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Engineering characterization of recycled asphalt concrete and aged bitumen mixed recycling agent

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Abstract A recycling agent is commonly used to restore the aged bitumen to a condition that resembles that of the virgin bitumen. Three reclaimed asphalt pavement (RAP) stockpiles were sampled, and the aged binders recovered from RAP binders were mixed with recycling agents at ten levels to produce bitumen blends. The blends using virgin bitumen as the softening agent exhibited a significantly different rheological behavior from ones using the rejuvenating agent. The addition of a recycling agent could shift up or down the master curve of the blend vertically, depending on the engineering properties of the recycling agent. A normalized viscosity ratio (NVR) model was used to characterize the rheological properties of aged bitumen mixed with softening and rejuvenating agents. An interaction parameter was introduced into the model to consider the physico-chemical reaction between aged bitumen and recycling agent. This mixing rule was compared to the method specified in the blending chart by the Asphalt Institute (AI). The blending chart was shown to be applicable to determine the amount of the softening agent required to meet the target viscosity. The NVR model appeared to be a better tool for the rejuvenating agent to predict the viscosity of a recovered bitumen blend than the AI chart.

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Introduction

Decreasing supplies of locally available quality aggregate in many regions around the world, growing concern over waste disposal, and the rising cost of bitumen binder have resulted in greater use of reclaimed asphalt pavement (RAP) for road construction. Experience has indicated that the recycling of asphalt pavements is a beneficial approach from technical, economical, and environmental perspectives [1–3]. After several years of service, the binder in the reclaimed asphalt pavement becomes aged and much stiffer than desired. The degree of aging depends on many factors, such as temperature, air void content of the mixture, and chemical composition of the binder. The aged bitumen present in a RAP has physical properties that make it undesirable for reuse without modification. If the recycled pavements show excessive deterioration, the cost and resource saving realized during pavement service may be lost through excessive maintenance. Materials have been developed to restore the old binder to a condition suitable for reuse. This concept is not new and has been the subject of a number of extensive studies [1–6].

In hot-mix-plant or in-place asphalt recycling operations, new binder and aggregate are mixed together with reclaimed asphalt material in order to reduce the negative influence of aging to a minimum. The new binder should be a recycling agent so that the final mix of old and new binders will have an acceptable consistency and a sound chemical constitution. The recycling agent selected for blending with the aged binder can be categorized into two main types as follows: softening agent and rejuvenating agent. The softening agent such as AC-5 and AC-10 lowers the viscosity of the aged bitumen. The rejuvenator is commercially available and is aimed to restore the physical and chemical properties of the aged binder [4–6].

It concerns some highway engineers that RAP may act as a black rock, i.e., the aged binder in RAP may not have any interaction with virgin bitumen. Complete blending will not exist if RAP is a black rock. Often, the question of whether or not RAP should be considered as a black rock is raised. If RAP behaves like a black rock, the assumption using a blending chart in the design of recycled asphalt concrete may not be valid. It is imperative to study the interaction between new and old binders in mixtures containing RAP.

Common practices call for extracting the aged bitumen and mixing it with virgin materials in order to determine the amount of the recycling agent required. Several binder selection procedures were developed in the 1970's and 1980's for recycled asphalt pavements. These procedures which primarily consist of selection of virgin bitumen or a rejuvenator have remained largely unchanged over the years. Traditional determination of the RAP quantity allowed for addition to an asphalt mix is based on the viscosity measurement of a blended binder. The approach for estimating the content of RAP to be used has been documented by the Asphalt Institute and in ASTM D 4887 [7, 8].

However, the extent to which aged bitumen will be changed by a recycling agent during the hot-mix procedure, and hence the characteristics of the recovered bitumen blend and the resulting performance, has not been widely reported. For example, in some cases the viscosity of the recovered bitumen blend has been considerably lower than the target viscosity [9]. Large errors may require actual blending to determine the viscosity of a mix. Epps et al. (1980) indicated that some degree of trial and error blending may be necessary to achieve an estimated viscosity for a recycled binder [10].

Although many previous recycling studies have been conducted, few tools have been developed to explain the viscoelastic properties of recovered bitumen mixed with softening and rejuvenating agents. Instead, most of recycling projects have been conducted using whichever recycling agents are available. This may or may not result in pavements with better performance than the original bitumen. The goal of this study is to propose a mixing rule that could better characterize the rheological behavior of the recovered bitumen blend.

Theoretical background

A recovered bitumen blend composed of aged bitumen mixed a recycling agent can be considered as a composite liquid mixture. From the viewpoint of composites, the recycling agent is the liquid phase and aged bitumen is the matrix phase. Arrhenius (1887) was the first person to develop an equation to predict the viscosity of such a mix [11]. The Arrhenius equation is a function of individual phase times its fraction, and is expressed as follows:

$$\ln \eta_{\text{mix}} = f_{\text{old}} \cdot \ln\eta_{\text{old}} + f_{\text{new}} \cdot \ln\eta_{\text{new}} \quad (1)$$

where η is the viscosity; the subscripts mix, old and new refer to the resulting blend, aged bitumen and the recycling agent, respectively. In Eq. (1), the letter f may represent a mass function, a mole function, or a volumetric function.

The Asphalt Institute (AI) develops a blending chart that is commonly used to determine the quantity of a recycling agent to be added to the old binder to restore the properties of aged bitumen according to the Arrhenius equation [7]. A similar approach is also adopted in ASTM D 4887 to estimate the amount of a new agent for the aged bitumen [8]. The percentage of a new agent required to obtain a certain target viscosity could be determined on a weight basis by the use of a viscosity blend chart as illustrated in Fig. 1. The 60 °C viscosity of the aged bitumen is plotted on the left-hand vertical scale as point A. The 60 °C viscosity of the new agent is plotted on the right-hand vertical scale as point B. A straight line is drawn to connect points A and B. Then a horizontal dash line through the target viscosity intersects the component viscosity line (AB) at point C. The projection of point C yields the estimate of percent virgin bitumen or rejuvenating agent required to meet the target viscosity in the blend. As shown in Fig. 1, the Arrhenius equation takes into account the physical filling of a new agent into the old matrix.

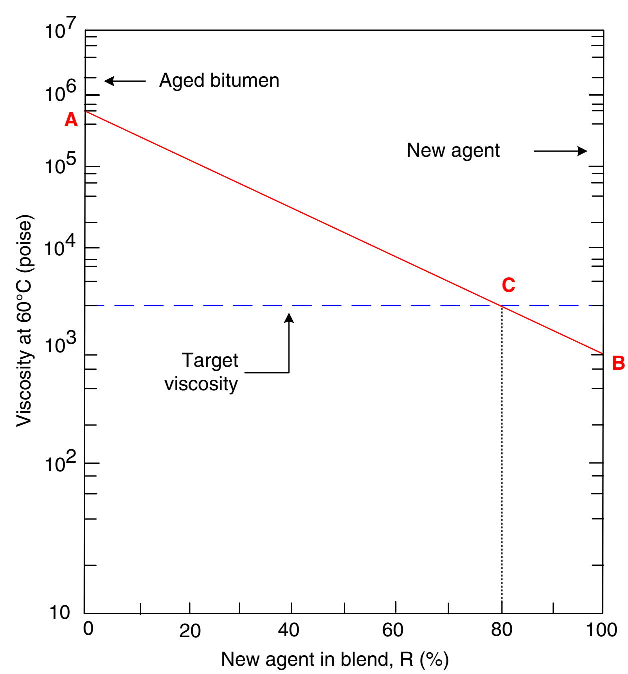

Fig. 1 Blending chart by Asphalt Institute

Bitumen is a complex binder consisting of different chemical compound. A physico-chemical interaction would occur when a recycling agent is mixed with an oxidized binder. The Arrhenius equation needs to be modified to characterize the interaction. The mixing equation is rearranged as follows [12]:

$$\ln \eta_{mix} = f_{old} \cdot \ln\eta_{old} + f_{new} \cdot \ln\eta_{new} + f_{old} \cdot f_{new} \cdot I_{inter} \quad (2)$$

where I_{inter} is the interaction parameter.

This general pattern as shown in Eq. (2) is exhibited by many naturally occurring phenomena that change with adding a new material. Examples are salty water, air circulation and petrochemical products. Evidences indicate that the engineering properties of bitumen are proportional to the degree of molecular association in terms of functional groups. The above equation can be rewritten to obtain a dimensionless viscosity by subtracting the viscosity of the aged bitumen:

$$\ln \eta_{mix} - \ln\eta_{old} = f_{old} \cdot \ln\eta_{old} - \ln\eta_{old} + f_{new} \cdot \ln\eta_{new} + f_{old} \cdot f_{new} \cdot I_{inter} \quad (3)$$

This equation is expressed in the following form:

$$\ln \frac{\eta_{mix}}{\eta_{old}} = \ln\eta_{old}\,(f_{old} - 1) + f_{new} \cdot \ln\eta_{new} + f_{old} \cdot f_{new} \cdot I_{inter} \quad (4)$$

The total mass fraction is equal to 100%, i.e., $f_{old} + f_{new} = 1$. We can substitute ($-f_{new}$) for ($f_{old}-1$), and rearrange this equation as follows:

$$\begin{aligned}\ln \frac{\eta_{mix}}{\eta_{old}} &= -f_{new} \cdot \ln\eta_{old} + f_{new} \cdot \ln\eta_{new} + f_{old} \cdot f_{new} \cdot I_{inter} \\ &= f_{new} \cdot (\ln\eta_{new} - \ln\eta_{old}) + f_{old} \cdot f_{new} \cdot I_{inter} \\ &= f_{new} \cdot \ln \frac{\eta_{new}}{\eta_{old}} + f_{old} \cdot f_{new} \cdot I_{inter}\end{aligned} \quad (5)$$

Dividing both sides of Equation (2) by $\ln \frac{\eta_{new}}{\eta_{old}}$, we obtain

$$\begin{aligned}\frac{\ln(\eta_{mix}/\eta_{old})}{\ln(\eta_{new}/\eta_{old})} &= f_{new} + f_{old} \cdot f_{new} \cdot \frac{I_{inter}}{\ln(\eta_{new}/\eta_{old})} \\ &= f_{new} \cdot \left[1 + f_{old} \cdot \frac{I_{inter}}{\ln(\eta_{new}/\eta_{old})}\right] \\ &= f_{new} \cdot \left[1 + (1 - f_{new}) \cdot \frac{I_{inter}}{\ln(\eta_{new}/\eta_{old})}\right]\end{aligned} \quad (6)$$

The normalized viscosity ratio (NVR) for mixing is, then, derived as follows:

$$\mathrm{NVR} = \frac{\ln(\eta_{mix}/\eta_{old})}{\ln(\eta_{new}/\eta_{old})} = f_{new} \cdot \left[1 + \frac{I_{inter}}{\ln(\eta_{new}/\eta_{old})}\right] + f_{new}^2 \cdot \left[\frac{-I_{inter}}{\ln(\eta_{new}/\eta_{old})}\right] \quad (7)$$

Equation (7) is a second-order polynomial regression incorporating an independent variable (i.e., f_{new}) in making predictions of NVR. Since the viscosity of each phase is measured individually, the interaction parameter (i.e., I_{inter}) could be then estimated.

Materials and methods

Recycled asphalt concrete

Three RAP projects ranging in age from 4, 6 to 10 years were chosen for comparison, and they are called RAP-1, RAP-2, and RAP-3, respectively. These recycled projects were selected in order to have their construction in the same time frame, by the same contractor if possible, similar mix design, and traffic. To determine if blending occurs between the aged binder and the recycling agent, the researchers evaluated the properties of mixtures with three different scenarios representing standard practice, total blending and black rock.

The recycled asphalt concrete was prepared by mixing reclaimed asphalt pavements, new aggregate and virgin bitumen (AC-10). The reason why an AC-10 was used is that the rejuvenating agent would be mixed just as well as, if not better, with aged bitumen if an AC-10 is found to be blended well with RAP. The mixes consisted of three RAP sources and one RAP ratio, i.e., 40%. Under the current Public Construction Commission quality assurance/quality assurance specifications in Taiwan, a maximum of 40% RAP is allowed in the surface mix. The mixes were designed based on the RAP mixture design process by the Asphalt Institute [7]. Limestone was the aggregate used for all mixes. An overall mixture gradation is listed in Table 1. This mixture is a dense gradation having a nominal maximum aggregate size of 12 mm. The relative proportions of coarse and fine aggregates were held constant for different mixtures to maintain the same aggregate gradation. The total binder content was also kept constant for each mixture.

Three mixtures cases were designed to simulate three possible interactions as follows: standard practice (SP), total blending (TB), and black rock (BR). The standard practice represented a real paving process in which a new AC-10 binder and aggregate were mixed with RAP. This case described what occurs in real world between new and old binders in recycled asphalt concrete. The total blending

Table 1 Aggregate gradation

Sieve size (mm)	37.5	25	12.5	9.5	4.75	2.5	0.63	0.3	0.075
Percent passing	100	100	94	71	57	45	24	18	5.5

Note: Binder content: 5.1%, VMA: 16.5%

started with a new AC-10 binder physically mixed with recovered bitumen. The blended binder was then mixed with virgin aggregate and extracted RAP aggregate. The black rock was to mix a new AC-10 binder with virgin aggregate and extracted RAP aggregate without aged binder. This process was to simulate the ''black rock'' case where no interaction between new and old binders occurs. Each case had three replicates for measuring the engineering properties of asphalt mixtures containing 40% RAP.

The rationale behind this experimental design is explained as follows: If RAP is a black rock, SP and BR should have similar results. If RAP is mixed well with the new binder, SP and TB should produce similar results. If RAP is mixed partially well with the new binder, the results of SP should be between the results of TB and BR.

Recovered bitumen binder (RBB)

Cores were taken at each reclaimed asphalt pavement for recovering binder using trichloroethylene to separate bitumen from the mineral aggregate according to ASTM D 2172 and D 5404. The asphalt-solvent mixture was subjected to centrifuge extraction before final distillation of the solvent to ensure complete removal of aged bitumen from aggregate. The recovered bitumen was then characterized by the viscosity, the penetration value and the softening point. The results are presented in Table 2. The recovered bitumen binder taken from RAP-1, RAP-2 and RAP-3 was labeled as RBB-1, RBB-2 and RBB-3 with the viscosity of 21,500, 33,100 and 45,600 poise, respectively. Note that these values show a limited range of viscosity for aged binders, and they are representative of RAP found in Taiwan.

Recycling agent

After the recovered bitumen binders were produced, they were consequently mixed with recycling agents by melt blending. The concentration of recovered binder ranged from 10% to 100% at an interval of 10% by weight of the blend. Blends without any recycling agents were used as the control blends. After aged bitumen was weighed into tins, the softening or rejuvenating agent was added and mixed at 155 °C for 5 min to produce a homogenous blend. The mixer applied a constant mixing speed of 150 rpm to ensure no voids created in the blend.

Table 2 Physical properties of recovered bitumen binder

	60 °C viscosity (poise)	25 °C penetration (dmm)	Softening point (°C)
RBB-1	21,500	48	63
RBB-2	33,100	32	66
RBB-3	45,600	21	68

Five different types of low-viscosity recycling agents were selected for blending with aged bitumen. The recycling agents are further classified into two major types: softening agent and rejuvenating agent (RA). Table 3 lists the basic properties of the recycling agents provided by the Chinese Petroleum Corporation (CPC). The softening agents used in this study were fuel oil, AC-5 and AC-10 viscosity-graded bitumen. The reason of selecting fuel oil in this study is that contractors sometimes use fuel oil to reduce the viscosity of recycled asphalt mixtures to meet the target viscosity. Two rejuvenating agents were used to restore the old binder to the AC-20 classification range. The rejuvenating agents are a petrol lubricant type used to modify the old binder and compensate the aging process. These two types used were RA-75 and RA-250 graded according to ASTM D 4552.

Engineering properties

The indirect tension test was conducted to exam how well RAP was mixed in the recycled asphalt concrete. The resilient modulus and the indirect tensile strength were measured for asphalt mixtures containing 40% RAP. Each test had three replicates. The repeated-load indirect tension test for determining the resilient modulus was conducted by applying compressive loads with a haversine waveform according to ASTM D4123. The load was applied vertically in the vertical diameter plane of a cylindrical specimen of asphalt concrete through a curved loading strip. The resulting horizontal deformation was measured and used to calculate the resilient modulus (Mr) by the following equation:

$$M_r = \frac{P \cdot (v + 0.27)}{t \cdot H} \quad (8)$$

where, P = repeated load, v = Poisson's ratio, t = thickness of specimen, H = total recoverable horizontal deformation.

Table 3 Properties and composition of recycling agents

	Specific gravity	60°C viscosity (poise)	Flash point (°C)	Asphaltene (wt%)	Saturate (wt%)	Aromatic (wt%)	Resin (wt%)
AC-10	0.99	1,010	256	12.6	23.5	38.6	25.3
AC-5	0.99	560	236	10.5	31.5	40.2	17.8
Fuel oil	0.92	4	138	1.8	68.8	13.8	15.6
RA-75	0.96	63	225	2.3	7.1	82.7	7.9
RA-250	0.99	319	230	3.2	12.4	72.2	12.2

A Poisson's ratio was calculated using the measured recoverable vertical and horizontal deformation. The tensile strength (S_T) was calculated as follows:

$$S_T = \frac{2 \cdot P_{ult}}{\pi \cdot t \cdot D} \tag{9}$$

where, P_{ult} = ultimate applied load required to fail specimen, t = thickness of specimen, D = diameter of specimen.

Viscosity

The Brookfield Model DV-II Viscometer and the thermosel temperature control system were used to measure the viscosity of the bitumen cement at application temperatures. This rotational viscometer is a spindle-type viscometer that is operated according to ASTM D 4402. The viscosity in poise was calculated by multiplying the viscometer calibration factor, and can be directly read from the Brookfield Viscometer. Each aged bitumen-recycling agent pair had three replicates. The viscosity at 60 °C is generally used for grading bitumen blends by their consistency. The coefficient of variation (CV) is the ratio of standard deviation to mean value, and used as an evaluation of the repeatability of measurements. A CV value less than 5% for all the samples shows that the results are repeatable, and the blends used in this study were homogenous.

Dynamic shear rheometer

The rheological properties of aged bitumen/recycling agent blends were measured by a dynamic shear rheometer (DSR) over a broad range of temperatures. The DSR is an AR-500 model manufactured by the Carri-Med Corporation. For tests at 40 °C and higher, a 1-mm gap and a 25-mm diameter plate were used. For tests below 40 °C, a 2-mm gap and an 8-mm diameter plate were used. Approximately 1 g of binder was applied to the bottom plate, covering the entire surface, and the plate was mounted in the rheometer. After heating to the test temperature of the binder, the top plate was brought into contact with the sample and the sample was trimmed. An actuator then applied a sinusoidal strain. Viscoelastic properties at different temperatures and frequencies were obtained. A specific strain level was determined at each testing temperature for each sample running a strain sweep at 100 rad/s prior to any frequency sweep. The strain was kept low enough so that all tests were performed within the linear viscoelastic range. The actual strain and torque were measured and input to a computer for calculating various viscoelastic parameters, including complex modulus (G*) and phase angle (δ). The G* is a measure of the total resistance of a material to deformation when repeatedly sheared. The δ is an indicator of the relative amount of recoverable and non-recoverable deformation. Three samples were measured for each aged bitumen-recycling agent system. It is observed that all CV's are less than 10%. The low CV value indicates that the data can be measured within good precision.

Results and discussion

Blending condition

Figures 2 and 3 show the test results of indirect tensile strength and resilient modulus for mixtures containing 40% RAP. Each value in the figure represents the average of three samples. The coefficient of variation of indirect tensile strength and resilient modulus is 12% and 15%, respectively, which are comparable with values reported by

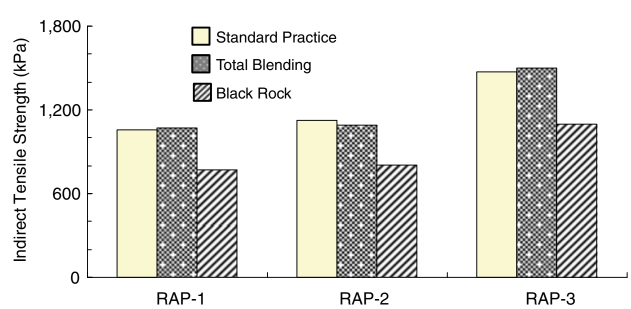

Fig. 2 Indirect tensile strength of asphalt mixtures containing 40% RAP

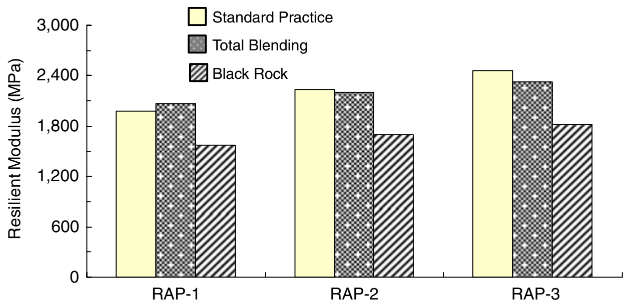

Fig. 3 Resilient modulus of asphalt mixtures containing 40% RAP

other researchers [13]. As more aged RAP is included in the asphalt mixture, the ability of the mix resistance to deformation is increased. The RAP-3 mixtures with the most aged bitumen exhibit the highest indirect tensile strength and resilient modulus, as logic would indicate.

The indirect tensile strength of black rock possesses lower values, and is significantly from that of standard practice and total blending. The concept of black rock refers to RAP's which are coated with aged binder and experience incomplete blending with the recycling agent during production. Figures 2 and 3 demonstrate that the standard practice, i.e., the real world scenario, mixtures are closer to total blending than to black rock. With 40% RAP, there exists no significant difference between standard practice and total blending. The standard practice specimens are more similar to total blending than to the black rock. Test results indicate that a significant amount of bleeding occurs between the aged bitumen and the virgin binder. This observation is in agreement with results reported by other researchers [14, 15]. Note that the findings are limited to the testing of three RAP materials and the recycling agents in this study. Asphalt mixtures containing very high RAP contents or very stiff RAP may behave differently from the findings presented here.

Viscosity

Aged bitumen was recovered from a RAP and blended with softening or rejuvenating agents to produce recycled bitumen binder. The first experiment was performed using RBB-1 as the aged bitumen mixed with softening and rejuvenating agents. The content of aged bitumen varied from 0% to 100% in 10% increments. As shown in Fig. 4, the viscosity of the RBB-1 blend increases with increasing the weight fraction of aged bitumen, but decreases with decreasing the viscosity of the recycling agent. In general, two softening agents (i.e., AC-5 and AC-10) and two rejuvenators (i.e., RA-75 and RA-250) are successful in restoring the aged bitumen to the AC-20 specification range except fuel oil.

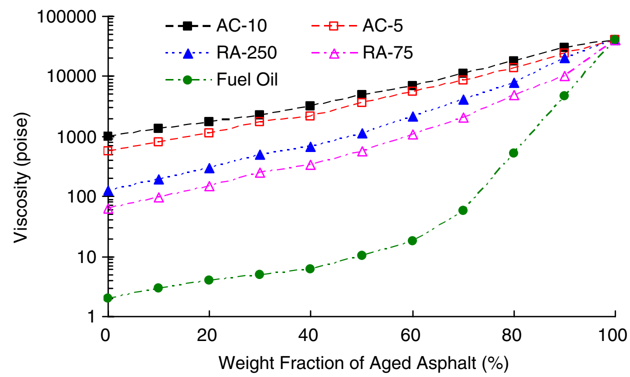

Fig. 4 60 °C Viscosity of RBB-1 blends

The addition of fuel oil has relatively little influence on the viscosity of the RBB-1 blend. The slow increase in viscosity indicates that the mutually solubility of fuel oil and aged bitumen is poor. As listed in Table 3, fuel oil contains 68.8 wt% saturates that exceed the maximum limit of 30 wt% specified in ASTM D 4552 for a recycling agent. Saturates are non-polar viscous oils that are relatively incompatibility with aged bitumen. Two distinct phases were observed to be present in the fuel-oil blend, and there existed phase separation leading to the low viscosity value. The other two RBB blends mixed with fuel oil also show similar results; therefore, it is inadequate to use fuel oil as a softening agent.

Rheological properties

The experimental data of RBB-1 results in a fairly smooth viscoelastic function as shown in Fig. 5. The other two recycled bitumen binders and their blends also show a similar trend. The aged binders and their blends are demonstrated to be a thermorheologically simple material because the time-temperature superposition is valid for these binders. At very short loading times, the complex modulus approaches a limiting value called the glassy modulus, which has a value close to 4 GPa as shown in Fig. 5. This glassy modulus results from the stiffness of

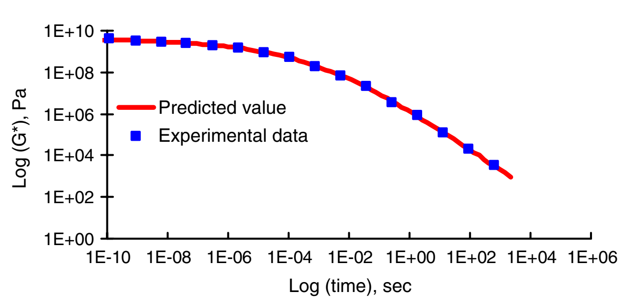

Fig. 5 Master curve for RBB-1

carbon–carbon backbone of which bitumen is largely formed. At very long loading time, the slope of the log-log plot of complex modulus versus time approaches negative one, indicating that a viscous flow exists and RBB behaves as a Newtonian fluid. For this reason, an asymptote drawn through this portion of the master curve is called the viscous asymptote. The intermediate region is located around the intersection of the glassy and viscous asymptotes, and the deformation occurring during this region is related to the delayed elastic behavior. According to the time-temperature principle, the long loading time can be an indicator of bitumen being treated in high temperatures.

A set of master curves for RBB-3 mixed with softening and rejuvenating agents is shown in Fig. 6. With marks for every experiment point would clog the figure and confuse readers. For the reason of clarity, the individual data were omitted and the master curves were constructed from the time-temperature superposition principle. A standard reference temperature was selected at 25 °C in this study. A smooth curve can be formed for the RBB-3 blends, as demonstrated in Fig. 6. The time-temperature superposition principle is shown to be a useful means of analyzing rheological data for the recovered bitumen blend.

The blends mixed with softening agents, i.e., AC-10 and AC-5, show higher complex moduli than ones mixed with rejuvenating agents, i.e., RA-75 and RA-250. Since the general shape for all curves is similar, it is believed that the viscoelastic characteristic of the blend inherits from the aged bitumen. Furthermore, both softening and rejuvenating agents could shift up or down the master curve of the blend vertically, respectively, depending on the engineering properties of recycling agents. The complex moduli for RBB-3 are higher with AC-10 than with RA-75. This is due to the fact that the basic engineering property of AC-10 is higher than one of RA-75. The same trend is also observed in RBB-1 and RBB-2 blends.

Another approach to rheological characterization of recovered bitumen blends involves analysis of the complex modulus and the phase angle developed by the Strategic Highway Research Program (SHRP). The specifications established by SHRP suggest that the average maximum weekly temperature reached by a pavement, the value of $G^*/\sin\delta$ should remain above 1 kPa at a frequency of 10 rad/s for a bitumen to resist pavement rutting. Figure 7 shows the $G^*/\sin\delta$ versus target viscosity for the RBB-2 blend. Since the pavement temperature in summer is close to 60 °C in Taiwan, the test was conducted at the mean highest weekly average temperature 60 °C. A recovered bitumen blend set at a target viscosity would meet $G^*/\sin\delta$ = 1 kPa requirement. The data obtained for RBB-1 and RBB-3 blends also demonstrate similar observations. This is logical because the addition of RAP increases the $G^*/\sin\delta$ value of bitumen, thus enhancing the resistance to permanent deformation. The blend using the low-viscosity softening agent shows higher $G^*/\sin\delta$ values than one using the rejuvenating agent. Note that the $G^*/\sin\delta$ value is a function of complex modulus and phase angle, but this parameter is not linearly correlated with viscosity.

Normalized viscosity ratio

Figure 8 shows the normalized viscosity ratio (NVR) plotted as a function of mass fraction for the RBB-1 blend. The dotted lines present the predicted values, indicating that blends mixed with both softening and rejuvenating agents can be modeled using the NVR equation. The predicted values are comparable with those measured from the viscometer. Low-viscosity bitumen softening agents (i.e., AC-5 and AC-10) behave differently from rejuvenating agents (i.e., RA-75 and RA-250). The data for low-viscosity softening agents do not converge to a single grouping of data as would be expected by the AI nomograph. The AC-10 blend is better predicted by the AI nomograph, but the AC-5 blend exhibits positive deviation. This suggests that the RBB-1 blend mixed with a softening agent having viscosity relatively closer to that of aged bitumen could be better described by the Arrhenius equation.

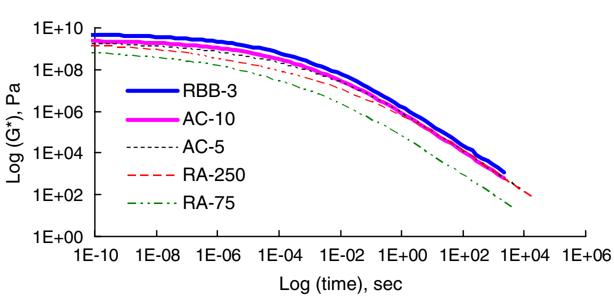

Fig. 6 Master curves for RBB-3 blends mixed with 40% aged bitumen

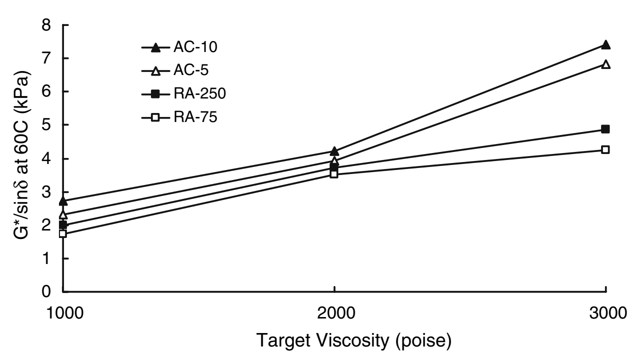

Fig. 7 Rheological parameter, $G^*/\sin\delta$, changing with target viscosity for RBB-2 blends

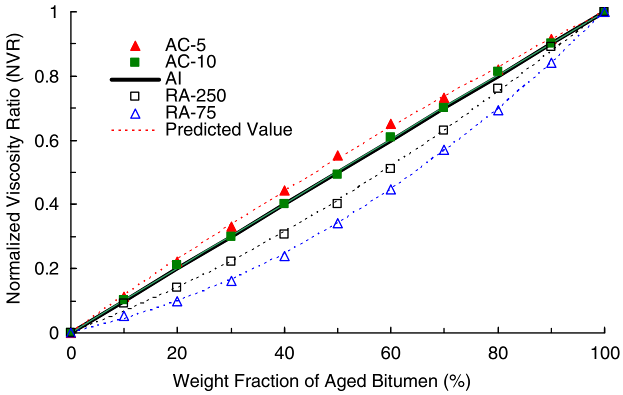

Fig. 8 Normalized viscosity ratio for RBB-1 blends

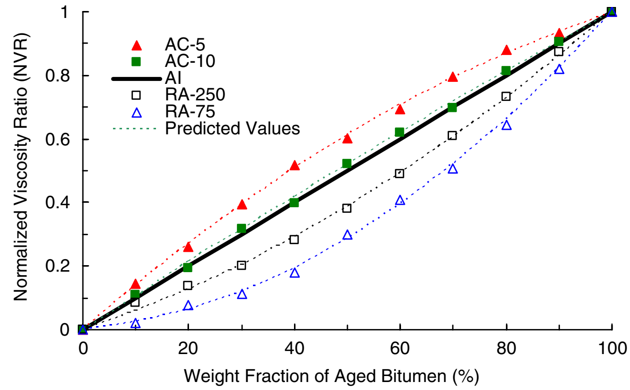

Fig. 9 Normalized viscosity ratio for RBB-3 blends

The positive deviation may result from the instability between aged bitumen and softening agent AC-5. During bitumen oxidative aging, the saturates remain the same while the solubilizing aromatics decrease in quantity. In Table 3 the saturate and aromatic contents of AC-5 are 31.5% and 40.2%, respectively. The aromatics react with oxygen to produce asphaltene, which causes the asphaltene content to increase. Because the saturates and asphaltenes are not soluble in one another, the increase in asphaltene, accompanied by the decrease in solubilizing aromatics, leads to instability. The positive interaction shows that the AC-5 blend is more viscous than would be predicted by the AI mixing rule.

RA-75 and RA-250 show negative deviation as illustrated in Fig. 8. Rejuvenating agents tend to reestablish the compatibility and performance of the old material. The physico-chemical interaction between aged bitumen and rejuvenator takes longer time to reach a stable condition in which the fluxing of the existing binder takes place gradually by migration. As listed in Table 3, the saturate content of the rejuvenating agent varies from 7% to 12%, and aromatic content from 72% to 83%. The rejuvenating agent is rich in aromatics and low in saturates, which could improve the compatibility and ductility of aged bitumen. The rejuvenating process continues to occur after mixing, leading to further softening of the aged bitumen. The negative interaction indicates that a blend of aged bitumen and rejuvenator is less viscous than would be predicted by the AI mixing rule. It is reported that full rejuvenation is usually achieved within about 3–6 months after the completion of the rejuvenating [16]. The negative deviation implies that a rejuvenating agent would gradually restore the rheological properties of a binder to their original condition by fluxing the oxidized binder.

The NVR results for RBB-3 mixed with softening and rejuvenating agents are shown in Fig. 9. Values predicted by the normalized viscosity ratio equation are in good agreement with ones obtained from experiments. There is significant deviation between the rejuvenating agent and the softening agents. AC-5 and AC-10 show positive deviation from the AI nomograph with the aged bitumen, while RA-75 and RA-250 exhibit negative deviation. Similar results are also observed for the RBB-2 blend. It is demonstrated in Fig. 9 that a relatively high-viscosity rejuvenating agent (RA-250) shows moderate deviation compared to the other rejuvenating agent (RA-75). The deviation from the AI method seems to be related to the viscosity difference between aged bitumen and recycling agent. Note that there is more scatter among the mixture data for RBB-3 blends than for RBB-1 blends, even though these blends have similar viscosities. This implies that the rheological behavior of a recovered bitumen blend could be altered by the choice of rejuvenating agent.

Comparison

Table 4 lists the viscosity difference between experimental and predicted values. All of the data collected for the recycling agents were arranged on the plot of NVR versus weight fraction of aged bitumen. The NVR values were obtained from fitting the data into the Eq. (7). The traditional blending chart developed by AI was used to estimate the viscosity of the blend for comparison. The selection of 2,000 poises as the target viscosity is due to the fact that most highway agencies choose this value for recycled asphalt concrete. Table 4 shows that the viscosity of the recovered bitumen blend predicted by using the NVR mixing rule differs significantly from those predicted by the AI blending chart.

It is obvious in Table 4 that the NVR mixing rule predicts the viscosity value much closer to the measured one than the AI blending chart. The AI nomograph procedure is best at predicting the low-viscosity bitumen softening agent data such as RBB-1 and RBB-2. The AI nomograph results in relatively low viscosities for both RA-250 and RA-75. The AI method appears to underestimate the

Table 4 Differences between experimental data and predicted viscosity values

Source	Recycling agent	Measured (1)	NVR (2)	AI (3)	$\frac{\|(1)-(2)\|}{(1)} * 100$	$\frac{\|(1)-(3)\|}{(1)} * 100$
RBB-1	AC-5	2,124	2,068	2,306	2.6	8.6
	AC-10	2,293	2,196	2,499	4.2	9.0
	RA-75	2,081	2,195	1,821	5.5	12.5
	RA-250	2,055	2,132	1,752	3.7	14.7
RBB-2	AC-5	2,091	1,987	2,334	5.0	11.6
	AC-10	2,116	1,998	2,352	5.6	11.2
	RA-75	2,174	2,365	1,667	8.8	23.3
	RA-250	2,142	2,337	1,598	9.1	25.4
RBB-3	AC-5	2,095	1,902	2,494	9.2	19.0
	AC-10	2,112	1,915	2,498	9.3	18.3
	RA-75	2,167	2,367	1,472	9.2	32.1
	RA-250	2,123	2,047	1,321	3.6	37.8

viscosity of blends mixed with recycling agents. The underestimation of viscosity by the AI method would lead to a high RAP content applied to pavement construction. The NVR model is shown to be adequate to estimate the proper amount of rejuvenating agents used in aged bitumen. This is because the NVR equation involves the interaction parameter that demonstrates through positive and negative deviation for recycling agents, whereas the AI method only considers the filling effect of a recycling agent on a recovered bitumen blend.

Conclusions

The reclaimed asphalt pavement (RAP) used in this study was obtained from three different aged pavement projects. Three possible interactions between the aged binder and the virgin binder were considered, i.e., standard practice, total blending and black rock. The recycling agents applied to RAP included three softening agents and two rejuvenating agents. The addition of the recovered binder was from to 10% to 100% at in interval of 10% by weight of the blend. According to the limited materials and tests conducted in this study, the following conclusions could be drawn:

- For asphalt mixtures containing 40% RAP, the standard practice (i.e., the real world scenario) mixtures are closer to the total blending. RAP does not appear to act like a black rock for asphalt mixtures containing 40% RAP. RAP should not be considered as a black rock because significant bleeding occurs between RAP and virgin binder.
- The time-temperature principle is shown to be adequate to characterize the rheological behavior of aged bitumen mixed recycling agents. The introduction of a softening agent or a rejuvenating agent generally causes a decrease in complex modulus for aged bitumen, but the degree of softening varies significantly. A noticeable low viscosity of the fuel oil blend mixed with aged bitumen is observed. This change in blend properties suggests that the addition of fuel oil seems to have the least effect on the viscosity of the RBB blend among these five additives.
- The relationship between viscosity and blend's mass fraction can be well described by the normalized viscosity ratio (NVR) model. The NVR model includes an interaction parameter that explains the physico-chemical action between blend components. Blends mixed with softening agents and rejuvenating agents behave differently from each other. The low-viscosity softening agents have positive interaction parameters, implying that a blend of aged material and low-viscosity bitumen may be more viscous that would be predicted by the traditional mixing method.
- The negative deviation from rejuvenating agents is shown in viscosities below those predicted by the current standard mixing rule. NVR data for all of the recycling agent blends show little variation between measured and predicted values. It is also imperative to indicate that the significant results obtained may be limited to the materials used and the test conditions applied in this test.

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