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Correlation between the Properties of Superpave Binder and Engineering Properties of Recycled Aged CRM Mixtures

재생 CRM 바인더와 혼합물의 성능 상관성 연구

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ABSTRACT

PURPOSES : The performance properties (indirect tensile strength, rutting resistance, and resilient modulus) of recycled aged CRM mixtures and their correlation with Superpave binder properties (viscosity, high failure temperature, G*sinδ, and stiffness) were investigated.

METHODS : A series of Superpave binder tests was performed by using a rotational viscometer, DSR, and BBR to evaluate the performance properties. In addition, the CRM mixes were artificially aged through accelerated aging processes, and their properties were evaluated. The correlation between the properties of recycled aged CRM binders and the engineering properties of recycled aged CRM mixtures was experimentally determined.

RESULTS : The rut depth values decreased and the ITS values increased with increasing high failure temperature. In general, the resilient modulus properties seemed to be poorly correlated with the high-temperature values, regardless of the aggregate source.

CONCLUSIONS : The recycled aged CRM binders and mixtures can lead to satisfactory performance, and the properties of these binders are strongly correlated with the engineering properties of the mixtures.

Keywords
crumb rubber, recycling, rubberized binder, engineering properties

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1. INTRODUCTION

1.1. Background

More than 300 million scrap tires are disposed of in the United States every year. Currently, approximately 67% of these are utilized for applications such as tire-derived fuel, molded products, and crumb rubber (Amirkhanian and Corley 2004; Lee et al. 2011). There is an increasing interest in using crumb rubber modified (CRM) binders in hot mix asphalt (HMA) pavements in the Unites States and other countries (Akisetty et al. 2011; Bahia and Davies 1994; Shen et al. 2005). This motivation was supported by previous studies reporting that CRM binders can produce asphalt pavements that exhibit increased pavement life, decreased traffic noise, reduced maintenance costs and resistance to rutting and cracking (Huang et al. 2002; Liang and Lee 1996; Ruth and Roque 1995).

Using CRM to modify asphalt binders in pavement engineering began more than four decades ago in the United States. The recycling of rubberized asphalt pavement is a very important issue because many of these pavements were built over 10-20 years ago and some of them may now be a candidate for recycling. Research on the recycling of rubberized asphalt concrete (RAC), which was conducted primarily by some state departments of transportation (DOTs) (Albritton et al. 1999; Bischoff et al. 2004; Crockford et al. 1995; Gunkel 1994) has focused on investigating the in-field paving properties regarding the feasibility of recycling rubber-modified paving materials. The majority of the limited number of studies on the use of reclaimed rubberized materials in recycled asphalt paving mixtures indicate that these reclaimed materials can be successfully incorporated into other bituminous paving mixes (Caltrans 2005). However, particularly for long-term performance characterizations, it is important to be able to identify the aging and recycling properties of rubberized binders to predict the long-term performance of these mixtures and to suggest guidelines for the recycling of RAC.

2. RESEARCH OBJECTIVE and SCOPE

The main objective of this research was to gain an improved understanding of the properties of recycled aged CRM binders and to evaluate the relation of the Superpave binder test results with the performance properties of the recycled aged CRM mixtures. The CRM binders were produced in the laboratory incorporating one CRM source (ambient passenger tire) and one CRM percentage (10% by weight of asphalt binder). The CRM binders were artificially aged using rolling thin film oven (RTFO) + pressure aging vessel (PAV) procedures, and the aged CRM binders were recycled using two base binders (performance grade (PG) 64-22 for 0% and 15% RAP binders, and PG 58-22 for 25% and 35% RAP binders). The recycled aged CRM binders were artificially aged using the same RTFO+PAV methods. Figure 1 shows a flow chart of the experimental design for CRM binders. The CRM mixes were produced in the laboratory using two aggregate sources and artificially aged in an accelerated aging process. The aged CRM mixes were recycled using the same virgin aggregate and two base binders (PG 64-22 for 15% recycling, and PG 58-28 for 25% and 35% recycling). Figure 2 shows a flow chart of the experimental design for CRM mixtures.

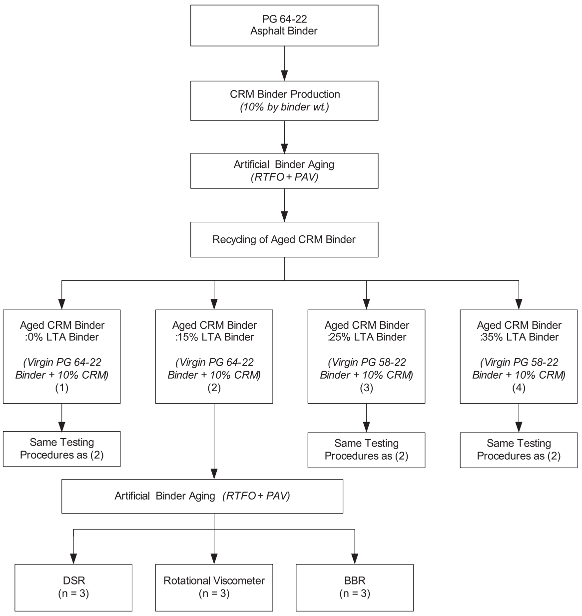


Fig. 1 Flow Chart of Experimental Design Procedures for Rubberized Binders

3. MATERIALS and TEST PROGRAM

3.1. Materials

3.1.1. Crumb rubber modifier (CRM)

The CRM, produced by mechanical shredding at ambient temperature, was obtained from one source: -40 mesh (0.425

Table 1. Gradation of CRM Used in This Study

Sieve no. (mm)	Ambient CRM	
	% Retained	% Cumulative retained
30 (600)	0	0
40 (425)	9.0	9.0
50 (300)	31.9	40.9
80 (180)	32.9	73.8
100 (150)	7.6	81.4
200 (75)	18.6	100.0

mm) and used with a gradation as shown in Table 1, which is widely used to produce the CRM mixtures in South Carolina. To ensure that the consistency of the CRM was maintained throughout the study, only one batch of crumb rubber was used in this study.

3.1.2. Asphalt binders

Two base binders of PG 58-22 and PG 64-22 were used to produce rubberized binders throughout the study. Table 2 summarizes the properties of the binders included in this study.

Table 2. Properties of the Binders Used in This Study

Aging states	Test properties	Base 1 (PG 58-22)	Base 2 (PG 64-22)	CRM 1 (PG 58-22 + 10% rubber)	CRM 2 (PG 64-22 + 10% rubber)
Unaged binder	Viscosity @ 135 ℃ (Pa-s)	0.287	0.409	0.771	1.302
	$G^*/\sin\delta$ @ 64 ℃ (kPa)	0.590	1.194	-	-
	$G^*/\sin\delta$ @ 70 ℃ (kPa)	-	-	0.883	1.633
RTFO aged residue	$G^*/\sin\delta$ @ 64 ℃ (kPa)	1.054	2.430	-	-
	$G^*/\sin\delta$ @ 70 ℃ (kPa)	-	-	2.295	2.774
RTFO+ PAV aged residue	$G^*\sin\delta$ @ 25 ℃ (kPa)	1208.7	2335.0	1102.7	1963.5
	Stiffness @ -12 ℃ (MPa)	114	187	86	149
	m-value @ -12 ℃	0.378	0.337	0.350	0.322

3.1.3. Aggregates

The mineral aggregates used for this study were obtained from two different locations in South Carolina and designated as aggregate sources B and L. Table 3 shows the properties of two aggregates. Hydrated lime, used as an anti-strip additive, was added at a rate of 1% by dry mass of aggregate.

Table 3. Properties of Aggregates B and L

Properties	Standard method	Aggregate B	Aggregate L
Apparent specific gravity	AASHTO T 85	2.860	2.680
Bulk specific gravity	AASHTO T 85	2.820	2.650
Absorption	AASHTO T 85	0.5	0.6
LA abrasion	AASHTO T 96	26	52
Soundness	AASHTO T 104	0.6	0.2

* Aggregate B: marble-schist

* Aggregate L: granite

3.2. Rubberized Binder Production and Aging

The binder mixing used in this study was the wet process, in which the CRM is added to the base asphalt binder before introducing it in the asphalt concrete matrix. The rubberized binder was manufactured in the laboratory by mixing the CRM with the binder at 177 ℃ using an open blade mixer at a blending speed of 700 rpm for 30 minutes (Shen et al. 2006). The percentage of crumb rubber added for the rubberized binder was 10% by weight of the base binder. This mixing condition matches the field practices used in South Carolina to produce field mixtures. The rubberized binders were then artificially aged through a series of accelerated aging processes (RTFO aging for 85 minutes at 163 ℃ followed by PAV aging for 20 hours at 100 ℃) (The Asphalt Institute 2003).

3.3. Recycling of Aged Rubberized Binders

Virgin rubberized binders produced using PG 64-22 base binders were used for the recycling of 0% and 15% RAP binders. The virgin binder grade was selected based on the previous research which concluded that in the case of 15% RAP, the PG grade of the asphalt binder added for the recycling can be the same as that used in 0% RAP (Pavement Recycling Guideline 1997; Shen et al. 2006). With respect to the 25% and 35% RAP binders, the PG 58-22 base binders were utilized to produce virgin rubberized binders for the recycling (Figure 1). The recycled aged rubberized binders were then artificially aged using RTFO and PAV processes.

3.4. Superpave Binder Tests

The properties of these rubberized binders were evaluated using selected Superpave binder test procedures including the viscosity test (AASHTO T 316), the BBR test (AASHTO T 313), and the DSR test (AASHTO T 315: with the plate gap adjusted to 2 mm). The plate gap adjustment was used to eliminate the influence of rubber particle size (Heitzman 1992; Kim et al. 2001; Zanzotto and Kennepohl 1996). Three duplicate samples were tested by the rotational viscometer, the BBR, and the DSR. The results were reported as the average of these tests.

3.5. Recycling of Aged Rubberized Mixtures

The rubberized binder produced using a base binder of PG 64-22 was used for 0% and 15% mixture recycling. In case of 25% and 35% recycling, the base binder of PG 58-22 was selected to produce the virgin CRM binder for the recycling (Figure 2).

The eight CRM mixtures (2 aggregates ´ 4 recycling percentages of 0%, 15%, 25%, and 35%) were designed according to AASHTO M 323-04. Optimum asphalt contents (OAC) were determined from these designs, and used to produce the recycled aged CRM mixtures.

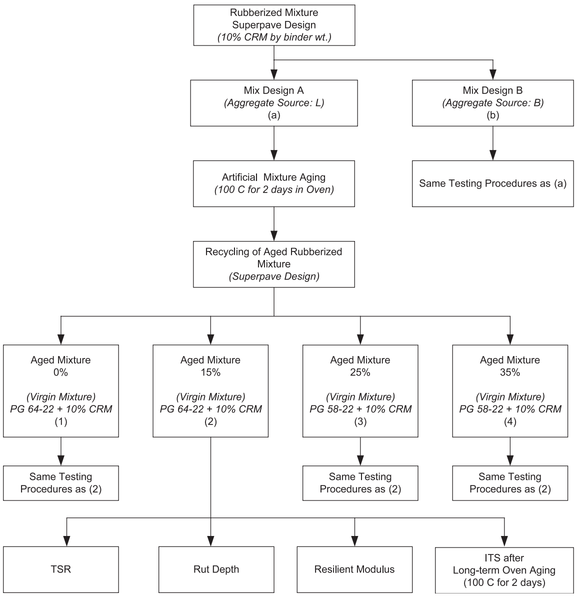


Fig. 2 Flow Chart of Experimental Design Procedures for Rubberized Mixes

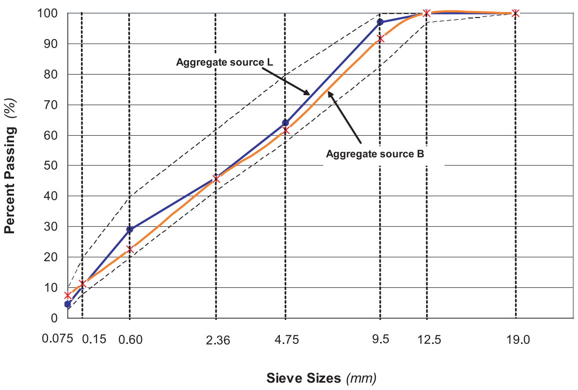


Fig. 3 Aggregate Gradations for Two Rubberized Mixtures

3.6. Indirect tensile strength (ITS)

The indirect tensile strength (ITS) properties were measured to evaluate the moisture susceptibility of the mixtures. Two sets of 3 samples each were tested at 25 ℃ in dry and wet states. The samples were 150 mm diameter having a height of 95 mm and an air void content of 7±1%. The ITS and tensile strength ratio (TSR) values were calculated, and the results were reported as the average.

3.7. Asphalt pavement analyzer (APA)

The APA test in this study was conducted on cylindrical samples with an air void content of 4±0.5%, a height of 75 mm and a diameter of 150 mm. The test temperature was 64 ℃, the hose pressure was 690 kPa, and the wheel load was 445 N. The rut depth was recorded and measured manually after 8,000 cycles.

3.8. Resilient modulus (Mr)

The resilient modulus test was carried out at temperatures of 5, 25, and 40 ℃ according to ASTM 4123. Four duplicate samples with 150 mm diameter and 95 mm thickness were compacted using the Superpave Gyratory Compactor (SGC) to an air void content of 4±0.5%. One of the four samples was used to measure the ITS value by which the repeated load is determined, specifically 30%, 15% and 5% of the ITS was used as the repeated load for the tests at 5, 25 and 40 ℃; respectively. The resilient modulus value was reported as an average of three samples.

3.9. Indirect tensile strength (ITS) after long-term oven aging

The recycled aged CRM mixtures were artificially aged using an accelerated aging process (an oven aging for 2 days at 100 ℃) in the laboratory (Shen et al. 2006). The indirect tensile strength (ITS) tests were conducted to evaluate the properties of recycled aged CRM mixtures after artificial long-term aging. One set of 3 samples for each mixture was tested at 25 ℃ in dry state. The samples were 150 mm diameter having a height of 95 mm and an air void content of 4±0.5%.

4. RESULTS and DISCUSSIONS

4.1. Analysis of Superpave Binder Properties

Table 4 shows the results of Superpave binder tests on the recycled aged CRM binders in the three aging states: original (unaged), RTFO residual, and RTFO+PAV residual. CRM binders with 15% and 25% RAP binders resulted in the highest and lowest viscosity values, respectively. Based on the DSR test results, 15% recycling (15% aged CRM binder + 85% virgin CRM binder) seemed to lead to better rutting properties for aged CRM binders. Relatively, the 25% recycling using a softer virgin binder were found to have lower stiffness values which relate to a better resistance to low temperature cracking. In general, the laboratory-prepared RAP binders containing CRM were utilized up to 35%, and the performance properties (i.e., rutting, fatigue cracking, and low temperature cracking properties) of recycled aged CRM binders showed the results satisfying current Superpave binder requirements.

Table 4. Superpave Binder Properties of Mixed Aged Rubberized Bidners

Aging states	Test properties	Mixing percentage			
		0%*	15%	25%	35%
Unaged binder	Viscosity @ 135 ℃ (Pa-s)	1.302	1.608	1.191	1.535
	High failure temperature (℃)	73.9	79.1	76.3	78.1
RTFO aged residue	High failure temperature (℃)	72.8	78.7	75.7	76.5
RTFO +PAV aged residue	G*sin δ @ 25 ℃ (kPa)	2161	2424	1068	1650
	Stiffness @ -12 ℃ (MPa)	142	150	94	124
	m-value @ -12 ℃	0.322	0.295	0.348	0.321

* 0% aged rubberized binder + 100% virgin rubberized binder.

4.2. Analysis of Engineering Properties

Table 5 shows the properties of recycled aged CRM mixtures, including the ITS test results in dry and wet conditions, the final rut depth values measured from the APA, the resilient modulus test results at temperatures of 5 ℃, 25 ℃, and 40 ℃, and the ITS test results of the CRM mixtures that were long-term aged for two days at 100 ℃. The ITS values of mixtures with 15% RAP were highest for all mixes within each aggregate source. From the APA test results, the 15% recycled CRM mixtures were found to have the lowest rut depth with each aggregate source, followed by 0% recycled CRM mixtures. In terms of resilient modulus, a general trend was found that the 25% and 35% recycled CRM mixtures had similar results within each aggregate source and test temperature. After long-term oven aging, the 15% recycled CRM mixtures showed the highest ITS values among all mixes within each aggregate source.

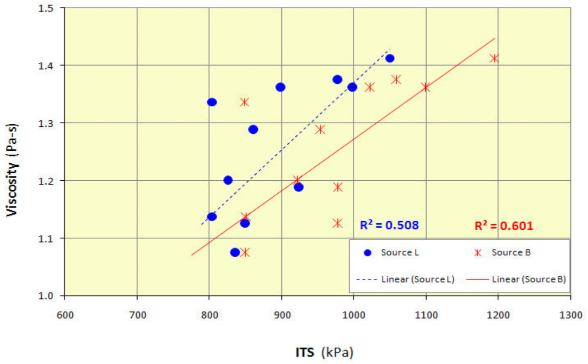
Table 5. Engineering Properties of Recycled Aged Rubberized Mixtures

Properties	RAP (%)	Aggregate sources	
		L	B
Dry ITS (kPa)	0 (control)	888.6	978.5
	15	982.8	1105.9
	25	825.6	868.4
	35	844.5	892.6
Wet ITS (kPa)	0 (control)	811.3	849.0
	15	852.5	912.7
	25	730.1	761.7
	35	763.9	788.1
Final rut depth (mm)	0 (control)	3.54	2.21
	15	3.18	2.14
	25	4.92	2.78
	35	4.99	2.56
Resilient modulus at 5, 25, 40 ℃ (MPa)	0 (control)	6216.6 2249.1 755.6	13658.4 4989.9 1718.6
	15	6133.7 2732.8 746.1	10538.4 2405.7 746.1
	25	4457.2 1297.0 451.0	5510.2 2015.9 496.8
	35	4074.8 1287.3 411.3	5428.5 1491.8 698.5
Dry ITS after long-term oven aging (kPa)	0 (control)	1328.4	1532.7
	15	1369.3	1583.6
	25	1182.2	1385.1
	35	1231.7	1399.9

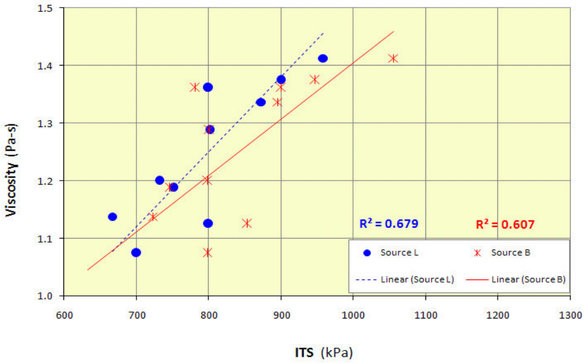
4.3. Regression Analysis

4.3.1. Correlation between viscosity, high failure temperature and ITS

ITS test results are found to indicate the moisture susceptibility of asphalt mixtures, and in some cases the cracking potential of mixes (Akisetty et al. 2011). In this study the ITS values of asphalt mixtures were correlated with the viscosity values of binders (Figure 4), and it was observed that the ITS values increased with the increase in viscosity of the binders. The viscosity values were correlated with the dry ITS values of recycled aged CRM mixtures with reasonable

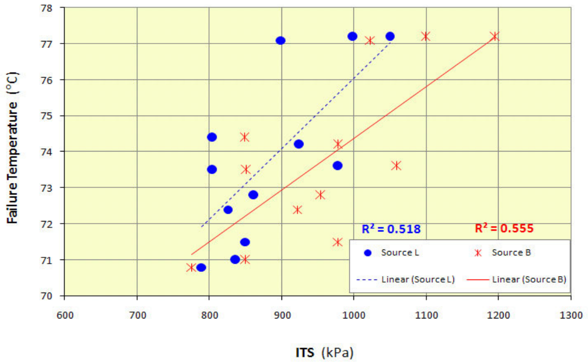


(a) Dry ITS

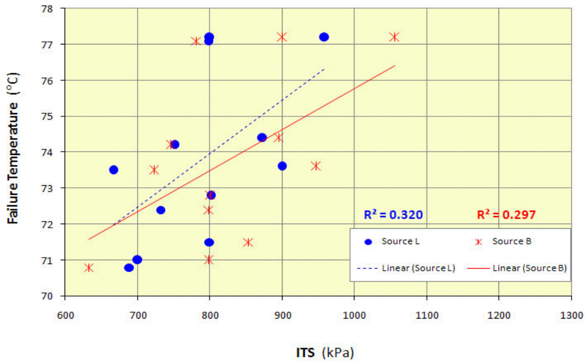


(b) Wet ITS

Fig. 4 Relation of the Viscosity at 135 ℃ of Mixed Rubberized Binders with Indirect Tensile Strength(ITS) of Recycled Aged Rubberized Mixtures



(a) Dry ITS



(b) Wet ITS

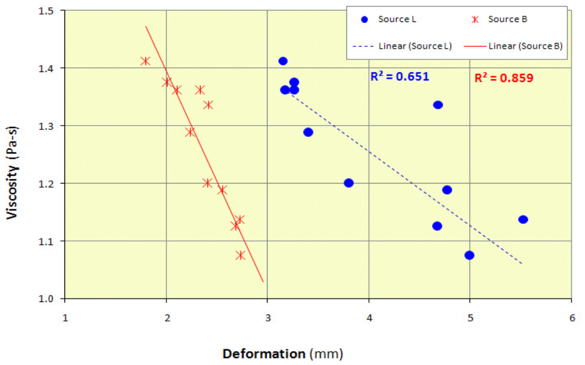
Fig. 5 Relation of the High Failure Temperature of Mixed Rubberized Binders with Indirect Tensile Strength(ITS) of Recycled Aged Rubberized Mixtures

R² values (over 0.55 on the average). With regard to the wet ITS values, they showed somewhat higher correlations (over 0.64 on the average) with corresponding viscosity values than the dry ITS values. In general, it was observed that asphalt binder viscosity had a significant effect on the ITS values of the recycled aged CRM mixtures regardless of aggregate source (L and B).

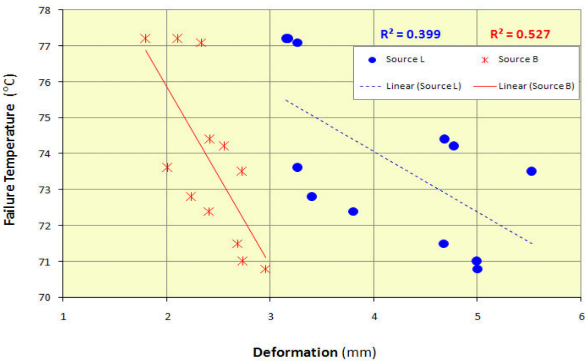
In general, the ITS values were observed to increase as the high failure temperature values from the DSR test increased (Figure 5). It was noticed that the failure temperature values have better correlation with the dry ITS values (over 0.54 on the average) than the wet ITS values (over 0.31 on the average), irrespective of the aggregate source.

4.3.2. Correlation between viscosity, high failure temperature and rut depth

The viscosity values of recycled aged CRM binders were compared with rutting depth values from the APA test and it was found that rut depth was decreasing with increasing viscosity (Figure 6a), suggesting that the higher viscosity resulted in an increase in the rutting resistance of CRM



(a) Viscosity at 135℃



(b) High Failure Temperature

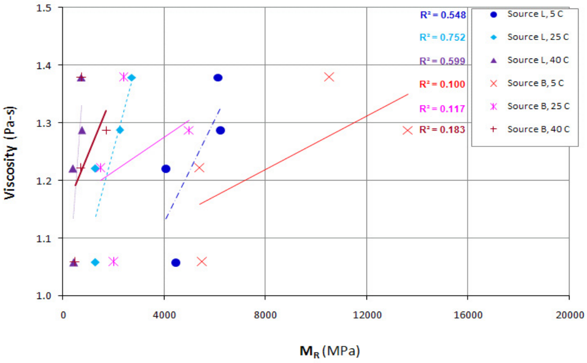
Fig. 6 Relation of the Properties of Mixed Rubberized Binders with Final Rut Depth of Recycled Aged Rubberized Mixtures

mixtures. When compared between each aggregate source, the final rut depth values of the mixtures with source B showed a very good correlation with the viscosity values (R^2 value of 0.859). The rut depth values of mixtures with source B were relatively lower than those with source L; therefore, suggesting that the mixture less susceptible to rutting seemed to have better correlation with the viscosity values.

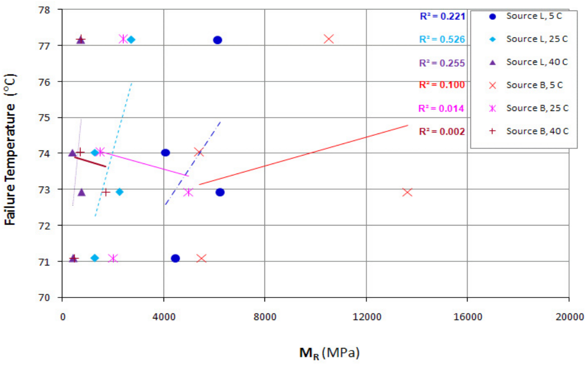
Generally, the higher failure temperature values are considered desirable attributes from the standpoint of resistance to rutting of the pavements. The correlation results showed that the rut depth values decreased as the high failure temperature values increased (Figure 6b). Similar to the viscosity and rut depth values, the final rut depth values of the mixture manufactured with source B resulted in better correlation with the failure temperature values (R^2 value of 0.527).

4.3.3. Correlation between viscosity, high failure temperature and resilient modulus

A comparison of the MR values at 5, 25 and 40 ℃ of the recycled aged CRM mixtures with the viscosity values of the binders at 135 ℃ showed a reasonable correlation for aggregate source L (R^2 value 0.63 on average) (Figure 7a). This indicates that the increase in the viscosity leads to the higher stiffness in the mixtures. This finding is consistent with another research (Xiao and Amirkhanian 2008).



(a) Viscosity at 135℃



(b) High Failure Temperature

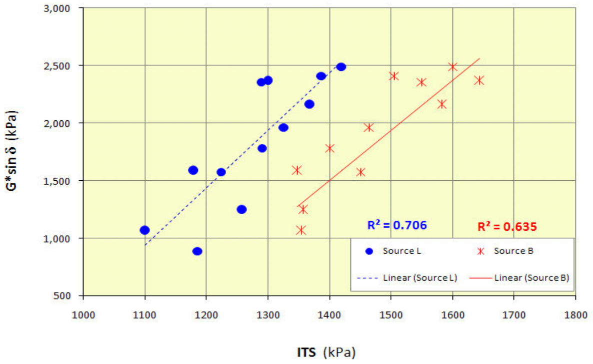
Fig. 7 Relation of the Properties of Mixed Rubberized Binders with Resilient Modulus of Recycled Aged Rubberized Mixtures

In general, high resilient modulus values indicate higher stiffness of the mixtures, which is a required attribute to resist deformation and cracking at intermediate temperatures. The resilient modulus properties of the CRM mixtures seemed to have poor correlation with the high failure temperature values (Figure 7b), regardless of the aggregate source (L and B) and the testing temperature (5, 25, and 40 ℃). The failure temperature and resilient modulus values showed the mean R^2 value of 0.186. A MR test method is known to have quite high variance of test results. The characteristics of test method itself are considered to be main reasons of poor correlation with the failure temperature.

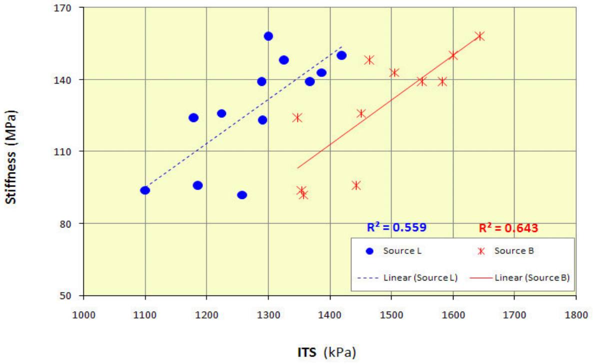
4.3.4. Correlation between G*sin δ, stiffness and ITS

In Superpave binder specifications, the project of the complex shear modulus, G*, and the sine of the phase angle (δ), is used as an indicator of fatigue cracking in asphalt pavements. Lower G*sin δ values are generally considered desirable attributes from the standpoint of resistance to fatigue cracking. Figure 8a shows the relation of the G*sin δ values of the CRM binders (RTFO+PAV residual) with dry ITS values of the CRM mixtures after long-term oven aging. As expected, it was found that the higher G*sin δ values caused an increase in the ITS values. The ITS properties of the mixtures after long-term aging and G*sin δ values of the binders after RTFO+PAV aging are observed to have a good relation (R^2 value of 0.67 on average), provided the variability of long-term aging methods between the CRM binders and the CRM mixtures. This is also thought to be related to the lower air void contents (i.e., 3.5-4.5%) of specimens for the ITS test.

The ITS values of the CRM mixtures after long-term aging were compared to the creep stiffness of the CRM binders at -12 ℃ (Figure 8b). The creep stiffness values were observed to increase with the ITS values for the mixtures with both aggregate sources, mixture made with aggregate B showing higher correlation (R^2 = 0.643), compared to mixtures with aggregate L, showing that aggregate source also has an influence on the mixture stiffness.



(a) G*sin δ at 25 ℃



(b) stiffness at -12 ℃

Fig. 8 Relation of the Pproperties of Mixed Rubberized Binders (RTFO+PAV residual) with Indirect Tensile Strength (ITS) of Recycled Aged Rubberized Mixtures After Long-Term Oven Aging

5. SUMMARY and CONCLUSIONS

To investigate the correlation between the Superpave binder properties and the mixture properties, the CRM binders were artificially aged through accelerated aging procedures. The aged CRM binders were recycled at 0%, 15%, 25%, and 35% RAP binder percentages by total binder weight, and then artificially aged using the RTFO and PAV processes. A series of Superpave binder tests were carried out using the rotational viscometer, the DSR, and the BBR to evaluate the performance properties. Also, the CRM mixes were artificially aged through accelerated aging processes. The aged CRM mixes were recycled at RAP contents of 0%, 15%, 25%, and 35%. A series of mixture tests were conducted to obtain the ITS, the rut depth, the resilient modulus, and the ITS properties after long-term oven aging. From these test results, the following conclusions were drawn for the limited materials used in this study.

- The aged CRM binders were utilized up to 35%, and in most cases, the performance properties (i.e., rutting, fatigue cracking, and low temperature cracking properties) showed the results meeting current Superpave binder requirements.
- Generally, artificially aged CRM mixes were recycled up to 35%, and the engineering properties of the recycled mixtures showed the results satisfying current the requirements for conventional HMA mixtures.
- The recycled aged CRM binders with higher failure temperature related to higher ITS values of the recycled aged CRM mixtures. In general, samples in the dry state were observed to have higher coefficient of determination (R^2) values than samples in the wet state.
- Both the higher viscosity and the higher failure temperature values seemed to lead to an increase in the rutting resistance of the mixtures. However, resilient modulus test results were insignificantly correlated with the viscosity and high failure temperature values.
- The ITS test results of recycled aged CRM mixtures after long-term aging were strongly correlated with the G*sin δ and creep stiffness values of recycled aged CRM binders (RTFO + PAV residual).
- It is recommended to conduct another study to evaluate the HMA mixture properties using different CRM binders and aggregate sources, and correlate the Superpave binder properties with the mixture properties to generalize these findings.

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