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Study on the warm-recycled mechanism of SMA and the road performance

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Abstract. In order to evaluate the performance of warm-recycled asphalt mixture with SMA, based on analyzing the characteristics of gradation ,aggregate and aging asphalt with reclaimed asphalt pavement (RAP), The regeneration methods of high grade soft asphalt mixed at low temperature and hard natural asphalt remixed with modification to enhance are proposed, and it was used to prepare recycled asphalt mixture with SMA and different RAP contents(0,10%,20%,30%). And its high temperature performance, water stability, low temperature performance and fatigue performance were comprehensively evaluated. The result showed that soft and rock compound regeneration technology is feasibility, the natural asphalt with strong polar functional groups was modified and strengthened by remixing to improve the comprehensive performance of asphalt; the performance of warm mix recycled mixture with the 7:3 ratio of 110 # asphalt matrix and TLA lake asphalt is better; the best dosage of RAP is 20%;compared with HMA and SBS modified asphalt mixture, temperature can reduce 15°C and 30°C to 35°C respectively.

Key words: Road engineering; warm recycling; soft and rock asphalt compound; RAP; road performance.

1. Introduction

With the rapid development of expressway construction in China, the period of highway construction has gradually changed from high-speed construction to maintenance. The recycling of waste asphalt mixture after a large number of digging and milling has become an issue of great concern to the road engineering community. Plant-mix hot regeneration technology has been widely used and promoted for its advantages of high construction efficiency, low environmental pollution and low traffic disturbance [1~3]. However, in order to ensure that the road performance of recycled asphalt mixture does not decrease, RAP has to be heated at high temperature twice during the hot recycling process of plant mixing, which leads to the re-aging of RAP and the increase of exhaust gas emissions. Therefore, in order to prevent the re-aging of hot mix recycled asphalt mixture and protect the environment, warm mix regeneration technology came into being.



The current reproduction technology by means of a warm mix warm mix of waste acting agents for warm-mix asphalt mixture regeneration. Warm mix recycled asphalt mixture can effectively reduce the mixing temperature at 30 °C above, and its energy saving and emission reduction effects are obvious [4, 5]. However, the price of warm mix is expensive and the mixing process of warm mix asphalt mixture is complex, the mixing of warm mix agent damages part of the road performance of the mixture, the effect of warm mix is difficult to evaluate, therefore, the deve alwayslopment of warm mix regeneration technology is limited [6-8].

In this paper, another warm mixing technology is proposed. First, RAP is first mixed with high-grade soft asphalt at lower temperature to reduce emissions and ensure the ease of mixing in construction. Then the mixture is mixed with hard natural asphalt to achieve the purpose of low carbon environmental protection and performance improvement. High grade matrix asphalt has good fluidity at low temperature, which can guarantee the bonding performance of the mixture at low temperature. At the same time, secondary mixing lake asphalt can further enhance the modification of the matrix asphalt, improve the road performance of the composite binder, and achieve the effect of warm mixing.

2. RAP performance evaluation

The extraction test of old SMA-13 graded asphalt mixture (RAP) milled from Beijing-Hong Kong-Macao expressway pavement was carried out in accordance with the relevant provisions of "Technical Specification for Road Asphalt Pavement Regeneration" (JTG F41-2008) [9]. The performance of RAP gradation, RAP density and recycled asphalt (Shell 70_matrix asphalt) after extraction was tested. The test results are shown in Table 1 to 3, and the RAP 1 and RAP 2 asphalt content (mass fraction) were 5.6% and 5.8%, respectively.

From the grading of RAP aggregates, it can be seen that the passing rate of aggregates in 13.2mm and 9.5mm sieve holes has an increasing trend, and the coarse aggregates of aggregates are refined. 4.75mm, 2.36mm, 0.3mm, 0.15mm, 0.075mm particle size of ore refining phenomenon is not significant; Large particle size aggregate is broken into small particle size particles, and the small particle size aggregate is basically not refined, which results in the increase in the size range of mineral particle and the decrease of pass rate.

Table 1. Gradation of RAP after extraction

Passing ratios (%) for sieving sizes (mm)	16	13.2	9.5	4.75	2.36	1.18	0.6	0.3	0.15	0.075
RAP1	100	97.2	73.1	36.2	24.1	19.9	16.6	14.3	12.1	9.5
RAP2	100	96.1	70.7	33.3	23.9	18.1	15.0	12.2	10.7	9.0
Upper limit of gradation	100	90.0	50.0	20.0	15.0	14.0	12.0	10.0	9.0	8.0
Lower limit of gradation	100	100	75.0	34.0	26.0	24.0	20.0	16.0	15.0	12.0
Gradation median	100	95.0	62.5	27.0	20.5	19.0	16.0	13.0	12.0	10.0

Table 2. Density of RAP after extraction

Test Indicator	Apparent relative density	Relative density of gross volume	Surface dry relative density	Oilstone ratio (%)
RAP1	2.831	2.454	2.710	5.6
RAP2	2.798	2.429	2.650	5.8

Table 3. Performance of raw and recycled asphalt

Test Indicator	Penetration (25°C) (0.1mm)	Softening point (°C)	Ductility (15°C) (cm)	Kinematic viscosity (135°C) (Pa.s)
Recycled asphalt	33.2	72.9	6.9	3.51
Raw asphalt	70.2	52	15	1.52

3. Raw material performance and grading design

3.1. Asphalt

The asphalt used was Zhonghai 110# asphalt, Trinidad TLA lake asphalt, and Shell SBS. The performance test results are shown in Table 4 to 5 below.

3.2. Mineral materials

The particle size specifications of each grade are 10~15mm gravel, 5~10mm gravel, 3~5mm gravel and 0~3mm stone aggregate. The mineral powder is limestone, and the mineral material performance test meets the specification requirements.

3.3. Fiber

Using lignin fiber, the technical requirements of wood fiber are shown in Table 6.

Table 4. Performance test results of zhonghai 110# asphalt

Test Indicators	Units	Measured Values	Technical Requirements
Penetration (100 g, 5 s, 25 °C)	0.1mm	110	100~120
Softening point	°C	43.5	≥43
Ductility (5 cm/min, 15 °C)	cm	≥150	≥100
Open flash point,	°C	258	≥230
Density, 25 °C	G/cm3	1.0040	Measured Values
Dynamic viscosity of 60 °C	Pa.s	183	≥120
Mass loss	%	-0.2	≤±0.8
After RTFOT residual penetration ratio (25°C)	%	59.0	≥55
Ductility (5 cm/min, 10 °C)	cm	15	≥10

Table 5. Performance test results of Trinidad TLA lake asphalt

Test Indicators	Units	Measured Values	Indonesia index
Penetration (100g, 5s, 25 C)	0.1mm	1.39	0~5
Softening point	°C	94.75	85~99
Ash content	%	35.78	33~38
Asphalt content	%	52.45	52~62
Density, 25 C	G/cm3	1.39	1.0~1.5
Mass loss	%	0.29	≤±0.8
After RTFOT residual penetration ratio (25°C)	%	71	≥50

Table 6. Standards for lignin flocculent fibers

Test project	Quality standard
Screen analysis: method A: air-blast screen analysis of fiber	<6
length (mm)	70±10
Pass through 0.15mm sieve (%)	<6
Method B; Fiber length (mm)	85±10
Pass through 0.85mm sieve (%)	65±10
Pass through 0.425mm sieve (%)	30±10
Pass through 0.106mm sieve (%)	
Ash content (%)	18±5, No volatiles
PH	7.5±1.0
Oil absorption rate	Mass (5.0±1.0) times
Moisture content (%)	<5(Quality measure)

3.4. Gradation Design and Optimum Oil-Stone Ratio

SMA-13 gradation asphalt mixture was designed according to the hot recycling method of plant mixing, and then 0.3% lignocellulose, 0%, 10%, 20% RAP and 30% (mass fraction) synthetic graded recycled asphalt mixture were prepared, as shown in Table 7 below. The optimum asphalt content of recycled asphalt mixture was determined by Marshall design method, as shown in Table 8. According to the content of RAP asphalt, after calculation, the amount of mixed asphalt required for resupply (110#: TLA mass ratio of 7:3).

Table 7. Synthetic Gradation of Recycled Asphalt Mixture

Sieve size /mm	Passing rate % at different RAP content (%)			
	0	10	20	30
16	100.0	100.0	99.0	99.0
13.2	95.4	94.1	92.1	90.1
9.5	61.3	56.7	58.2	60.9
4.75	25.0	30.3	28.1	27.2
2.36	19.4	20.9	21.6	22.9
1.18	18.4	18.1	17.6	16.9
0.6	16.5	15.0	15.2	15.5
0.3	13.4	13.6	14.0	14.2
0.15	12.6	11.7	12.7	13.1
0.075	9.0	10.0	10.5	11.0

Table 8. Optimum Asphalt Content of Regenerated Asphalt Mixture

RAP content (%)	Measured density (g/m ³)	Voidage (%)	Saturation (%)	Marshall stability (KN)	Optimum oil-stone ratio (%)
0	2.465	4.2	72.2	13.4	6.5
10	2.472	4.1	71.3	12.0	6.3
20	2.486	3.8	71.8	12.3	6.2
30	2.463	3.9	70.5	10.0	5.9

It can be seen that when the waste asphalt mixture is mixed in different amounts, the Marshall test results of the asphalt mixture meet the requirements of the specification. Under the condition of warm mixing, when the amount of waste asphalt mixture is about 20%, the void fraction of the mixture is the

smallest, that is, its compaction performance is the best, but the overall void fraction does not change much.

3.5. Mixing and Compaction Temperature Determination

The optimum mixing and compacting temperature is determined by choosing the compacting characteristics of Warm-Mix recycled asphalt mixture with 20% old material and at different forming temperatures (110-140 °C compacting).

Firstly, RAP is heated to 110 °C in the mixing pot. New aggregate is heated to a certain temperature. New aggregate and fibre are poured into the mixing pot for 40 seconds. Then, the required Zhonghai 110# asphalt is added to mix the asphalt and aggregate evenly. Then, a quantitative natural asphalt powder is added to mix the asphalt for 40 seconds to fully mix and enhance the strength of the mixture. After 30 seconds of stirring with a certain amount of ore powder, splitting test is carried out on the formed specimens. The specific heating, forming temperature and test results are shown in Table 9.

Table 9. Heating, Forming Temperature and Splitting Test Results of Warm Mix Recycled Asphalt Mixture

New aggregate heating temperature (°C)	110	120	130	140	150
RAP heating temperature (°C)	110	110	110	110	110
110# heating temperature (°C)	115	125	135	145	155
Mixing temperature (°C)	110	120	130	140	150
Compaction temperature (°C)	100	110	120	130	140
Splitting tensile strength (MPa)	0.68	0.75	0.80	0.87	0.89

It can be seen from the test results that the strength of the mixture increases with the increase of mixing temperature. When mixing temperature under 130°C, the strength increases almost linearly, and the rate is very high. When the mixing temperature exceeds 130 °C, the rate of strength increase slows down gradually, and when the mixing temperature exceeds 140 °C, the rate of increase is almost zero, and the mixture maintains a high strength. Based on the concept of low carbon, environmental protection and economy, it is recommended to adopt 130 °C for the mixing temperature.

4. Study on Mechanism of Asphalt Aging and Regeneration

4.1. Asphalt component analysis

The pavement performance of asphalt is closely related to the chemical composition of asphalt. Therefore, the four components of 70# original asphalt, aged asphalt, Zhonghai 110# and TLA lake asphalt were tested and analyzed by solvent precipitation and column method. The four component test results are shown in Table 10.

Table 10. Four-component test results of asphalt

Asphalt Type	Four Components/%			
	Saturated,	aromatics	Colloid	Asphaltene
Zhonghai 110#	18.42	42.64	30.34	8.60
Lake Asphalt	1.35	14.41	47.55	36.69
Recycled asphalt	19.39	29.10	37.02	14.49
Raw asphalt	20.63	35.22	33.57	10.58

By comparing the aged asphalt with the original asphalt, it can be seen that the recycled asphalt is aging continuously due to the long-term environmental effects. During the aging process of asphalt, the saturation content is relatively inert and less reduced; the aroma content is reduced, the asphaltene content is increased, and the resin is slightly increased.

Compared with recycled aged asphalt, 110# zhonghai matrix asphalt has higher saturation and aromatic content. The mixture of 110# zhonghai matrix asphalt can supplement the saturation and aromatic content of aged asphalt, increase its penetration and ductility, and restore its low-temperature performance. The addition of natural asphalt can be modified and enhanced by mixing to improve the overall performance of asphalt.

4.2. Microscopic mechanism of aged asphalt modification

Fourier transform infrared spectrometer can accurately analyze the chemical structure of asphalt and modified asphalt functional groups [10]. Infrared spectroscopy was used to observe the absorption peaks of recovered aged asphalt, Zhonghai 110# matrix asphalt and composite modified asphalt, and to understand the main functional groups and chemical composition, in order to uncover the microscopic modification mechanism. The results of the infrared spectroscopy test are shown in Figures 1 and 2.

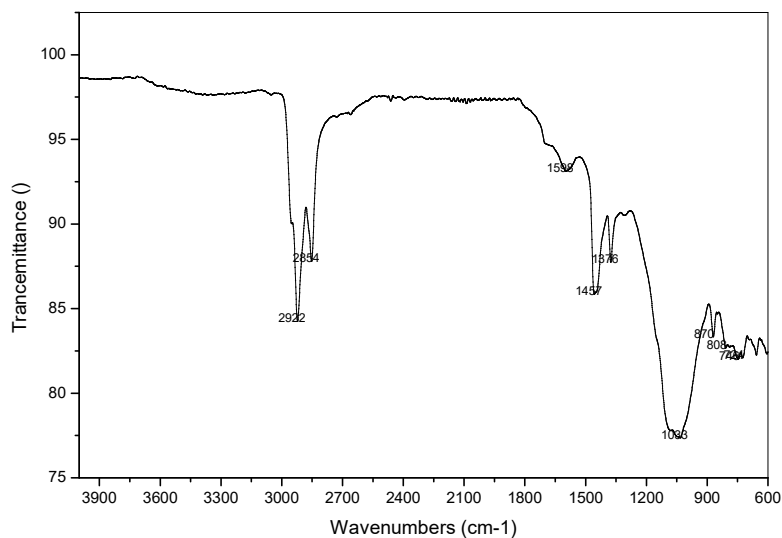


Figure 1. Infrared spectrum of aged asphalt

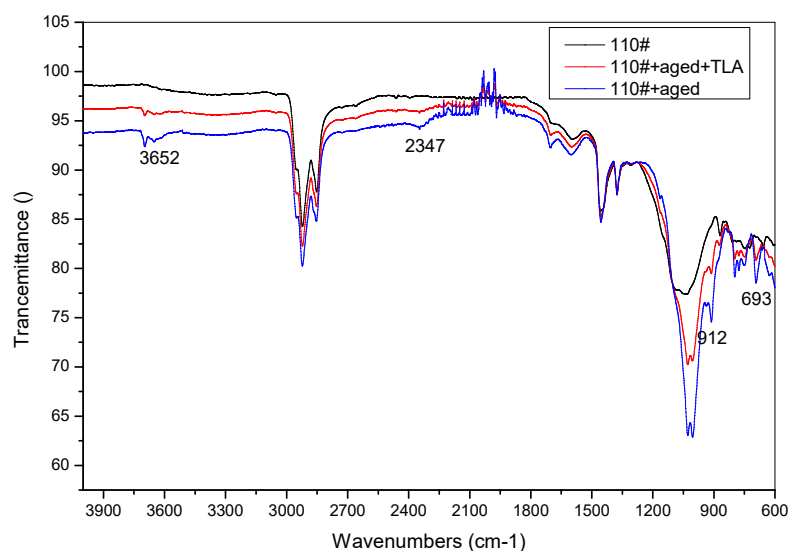


Figure 2. Infrared spectrum of 110# and composite modified asphalt

Through the change of the transmittance of each absorption peak before and after the aging of the asphalt, it is found that the overall absorption of the asphalt after aging is much stronger, and the -CH₂-anti-symmetric stretching absorption at 2919 cm⁻¹ and 2850 cm⁻¹ is not changed much, but careful observation It was found that there was an increase, indicating that the -CH₂- and -CH₃ groups increased to some extent during the aging process. During the aging process, many short-chain hydrocarbons were added and polymerized, resulting in more Long-chain compounds, aromatics and gums are converted to asphaltenes, accompanied by hardening and embrittlement of the asphalt.

The infrared spectrum of Zhonghai 110# asphalt shows a strong absorption peak around 3000~2900cm⁻¹, which is the result of CH stretching vibration of alkane; the peak is absorbed at 1600cm⁻¹, which is the result of the stretching vibration of aromatic ring C=C; The absorption peak around 1033 cm⁻¹ is caused by the stretching vibration of C=O; the appearance of the absorption peaks of 812 cm⁻¹ and 868 cm⁻¹ is the result of the vibration of CH on the C=C in the benzene ring substitution zone, 725 cm⁻¹ The appearance of the absorption peak at the position is the result of the stretching of the benzene ring -CH₂- stretching vibration, and the strong absorption peak near 670 cm⁻¹ is the result of the bending vibration of the benzene-hydrogen bond.

The infrared spectrum of natural asphalt shows different -oh - stretching vibration peaks with different strength between 4000 ~ 3500cm⁻¹, while the matrix asphalt does not have -oh -, and the presence of hydroxyl peak can enhance the viscosity of the composite binder. The strong absorption peak of infrared spectrum at 1028 cm⁻¹ is the result of the stretching vibration of si-o. Si-o content can promote the crosslinking polymerization of asphalt and enhance the adhesive force of modified asphalt. Natural asphalt and modified asphalt infrared spectrum between 2400-2000 - cm - 1 appear many weak peaks, it is C≡C、P-H、C≡N to sway the results of the vibration. After asphalt modification, functional groups such as -p and -n are added, which have strong polarity and can absorb the free energy of the stone surface well, thus resisting the erosion and oxidation of the external environment and improving the anti-peeling and anti-aging performance of asphalt mixture.

5. Performance Analysis of Warm Mix Recycled Asphalt Mixture

The high temperature performance, low temperature performance, water stability and fatigue properties were compared to analyze the road performance of the warm mixed recycled asphalt mixture of 110 # ordinary asphalt: TLA lake asphalt = 7:3, the RAP temperature mixing different proportion of recycled asphalt mixture, mixing temperature 140°C, the compaction temperature 130°C), 70 # HMA and SBS modified asphalt mixture.

5.1. High temperature stability

Hamburg rutting test and uniaxial penetration test were used to evaluate the high temperature performance of asphalt mixture. The test results are shown in Table 11 and Table 12, respectively.

Table 11. The test results of Hamburg rutting

Asphalt type	RAP content (%)	Loading times (times)				
		0	500	1000	2000	3000
70#	0	0.00	0.55	1.04	1.45	1.89
SBS	0	0.00	0.62	0.95	1.39	1.73
110#+TLA	10	0.00	0.71	1.06	1.51	1.91
110#+TLA	20	0.00	0.52	0.85	1.29	1.63
110#+TLA	30	0.00	1.22	2.00	2.65	3.45
Asphalt type	RAP content (%)	4000	5000	6000	7000	8000
70#	0	2.02	2.61	3.23	3.85	5.02
SBS	0	1.88	2.33	2.85	3.52	4.58
110#+TLA	10	2.22	2.54	2.98	3.62	4.95
110#+TLA	20	1.78	2.21	2.73	3.38	4.41
110#+TLA	30	4.33	5.99	8.01	10.01	13.22

Table 12. The test results of uniaxial penetration

Asphalt type	RAP content /(%)	Shear strength (MPa)
70#	0	1.03
SBS	0	1.21
	10	1.35
110#+TLA	20	1.43
	30	1.24

It can be seen from Table 11 that, compared with 70#HMA, the anti-rutting performance of the recycled asphalt mixture after adding RAP is obviously improved. The rutting depth of 10%, 20% and 30% RAP is 4.95 mm, 4.41 mm and 13.22 mm, respectively. The rutting resistance of warm mix recycled asphalt mixture at high temperature is better than that of SBS modified asphalt mixture, and the warm mix effect is remarkable. The recycled asphalt mixture with 20% RAP has the best high temperature performance, which is close to SBS modified asphalt mixture.

From Table 12, the shear strength of recycled asphalt mixture is obtained. Compared with 70 # HMA, the high temperature resistance of recycled asphalt mixture with RAP is obviously improved. The shear strength of recycled asphalt mixture with RAP content of 10%, 20% and 30% is 1.35 MPa, 1.43 MPa and 1.24 MPa, respectively, which are higher than that of SBS modified asphalt mixture, and the recycled asphalt mixture with RAP content of 20% has the best shear strength. The uniaxial penetration test is consistent with the Hamburg rutting test, which further verifies that the high temperature stability of warm mix recycled asphalt mixture can be improved significantly.

5.2. Water stability

Immersion Marshall test, freeze-thaw cleavage test and kentapau immersion dispersion test were used to evaluate the water stability of warm mix asphalt mixture, the evaluation indexes are residual stability MS0 immersion, freeze-thaw cleavage tensile strength ratio TSR, immersion dispersion loss delta S, the test results are shown in Table 13.

Table 13. The test results of water stability

Asphalt type	RAP content (%)	MS ₀ (%)	TSR(%)	ΔS(%)
70#	0	93.6	92.3	8.4
SBS	0	97.5	95.2	5.9
	10	95.9	92.8	6.2
110#+TLA	20	96.2	94.6	5.6
	30	93.4	91.1	6.5

The results of table 13 show that the water stability of warm mix recycled asphalt mixture is better than 70 #HMA; the water immersion Marshall test, freeze-thaw splitting test and Kentucky water immersion dispersion test all show that the 20% RAP content recycled asphalt mixture has the best water stability, which is close to SBS modified asphalt mixture.

5.3. Low temperature performance

The low temperature performance of asphalt mixture is the main determinant of the crack resistance of asphalt pavement. Therefore, good asphalt mixture needs to have good low temperature performance. According to the test method of asphalt and mixture, the bending test of the trabecular specimen is carried out under the temperature condition of (-10±0.5) °C. The test results are shown in Table 14.

Table 14. Trabecular bending test results

Asphalt type	RAP content (%)	Flexural tensile strength (MPa)	Stiffness modulus (MPa)	Maximum flexural strain($\mu\epsilon$)
70#	0	8.53	3365.1	1833.5
SBS	0	9.45	3000.2	2231.7
	10	8.33	3465.6	2008.5
110#+TLA	20	8.99	3652.3	1705.3
	30	7.62	4000.5	1432.0

From the results of trabecular bending test in Table 4.4, it can be seen that under warm mixing conditions, the flexural-tensile strain of asphalt mixture decreases with the increase of RAP content, the stiffness modulus increases with the increase of RAP content, and the low temperature performance decreases with the increase of RAP content.

The low temperature performance of warm-mix recycled asphalt mixture is obviously inferior to that of Hot-Mix SBS modified asphalt mixture. When the content of asphalt is increased to 30%, the low temperature performance of asphalt is not as good as the 70# matrix asphalt. Therefore, the maximum dosage of RAP must be limited.

5.4. Fatigue performance of asphalt mixture

The fatigue performance of asphalt mixture was studied by UTM130 multifunctional testing machine. By strain loading mode, the strain of 300 $\mu\epsilon$, test the temperature of 15 °C, when the stiffness modulus decreased to 50% of the initial stiffness modulus when the termination. The test results are shown in Table 15.

Table 15. Fatigue test results

Asphalt type	RAP content (%)	Initial modulus of stiffness (MPa)	Fatigue times (10^6)	Total dissipative energy (MPa)
70#	0	4548	2.149	475.2
	10	8449	5.192	1562.5
110#+TLA	20	8246	5.223	1188.9
	30	6119	4.622	982.6

(1) For 110#+TLA warm mixed recycled asphalt mixture, RAP increased from 10% to 30%, the total dissipated energy decreased continuously, and the fatigue life decreased continuously; when the RAP content was 10%, the fatigue life was optimal. It indicates that the increase in RAP content adversely affects the long-term performance of the recycled mix.

(2) The total dissipative energy and fatigue life of the recycled mixture with RAP were larger than that of 70#HMA without RAP. This is mainly due to the change of the microstructure of the asphalt after the soft-hard compound regeneration modification, resulting in an increase in the stiffness modulus of the mixture. Under the action of the same stress, the warm mix asphalt mixture should be changed little, resulting in a decrease in the energy required to be dissipated per unit period and an increase in fatigue life.

6. Conclusion

The regeneration methods of high grade soft asphalt mixed at low temperature and hard natural asphalt remixed with modification to enhance is proposed. Dry mixing technology was adopted to pre-mix RAP with high grade matrix asphalt at a relatively low temperature, and then the mixture was modified and reinforced with hard natural asphalt to achieve the effect of warm mixing regeneration. The mechanism of asphalt aging and warm regeneration modification was revealed through micro-mechanism analysis. The feasibility of soft-hard mixture warm mix regeneration modification technology was verified from micro-level.

1. The proposed warm regeneration technology can reduce the regeneration SMA asphalt mixture mixing and paving temperature 30°C, temperature, the warm mixing effect is remarkable, and can achieve road performance of the SBS modified asphalt mixture .

2. After asphalt aging, the saturated fraction is relatively inert, the aromatic fraction decreases, the asphaltene increases, and the gum slightly increases; The mixture of 110# zhonghai matrix asphalt can supplement the saturated and aromatic content of aging asphalt and restore its low temperature performance. The addition of natural asphalt can be modified and enhanced by remixing to improve the overall performance of asphalt. At the same time, natural asphalt has a strong polarity of functional groups, which can well absorb the free energy of the stone surface, thus resisting the erosion and oxidation of the external environment, and improving the anti-peeling and anti-aging performance of asphalt mixture.

3. With the increase of RAP content, SMA warm mix recycled asphalt mixture of high temperature performance first rise and then fall, water stability, low temperature, fatigue resistance gradually decreased, so it is recommended that RAP content should be controlled within 30%, the optimal content of 20% is recommended.

References

- [1] X.D.Zha, B.Min, W.Song. Analysis of influence of RAP content on performance of hot recycled asphalt mixture , China J. Journal of changsha university of science and technology: natural science edition,2013,10(4): 1-8 (in Chinese).
- [2] S.Z.Ren. Research on thermal regeneration of asphalt pavement plant and its key technology. Xi 'an: chang 'an university, 2008(in Chinese).
- [3] Asphalt Recycling and Reclaiming Association. An Over of Recycling and Reclamation Methods for Asphalt Pavement Rehabilitation.USA, Maryland, 1992.
- [4] H.L.Wang, Y.S.Xie, et al. Current situation and countermeasures of greenhouse gas emission reduction in transportation. China J.Energy research and management, 2011, (3): 9-11(in Chinese).
- [5] R.Y.Lin, A.M.Sha , et al. Evaluation method of greenhouse gas emission from asphalt pavement . China J.Journal of chang 'an university (natural science edition, 2014, 34(6): 19-26(in Chinese).
- [6] D.C.Li. Review of warm mix asphalt mixture technology. China J. Petroleum asphalt, 2008, 22(5): 1-5(in Chinese).
- [7] Z.F.Liu, S.P.Wu , M.Z.Chen, et al. Current situation and existing problems of warm asphalt mixture. China J. Journal of wuhan university of technology, 2009, 31(4): 171-172.
- [8] L.H.Li, F.Wang , J.Ou Y . experimental study on strength characteristics of soft-hard asphalt mixture . China J Journal of building materials, 2011, 14(5): 708-711. (in Chinese).
- [9] JTG F41-2008, Technical Specification for Highway Asphalt Pavement Regeneration . China Communications Press, Beijing, 2008(in Chinese).
- [10] B.Chen, C.X.Huang, D.L.Lu. Application of multi-scale decomposition and principal component analysis in near infrared spectroscopy. China J. Journal of Jiangsu University (Natural Science Edition). 2004.25 (2): 105-1081(in Chinese).