The Design Method of Aggregate Gradation of GAC-20 Modified Asphalt Mixture Based on Road Performance

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Abstract. The road performance prediction models are established through a large number of road performance test, the road performance of GAC-20 modified asphalt mixture is predicted in the design calculation process. The gradation test prediction models are established to identify the skeleton structure type of GAC-20 modified asphalt mixture. The GAC-20 modified asphalt mixture design method based on road performance is proposed on the basis, which makes the GAC-20 modified asphalt mixture achieve the optimal in the design process and reduce the unnecessary test amount.

1. Introduction
Asphalt mixture design is one of the important factors that affect the asphalt pavement performance, and good gradation is an important guarantee for high quality road performance. The design work of asphalt mixture is done well is the basis and premise to ensure that the asphalt pavement has good road performance. Aiming at the characteristics of climate, materials and transportation in the northeast region, the design method of GAC-20 modified asphalt mixture based on road performance is proposed by applying the fractal theory.

2. The raw material performance test
Liaohe petroleum asphalt grade A No.90, which is widely used in the northeast of China and the basic performance test results are shown in Table 1, the basic performance test results of SBS modified asphalt is shown in Table 2. [1]

| Detection index              | Unit | Test value | Specification requirements |
|-----------------------------|------|------------|---------------------------|
| Penetration (25°C, 100g, 5s) | 0.1mm| 86.3       | 80-100                    |
| Ductility (15°C)            | cm   | >100       | ≥50                       |
| Softening Point (R&B)       | °C   | 45.9       | ≥45                       |

The coarse and fine aggregate of GAC-20 modified asphalt mixture use limestone gravel produced by Liaoyang Xiaotun victory quarry. The basic performance test results are shown in table 3. [3] Grade A No. 90 road petroleum asphalt, SBS modified additives and limestone was tested in accordance with the requirements of the road usage.
| Table 2. SBS Modified asphalt technical index |
|---------------------------------------------|
| Detection index                            | Unit   | Test value | Specification requirements | Conclusion |
| Penetration (25°C, 5s, 100g)                | 0.1mm  | 83.6       | 80~100                      |
| Softening Point (R&B)                       | °C     | 52.0       | ≥50                         |
| Ductility (5°C, 5cm/min)                    | cm     | >100       | ≥40                         |
| Kinematic viscosity (135°C)                 | Pa·s   | 2.7        | ≤3                          |
| Elastic recovery (25°C)                     | %      | 91.2       | ≥90                         |

| Table 3. Technical index of limestone coarse aggregate |
|--------------------------------------------------------|
| Material specification (mm)                            | 26.5-31.5 | 19-26.5 | 16-19 | 13.2-16 | 9.5-13.2 | 4.75-9.5 |
| Technical index                                        | Standard value | Test value |
| Crushing value (%)                                      | ≤24 | 15 | |
| Apparent relative density (T/m^3)                       | ≥2.5 | 2.729 | 2.726 | 2.73 | 2.718 | 2.729 | 2.732 |
| Water absorption rate (%)                               | ≤2.0 | 0.12 | 1.18 | 0.26 | 0.28 | 0.38 | 0.62 |
| Adhesion with asphalt (Grade)                           | ≥4 | 4 | |
| Consistency (%)                                         | ≤8 | 8 | |
| Content of needle and sheet granular (%)                | ≤12 | 12 | |
| <0.075 Particle content (%)                             | ≤1 | 0.3 | 0.3 | 0.3 | 0.3 | 0.3 |

3. Road performance test
The 25 groups of GAC-20 modified asphalt mixture were designed by orthogonal test method, and the rutting test, water stability test and low temperature performance test were carried out under the conditions of tire ground pressure 0.84 MPa. The results of the experiment are shown in table 4.

3.1 High temperature performance test
The technical requirements for the dynamic stability of asphalt mixture rutting test are different according to different climate zones and the type of asphalt and mixture in the current specification, Climate zoning in the Northeast of China is belonging to the 2-1 area (hot in summer and severe cold in winter) and 2-2 area (hot in summer and cold in winter), due to the wheel pressure 0.84 MPa was adopted in rutting test, dynamic stability should be reduced from relevant literature to meet greater than or equal to 2000 times / mm. Therefore, the high temperature stability of GAC-20 modified asphalt mixture with the grading number of 3, 8, 11, 13, 9, 17 and 24 can meet the requirements. [12]

3.2 Water stability test
The dynamic stability ratio of asphalt mixture was proposed to evaluate the water stability of it. The dynamic stability ratio is defined as the ratio of the dynamic stability of the specimen after freezing thawing cycles and the dynamic stability of non freezing and thawing cycles specimen.[5][16]
The GAC-20 modified asphalt mixture which aggregate gradation number is 2, 3, 4, 6, 8, 9, 12, 13, 15, 18, 20 and 24 meet the water stability requirements.

4. Low temperature performance test
Because of the low temperature in winter in the Northeast area, it is prone to arise sudden changes of temperature and large temperature difference between day and so on, the low temperature performance requirements of asphalt mixture is high. The low temperature performance needs to meet the technical requirements of the specification in the Northeast region. The low temperature bending test is done by the microcomputer controlled test system for asphalt mixture according to E20 JTG - 2011 "Standard Test Methods of bitumen and bituminous mixtures for highway Engineering." (T0715) .Test results are shown in table 4.

5. Road performance prediction model
Asphalt mixture high temperature stability, water stability and low temperature stability are important road performance of asphalt pavement, if we can establish the correlation model between the fractal dimension of asphalt mixture and the evaluation index of high temperature stability, water stability and low temperature stability and the road performance of asphalt mixture can be predicted through the gradation fractal dimension to reduce the amount of test work. The prediction models of the high temperature performance, water stability and low temperature performance are established by applying

| Gradation | D | Dc | Df | $D_S^0$ | DSR | Failure strain/με |
|-----------|---|----|----|---------|------|------------------|
| GAC-20-1  | 2.4914 | 2.5189 | 2.5685 | 1182 | - | 1512 |
| GAC-20-2  | 2.5552 | 2.5046 | 2.5104 | 1432 | 0.95 | 2973 |
| GAC-20-3  | 2.5665 | 2.4692 | 2.4484 | 3103 | 0.93 | 1584 |
| GAC-20-4  | 2.4400 | 2.4559 | 2.3865 | 1892 | 1.19 | 2250 |
| GAC-20-5  | 2.3661 | 2.4102 | 2.3077 | 593 | - | 1877 |
| GAC-20-6  | 2.4171 | 2.4080 | 2.5217 | 1869 | 0.87 | 1728 |
| GAC-20-7  | 2.3405 | 2.3767 | 2.4636 | 712 | - | 3010 |
| GAC-20-8  | 2.5739 | 2.5044 | 2.4017 | 2192 | 0.92 | 1800 |
| GAC-20-9  | 2.5367 | 2.4487 | 2.5468 | 2042 | 0.93 | 2818 |
| GAC-20-10 | 2.5369 | 2.6229 | 2.3127 | 4733 | - | - |
| GAC-20-11 | 2.5026 | 2.3988 | 2.4749 | 2413 | 0.83 | 3254 |
| GAC-20-12 | 2.5012 | 2.5892 | 2.4168 | 1645 | 0.95 | 2484 |
| GAC-20-13 | 2.4535 | 2.5041 | 2.3420 | 3124 | 0.88 | 2628 |
| GAC-20-14 | 2.3544 | 2.3287 | 2.5518 | 1079 | 0.80 | 1985 |
| GAC-20-15 | 2.5993 | 2.5381 | 2.4859 | 1207 | 1.08 | 1476 |
| GAC-20-16 | 2.3388 | 2.3048 | 2.4281 | 602 | 0.75 | 2883 |
| GAC-20-17 | 2.5394 | 2.4417 | 2.3571 | 4827 | 0.63 | - |
| GAC-20-18 | 2.5572 | 2.6102 | 2.5669 | 1261 | 0.93 | 2358 |
| GAC-20-19 | 2.5185 | 2.5892 | 2.5050 | - | - | 1418 |
| GAC-20-20 | 2.4669 | 2.4130 | 2.4931 | 1690 | 0.9 | 2052 |
| GAC-20-21 | 2.4860 | 2.5171 | 2.3734 | - | - | 3765 |
| GAC-20-22 | 2.4282 | 2.4895 | 2.5870 | 805 | - | 3371 |
| GAC-20-23 | 2.3507 | 2.2856 | 2.5251 | 905 | 0.82 | 1350 |
| GAC-20-24 | 2.5835 | 2.5044 | 2.4632 | 3745 | 0.95 | 2812 |
| GAC-20-25 | 2.5783 | 2.5623 | 2.3973 | 595 | - | 1877 |

Note: "-" indicate the test data is not listed in the table, it needs further verification.
MATLAB software and analyzing the correlation between the fractal dimension and the evaluation indexes such as dynamic stability, dynamic stability ratio and low temperature bending failure strain, the road performance prediction models of asphalt mixture are recommended through multiple model comparison. [12][9][16] They are shown in table 5.

Table 5. Prediction model of GAC-20 modified asphalt mixture road performance

| Road performance name | Prediction model | Regression coefficient $R^2$ |
|-----------------------|------------------|-------------------------------|
| High temperature      | DS=3206.5+16056.8D-2605.5Dc-14025.4Df | 0.9370                       |
| Low temperature       | $\varepsilon_b=-524.3-2779.6D+2999.9Dc+1210.9Df$ | 0.9446                       |
| Water stability       | DSR=-1.2919+0.3012D+0.3414Dc+0.2462Df | 0.9417                       |

The fractal parameter ranges for GAC-20 modified asphalt mixture meeting the road performance requirements

The rutting test results of meeting the above high temperature stability requirements in the Northeast of China and the corresponding fractal dimension are summarized in Table 6.

Table 6. GAC-20 grading fractal dimension and dynamic stability data

| Grading    | Grading fractal dimension $D$ | Coarse aggregate fractal dimension $D_c$ | Fine aggregate fractal dimension $D_f$ | Dynamic stability DS (times/mm) |
|------------|-------------------------------|----------------------------------------|--------------------------------------|-------------------------------|
| GAC-20-3   | 2.5665                        | 2.4692                                 | 2.4484                                | 3103                          |
| GAC-20-8   | 2.5739                        | 2.5044                                 | 2.4017                                | 2192                          |
| GAC-20-9   | 2.5367                        | 2.4487                                 | 2.5468                                | 2042                          |
| GAC-20-10  | 2.5369                        | 2.6229                                 | 2.3127                                | 4733                          |
| GAC-20-11  | 2.5026                        | 2.3988                                 | 2.4749                                | 2413                          |
| GAC-20-13  | 2.4535                        | 2.5041                                 | 2.3420                                | 3124                          |
| GAC-20-17  | 2.5394                        | 2.4417                                 | 2.3571                                | 4827                          |
| GAC-20-24  | 2.5835                        | 2.5044                                 | 2.4632                                | 3745                          |

As can be seen from table 6, the fractal dimension range of meeting the requirement of dynamic stability is $D=[2.4535,2.5835], D_c=[2.3988,2.6229], D_f=[2.3127, 2.5468]$.

The fractal dimension of 25 group gradations meeting asphalt mixture high temperature stability, low temperature performance and water stability were aggregated, the fractal dimension ranges which meet the road performance requirements of asphalt mixture are obtained, the fractal dimension ranges are shown in Table 7.

Table 7. The fractal dimension ranges for GAC-20 modified asphalt mixture meeting the road performance requirements

| Technical requirement       | $D$             | $D_c$          | $D_f$          |
|----------------------------|-----------------|----------------|----------------|
| High temperature performance | 2.4535-2.5835   | 2.3988-2.6229  | 2.3127-2.5468  |
| Low temperature performance | 2.3388-2.5835   | 2.3048-2.5171  | 2.3734-2.5870  |
| Water stability             | 2.4171-2.5993   | 2.4080-2.6102  | 2.3420-2.5669  |
| Comprehensive performance   | 2.4535-2.5835   | 2.4080-2.5171  | 2.3734-2.5468  |

According to the requirements of various technical performances in the Northeast of China, Reference to the road performance requirements in the current specifications, draw on the experience of the previous research results of the research group, the technical performance requirements of GAC-20 modified asphalt mixtures are proposed in the Northeast of China, as is shown in Table 8.
Table 8. The technical requirements of GAC-20 modified asphalt mixture road performance in the Northeast of China

| Performance name                  | The technical requirements     |
|-----------------------------------|--------------------------------|
| High temperature performance      | DS ≥ 2000 times/mm             |
| Low temperature performance       | εB ≥ 2800με                   |
| Water stability                   | DSR ≥ 0.85                    |

The inequality is listed according to the technical requirements of asphalt mixture in the northeast region of China.

\[
\begin{align*}
DS &= 3206.5 + 16056.8D - 2605.5D_c - 14025.4D_f \geq 2000 \\
\varepsilon_B &= -524.3 - 2779.6D + 2999.9D_c + 1210.9D_f \geq 2800 \\
DSR &= -1.2919 + 0.3012D + 0.3414D_c + 0.2462D_f \geq 0.85
\end{align*}
\]

Using MATLAB programming to get the solution of inequality, we cannot solve the range of fractal dimension.

In order to avoid the blindness of selecting the fractal dimension in the design process, the fractal dimension ranges which meet the requirements of various performance techniques are proposed in Table 7.

6. Design method of asphalt mixture based on road performance

6.1 Selection of fractal dimension

On the basis of the preliminary work of the research group, the fractal dimension of gradation meeting the requirements of the high temperature stability, low temperature performance and water stability in 25 group gradation is summarized; the fractal dimension range of meeting asphalt mixture road performance requirements is obtained. As is shown in table 7. Namely, the aggregate gradation fractal dimension $D$ value range of 2.4535-2.5835, coarse aggregate fractal dimension $D_c$ value range of 2.4080-2.5171 and fine aggregate fractal dimension $D_f$ value range of 2.3734-2.5468 are recommended.

6.2 Aggregate pass rate derivation

The quality distribution of asphalt mixture has fractal characteristics; the quality distribution function of aggregate is shown in the formula (2).

\[
P(r) = \frac{r^{3-D} - r_{\text{min}}^{3-D}}{r_{\text{max}}^{3-D} - r_{\text{min}}^{3-D}}
\]

$P(r)$ is pass rate of sieve size $r$ in the aggregate of maximum size $r_{\text{max}}$ (%).

If the fractal dimension is known, the pass rate of seives can be calculated and analyzed by the formula (2).

When the fractal dimension of the aggregate particle size distribution is calculated by using the nominal maximum size NMPS of aggregate, the formula (2) can be adjusted to the formula (3).

\[
P(r) = \frac{r^{3-D} - r_{\text{min}}^{3-D}}{NMPS^{3-D} - r_{\text{min}}^{3-D}}P_0
\]

Formula: $P_0$ is the pass rate of the nominal maximum size NMPS, take 90%---100%.

$D$ is the fractal dimension of aggregate particle size distribution, which is hereafter referred to as aggregate gradation fractal dimension.
Therefore, it can be inferred that the formula (4) can be established when \( r \) lies between PCS and NMPS, namely, When \( r \in (PCS, NMPS) \), formula (4) is established.

\[
P(r) = \frac{r^{3-D_c} - r_{min}^{3-D_c}}{NMPS^{3-D_c} - r_{min}^{3-D_c}}
\]  

(4)

When \( r \in (0.075, PCS) \), formula (5) is established.

\[
P(r) = \frac{r^{3-D_f} - r_{min}^{3-D_f}}{PCS^{3-D_f} - r_{min}^{3-D_f}} \times P(PCS) = \frac{r^{3-D_f} - r_{min}^{3-D_f}}{PCS^{3-D_f} - r_{min}^{3-D_f}} \times \frac{PCS^{3-D_c} - r_{min}^{3-D_c}}{NMPS^{3-D_c} - r_{min}^{3-D_c}} \times P_0
\]  

(5)

Formula, PCS is the size of boundary points of coarse and fine aggregates; NMPS is normal maximum particle sieve size. \( r_{min} \) is the smallest particle size; \( D_c \) is the coarse aggregate grading fractal dimension which particle size is in the range of NMPS to PCS, \( D_f \) is the fine aggregate grading fractal dimension which particle size is in the range of PCS and 0.075mm.

As \( r_{min} \) tends to 0, and the pass rate of \( r_{min} \) is approximately 0, to simplify the formula, the \( r_{min}^{3-D} \) of the formula (4) and (5) is given up to get the simplified formula, as is shown in formula (6) and (7).

When \( r \in (PCS, NMPS) \), formula (6) is established.

\[
P(r) = \left(\frac{r}{NMPS}\right)^{3-D_f} \cdot P_0
\]  

(6)

When \( r \in (0.075, PCS) \), formula (7) is established.

\[
P(r) = \frac{r^{3-D_f} - r_{min}^{3-D_f}}{PCS^{3-D_f} - r_{min}^{3-D_f}} \times P(PCS) = \frac{r^{3-D_f} - r_{min}^{3-D_f}}{PCS^{3-D_f} - r_{min}^{3-D_f}} \times \frac{PCS^{3-D_c} - r_{min}^{3-D_c}}{NMPS^{3-D_c} - r_{min}^{3-D_c}} \times P_0
\]  

(7)

For continuous grading, the particle distributing between 0.075mm and NMPS (nominal maximum size) is a fractal distribution, that is, only a fractal dimension \( D \) can describe the distribution of aggregate particles. For discontinuous gradation, the aggregate gradation is in the scale range of the critical point of the coarse and fine aggregate being taken as the dividing point. There are two fractal dimensions between the particle size of 0.075mm and NMPS (nominal maximum size). Namely, the multifractal distribution requires two fractal dimensions to accurately describe the distribution of particle. Formula (6) and (7) can be used as a formula of the fractal gradation theory for calculating the grading. For the ideal continuous gradation, \( D_c = D_f = D \), for the dense gradation, \( D_c = D_f \), and for discontinuous gradation, there is a great difference between \( D_c \) and \( D_f \).

6.3 Road performance prediction

The high temperature stability, low temperature stability and water stability of GAC-20 modified asphalt mixture were predicted by the performance prediction model established in Table 5. In the forecast model, the forecast value of each index is calculated by fractal dimension \( D_c \), \( D_f \) and \( D \). The fractal dimension is resolicited in the recommended range if the road performance evaluation index cannot meet requirements until the prediction results are satisfied with the performance requirements of the road.

6.4 Grading test

According to the previous research results, the correlation model between the fractal volume parameter and the fractal dimension is established to test gradation. The prediction and test are done when the fractal dimension of coarse and fine aggregate meeting the road performance requirements are substituted to these prediction models of coarse aggregate fractal void volume \( V_{co} \) and fractal
volume of fine aggregate in coarse aggregate $V_f$, the coarse aggregate can form an effective framework when coarse aggregate fractal void volume $V_{co}$ is larger than the fractal volume of fine aggregate in coarse aggregate $V_f$, the fractal dimension is adjusted to form a skeleton if the skeleton is not formed.$^{[11]}$

The prediction model of fractal volume parameters is shown in table 9.

**Table 9. The Prediction Model of Fractal Volume Parameter**

| Grading test index                                      | Prediction model                                   | Regression parameters $R^2$ |
|---------------------------------------------------------|----------------------------------------------------|-----------------------------|
| Coarse aggregate fractal void volume $V_{co}$           | $V_{co} = -1.5783 -0.4599D_{c} + 1.2698D_{f}$      | 0.9439                      |
| Fractal volume of fine aggregate in coarse aggregate $V_f$ | $V_f = -1.0892 +0.6795D_{c} - 0.1456D_{f}$         | 0.9741                      |
| $V_{co} \geq V_f$                                       | $1.1394D_{c} -1.4154D_{f} \leq 0.4891$           |                             |

6.5 Test and Inspection

The high temperature stability, low temperature performance, water stability and other performance of asphalt mixture are tested for grading meeting the above steps, the design of the grading is qualified if all the requirements are meet, otherwise, the reasons should be timely found and corrected, or the gradation is redesigned in accordance with the above method steps until the requirements are meet.

7. conclusion

Based on the previous work, the design method of GAC-20 modified asphalt mixture based on road performance in Northeast of China was put forward.

The fractal dimension for meeting the road performance requirements will be taken as a design parameter by applying the fractal theory and each sieve passing rate is deduced by the fractal dimension. The road performance of GAC-20 modified asphalt mixture can be predicted by using the performance prediction model established, the gradation skeleton structure are test by using the fractal volume parameters prediction model. Finally, the GAC-20 modified asphalt mixture which meets the predictive road performance requirements was tested to get excellent performance gradation.

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