it is inevitable that the gradation of HMA varies (Zhang et al. 2020). From the perspective of qualitative analysis, it is easy to infer that the gradation variability (asphalt content remains unchanged) will inevitably bring about changing of volume parameters and performances of HMA, but the changing direction and influence degree caused by the change may be known only through quantitative research. Based on the design of reasonable BMAG, this paper made an in-depth study on the change of HMA parameters caused by gradation variability and obtained the following main conclusions:

(1) Once the skeleton density gradation designed according to the method in this paper changes, whether the gradation becomes coarser or finer, AV, VMA, and VFA of the compacted HMAs will change in different degrees. Compared with the HMA of BMAG, AV and VMA of the HMA decrease and VFA increases when the fine material becomes finer. AV and VMA of HMA increase while the VFA decreases after the coarse aggregate becomes coarser or finer.

(2) Compared with the HMA of BMAG, the water stability of the designed variable gradation HMAs decreases by more than 50% on the whole. The thickness of asphalt film decreases significantly when the amount of fine material increases, and the more the fine material is, the more the water stability decreases. After the variability of coarse aggregate, the change of asphalt film thickness is relatively small, but the change of AV is large, resulting in a decrease in water stability.

(3) Compared with the HMA of BMAG, the high-temperature performances of all the HMAs of variable gradations decrease significantly. The more the fine material is, the lower the high-temperature performance gets. The higher the degree of suspension is, the greater the degradation of high-temperature performance will be.

(4) The performance degradation of the variable gradation HMA shows that the performance of HMA of BMAG determined by the design theory for dense skeleton gradation is optimal, which indirectly reflects that the design theory for dense skeleton gradation adopted in this study is feasible and effective.

(5) It is very important to determine the BMAG when studying the character change of HMA brought by gradation variation. If the unreasonable gradation is used as the BMAG, the properties of HMA may change in a good direction after gradation variation, so the problems caused by gradation variation cannot be found. As a theoretical basis for the study of gradation variation, the design theory for dense skeleton gradation established by the first author is a key technology, which has its originality and own characteristic.

DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/Supplementary Material; further inquiries can be directed to the corresponding authors.

AUTHOR CONTRIBUTIONS

LS was responsible for the analysis of experimental data and the writing of the manuscript. ZL was mainly responsible for organizing test operation and data proofreading. ZH (the first corresponding author) was primarily responsible for the determination of the overall study program. LT assisted in the conduct of trials and the recording of trial data. JP was responsible for the preparation of test materials. And CW (the second corresponding author) proofread the test plan and supervised the test progress and plan execution.

ACKNOWLEDGMENTS

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