Construction and Building Materials 111 (2016) 139–146

Contents lists available at ScienceDirect

Construction and Building Materials

journal homepage: www.elsevier.com/locate/conbuildmat

Characterizing the chemical and rheological properties of severely aged reclaimed asphalt pavement materials with high recycling rate

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HIGHLIGHTS

- A method corrects the issue that AI blending chart overpredicts the rejuvenator dose.
- The PDI from GPC analysis is a useful tool to identify the rejuvenated RABs.
- The Glover–Rowe damage zone demonstrates a clearly distinct severity of aging level.

ARTICLE INFO

Article history:
Received 21 April 2015
Received in revised form 16 December 2015
Accepted 17 February 2016

Keywords:
High percentage RAP
Severe aged reclaimed asphalt binder
Rejuvenator
Rheology
GPC
MSCR

ABSTRACT

Frequent mill and overlay activities result in the production of a considerable amount of reclaimed asphalt pavement (RAP) materials. Many pavements that incorporated RAP exhibit a shorter service life than do those without RAP. One of the possible reasons is that certain RAP materials have already undergone multiple recycling processes during the past decade. This results in severe aging of the reclaimed asphalt binder (RAB). In this study, three severely aged RABs, two RAP blending scenarios, two virgin binders, and two commercial rejuvenators were used to investigate the feasibility of using severely aged binders for constructing pavements. The chemical and rheological properties of the rejuvenated severely aged binders were evaluated using high-performance gel permeation chromatography and a dynamic shear rheometer. The molecular size distributions of rejuvenated RABs revealed that the rejuvenators used in this study could rebalance the proportions of large, medium, and small molecular components among the rejuvenated RABs. However, the polydispersity values still enabled clearly distinguishing between virgin binders and rejuvenated RABs. Two performance parameters were used to evaluate the potential of age-induced damage as well as permanent rutting in the binders. A Glover–Rowe damage zone was evaluated, and it revealed promising results to distinguish among severely aged binders, virgin binders, and rejuvenated binders. Oscillation and multiple stress creep and recovery tests were performed to obtain rutting potential parameter $G^*/\sin(\delta)$ and J_{nr}, respectively. The results indicated that all rejuvenated aged binders exhibited higher $G^*/\sin(\delta)$ values and lower J_{nr} values compared with the control virgin binders.

1. Introduction

Traffic loading and pavement service environments are widely considered to influence pavement performance. Taiwan is highly urbanized, with most of its population living in high-rise condominiums. Most utility lines such as water, natural gas, electricity, and telecommunication lines are embedded underneath city and county roads. Maintaining and repairing utility lines necessitates the frequent digging and patching of such roads. In addition, Taiwan lies across the Tropic of Cancer. Therefore, northern and central Taiwan have a humid subtropical climate, with substantial seasonal temperature variations. By contrast, most of southern and southeastern Taiwan are characterized by a tropical monsoon climate involving less noticeable seasonal temperature variations, with temperatures typically varying from warm to hot. Asphalt materials age faster in hot and humid climates than in other climate types. The high traffic loading, frequent utility patching, and hot and humid climate lead to faster deterioration of pavements, which consequently necessitates frequent maintenance and repair. Milling and overlay are one of the most commonly used maintenance and rehabilitation (M&R) techniques for flexible pavements in Taiwan. Frequent milling and overlay activities produce a considerable amount of reclaimed asphalt pavement (RAP).

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http://dx.doi.org/10.1016/j.conbuildmat.2016.02.058
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Therefore, since the late 1990 s, the construction specification chapter 02966 allows incorporating at most 40% of RAP into new hot-mix asphalt (HMA). Wang [1] performed a survey on RAP in northern Taiwan and found that a reclaimed asphalt binder (RAB) had an average viscosity of 18,000–34,000 P at 60 °C. Lee [2] recently conducted a survey on RAP materials in southern Taiwan and revealed that the viscosity aging of RABs could be as high as 500,000 P at 60 °C. Lee considered that such a severe aging level was because certain RAP materials, namely repeated RAP (RRAP) materials, have been subjected to a multiple recycling process during the past decade. When a severely aged RAB is incorporated into new mixes, the mixture stiffness may increase and the durability may decrease, thus resulting in premature field failure of pavements, which ultimately leads to more frequent M&R activities on pavement.

Studies have reported that when the RAP rate was less than 25%, asphalt mixtures demonstrated similar performance levels to those of mixtures without RAP [3–6]. In recent years, the demand to increase construction sustainability as well as to lower construction costs have urged the paving industry to use higher RAP percentages in the construction and rehabilitation of asphalt pavements. A recent National Cooperative Highway Research Program study defined a high-RAP mixture as that involving 25–50% or greater of RAP [7]. In general, several studies have shown using high RAP content necessitates single- or double-bumping binder grades or adding rejuvenating agents to adjust the stiffening effect of aged binders [8–10].

To restore the rheological properties of an aged binder, a softening agent or rejuvenator may be mixed with the aged RAB. A softening agent typically lowers the viscosity of aged binders. A rejuvenator lowers the viscosity of an aged binder and facilitate rebalancing the chemical composition of an aged binder that has lost its light molecular weight fractions during the construction and service periods [11,12]. Previous studies have described the effects of softening agents or rejuvenators on the physical, chemical, and engineering properties of asphalt mixes and/or binders [12–14]. Another essential purpose of integrating rejuvenators with RAP is to determine the blending dose. Shen et al. [15] reported that the quantity of rejuvenators could significantly affect the properties of rejuvenated RABs. They suggested the optimum percentages of rejuvenator required to satisfy Strategic Highway Research Program specifications. Tran et al. [16] also used a similar approach to determine the optimum quantity of rejuvenators required to restore the performance properties of RAP and reclaimed asphalt shingles [16]. In Taiwan, the optimum rejuvenator content is usually determined using the blending chart developed by the Asphalt Institute (AI) [17]. This chart shows a linear relationship between the logarithm of viscosity at 60 °C and the percentage of new asphalt or percent recycling agent in the blend. However, when the viscosity of an aged binder exceeds 100 kP, the blending chart might overpredict the rejuvenator dose, consequently resulting in rejuvenated RABs that are softer than expected.

The objectives of this study were threefold: (1) to develop a method, which is a modified version of the viscosity blending chart, with high repeatability to determine the appropriate blending dose of severely aged RABs; (2) to study the change in the molecular weight distribution of rejuvenated RABs; and (3) to evaluate the performance-based rheological properties of rejuvenated high-percentage severely aged RABs.

2. Materials and methodology

2.1. Raw materials

Asphalt materials with three aging levels (RAB100, RAB300, and RAB500) recovered from RAP materials were blended with one type of virgin asphalt (A1) and two types of rejuvenator (R1 and R2). The RAP materials were obtained from the milled pavements in southern Taiwan. The target pavements have been milled and overlaid once or twice in the past 10 years. The results were compared with a control virgin asphalt binder (A2) that is widely used in Taiwan. Table 1 shows the viscosity grade and high-temperature performance grade (PG) properties of virgin and aged asphalt. The high-temperature PG of A1, A2, RAB100, RAB200, and RAB300 were 64, 70, 82, 88, and 94 respectively. This study applied two commercial rejuvenators (R1 and R2), and Table 2 shows their physical properties, which were determined according to ASTM D4552, a standard that describes the classification of hot-mix recycling agent (RA) grades. The viscosities of the R1 and R2 rejuvenators at 60 °C are approximately 60 and 15 P, which meet the specifications of RA 75 and RA 25, respectively. At 60 °C, the viscosity of RA 25 ranges between 9 and 45 P and that of RA 75 ranges between 45 and 125 P.

2.2. Experimental methods

Two blending scenarios involving 30% RAP (RAP30) and 50% RAP (RAP50) were evaluated in this study. The binder content of RAP was assumed to be 4% and the target binder content of the new mix was assumed to be 5%. Therefore, for the RAP30 blending scenario, the RAB contributed 24% of the binder content in the new mix and virgin asphalt, whereas the rejuvenator contributed the remaining 76%. In the RAP50 blending scenario, the RAB formed 40% of the binder content in the new mix and virgin asphalt, whereas the rejuvenator constituted 60% of the binder content in the new mix. The rejuvenated RABs were compared with the control asphalt binder A2 for determining their chemical and rheological properties. Fig. 1 shows the experimental procedures of this study. The molecular weight distributions of the binders were investigated using a Viscotek RImax high-performance gel permeation chromatography (HP-GPC). The system testing temperature was 40 °C. In the analysis, a 2% by weight asphalt solution was prepared in tetrahydrofuran (THF) and a 0.1-mL sample solution was injected into the column. The flow rate of the THF mobile phase was 1 mL/min. To calibrate the instrument, several polystyrene standards were used. The viscosity was measured using a Brookfield rotational viscometer (DV-III) with a spindle spinning at 20 rpm, and the spindle size was varied (#21, #27, and #29) depending on the sample's viscosity. The high and intermediate rheological properties of each binder were measured using a TA AR1500ex dynamic shear rheometer (DSR). An oscillation test was performed at temperatures ranging from 20 °C to 70 °C, with an interval of 10 °C, to measure the complex shear modulus (G^*) and phase angle (δ) of the binders according to AASHTO T315 specifications. The results were used to calculate the Superpave parameter $G^*/\sin\delta$ for potential rutting according to the AASHTO M320 specification. In addition, the permanent deformation potential of the binders was studied by conducting a multiple stress creep and recovery (MSCR) test according to the ASTM D7405 specification. In the MSCR test, a specimen was subjected to creep loading for 1 s and then unloaded and allowed to recover for 9 s. Two stress levels (i.e., 0.1 and 3.2 kPa) were applied for 10 creep recovery cycles individually. The results were used to calculate the new rutting performance parameters as an average recovery percentage, R, and nonrecoverable compliance, J_{nr}.

2.2.1. Modification of the AI blending chart

As mentioned, the most common method of determining rejuvenator dose in Taiwan is to use the viscosity-blending chart developed by the AI. In this study, the target viscosity at 60 °C was set to 2000 P. However, at the early stage of this study, the researchers noticed that the blending chart overpredicts the quantity of rejuvenators required to induce excessive binder softening. To rectify this problem, the following steps were used.

Step 1.

No rejuvenator: in this step, only the aged binder (RAB) was blended with a virgin binder (A). The Arrhenius mixing law, as shown in Eq. (1), was adopted to calculate the viscosity of the blend η_{RAB-A} [18]:

$$\ln(\eta_{RAB-A}) = f_{RAB}\ln(\eta_{RAB}) + f_{A0}\ln(\eta_A) \quad (1)$$

Step 2.

AI blending chart: according to the viscosity blending chart, the proportions of an aged binder (RAB), virgin binder (A), and rejuvenator (R) could be obtained, and the viscosity of such a blend was calculated as follows [17]:

$$\ln\eta_{RAB-A-R} = f_{RAB}\ln\eta_{RAB} + f_{A1}\ln\eta_A + f_{R1}\ln\eta_R \quad (2)$$

Table 1
Viscosity grade and PG high temperature grade of virgin asphalt and RABs.

Asphalt binder	Viscosity grade	PG grade	Viscosity (60 °C, poise)
A1	AC10	64	1155
A2	AC20	70	2350
RAB100	–	82	19,600
RAB300	–	88	31,500
RAB500	–	94	56,500

Table 2
Physical properties of HMA recycling agents (ASTM D4552).

Type	R1 (75)		R2 (25)	
Tests	Results	Specification	Results	Specification
Viscosity 60 °C (poise)	59.96	45–125	14.78	9–45
Flash point, COC, (°F)	Pass	>425	Pass	>425
Specific gravity	1.034	Report	1.015	Report
Saturate (%)	16	<30	23	<30
Viscosity ratio (%)	1.63	<3	1.37	<3
Residue from RTFO (%)	1.89	<3	1.98	<3

Step 3.
Modified blend: an interpolation technique, as shown in Eq. (3), was used to obtain the accurate blending proportions for the virgin binder (A) and rejuvenator (R) corresponding to a 2000-P target viscosity:

$$\ln(2000) = f_{RAB} \ln \eta_{RAB} + f_{A2} \ln \eta_{A2} + f_{R2} \ln \eta_{R2} \quad (3)$$

where

η_{RAB-A} is the viscosity of the blend containing aged binder and virgin binder only;
$\eta_{RAB-A-R}$ is the viscosity of the blend containing aged binder, virgin binder, and rejuvenator;
f_{RAB} is the fraction of the aged binder in the blend;
f_{A0} is the fraction of the virgin binder in the blend containing only the aged and virgin binders;
f_{R0} is fraction of the rejuvenator in the blend containing only aged and virgin binders;
f_{A1} is the fraction of the virgin binder in the blend according to the AI blending chart;
f_{R1} is the fraction of the rejuvenator in the blend according to the AI blending chart;
f_{A2} is the modified fraction of the virgin binder in the blend used in the study; and
f_{R2} is the modified fraction of the virgin binder in the blend used in the study.

The percentages of the virgin binders and rejuvenator in the various RAP blending scenarios and RAB aging levels were determined using the aforementioned procedures, as shown in Table 3. This table also shows the resulting viscosity of each rejuvenated RAB. The proposed methodology enabled restoring the viscosity of the aged binder close to the 2000-P target for all blending scenarios (Table 3). In addition, favorable viscosity measurement repeatability was observed for the different blending scenarios. The coefficient of variation (COV) was generally between 0.8% and 3.8%.

3. Results and discussion

3.1. Molecular size distribution

Previous studies have demonstrated the effectiveness HP-GPC in characterizing binder-age-induced changes in molecular size changes [19,20]. In a HP-GPC chromatogram, the horizontal axis indicates the elution time of the test sample (samples with a higher molecular fraction appear earlier) and the vertical axis indicates the response intensity (a higher response intensity represents a higher concentration). Fig. 2 illustrates GPC chromatograms of the aged binders (RAB100, RAB300, and RAB500) as well as the control virgin binder (A2). The elution times of RAB500, RAB300, RAB100, and A2 were 7.2, 7.4, 7.5, and 7.8 min, respectively. All the aged binders appeared earlier than the virgin binder did, indicating that the molecular weights in the aged binders were relatively higher than that in the virgin binder. Although RAB300 and RAB100 demonstrated similar elution times, RAB300

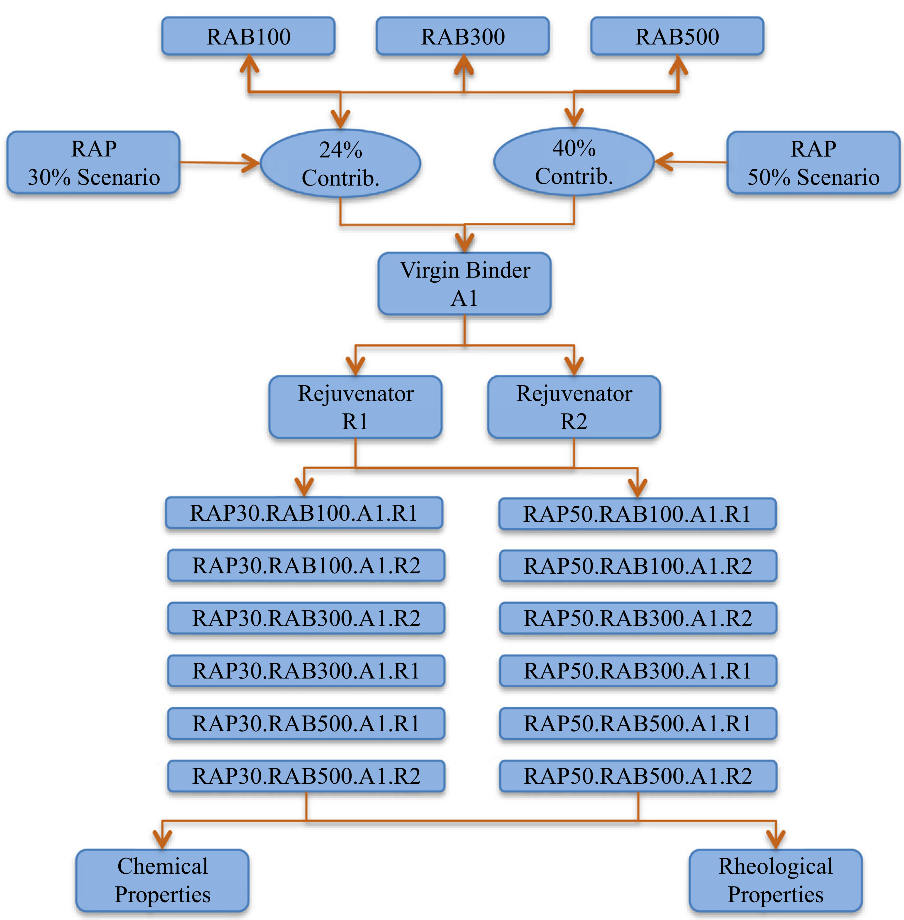

Fig. 1. Experimental procedures.

Table 3
Blending percentage of each component and viscosity for rejuvenated RABs.

Asphalt blends	Blending percentage (%)			Viscosity	COV (%)
	RAB	Virgin binder	Rejuvenator		
RAP30RAB100A1R1	24	70	6	2025	1.3
RAP30RAB300A1R1		70	6	2120	2.1
RAP30RAB500A1R1		66	10	1780	0.8
RAP30RAB100A1R2		69	7	2036	1.1
RAP30RAB300A1R2		67	9	2156	0.9
RAP30RAB500A1R2		62	14	1870	2.1
RAP50RAB100A1R1	40	43	17	1950	2.3
RAP50RAB300A1R1		42	18	1948	1.4
RAP50RAB500A1R1		40	20	2025	1.6
RAP50RAB100A1R2		40	20	2244	2.6
RAP50RAB300A1R2		33	27	1910	3.8
RAP50RAB500A1R2		30	30	1840	2.9

exhibited a greater response at 7.5–8 min, implying that RAB300 had a higher molecular concentration during that period. Table 4 shows a summary of the GPC results. To determine the molecular weight of the samples, this study applied several polystyrene standards. The contents of each binder blend were determined by normalizing the areas of the chromatograms. When the severity of asphalt aging increased, the weight-average molecular weight (Mw), number-average molecular weight (Mn), and polydispersity (PDI = Mw/Mn) increased (Table 4). The results presented in Table 4 are averages of three duplicates with coefficient of variance (COV) varies from 0.8% to 1.8%, indicating that the GPC tests results of these duplicates are almost identical. Comparing the results of virgin binder A2 and rejuvenated RAB revealed that the Mn value of the rejuvenated RAB was lower than that of virgin binder A2. Although the Mw value of the rejuvenated RAB also decreased, it was still higher than that of virgin binder A2. This is because even though rejuvenator complemented the light molecular weight component (maltene) of the aged RAB, large molecular weight components still existed. The large molecular weight component substantially contributes to the calculation of Mw. Therefore, the Mw-to-Mn ratio can be used to predict the dispersity of a polymer blend. All the rejuvenated RAB blends exhibited higher PDI values than that of virgin asphalt A2. Hence, the rejuvenators used in this study could not restore the chemical composition of the aged binder. This finding suggests that GPC can be a useful tool for evaluating whether an asphalt mixture contains RAP and whether a rejuvenator can reverse the aging process of an asphalt binder. This process is particularly valuable in areas in which performance-based tests are not implemented. A contractor may add a higher proportion of RAP for economy and use inadequate recycling agents to temporarily improve workability, which may lead to premature pavement failure such as rutting or bleeding. Fig. 3 illustrates the molecular size distributions in virgin binder A2 and the rejuvenated RAB blends. The distributions of large molecular sizes (LMS), medium molecular sizes (MMS), and small

Table 4
GPC parameters for raw and rejuvenated RABs.

	Material	Mn	Mw	Mp	PDI
Raw materials	AC2	650	1757	951	2.706
	RA1	320	1062	422	3.329
	RA2	286	776	395	2.731
	AC1	591	1648	882	2.79
	RAB100	779	3207	946	4.115
	RAB300	782	3345	944	4.276
	RAB500	837	4196	931	5.013
A1.R1	RAP30RAB100	612	2152	883	3.518
	RAP50RAB100	588	2391	844	4.066
	RAP30RAB300	608	2094	874	3.446
	RAP50RAB300	557	2231	810	4.007
	RAP30RAB500	567	2111	837	3.722
	RAP50RAB500	551	2416	791	4.389
A1.R2	RAP30RAB100	621	2163	883	3.485
	RAP50RAB100	591	2167	860	3.668
	RAP30RAB300	617	2062	888	3.342
	RAP50RAB300	578	2270	841	3.927
	RAP30RAB500	601	2074	884	3.453
	RAP50RAB500	578	2185	853	3.784

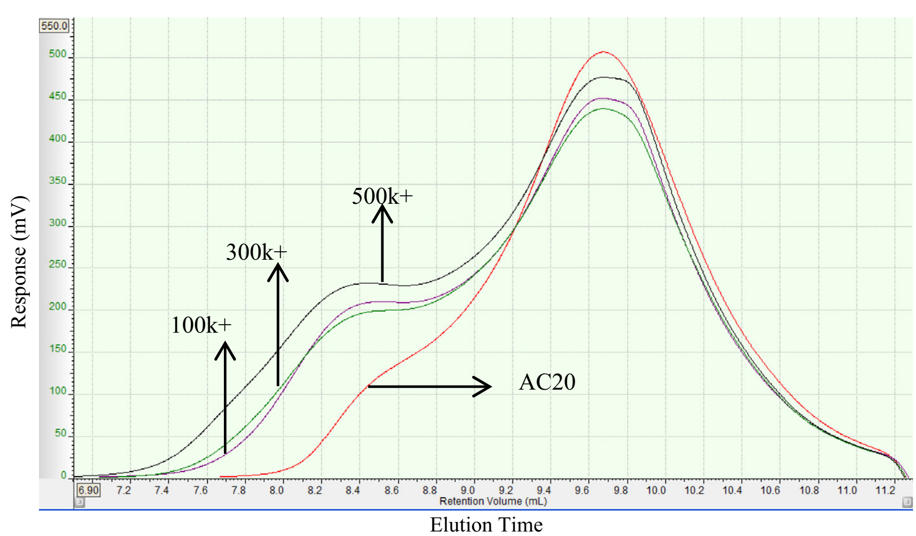

Fig. 2. GPC chromatogram illustrating the effects of asphalt aging.

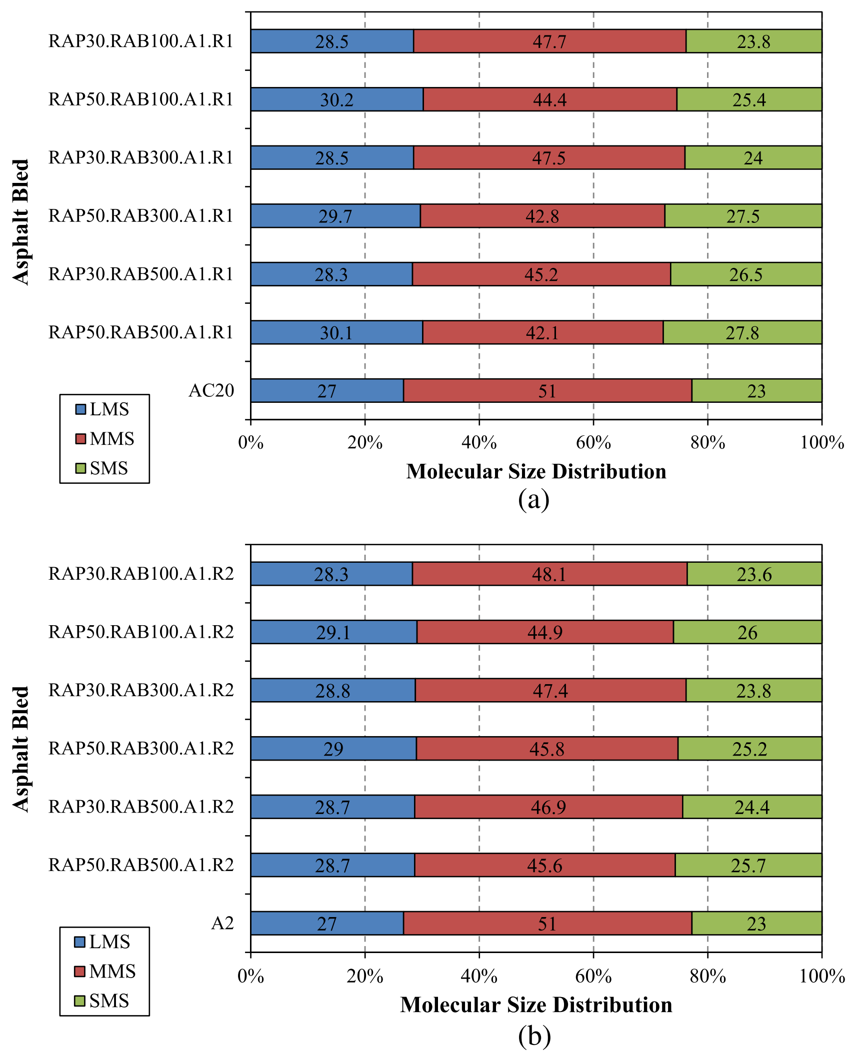

Fig. 3. Molecular size distribution of (a) virgin binder A1 and the RABs blended with rejuvenator R1, and (b) virgin binder A1 and the RABs blended with rejuvenator R2.

molecular sizes (SMS) in virgin binder A2 were 27%, 51%, and 23%, respectively. As shown in Fig. 3(a), when rejuvenator R1 was used, the RAB blends demonstrated higher percentages of LMS and SMS compared with virgin binder A2. Furthermore, the percentages of LMS in the RAP50 blending scenario were all higher than those in the RAP30 blending scenario. Similarly, applying rejuvenator R2 also resulted in higher percentages of LMS and SMS and lower percentages of MMS (Fig. 3(b)). However, the distributions of LMS, MMS, and SMS when the rejuvenators were used were closer to the molecular size distribution of virgin binder A2. Notably, determining the quantity of virgin binders and rejuvenators used in each blend depended on restoring the viscosity grade of the rejuvenated RAB materials to ensure that it matched that of virgin binder A2. Therefore, the difference in molecular size distribution between the rejuvenated RAB blends and virgin binder A2 was expected. Overall, rejuvenator R2 demonstrated a higher effectiveness in rebalancing the distributions of LMS, MMS, and SMS in a rejuvenated RAB blend compared with rejuvenator R1. Moreover, restoring the molecular size distribution to the state of virgin binder A2 was more difficult in the RAP50 blending scenario than in the RAP30 blending scenario.

3.2. Complex modulus and phase angle

The frequency sweep results of the asphalt blends were used to construct complex modulus (G^*) and phase angle (δ) master curves for the virgin binder and various rejuvenated RAB blends by employing the time–temperature superposition principle at 25 °C. Asphalt is a viscoelastic material because it exhibits elastic or viscous behavior depending on the temperature and loading frequency. At low temperature or high loading frequency, asphalt behaves as an elastic solid, and at high temperature or low loading frequency, it demonstrates a more obvious viscous property. Figs. 4 and 5 illustrate the complex modulus and phase angle master curves for the virgin binder and the various rejuvenated RAB blends. In general, the rejuvenated RAB blends had a lower complex modulus than that of virgin binder A2. A higher complex modulus indicates higher resistance to flow deformation. Regarding the phase angle, the rejuvenated RAB blends showed a slightly lower phase angle than that of the virgin binder in the high-frequency portion. By contrast, in the low-frequency portion, certain rejuvenated RAB blends exhibited a higher phase angle than that of virgin asphalt, whereas the remaining demonstrated a lower phase angle.

3.3. Performance-based indicators

3.3.1. Age-induced damage parameter

Rheological data of raw materials were plotted on a Black space diagram in addition to a Glover–Rowe damage zone and Christensen–Anderson model parameters (i.e., *R*-values) to observe the effect of aging on the damage potential of the materials (Fig. 6) [21–24]. King et al. [22] suggested that *R*-values ranging from 2.3

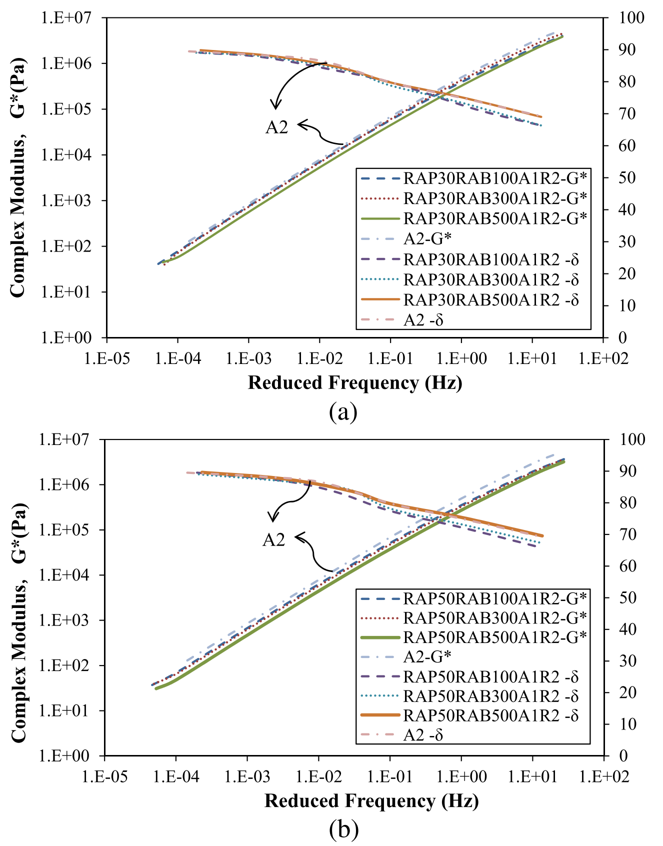

Fig. 4. Complex modulus and phase angle of virgin binder A2 compared with the blends of virgin binder A1 with various aged binders involving rejuvenator R1 in (a) RAP30 and (b) RAP50 blending scenarios.

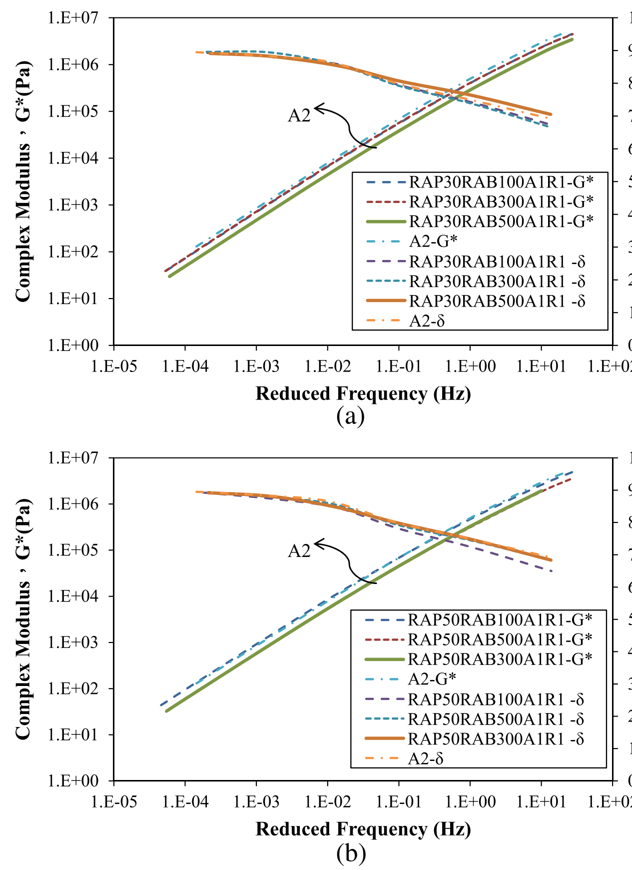

Fig. 5. Complex modulus and phase angle of virgin binder A2 compared with the blends of virgin binder A1 with various aged binders involving rejuvenator R2 in (a) RAP30 and (b) RAP50 blending scenarios.

to 2.7 can be used to predict the onset and propagation of damage [22]. Glover–Rowe also proposed a damage zone on a Black space diagram for predicting the onset of pavement damage. The current study determined that the aged RABs, virgin binders A1 and A2, and rejuvenators R1 and R2 appeared in three distinctive zones on the Black space diagram. According to Glover–Rowe theory, all three aged binders were located above the Glover–Rowe damage zone and two virgin binders and rejuvenators were below the Glover–Rowe damage zone. The rejuvenators were farther from the damage zone compared with the virgin binders. The aged RABs (RAB100 and RAB300) were located on the line corresponding to an *R*-value of 2 in the Christensen–Anderson model, indicating that no damage occurred. Figs. 7 and 8 show the Black space diagrams for all the rejuvenated RAB blends. The rejuvenating agent engendered the shifting of the aged RABs to below the Glover–Rowe damage zone and their movement away from the line associated with an *R*-value of 2.3 (which represents the onset of damage) in the Christensen–Anderson model. The results suggest that the Glover–Rowe damage zone can be used to track the rheological evolution of binder aging. Furthermore, the Glover–Rowe damage parameters can potentially serve as indicators of age-induced cracking, and such indicators can be used for predicting the timing of preservation treatment to reduce the aging of pavement surface courses.

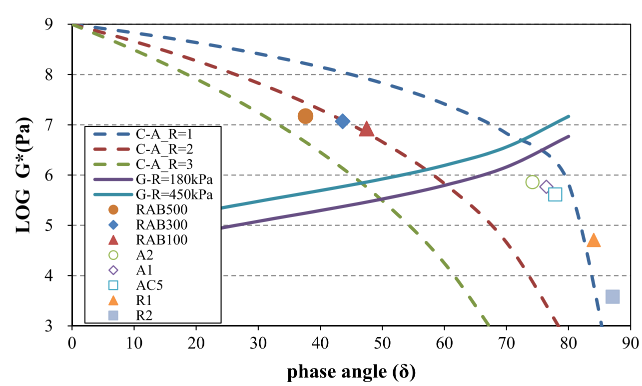

Fig. 6. Black space diagram of raw materials.

3.3.2. Superpave rutting performance indicator

In Taiwan, permanent pavement deformation at high temperature draws considerable concern. The Superpave binder test entails applying the expression $G^*/\sin(\delta)$, measured at $\omega = 10$ rad/s, as an indicator of rutting. This test requires that $G^*/\sin\delta > 1.0$ kPa for an original unaged binder to ensure that HMA possesses high rutting resistance (AASHTO M320). Fig. 9 shows the $G^*/\sin(\delta)$ values of virgin binder A2 and the rejuvenated RAB blends at 60 °C, which is the typical pavement temperature on hot days in Taiwan. The $G^*/\sin(\delta)$ values of all the rejuvenated aged binders were greater than 1.0 kPa. In the RAP30 blending scenario, the $G^*/\sin(\delta)$ values derived when rejuvenator R1 was used were lower than those derived when rejuvenator R2 was used. By contrast, in the RAP50 blending scenario, the $G^*/\sin(\delta)$ values obtained when rejuvenator R1 was used were higher than those obtained when rejuvenator R2 was used.

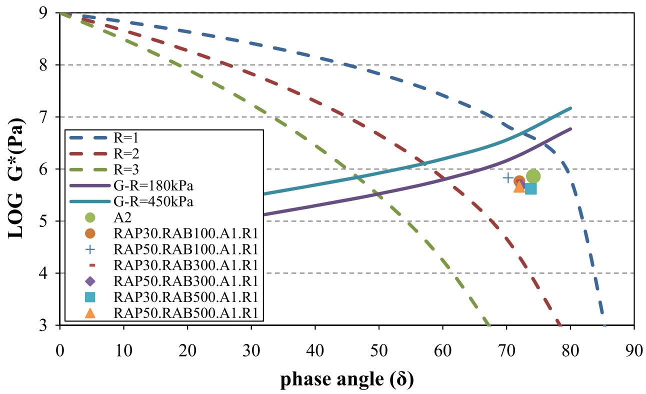

Fig. 7. Black space diagram of virgin binder A2 compared with the blends of virgin binder A1 with various aged binders involving rejuvenator R1.

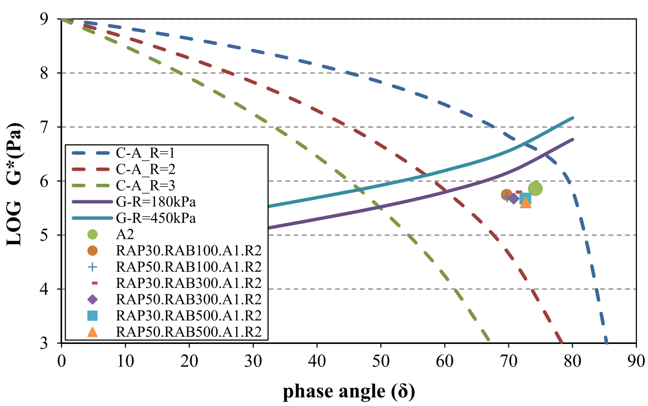

Fig. 8. Black space diagram of virgin binder A2 compared with the blends of virgin binder A1 with various aged binders involving rejuvenator R2.

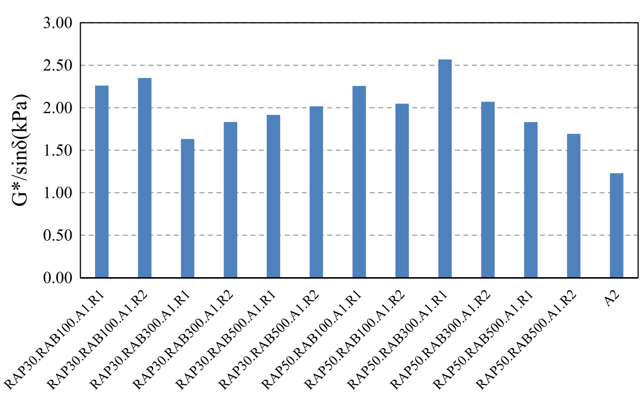

Fig. 9. $G^{*}/\sin(\delta)$ values of the rejuvenated RAB blends and virgin binders.

3.3.3. MSCR test

Another approach to evaluate the rutting performance of asphalt binders is to evaluate the plastic component of the binders. The accumulated strain in asphalt binders is considered to be mainly responsible for the permanent deformation of asphalt pavements. To predict potential pavement rutting according to the rheological properties of binders, this study applied the MSCR test to evaluate the nonrecoverable creep compliance of the binders. This test was performed at 60 °C to simulate the typical pavement temperature on a hot summer day in Taiwan. Fig. 10 illustrates the nonrecoverable creep compliance (J_{nr}) values of virgin binder A2 and the rejuvenated RAB blends, indicating that all rejuvenated aged binders exhibit lower J_{nr} values than that of virgin binder A2. This result is consistent with the authors' expectation that adding aged binders can enhance higher resistance to permanent deformation. No obvious trend in the distribution of the J_{nr} values was observed between the rejuvenators or between the RAP blending scenarios.

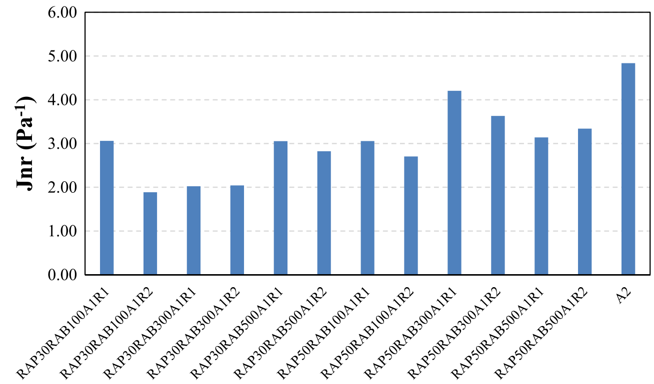

Fig. 10. Nonrecoverable creep compliance (J_{nr}) values of the rejuvenated RAB blends and virgin binders.

4. Conclusions

Incorporating high RAP content into asphalt mixtures has received considerable attention in recent years because of its increasing environmental restriction and economic incentive. However, subjecting pavements to multiple recycling activities may result in severely aged RAP (viscosity of reclaimed binder at 60 °C may exceed 100 kP). The blending chart conventionally used to design asphalt mixtures was determined to overpredict the usage of rejuvenating agents when severely aged RAP was used. The present study thus proposes a modified approach for determining the appropriate blending content of severely aged RABs, virgin binders, and rejuvenators. Furthermore, two RAP blending scenarios, three aging levels, and two types of rejuvenator were investigated for determining their corresponding molecular weight distributions. The investigation was conducted using GPC and the rheological characteristics of the rejuvenated RABs, with the virgin binders serving as controls. The following conclusions are drawn:

- When severely aged RAP was used, the AI blending chart may overpredict the appropriate rejuvenator amount required for restoring the viscosity of aged binders. This study thus proposes a methodology that can yield the appropriate blending proportion to facilitate accurately restoring the aged binder to the target viscosity.
- HP-GPC is a useful tool for identifying aged and virgin binders. Although the rejuvenating agents could restore the viscosity of the severely aged binder, the PDI results of the virgin and rejuvenated binders clearly reveal that the virgin binder and rejuvenated RABs demonstrated different chemical compositions.
- The rheological properties of the rejuvenated RABs were investigated using a DSR. In general, both the complex modulus and phase angle of the rejuvenated RABs were similar to those of the virgin binder. The complex modulus values of the rejuvenated RABs were slightly lower than that of virgin binder A2. No significant pattern regarding the phase angle was observed between the rejuvenated RABs and virgin binder.
- Two age-induced damage parameters were used to evaluate the cracking potential of the rejuvenated RABs. The Glover–Rowe damage zone demonstrates a clearly distinct severity of aging level as well as virgin and rejuvenating agent.

- All rejuvenated RABs exhibited higher $G^{*}/\sin(\delta)$ values compared with virgin binder A2, implying that blends with RAB have higher resistance to rutting. The two rejuvenators showed opposite effects in the RAP30 and RAP50 blending scenario.
- All the rejuvenated RABs demonstrated lower J_{nr} values compared with virgin binder A2, signifying that blends with RAB have less susceptibility to rutting. No particular trend was found between the rejuvenators.

Notation table

Abbreviation	Note
A1	Viscosity grade binder AC10
A2	Viscosity grade binder AC20
RAB100	Reclaimed asphalt binder of viscosity at 60 °C between 100 k and 200 k poise
RAB300	Reclaimed asphalt binder of viscosity at 60 °C between 300 k and 400 k poise
RAB500	Reclaimed asphalt binder of viscosity at 60 °C between 500 k and 600 k poise
R1 (75)	Rejuvenator agent with viscosity at 60 °C between 45and 125 poise
R2 (25)	Rejuvenator agent with viscosity at 60 °C between 9 and 45 poise
RAP30	30% usage of reclaimed asphalt pavement
RAP50	50% usage of reclaimed asphalt pavement

References

[1] J.M. Wang, A study of improving durability of recycled asphalt concrete applied in subtropical areas (Doctoral dissertation), National Central University, Taoyuan, Taiwan, 2009.

[2] L.C. Lee, Performance based properties of rejuvenated severe aged asphalt binder (Master thesis), National Cheng Kung University, Tainan, Taiwan, 2014.

[3] F. Xiao, S.N. Amirkhanian, J. Shen, B. Putman, Influences of crumb rubber size and type on reclaimed asphalt pavement (RAP) mixtures, Constr. Build. Mater. 23 (2) (2009) 1028–1034.

[4] R. McDaniel, H. Soleymani, R. Anderson, P. Turner, R. Peterson, Recommended use of reclaimed asphalt pavement in the Superpave mix design method, NCHRP Web Document 30 (Project D9–12): Contractor's Final Report; 2000.

[5] A. Copeland, Reclaimed asphalt pavement in asphalt mixtures: state of the practice (No. FHWA-HRT-11-021), 2011.

[6] X. Li, M.O. Marasteanu, R.C. Williams, T.R. Clyne, Effect of RAP (proportion and type) and binder grade on the properties of asphalt mixtures, Transp. Res. Rec. J. Transp. Res. Board 2051 (2008) 90–97.

[7] R.C. West, G.R. Rada, J.R. Willis, M.O. Marasteanu, Improved mix design, evaluation, and materials management practices for hot mix asphalt with high reclaimed asphalt pavement content, Transp. Res. Board (2013).

[8] Feipeng Xiao, Serji N. Amirkhanian, Laboratory investigation of utilizing high percentage of RAP in rubberized asphalt mixture, Mater. Struct. 43 (1–2) (2010) 223–233.

[9] G. Valdés, F. Pérez-Jiménez, R. Miró, A. Martínez, R. Botella, Experimental study of recycled asphalt mixtures with high percentages of reclaimed asphalt pavement (RAP), Constr. Build. Mater. 25 (3) (2011) 1289–1297.

[10] I.L. Al-Qadi, Q. Aurangzeb, S.H. Carpenter, W.J. Pine, J. Trepanier, Impact of high RAP contents on structural and performance properties of asphalt mixtures, FHWA-ICT-12-002, 2012.

[11] M.A. Elseifi, L.N. Mohammad, S.B. Cooper III, Laboratory evaluation of asphalt mixtures containing sustainable technologies, J. Assoc. Asphalt Paving Technol. 80 (2011) 227–254.

[12] M. Zaumanis, R.B. Mallick, R. Frank, Evaluation of rejuvenator's effectiveness with conventional mix testing for 100% RAP mixtures, Transportation Research Board CD-ROM, 2013.

[13] B. Colbert, Z. You, The properties of asphalt binder blended with variable quantities of recycled asphalt using short term and long term aging simulations, Constr. Build. Mater. 26 (1) (2012) 552–557.

[14] S. Im, F. Zhou, R. Lee, T. Scullion, Impacts of rejuvenators on performance and engineering properties of asphalt mixtures containing recycled materials, Constr. Build. Mater. 53 (2014) 596–603.

[15] J. Shen, S. Amirkhanian, J. Aune Miller, Effects of rejuvenating agents on Superpave mixtures containing reclaimed asphalt pavement, J. Mater. Civil Eng. 19 (5) (2007) 376–384.

[16] N.H. Tran, A. Taylor, R. Willis, Effect of rejuvenator on performance properties of HMA mixtures with high RAP and RAS contents. Auburn, AL: National Center for Asphalt Technology, Report Number 12-05, 2012.

[17] Asphalt Institute, Mix Design Methods for Asphalt, sixth ed., MS-02, Lexington, KY.

[18] S. Arrhenius, The viscosity of aqueous mixture, Phys. Chem. 1 (1887) 285–298.

[19] E.V. Churchill, S.N. Amirkhanian, J.L. Burati Jr., HP-GPC characterization of asphalt aging and selected properties, J. Mater. Civil Eng. 7 (1) (1995) 41–49.

[20] A.S. Noureldin, L.E. Wood, Variations in molecular size distribution of virgin and recycled asphalt binders associated with aging, Transp. Res. Rec. 1228 (1989).

[21] D.W. Christensen, D.A. Anderson, Interpretation of dynamic mechanical test data for paving grade asphalt cements (with discussion), J. Assoc. Asphalt Paving Technol. 61 (1992).

[22] G. King, M. Anderson, D. Hanson, P. Blankenship, Using black space diagrams to predict age-induced cracking, in: Paper presented at the 7th RILEM International Conference on Cracking in Pavements, 2012.

[23] C.J. Glover, R.R. Davison, C.H. Domke, Y. Ruan, P. Juristyarini, D.B. Knorr, S.H. Jung, Development of a New Method for Assessing Asphalt Binder Durability with Field Validation, Texas Transportation Institute, Texas A & M University System, 2005.

[24] G. King, G. Rowe, G. Reinke, Newark airport runway, Transp. Res. Rec. J. Transp. Res. Board 2372 (1) (2013) 9–16.