Dynamic Viscosity Standard of High Viscosity Modified Asphalt Considering Temperature and Load Coupling Effect

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Abstract. The anti-ravelling and anti-rutting performances of porous asphalt pavement are significantly affected by dynamic viscosity of high viscosity modified asphalt. Climatic and traffic conditions vary greatly due to the vast territory of China, and dynamic viscosity standard has not been recommended up to now aiming at different temperature and load conditions. The influence of high viscosity additive dosage on key property indexes was firstly analysed for asphalt and asphalt mixture, and appropriate dosage was recommended. The dynamic stability changing law of porous asphalt mixture was revealed under different temperature, load and their coupling conditions. Multiple regression relation of them was established. Finally dynamic viscosity standard was proposed considering temperature/load coupling effect. The research results show that when high viscosity additive dosage exceeds 10% for 70# base asphalt, the increasing trend of dynamic viscosity becomes slowing down. Semi-logarithmic relations of dynamic stability with ravelling loss, Marshall stability were respectively found, and double-logarithmic relation of that with dynamic viscosity was found. The appropriate dosage of high viscosity additive is recommended as 12%. Based on multiple regression formula of dynamic stability with dynamic viscosity, temperature and load, the lower limit of 60℃ dynamic viscosity is recommended as 50000Pa•s for normal region, 100000Pa•s for heavy-load region, 200000Pa•s for high-temperature region, and 400000Pa•s for heavy-load & high-temperature region.

1. Introduction
The previous research shows that the asphalt binder with good performance can significantly enhance the performance of porous asphalt mixture in all aspects [1]. A large number of engineering practices also show that the performance of porous asphalt cement plays a decisive role in the durability of porous asphalt pavement. In the early stage, OGFC commonly used ordinary asphalt in the USA, but the road performances are poor. So some states once banned the use of such surfaces. The results of NCAT investigation in 1998 showed that OGFC using modified asphalt showed better road performance [2-4].

In Europe, the porous asphalt pavement is mostly made of modified asphalt. Fibre (mineral or lignin fibre) and anti-stripping agent (hydrated lime or amine) are added, and the road performance is generally good. Therefore, in recent years, the United States learned from Europe and developed a
new generation of OGFC, promoting the use of modified asphalt and adding mineral fibre or lignin fibre to avoid asphalt flow and segregation of coarse and fine aggregates in the process of transportation and paving of the mixture.

In the research and application of porous asphalt pavement, Japan has fully learned from the experience of Europe and the United States. Modified asphalt was used at the beginning, but due to the inadaptability to the high temperature environment and traffic conditions in summer in Japan, the high temperature rutting problem still appeared in the early stage of porous asphalt pavement built with common modified asphalt. Later, modified asphalt with better adaptability and high viscosity was developed, which made the porous asphalt pavement widely used in Japan. Although the technical specifications of Japan stipulate that modified type I and modified type II bitumen can also be used, in fact, high viscosity bitumen is commonly used, which shows good application effect in use. The technical guidelines for porous asphalt pavement issued by Japan road association has put forward clear technical standards for high viscosity modified asphalt and its mixture [5].

Because of the different weather conditions, traffic conditions and test methods in foreign countries, China cannot directly use foreign technical standards. The climate conditions in Europe are relatively mild. The summer temperature in Japan is similar to that in southern China in terms of high temperature, but the traffic load standard in Japan is far lower than that in China. When constructing porous asphalt pavement in China, high performance asphalt should be selected according to the local climate and traffic conditions. By referring to the experience of foreign countries, the asphalt technical indexes and standards of economic and technical rationality are formulated to ensure the performance and durability of the asphalt pavement in heavy traffic and high temperature and rainy areas [6-14].

In 2004, Yulin expressway in Chongqing city constructed a 3 km test section of porous asphalt pavement. The performance comparison between SBS modified asphalt and high viscosity modified asphalt is specially arranged, in which the design void ratio of SBS modified porous asphalt pavement is 17% and that of high viscosity modified porous asphalt pavement is 20%. According to the follow-up observation in the later period, it was found that the porous asphalt pavement with SBS modified asphalt showed a certain degree of early damage after using less than 2 years, mainly manifested as pits and ruts, while the test section with high viscosity modified asphalt basically had no disease.

![Figure 1. Disease of porous asphalt pavement with SBS modified asphalt(left: pits; right: ruts).](image)

The engineering application of Yulin expressway fully proves the research results of laboratory tests. The performance of the asphalt mixture with common asphalt as binder is very poor, and the pavement is prone to serious early damage. When the void ratio of SBS modified asphalt mixture is large, there is the possibility of serious moisture damage. It is necessary to strictly carry out a comprehensive performance test or adopt technical measures such as adding hydrated lime. Modified asphalt with high viscosity can significantly improve the anti-moisture damage ability, anti-rutting ability and anti-ravelling damage of the porous asphalt mixture, and improve its durability [15]. It is a kind of asphalt binder with excellent performance and can be used for the porous asphalt pavement under high temperature and heavy traffic conditions.
2. Materials and test design

2.1. Materials design
Mitsubishi 70# A-grade matrix asphalt was adopted, and the test results of main technical indicators are shown in table 1. The test results of main technical indexes of high viscosity additives (HVA) are shown in table 2. The aggregate gradation composition of porous asphalt mixture is shown in table 3. The maximum nominal particle size of porous asphalt (PA) is 13.2mm, referred to as PA-13 for short, and its optimal oil stone ratio is 4.5%, and the designed voidage is 20%. Among the other constituent materials, coarse aggregate and fine aggregate are rolled from basalt, and the filler is limestone mineral powder, all of which meet the relevant provisions of JTG F40-2004 Technical specifications for construction of highway asphalt pavement.

Table 1. Main technical indexes of matrix asphalt.

| Technical index       | Unit | Test value | Technical requirement | Test method        |
|-----------------------|------|------------|-----------------------|--------------------|
| Penetration degree    | 0.1mm| 69         | 60~80                 | T 0604-2011        |
| Softening point       | °C   | 47         | ≥46                   | T 0606-2011        |
| Ductility             | cm   | 22         | ≥15                   | T 0605-2011        |
| Solubility            | %    | 99.6       | 99.5                  | T 0607-2011        |
| Relative density      | /    | 1.030      | Actual measurement    | T 0603-2011        |
| After TFOT test       |       |            |                       | T 0609-2011        |
| Quality change        | %    | -0.02      | ±1.0                  | T 0609-2011        |
| Penetration degree ratio | %   | 65.2       | 61                    | T 0604-2011        |
| Ductility             | cm   | 7          | 6                     | T 0605-2011        |

Table 2. Main technical indexes of high viscosity additive.

| Technical index       | Unit | Test value       | Technical requirement | Test method     |
|-----------------------|------|------------------|-----------------------|-----------------|
| Shape                 | /    | Granular, even, full | Granular, even, full | /               |
| Single particle mass  | g    | 0.015            | ≥0.03                 | GB/T 1033-2008  |
| Density               | g/cm³| 0.983            | 0.90~1.00             | GB/T 3682-2000  |
| Melt index            | g/10min | 4.5              | ≤2.0                  | T 0614-2011     |
| Ash content           | %    | 0.9              | ≥2                    | T 0614-2011     |

Table 3. Aggregate gradation composition of porous asphalt mixture.

| Technical index       | Quality passing rate through the following sieve pore(mm) |
|-----------------------|-----------------------------------------------------------|
|                       | 0.15 0.075 0.3 0.6 1.18 2.36 4.75 9.5 13.2 16 | |
| Aggregate gradation(%)| 8.5 6.5 5.0 10.0 15.0 17.0 19.0 55.5 95.0 100 | |
2.2. Test design

Four different HVA admixtures were selected, which were 0, 5, 10, 15 percentage respectively, and 0 was the control test. High viscosity modified asphalt and asphalt mixture with different HVA content were prepared and key performance indexes were tested. Asphalt test indexes including 60 °C dynamic viscosity and softening point. The test indexes of asphalt mixture include ravelling loss, Marshall stability and dynamic stability. By analysing the relationship between HVA content and each key performance index, the appropriate HVA content is recommended for the follow-up study.

The recommended HVA content was selected to form the PA-13 specimen, and the rut test was carried out under different test temperatures and loads. Test temperature was chosen as 55 ℃, 60 ℃, 65 ℃, 70 ℃ and 75 ℃. The loads were 0.5 MPa, 0.6 MPa, 0.7 MPa, 0.8 MPa and 0.9 MPa. By analysing the relationship between test temperature, load and dynamic stability, the functional formulas of them with dynamic stability are obtained by regression, respectively.

Using uniform design method, considering temperature, load, and dynamic viscosity, taking dynamic stability as the target variable, the influence rule of dynamic viscosity on dynamic stability under the coupling action of temperature and load was analysed. The functional formulae of temperature, load, dynamic viscosity with dynamic stability were obtained by further multiple regression.

| Table 4. Factors and levels to be considered in uniform test. |
|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| Effect factors  | Unit            | Effect levels   |                 |                 |                 |                 |                 |                 |                 |
| dynamic viscosity(Measured by HVA content)  | %  | 0   | 2.5  | 5.0  | 7.5  | 10.0 | 12.5 | 15.0 | 17.5 | 20.0 |
| temperature     | ℃              | 50  | 53  | 56  | 59  | 62  | 65  | 68  | 71  | 74  |
| load            | MPa            | 0.50 | 0.55 | 0.60 | 0.65 | 0.70 | 0.75 | 0.80 | 0.85 | 0.90 |

| Table 5. Test design scheme. |
|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| Test number     | HVA content (%) | Corresponding dynamic viscosity(Pa·s) | Temperature(℃) | Load(MPa) |
| 1#              | 0               | 249.4           | 65              | 0.6          |
| 2#              | 2.5             | 376.3           | 53              | 0.85         |
| 3#              | 5.0             | 600.4           | 74              | 0.75         |
| 4#              | 7.5             | 1782.0          | 56              | 0.5          |
| 5#              | 10.0            | 21915.3         | 62              | 0.7          |
| 6#              | 12.5            | 63112.0         | 68*             | 0.9          |
| 7#              | 15.0            | 174978.7        | 50              | 0.65         |
| 8#              | 17.5            | 620190.2        | 71              | 0.55         |
| 9#              | 20.0            | 2146347.3*      | 59              | 0.8          |
3. Test results and discussion

3.1. Optimum dosage of HVA

3.1.1. Relationship between HVA dosage and asphalt properties
Dynamic viscosity and softening point of asphalt prepared with different HVA content were measured. The test results were shown in figure 2.

![Figure 2. Relationship between HVA dosage and asphalt properties.](image)

Figure 2 shows that the dynamic viscosity has a significant nonlinear relationship with the content of modifier. When the modifier content exceeds 10%, the dynamic viscosity increases rapidly. Also, the relation between softening point and modifier content is nonlinear. When the content of modifier is low, the increase is not so much. It increases sharply between 5% and 10%, and then tends to increase slowly after 10% dosage.

3.1.2. Relationship between HVA dosage and asphalt mixture performances
Ravelling loss, Marshall stability and dynamic stability of asphalt mixture prepared with different HVA content were measured. The test results were shown in figure 3.

![Figure 3. Relationship between HVA dosage and asphalt mixture performances.](image)
Figure 3(a) shows that the ravelling loss decreases with the increase of dynamic viscosity. When the modifier content increases from 0 to 15%, the ravelling loss decreases from 35.5% to 13.1%, indicating that the high viscosity asphalt has a significant contribution to the anti-ravelling performance of the porous asphalt mixture. One of the most common problems of porous asphalt pavement is the problem of particle ravelling, and improving the viscosity of asphalt can effectively solve this problem.

Figure 3(b) shows that the relationship between Marshall stability and modifier content is similar to that of dynamic viscosity, while figure 3(c) shows that the relationship between dynamic stability and modifier content is similar to that of softening point. Considering that the content of modifier directly corresponds to dynamic viscosity, rutting is the main disease of asphalt pavement in high temperature and heavy load area. It is necessary to establish the relationship between dynamic viscosity and dynamic stability. But the nonlinear relationship between dynamic stability and dynamic viscosity is obvious. By taking logarithm of dynamic stability and dynamic viscosity, it is found that they have linear relationship. The regression diagram is shown in figure 4.

![Figure 4](image.png)

**Figure 4.** Relationship between dynamic viscosity and dynamic stability. DS means dynamic stability, \( \eta \) means dynamic viscosity.

Figure 4 shows that after taking logarithms of dynamic stability and dynamic viscosity, the linear relationship between them is good, and the correlation coefficient \( R^2 \) reaches 0.8939. As an important evaluation index of asphalt pavement high temperature performance, the content of modifier is finally recommended to be 12% as the optimal content of 70# matrix asphalt based on its relationship with dynamic stability.

3.2. Independent effect of load and temperature on DS

3.2.1. Effect of load on DS

Set the temperature of rutting test for 60 \(^\circ\)C, and the loads respectively are 0.5 MPa, 0.6 MPa, 0.7 MPa, 0.8 MPa and 0.9 MPa. The dynamic stability index of porous asphalt mixture was tested to analyze the rutting resistance under different loads. The dynamic stability test results under different load conditions are shown in figure 5.

The pressure of the test wheel is controlled by the calibration pressure and the grounding area of the test wheel. For the load of 0.9 MPa, the test wheels with higher hardness rubber are required. For the load of 0.5 MPa, rubber test wheels with low hardness are required.
Figure 5. Relationship between dynamic stability and load

Figure 5 shows that with the increase of load, the dynamic stability index of rut test gradually decreases, but there is a mutation around 0.6 MPa. This shows that heavy traffic will make the high temperature stability of porous asphalt mixture worse, but high viscosity asphalt will weaken this effect, so that the dynamic stability of asphalt mixture can still reach 4,371 cycles /mm under the load of 0.9MPa.

3.2.2. Effect of temperature on DS
Set the load of rutting test for 0.7MPa, and the temperature respectively are 55 °C, 60 °C, 65 °C, 70 °C and 75 °C. The dynamic stability index of porous asphalt mixture was tested to analyze the rutting resistance under different temperature. The dynamic stability test results under different temperature conditions are shown in figure 6.

Although the pressure is set as constant in the test, the temperature will affect the hardness of the rubber test wheel, thus affecting the grounding area and pressure of the test wheel. Therefore, it is necessary to first keep the temperature constant, and then achieve the predetermined load by repeatedly adjusting the pressure and measuring the grounding area of the test wheel.

Figure 6. Relationship between dynamic stability and temperature.

Figure 6 shows that with the increase of temperature, the dynamic stability of rut test decreases. Compared with the rut test results under different load conditions, the dynamic stability of porous asphalt mixture is more sensitive to the change of temperature. The influence of temperature on the stability of high temperature is obviously more than that of load, so the damage of rutting caused by high temperature should be paid more attention.

In addition, after taking logarithms of the dynamic stability under different loads and temperatures, linear regression was performed respectively. Together with linear regression of dynamic viscosity, the summary is shown in table 6. This regression relationship lays a foundation for the subsequent analysis of the coupling effect of temperature and load on dynamic stability.
Table 6. Linear regression equation of dynamic viscosity, load, temperature.

| Serial number | Effect factors          | Equation                                      | R²  |
|---------------|-------------------------|-----------------------------------------------|-----|
| 1             | dynamic viscosity       | \( \log(DS) = 0.4419 \log \eta + 1.8992 \)   | 0.8939 |
| 2             | Load                    | \( \log(DS) = -0.8926p + 4.4514 \)           | 0.9567 |
| 3             | temperature             | \( \log(DS) = -0.0498T + 6.7592 \)           | 0.9741 |

\( p \) indicates load and \( T \) indicates temperature.

3.3. Coupling effect of load and temperature on DS

The effects of single factors such as asphalt viscosity, load and temperature on the rutting resistance of porous asphalt mixture were analyzed, but a combination of high temperature and heavy load may be formed in engineering practice. On the other hand, engineers are often concerned about how to determine the dynamic viscosity requirements of asphalt under a specific climate and traffic load conditions, so that PA can meet the requirements of high temperature use, but not too wasteful and save costs. It is necessary to analyze the influence of temperature, load and dynamic viscosity of asphalt on the rutting resistance of pavement when the three factors change at the same time. Temperature and load are the external factors, asphalt dynamic viscosity is the internal factors.

Carry out this part of test according to the test scheme in table 5. The test results are shown in table 7. The equation (1) can be obtained by regression analysis of the test results in table 7. The correlation coefficient of this equation is 0.892.

Table 7. Rutting test results of uniform design scheme.

| Test number | Dynamic viscosity (Pa·s) | Temperature (°C) | Load (MPa) | DS (cycle /mm) |
|------------|--------------------------|------------------|------------|----------------|
| 1#         | 249.4                    | 65               | 0.6        | 22.3           |
| 2#         | 376.3                    | 53               | 0.85       | 2154.2         |
| 3#         | 600.4                    | 74               | 0.75       | 33.2           |
| 4#         | 1782.0                   | 56               | 0.5        | 7717.5         |
| 5#         | 21915.3                  | 62               | 0.7        | 3244.8         |
| 6#         | 63112.0                  | 68*              | 0.9        | 4470.1         |
| 7#         | 174978.7                 | 50               | 0.65       | 12308.7        |
| 8#         | 620190.2                 | 71               | 0.55       | 3881.7         |
| 9#         | 2146347.3*               | 59               | 0.8        | 10248.9        |

\( \log(DS) = 0.535\log \eta - 0.63p - 0.0653T + 5.592 \)  \hspace{1cm} (1)

According to the technical guide for drainage pavement (case) of Japan and relevant literature, the technical requirement for dynamic stability of porous asphalt mixture in rut test should be no less than 3000 cycles /mm. However, in practical engineering, rutting resistance often leaves a certain safety reserve, and its dynamic stability is more than 4000 ~ 6000 cycles /mm. The load of rut test in China is consistent with the standard wheel load of pavement design in China, which is 0.7 MPa.

Based on the overload investigation results of expressway, the tire grounding pressure can reach 0.83 MPa when overload is 50%, 0.91 MPa when overload is 100%, and 0.99 MPa when overload is
200%. Rutting test temperature may be different in different countries, such as the UK using 45 °C, in many parts of the Japanese using 60 °C except Hokkaido area using 45 °C, but the principle is that it can reflect the region surface temperature in the summer.

Using equation 1, the dynamic viscosity which meets the design requirements of different dynamic stability under different load and temperature conditions can be calculated. See table 8 for details. Further, the limit dynamic viscosity of different typical regions are as shown in table 9.

| Design load(MPa) | Dynamic viscosity (Pa·s) under the following design temperature |
|------------------|---------------------------------------------------------------|
|                  | 55°C | 60°C | 62.5°C | 65°C | 67.5°C |
| 4000             | 6575 | 26801| 54112 | 109252| 220582|
| 0.7              | 9977 | 40671| 82116 | 165794| 334742|
| 5000             | 14029| 57186| 115460| 233116| 470666|
| 6000             | 8622 | 35148| 70965 | 143280| 289286|
| 0.8              | 13085| 53339| 107693| 217434| 439003|
| 5000             | 18398| 74998| 151422| 305724| 617262|
| 6000             | 11308| 46096| 93069 | 187907| 379388|
| 0.9              | 17160| 69953| 141236| 285157| 575737|
| 5000             | 24128| 98357| 198585| 400947| 809518|
| 6000             | 14830| 60453| 122056| 246434| 497555|
| 1.0              | 22505| 91740| 185226| 373974| 755060|
|                  | 31643| 128992| 260437| 525828| 1061656|

Table 9. The limit dynamic viscosity for typical regions.

| Region type                  | load(MPa) | temperature(°C) | DS (cycles /mm) | Dynamic viscosity(Pa·s) |
|------------------------------|-----------|-----------------|-----------------|------------------------|
| Normal region                | 0.7       | 60              | 5000            | 50000                  |
| Heavy-load region            | 0.9       | 60              | 5000            | 100000                 |
| High-temperature region      | 0.7       | 65              | 5000            | 200000                 |
| High-temperature & heavy-load region | 0.9 | 65              | 6000            | 400000                 |
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