Performance study and application of porous ultra-thin wearing course for asphalt pavement maintenance

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Abstract. An ultra-thin layer wearing course with thickness between 15mm and 30mm are developed and applied for maintenance of asphalt pavement. The maximum size of the coarse aggregate is 10 mm. In this study, the high viscosity modified bitumen is used as binder for improving the anti-rutting and raveling performance of a porous mixture. Mixture designed study is carried out by combing the functional and structural performance measurements. The target air voids contents for those ultra-thin surfaces are between 15% and 20%. Important factors presenting the high temperature property, moisture feature, low temperature feature and anti-raveling performance are investigated in lab. Meanwhile, surface characteristic which reflect the sound absorption is also observed. A feasibility of using the ultra-thin wearing course mixture in China is proved. Trial sections are constructed in southeast part of China for studying the performance of ultra-thin waring course in maintenance engineering. The achievements from the study will provide technical support for the maintenance of asphalt pavement with moderate surface damage. It will also improve the skid resistance and the noise reducing function of the old pavement, which presents superior social and environmental benefits.

1. Introduction

A thin layer wearing course is commonly used as noise reducing pavement in European countries such as Germany and the Netherlands, and is used as open graded friction course (OGFC) in the United States. Due to definitions in different countries, it generally refers to the asphalt pavement with small size aggregate (the maximum particle size is less than 10 mm), thickness of 15-30 mm and designed air voids content greater than 14%. It can improve the safety and service life of road structure. In China, this surface type is called Ultra-Thin Wearing Course. A porous ultra-thin wearing course (PUC) has the air voids contents no less than 18%.

The most typical structural disease form of a porous asphalt pavement is the raveling caused by the strip of coarse aggregate. This disease is also particularly prominent for ultra-thin wearing courses. Because of the small nominal maximum particle size of aggregate and the low embedding force of coarse aggregate in PUC, it is easier to destabilize and disperse under the action of external loads and
environmental factors. Therefore, asphalt binder is required to have strong encapsulation ability and high adhesion to coarse aggregate. For the binder of porous asphalt pavement and ultra-thin abrasive layer, there are many studies on rubber asphalt (AR), SBS, PG (performance grade), matrix asphalt and epoxy asphalt at home and abroad. Woldekidan [1] analyzed the performance of asphalt mortar and mortar of porous asphalt pavement by dynamic rheological test, and simulated the fracture performance of asphalt mortar in porous asphalt pavement material system by means of mesoscale mechanics. Hagos [2] studied the aging mechanism and influencing factors of asphalt binder in the course of using porous asphalt pavement.

In the development of porous asphalt in China, in order to adapt to high temperature and heavy traffic conditions in summer, high-viscosity modified asphalt has been gradually used. The dynamic viscosity of this type of asphalt is greater than 20000 Pa·s at 60°C, which helps to enhance the bonding strength, improve the overall performance of pavement structure. Xu et al. [3] observed the high temperature performance of aged high viscosity modified asphalt and its adhesion to coarse aggregate by means of multi-stress creep recovery and ultraviolet spectroscopy. Qin et.al. investigated the influence of temperature and frequency on anti-rutting performance of high-viscosity modified asphalt [4], and Li et.al. analyzed the rheological properties of high viscosity modified asphalt made from low-grade asphalt [5].

For the performance of thin layer asphalt mixtures, Ahmed et al. [6] predicted and analyzed the temperature and reflection crack development of ultra-thin wear layer mixture by fracture energy test and finite element numerical simulation. Chen et al. [7] observed and evaluated the long-term performance of the ultra-thin wearing course.

The acoustic performance of asphalt pavement is mainly affected by the geometric structure of the pavement surface and the internal void condition of the surface layer. The acoustic properties of porous asphalt mixtures are generally analyzed from surface texture and noise absorption properties. Sanberg [8] studied the effects of noise texture and texture depth on porous asphalt pavement. Berengier et al. [9], Attenborough et al. [10] and other scholars have established phenomenological and microstructural models to simulate the acoustic impedance and sound absorption properties of porous asphalt mixture media. For the acoustic performance of thin layer wearing course, the main research is mainly based on experimental research. Li et al. [11] used laser scanning to analyze the apparent depth of the thin-layer overcoat structure and the sound pressure (P)-particle velocity (U).

Since the durability is lowered with the increasing air voids contents, the thin-layer course currently used has a voids content which is generally not high, and is mostly about 15% or less. In this study, the high-viscosity modified asphalt commonly used in China's porous asphalt was applied as the main binding material, and performances of PUC mixture with a maximum aggregate size of 10 mm was studied. The mixture and sound absorption performance were tested and investigated. With the analysis, a suitable PUC mixture that can be used in highway maintenance engineering is obtained. Application of this type of material was carried out in a test section in actual engineering. The research results provide a road surface structure with functional and structural advantages for highway maintenance.

2. Materials and Gradation Design

2.1. High viscosity modified asphalt

The binder used in the study is SBS modified asphalt, and the high and low temperature performances of the binder and mixture are improved by adding high viscosity modification additives (HVA). The test results of various performances of high viscosity modified asphalt with the ratio of SBS: HVA=92:8 are shown in Table 1. The test method is based on the Chinese standard “Standard Test Methods of Bitumen and Bituminous Mixtures for Highway Engineering” (JTG E20-2011).
Table 1. Features of high viscosity modified asphalt

| Asphalt performance indicator | Unit   | Test value | Standard value |
|-------------------------------|--------|------------|----------------|
| Needle Penetration, 25℃, 100g, 5s | 0.1mm  | 47.6       | ≤40            |
| Softening point (T<sub>R&B</sub>) | ℃      | 91.5       | ≤90            |
| Ductility (5℃, 5cm/min)        | cm     | 32         | ≤30            |
| Dynamic viscosity (60℃)        | Pa·s   | 777548     | ≤400000        |
| Brookfield viscosity (170℃)    | Pa·s   | 1.069      | ≥3.0           |

2.2. Gradation design
The overall design principle of asphalt mixture grading is adjusted to meet the target air voids content by controlling the passing percentage of key mesh sizes (4.75mm, 2.36mm) and the sieve allowance below 0.075mm.

The size of fine aggregates of PUC-10 is from 0 to 3 mm and the coarse aggregate size is from 4.75 to 9.5 mm. Considering that the range of 4.75～9.5mm gear aggregate is too large, it was decided to increase a 7.5mm mesh for the mixture design. Among them, 4.75～7.5mm and 7.5～9.5mm are mainly used as the coarse skeleton structure to ensure the skeleton embedding, while the 0～3mm fine aggregate mainly plays the role of filling the gaps.

The test obtained the voids of coarse aggregate (VCA) of the coarse aggregate skeleton structure by comparing the different blending ratios of the 4.75-7.5 mm and 7.5-9.5 mm aggregates, as shown in Figure 1. The existing research shows that the smaller the skeleton gap ratio of the aggregate, the denser the aggregate and the stronger the intercalation between the aggregates. It can be seen from the figure that the VCA minimum is about 1:2, so the PUC-10 mixture skeleton structure selection (4.75-7.5mm); (7.5-9.5mm) is 1:2 ratio, and the mixture ratio is designed to The target void ratios of 20%, 18%, and 15% were met, and the three void ratios were determined as shown in the table.

![Figure 1. VCA of PUC-10 for different blending ratios of the 4.75-7.5 mm and 7.5-9.5 mm aggregates](image1)

![Figure 2. The gradation curve for PUC-10 mixture with different air voids content](image2)

2.3. Asphalt content
Based on the porous characteristics of the ultra-thin wearing course of large voids, the combination of the drainage and the raveling test is used to determine the optimum asphalt content according to the "inflection point" of the curve. In this study, for Gradation A, B and C, the optimum asphalt content are 4.7%, 5.0% and 5.1% respectively.

3. Sound absorption performance analysis
Aiming at the main influencing factors of road surface noise reduction, the sound absorption
performance of porous thin layer pavement is analyzed. The influence of the air voids content changes on the sound absorption coefficient are to be compared with various thicknesses. Considering the thickness of ultra-thin wearing course, the common pavement surface layer and the sample thickness, three specimens with thicknesses of 25mm, 40mm and 63.5mm were respectively formed. The air voids content was designed to be 20%, 18%, 15%. The sound absorption coefficient test by impedance tube method on the PUC-10 mixture is shown in Figure 3.

As can be seen from the figure:

1. The sound absorption coefficient-frequency curves of different air voids contents all showed similar trends. As the frequency increases, the sound absorption coefficient of the mixture gradually increases, and gradually decreases after reaching the peak value.

2. Within a certain thickness range, the peak frequency of the same thickness mixture is in the range of 500~1400 Hz, and the peak of the sound absorption coefficient becomes "high and wide" with the increase of the air voids content, which is very obvious for the improvement of the sound absorption effect of the asphalt mixture. The peak value of the curve increases as the air voids content increases, and the corresponding frequency of the peak also gradually shifts toward the high frequency direction.

3. In particular, when the thickness is increased to a certain range, even if the thickness of the mixture is kept constant, the peaks of the sound absorption coefficient of the mixture of different void ratios tend to gradually close together, so that the peak of the sound absorption coefficient corresponds to the tendency of the frequency to shift toward the high frequency.

![Sound absorption curves for PUC-10 mixtures](image)

Figure 3. Sound absorption curves for PUC-10 mixtures

4. Mixture performance analysis

4.1. Freeze-thaw split tensile strength

The freeze-thaw split test is to determine the strength ratio of the asphalt mixture test sample before and after the water damage, so as to evaluate the water stability of the asphalt mixture. The test was carried out for two groups of specimens. The first group was stored at room temperature. The second group was vacuumed for 15 minutes and then immersed in the water for 0.5 h. The bag was placed in an incubator at -18 °C for 16 h, and then placed in a constant temperature water bath at 60 °C for
24h. The test results are shown in Figure 4.

It can be seen from Figure 4 that the 20% and 18% void ratio PUC-10 asphalt mixture freeze-thaw splitting tensile strength ratio is slightly lower than the conventional 80% requirement of China Highway, and the 15% void ratio asphalt mixture meets the specification requirements. In response to this situation, we conducted repeated experiments through the following three scenarios to improve the performance:

- a. Replace asphalt for another SBS modified asphalt
- b. Replace mineral filler
- c. Replace the filler with 50% hydrated lime

The results of the freeze-thaw split test for the three schemes above are shown in Figure 5.

(1) By replacing the test raw material asphalt and mineral filler, the influence on the performance is insignificant.

(2) Using 50% hydrated lime to replace the original filler can increase the freeze-thaw splitting tensile strength ratio, but this may bring about changes in other test indexes of porous asphalt mixture, which should be based on the actual engineering technology.

![Figure 4](image1.png) **Figure 4.** Residual split tensile strength for PUC-10 mixtures

![Figure 5](image2.png) **Figure 5.** Residual split tensile strength for PUC-10 with material adjustment

### 4.2. Anti-raveling performance

Raveling is a significant disease of mixture with large porosity. The test was conducted by the Los Angeles Abrasion Tester. The test results of standard raveling and immersion raveling are shown in Figure 6. It shows that:

(1) The results of standard raveling test show that with the decrease of void ratio, the raveling loss of PUC-10 mixture decreases significantly, and the raveling loss percentage of asphalt mixture of 15%, 18% and 20% can meet the technical requirements of porous asphalt mixture in China, which is generally 15% for expressway.

(2) The results of water immersion raveling test show that the PUC-10 mixture with 15%, 18% and 20% air voids content has little water immersion raveling loss, and the correlation with void variation is not remarkable. Mixture with all the air voids content show good performance for anti-raveling.
Long-term aging performance

Asphalt mixture will gradually age in service process, and asphalt pavement damage often occurs in different periods. Therefore, it is necessary to conduct long-term aging test on porous asphalt mixture to analyze mixture performance.

In the test, PUC asphalt mixture was heated for 4 hours under the forced air condition of $135 \degree C \pm 3 \degree C$ for short-term aging, and specimens were continuously heated in an oven at $85 \degree C \pm 3 \degree C$ for 5 days. The test results are shown in Table 2.

It can be seen from Table 2 that after long-term aging, the immersion raveling rate increases by about 11%, and Marshall stability, residual stability, standard raveling loss, and freeze-thaw splitting residual strength were improved. All indicators meet the requirements of an engineering requirement in China, which means the current design of PUC-10 material can adapt to the environmental effects in long-term use.

| Performance                                      | Test results                         | Requirements |
|--------------------------------------------------|--------------------------------------|--------------|
| Marshall stability, kN                           | Before ageing: 7.43                  | ≥5.0         |
|                                                  | After ageing: 7.49                   |              |
| Residual Marshall stability percentage, %        | Before ageing: 94.30                 | ≥85          |
|                                                  | After ageing: 100                    |              |
| Standard raveling loss percentage, %             | Before ageing: 10.55                 | ≤15          |
|                                                  | After ageing: 7.3                    |              |
| Immersion raveling loss percentage, %            | Before ageing: 5.59                  | ≤20          |
|                                                  | After ageing: 6.2                    |              |
| Residual Freeze-thaw split tensile strength ratio | Before ageing: 86.5                  | ≥80          |
|                                                  | After ageing: 88.6                   |              |

Frost resistance

At low temperature, porous asphalt pavements may experience freezing and thawing process. Unlike ordinary pavement, water exists in the pores of a porous pavement during freezing and thawing. Therefore, after mixture was subjected to several freeze-thaw cycles in fully immersed state, the frost resistance of porous asphalt mixture was evaluated by attenuation degree of road performance.

Test conditions

The “4+2” cycle was adopted in the freeze-thaw test. The PUC-10 asphalt mixture with a voids content of 20% is firstly immersed in the water tank for 4 hours, and covered with plastic bag and
placed in an incubator at -18 °C for 4 hours. Then, it was taken out and placed in a water tank at room temperature for 2 hours. One cycle lasts for 6 hours and repeats continuously.

In particular, in the test process, it was difficult to achieve full saturated state after mixture specimen was covered with plastic bag. Most of them can only be partially infiltrated in the water, but this is also in line with the surface immersion of road as in rainy and snowy condition in practice. It is recommended to use a plastic box of appropriate specifications instead of a plastic bag to achieve full water saturation in the future, if it is necessary to simulate full saturated and frozen state of road surface.

4.4.2. Test results and analysis

In order to simulate the case where air voids content is relatively unfavorable, the test was carried out using PUC-10 specimen with 20% porosity. The changes in raveling loss rate and splitting tensile strength after 10, 20, 30, and 40 times freeze-thaw cycles of mixture are shown in Figure7.

According to the test results, following conclusions can be drawn:

(1) Asphalt mixture anti-raveling performance: As can be seen from Figure 10, raveling loss of PUC-10 mixture with 20% void ratio increases with the number of freeze-thaw cycles. When number of cycles reaches 30 to 40 times, the speed of raveling was significantly accelerated, but after 40 times of “4+2” freeze-thaw cycles, the raveling rate is still below 15%, which means an acceptable performance for road engineering in China. The reason is considered that pressure generated by expansion of water in the voids of the specimens is bounded by adhesive force of asphalt binder; asphalt mixture has good toughness, and its resistance to deformation is greater than mixture’s minor deformation caused by water frost.

(2) For splitting tensile strength, as shown in Figure 7(b), it decreases with the number of freeze-thaw cycles; when within 30 times of freeze-thaw cycles, tensile strength is reduced by about 0.05MPa for every 10 times of freeze-thaw cycles; when the number of freeze-thaw cycles is more than 30 times, tensile strength is obviously decreased. Compared with results of unfrozen-thaw test in 4.2, the freeze-thaw splitting strength rate after 40 freeze-thaw cycles is still about 70%.

(a) Standard ravelling

(b) Split tensile strength

Figure 7. Performance measurements for PUC-10 mixtures after freeze-thaw recycle

5. Trial section and road performance analysis

The porous asphalt pavement of coastal highways in Jiangsu province in China was completed and opened to traffic in 2005. It has been used in operation for more than 13 years. Field investigations showed that porous asphalt has been clogged to some extent. However, due to the rough texture of road surface helped to break the water film, it still has certain drainage function in rainy time. In order to improve safety performance in rainy days, it was planned to build PUC-10 porous ultra-thin wearing course for maintenance and repair of porous asphalt pavement. And during the service process, this technology will be verified and summarized. The specific maintenance section is K1125+200–K1124+190 in Nantong-Yancheng direction, and the total length is 1.0km. The thickness
of the trial section is 25mm. The results of measurements on the mixture and pavement surface are shown in Tables 3 and Table 4 respectively. It can be seen from tables that both the performances of mixture and surface can meet requirements for road service. The long-term performance and function of pavement will continue to be investigated in subsequent studies.

Table 3. Measurement results for asphalt mixtures for PUC-10 trial section

| Performance                        | Test results | Targets for the project |
|------------------------------------|--------------|-------------------------|
| Theoretical maximum specific gravity | 2.632        | /                       |
| Air voids content, %               | 21.5         | 17~23                   |
| Marshall stability, kN             | 5.98         | ≯5                      |
| Drainage percentage, %             | 0.07         | ≯0.8                    |
| Standard raveling loss percentage, % | 14.1         | ≯15                     |
| Immersion raveling loss percentage, % | 19.0         | ≯20                     |
| Residual Marshall stability percentage, % | 95.2         | ≯85                     |
| Residual Freeze-thaw split tensile strength ratio, % | 96.1         | ≯80                     |
| Dynamic Stability, time/mm        | 4922         | ≯4000                   |

Table 4. Measurement results on the newly paved PUC-10

| Position  | Lane     | Thicknes s, mm | Air voids content, % | Compaction Degree, % | Permeability (ml/min) | British pendulum number (BPN) |
|-----------|----------|----------------|----------------------|----------------------|-----------------------|-----------------------------|
| K1125+000 | Middle Lane | 24.7           | 23.0                 | 98.1                 | 5556                  | 57                          |
|           | Fast Lane | 27.3           | 23.9                 | 97.0                 | 5310                  | 61                          |
| K1124+700 | Middle Lane | 27.2           | 22.7                 | 98.5                 | 5279                  | 62                          |
|           | Fast Lane | 26.5           | 23.3                 | 97.7                 | 5357                  | 64                          |
| K1124+400 | Middle Lane | 24.2           | 21.5                 | 100.0                | 4700                  | 65                          |
|           | Heavy Lane | 28.3           | 21.6                 | 99.9                 | 5187                  | 60                          |

6. Conclusions and recommendations

In this paper, the comprehensive evaluation on design, sound absorption property and mixture performance of 10mm PUC-10 mixture was carried out, and long-term performance observation is to be performed by constructing the test section. The main conclusions and recommendations are as follows:

(1) The laboratory evaluation and analysis on noise-reducing performance of porous ultra-thin wearing course mixture was performed. The study showed that air voids content affects mixture’s
peak value and peak frequency of sound absorption coefficient, that is, when the air voids content is larger, peak value is higher, as well as a lower peak frequency correspondingly.

(2) According to the performance study on PUC mixture, for PUC type mixture with high viscosity modified asphalt as binder, when void ratio is 15%~20%, it can meet needs of high temperature, low temperature, water damage resistance, raveling resistance, long-term aging and frost resistance. The performance of water damage resistance can be improved by adding hydrated lime. For multiple freeze-thaw cycle test, comparison with dense graded ultra-thin wearing course is to be added in the future research work, and technical scheme for further strengthening fatigue resistance is also to be proposed.

(3) Based on the reconstruction project of Coastal Expressway in 2018, the preliminary application of PUC-10 porous ultra-thin wearing course technology was carried out. Mixtures produced in mixing plant and on-site inspections show that performance of mixture and road surface can both meet the requirements in using in China. Follow-up observations on trial section will be carried out, and construction techniques such as paving, rolling and temperature control will be improved as well.

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