

Article

Laboratory Performance Evaluation of Hot-Mix Asphalt Mixtures with Different Design Parameters

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Abstract: Aggregate gradation and asphalt type are traditional variables that affects mix design of Hot-Mix Asphalt (HMA). Recently, the number of design gyrations (N_{des}) has been increasingly accepted as another variable parameter during the design process. Due to the growing shortage of high-quality raw materials, it is necessary to make full use of the combined roles between these design parameters, instead of solely relying on their individual effect, to improve the HMA properties. Therefore, this study comprehensively explored the effect of aggregate gradation, N_{des} , and asphalt type on the performance of HMAs. Seven different combinations of aggregate gradation, N_{des} , and asphalt type were evaluated. The volumetric indicators, uniaxial penetration shear test (UPST), unconfined compression test (UCT), low-temperature bending test (LBT), four-point bending test (FPBT), and dynamic modulus test (DMT) were used to assess the performance of HMAs designed by various parameter combinations. It was found that the contribution of adopting harder asphalt binder was able to make up for the high-temperature resistance loss caused by lower N_{des} or coarser gradation. The dynamic modulus exhibited the similar phenomenon. By contrast, the harder asphalt binder led to the worse tenacity of HMAs at low temperature; however, the tenacity can be restored through using lower N_{des} or coarser gradation by increasing asphalt content. In addition, the fatigue life of HMAs went up significantly by about 36 ~ 41%, when both N_{des} and asphalt penetration grade decreased to one lower level.

Keywords: asphalt mixture; performance; aggregate gradation; design gyration; low/high-temperature properties

1. Introduction

The Superior Performing Asphalt Pavement (Superpave) design method is extensively used to design Hot-Mix Asphalt (HMA). This method adjusts the mixture aggregate gradations or even raw materials continuously until the output HMA meets the empirical volumetric and performance requirements [1]. In recent years, the number of design gyrations (N_{des}) has been gradually accepted as another parameter in the design process [2–4]. These design parameters may have different effects on the performance of asphalt mixtures. In addition, due to the performance-based mix design promoted, more attention is paid to the properties of asphalt mixtures [5,6], and the designers need to design the HMAs to meet the pavement requirements [6]. Faced with the increasing shortage of high-quality raw materials, it is necessary to fully explore combined effects of these design parameters on the properties of HMAs.

The influences of these design parameters on the properties of HMA have been explored previously. In 2006, National Cooperative Highway Research Program (NCHRP) conducted a comprehensive project evaluating the effects of different design parameters on HMA high-temperature performance [7]. The report from NCHRP implied that as the fineness modulus (FM_{300}) rose by 6% during design,

the rutting resistance of the mixture increased by about 2.0 to 2.5 times. As the number of N_{des} increased by 25, the rutting resistance was improved by approximately 15% to 25%; Moreover, as the high-temperature PG-grade of the asphalt increased by one level (6 °C), the rutting resistance of HMA went up by about 2.5 times [7]. The above NCHRP project only focused on the mixture's high-temperature performance. The assessments for other HMA properties (i.e., low-temperature performance and fatigue performance), however, were not performed in this project.

Some other studies also explored the individual influence of design parameters on the mixture properties. In terms of the effect of aggregate gradation, Brown et al. found that the HMA with coarse gradation (below restricted zone) exhibited weak deformation resistance under high temperatures [8]. Haddock et al. found the similar patterns as Brown et al. [9]. Sousa et al. found that HMAs using fine gradation (above or through restricted zone) had better fatigue performance as compared with those using coarse gradation [10]. In terms of the effort of N_{des} , Khosla et al. discovered that with an increase in N_{des} , the high-temperature properties and dynamic modulus of the mixtures were significantly improved [3,11]. Moreover, Sun et al. reported that the rise in N_{des} by 25 resulted in a decrease in fatigue life by 10–20%, and a decrease in low-temperature flexural-tensile strain by 10–50% [2]. As for the effect of asphalt type, the HMAs with modified binder (i.e., PG 76-22) were found to suffer less rutting by about 60% compared with those using neat binder (i.e., PG 67-22) [12].

Above studies indicated that all design parameters, including aggregate gradation, asphalt type and N_{des} , affected the HMA properties notably. Previous studies mainly evaluated the individual influence of design parameter on the mixture properties. The combined effects of those parameters, however, need to be further investigated. In addition, several other essential properties of HMAs (i.e., low-temperature cracking) also need to be further included during investigation. Therefore, this study aimed to systematically explore the influence of three different design parameters, namely aggregate gradation, N_{des} , and asphalt type, on the properties of HMAs. The high- and low-temperature, fatigue, and dynamic modulus properties of the mixture were included for evaluation.

2. Experimental Design

The flowchart of the experimental design of this research is presented in Figure 1. In this experiment, 30, 50 and 75 were selected as design gyration (N_{des}) variables. Fine, middle, and coarse gradation were adopted as aggregate gradation variables. Moreover, 30#, 50#, and 70# penetration graded binder was selected as asphalt type variables. Seven different combinations of the above design variables were included and analyzed, as shown in Table 1. As a result, the individual and combined effects of these design parameters on the mixture properties were fully explored.

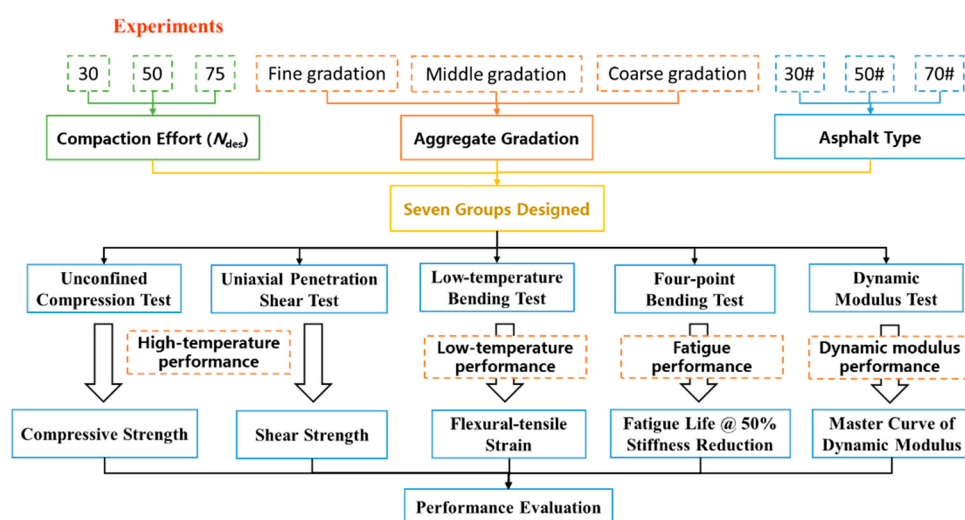


Figure 1. The flowchart of the experimental design of this research.

Table 1. The seven combinations of design parameters.

Experiment	Design Parameters		
	Aggregate Gradation	N _{des} (numbers)	Asphalt Type
Group 1	Middle gradation	30	30#
Group 2	Fine gradation	50	30#
Group 3	Middle gradation	50	30#
Group 4	Coarse gradation	50	30#
Group 5	Middle gradation	50	50#
Group 6	Middle gradation	50	70#
Group 7	Middle gradation	75	70#

3. Materials

3.1. Asphalt Binder

Three types of asphalt binders were adopted in this experiment. The 30# asphalt binder was used in Group 1–4, and it exhibited a penetration of 33.6 (0.1 mm) and a softening point of 58.7 °C (Ring and Ball Method). The 50# asphalt binder was used in Group 5, and it exhibited a penetration of 47.4 (0.1 mm) and a softening point of 53.0 °C. In addition, the 70# asphalt binder was used in Group 6–7, and it exhibited a penetration of 67.5 (0.1 mm) and a softening point of 47.5 °C [13].

3.2. Aggregates

The aggregates used in this experiment were limestone types. The properties of these aggregates are summarized in Table 2. In addition, three different gradation curves within the range of AC-16 gradation were used in this study. The AC-16 was frequently used in the pavement projects in China [14]. The fine gradation curve was adopted in Group 2. The middle gradation curve was adopted in Group 1, 3, and 5–7. The coarse gradation curve was adopted in Group 4. The aggregate gradations are presented in Table 2.

Table 2. The gradations and properties of aggregates.

Aggregate Gradation	Sieve Size	19	16	13.2	9.5	4.75	2.36	1.18	0.6	0.3	0.15	0.075
	Fine Gradation	100	97.5	93.5	84.1	66.6	38.9	22.9	18.4	11.4	8.6	6.4
	Middle Gradation	100	95.8	89.2	73.6	48.0	28.2	17.2	14.1	9.3	7.2	5.6
	Coarse Gradation	100	95.0	87.0	68.3	38.7	22.9	14.3	11.9	8.1	6.5	5.1
Aggregate Property	Sieve Size	10–15			3–5			0–3			Mineral	
	Bulk Specific Gravity	2.696			2.756			2.776			2.752	
	Crushing Stone Value = 22.8%	Los Angeles Abrasion = 16.2%			Flat and Elongated Particle Content = 16.4%							

3.3. Specimen Preparation

The HMAs for testing were formed through the Superpave gyratory compactor. In Superpave, the air void was recommended to be maintained at an empirical level of 3–5% [7]. Since air void significantly affects the HMA performance [7], the air voids of all HMAs testing in this research were maintained at around 4%. The HMA optimal asphalt content (OAC) was determined when controlling its air void. The volumetric indicators of HMAs corresponding to seven design parameter combinations are presented in Table 3.

Table 3. The volumetric indicators of HMAs corresponding to seven combinations.

Experiment	Asphalt Content (%)	Air Void (%)	Density (g/cm ³)	VMA (%)	VFA (%)
Group 1 (30#; N _{des} = 30; middle gradation)	5.70	3.8	2.432	16.5	77.0
Group 2 (30#; N _{des} = 50; fine gradation)	5.50	3.7	2.446	16.1	76.9
Group 3 (30#; N _{des} = 50; middle gradation)	5.40	3.9	2.460	16.1	76.0
Group 4 (30#; N _{des} = 50; coarse gradation)	5.70	4.1	2.421	16.7	75.7
Group 5 (50#; N _{des} = 50; middle gradation)	5.30	3.7	2.455	15.7	76.4
Group 6 (70#; N _{des} = 50; middle gradation)	5.25	4.4	2.416	16.1	72.4
Group 7 (70#; N _{des} = 75; middle gradation)	4.90	4.5	2.437	15.5	71.1

As seen from the results regarding Groups 1, 3 and Groups 6, 7, when the N_{des} decreases by one level (25 numbers), the Voids in Mineral Aggregate (VMA) of HMA increases by about 0.5%, while the OAC increases by about 0.3%. No apparent difference was observed for the volumetric indicators of HMAs using fine and middle gradations (Group 2, 3). However, when the HMA gradation became coarse one (Group 4), its VMA increased rapidly by about 0.6%, and the OAC increased by 0.3%. In addition, the effects of asphalt type on the HMAs' volumetric properties were slight (Group 3, 5, and 6).

4. Test Procedures

Based on the HMAs listed in Table 3, the high- and low-temperature, fatigue, and dynamic modulus properties of the mixtures designed by different variable combinations were evaluated using different tests. The uniaxial penetration shear test (UPST) and unconfined compression test (UCT) were chosen to analyze HMA high-temperature performance. The specimens of above tests had diameters of 100 mm and heights of 100 mm, and they were formed by gyratory compactor. The low-temperature bending test (LTBT) was used to evaluate the HMA low-temperature performance. The specimens for bending test, which were formed using rolling wheel compactor, had dimensions of 250 mm × 30 mm × 35 mm. The four-point bending fatigue test (4PBT) was applied to assess the HMA fatigue property. The corresponding specimens had dimensions of 380 mm × 50 mm × 63 mm and were formed by vibrating compactor. The uniaxial compressive modulus test (UCMT) was used to measure the HMA dynamic modulus. The specimens for the dynamic modulus test were prepared by gyratory compactor, and had diameters of 100 mm and heights of 150 mm. In addition, the detailed tests arranged for different groups of HMAs are summarized in Table 4.

Table 4. The detailed tests arranged for different groups of HMAs.

Experiments	UCT	UPST	LTBT	4PBT	UCMT
Group 1	√	√	√	√	√
Group 2	√	√	√	√	√
Group 3	√	√	√	√	√
Group 4	√	√	√	√	√
Group 5	√	√	√	√	√
Group 6	√	√	√	√	√
Group 7	√	√	√	√	√

The UPST reflects the shear strength of HMA at high temperature (60 °C) [15–17]. The experimental device of UPST is presented in Figure 2a. During the experiment, an indenter with a diameter of 28.5 mm was loaded on the asphalt mixtures at a rate of 1 mm/min. The maximum force was recorded to calculate the shear strength of asphalt mixtures, as shown in Equation (1) [18].

$$R_{\tau} = f_{\tau} \cdot \frac{P}{A} \quad (1)$$

where R_{τ} is shear strength (MPa); P is the maximum force (N); A is the contact area of indenter (mm²); and f_{τ} is the correction factor (i.e., $f_{\tau} = 0.34$).

The UCT mainly reflects the compressive strength of HMA at high temperature (60 °C). The experimental device of UCT is presented in Figure 2b. In contrast to UPST, the surface of asphalt mixtures in UCT was subjected to uniform indenter load, and the loading rate was controlled at 1mm/min. During the process, the maximum force was recorded to calculate the compressive strength of asphalt mixtures [13].

The LTBT characterizes the tenacity of asphalt mixtures at low temperature (−10 °C). The experimental device of LTBT is presented in Figure 2c. During the experiment, the load was applied to the midspan of rectangular asphalt mixtures, and the loading rate was controlled at 50mm/min. The deflection of the midspan d corresponding to the maximum force was recorded. Then, the

flexural-tensile strain ε_B of asphalt mixtures at failure was calculated according to the following Equation [13].

$$\varepsilon_B = \frac{6 \times h \times d}{L^2} \quad (2)$$

where ε_B is the flexural-tensile strain at low temperature ($\mu\epsilon$); L is the span of beam (mm); h is the height of midspan (mm); and d is the deflection of midspan in failure (mm).

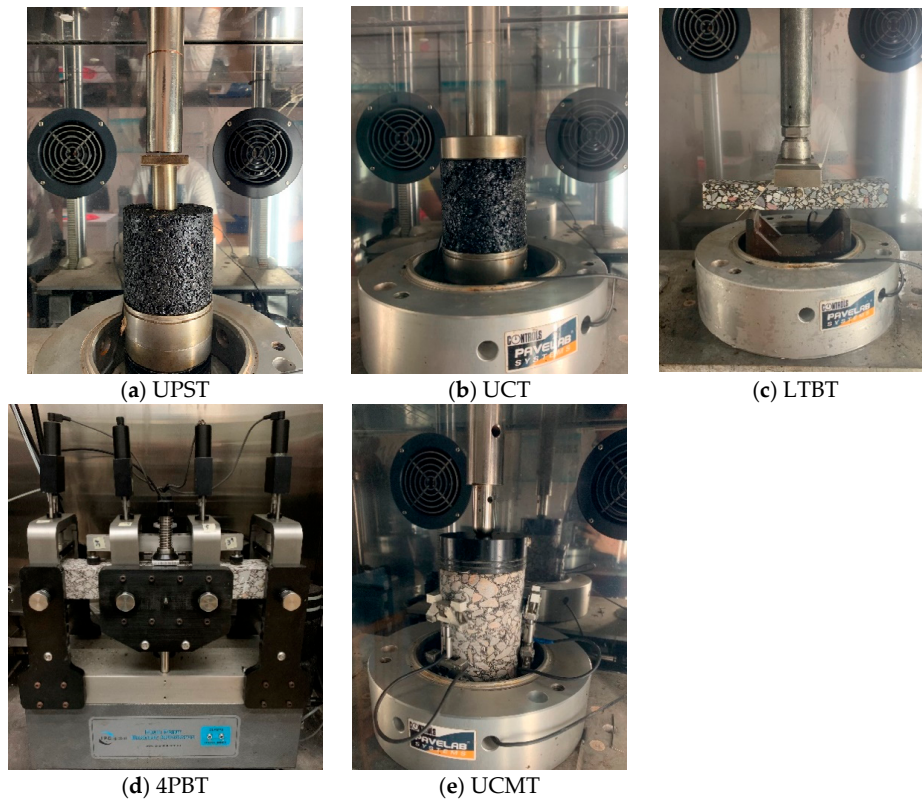


Figure 2. The devices of experiments in this study: (a) UPST, (b) UCT, (c) LTBT, (d) 4PBT, (e) UCMT.

The four-point bending test (4PBT) was used to characterize the fatigue life of asphalt mixtures [10]. The experimental device of FPBT is presented in Figure 2d. During the test process, the experiment maintained the loading frequency at 10 Hz, constant strain at 300 $\mu\epsilon$ and temperature at 15 °C. The initial stiffness of asphalt mixture was defined at the 50th load, and the indicator of fatigue life was regarded as the number of loads when the stiffness reduced to half [19].

The experimental device of UCMT is presented in Figure 2e. The UCMT was conducted at six frequencies of 0.1, 0.5, 1, 5, 10, and 25 Hz and five temperatures of −10, 4.4, 21.1, 37.8, and 54.4 °C. Then, the master curves of dynamic modulus were fitted using the Sigmoid model, shown as Equations (3) and (4) [20].

$$\log|E^*| = \delta + \frac{\alpha}{1 + e^{\beta - \gamma \log(\tau a_T)}} \quad (3)$$

where $|E^*|$ is dynamic modulus (MPa); δ , α , β , and γ are regression parameters; and τ is the frequency at the reference temperature (Hz); a_T is the shift factor which converts the frequency at measured temperature to the reference temperature.

$$\log(a_T) = \frac{C_1 \cdot (T - T_{\text{ref}})}{C_2 + (T - T_{\text{ref}})} \quad (4)$$

where C_1 and C_2 are regression parameters, T is the measured temperature (°C), and T_{ref} is the reference temperature (i.e., 21 °C).

5. Results and Analysis

5.1. High-Temperature Performance

The results of UPST are presented in Figure 3. For comparison purposes, the shear strength of HMAs with different asphalt types and numbers of N_{des} (at middle gradation) are presented in Figure 3a, and the shear strength of HMAs with different asphalt types and aggregate gradations (at $N_{des} = 50$) are presented in Figure 3b.

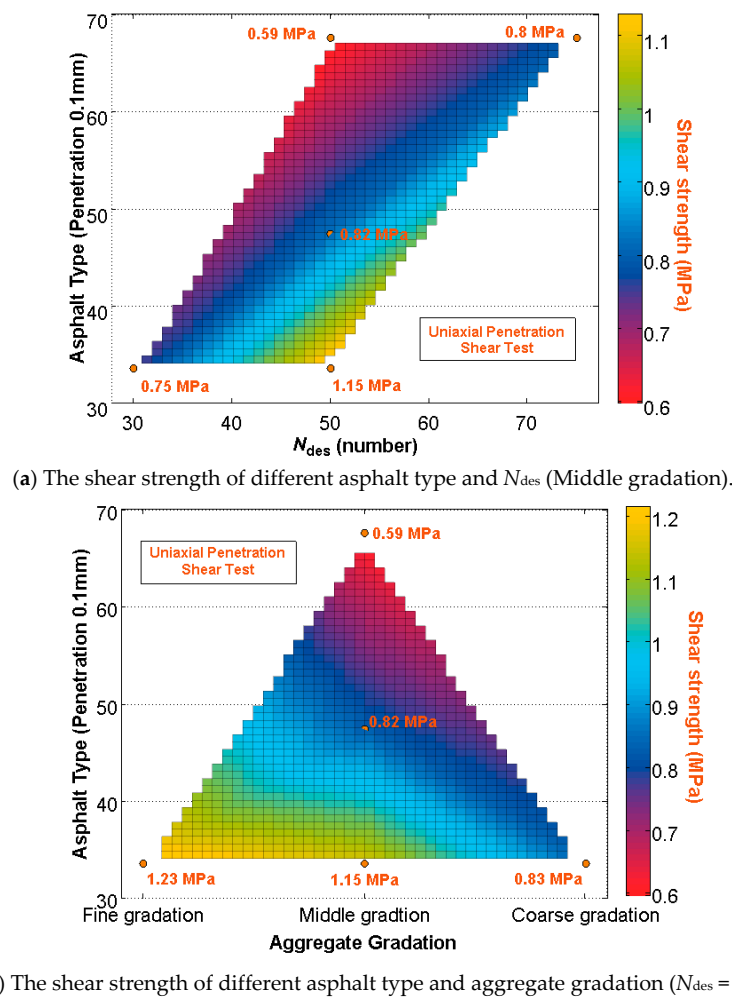
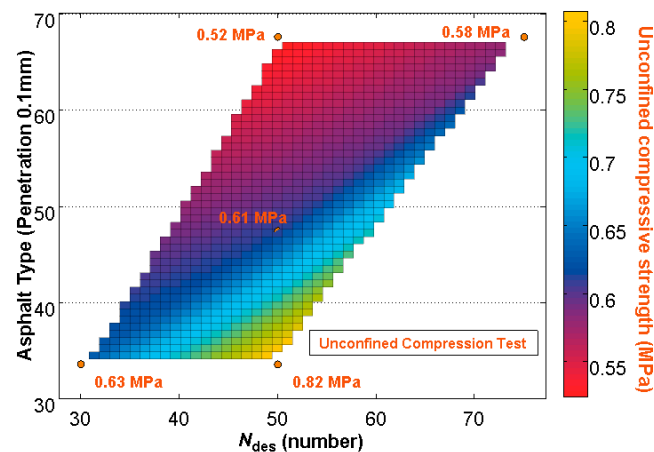


Figure 3. The result of uniaxial penetration shear test.

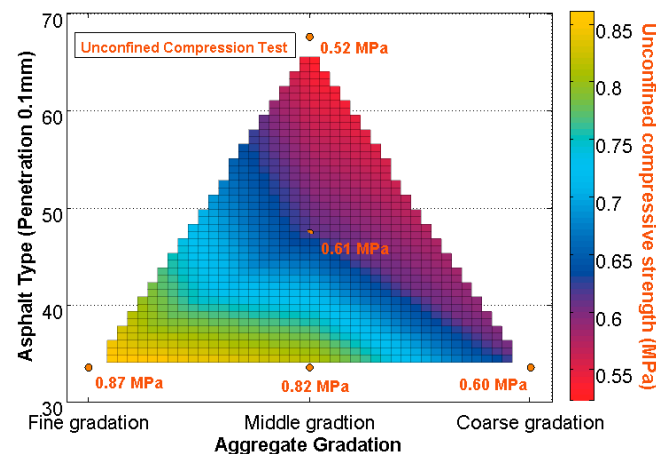
As shown in Figure 3a, with the N_{des} increasing by one level (25 numbers), the shear strength of HMA rises by approximately 0.21–0.4 MPa, which corresponds to 26–43% rise. When the binder penetration grade decreased by one level (20#), the shear strength of HMA was improved by about 0.23–0.33 MPa. In addition, the HMAs with asphalt = 30# and $N_{des} = 30$ had almost the same shear strength as those with asphalt = 50# and $N_{des} = 50$ or asphalt = 70# and $N_{des} = 75$. This fact proves that increasing the gyration number (N_{des}) contributes to increasing the HMA shear resistance, and the contribution of increasing gyration number for shear resistance enhancement is able to make up for the shear resistance loss caused by increasing asphalt binder grade.

As shown in Figure 3b, aggregate gradation has a significant impact on the shear properties of asphalt mixture. The finer the gradation corresponded to the better the shear resistance for the HMA. Moreover, the shear strength of HMA with 30# binder and coarse gradation was equivalent to that of HMA with 50# binder and middle gradation.

The results of UCT were presented in Figure 4. As shown in Figure 4a, when the N_{des} increases by 25 numbers, the compressive strength of HMA rises by approximately 10~23%. With the binder penetration grade decreasing to one lower level (20#), the compressive strength of HMA increased by about 15–25%. In addition, there was also no significant difference appeared in compressive resistance between the HMAs with binder = 30# and N_{des} = 30 and those with binder = 50# and N_{des} = 50, or binder = 70# and N_{des} = 75. This further proves the substitutability of these two design parameters for HMA high-temperature properties. As shown in Figure 4b, the finer gradation presented the better compressive resistance, and compared with fine and middle gradation, coarse gradation appeared to be more sensitive to the high-temperature resistance. In general, the high-temperature properties of HMAs exhibited in UCT were similar to those in UPST.



(a) The compressive strength of different asphalt type and N_{des} (Middle gradation).



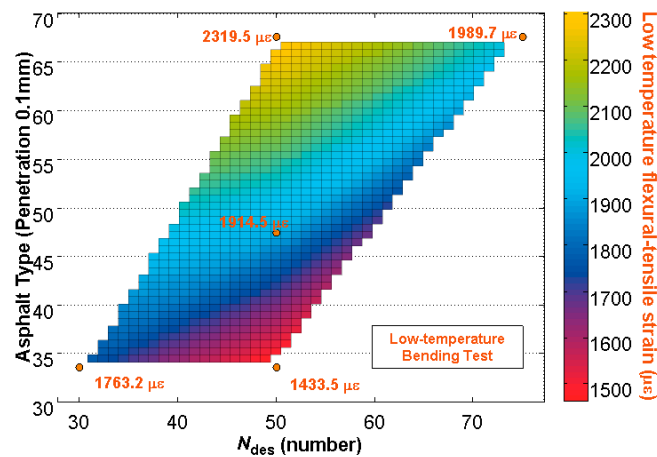
(b) The compressive strength of different asphalt type and aggregate gradation (N_{des} = 50).

Figure 4. The result of unconfined compression test.

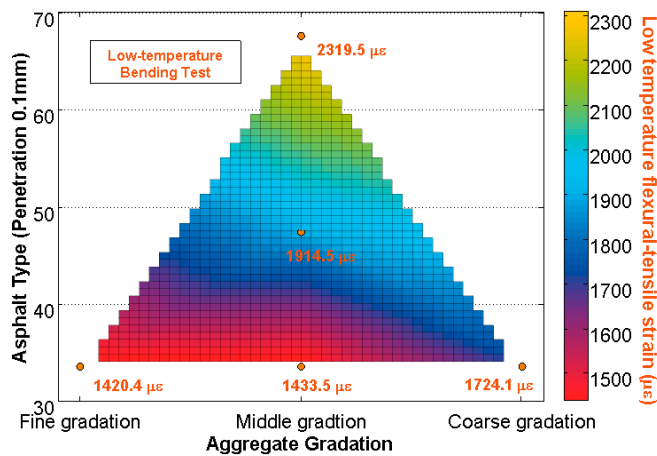
In addition, three design parameters affected the high-temperature performance of HMAs in different ways. Specifically, the effects of compaction effort (N_{des}) and aggregate gradation on HMA' properties were realized through VMA and asphalt content in the design process, while the effects of asphalt type was realized by the viscosity of binder.

5.2. Low-Temperature Performance

The results of LTBT are presented in Figure 5. In contrast to high-temperature testing results, the low-temperature properties of HMAs increased with the reduction in N_{des} , the increase in binder grade, and the coarser aggregate gradation.



(a) The low-temperature strain of different asphalt type and N_{des} (Middle gradation).



(b) The low-temperature strain of different asphalt type and aggregate gradation ($N_{des} = 50$).

Figure 5. The result of low-temperature bending test.

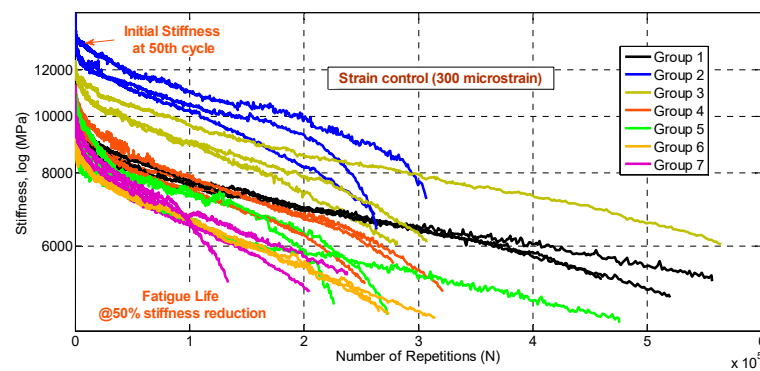
As shown in Figure 5a, with the N_{des} decreasing by one level (25 numbers), the flexural-tensile strain of asphalt mixtures increased by approximately 330–412 $\mu\epsilon$ (14–23%). When the binder penetration grade increased by one level (20#), the flexural-tensile strain would increase by about 405–481 $\mu\epsilon$ (17–25%). In addition, when the N_{des} and asphalt grade decreased to one lower level simultaneously, the flexure-strains of the corresponding HMAs remained almost unchanged, implying that the N_{des} and the asphalt binder were able to complement with each other to maintain the HMAs' high- and low-temperature properties.

As shown in Figure 5b, with the aggregate gradation becoming coarser, the low-temperature property of asphalt mixtures increased obviously. Moreover, the flexural-tensile strain of HMA with coarse gradation and $N_{des} = 50$ (Group 4) was similar to that with middle gradation and $N_{des} = 30$ (Group 1).

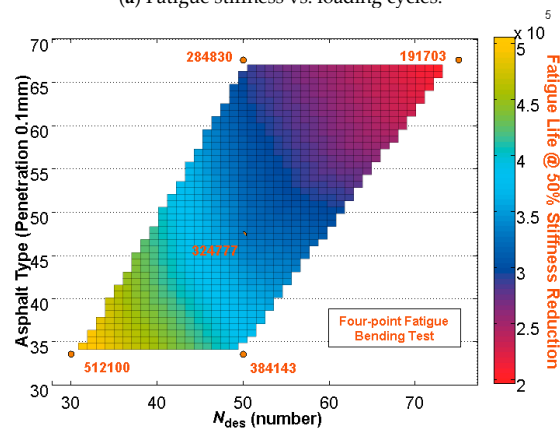
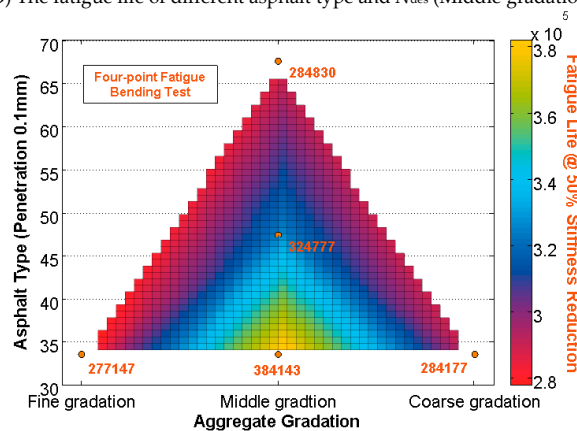
Three design parameters affected the low-temperature performance of HMAs in different ways. The less N_{des} or coarser gradation, the more asphalt content required, which may help to improve the low-temperature resistance of HMAs. By contrast, the effects of softer asphalt type may be realized by the larger tenacity of binder itself.

5.3. Fatigue Performance

The fatigue results HMAs are presented in Figure 6. An interesting phenomenon can be found here was that the three different design parameters have different effects on the fatigue life of asphalt mixtures.



(a) Fatigue stiffness vs. loading cycles.

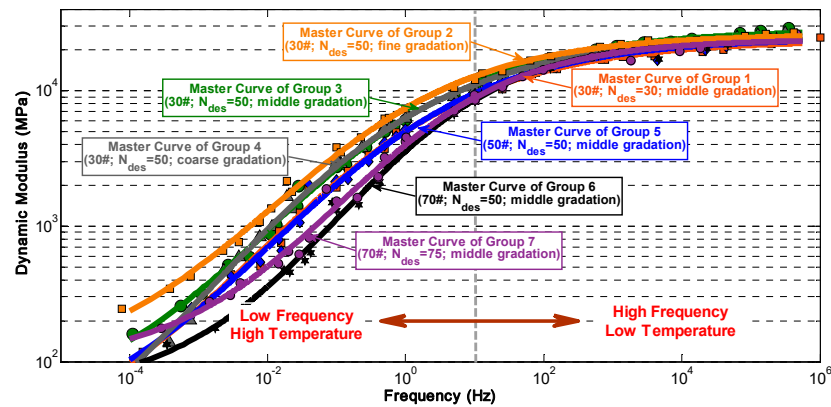
(b) The fatigue life of different asphalt type and N_{des} (Middle gradation).(c) The fatigue life of different asphalt type and aggregate gradation ($N_{des} = 50$).**Figure 6.** The result of four-point bending test.

As shown in Figure 6, with the N_{des} decreasing by 25, the fatigue life of HMA increased by approximately 32%. When the binder penetration grade decreased by one level (20#), the fatigue life increased by about 12~15%, which indicated that HMAs with harder asphalt could perform better fatigue resistance. Moreover, different from the high- and low-temperature performance, when the N_{des} and asphalt grade decreased by one level together, the fatigue life of HMAs improved significantly by about 36~41%. In addition, It can be seen that HMAs with middle gradation performed the better fatigue life than those with fine or coarse gradation.

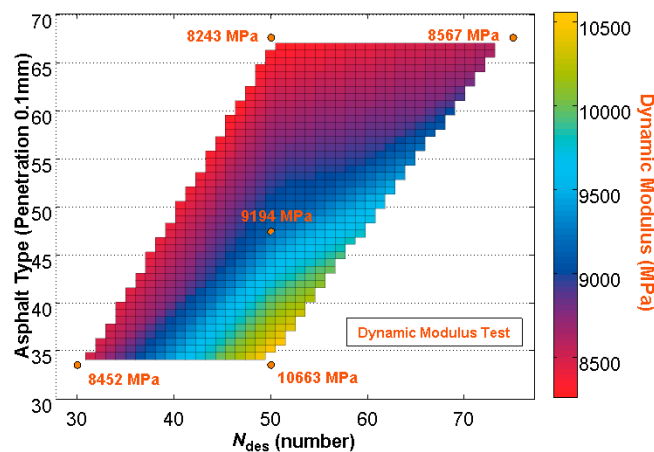
This results can be used to guide the design of HMA in the laboratory. If the high-temperature resistance of HMA is insufficient, it can be made up by using harder asphalt or finer gradation (middle gradation), which can also improve the fatigue resistance. On the contrary, if the low-temperature resistance of HMA cannot meet the requirements, it is better to reduce the N_{des} to increase the tenacity, and the fatigue life of HMA was also improved.

5.4. Dynamic Modulus

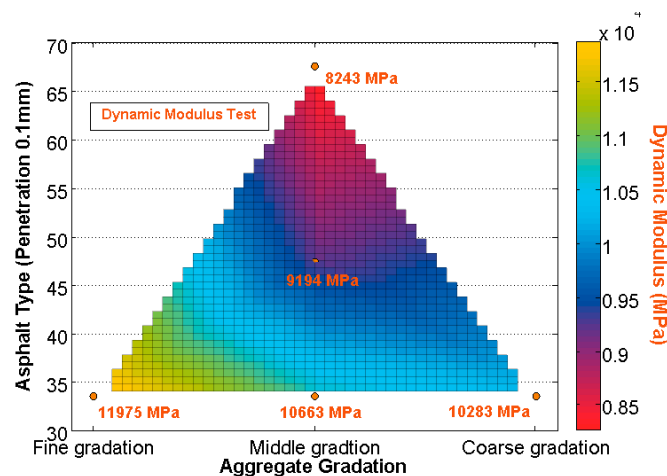
The experiment results of dynamic modulus were presented in Figure 7. The master curves of dynamic modulus of seven group were fitted, as shown in Figure 7a. Then the data of dynamic modulus at 10 Hz and 21 °C was put together for comparison, as shown in Figure 7b,c.



(a) The master curves of four groups.



(b) The modulus at 10 Hz and 21 °C of different asphalt type and N_{des} (Middle gradation).



(c) The modulus at 10 Hz and 21 °C of different asphalt type and gradation ($N_{des} = 50$).

Figure 7. The result of dynamic modulus test.

As shown in Figure 7b, with the N_{des} increasing by one level (25 numbers), the dynamic modulus of HMAs increased by approximately 4 ~ 26%; When the binder penetration grade decreased by one

level (20#), the dynamic modulus of HMAs increased by about 10 ~ 14%. In addition, as shown in Figure 7c, the aggregate gradation influenced the dynamic modulus properties of asphalt mixtures. The finer gradation performed the larger modulus. However, the effect of aggregate gradation on dynamic modulus was not as significant as that of N_{des} and asphalt type.

6. Summary and Conclusions

This study aimed to systematically explore the influence of three different design parameters, namely aggregate gradation, N_{des} , and asphalt type, on the properties of HMAs. The high- and low-temperature, fatigue, and dynamic modulus properties of the mixture were included for evaluation. Based on the findings, the following conclusions can be drawn:

1. The high-temperature resistance of HMAs increased with the rise in N_{des} , the reduction in asphalt penetration grade and the finer gradation. In addition, the contribution of increasing gyration number for shear resistance enhancement is able to make up for the shear resistance loss caused by increasing asphalt penetration grade.

2. The flexural-tensile strain of HMAs at low temperatures increased with the lower N_{des} or coarser gradation. In addition, when the asphalt penetration grade increased to one higher level, the flexural-tensile strain of the HMA increased by around 17 ~ 25%. Moreover, the low-temperature resistance loss caused by harder asphalt binder can be restored through using lower N_{des} or coarser gradation by increasing asphalt content.

3. The fatigue life of HMAs increased by about 32% when the N_{des} decreased by 25. The HMA fatigue life rised around by 12 ~ 15% when the asphalt grade decreased to one lower level. Moreover, when both N_{des} and asphalt grade decreased by one level together, the fatigue life could be significantly improved by approximately 36 ~ 41%. This may indicate that the combination of hard asphalt and low N_{des} has more potential than traditional one.

4. The dynamic modulus of HMAs decreased significantly with the reduction in N_{des} , the rise in asphalt binder grade, or coarser gradation. Specifically, the dynamic modulus of HMA decreased by about 4 ~ 26% when the N_{des} decreased to one lower level. Moreover, the HMA modulus declined by 10 ~ 14% when the asphalt grade increased to one higher level.

5. Under the combination of design parameters, more design possibilities can be obtained to achieve the expected performance compared with traditional methods, and thus the flexibility in the design of HMAs was further improved.

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