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ABSTRACT

This paper presented the details of various investigations conducted for the laboratory evaluation of a sand anti-fracture mix (SAF) mixed with a newly developed stabilized rubber modified asphalt (NEW-SRMA), used for mitigating reflective cracking of semi-rigid asphalt pavement in Xinjiang. Two local asphalt binders, Karamay asphalt to Kuqa asphalt, were mixed as the base asphalt for the modification and their mixing ratio was obtained based on compositions analysis. Crumb rubber (CR) was devulcanized to improve its compatibility with asphalt phase. Continuous dense aggregate gradation for the 4.75 mm SAF was designed in the investigation. Compared to styrene-butadiene-styrene modified asphalt binder (SBS-asphalt), NEW SRMA was found to have better performance temperature range, fatigue resistance, and similar workability; corresponding mixes had improved permanent deformation, low-temperature cracking, and fatigue characteristics. Application in practical projects also proves the applicability of NEW-SRMA and corresponding SAF mix for purpose of mitigating reflective cracking in Xinjiang.

Keywords

new stabilized rubber modified asphalt (NEW-SRMA), sand anti-fracture mix (SAF), stress absorbing membrane interlayer (SAMI), performance evaluation

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Introduction

Reflective cracking is one of the major distresses of asphalt pavements in China [1]. A common contributor to this failure is the utilization of semi-rigid materials such as cement (or lime-fly ash) treated gravel as subbase layer in pavement construction. It is only a matter of time before cracks in semi-rigid subbase reflect to pavement surface [2]. Due to heavy traffic loading, obvious sunshine, and annual temperature difference, reflective cracking failure is more severe in Xinjiang's semi-rigid asphalt pavement than other areas in China.

The interest of asphalt rubber (AR) in pavement construction continues to be high as several laboratory and field tests adequately demonstrated that asphalt mixes with crumb rubber (CR) give improved performance [3–8]. Asphalt rubber membrane interlayer (ARMI) is one specific type of stress absorbing membrane interlayer that was suggested to mitigate reflective cracking [9–12]. Some trials of ARMI have also been performed with good performance in China [13,14].

Although AR could provide improved mechanical properties, the poor hot storage stability is still an obstacle in its plant application. During the hot storage, further continuous rubber digestion leads to the deterioration of properties of AR at high temperatures [15]. Furthermore, the precipitation of these insoluble rubber particles could spoil AR [16]. To improve the storage performance of AR, many efforts have been devoted [17–22].

The present investigation was an expanding research on stabilized rubber modified asphalt (SRMA) developed by Geng et al. since 2009 [23,24]. In the former research, a processing technic was proposed for producing SRMA with Qilu No. Seventy asphalt binder (a local commercial road petroleum asphalt binder in Shandong province, 60/80 penetration grade, PG 64-22), pre-processed crumb rubber, and certain stabilizer. This SRMA shows no sharp deterioration in properties and relatively homogeneous modified asphalt system after being stored for a period of time. The main focus of the present investigation was to produce a new type of SRMA (NEW-SRMA for short) with two local binders of Xinjiang province as base asphalt with the SRMA processing technic, and then to design a sand anti-fracture (SAF) mix taking the NEW-SRMA as binder for the purpose of mitigating reflective cracking.

Preparation of NEW-SRMA in Xinjiang

Karamay asphalt (80/100 penetration grade, PG 64-28) and Kuqa asphalt (50/70 penetration grade, PG 64-16) are two local road petroleum asphalt binders traditionally used for pavement construction in Xinjiang. Whereas the former is widely used in most regions of Xinjiang, the latter is used in extraordinarily hot regions at times because of its poor low-temperature

TABLE 1 Properties of virgin binders.

Parameter Measured	Karamay	Kuqa
Asphaltenes, %	0.072	24.35
Resins, %	39.26	23.72
Saturates, %	31.67	19.87
Aromatics, %	29.00	32.06
Penetration (25°C), 0.1 mm	83.2	55.5
Ductility (5 cm/min, 10°C), cm	>150	5
Softening point, °C	46.8	48.3

performance; however, it is cheaper than the former. Properties of two binders are tested as per Chinese Standard Test Methods of Bitumen and Bituminous Mixtures for Highway Engineering (JTG E20-2011 [25]) and given in **Table 1**. As can be seen from the table, Karamay asphalt has extremely low asphaltene content (less than 0.1 %) compared to other indigenous binders used for modification in China (from 6 to 8 %) [26]. Unsatisfactory chemical components of Karamay asphalt may be the reason of several former failure trials on binder modification [27,28]. It can also be seen that Kuqa asphalt has a high asphaltene content (exceeds 24 %). If the two base binders were mixed at a proper ratio, the acquisition might have an appropriate composition and be suitable for modification. However, the research on binder modification with the mix of these two asphalt binders has not been reported in literature. Based on the compositions results in **Table 1**, a 7:3 ratio of Karamay asphalt to Kuqa asphalt is selected. As a result, the percentage of Asphaltenes, Resins, Saturates, and Aromatics in the mixed binder is 7.35, 34.60, 28.13, and 29.91 %, respectively. This composition is similar to those frequently used asphalt binders [26].

The –40 mesh CR was employed for pre-processing in this study. The gradations test of the CR was conducted following Chinese Specification Asphalt Rubber for Highway Engineering (JT/T 798 2011 [29]), shown in **Table 2**. The reclaimed CR was devulcanized at a high temperature and a high pressure to obtain the plastic state. In this way, the compatibility of CR and asphalt phase could be improved as the partially degradation of rigid three-dimension net works. Sulfur base stabilizer is also used for the binder modification.

The specifications developed earlier were used for blending CR with mixed asphalt [23]. In this procedure, the mixed

TABLE 2 Gradations of crumb rubber (–40 mesh).

Sieve Number (μm)	% Passing
30	100
40	100
50	92.4
80	62.3
100	28.4
300	17.5

TABLE 3 Engineering properties of modified binders.

Parameter Measured	NEW-SRMA PG 76-28	SBS-Asphalt PG 76-22	SRMA ^[16] PG 76-28
Penetration (25°C), 0.1 mm	74	76	67
Ductility (5 cm/min, 5°C), cm	18	30	17
Softening point, °C	56.8	51.0	58.9
Softening point difference(165°C, 48 h), °C	3.0	1.6	5.7
Viscosity at 135°C, Pa·s	2.97	2.30	3.96
Viscosity at 175°C, Pa·s	0.79	0.73	0.77
$G^*/\sin\delta$ at 82°C, kPa	1.736	1.584	1.871
After RTFOT, change of mass, %	−0.14	−0.32	−0.12
After RTFOT at 76°C, $G^*/\sin\delta$, kPa	2.443	2.225	2.796
After RTFOT + PAV, $G^*\sin\delta$ at 16°C, kPa	3550	6880	3945
After RTFOT + PAV, Stiffness, MPa	164(−18°C)	270(−12°C)	189(−18°C)
After RTFOT + PAV, m -value	0.324(−18°C)	0.308(−12°C)	0.315(−18°C)

asphalt is heated to 185°C before 24 % CR (by weight of asphalt) is added. The blend is agitated vigorously for about 30 min using a mechanical stirrer operated. Then 0.15 % stabilizer (by weight of asphalt) is added into the mixture followed by another stirring for 30 min.

Properties of NEW-SRMA prepared in this research are given in **Table 3**. Penetration, ductility, softening point, and softening point difference tests were conducted following JTG E20-2011 [25]. Other properties were tested using typical binder test methods developed by the Strategic Highway Research Program (SHRP). Properties of a commercial styrene-butadiene-styrene modified asphalt (SBS-asphalt for short) commonly used in Xinjiang and SRMA developed earlier are also listed.

These results in **Table 3** indicate that NEW-SRMA has got a good performance temperature range, which is the same with early SRMA but is better in comparison with the SBS-asphalt. Also, NEW-SRMA demonstrates a similar viscosity at operating temperature (135°C) with that of SBS modified asphalt. Other improvements noticed in the case of NEW-SRMA are the least fatigue factor ($G^*\sin\delta$) value at moderate temperature, the least stiffness, and the largest m values at low temperature. It should be noted that softening point and $G^*/\sin\delta$ values of NEW-SRMA are less than those of early SRMA, but they are greater than those of SBS-asphalt.

To evaluate the storage stability, another three batches of NEW-SRMA binders (Batch A, B, and C) were prepared and then were placed in 165°C oven for different periods, shown in **Table 4**. Penetration, softening point, ductility, and viscosity tests were conducted on the fresh and aged samples. The test results are presented in **Fig. 1–4**.

TABLE 4 Aging plan of NEW-SRMA binders.

Batch number	A	B	C
Aged time, days	1, 11, 15	3, 7, 17	5, 9, 13

FIG. 1 Variation of penetration with storage time for different batch of binders.

FIG. 2 Variation of ductility with storage time for different batch of binders.

FIG. 3 Variation of softening point with storage time for different batch of binders.

FIG. 4 Variation of viscosity with storage time for different batch of binders.

FIG. 5 Selected gradation of SAF.

TABLE 5 Apparent density of aggregates.

Sieve size, mm	4.75	2.36	1.18	0.6	0.3	0.15	0.075
Apparent density, g/cm ³	2.852	2.859	2.834	2.817	2.815	2.802	2.812

It can be observed from Fig. 1–4 that penetration, softening point, ductility, and viscosity of NEW-SRMA were little affected by the storage time within the given aged periods, indicating inconsiderable changes in its physical-chemical composition. NEW-SRMA binder, therefore, is expected to maintain good workability, fatigue resistance, and low temperature performance. Furthermore, due to the low price of CR and Kuqa asphalt, NEW-SRMA has around 20 % lower material cost than conventional SBS-modified asphalt.

Preparation of Sand Anti-Fracture Mix

Previous research showed that sand anti-fracture mixes (SAF) has good capacity to mitigate reflective cracking [30,31]. In this study, conventional continuous dense aggregate gradation for the 4.75 mm SAF was selected in accordance with JTG F40-2004 [32]. The combined gradation is shown in Fig. 5. Basalt stone collected from a quarry situated near Urumqi were used as aggregates. Limestone mineral powder was selected as filler material. Physical properties of different aggregate materials are tested in accordance with Chinese Standard Test Methods of aggregate for highway Engineering (JTG E42-2005 [33]), which are given in Tables 5 and 6.

Marshall Method was adopted for preparation of specimens with NEW-SRMA, and a mixing temperature of 175°C and a compaction temperature of 165°C was selected in accordance with previous research projects. A high binder content is expected to ensure the anti-reflective cracking capability of SAF, thus 3 % maximum air voids and 20 % minimum voids in mineral aggregate (VMA) were used as the control criterion. The optimum binder content (OBC) during the mix design process was defined at a given number of blows (75 times per face on the specimens). The results are presented in Table 7.

Performance Testing

A series of laboratory tests were performed to estimate properties of SAF mixed with NEW-SRMA binder. Samples mixed with SBS-asphalt mentioned above were also prepared at the

TABLE 6 Properties of filler material.

Apparent Density, g/cm ³	Water Content (by mass), %	%Passing		
		<0.6 mm	<0.15 mm	<0.075 mm
2.695	0.46	100	96.8	83.5

TABLE 7 Marshall Characteristics at optimum binder contents.

Binder Content, %	VMA, %	Air Voids, %	Voids Filled With Asphalt, %	Marshall Stability, kN	Flow Value, mm
8.0	20.1	2.77	86.2	14.43	3.43

same aggregate gradation and binder content for comparison, while the mixing temperature of 170°C and the compaction temperature of 165°C were used. SRMA developed in the former research was not used as binder of SAF mix for comparison because of the extreme long haul distance (over 3000 km).

High-temperature performance of SAF was evaluated by wheel track test. Three specimens for each binder type were prepared by the wheel rolling compactor as per Chinese Standard T0703 [34]. All specimens had a length of 300 mm, a width of 300 mm, and a height of 50 mm. The plates were placed in an oven at 60°C for 6 h and then tested for dynamic stability values based on Chinese Standard T0719 [35].

Bending test was used to access the low-temperature performance of SAF. Wheel track test specimens were sawn to beam with the following dimensions: 250 mm long, 30 mm wide, and 35 mm thick. Four beams were prepared for each binder type. These beam specimens were cured at −10°C for 2 h and then subjected to a bending load at a speed of 50 mm per minute to determine failure strain and flexural tensile strength values based on Chinese standard T0715.

Tensile strength ratio was determined to evaluate the moisture susceptibility of the mixes in accordance with Chinese Standard T0729 [36]. Tensile strength ratio is the average static indirect tensile strength of four conditioned Marshall specimens expressed as percentage of the average static indirect tensile strength of four unconditioned specimens. Conditioning was done by keeping the saturated specimens in −18°C fridge for 16 h and by keeping in water maintained at 60°C for 24 h, then by curing at 25°C for 2 h before commencing the test. The test was conducted at 25°C.

Beam fatigue tests were utilized to evaluate fatigue performance of SAF. Four beams of each mix type were made and tested with beam fatigue apparatus (BFA). A large wheel rolling compactor was used to fabricate the beams. The compacted beam was sawed into four smaller fatigue beams after the bulk specific gravity was determined. Test specimens were sawed to the following dimensions: 380 mm long, 63 mm wide, and 50 mm thick. The beams were placed in a temperature-controlled chamber at 15°C for 4 h prior to the test. A repeated sinusoidal loading at a frequency of 10 Hz was used. The control and data acquisition software measured the deflection of the beam specimen, computed the strain in the specimen, and adjusted the load applied by BFA device. A detailed description of the test method is given in AASHTO T321 [37].

The performance test results of SAF are presented in **Table 8**. It indicates that the tensile strength ratio value of SAF using NEW-SRMA is similar to that using SBS-asphalt.

However, the results show that NEW-SRMA-modified SAF had greater dynamic stability, failure strain, flexural tensile strength, and fatigue life values than those mixed with SBS-asphalt, indicating better engineering properties of NEW-SRMA.

Dynamic mechanical performance of asphalt mix is important for pavement design since it relates to pavement distresses such as cracking and rutting [38]. Master curves can be used to describe the dynamic modulus and phase angle of the asphalt mix as a function of temperature and loading rate. In this research, Dynamic modulus tests of SAF were also performed by Superpave Simple Performance Tester (SPT) in accordance with NCHRP Project 9–29 [39].

Three cylindrical specimens for each mix type were compacted to 2.8 ± 0.2 % air voids using a Superpave gyratory compactor. The specimens were cored and sawed to 100 mm diameter and 150 mm height. Five testing temperatures 5, 15, 25, 35, and 45°C were chosen. At each temperature, the loading frequencies of 20, 10, 5.0, 1.0, 0.5, and 0.1 Hz were selected. Dynamic modulus tests were performed on the SAF mixes by a Superpave simple performance tester, manufactured by IPC global. The average dynamic modulus and phase angle were obtained. Then, based on test results, master curves of dynamic modulus were constructed using the principle of time-temperature superposition. The sigmoidal function was used to describe the frequency dependency of the dynamic modulus [40].

$$\log|E^*| = \delta + \frac{Max - \delta}{1 + e^{\beta + \gamma \log f_r}} \quad (1)$$

where:

$|E^*|$ = the dynamic modulus,

Max and δ = the maximum and minimum values of dynamic modulus, respectively,

f_r = the reduced frequency, and

β and γ = shape parameters.

The reduced frequency f_r can be described as

$$f_r = f \cdot \alpha(T) \quad (2)$$

TABLE 8 Performance of SAF.

Parameter Measured	NEW-SRMA	SBS-Asphalt
Dynamic stability (60°C), passes/mm	2809	803
Failure strain (−10°C), 10^{-6} mm/mm	8595	4810
Flexural tensile strength (−10°C), MPa	17.1	15.5
Tensile strength ratio, %	96.2	98.1
Fatigue life (900 micro strain, 15°C), times	103910	95980

TABLE 9 Fitting parameters of SAF.

Binder Type	δ	B	γ	ΔE_a
NSRMA	4.0534	0.0238	-0.4595	199,999.9999
SBS-asphalt	3.8066	0.1170	-0.4355	199,999.9999

Where, f is the loading frequency and $\alpha(T)$ is the shift factor, which can be calculated by [41]

$$\log[a(T)] = \frac{\Delta E_a}{19.14714} \left(\frac{1}{T} - \frac{1}{T_r} \right) \quad (3)$$

where:

ΔE_a = the activation energy, and

T_r = the reference temperature.

Thus,

$$\log|E^*| = \delta + \frac{Max - \delta}{1 + e^{\beta + \gamma \left\{ \log f + \frac{\Delta E_a}{19.14714} \left[\left(\frac{1}{T} \right) - \left(\frac{1}{T_r} \right) \right] \right\}}} \quad (4)$$

In Eq 4, Max can be evaluated by the Hirsch mode, and other parameters, δ , β , γ , and ΔE_a , need to be fitted through regression analysis.

In this study, the reference temperature was taken as 25°C. Fitting parameters in Eq 4 were calculated by nonlinear square least square regression according to the testing results, shown in Table 9. Then the shift factors were calculated using Eq 3. With the same shift factors, master curves of dynamic modulus and phase angle were obtained, shown in Figs. 6 and 7.

As is shown in Figs. 6 and 7, the dynamic modulus and phase angle of SAF mixed with NEW-SRMA are about 1.5 to 2 times higher and from 10 to 25 % less than those having SBS-asphalt at low-frequency loading (high temperature), indicating that NEW-SRMA binder can be more stiff and elastic at high temperature. In case of high frequency (low temperature), the modulus and phase angle of NEW-SRMA-modified SAF are similar with those using SBS-asphalt.

FIG. 6 Master curve of dynamic modulus. **FIG. 7** Master curve of phase angle.

Application

The presented NEW-SRMA-modified SAF have been applied in Urho-Aletai expressway construction in Xinjiang in September 2013. The designed pavement structure is “4 cm AC-13 (SBS modified asphalt binder, nominal maximum aggregate size, NMAS = 13.2 mm) + 6 cm AC-20 (Karamay asphalt binder, NMAS = 19 mm) + 8 cm AC-25 (Karamay asphalt binder, NMAS = 26.5 mm) + 2 cm NEW-SRMA-modified SAF mix + 36 cm cement treated gravel subbase.” The NEW-SRMA binder was produced in Urumchi city. After being transported for about 400 km and stored for 15 days in the plant, this binder was used for SAF producing and paving. No reflective cracking or other failures were found up to date.

Summary

In this paper, a new stabilized rubber modified asphalt (NEW-SRMA) was developed by using the composite of two local asphalt binders in Xinjiang. And a kind of SAF was designed with the presented NEW-SRMA for mitigating reflective cracking. In addition to experimental evaluation on performance characteristics of the developed materials in the laboratory, application in actual pavement construction was performed. On the basis of results from this work, the following conclusions may be drawn:

- (1) The NEW-SRMA has been developed from the mix of two local base asphalt, pre-processed CR, and sulfur base stabilizer to improve the compatibility of CR and asphalt phase. Binder tests show that NEW-SRMA has satisfactory engineering properties.
- (2) Performance tests show that NEW-SRMA-modified SAF has satisfactory road service performance. The dynamic stability, failure strain, and fatigue life are greater than those mixed with SBS-asphalt.

- (3) Application results in practical projects and economic analysis prove the applicability of NEW-SRMA and corresponding SAF for purpose of mitigating reflective cracking in Xinjiang.

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References

- [1] Wang, X. D., Li, M. J., and Lu, K. J., *The Applied Technology of the Crumb Rubber in the Asphalt and Mixture*, China Communications Press, Beijing, China, 2008 (in Chinese).
- [2] Chen, Y., Lopp, G., and Roque, R., "Effect of an Asphalt Rubber Membrane Interlayer on Pavement Reflective Cracking Performance," *J. Mater. Civ. Eng.*, Vol. 25, No. 12, 2013, pp. 1936–1940.
- [3] Way, G. B., "Asphalt Rubber—Research and Development, 35 Years of Progress and Controversy," presented at the *ETRA Annual Meeting, Brussels, Belgium*, 2000.
- [4] Kaloush, K. E., Witczak, M. W., and Way, G. B., "Performance Evaluation of Arizona Asphalt Rubber Mixtures Using Advanced Dynamic Material Characterization Tests," *Final Report*, Department of Civil Engineering, Arizona State University, Tempe, AZ, 2002.
- [5] Liseane, P. T. L. F., Glicério, T., Jorge, C., Pais, Paulo, A. A. P., and Manuel, J. C. M., "Laboratory Performance of Asphalt Rubber Mixtures," presented at the *Asphalt Rubber 2009 Conference*, Nanjing, China, November 2–4, 2009, Sponsor, Sponsor Location, -unpublished.
- [6] Dong, Y., Tan, Y., and Yang, L., "Evaluation of Performance on Crumb-Rubber-Modified Asphalt Mixture," *J. Test. Eval.*, Vol. 40, No. 7, 2012, pp. 1–5.
- [7] Wu, C., Liu, K., Li, A., and Liu, A., "Research on Application of Terminal Blended Asphalt Rubber in Steel Deck Pavement," *J. Test. Eval.*, Vol. 42, No. 5, 2014, pp. 1–7.
- [8] Cao, W. and Liu, S., "Performance Evaluation of Asphalt-Rubber Stone Matrix Asphalt Mixtures With Warm Mix Asphalt Additives," *J. Test. Eval.*, Vol. 41, No. 1, 2012, pp. 1–7.
- [9] Ahlrich, R. C., "User's Guide: Asphalt Rubber and Geotextile Interlayers," *Final Report No. FEAP-UG-92/08*, U.S. Army Corps of Engineers, Fort Belvoir, VA, 1992.
- [10] Vallerger, B. A., Morris, G. R., Huffman, J. E., and Huff, J., "Applicability of Asphalt-Rubber Membranes in Reducing Reflection Cracking," *Proc. Assoc. Asphalt Pav. Technol.*, Vol. 49, 1980, pp. 330–353.
- [11] Scofield, L. A., "History, Development, and Performance of Asphalt Rubber at ADOT," *Report No. AZ-SP-8902*, Arizona Department of Transportation, Phoenix, AZ, 1989.
- [12] Sousa, J., Pais, J., Saim, R., Way, G., and Stubstad, R., "Development of a Mechanistic Overlay Design Method Based on Reflective Cracking Concepts," *Final Report for Rubber Pavements Association*, Consulpav International, Mafra, Portugal, 2001.
- [13] Li, Y. G. and Li, C. H., "Application Study on the Composite Technology of Impact Compaction, Asphalt Rubber and Stress Absorbing Membrane Interlayer in Road Engineering," *J. Univ. Sci. Technol. Beijing*, Vol. 33, 2011, pp. 244–249 (in Chinese).
- [14] Huang, W. D., Tian, J. J., Li, B. L., and Li, Y. W., "Research on Stress Absorbing Interlayer of Continuous Dense-Graded Asphalt Rubber Mixture," *J. Build. Mater.*, Vol. 17, 2014, pp. 856–861 (in Chinese).
- [15] Bahia, H. U. and Zhai, H., "A New Method for the Storage Stability Test of Modified Asphalt," *Am. Chem. Soc., Div. Fuel Chem.*, Vol. 43, 1998, pp. 1041–1405.
- [16] Tortum, A., Celik, C., and Aydin, A. C., "Determination of the Optimum Conditions for Tire Rubber in Asphalt Concrete," *Build. Environ.*, Vol. 40, No. 11, 2005, pp. 492–504.
- [17] Palit, S. K., Reddy, K. S., and Pandey, B. B., "Laboratory Evaluation of Crumb Rubber Modified Asphalt Mixes," *J. Mater. Civ. Eng.*, Vol. 16, No. 1, 2004, pp. 45–53.
- [18] Doh, Y. S., Park, T. W., Kim, H. H., and Kim, K. W., "Evaluation of Stripping and Rutting Properties of CRM Modified Asphalt Mixtures," *J. Korean Soc. Road Eng.*, Vol. 9, No. 4, 2007, pp. 149–158.
- [19] Doh, Y. S., Park, T. W., Kim, H. H., and Kim, K. W., "Estimation of Freezing and Thawing Resistance of CRM-Modified Asphalt Mixture," presented at the *Conference of Korean Society of Road Engineers*, 2007, pp. 257–262.
- [20] Putman, B. J. and Amirkhanian, S. N., "Laboratory Evaluation of Anti-Strip Additives in Hot-Mix Asphalt," *Report No. FHWA-SC-06-07*, SCDOT and Clemson University, Clemson, SC, 2006.
- [21] Morris, G. R. and McDonald, C. H., "Asphalt-Rubber Stress Absorbing Membranes—Field Performance and State-of-the-Art," *Transp. Res. Rec.*, Vol. 595, 1976, pp. 52–58.
- [22] Li, J. L., Zhu, Y. Q., Wang, H. B., Wang, S. F., Zhang, Y., and Zhang, Y. X., "Study on Hot Storage Stability of Reclaimed Rubber Modified Asphalt," presented at the *Asphalt Rubber 2009 Conference*, Nanjing, China, November 2–4, 2009, Jiangsu Provincial Communications Department, Nanjing, China, pp. 449–459, http://data.abacus.hr/h-a-d/radovi_s_kongresa/asphalt_rubber_2009/AR2009_Part1.pdf.
- [23] Geng, L., Wang, X., Ren, R., Chen, F., and Yang, X., "Performance Evaluation of Dense Mixtures With Stabilised Rubber Modified Asphalt," *Road Mater. Pave. Des.*, Vol. 15, No. 4, 2014, pp. 953–965.
- [24] Jing, J., Dong, G. B., Zhou, T., and Geng, L. T., "Design and Application of Stabilized Rubber Modified Asphalt Mixture," *J. Shandong Jianzhu Univ.*, Vol. 30, 2015, pp. 92–95 (in Chinese).
- [25] JTG E20-2011, 2011, Research Institute of Highway Ministry of Transport. "Standard Test Methods of Bitumen and Bituminous Mixture for Highway Engineering," transportation industry standard of the People's Republic of China, Standard No. JTG E20-2011. China Communications Press, Beijing, China, 2011 (in Chinese).
- [26] Zhao, J., Wang, S. Y., Peng, Y. H., and Zhang, X. N., "Technology and Effect Appraising About SBS Modified Asphalt," *Chin. J. Highw. Transport*, Vol. 10, 1997, pp. 18–24 (in Chinese).

- [27] Zhang, X. and Zhang, Y. M., "Experimental Study of Modifying Kelamayi Asphalt by Using SBS Modifiers," *J. Xi'an Shiyou Univ. (Nat. Sci. Ed.)*, Vol. 19, 2004, pp. 59–61 (in Chinese).
- [28] Chen, W. Y., "Binder Selection in Xinjiang's Asphalt Pavement Design," *Highway*, Vol. 58, 2013, pp. 59–61 (in Chinese).
- [29] JT/T 798 2011, 2011, Research Institute of Highway Ministry of Transport. "Asphalt rubber for highway engineering," transportation industry standard of the People's Republic of China, Standard No. JT/T 798 2011. China Communications Press, Beijing, China, 2011 (in Chinese).
- [30] Ge, Z. and Huang, X., "Study on Asphalt Mixtures Fatigue Properties by Testing," *J. Traffic Transp. Eng.*, Vol. 2, 2002, pp. 34–37.
- [31] Tan, Y., Shi, K., Li, L., Chen, G., and Ji, L., "Prevention of Reflective Cracks With High Viscous Asphalt Stress Absorbing Layer," *J. Harbin Inst. Technol.*, Vol. 40, 2008, pp. 241–245.
- [32] JTG F40-2004, 2004, Research Institute of Highway Ministry of Transport. "Technical Specifications for Construction of Highway Asphalt Pavements," transportation industry standard of the People's Republic of China, Standard No. JTG F40-2004. China Communications Press, Beijing, China, 2004 (in Chinese).
- [33] JTG E42-2005, 2005, Research Institute of Highway Ministry of Transport. "Test Methods of Aggregate for Highway Engineering," transportation industry standard of the People's Republic of China, Standard No. JTG E42-2005. China Communications Press, Beijing, China, 2005 (in Chinese).
- [34] TO703, 2011, Research Institute of Highway Ministry of Transport. "Standard Practice for Preparation of Bituminous Mixture Test Specimens by Means of wheel rolling compactor," Standard No. T0703-2011 (in Chinese).
- [35] T0719, 2011, Research Institute of Highway Ministry of Transport. "Standard Practice for Wheel Track Test of Bituminous Mixture Test Specimens," Standard No. T0719-2011 (in Chinese).
- [36] T0729, 2011, Research Institute of Highway Ministry of Transport. "Standard Practice for Freezing-Thawing Split-Strength Test of Bituminous Mixture Test Specimens," Standard No. T0729-2011 (in Chinese).
- [37] AASHTO T321, 2003, "Standard Method of Test for Determining the Fatigue Life of Compacted Hot-Mix Asphalt (HMA) Subjected to Repeated Flexural Bending," AASHTO Designation: T 321-03.
- [38] Gibson, N. H., Kutay, M. E., Keramat, D., and Youtcheff, J., "Multiaxial Strain Response of Asphalt Concrete Measured During Flow Number Simple Performance Test," *J. Assoc. Asphalt Paving Technol.*, Vol. 78, 2009, pp. 25–66.
- [39] Bonaquist, R., "Refining the Simple Performance Tester for Use in Routine Practice," *NCHRP Project 9-29, Report No. 614*, Transportation Research Board, National Research Council, Washington, D.C., 2008.
- [40] Pellinen, T. K. and Witczak, M. W., "Stress Dependent Master Curve Construction for Dynamic (Complex) Modulus," *J. Assoc. Asphalt Paving Technol.*, Vol. 71, 2002, pp. 281–309.
- [41] Christensen, D. W., Pellinen, T., and Bonaquist, R. F., "Hirsch Model for Estimating the Modulus of Asphalt Concrete," *J. Assoc. Asphalt Paving Technol.*, Vol. 72, 2003, pp. 97–121.