MECHANICAL RESPONSE OF SUPERPAVE RECYCLED HOT MIXTURES IN ONTARIO

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Abstract

The use of reclaimed asphalt pavement (RAP) for surface course layers is still conservative and even restricted in some instances. The main concern is related to the uncertainty of the long-term performance and effect of RAP in the stiffness of the mix. To counteract this effect, softer virgin asphalt is incorporated in the mix. A laboratory study was conducted on six different Superpave SP12.5 mixtures to determine the impact that RAP has on the dynamic modulus and phase angle of the mixtures, and to quantify the effect of binder bump in the mix behavior. The mixtures were designed and elaborated in the laboratory, and tested following the AASHTO TP-62 standard. Two virgin mixtures, two 20% RAP mixtures, and two 40% RAP mixtures were created with different virgin asphalt performance grades (PG). The results show that laboratory mixtures can be produced with up to 40%RAP with comparable results to the virgin mixtures, and that the use of a softer grade does not always represent a significant enhancement of the stiffness characteristics of the mixtures.

1. INTRODUCTION

The Ministry of Transportation Ontario is committed to having the greenest roads in North America (MTO, 2011). Ontario has one of the maximum allowances of Reclaimed Asphalt Pavement (RAP) content for new Hot Mix Asphalt (HMA) (O'Reilly, 2012). Currently, up to 20% RAP by mass is allowed for Superpave surface courses and 40% for binder courses. The use of RAP in HMA is a common practice in Ontario. Increased use of RAP is also being promoted because of its environmental and economic advantages. Using RAP in HMA has many proven benefits including: the reuse of high quality materials, the saving of dwindling non-renewable aggregate and asphalt resources, the diversion of large volumes of materials from overloaded landfills, and the reduction of road building costs (OHMPA, 2007a).

Asphalt mixtures are viscoelastic materials. The mechanical response, in terms of stresses and strains, of viscoelastic materials under repetitive load is a function of the temperature, the magnitude of the load, and the frequency of load application. Low frequencies and high temperatures are the conditions for rutting. At moderate temperatures, the mixtures are prone to permanent deformation and fatigue cracking, while low temperatures are related with thermal cracking. Considering that the addition of RAP would stiffen the mix, a softer virgin binder is usually incorporated to counteract this effect and control the appearance of distresses.

The objective of this study was to model and evaluate the impact of RAP in the performance of Superpave recycled hot mixtures and the effect of the virgin asphalt performance grade (PG). The samples were prepared in the laboratory and tested using a Materials Testing System (MTS) according to the standard method of test for determining the dynamic modulus of hot mix asphalt AASHTO TP 62-07. The master curves for the six mixtures were built and compared. To determine the significance of the results the result were statistically analyzed using t-test. It is expected that the outcomes of this study encourage the proper design of the recycled hot mixtures, and the correct selection of the asphalt to account for the environmental imposed stresses applicable to the site where the mixture is going to be placed.

1.1 Previous testing

The same mixtures were also tested for low temperature cracking using the thermal stress restrained specimen test (TSRST). It was found that all of the mixtures achieve a failure temperature higher or equal to -28°C, however, the samples with RAP incorporated did not achieve -34°C even when the PG52-40 was used (Ambaiowei, Sanchez, Safiuddin, Aurilio, & Tighe, 2013).

Also, the rutting susceptibility was evaluated with the Hamburg wheel rutting device. As expected, it was found that rutting was not a concern for hot recycled mixtures, as all of them have an average rut below 7mm after 10000 cycles (Varamini, Ambaiowei, Sanchez, & Tighe, 2014).

2. BACKGROUND

The dynamic modulus of hot mix asphalt allows the evaluation of two parameters: complex modulus and phase angle. The modulus of a viscoelastic material is better represented by a complex number, with a real portion representing the storage or elastic modulus, and an imaginary portion representing the loss or viscous modulus, as shown in Figure 1. The angle shown represents the lag between the moment when the load is applied and the moment when the deformation starts. When a cyclic load is applied to an elastic material, the material deforms immediately and the angle is 0°; while for a perfectly viscous material, the angle is 90°. Then, for a viscoelastic material the angle is between 0° and 90°. An ideal asphalt mixture should be stiff enough to resist permanent deformation but no excessively stiff that allows for fatigue and thermal cracking.

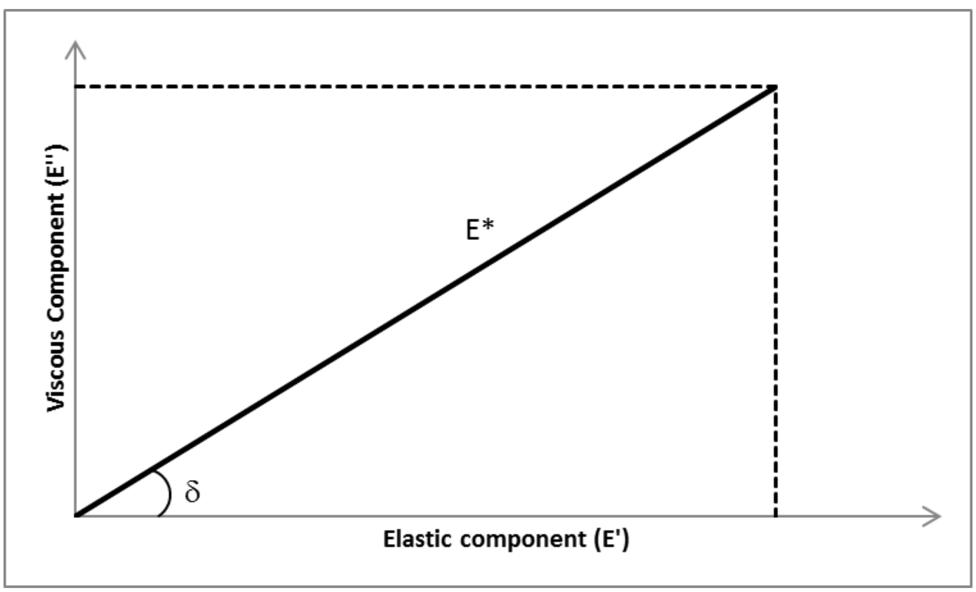

Figure 1. Representation of complex modulus and phase angle

2.1 Complex Modulus E*

The Complex Modulus (E*) describes the relationship between stress and strain of the material. When the complex modulus is higher, the material is stiffer. It is expected that the addition of RAP would make the mix stiffer in term of complex modulus.

Each temperature and frequency yields a different stress vs strain curve. In order to properly present the information, isotherms are constructed. An isotherm describes the complex modulus at the different frequencies for only one temperature. When all the isotherms are available, the master curves can be built. A master curve characterizes the response of the material at a given reference temperature.

2.2 Phase Angle

The phase angle characterizes the viscoelastic behavior of the mix. A higher angle indicates a lower elastic component, while a smaller angle indicates a lower viscous component of the complex modulus. It would be expected that when RAP is added, the phase angle decreases. The decrease in phase angle corresponds to an increase in the elastic properties and a reduction in the viscous properties of the mix.

2.3 Literature Review

Significant amounts of laboratory testing and field evaluation of HMA mixes containing varying percentages of RAP have been completed and are documented in the literature. The majority of the research studies have been done on mixes containing a maximum of 40 percent RAP. The results indicate that the addition of RAP into HMA mixes increases the stiffness of the mix. This was shown through dynamic and resilient modulus testing done by Sondag et al. (Sondag, Chadbourn, & Drescher, 2002), in which both the resilient and dynamic (complex) modulus values increased with increasing the RAP percentages. It is important to note that the phase angle of the mix decreased with increasing RAP percentages.

Regarding the dynamic modulus of mixtures containing RAP and different PG binders, Li et al. (Li, Marasteanu, Williams, & Clyne, 2008) found that the addition of RAP impacted the dynamic modulus of the mixtures, giving higher results than the control mixtures, but the dynamic modulus for 20% RAP mixtures was the highest for high frequencies.

In a study examining effects of RAP percentages and sources, Li et al. (Li, Clyne, & Marasteanu, 2004) found that as the percentage of RAP in a mix increased, there was increased variability in the dynamic modulus values at lower temperatures.

It was also shown that the complex modulus of the mix is sensitive to the changes in mixture volumetric properties and binder stiffness (Shah, McDaniel, & Gallivan, 2005). Considering these aspects the recycled asphalt mixtures requires a careful design and production.

In the research conducted by Hajj et al. (Hajj et al., 2011), it was found that overall, the field-produced and laboratory produced mixtures ranking was similar for dynamic modulus test. The results for laboratory prepared samples are different that the field samples, however, the mixtures will rank similarly and the results can be interpreted accordingly.

3. MATERIALS AND METHODS

The experimental matrix is shown in Table 1. The aggregates and RAP were collected from a local provider. The RAP was fractionated on the ½" sieve at the plant. Also, each binder was collected from different suppliers across Southern Ontario.

Table 1. Experimental matrix

RAP Content	*Binder PG*			
	Zone 3		*Zone 2*	
	PG 58 -28	*PG 52-34*	*PG 58-34*	*PG 52-40*
0%	0-58-28	0-52-34*		
20%			20-58-34	20-52-40
40%	40-58-28*			40-52-40

Notes: *These mixes are not used in Zone 3 in the practice (0-52-34 is used in Zone 1)

For design purposes, the AC content of the RAP was determined as 4.5%. Table 2 shows the temperatures for which the Superpave requirement for rutting, fatigue and thermal cracking are met, indicating that the Performance Grade of the RAP binder is PG76-22. The continuous grade of all the binders was determined and summarized in Table 3.

Table 2. RAP Binder Tests Results

Condition	*Criteria*	*Specification*	*Results*	*Test Temperature (°C)*
Abson Recovered	$G^*/\sin\delta$, kPa	>= 2.20	2.32	76
PAV	$G^* \sin\delta$, kPa	<= 5000	4810	25
	S, MPa	<= 300	147	-12
	m-value	>= 0.30	0.305	-12

Table 3. Binders Sources

Virgin Binder PG	*Provider*	*High Grade (°C)*	*Low Grade (°C)*
58-28	Canadian Asphalt	60.9	-30.0
52-34	Bitumar	62.7	-35.1
58-34	Coco Paving	54.7	-34.7
52-40*	Mc Asphalt	56.4	-40.6

The mixtures were designed to meet all the requirements for a Superpave 12.5mm surface course for traffic Category C. Considering the findings in (Shah, McDaniel, & Gallivan, 2005), the volumetric properties of the mixtures were similar to control that source of variability. Table 4 presents the summary of the design for the six mixtures selected.

Table 4. Summary of the Designs

RAP content (%)	*Virgin Asphalt PG*	*AC (%)*	*AC from RAP (%)*	*Virgin AC (%)*	*BRD g/cm^3*	*MRD g/cm^3*	*Air Voids (%)*	*VMA (%)*	*VFA (%)*	*Dust Proportion (%)*
0	52-34	5.2	0.0	5.2	2.433	2.534	4.0	15.0	73.4	0.7
0	58-28	5.2	0.0	5.2	2.44	2.541	4.0	14.8	73.1	0.7
20	52-40	5.2	0.9	4.3	2.449	2.551	4.0	14.3	72.1	1.2
20	58-34	5.2	0.9	4.3	2.446	2.547	4.0	14.7	73.1	1.2
40	52-40	4.9	1.8	3.1	2.451	2.554	4.0	14.2	71.5	1.1
40	58-28	5.1	1.8	3.3	2.451	2.553	4.0	14.3	72.1	1.1
Min.							4.0	14.0	65.0	0.6
Max.									75.0	1.2

Notes: BRD=Bulk Relative Density, MRD=Maximum Relative Density, VMA=Void in Mineral Aggregate, VFA=Voids Filled with Asphalt

After the mixtures were produced in the laboratory, the samples for dynamic modulus were obtained by means of the Superpave Gyratory Compactor (SGC) following the AASHTO T 312 standard (AASHTO, 2009). When the samples were cold, a 100mm diameter and 150mm height specimen, was cored from the SGC cylinder. The ends were cut and grinded to ensure a levelled surface. The air void content for the specimens was checked for a target of 7.0%±0.5%. Steel pins were glued at equal spacing around the perimeter of the sample. The vertical distance between the pins was 100mm. Three extensometers (Epsilon Model 3910) with 100mm gauge length were attached magnetically to the pins. The range of the transducer was ±1mm, with 0.0001mm resolution. The test set up is shown in Figure 2.

Three replicates were tested per mixture. A Material Testing System (MTS) frame was used, in conjunction with an environmental chamber capable of achieving and maintaining the test temperatures. MTS Model 793.67 System Software was used for creating and running the test routine (MTS, 2003). Five test temperatures were tested: -10, 4, 21, 37 and 54°C. For each temperature, six frequencies were applied: 25, 10, 5, 1, 0.5 and 0.1 Hz. With the information collected, the Dynamic Modulus (E*) and phase angle were then calculated for each temperature and frequency.

Figure 2. Dynamic modulus test samples production

4. RESULT AND DISCUSION

The objective of the following analysis is not to determine which mix is better. The selection of a mix shall depend on the specific site conditions and project requirements among other considerations. The purpose of the comparison is identifying the impact of the RAP content and the effect of using a softer binder in the recycled mixtures.

The resulting master curves at a reference temperature of 20°C are shown in Figure 3. It is observed here that overall, the stiffest mix is the 20%RAP PG52-40, while the least stiff mix would be the 0%RAP PG52-34. From the master curves, it can also be observed that for the low frequencies or high temperatures, the curves are visibly separated and there are clear differences between the virgin and the RAP mixtures. However, as the frequency increases or the temperature decreases it can be noticed that the curves start to approach.

The frequency shown in the graph is known as the reduced frequency. To convert this reduced frequency to the real frequency for a given temperature, a shifting equation is required. There are several methods available for shifting the isotherms and fitting them to a master curve through mathematical models (Booshehrian, Mogawer, & Bonaquist, 2012). In this research, the software RHEA™ - Rheology Analysis by Abatech Inc. (Abatech Inc., 2011) was used to obtain the master curves.

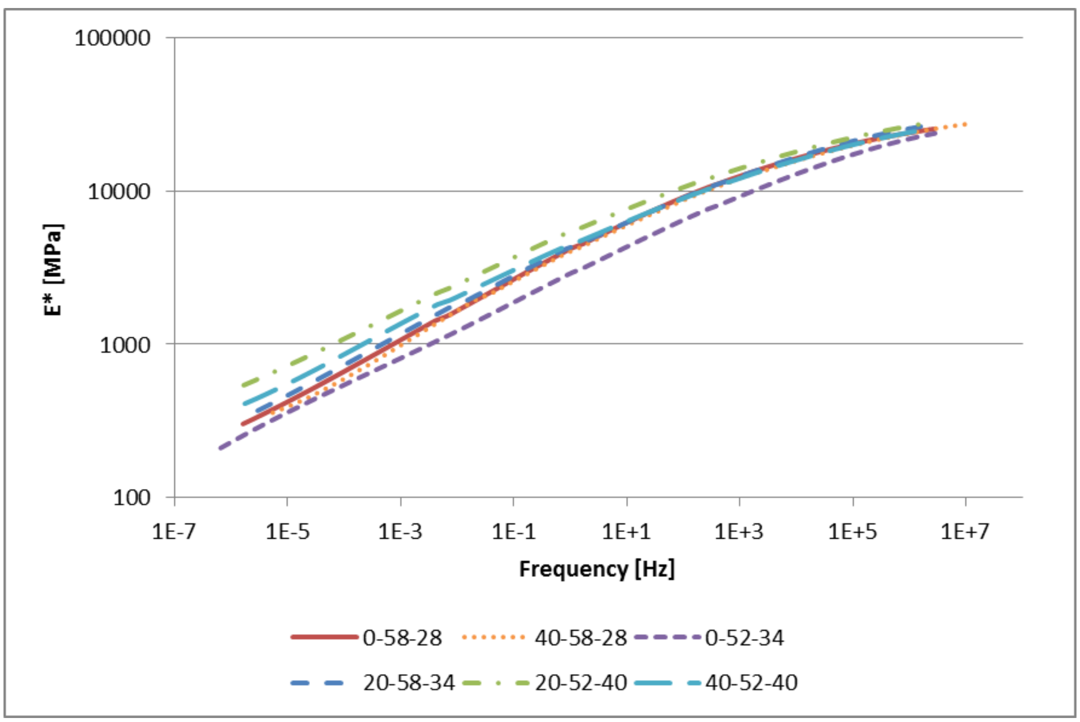

Figure 3. Master curves for studied mixes

4.1 Complex Modulus

The data for 21°C and 10 Hz was extracted, as seen in Table 5. From this table, it can be observed that the least stiff mix is the 0% RAP PG52-34. A graphical representation of the results is shown in Figure 4. It is observed that the mixture with 20%RAP PG52-40 would have a higher modulus, which confirms the appreciation from the master curves. High dispersions were observed for the 20%RAP PG52-40 and 40%RAP PG58-28 combinations.

Table 5. Complex modulus at 21°C and 10Hz

RAP Content	*Complex Modulus (MPa) Average/COV*			
	Zone 3 (Southern Ontario)		*Zone 2 (Middle Ontario)*	
	58-28	*52-34*	*58-34*	*52-40*
0%	6195.6/5.7%	4293.0/5%		
20%			6116.9/12.9%	7393.0/16.5%
40%	5853.6/20.3%			6217.0/11%

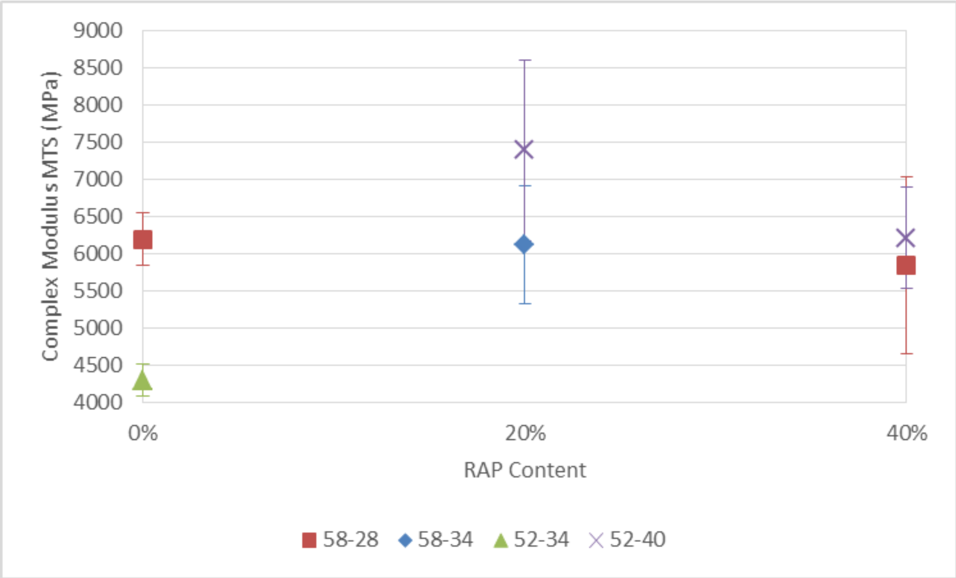

Figure 4. Complex Modulus at 21°C and 10Hz

To verify the statistical significance of the test results from the triplicated specimens, a t-test analysis was conducted on the original data for the Complex Modulus at 21°C and 10Hz. Table 6 summarizes the p-value. When the p-value is under 0.05, it can be concluded that the results are statistically different with 95% confidence level. The cells highlighted identify the results that are significantly different at 95% confidence level.

Table 6. T-test complex for modulus at 21°C and 10Hz

Mix Type	*0-58-28*	*40-58-28*	*0-52-34*	*20-58-34*	*20-52-40*	*40-52-40*
0-58-28	-	0.66	<0.01	0.88	0.18	0.96
40-58-28		-	0.09	0.77	0.19	0.67
0-52-34			-	0.02	0.01	0.01
20-58-34				-	0.20	0.88
20-52-40					-	0.22

From the results presented in Table 6, the following can be observed:

-0% RAP PG58-28 is not statistically different to 40% RAP PG58-28 (RAP Effect)

-20% RAP PG52-40 is not statistically different to 40% RAP PG52-40 (RAP Effect)

-0% RAP PG58-28 is higher than 0% RAP PG52-34 (Grade Effect)

-20% RAP PG58-34 is not statistically different to 20% RAP PG52-40 (Grade Effect)

-40% RAP PG58-28 is not statistically different to 40% RAP PG52-40 (Grade Effect)

From the above discussion it can be concluded that the mix with 0%RAP PG52-34 would have a significantly less stiffness than the rest of the studied mixtures. It can also be concluded that the RAP did not have a significant effect in the complex modulus of the mixtures. Also the change of grade did not show a significant enhancement of the complex modulus for the RAP mixtures. As expected the complex modulus of the 0%RAP PG58-28 was higher than the result for the 0%RAP PG52-34, considering that the last mix contains a softer binder.

4.2 Phase Angle

The results for the phase angle are shown in Table 7 and in Figure 5. It can be noticed that the higher values were obtained for the virgin mixtures. It was observed a lower variability of the phase angle compared to the complex modulus results. The highest dispersion was obtained for the 0%RAP PG52-34.

Table 7. Phase angle at 21°C and 10Hz

RAP Content	*Phase Angle (°) Average/StDev*			
	Zone 3 (Southern Ontario)		*Zone 2 (Middle Ontario)*	
	58-28	*52-34*	*58-34*	*52-40*
0%	19.0/1.3	19.7/1.5		
20%			18.4/0.4	15.1/1.2
40%	18.6/0.9			15.8/0.1

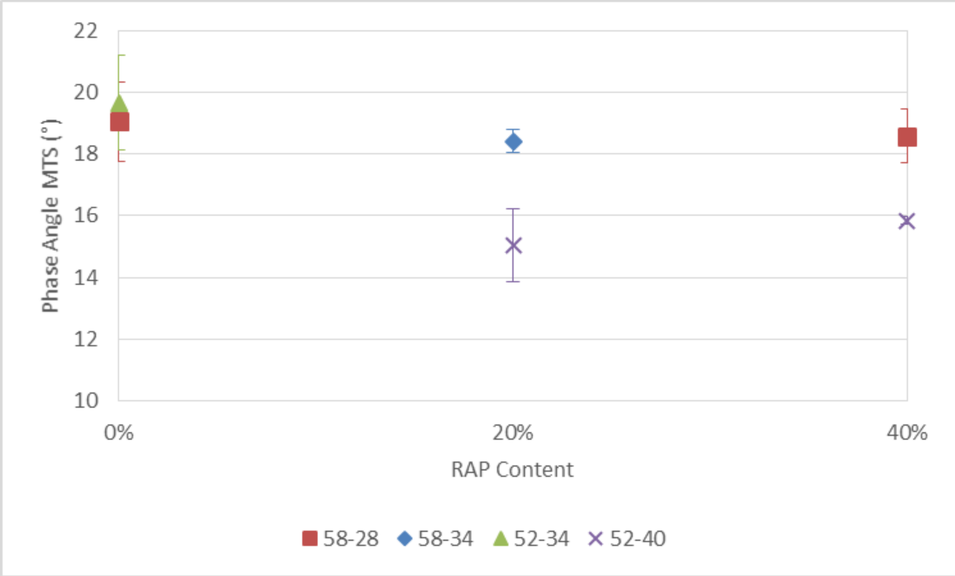

Figure 5. Phase angle at 21°C and 10Hz

Similarly to the complex modulus, t-test analysis was conducted on the original data for the phase angle at 21°C and 10Hz. The cells highlighted in Table 8 identify the results that are significantly different at 95% confidence level.

Table 8. T-test for phase angle

Mix Type	*0-58-28*	*40-58-28*	*0-52-34*	*20-58-34*	*20-52-40*	*40-52-40*
0-58-28	-	0.63	0.62	0.46	0.02	0.01
40-58-28		-	0.35	0.78	0.01	0.01
0-52-34			-	0.24	0.01	0.01
20-58-34				-	0.01	<0.01
20-52-40					-	0.32

From the results, the following can be observed:

-0% RAP PG58-28 is not statistically different to 40% RAP PG58-28 (RAP Effect)

-20% RAP PG52-40 is not statistically different to 40% RAP PG52-40 (RAP Effect)

-0% RAP PG58-28 is not statistically different to 0% RAP PG52-34 (Grade Effect)

-20% RAP PG58-34 is higher than 20% RAP PG52-40 (Grade Effect)

-40% RAP PG58-28 is higher than 40% RAP PG52-40 (Grade Effect)

It can be then concluded that the mixtures with PG52-40 showed significantly different behaviour as compared to the rest of the studied mixtures in terms of phase angle. The phase angle of those mixtures was smaller, regardless of the binder grade used, indicating that the addition of RAP would impact their elastic behaviour.

5. CONCLUSIONS

The dynamic modulus test is a comprehensive test from which considerable information can be obtained. The mixtures for this research were designed to meet the Superpave mix design requirements. For this paper, the analysis was focused on the viscoelastic response of the mixtures.

From the results, all the mixtures showed a comparable complex modulus, indicating that the addition of RAP or the use of a softer binder would not impact the stiffness of the mixture at intermediate temperatures. However, it was also found that the complex modulus of the RAP mixtures had a higher variability than the virgin mixtures. In terms of phase angle, for the mixtures with PG52-40 a lower result was obtained which would indicate that those mixtures could underperform compared to the rest of the studied mixtures.

This study presented a procedure to analyze statistically the impact of RAP content and the effect of using softer binders in recycled hot mixtures. The results depends the source of the RAP and virgin materials. The main finding of this study is that it is possible to design recycled hot mixtures with high contents of RAP, with a similar mechanical response to virgin mixtures. However, the selection of the fresh binder shall also consider the control of low temperature cracking and permanent deformation.

It is important to clarify that the performance of the mixtures is related to the degree of blending achieved between the new and the aged binder in the RAP. The conclusions obtained are based on the results obtained for laboratory produced mixtures. It is recommended to confirm this information for plant produced mixtures. The evaluation of in-service pavements could also contribute to validate the results.

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