Mechanistic and Volumetric Properties of Asphalt Mixtures with RAP

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ABSTRACT

This research examines how the addition of RAP changes the volumetric and mechanistic properties of asphalt mixtures. A Superpave 19 mm mixture containing 0% RAP was used as the control for evaluating properties of mixes containing 15%, 25%, and 40% RAP. Two types of RAP were evaluated: a processed RAP and an unprocessed RAP (grindings). Testing included dynamic modulus in tension and compression, creep compliance in compression, and creep flow in compression. Using the time-temperature superposition principle, dynamic modulus and creep compliance master curves were constructed to describe the behavior of each mix over a range of temperatures. The VMA and VFA of the RAP mixtures increased at the 25% and 40% levels, and there was also an influence of pre-heating time on the volumetric properties. The dynamic modulus of the processed RAP mixtures increased from the control to 15% RAP level, but the 25% and 40% RAP mixtures had dynamic modulus curves similar to the control mixture in both tension and compression. The creep compliance curves showed similar trends. A combination of gradation, asphalt content, and volumetric properties is likely the cause of these trends.

INTRODUCTION

The use of recycled asphalt pavement (RAP) material is increasing as local, state and federal transportation agencies make more efficient use of their resources. RAP material is generated when old, damaged pavement materials are milled and crushed for addition as a component to new mixtures placed in the pavement structure. Historically, old pavement material was removed and disposed of in landfills. As landfilling these materials has become less practical and more expensive and the availability of quality virgin materials declines, the addition of RAP to pavement mixtures has become more and more prevalent. Recycling of pavement material can be done as an in-place process or a central plant process. The in-place process combines the reclamation, mixing, laydown, and compaction procedures into a single paving train in the field. In-place recycled materials are typically used for base or binder courses and are typically overlaid with a surface course. The central plant process involves stockpiling RAP at the asphalt plant, which is then mixed with virgin materials at the plant and trucked to the construction site for laydown and compaction. Currently, the state of New Hampshire allows up to 30% RAP from a known source or 15% RAP from an unknown source to be used in a mixture. These values were selected based on general guidelines developed at the national level for the use of RAP in HMA *(1,2,3)*, however, the actual effect of the RAP on the mixture properties and field performance of these mixtures is unknown.

The addition of RAP to an asphalt mixture changes the mechanistic properties (i.e., strength, durability) of the mixture and affects its performance (i.e., resistance to cracking and deformation) in the field. The mechanistic properties change as a result of the aged binder introduced to the mixture as part of the RAP. The binder in the RAP will have a different chemical composition and different properties than the virgin binder added during the mixing process. These two binders will mix to some extent, changing the properties of the mixture containing RAP from one that contains only virgin material. A study by Huang, et al *(4)* showed that the addition of RAP increased mixture stiffness, measured by the indirect tension and semi-circular bending tests. As the pavement industry moves towards more mechanistic based pavement design and analysis methods such as the American Association of State Highway and

Transportation Officials (AASHTO) Design Guide and proposed Simple Performance Test *(5)*, it is essential to evaluate the effect of RAP on the properties of asphalt mixtures.

The objective of this research study was to determine how the volumetric properties, dynamic modulus, and creep of mixtures change with the addition of RAP. Two RAP sources were used to study the change in volumetric properties and one RAP source was used for dynamic modulus and creep testing. A control mixture containing only virgin materials (0% RAP) was tested along with mixtures containing 15%, 25%, and 40% RAP.

MATERIALS AND MIX DESIGN

The materials for the asphalt mixtures tested in this study were obtained from Hooksett Crushed Stone in Hooksett NH, a division of PIKE, with the assistance of the New Hampshire Department of Transportation (NHDOT) Bureau of Materials and Research. A 19 mm Superpave gradation designed for low volume roads (0.3-3 ESALs) was used with an unmodified PG 58-28 binder. Two types of RAP were used in this study; a processed RAP and an unprocessed RAP, or grindings. The processed RAP contains a mix of recycled asphalt pavement, portland cement concrete, and sometimes slight amounts of organic material with an asphalt content of 3.6%. The extracted processed RAP binder has a grade of PG 94-14. The unprocessed RAP, hereinafter referred to as grindings, is material milled from a pavement surface and contains recycled asphalt pavement with an asphalt content of 4.9%. The extracted grindings binder has a grade of PG 82-22.

Mix Design

The mixes are designed based on a NHDOT approved 19 mm Superpave mixes containing 15% RAP performed by PIKE. The existing mix designs were verified at UNH and are used for fabricating the 15% RAP specimens. For the remaining mixtures (control, 25% RAP, 40% RAP), the stockpile percentages were adjusted to achieve an overall mixture gradation similar to the original 15% RAP gradation. The relative proportions of blast rock and sand stockpiles were held constant for the different mixtures to maintain the same relative structure (particle angularity, type of material) for the virgin material in the mixture. The gradations for the processed and grindings RAP mixtures are shown in Figures 1a and 1b, respectively. For the processed RAP mixtures, the increasing percentages of RAP cause the gradations to become finer at the smaller sieve sizes, with the 40% RAP mixture going into the restricted zone. All of the other gradations fall on the coarse side of the restricted zone. The three mixtures containing the grindings produce slightly finer gradations at the #30 sieve size, but are essentially the same as the control mix. The asphalt contents and volumetric properties of the mixtures are shown in Table 1. Mixing and compaction temperatures were kept constant for all of the RAP percentages; the RAP material was preheated at the mixing temperature.

SPECIMEN FABRICATION AND TESTING

Specimens were fabricated for both tension and compression testing, using the processed RAP only. The loose mixture was compacted into cylindrical specimens 150 mm in diameter and approximately 180 mm tall using a Superpave Gyratory Compactor (SGC). The final test specimens were cut and cored from the gyratory cylinders thus producing specimens 100 mm in diameter and 150 mm tall for the compression tests and 75 mm in diameter and 150 mm tall for the tension tests. These specimens have the most consistent air void distribution in both the vertical and radial directions based on the study by Chehab et al. *(6)*. These are the specimen geometries currently recommended for the simple performance test *(5)* and used in constitutive modeling of asphalt concrete in tension and compression *(7,8,9).*

Specimens were tested using a closed-loop servo hydraulic Instron testing system with computer control and data acquisition. An environmental chamber was used to control the testing temperature. The specimens were conditioned to the test temperature for several hours; the specimen temperature was monitored using a dummy specimen with an embedded thermocouple that had been subject to the same temperature history as the test specimen. Four LVDTs were mounted on the specimen to measure deformations over the middle 100 mm of the specimen height. For the compression tests, frictionless membranes were placed between the specimen ends and loading plates to allow the specimen to expand radially during loading, preventing a barreling effect due to restrained ends. The tension test specimens were glued to end plates that are then rigidly connected to the loading frame. The compression and tension test set-ups are shown in Figures 2a and 2b, respectively. Complex modulus and creep tests were performed on the specimens.

Complex Modulus Testing

The complex modulus test measures the response of the material to cyclic loading at different frequencies (usually ranging from 0.1-30 Hz) in the undamaged state. Asphalt concrete is a viscoelastic material, meaning that its response to a particular load depends on the magnitude of the load, the rate of application, and the duration of the load. Therefore, it is important to evaluate how the material responds to different frequencies or rates of loading, which correspond to the different traffic speeds a pavement could experience in the field. The complex modulus test consists of applying a sinusoidal load history to the specimen at different frequencies. The load amplitude is adjusted based on the material stiffness, temperature, and frequency to keep the strain response within the linear viscoelastic range.

The dynamic modulus, $|E^*|$, at each frequency is calculated by dividing the steady state stress amplitude (σ_{amp}) by the strain amplitude (ε_{amp}) as follows:

$$\left|E^*\right| = \frac{\sigma_{amp}}{\varepsilon_{amp}} \qquad (1)$$

Static Creep Compliance

The creep test measures the time-dependent deformation of the material under a static load. A constant load is applied and the strain response is measured during this test. The deformation or strain response can be divided into three zones:

1. Primary zone – where the strain rate decreases with loading time;
2. Secondary zone – where the strain rate remains constant with loading time; and
3. Tertiary zone – where the strain rate increases with loading time.

The creep compliance, a viscoelastic material property, can be determined when testing is conducted at a load level low enough not to induce any damage in the material. The appropriate load level for creep compliance testing is determined by testing a specimen with increasing load levels, each of which is followed by a low magnitude reference load to determine the linear viscoelastic range. This procedure is described further by McGraw *(10).* In this study, creep loading was applied to the specimen for 100 seconds at each test temperature. The creep compliance is calculated using the quasi-elastic method to approximate the linear viscoelastic convolution integral *(11):*

$$D(t) = \frac{\varepsilon(t)}{\sigma(t)} \qquad (2)$$

The static creep test is also performed at higher load levels to determine flow time, the time at which the tertiary zone begins, which is one of the Simple Performance Tests *(5)*. In this study, creep tests were performed at a stress level of 87 psi and a temperature of 45 C to determine flow time.

Master Curve Construction

Due to the temperature and rate dependent nature of asphalt concrete, it is necessary to describe the material behavior over a wide range of temperatures and loading rates, or time. Practical constraints on testing time and equipment constraints associated with collecting data at very short times (10^{-4} seconds) restrict the range of behavior that can be measured from a single test. Asphalt concrete is a thermorheologically simple material, thus the time-temperature superposition principle applies. Using the time-temperature superposition principle, the time and temperature dependent material properties can be represented using reduced time, ξ. For a constant temperature, the reduced time is defined as:

$$\xi \equiv \frac{t}{a_T} \qquad (3)$$

where a_T is the time-temperature shift factor. Complex modulus is described as a function of frequency, so in this case reduced frequency, γ, is used:

$$\gamma = f * a_T \qquad (4)$$

The same value of a_T at a particular temperature applies to any of the viscoelastic material properties. The data obtained from testing at several individual temperatures are shifted along the time or frequency axis to construct a master curve. The material properties at any temperature or rate of loading can then be determined by simply shifting the master curve to the desired range using the time-temperature shift factors. The dynamic modulus master curves are shifted to minimize the error between the measured data and a predicted equation of the form:

$$Log\left|E^*\right| = a + \frac{b}{1 + \frac{1}{e^{c + d\log\gamma}}} \qquad (5)$$

where a, b, c, and d are regression coefficients and γ is the reduced frequency. This sigmoidal equation accurately represents the upper and lower asymptotes that are characteristic of the dynamic modulus curve.

Dynamic modulus and creep compliance tests were conducted at temperatures of -10C, 0C, 10C, 20C, and 30C for all of the processed RAP mixtures.

EFFECT OF RAP ON VOLUMETRIC PROPERTIES

The volumetric properties of the processed and grindings RAP mixtures are shown in Table 1. For the processed RAP mixtures, the VMA and VFA values for the 25% and 40% RAP mixtures were higher than those for the control and 15% mixtures. For the grindings RAP mixtures, the VMA values increase with RAP percentage and the VFA values for all of the RAP mixtures are higher than the control mix. It is hypothesized that this difference is due to the extent of blending of the RAP material with the virgin materials. As part of the mixing procedure, the

RAP is preheated in the oven for a period of two hours prior to mixing with the virgin asphalt and binder. This is the procedure that the New Hampshire DOT uses to simulate plant operations. If the RAP material is not heated sufficiently, the RAP binder does not blend with the virgin binder to the extent possible and the RAP then tends to act more like a black rock material. The RAP particles have a coarser gradation than the RAP aggregate. Therefore, if the RAP particles do not completely break down and blend with the virgin materials the overall mixture gradation will be coarser and, with the same compaction effort, an increase in VMA is expected *(12)*.

To test whether heating time had an effect on the mixture volumetrics, several specimens with the 40% processed RAP were fabricated by heating the RAP for 2 hours, 3.5 hours, and 8 hours at the mixing temperature. The two hour time is the standard procedure used by the New Hampshire DOT. The 3.5 hour time is the time required for the RAP to reach mixing temperature, and 8 hours is equivalent to the time the aggregate is heated (usually overnight) in the oven. The same compaction effort was used in fabricating all of the specimens and the result of this testing is shown in Table 2. The VMA decreases by 0.5% when the heating time increases from 2 to 3.5 hours, and then increases by almost 3% with the longer heating time. At the shorter heating time, the RAP is not heated enough to allow the RAP particles to break up into smaller pieces and blend with the virgin materials. At the longer heating time, the RAP has likely aged further and the RAP particles have hardened and even fewer of them are able to break down and blend with the virgin material. This indicates that there is an optimum heating time for the RAP material to allow for the greatest extent of blending between the virgin and RAP materials.

The VMA values for a design air void content of 4% were calculated and shown in Table 2. The longer heating times decrease the VMA values, and may affect the mixture design and design asphalt content. A RAP mixture may not meet the Superpave VMA requirements when the RAP is heated for a particular amount of time, but may meet the requirements if the RAP is heated for a different amount of time. Therefore, it is very important that the laboratory procedures for producing RAP mixture simulate the plant operations as close as possible. More research is needed in this area, as the way RAP is handled in the lab can significantly affect the mix design and therefore the performance of the mix in the field.

EFFECT OF RAP ON VISCOELASTIC MATERIAL PROPERTIES

Dynamic Modulus

The dynamic modulus master curve for each test specimen was created independently. The master curves for all specimens of each mixture were combined and a regression line fit to describe the mean value of the dynamic modulus for that mixture. The regression line is the same form (Equation 5) that is used to construct the individual master curves. At least two replicate specimens were fabricated and tested to construct the dynamic modulus master curves for the mixtures. The mean square error from the regression analysis for each mixture is shown in Table 3. The mean square error increases with increasing percentages of RAP for the compression tests, indicating that the specimen to specimen variability is higher with these mixtures. This is expected due to the variability of the RAP itself and also due to the mixing procedures. The aggregate structure (gradation) for each mixture was designed using the overall gradation for the RAP stockpile. In fabricating the specimens containing RAP, a specific quantity of RAP was added using representative sampling methods. This introduces more variability in the actual specimens because the different sizes of the RAP stockpile cannot be separated and added exactly according to the gradation (the individual aggregate particles are combined with the asphalt and impossible to separate into individual size fractions). Therefore, with increasing amounts of RAP, higher variability is expected in the material properties. The higher variability was not seen when testing in tension, however. The three RAP mixtures have similar values for the mean square error, all lower than that for the control mixture. This indicates that the variability in the mixture is not as evident in tension testing as in compression testing. The changes in gradation will be noticed more in compression testing because the aggregate skeleton contributes more to the overall strength of the material than in tension.

Figures 3a and 3b show a comparison of the dynamic modulus master curves at 20^{o}C for the control and 15% RAP mixtures tested in compression and tension, respectively. The addition of RAP increases the stiffness of the mixture in both cases; however, that increase is greater in compression than in tension. At lower frequencies, the mixtures have similar stiffness in both tension and compression. The difference in stiffness between the two mixtures increases with frequency in compression and appears to reach a constant difference after a point in tension. Relating this to the anticipated performance of the mixtures in the field, the two mixtures would be expected to have similar resistance to rutting as the low frequency stiffness in compression is similar. The low frequency material behavior is representative of the stiffness of the mixture under slow or standing traffic and/or the behavior at high temperatures, both critical conditions for permanent deformation. To evaluate the performance of the mixtures with respect to fatigue and thermal cracking, the tensile material stiffnesses at higher frequencies, corresponding to lower temperatures, are compared. The mixture containing 15% RAP exhibits higher stiffness than the control mixture. The stiffness alone is does not give the full picture however, because the ductility or brittleness of the mixture will also affect its performance with respect to cracking. The 15% RAP mixture contains a percentage of aged asphalt binder, which is more brittle than virgin binder; therefore it is reasonable to expect the 15% RAP mixture to be more brittle than the control mix. The combination of higher stiffness and more brittle behavior will likely result in a shorter fatigue life and a higher probability of thermal cracking occurring in the field. It should also be noted that the thicknesses of the asphalt layer and the total pavement structure have a significant effect on the fatigue performance of mixtures and cannot be discounted in the determination of overall performance.

The mean fit curves for the dynamic modulus master curves at 20^{o}C of all four processed RAP mixtures tested in compression and tension are shown in Figures 4a and 4b, respectively. The dynamic modulus curves for the 25% RAP and 40% RAP mixtures are similar to that for the control mixture, when it would be expected that they would have higher dynamic modulus values than the 15% RAP mixture, especially at the higher frequencies. The air void content of all the specimens tested is 4 ±0.5% and should have minimal effect on the dynamic modulus variation seen. There are several possible explanations for the unexpected results. First, the 25% RAP mixture has an asphalt content that is higher than that of the 15% RAP mix. Mixtures with higher asphalt content have been shown to have lower dynamic modulus values *(9)*. Secondly, the gradations for the 25% and 40% processed RAP mixtures are finer, especially in the 0.3 mm to 2.36 mm particle size range and finer gradations typically have lower stiffness *(9)*. The gradations among the different mixtures in this project were allowed to vary to maintain the same relative percentages of blast rock and sand for the virgin aggregate. This was done to maintain consistent aggregate properties (aggregate angularity and specific gravity) for the virgin material in each mixture.

Table 4 shows the uncompacted void contents, a measure of fine aggregate angularity, for the virgin aggregate stockpiles and the aggregate extracted from the processed RAP. The processed RAP aggregate has slightly lower angularity than the blast rock stockpiles, but not as low as the natural sand. The combined values for the various mixtures are also shown in Table 4. The aggregate angularity decreases with increasing percentages of RAP, but all of the values are above the Superpave minimum value of 40%. The effect of the aggregate angularity is expected be more pronounced in compression testing, where the aggregate structure has a greater contribution to the overall mixture stiffness. The dynamic modulus mastercurves in Figure 5 do not show much difference between tensile and compressive testing, indicating that the differences in fine aggregate angularity between the different mixtures with varying percentages of RAP are not significant enough to affect the measured values. A Florida study *(13)* found that there was no correlation between fine aggregate shear strength and fine aggregate angularity and that fine aggregate angularity alone did not reflect the rutting performance measured in the lab using the Asphalt Pavement Analyzer.

It is hypothesized that the lower than expected dynamic modulus curve for the 25% RAP mixture is due to a combination of higher asphalt content, finer gradation, and higher VMA and VFA. The 40% RAP mixture likely exhibits lower dynamic modulus due to the finer gradation and higher VMA and VFA. This follows the findings of the Florida study *(13,14)* where mixes with higher VMA exhibited lower stiffness.

Creep Compliance in Compression

The creep compliance master curve was constructed for each individual specimen tested in compression only. The creep master curves for each mixture were then fit using a modified power law to describe the mean value of compressive creep compliance for that mixture. The form of the modified power law (MPL) is:

$$D(t) = D_0 + \frac{D_\infty - D_0}{\left(1 - \frac{\tau_0}{t}\right)^n} \tag{6}$$

where τ_0 is a regression coefficient, n is the slope of the linear region of the creep curve on a log-log scale, and D_0 and D_∞ are the values of the lower and upper asymptotes, respectively. The MPL creep compliance curves at 20°C for the four mixtures are shown in Figure 6. The increase in stiffness, or decrease in compliance, is evident for the mixture containing 15% RAP. This is similar to the change in creep compliance for a mixture that is subject to aging, as shown in Figure 7 *(15).* The STA curve is for a mixture subject to short term oven aging and the LTA curves represent increasing levels of long term oven aging in the laboratory. It is rational to expect the creep compliance curves for mixtures with increasing percentages of RAP to follow the same trend as a mixture at various levels of aging. The RAP in the mixture is essentially adding aged binder to the mixture; therefore larger percentages of RAP are expected to have the same effect as increased aging. The 25% RAP and 40% RAP mixtures do not follow the expected trend. The relationship among the creep compliance master curves is similar to the dynamic modulus master curves, indicating that the difference in gradation and volumetric properties between the mixtures is significantly affecting the material properties. Researchers in Florida found that high VMA mixtures exhibited higher creep compliance and lower stiffness *(14)*. The differences in the master curves are due to a combination of the amount of RAP, the asphalt content, the gradation of the mixture, and the mixture volumetrics. These effects are impossible to separate without further testing.

The results of the creep flow time tests are presented in Table 5. The creep flow time increased with higher processed RAP percentages, with the exception of the 25% RAP mixture. It is expected that the processed RAP will increase the stiffness of the mixture, which will increase the creep flow time. The 25% mixture exhibits a shorter flow time, likely due to the higher asphalt content.

SUMMARY AND CONCLUSIONS

The purpose of this study was to examine the effect of RAP on the volumetric properties and stiffness of HMA. The addition of RAP increased the VMA and VFA of the mixtures. Also, the study indicated that there is an optimal pre-heating time for RAP to allow the particles to soften, break down, and blend with the virgin materials. Further research in this area is needed to determine how best to simulate the plant operations in the lab, especially for mix design.

The tension and compression dynamic modulus, and compression creep compliance master curves for a control mixture and mixtures containing 15%, 25%, and 40% processed RAP were presented and discussed. The addition of 15% RAP increased the stiffness of the mixture and decreased the compliance, as would be expected. This indicates that the mixture containing RAP will be more resistant to permanent deformation and less resistant to fatigue and thermal cracking in the field. The addition of RAP to a mixture adds a proportion of aged binder and the effect of 15% RAP on the rheological properties of the mixture is similar to that reported for aged mixtures.

The mixtures containing 25% and 40% RAP did not follow the expected trends. Instead, the dynamic modulus and creep compliance curves were similar to that for the control mixture. It is likely that a combination of variables is influencing the material behavior for these mixtures: the 25% RAP mixture has higher asphalt content and a finer gradation, and the 40% RAP mixture has a gradation finer than that for the 25% RAP mixture. The 25% and 40% RAP mixtures also have higher VMA and VFA values than those for the control and 15% mixtures. All of these effects will tend to soften the mixture, decreasing the dynamic modulus and increasing the creep compliance. Creep flow time tests were also conducted; the flow time increases with the addition of RAP, except for the 25% mixture.

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TABLE 1 Mix Design Parameters

		Processed			Grindings		
	Control	**15% RAP**	**25% RAP**	**40% RAP**	**15% RAP**	**25% RAP**	**40% RAP**
% ac	4.8	5.1	5.4	4.9	4.9	5.2	5.2
Gmm	2.451	2.483	2.445	2.466	2.452	2.460	2.475
VMA	13.1	13.3	16.3	15.2	13.8	14.3	14.7
VFA	69.4	69.9	75.4	73.6	71.8	71.0	73.0
DP	1.14	1.10	0.88	1.02	0.91	0.75	0.75

TABLE 2 Effect of RAP Heating Time on 40% Processed RAP Mixture Volumetrics

		Duration of Preheating		
		2 hours	**3.5 hours**	**8 hours**
	Gmm	2.484	2.480	2.479
Same Compaction Effort	**Air Voids**	4.0%	4.4%	7.6%
	VMA	15.1%	14.6%	17.5%
	VFA	73.6%	70.1%	56.3%
Same Air Void Content	**Air Voids**	4.0%	4.0%	4.0%
	VMA	15.1%	14.2%	14.4%
	VFA	73.6%	71.2%	72.2%

TABLE 3 Mean Square Errors from Dynamic Modulus Master Curve Regressions

		Mean Square Error (kPa)
Compression	Control	12690
	15% Proc RAP	13817
	25% Proc RAP	24876
	40% Proc RAP	28935
Tension	Control	21513
	15% Proc RAP	16144
	25% Proc RAP	14470
	40% Proc RAP	14683

TABLE 4 Uncompacted Void Contents for Fine Aggregates

		Uncompacted Void Content*
Aggregate Stockpiles	Bank Run Sand	41.8
	Washed Machine Sand	48.1
	Unwashed Sand	48.7
	Baghouse Fines	48.7
	Processed RAP	46.2
Mixtures	Control	47.1
	15% RAP	46.4
	25% RAP	46.1
	40% RAP	45.9

*Determined using ASTM 1252 Method A

TABLE 5 Creep Flow Times for Processed RAP Mixtures

Mixture	Creep Flow Time (s)
Control	553
15% RAP	1445
25% RAP	350
40% RAP	3050

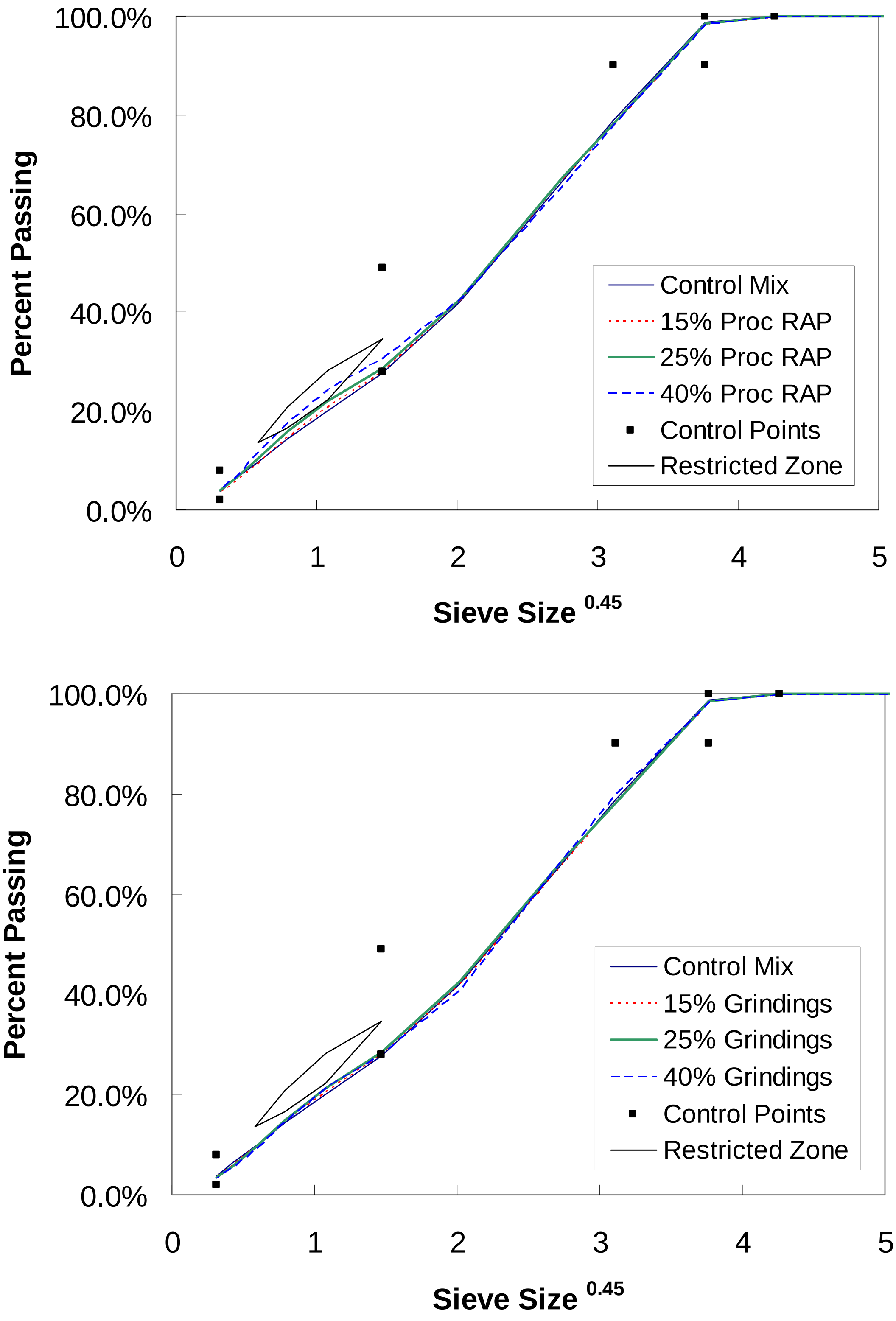


FIGURE 1 Asphalt Mixture Gradations (a) Processed RAP Mixtures (b) Grindings RAP Mixtures

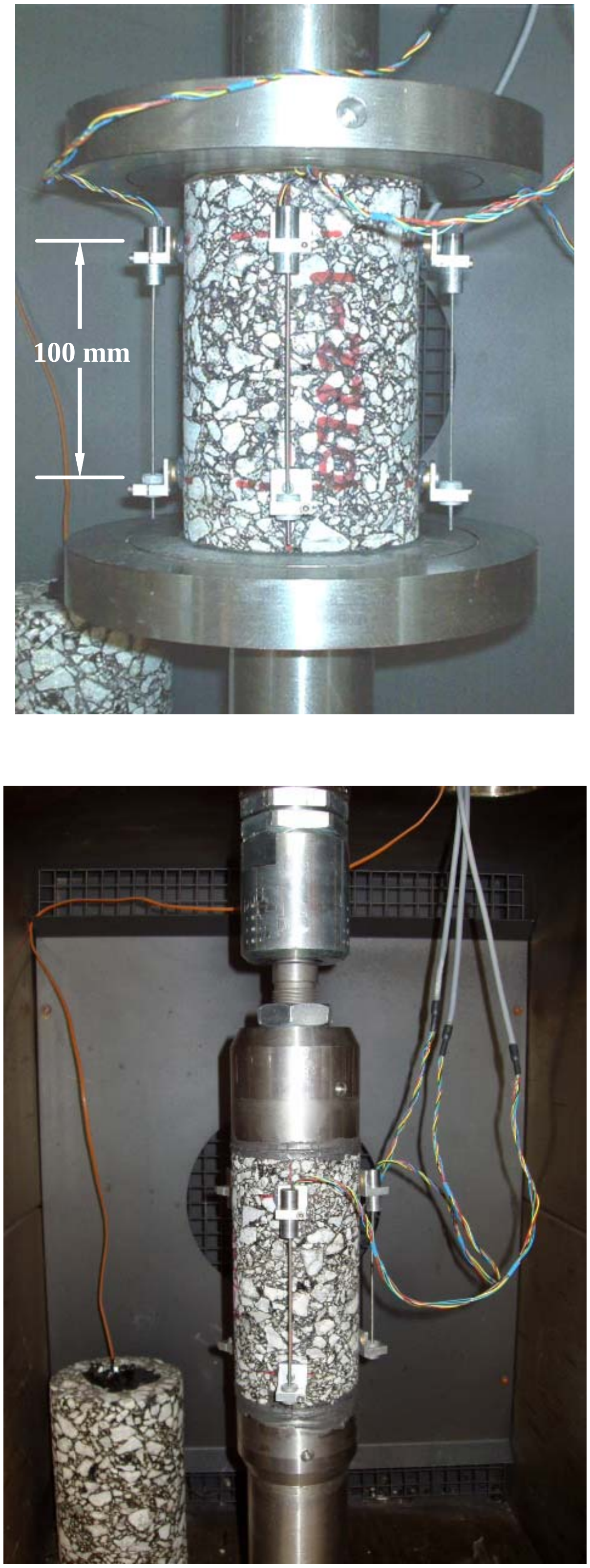
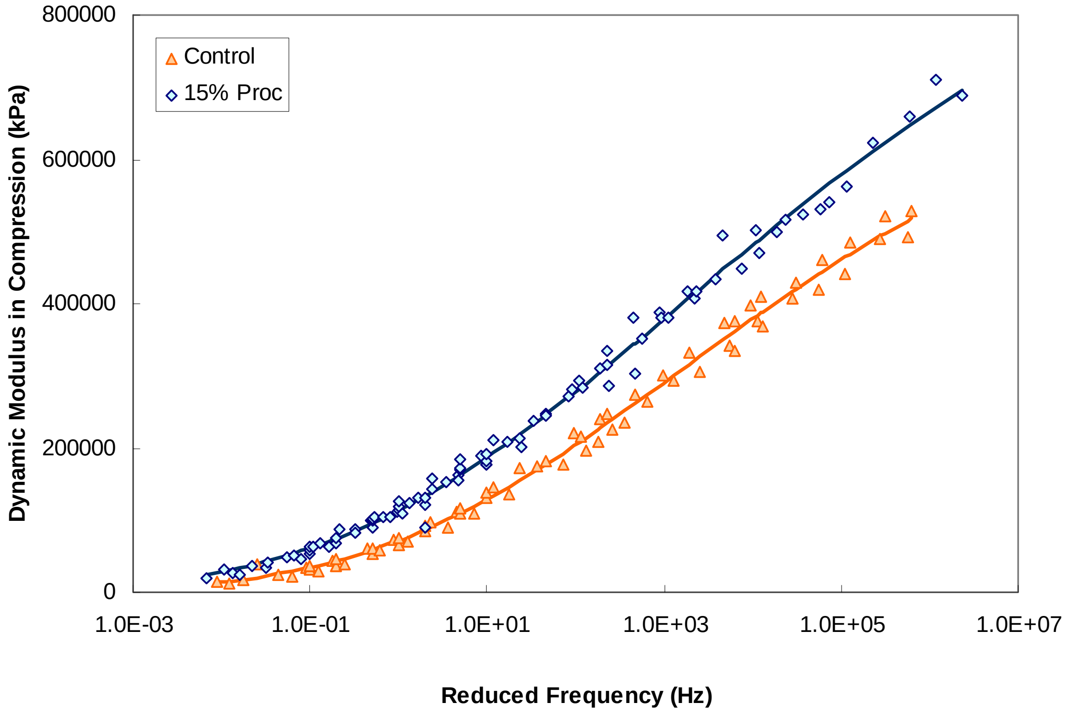


FIGURE 2 Test Setup (a) Compression (b) Tension



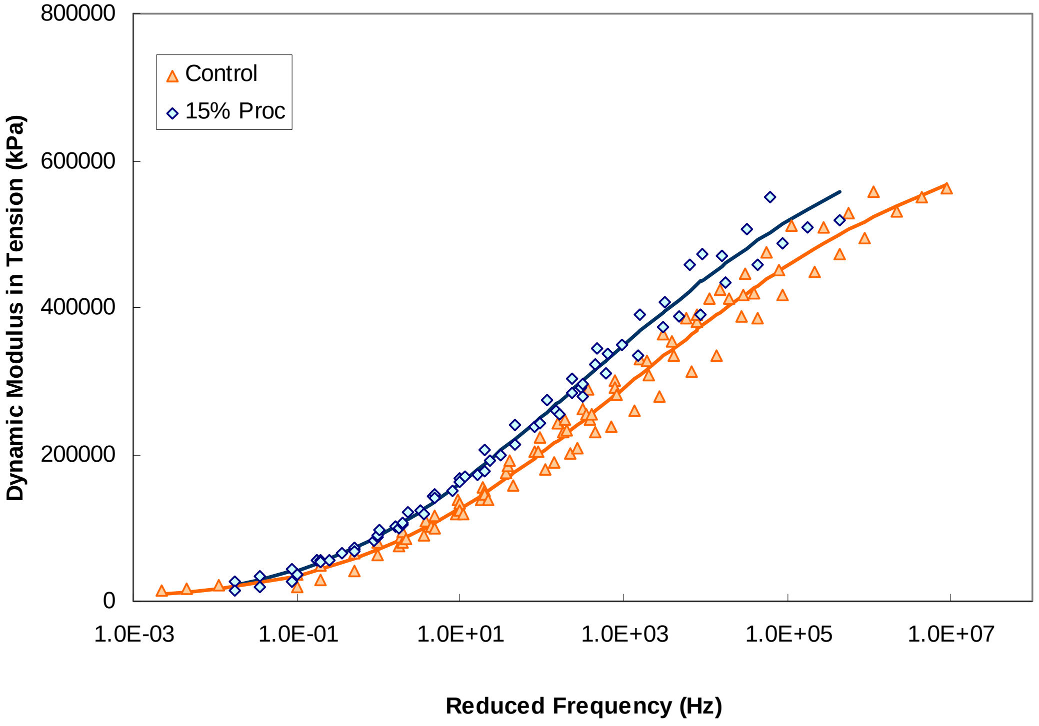
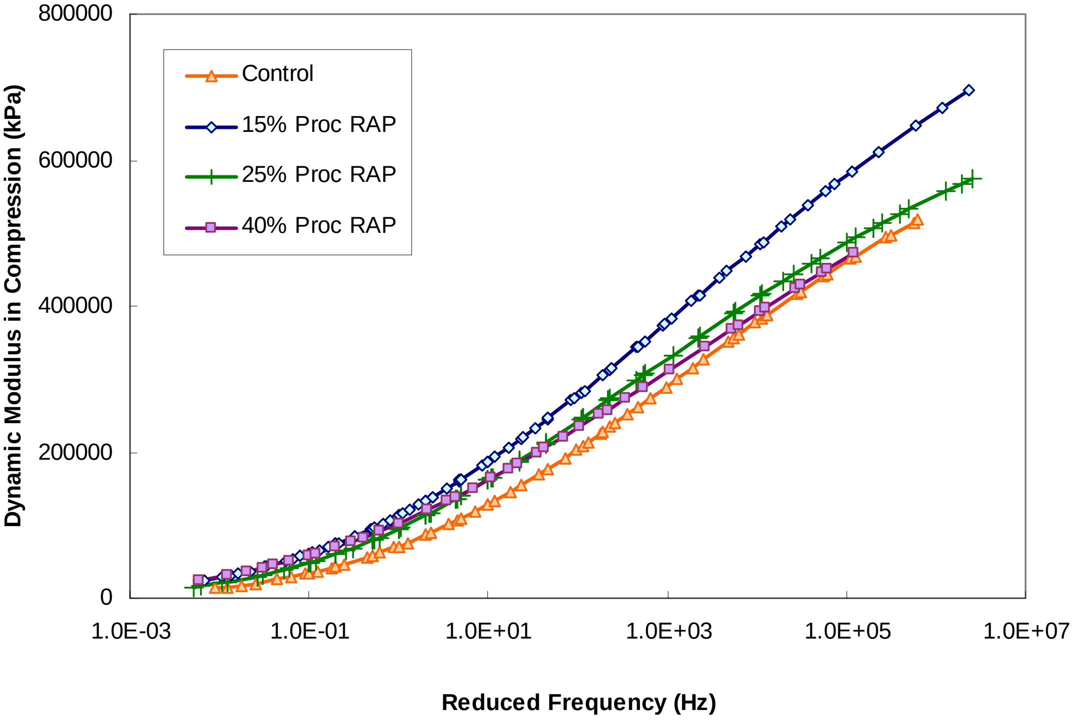


FIGURE 3 Comparison of Control and 15% RAP Dynamic Modulus Master Curves at 20°C Tested in (a) Compression (b) Tension



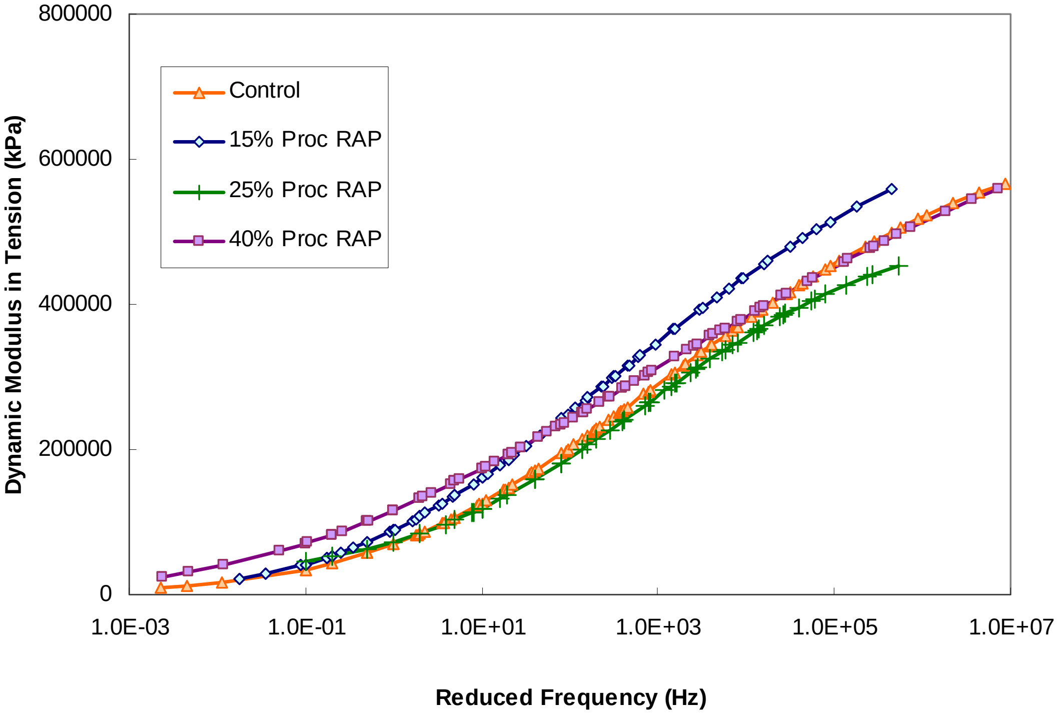


FIGURE 4 Dynamic Modulus Master Curves at 20^{o}C (mean fit lines) for All Mixtures Tested in (a) Compression (b) Tension

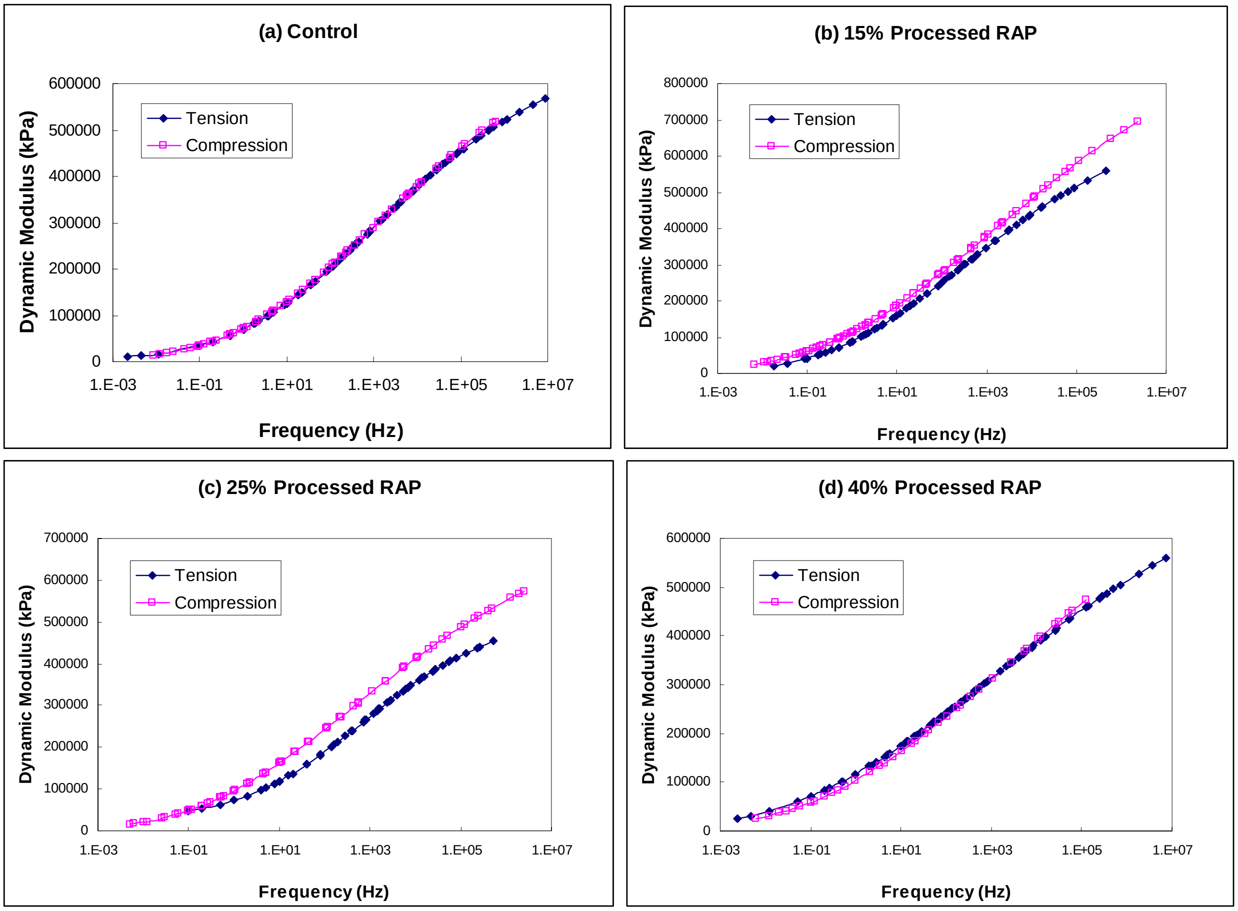


FIGURE 5 Comparison of Compression and Tension Dynamic Modulus Curves at 20^{o}C (a) Control (b) 15% Processed RAP (c) 25% Processed RAP (d) 40% Processed RAP

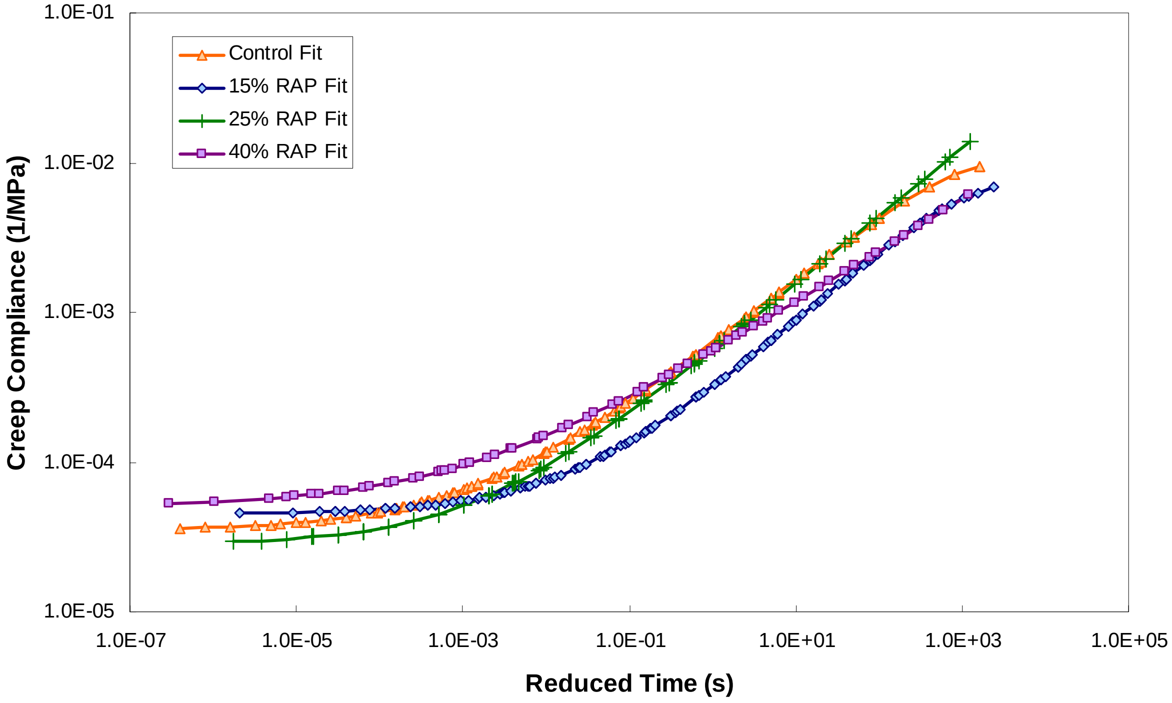


FIGURE 6 Compression Creep Compliance Master Curves at 20°C (MPL fit lines) for All Processed RAP Mixtures

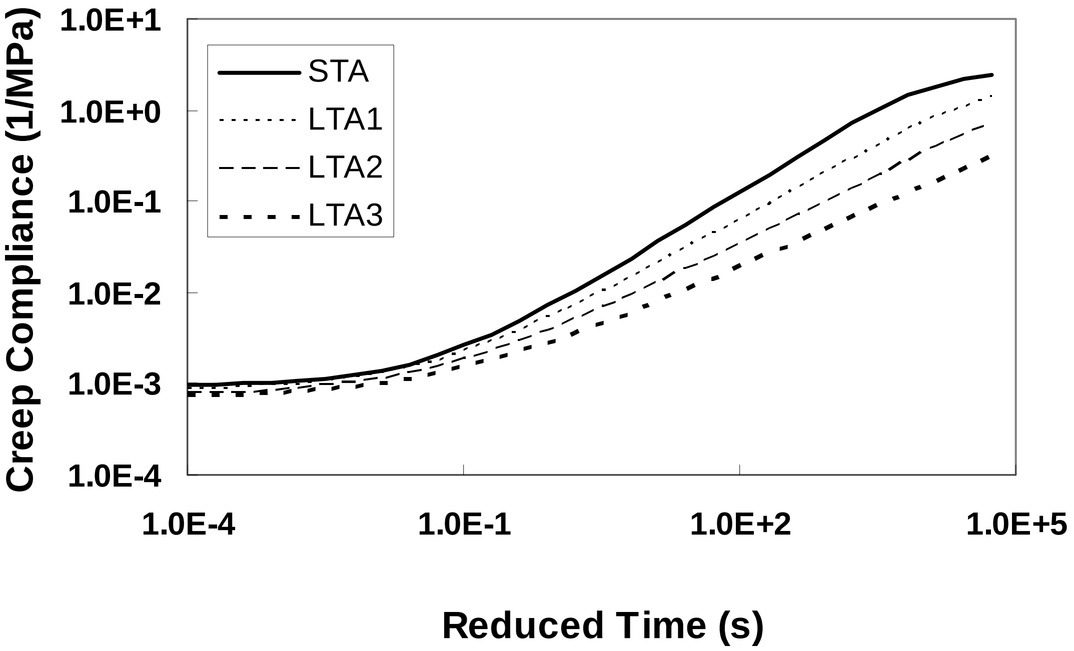


FIGURE 7 Creep Compliance Curves for Various Levels of Aging (from Daniel and Kim, 1998)