Research review on the Key Technology of Preventive Maintenance: The Durability of 4.75mm NMAS Stone Mastic Asphalt (SMA-5) Ultra-thin Overlay

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Abstract. SMA-5 Ultra-thin Overlay is a kind of preventive maintenance material which has the advantages of fast construction, good surface texture depth, cost-effective and environmentally friendly. It is also suitable for the maintenance of bridge and tunnel which have restriction on elevation. However, the insufficient durability is the key factor which restricts the development of SMA-5. This article summarizes the key technology to enhance the durability of SMA-5 in terms of its material composition, grading and mixture design methods, which provide a reference for improving the durability of SMA-5 and promoting the application of SMA-5.

1. Introduction
Preventative maintenance of pavements is designed to improve the pavement function without significantly increasing the pavement structure bearing capacity [[1]]. Compared with other corrective or routine maintenance method, it is usually done when a pavement is structurally sound and with little or on distress. Thus, it is cost-effective and environmental-friendly [[2]]. With these advantages, preventative maintenance now is considered as top maintenance strategies in highway management system.

Preventive maintenance technology includes thin-layer overlays, micro-surfaces, gravel seals, slurry seals and mist seals [[3]-[4]]. Among them, the pavement thickness of 4.75mm nominal maximum aggregate size (NMAS) Stone Mastic Asphalt (SMA-5) is only 10~15mm, and has the advantages of good surface texture, fast construction and low cost. Therefore, SMA-5 is getting more and more attention on scholars. The Louisiana Department of Transportation proposed that reducing the NMAS of SMA to 10mm can make SMA cost-effectiveness, solve the stockpile of aggregates in low-flow road, as well as make the surface smoother [[5]]. Subsequently, more and more states in the U.S., such as Alabama, Maryland, and Georgia, have successfully applied smaller NMAS SMA (SMA-5) in low-flow roads, ultra-thin overlays and preventive maintenance. In these projects SMA-5 showed good road performance. In 2002, the U.S. National Asphalt Technology Center formulated the design standard for 4.75mm NMAS mixture [[6]]. At present, SMA-5 is widely used in preventive maintenance and bridge deck paving in U.S., France, Japan and other countries. China has launched a series of research work on the road performance of SMA-5. Chen [[7]], proposed the mixture design method of SMA-5. Sun Baosheng [8] proposed that the SMA-5 can effectively extend the service life, reduce the noise, and improve the driving comfort and safety. Lin [[9]] found that SMA-5 has a stable...
skeleton structure, excellent high temperature stability and water stability. Luo [[10]] proposed that cold-mix SMA-5 is a new attempt for preventive maintenance of highway in China.

However, more and more researches proposed that the insufficient durability is the key factor which restricts the development of SMA-5. On the Guangzhou to Shenzhen high-speed tests road, the anti-skid performance of SMA-5 declined rapidly after a short period of time after open to traffic [11]. Not only that, the SMA-5 test road in INDOT also showed some pavement disease in a short time such as looseness and pitting. In order to improve the long-term performance of SMA-5, scholars are committed to comprehensively improving the durability of SMA-5 from the aspects of material composition, gradation and mixture design methods. In this article, a summarize will be done from the above-mentioned aspects, which can provide a reference to improving the durability of SMA-5 and promoting the application of SMA-5.

2. Materials

2.1. Binders

Due to the small particle size of the aggregates used in SMA-5, it is more likely to cause instability damage such as loosening and falling off under the abrasion and impact of the wheel load and external environment. For these reasons, SMA-5 asphalt binder should have good adhesion, flowability resistance, water resistance and anti-aging properties. In addition, a thicker asphalt film should be formed around the aggregate to make sure the durability of mixture as well as the adhesion to the underlying layer. Some researchers used high-viscosity asphalt such as SINOTPS, rubber asphalt to improve the adhesive performance between asphalt and aggregates in SMA-5 [[12]-14]. The results indicated that high-viscosity asphalt can significantly increase the durability of SMA-5 in hot humid area. Lia [[15]] proposed that use waterborne epoxy resin (WER) as a binder added to the SBS modified emulsified asphalt, can greatly improve the dispersibility of emulsified asphalt, so as to improve the anti-shear performance of SMA-5 mixture as well as the anti-skid performance.

2.2. Additive

Fiber is the most commonly used additive in SMA-5, which plays a role in reinforcing, dispersing, stabilizing, and thickening in the mixture. Fibers commonly used in SMA include lignin, basalt polyester and so on. Among these, basalt fiber has the advantages of low water absorption, high melting point and environmentally friendly and good mechanical properties. Moreover, it can form a unique network structure in the mixture, which can enhance the shear strength and viscosity of the mixture, so as to effectively improve the water stability and low temperature performance of the ultra-thin overlay [[16]-[17]].

Some researches indicated that the addition of steel slag can effectively improve the skid-resistance performance and durability of SMA-5. He [[18]] proposed that the addition of steel slag can enhance the road performance of SMA-5, especially improve the skid-resistance performance. Compared with ordinary size asphalt mixtures, the adhesion between the aggregates and asphalt of SMA-5 is much better. Zhong [[16]] adopt slag and basalt to prepare SMA-5, the results show that the slag with high basic oxide content and rough surface can effectively improve the adhesive performance. And the three kinds of SMA-5 with different slags are all show higher texture depth, BPN and dynamic stability in comparison with the control group. Which illustrate the use of slag can significantly improve the skid-resistance performance and high-temperature stability.

Wei[[19]] pointed out that the addition of rubber crumbs in SMA-5 can effectively improve the resistance to moisture ability, low temperature cracking, fatigue cracking and rutting while reduce the traffic noise [[20]-[21]].Zhang [[22]] shows SMA-5 rubber asphalt mixture mixed with an appropriate amount of Vita Linking agent (TOR) to prepare the Vita rubber asphalt mixture, which can effectively improve the compatibility of rubber asphalt and the workability of the mixture while enhancing the adhesion between the asphalt and aggregates, so as to improve the road performance of the mixture. However, it has little improvement on its bearing capacity.
2.3. Aggregates
As the aggregate particle size of SMA-5 is smaller, compared with ordinary size asphalt mixture, it is more prone to aggregate crushing and abrasion under vehicle load, resulting in pavement disease such as rutting and the descent of skid resistance which seriously affect the durability of SMA-5. Therefore, high-quality aggregate is one of the key factors to ensure the road performance of SMA-5. The mass of the coarse aggregate in SMA-5 is more than 70%, so the inter-lock between the coarse aggregates in SMA-5 plays an important role in the mechanical property of the mixture, which will directly affect the road performance. The coarse aggregate used in SMA-5 should not only have good shape, uniform quality, clean and dry, no impurities and no weathering, but also have sufficient strength, impact resistance, freeze corrosion resistance and wear resistance etc. Liu [12] adopt diabase, limestone and basalt as aggregates to comparatively study the influence of aggregates type on the road performance of SMA-5 by the help of British pendulum number (BPN) and loss polishing stone value (LPSV), as well as X-Ray Diffraction (XRD) experiments. The result shows that the angularity reduction was the main component of abrasion loss. For pavements with high performance requirement, coarse aggregates with large angularity and low abrasion value should be preferred, whereas the quantity of particles with excessively high F and E ratio should be controlled. Because the mineral crystal particles of basalt and diabase are small, which lead to a large contact surface between the aggregates and binder, which can guarantee a strong wear resistance ability [23].

3. Gradation
Gradation is a key factor affecting the mixture design, construction and road performance of SMA-5. In the target mixture proportion design of SMA-5, the small particle size of the aggregates has a great impact on the volume parameters, physical and mechanical properties of the mixture. Therefore, the determination of the screening size of the coarse and fine aggregate is the basis of SMA-5 gradation design.

Conventional asphalt mixture is generally used 4.75mm sieve as the coarse aggregate and fine aggregate boundary screen. However, the NMAS of SMA-5 is 4.75mm, it is not feasible to continue use 4.75mm sieve as the boundary screen. According to Bailey method, 1.18mm sieve is the boundary sieve for the SMA-5 [24].

Consider 1.18mm sieve as the primary control sieve of SMA-5, the mixture could form a stable stone to stone interlock structure and the high friction resistance between the coarse aggregate was formed, so as to enhance the high temperature deformation performance of the mixture. The volume parameters of SMA-5 also confirm this point. Studies also show that, in addition to 1.18mm sieve, 2.36mm and 0.075mm sieve is also the critical sieve of SMA-5, which control the trend of SMA-5 grading curve [22]. Xing [25] studied the gradation of SMA-5 based on the Grey Entropy Method and the recommended grading is shown in Table 1. And the key control sieves for SMA-5 is 2.36mm, 1.18mm and 0.3mm.

Table 1. Recommended gradation for SMA-5.

| gradation | Passing rate/% |
|-----------|---------------|
| Sieve size/mm | China | American |
| 9.5 | 100 | 100 |
| 4.75 | 98-92 | 100-90 |
| 2.36 | 38-28 | 65-28 |
| 1.18 | 34-21 | 36-22 |
| 0.6 | 29-18 | 28-18 |
| 0.3 | 25-15 | 22-15 |
| 0.15 | 21-13 | 18-13 |
| 0.075 | 16-12 | 15-12 |
4. Mixture design method

In the mix design of SMA-5, how to make the aggregate skeleton into full play and ensure sufficient thickness of asphalt film around the aggregates to improve the skid resistance of the mixture and its durability are the key factors. The Coarse Aggregate Void Filling Method (CAVF) proposed by Zhang Xiaoning realizes the design of asphalt mixture using the volume method, and successfully apply it in SMA, shown in Eq. 1. The use of CAVF method can make the skeleton effect of coarse aggregate into full play into full play, increase the internal friction of the asphalt mixture and finally form a skeleton dense structure with high stability[[26]]. However, only when the coarse and fine aggregates themselves are in an appropriate proportion while appropriate to each other, can form a stable skeleton structure and the desired air voids content [[27]]. However, this method does not clearly propose the gradation composition of coarse and fine aggregates respectively, and the amount of mineral powder and asphalt also need to be estimated by empirical [[28]-29].

\[
\omega_c + \omega_f + \omega_p = 1
\]  
\[\frac{\omega_c}{\rho_{sc}} (VCA - V_{sc}) = \left( \frac{\omega_f}{\rho_{tf}} + \frac{\omega_p}{\rho_{tp}} \right) + \frac{(1 + \omega_f)\omega_{fib}}{\rho_{fib}} \]  

Where \(\omega_c, \omega_f, \text{ and } \omega_p\) are the proportion of coarse aggregates, fine aggregates and mineral powder by mass of mixture respectively; \(\omega_a\) is asphalt aggregate ratio; \(\omega_{fib}\) is the proportion of fiber by mass of the mixture; \(VCA\) is clearance percentage of coarse aggregates and \(V_{sc}\) is the target voids ratio; \(\rho_{sc}\) is the tamped density of coarse aggregate; \(\rho_{tf}, \rho_{tp}\) are the apparent density of fine aggregate and mineral powder respectively; \(\rho_a\) and \(\rho_{fib}\) are the density of asphalt and fiber respectively.

Li [30] used the volumetric mix design method based on multi-supporting framework condition (V-S) and Marshall method to design small-size asphalt mixtures. And the high temperature performance, water stability and anti-skid performance are comparatively studied. The results show that compared with Marshall design method, the small-size asphalt mixtures designed by V-S method show better high temperature and water stability performance. In addition, the experiment also verified the ability of small-size asphalt mixtures designed by V-S method to repair the existing pavement rutting. The steps of V-S method are as follows.

1. According to the density of the material and the clearance percentage of single particle size of coarse aggregates \(V_0\), the theoretical gradation of the coarse aggregate is calculated according to formula 3.

\[ \frac{V_0}{V_1} = \left( \frac{D + d}{D} \right)^n \]  
\[ V_1 = \frac{V_0}{(1 + \frac{d}{D})^n} \]

Where \(V_0\) is clearance percentage of single particle size of coarse aggregates, \(V_1\) is the volume ratio of the coarse primary aggregate; \(D\) is the coarse primary particle size (mm); \(d\) is the particle size of the fine primary particles (mm).

2. The theoretical gradation and composite density of fine aggregate and filler can be calculated according to equation 4.

\[ P = \left( \frac{d_i}{D} \right)^n \times 100\% \]

Where \(d_i\) is the particle size of the fine aggregate (mm), \(P\) is the passing rate of \(d_i\); \(D\) is the maximum particle size in the fine aggregate; \(n\) is the test index, usually takes 0.25-0.45.

3. According to the gradation obtained from step (1), the dense stacking density of the coarse aggregate \(\rho_{sc}\) is determined by one-sided Marshall 100 times compaction, and the VCA is measured.

4. Select VMA and VV according to the maximum particle size of the mixture, and then substitute into equation 5 to calculate the amount of coarse aggregate and fine aggregate and the asphalt-aggregate ratio.
\[ G + g = 100\% \]
\[ \frac{g}{\rho_s} = \frac{G (\frac{VCA - VMA}{100})}{\rho_s} \]
\[ \frac{P_a}{\rho_a} = \left(\frac{VMA - VV}{100}\right) \frac{G}{\rho_s} \]

Where G is the proportion of coarse aggregate by mass (%); g is the proportion of the fine aggregate and filler (%); \( \rho_s \) is the density of the fine aggregate and the filler after mixing (g/cm³); \( \rho_a \) is the close packing density of the coarse aggregate (g/cm³); VMA is the voids of mineral aggregate (%); \( P_a \) is asphalt-aggregate ratio (%); \( \rho_s \) is the density of the asphalt (g/cm³); VV is the void ratio (%) of the asphalt mixture.

(5) according to the amount of coarse aggregate and fine aggregate, the above theoretical gradation was converted into the mixture gradation.

5. Conclusion
1. SMA-5 is a kind of preventive maintenance material which has the advantages of fast construction, good surface texture depth, cost-effective and environmentally friendly. For the thickness of SMA-5 is only 10~15 mm, it is suitable for the maintenance of bridge and tunnel which have restriction on elevation.
2. The use of high-viscosity modified asphalt can significantly improve the durability of SMA-5 in hot humid areas. The use of WER SBS modified emulsified asphalt can significantly improve the shear resistance of the SMA-5 mixture as well as the skid resistance performance.
3. The addition of steel slag can effectively improve the skid-resistance performance and durability of SMA-5. The addition of rubber crumbs in SMA-5 can effectively improve the resistance to moisture ability, low temperature cracking, fatigue cracking and rutting while reduce the traffic noise. The SMA-5 rubber asphalt mixture mixed with a proper amount of TOR which can effectively enhance the adhesion between the asphalt and aggregates and improve the road performance.
4. Compared with limestone aggregates such as basalt and diabase which have large angularity and low abrasion value should be preferred, whereas the quantity of particles with excessively high F and E ratio should be controlled.
5. 1.18 mm sieve, 2.36 mm sieve and 0.075 mm sieve are the key control sieve of SMA-5. The pass rate of 1.18 mm sieve should be between 25%-33%, and for 0.075 mm sieve should be controlled at 12-14%.
6. The CAVF and V-S Volume design method can fully exert the skeleton effect of the coarse aggregate in the SMA-5, increase the internal friction, and thus improve its comprehensive road performance.

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