

# Effects of rejuvenator on performance-based properties of rejuvenated asphalt binder and mixtures

Junan Shen <sup>a,\*</sup>, Serji Amirkhanian <sup>b</sup>, Boming Tang <sup>a</sup>

<sup>a</sup> Chongqing Jiaotong University, Chongqing 400074, PR China

<sup>b</sup> Civil Engineering Department, Clemson University, Clemson, SC 29634-0911, USA

Received 16 March 2006; received in revised form 27 March 2006; accepted 27 March 2006

Available online 15 June 2006

## Abstract

Firstly, the performance-based properties of rejuvenated aged asphalt binders, i.e., the blends of aged binders containing a rejuvenator at various percentages, were investigated under high, intermediate and low temperatures. The tests were conducted on the blends at three stages as follows: no aging, rolling thin film oven (RTFO) residuals and as well RTFO + pressure aging vessel (PAV) residuals through dynamic shear rheometer (DSR) and bending beam rheometer (BBR) tests. Optimum concentrations of the rejuvenator needed for the blends to reach a target PG grade were obtained from the blending charts of the rejuvenated aged binders in terms of performance properties. The rejuvenator is a soft binder containing a low asphaltene content of 2 wt%. Secondly, selected performance-based properties were conducted on hot mix asphalt (HMA) using the rejuvenated aged binder and a virgin HMA as a control mixture. Results showed that the rejuvenator affected significantly the performance-based properties of both the rejuvenated aged binders and the mixtures containing the rejuvenated aged binders. It was possible to get optimum concentrations of the rejuvenator using the blending charts so that the rejuvenated binders reach a target PG grade. The mean value of the concentrations was proved to be more reliable through the performance-based properties of the mixtures if it is used for a design value for recycling. The properties of the asphalt paving mixtures with the rejuvenated binders were even improved or in the same level as the properties of the virgin mixtures.

© 2006 Elsevier Ltd. All rights reserved.

*Keywords:* Asphalt binder; Hot mix asphalt; Rheological characteristics; Rejuvenator; Performance-based properties

## 1. Background and objectives of the study

### 1.1. Background and literature

The implementation of SHRP binder specifications has been carried out in most of the United States since the new specifications were developed in 1993 [1,2]. Even in countries that the new specifications have not been immediately introduced; however, researches related with the specifications are still in progress in both asphalt binders and mixtures. The use of reclaimed asphalt pavement (RAP) in virgin mixtures is increasing in quantity, and so

far the use of RAP has not followed the specifications because these specifications were not initiated for the recycling. Given these facts, it is practically meaningful to develop new technologies for a better use of the RAP in pavement engineering.

Rejuvenator is one of the recycling agents, suitable for either highly oxidized or for mixtures containing a large percentage of RAP. However, rejuvenator is not encouraged or even not allowed for the recycling in some states in USA because of the uncertainty of the rutting properties of recycled mixtures containing a rejuvenator. Researches have showed that aged asphalt binders containing a rejuvenator can reach target PG grades if the amount of the rejuvenator is appropriately determined and added [12]. However, the rejuvenator percentage may be crucial to the properties of the blended aged asphalt. The rejuvenator

\* Corresponding author. Tel.: +1 912 681 0084.

E-mail addresses: [junanshen@yahoo.com](mailto:junanshen@yahoo.com) (J. Shen), [kcdoc@clemson.edu](mailto:kcdoc@clemson.edu) (S. Amirkhanian), [tbm@netease.com](mailto:tbm@netease.com) (B. Tang).

should be properly added in terms of the properties of the blends so that the properties under low temperature are improved while the properties under high temperature are not adversely affected. Traditional methods to determine the percentage of the rejuvenator are predominantly based on blending charts of either a penetration or a viscosity criterion [3,4]. In addition, a more integrated approach for the determination of the rejuvenator percentage was proposed by considering not only the penetration or viscosity criterion, but the composition requirements for recycled asphalt as well [11]. However, some of these methods do not consider the performance-based properties of the rejuvenated aged asphalt binders using a rejuvenator as required by SHRP specifications.

### 1.2. Objectives and scope

The objectives of the study were as follows:

- (1) To investigate the effect of a rejuvenator on the performance-based properties of the rejuvenated aged binder, i.e., the blends of the aged binder containing the rejuvenator, using a series of dynamic shear rheometer (DSR) and bending beam rheometer (BBR) tests.
- (2) To study the influence of the rejuvenator on performance-based properties of hot mix asphalt (HMA) containing the rejuvenated aged binders, and to compare the properties of the mixtures containing the rejuvenated aged binders with those of virgin mixtures.

In this study, a series of DSR and BBR tests were conducted in the laboratory in order to establish the blending charts of aged binder containing a rejuvenator with different percentages. The tested blends were in three aging stages of no-aging, RTFO and RTFO + PAV aging. The percentages of the rejuvenator needed for the blends of aged binder and rejuvenator to reach a target PG grade were determined from blending charts. Selected performance-based properties of the mixtures using either the

rejuvenated aged binder or a virgin binder (as a control sample) were tested and compared.

## 2. Materials and testing procedures

### 2.1. Materials

Three types of asphalt binders were used in the study. The properties of the three binders are shown in Table 1. The aged asphalt binders used for producing the blends were not extracted directly from RAP, but were obtained by using an accelerated aging process in the laboratory on a virgin straight-run asphalt binder, Pen 60–80, representing those most popularly used in Japan. The virgin binder used for virgin mixtures was a Japanese standard quality of penetration level of 40–60 (1/10 mm) [9]. The Pen 40–60 virgin binder was selected as for virgin mixtures because the binder was graded as PG64-22, a target grade for the blends used for all the mixtures.

The rejuvenator used for the blends of rejuvenated aged binder and the mixtures is a soft binder with low asphaltene of 2 wt%, as listed in Table 2. The viscosity of the rejuvenator at 60 °C is 202 Pa s. The percentages of the rejuvenator for establishing blending charts of aged binder were 0, 6.0, 9.0 and 14.0 wt% of the aged binders.

Based on these blending charts, optimum percentages of the rejuvenator used for the rejuvenated aged binders to achieve PG64-22, a Performance Grade at which DSR will fail at 64 °C, and BBR will fail at –22 °C, were determined. Finally, both the low and high limits of the rejuvenator percentages, i.e., 2% and 7.4%, respectively, were obtained, Table 3.

A virgin mix design with HMA 13 conducted using virgin binder Pen 40–60 came out an optimum asphalt percentage (OAC) of 5.4 wt% of the dry aggregate. The OAC was obtained by Marshall Test at a compaction condition of 50 blows on each size of the samples. The compaction condition corresponds to a middle traffic. This value was used for all the asphalt mixture samples with the types and gradations of the aggregates being identical. Totally, three recycled mixture samples and one virgin mixture

Table 1  
Properties of straight-run base asphalts and aged asphalt binder

Sources	Penetration (25 °C, 1/10 mm)	Softening point (°C)	Ductility (cm)
Straight-run Pen 60–80	66	48	100+
Straight-run Pen 40–60	50	50	100+
Aged asphalt <sup>a</sup>	30	Not available	Not available

<sup>a</sup> Aged asphalt binder was produced artificially with straight-run Pen 60–80 by RTFO and PAV process.

Table 2  
Properties and composition of the rejuvenator

Dynamic viscosity 60 °C (Pa s)	Flash point (°C)	Ratio of viscosity	Unit weight (kN/m <sup>3</sup> )
202	232	1.37	9.9
Asphaltene	Saturate	Aromatic	Resin
2.0 wt%	51.9 wt%	33.2 wt%	12.7 wt%

Table 3  
Rejuvenator percentage (%) to meet PG64-22 for Pen 30

SHRP tests required	Percentage
DSR (original), $T = 64\text{ }^{\circ}\text{C}$ , $G^*/\sin\delta > 1.00\text{ kPa}$	<12.2
DSR (RTFO), $T = 64\text{ }^{\circ}\text{C}$ , $G^*/\sin\delta > 2.20\text{ kPa}$	<7.4
DSR(RTFO + PAV), $T = 25\text{ }^{\circ}\text{C}$ , $G^*\sin\delta < 5.00\text{ MPa}$	>0
BBR(RTFO + PAV), $T = -12\text{ }^{\circ}\text{C}$ , Stiffness < 300 MPa	>0
BBR (RTFO + PAV)@ $T = -12\text{ }^{\circ}\text{C}$ , $m > 0.30$	>2.0
Common region of the rejuvenator percentage	2.0–7.4
Average value of the rejuvenator percentage	4.7

sample were produced. The three recycled were produced using rejuvenated aged binders at 0%, 2.0% and 7.4% of rejuvenate percentages, respectively, and the virgin samples using a virgin binder Pen 40–60.

2.2. Test methods

DSR (AASHTO T315-2) and BBR (AASHTO T313-2) tests were used for determining the rheological and creep stiffness properties of the blends in different temperatures.

Wheel tracking test was used to determine rutting resistance properties of mixture samples under high temperatures. In this method, a solid wheel moves back and forth in the middle of the sample compacted by a roller compactor. Dynamic stability (DS), defined as the passes to get 1 mm rutting, is calculated from the test result.

Thermal stress restrained specimen (TSRS) was used to evaluate the fracture properties of the mixtures under low temperature. The specimen of 5 cm × 5 cm × 30 cm was made by cutting a compacted mixture slab, and was further fixed in a steel test frame at its two ends and then put into a cooling bath. Thermal stress in the mixture specimen is developed with the decreasing of temperature at a cooling

rate in the bath. The specimen is broken when the stress developed is greater than the strength of the specimen. The temperature and the strength at which the mixture is broken are called fracture temperature and fracture strength; respectively. The fracture strength measured in the study is the fracture propagation study.

In this study, two processes are carried out for the TSRS. One is a direct single cooling test, called single TSRS. The other is a repeated TSRS test. The initial temperature of the test is 10 °C, and the cooling rate is 10 °C/h for all the tests. The repeated TSRS test was also carried out between a temperature range of 0 °C and –10 °C for 20 cycles, and then followed by the single TSRS test.

The test program in the study was shown in Fig. 1. The first part is binder test flowchart, and the second is mixture test flowchart.

3. Results and discussions

3.1. Performance-properties of the blends of aged binders containing a rejuvenator

Figs. 2 and 3 show the relationship between rutting resistance parameter,  $G^*/\sin(\delta)$ , obtained using DSR testing procedures at 64 °C, and the percentage of the rejuvenator on original binders and RTFO residual; respectively. The  $G^*/\sin(\delta)$  of the blend, both in original state and RTFO residual, decreased linearly with the increase of the rejuvenator. As we expected, this fact indicated that rejuvenator can soften the hard aged asphalt binder efficiently. It should be noted that an over dose concentration of the rejuvenator will increase the rutting potential of the blend. Considering this fact, a maximum

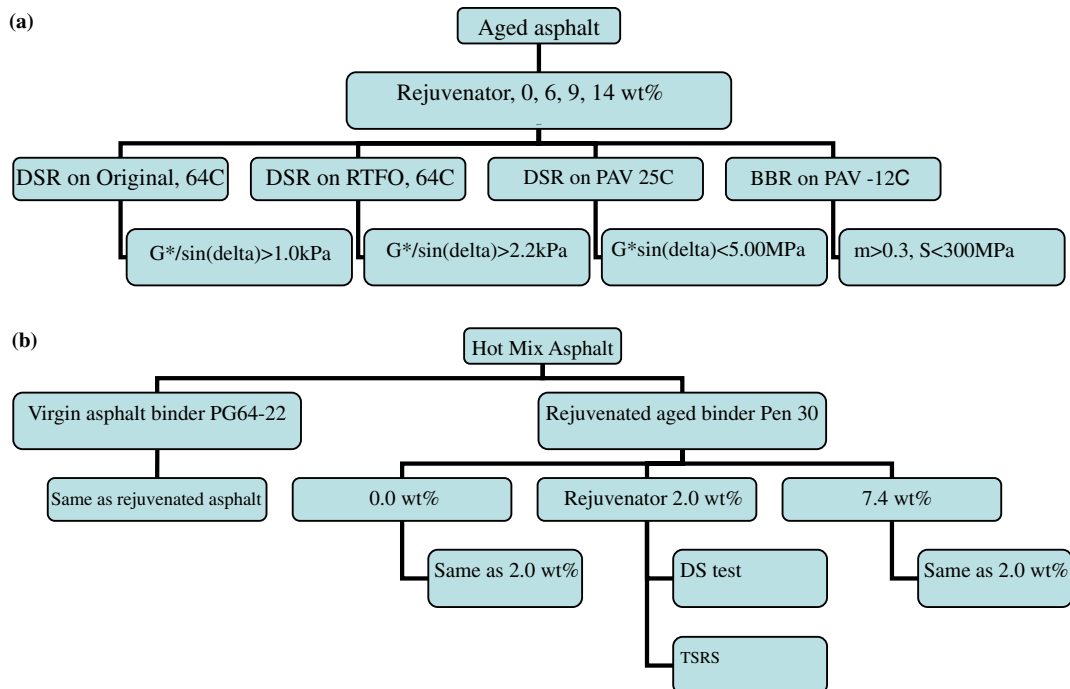


Fig. 1. Test program for: (a) blend of aged binders with rejuvenator; (b) rejuvenated mixtures.

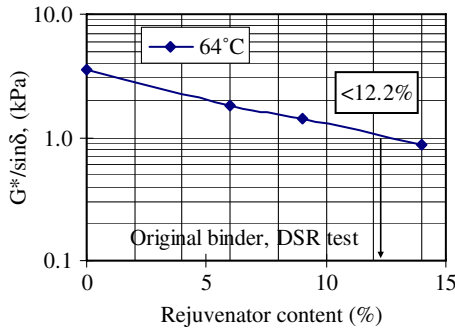


Fig. 2.  $G^*/\sin(\delta)$  versus rejuvenator percentage at 64 °C (DSR, original binder).

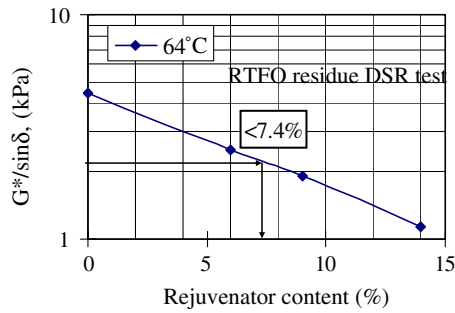


Fig. 3.  $G^*/\sin(\delta)$  versus rejuvenator percentage at 64 °C (DSR, RTFO residual).

percentage of the rejuvenator is to be controlled by the parameter  $G^*/\sin(\delta)$ . In order to get a target PG64-22, i.e., the high temperature grade is 64 °C, the  $G^*/\sin(\delta)$  should be less than 1.0 kPa for the blend in original state, less than 2.2 kPa for RTFO residual, according to SHRP binder specifications.

Fig. 4 shows the results of testing using DSR conducted at 25 °C that indicated the relationship between the fatigue parameter,  $G^*\sin(\delta)$ , and the percentage of the rejuvenator. The  $G^*\sin(\delta)$  of the blend in RTFO + PAV residual decreased linearly with the increase of the rejuvenator percentage. This fact indicated that rejuvenator can soften the hard aged asphalt binder with the fatigue properties of the blends significantly improved. In order to get a target PG64-22, according to SHRP binder specifications, the intermediate temperature grade must be 25 °C, and the  $G^*\sin(\delta)$  should be less than 5.0 MPa for the blend. In this study, it should be noted that even if no rejuvenator was

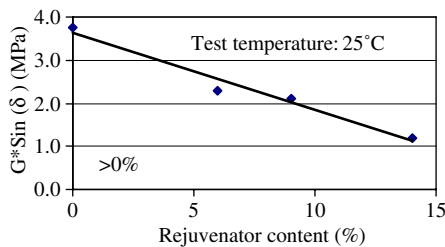


Fig. 4.  $G^*\sin(\delta)$  versus rejuvenator content in the blends at 25 °C (DSR, RTFO + PAV residual).

added (i.e., 0%), the parameter of  $G^*\sin(\delta)$  is still less than the standard value.

Figs. 5 and 6 show the relationship between low temperature properties parameters, stiffness and  $m$ -value of the blend in RTFO + PAV residual, and the percentage of the rejuvenator under BBR test temperatures of  $-15$  and  $-10$  °C. The stiffness decreased with the increase of the rejuvenator linearly, whereas the  $m$ -value increases with the increase of the rejuvenator. Both of the trends indicated that rejuvenator can soften the hard aged asphalt binder to a great extent, leading to the improvement of the shrinkage properties under low temperatures. In order to get a target PG64-22, the low temperature grade must be  $-22$  °C, the stiffness of the blend under test temperature  $-12$  °C should be less than 300 MPa, and the  $m$ -value larger than 0.3 according to SHRP binder specifications. The minimum percentages of the rejuvenator to satisfy the stiffness and  $m$ -value requirements are 0% and 2.0%; respectively, which are obtained by interpolation.

The required rejuvenator percentages needed for the aged binder with Pen 30 to reach PG64-22 can be summarized as shown in Table 3.

### 3.2. Rutting resistance – wheel tracking test

The rutting potential of an asphalt paving mixture under increased high temperatures may be evaluated by the wheel tracking test. The dynamic stability (DS) is adopted as an index to evaluate the rutting resistance of an asphalt mix-

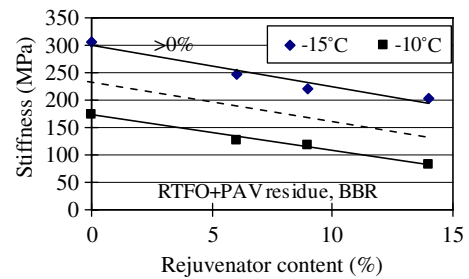


Fig. 5. Stiffness versus rejuvenator percentage of the blends at  $-12$  °C (BBR, RTFO + PAV residual) (interpolated using temperatures 15 and 10 °C).

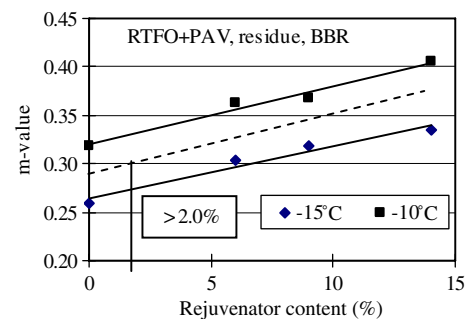


Fig. 6.  $m$ -Value versus rejuvenator percentage of the blends at  $-12$  °C (BBR, RTFO + PAV residual) (interpolated using temperatures 15 and 10 °C).

ture. The DS is defined as the number of passes required for the loaded wheel to produce a vertical plastic deformation of 1 mm on the surface of the test sample. The results of the wheel tracking test are listed in Table 4.

Fig. 7 shows the relationship between the DS of the paving mixtures and the rejuvenator percentage in the binder. The DS of the mixtures decreased as the amount of the rejuvenator percentage increased, which is similar to the finding for the blends, namely, the parameters,  $G^*/\sin(\delta)$ , of rejuvenated aged binders decreased as the rejuvenator percentage increased.

The DS of the mixtures containing rejuvenated aged binders decreased significantly from 2630 to 1310 passes/mm, a decreasing rate as much as 50%, with the rejuvenator percentages of 0% and 7.4%, respectively. Similarly, the DS of the mixtures containing rejuvenated aged binders at the rejuvenator percentages of 2.0% and 7.4% changed from 2100 to 1310 passes/mm, respectively. That means a decreased rate of about 38% in the DS was found for the mixtures containing rejuvenated binders even if the rejuvenated binders had the same design PG.

In general, the higher the DS value, the better performance of the mixtures at high temperature. Obviously, the DS of the mixture containing rejuvenated aged binder with the higher limit of rejuvenator percentage, 7.4%, could be of concern because the DS decreased greatly as it was 1310 passes/mm. It is, however, still 30% greater than the specified value of 1000 passes/mm for a normal dense graded asphalt mixture, although it is 12% less than the specified value of 1500 passes/mm for a dense graded asphalt mixture to be used in regions requiring high dynamic stability that is usually realized by special measures such as using modified asphalt binder and finer particles [5]. The DS of the recycled mixture with higher limit of rejuvenator of 7.4% is just 8% less than that of the virgin mixture.

As a whole, the DS of the mixture containing rejuvenated aged binder at higher rejuvenator percentages is a little bit lower than those of the referenced virgin mixture and the standard required in regions with high requirement of dynamic stability.

### 3.3. Fracture properties – thermal stress of restrained specimen test

It has been reported that the flexure strength of asphalt mixtures at low temperature does not differ from binder types, and is not variable with temperatures. Therefore,

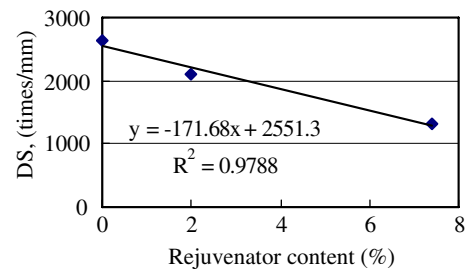


Fig. 7. Dynamic stability (DS) as a function of rejuvenator percentage in rejuvenated mixtures.

the thermal stress restrained specimen (TSRS) test has been used to characterize the properties at low temperature for some years [7,8,10].

The results from single TSRS tests of both the recycled and the virgin mixtures are shown in Fig. 8. Generally, the curves showing the relationships between the stress and the cooling temperature have a similar tendency for all the mixtures, and are similar to those of the virgin mixtures as reported before [6,13]. Within the high temperature region, the curves have a convex shape. In that region, stresses increase non-linearly with the decrease of temperature. In other words, the mixtures are in a non-linear elastic state for both the virgin and recycled mixtures. After the transition point, a temperature point in the curve as Fig. 8, the stresses appear to linearly increase as the temperature decreases. It is suggested that the asphalt mixtures are in an elastic state.

Figs. 9 and 10 show the fracture temperature and fracture strength versus the rejuvenator percentage of the mixtures containing rejuvenated aged binders; respectively. By increasing the rejuvenator percentage from 0% to 7.4%, the fracture temperature decreased from  $-22.0$  to  $-29.5$  °C and the fracture strength increases from 2.5 to 3.0 MPa. It is evident that the properties of mixtures containing reju-

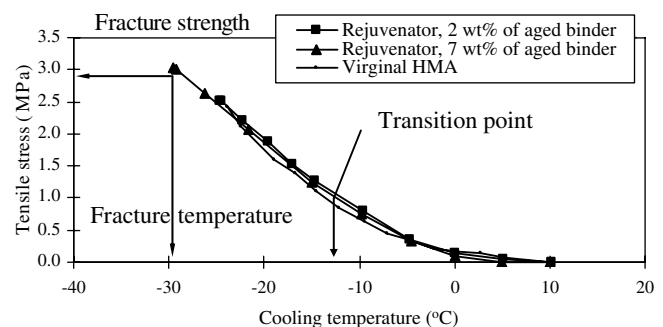


Fig. 8. Tensile stress developed as a function of cooling temperature.

Table 4  
Results of wheel tracking test

Mixture type	Virgin	Mixture with rejuvenated binder rejuvenator (%)			Code (JRA)
		0	2.0	7.4	
$d_0^a$ (mm)	1.2	1.55	1.26	1.33	
DS <sup>b</sup> (passes/mm)	1430	2630	2100	1310	1000–1500

<sup>a</sup> The vertical interception of the curve showing the rutting and loading cycling.

<sup>b</sup> Dynamic stability obtained as its definition.

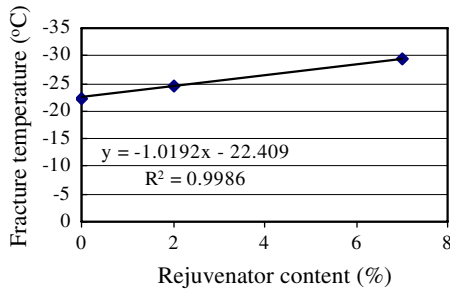


Fig. 9. Fracture temperature as a function of rejuvenator percentage.

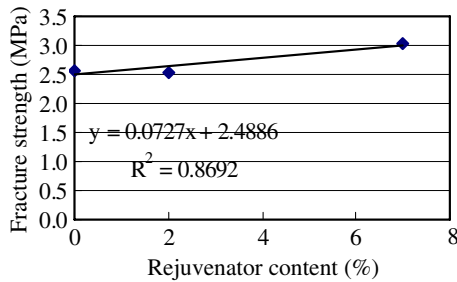


Fig. 10. Fracture strength as a function of rejuvenator percentage.

venated aged binders under low temperature were improved in a similar way that the properties of rejuvenated aged binders were improved by adding the rejuvenator percentage. The virgin mixture has a fracture temperature of  $-23.9\text{ }^{\circ}\text{C}$  and fracture strength of  $2.43\text{ MPa}$  (Table 5).

Naturally, the properties of the mixture containing rejuvenated aged binders with the low rejuvenator percentage are the most concerned for low temperatures in practice. The recycled mixture with a rejuvenator percentage of  $2.0\%$  fractured at  $-24.6\text{ }^{\circ}\text{C}$  with a fracture strength of  $2.5\text{ MPa}$ . This means that the fracture properties of the mixtures containing rejuvenated aged binders with low rejuvenator percentage are still better than the fracture properties of the virgin asphalt mixture (Table 5).

It should be pointed out that the fracture temperatures of both the two recycled mixtures and the virgin mixture are lower than  $-22\text{ }^{\circ}\text{C}$ , the low temperature grade of a binder classified as PG64-22. That means the low fracture temperature of a dense asphalt mixture can reach the grade of the asphalt binder used with regards to the cases considered in this study.

As shown in Fig. 11, the transition temperature of the mixtures containing rejuvenated aged binders increased as the rejuvenator percentage increased, indicating that the relaxation ability of the mixtures was improved as the amounts of rejuvenator increased. This result was in agreement with the fact that the stiffness and the  $m$ -value of the recycled asphalts, defined as the ratio of  $\log S(t)/\log(t)$  of the binder from BBR tests, were improved with the increased rejuvenator percentages. The transition temperatures were  $-16\text{ }^{\circ}\text{C}$  for the virgin asphalt mixture. The relaxation ability of the recycled asphalt mixtures was slightly worse than for the virgin asphalt mixture.

After 20 cycles of the repeated TSRS test, the samples were cooled further from an upper temperature  $0\text{ }^{\circ}\text{C}$  until the samples fractured. The results after 20 cycles were shown in Fig. 12 and Table 5. The fracture temperatures after 20 cycles of the repeated TSRS test were  $-24$  and  $-29\text{ }^{\circ}\text{C}$  and the fracture strengths were  $2.28$  and  $2.33\text{ MPa}$  for the recycled asphalt with  $2.0\%$  and  $7.4\%$  reju-

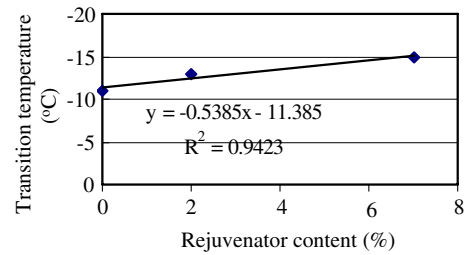


Fig. 11. Transition point as a function of rejuvenator percentage.

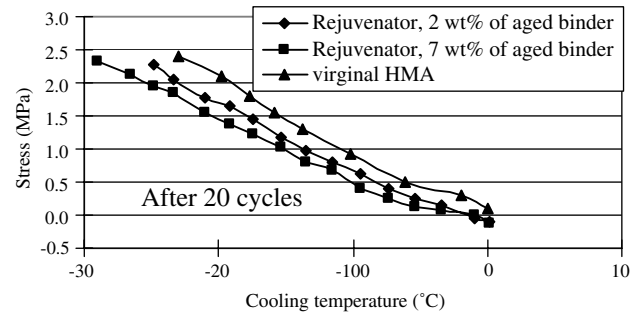


Fig. 12. Stress developed with cooling temperatures after the repeated TSRS.

Table 5  
Summary of the TSRS test of asphalt mixtures tested

Properties	Fracture temperature ( $^{\circ}\text{C}$ )		Fracture strength (MPa)		Transition point ( $^{\circ}\text{C}$ )
	Single	Repeated	Single	Repeated	
Mixtures with rejuvenated binder (%)					
0.0	-22.0	-21.5	2.50	2.15	-11.0
2.0	-24.6	-24.0	2.50	2.28	-13.0
7.4	-29.5	-29.0	3.00	2.33	-15.0
Virgin mixture	-23.9	-23.0	2.43	2.40	-16.0

venator percentages; respectively. The fracture temperature and fracture strength, after 20 cycles of the repeating TSRS test, were  $-23\text{ }^{\circ}\text{C}$  and 2.40 MPa; respectively, for the reference virgin mixture.

Compared with the results of single TSRS testing, there was not much change in the fracture temperatures but a slight change in the fracture strengths. This is perhaps due to the decrease in the elasticity of the samples. The repeated TSRS test with its 20 cycles may lead to some changes in the structure of the samples, resulting in decreasing of the elasticity of the samples.

In general, the results obtained from both single and repeated TSRS tests indicated that adding rejuvenator improves the fracture properties of the recycled mixtures. The fracture properties at low temperatures for the recycled mixtures having rejuvenator percentages determined by the proposed method, even when added at a low percentage, are better than the fracture properties of the referenced virgin mixture.

#### 4. Summary and conclusions

The influences of rejuvenator on the performance-based properties of the blends of aged binders and the rejuvenator were investigated using DSR and BBR tests based on SHRP binder specifications, and the influence of the rejuvenator on the selected performance-based properties of the mixtures containing rejuvenated aged binders were investigated by wheel tracking test and TSRS test as well. Some conclusions are drawn as follows:

- (1) The rejuvenator percentage affected greatly the performance-based properties of the blend of aged binder and the rejuvenator. The rutting resistance parameters decreased, while the fatigue resistance parameters and the shrinkage parameters improved as the rejuvenator percentage increased.
- (2) The rejuvenator percentage affected significantly the selected performance-based properties of the mixtures containing rejuvenated aged binders in the same ways it affected blends. The DS of the mixtures containing rejuvenated aged binders decreased, while the fracture properties improved as the rejuvenator percentage increased.
- (3) The optimum percentages of the rejuvenator needed for the blends to achieve a target PG grade can be obtained by satisfying SHRP specifications through the blending charts. The average value of the percentages was proved to be a more reliable when it was used as a design percentage.
- (4) The DS of the mixtures with the low limit percentage of the rejuvenator differs greatly from that with the high limit of the rejuvenator. The DS of the mixture containing the rejuvenated aged binder with the high percentage of the rejuvenator is lower than that of the virgin mixture, but it is still higher than the standard for a normal dense graded mixture.
- (5) The DS of the mixtures containing the rejuvenated binder at the average percentage of the low and high percentage limits is higher than that of the virgin mixture. In this regard, the average percentage is reliable and acceptable.
- (6) The fracture properties were better for asphalt mixtures containing the rejuvenated binder than virgin asphalt mixtures. Even for the case with low limit of the rejuvenator percentage, the asphalt mixtures containing rejuvenated aged binder still had low temperature properties as good as those of the virgin asphalt mixture.
- (7) The repeated TSRS test with 20 cycles did not change the fracture temperatures of the mixtures containing the rejuvenated aged binder and virgin asphalt. However, a decrease in fracture strength was found for the mixtures containing rejuvenated aged binders. The repeated cooling and heating may lead to changes in the sample structure and; therefore, decrease the elasticity of the samples.

#### References

- [1] Anderson DA, Kennedy TW. Development of SHRP specifications. *Proc Assoc Asphalt Paving Technol* 1993;62:481–507.
- [2] Hicks RG, Finn FN, Monismith CL, Leahy RB. Validation of SHRP binder specification through mix testing. *J Assoc Asphalt Paving Technol* 1993;62:615–38.
- [3] Japanese Road Association. *Guideline for Recycling Pavement Technology in Plant*, 1993. [In Japanese].
- [4] Japanese Road Association. *A Separate Volume for Pavement Test Methods*, 1996. [In Japanese].
- [5] Japanese Road Association. *Design Code for Asphalt Pavement*, 1992. [In Japanese].
- [6] Jung DH, Vinson TS. Low temperature cracking resistance of asphalt concrete mixtures. *J Assoc Asphalt Paving Technol* 1993;62:54–92.
- [7] Jung DH, Vinson TS. Low temperature cracking: Test selection, SHRP-A-400, 1994a.
- [8] Jung DH, Vinson TS. Low temperature cracking: binder validation, SHRP-A-399, 1994b.
- [9] Kennedy Thomas W, Tam Weng O, Solaimanian M. Optimizing use of reclaimed asphalt pavement with the superpave system. *Proc Assoc Asphalt Paving Technol* 1998:311–33.
- [10] Moriyoshi A, Fujiwara M. A research on thermal behavior of asphalt mixture. *J Jpn Soc Civil Eng* 1988;9(396):129–34 [In Japanese].
- [11] Servas VP, Edler AC, Ferreira MA, Assen EJ van. An integrated approach for determining additive requirements in hot mix recycling. *The sixth international conference structural design of asphalt pavements*, vol. 1. The University of Michigan; 1987, p. 23–33.
- [12] Shen J, Konno M, Takahashi M. Evaluation of recycled asphalt by SHRP binder specifications. *J Pavement Eng Jpn Soc Civil Eng* 2001;6:54–60.
- [13] Zeng H, Isacson U. Evaluation of low temperature properties of asphalt mixture. In: *Proceedings of the third international conference on road and Airfield Pavement Technology*, Beijing, China, vol. 1. 1998, p. 10–18.