Laboratory Evaluation of Asphalt Rubber Mixtures Using the Dynamic Modulus (E*) Test

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ABSTRACT

For thirty years, the Arizona Department of Transportation has been adding crumb rubber to the asphalt concrete with remarkable performance. A primary objective of this study was to evaluate the laboratory performance of these mixtures by conducting the Dynamic Complex Modulus (E*) test. Field samples of two Asphalt Rubber (AR) mixtures were used: Asphalt-Rubber-Asphalt-Concrete-Gap-Graded, and Asphalt-Rubber-Asphalt-Concrete-Friction-Course-Open-Graded mixes, which utilized a common base binder grade of PG 58-22. Tests were performed unconfined and confined (three different levels), and the E* master curves were developed for each mixture and test condition.

The E* test results for the AR mixes were compared with conventional dense graded mixtures test results available from previous studies at Arizona State University. A modular (E*) ratio was calculated for all mixtures using a conventional PG 64-22 mixture as a reference. A comparison of the modular ratios was done at 14°F and 100°F, for a selected frequency of 10 Hz.

For the unconfined tests, at 14°F, the AR exhibited the lowest modular ratio (lowest stiffness) and therefore the best performance against cracking. At 100°F, the AR mixtures had comparatively the lowest stiffness values. However, when the comparison of the ratios was made with confined test results, the AR mixtures showed higher modulus values, and therefore, the best performance against permanent deformation. Since the performance of the AR mixtures have been remarkable in the field, the results of this study showed the importance of using confined tests when comparing the performance of open graded to dense graded mixtures.

INTRODUCTION

For years, engineers and pavement designers have looked for ways to improve the performance of asphalt concrete pavements to prevent distresses like low temperature cracking or permanent deformation (rutting) at high temperatures. The addition of different types of modifiers or the use of different binder grades has been tried with variable results. In Arizona, the addition of crumb rubber to AC pavements goes back to the early 1970's and the performance of these pavements has been great. *Asphalt Rubber (AR)* mixtures have shown (through field performance) to prevent reflection cracking, to withstand the hot conditions of the Arizona desert, and the cold conditions at higher elevations (e.g. Flagstaff, AZ). Furthermore, AR pavements showed advantages in reducing tire noise, and improving the ride quality (1).

In the summer of 2001 the Arizona Department of Transportation and Federal Highway Administration in cooperation with FNF Construction entered into an agreement with Arizona State University to sample and test two asphalt rubber mixes being used on the Interstate I-40, Buffalo Range paving project, east of Flagstaff, Arizona. The asphalt rubber mixes that were sampled included a gap graded mix with 6.8 percent asphalt rubber binder and an open graded friction course mix with 8.8 percent asphalt rubber binder. The two mixes are typical of those used in Northern Arizona. The gap graded mix is generally placed 50 mm thick as an overlay, and the open graded is placed above the gap graded as the final wearing course 12.5 mm thick.

This testing program is part of a new research program at ASU to conduct asphalt mixture tests being evaluated as part of the NCHRP AASHTO 2002 Pavement Design Guide and Simple Performance Test research projects. The purpose of the testing is to characterize the rutting and fatigue cracking potential of each mix. Over time the results of the testing will be compared to the actual field performance of the asphalt rubber mixes. This paper presents the test results in a comparative manner to typically used Arizona dense graded asphalt mixes.

RESEARCH OBJECTIVES AND SCOPE OF WORK

The objective of this study was to evaluate the dynamic modulus properties of the AR mixtures included in the I-40 Project. The scope of work included conducting confined and unconfined laboratory dynamic modulus tests, develop the master curves, and compare the results to conventional ADOT mixtures and performances.

BACKGROUND OF THE DYNAMIC (COMPLEX) MODULUS TEST

For linear viscoelastic materials such as asphalt mixes, the stress to strain relationship under a continuous sinusoidal loading is defined by a complex number called the complex modulus E* (ASTM D3497). The complex modulus has a real and imaginary part that defines the elastic and viscous behavior of the linear viscoelastic material. The absolute value of the complex modulus $|E^*|$, is defined as the dynamic modulus. Mathematically, the dynamic modulus is defined as the maximum (peak) dynamic stress (σ_o) divided by the recoverable axial strain (ε_o):

$$|E^*| = \sigma_o / \varepsilon_o \quad (1)$$

By current practice, dynamic modulus testing of asphaltic materials is conducted on unconfined cylindrical specimens having a height to diameter ratio equal to 1.5 and uses a uniaxially applied sinusoidal (haversine) stress pattern (2, 3). Under such conditions, the sinusoidal stress at any given time t, is given as:

$$\sigma_t = \sigma_o \sin(\omega t) \tag{2}$$

where:

σ_o = peak dynamic stress amplitude (psi).
ω = angular frequency in radian per second.
t = time (sec).

The subsequent dynamic strain at any given time is given by:

$$\varepsilon_t = \varepsilon_o \sin(\omega t - \phi) \tag{3}$$

where

ε_o = peak recoverable strain (in/in).
ϕ = phase lag or angle (degrees).

The phase angle is simply the angle at which the ε_o lags σ_o, and is an indicator of the viscous or elastic properties of the material being evaluated. Mathematically this is expressed as:

$$\phi = (t_i / t_p) \times (360) \tag{4}$$

where

t_i = time lag between a cycle of stress and strain (sec).
t_p = time for a stress cycle (sec).

EXPERIMENTAL PROGRAM

Mixtures Properties

Two AR mixtures with the same base asphalt type (PG 58-22) with approximately 20% of crumb rubber (main particle size – 30 sieve), by weight of binder, were used: Asphalt Rubber Asphalt Concrete (ARAC) Gap Graded mixture, and Asphalt Rubber Asphalt Concrete Friction Course (AR-ACFC) Open Graded mixture. The aggregate nominal sizes for both mixtures were 19.0 and 9.0 mm, respectively. The ARAC mixture had average in-situ air voids of 11%, while the AR-ACFC mixture in-situ air voids were approximately 18%.

Laboratory Testing Conditions

Dynamic Modulus tests were conducted unconfined as well as using three levels of confinements: 10, 20, and 30 psi. Test specimens used were cored from laboratory compacted Gyratory plugs, approximately six inches in diameter and six inches high, to arrive at test specimens with a diameter of 4.0 inches and an approximate trimmed height of 6.0 inches. For each mixture, a full factorial of test frequencies (0.1, 0.5, 1, 5, 10, and 25 Hz) and temperatures

(14, 40, 70, 100, and 130°F) was used. Each specimen was tested in an increasing order of temperature, i.e. 14, 40, 70, 100, and 130°F. For each temperature level, specimens were tested in a decreasing order of frequency (25, 10, 5, 1, 0.5, and 0.1 Hz). This temperature-frequency sequence was carried out to cause minimum damage to the specimen before the next sequential test. At cold temperatures and high frequency level, the material behaves stronger compared to warmer temperatures and at low frequency levels.

A servo hydraulic testing machine was used to load the specimens. The load was varied with temperature to keep the specimen response within a linear range (initial microstrains about 20-25 micro-strain). A dynamic sinusoidal stress (continuous wave) was applied and measured through the machine load cell, whereas, the deformations were measured using spring-loaded LVDT's (Linear Variable Differential Transducers). The specimen instrumentation method used was the one developed by the ASU Research Team (4). The LVDT's were secured in place using brackets and studs glued on to the specimen; guiding rods were added to the instrumentation for alignment especially at high temperatures. A typical set-up of the test specimen instrumentation is shown in Figure 1.

For the ARAC mixture, three replicate specimens were used for the unconfined test, and three additional replicate specimens (total of six specimens) were used for all the confined tests in an increasing order of confinement (10, 20, and 30 psi). This was mainly done because the amount of material available for the ARAC mixture was limited. For the AR-ACFC mixture, material availability was not an issue; therefore three replicate specimens were used for the unconfined tests and for each level of confinement (total of twelve specimens). A round of unconfined E* tests were performed at room temperature (70°F) on all twelve specimens to ensure that they are true replicates and provide comparable results. This sequence of testing resulted in a total of 774 dynamic modulus tests on eighteen specimens.

Additional tests were performed on a formed (molded) crumb rubber specimen consisting of 80% crumb rubber and 20% urethane. This was done because the results of both AR mixtures showed a different behavior at higher temperatures. For that, the crumb rubber sample was prepared and tested unconfined at 70, 100, and 130°F using the same loading frequency levels. For this crumb rubber sample, a total of 18 dynamic modulus tests were conducted.

TEST RESULTS AND ANALYSIS

Detailed test results for the individual replicates tested including the Dynamic Modulus, phase angles, and volumetric properties can be found in References 5 and 6. The remainder of this paper presents a summary of the data analysis and a comparison of the AR mixture test results to conventional dense graded mixtures.

ARAC Gap Graded Mixture Test Results

Figure 2 and 3 are plots of (a) the effect of loading time on the measured dynamic modulus for a selected replicate test, (b) its corresponding shift factors plot, and (c) the master curve developed using the average of the three replicates. Figure 2 shows the results for the unconfined tests; whereas Figure 3 shows the results for the 30-psi confined tests. Figure 4 shows a comparison of the master curves obtained for the unconfined and confined tests.

The comparison of the results for the unconfined and confined tests in Figure 4 show that there is a significant increase in the E* values with confinement at higher temperatures and lower frequencies, compared to the low temperature part of the curve. The difference in E* results between the unconfined and confined tests at higher temperatures become less as the confinement is increased: 400% increment from unconfined conditions to a 10-psi confinement, 25% from 10 to 20-psi confinement, and 11% increment from 20 to 30-psi confinement. The difference between the unconfined and confined tests at lower temperatures is much less, but still significant between the different levels of confinement.

Additionally, as shown in Figure 3 (a), there were cases where the E* value of the specimens at 100 or 130°F were equivalent. It has been surmised that this is due in large measure to the decreased role of the asphalt cement in relationship to the increased role of the rubber particles at higher temperatures. Further analysis on this observation is discussed in subsequent sections.

AR-ACFC Open Graded Mixture Test Results

Figure 5 and 6 are plots of (a) the effect of loading time on the measured dynamic modulus for a selected replicate test, (b) its corresponding shift factors plot, and (c) the master curve developed using the average of the three replicates. Figure 5 shows the results for the unconfined tests; whereas Figure 6 shows the results for the 30-psi confined tests. Figure 7 shows a comparison of the master curves obtained for the unconfined and confined tests.

Similar trends to the ARAC mixture were observed for the AR-ACFC mixture. Figure 7 shows a significant increase in the E* values with confinement at higher temperatures and lower frequencies, compared to the low temperature part of the curve. The difference in E* results between the unconfined and confined tests at higher temperatures stay significant as the confinement level is increased: 250% increment from unconfined conditions to a 10-psi confinement, 61% from 10 to 20-psi confinement, and 62% increment from 20 to 30-psi confinement. In addition, this difference between the different levels of confinements is negligible at lower (cold) temperatures. However, the difference between the unconfined and confined tests is still significant (unlike the ARAC mix) at the lower temperatures.

Crumb Rubber Specimen Test Results

Because of the similarity in some of the test results obtained at 100 and 130°F, that is, the insignificant change in E* values at the higher temperatures, it was decided to conduct E* tests on a crumb rubber specimen (80% crumb rubber and 20% urethane) and observe its behavior at higher test temperatures. Figure 8 shows the result of E* at 70, 100, 130°F. It is observed that the E* values remain almost the same throughout the test at the different frequencies (loading time) and the three test temperatures. Note that the vertical scale of the plot highlights some differences, but in reality those differences are minimal. It can be concluded from this plot that there are no significant changes in E* values measured for the crumb rubber specimen due to temperature or time of loading (test frequency) changes. These results may explain, in part, some of the behavior of the AR mixture specimens when tested at high temperatures. One possibility for the insignificant differences in the E* test results at the higher temperatures is due to the decreased role of the asphalt cement and the increased role of the crumb rubber particles which seems to dominate the behavior of the mix as the test temperature increases.

COMPARISON OF ASPHALT RUBBER AND CONVENTIONAL MIXTURES

Test results for two conventional ADOT dense graded mixtures utilizing PG 76-16 and PG 64-22 binders were used as a comparison to the results of the AR mixtures. The E* master curves obtained using unconfined tests were compared as shown in Figure 9. In the figure, the conventional PG 76-16 mixture shows higher modulus values at all temperature and frequency conditions. The AR E* values are more comparable to the conventional PG 64-22 mixture. Despite the air void differences between the mixtures, the addition of crumb rubber indeed enhances the properties of a PG 58-22 conventional mixture. In fact, at high temperatures the AR mixture had higher modulus values than the PG 64-22 conventional mixture; and at low temperatures the AR mixtures had lower modulus values. Both results support the field observed performance of resistance to deformation at high temperatures, and to resistance to cracking at low temperatures.

Although it is clear that the PG 76-16 has a stiffer behavior, it should be also noticed that the difference in air void content between the mixes had an impact on the results. Higher air voids in the mix generally result in lower modulus values. Further comparison of these mixes at similar air voids contents (specifically for the gap graded mix) is needed.

Modular Ratio (R)

Using the E* unconfined test results at 14°F and 100°F, both at 10 Hz, for the AR mixes and test results available at ASU from previous studies, the ratio of the dynamic modulus between the different mixes and that of a reference selected mix can be calculated (2, 7, 8). A comparison table and ranking can be established for the different mixes. The modular ratio (R) was calculated using the following equation (9):

$$R = \frac{E^*_{mix}}{E^*_{Reference}} \tag{6}$$

where

R = Modular Ratio

E^*_{mix} = Dynamic Complex Modulus value for a given mixture

$E^*_{Reference}$ = Dynamic Complex Modulus value for the reference mixture

At cold temperatures, cracking is the most important consideration for an AC mixture. If the mix is too stiff, it will be more susceptible for cracking. Thus, to achieve the desired behavior of less or no cracking of an AC layer at a cold temperature, a lower stiffness is desirable. Therefore, in the ranking shown in Table 1 (a) for E* values at 14°F, the best performance will be that for the mix with the lowest E* value. Conversely, at high temperatures, rutting or permanent deformation is the most important distress that the AC mixture is affected by. The desired behavior of an AC mixture at high temperatures is to have as stiff a layer as possible. Therefore, the ranking presented in Table 1 (b), shows the best mix is the one that has the highest E* value at 100°F.

For this analysis, the PG 64-22 conventional ADOT mixture, mentioned in the previous section, was used as the reference mixture. At the low temperature, Table 1 (a) shows that the AR mixtures have the lowest E* values (lowest modular ratio), which is the desired behavior to prevent cracking. Table 1 (b) shows the modular ratio at 100°F. The AR mixtures are at the bottom section of the ranking. This was attributed to the lower stiffness values observed for these mixtures using unconfined E* tests, and also due to the fact that these mixes had much higher air void content.

However, the field experience with these mixes, observed from several Arizona projects, shows that the AR mixtures have excellent performance (great resistance to permanent deformation) at high temperatures. Since the field mixtures are subjected to different levels of confinement, it was decided to further compare the E* test results at confined testing conditions. Test results using 20-psi level of confinement were available for conventional and AR mixtures (2, 7). For this comparison the ARAC mixture was chosen as the reference mixture. Table 2 (a) and (b) show the modular ratio calculated for each mixture at 14°F and 100°F, respectively. Similarly to the unconfined test results, the AR mixes ranked at the top of Table 2 (a), showing the best performance (i.e. lowest dynamic modulus). However, Table 2 (b) shows that the ranking is opposite to what was observed in the unconfined tests. In fact, the ranking of the AR mixture was changed and topped the rankings of the conventional mixtures. The AR-ACFC Open Graded mixture had the highest stiffness followed by the ARAC Gap Graded mixture. This was an important and comforting finding, since this type of behavior (ranking order of mixes) is what is being observed in the field. Therefore, it should be emphasized that when comparing dense, gap and open graded mixtures, the confined E* tests would better rank and also describe the expected performance of the mixes in the field. This may sound contradictory to findings of NCHRP 9-19 Simple Performance Project, but in fact it is not. The reader is reminded that none of the mixes under the first evaluation phase of NCHRP 9-19 Project included open or gap graded mixtures.

SUMMARY AND CONCLUSIONS

Several tests were performed to obtain the Dynamic (Complex) Modulus properties of two Asphalt Rubber (AR) mixtures studied: ARAC Gap Graded and AR-ACFC Open Graded mixtures. Both mixtures utilized a base binder grade of PG 58-22. Additionally, a crumb rubber specimen consisting of 80% crumb rubber and 20% urethane was tested to verify the behavior of AR mixtures at high temperatures. There were cases where the dynamic modulus values at 100 or 130°F were equivalent. It has been surmised that this is due in large measure to the decreased role of the asphalt cement in relationship to the increased role of the rubber particles at higher temperatures.

In addition, unconfined dynamic modulus test results for the two AR mixtures were compared with available test results for conventional mixtures. The two conventional ADOT dense graded mixes include a mix with a PG 76-16 binder, and another one with a PG 64-22 binder. The AR mixtures had generally lower modulus values compared to the PG 76-16 mixture; while they had comparable modulus results with the PG 64-22 mixture. A modular ratio was calculated for the two AR mixtures as well as for several other mixtures available at ASU’s database. The modular ratio used the modulus values of a conventional PG 64-22 mixture as a reference, and ranking of the several mixtures were done at 14°F and 100°F, using the test frequency results at 10 Hz.

At low temperatures, the AR exhibited the lowest modular ratio (lowest stiffness) and therefore the best performance against cracking. At high temperatures, the unconfined test results did not show any disadvantage of using the AR mixtures as the results yielded low stiffness values (lower modular ratio). However, when a comparison of the stiffness/modular ratio, was made using the confined test results, the AR mixtures showed the highest stiffness (highest modular ratio) and therefore the best expected performance against permanent deformation. This was an important finding, since this type of behavior (ranking order of mixes) is what is being observed in the field.

Based on the laboratory test results and observations made in this research study, the following conclusions can be made:

1. The dynamic modulus test results obtained in this study showed that the use of crumb rubber modified binders enhances the properties of the asphalt mixture, both at low and high temperatures.
2. When conducting dynamic modulus tests on asphalt rubber mixtures using different levels of confinement, a significant increase in the modulus values is observed at high temperatures and low-test frequencies. The increment was not as significant when the test was performed at low temperatures for the AR-ACFC open graded mix.
3. When comparing the modulus values of unconfined and confined tests, the results showed that the level of confinement chosen would be important and would have an impact on the evaluation of the mixture performance. This was especially true for the asphalt rubber (AR-ACFC) open graded mixture.
4. The results of the confined dynamic modulus tests ranked both of the asphalt rubber mixture on top in their resistance to low temperature cracking and high temperature permanent deformation.
5. In several cases, equivalent unconfined modulus test results were obtained at test temperatures of 100 and 130°F. This behavior was attributed to the decreased role of the asphalt cement and the increased role of the crumb rubber particles, which seems to dominate the behavior of the mix as the test temperature increases. This type of behavior confirms the observed good field performance of these mixes against permanent deformation or rutting.

RECOMMENDATIONS

This study showed very promising results of utilizing the dynamic modulus test to evaluate / verify the field performance of the asphalt rubber mixtures. Because of the type of aggregate grading that these mixtures have (gap and open graded), further evaluation using confined testing is recommended to verify conclusions arrived at in this study. In addition, when comparing dense, gap and open graded mixtures, confined dynamic modulus tests are recommended to rank and compare the expected field performance of the different mixtures. It is emphasized that this is not contradictory to findings of NCHRP 9-19 Simple Performance Project, where the unconfined dynamic modulus test was recommended as one of the three candidates for the simple performance test. It is important to recognize that all of the mixtures evaluated under the first phase of NCHRP 9-19 Project were dense graded mixes, and the confinement level was not detected as a discriminating factor.

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Table 1. Summary of the Modular Ratio (R) - Unconfined Test Results

(a) Test Temperature 14°F

Mix ID	AC Type	AC (%)	Va (%)	Nominal Aggregate	Temp. (°F)	E*[2] (ksi)	R	Rank
AR-ACFC	58-22 (R)	8.8	17.6	9.0-mm OG	14	1237	0.59	1
ARAC	58-22 (R)	6.8	10.9	19.0-mm GG	14	1525	0.73	2
WesTrack Section C2	64-22	4.8	9.3	12.5-mm FDGM	14	1642	0.80	3
ALF Lane 8	Novophalt	4.7	11.9	19.0-mm DGM	14	1926	0.93	4
ADOT Conventional[1]	64-22	4.1	10.5	19.0-mm DGM	14	2065	1.00	5
ADOT Conventional	58-28	6.1	6.4	19.0-mm DGM	14	2245	1.09	6
MnRoad Cell 20	PEN 120/150	6.1	6.3	12.5-mm DGM	14	2715	1.32	7
ALF Lane 4	AC 20	4.9	9.7	19.0-mm DGM	14	2727	1.32	8
WesTrack Section C24	64-22	5.8	7.5	12.5-mm CDGM	14	2833	1.37	9
ADOT Conventional	76-16	4.9	7.9	19.0-mm DGM	14	3044	1.47	10
ALF Lane 3	AC-5	4.8	7.7	19.0-mm DGM	14	4101	1.986	11

(b) Test Temperature 100°F

Mix ID	AC Type	AC (%)	Va (%)	Nominal Aggregate	Temp. (°F)	E*[2] (ksi)	R	Rank
ADOT Conventional	76-16	4.9	7.9	19.0-mm DGM	100	490	4.01	1
WesTrack Section R4	64-22	5.2	6.6	12.5-mm FDGM	100	409	3.35	2
WesTrack Section R23	64-22	5.8	4.9	12.5-mm CDGM	100	327	2.68	3
ALF Lane 8	Novophalt	4.7	11.9	19.0-mm DGM	100	267	2.19	4
ALF Lane 12	AC-20	4.1	7.4	37.5-mm DGM	100	215	1.76	5
ADOT Conventional	58-28	6.1	6.4	19.0-mm DGM	100	196	1.61	6
ADOT Conventional[1]	64-22	4.1	10.5	19.0-mm DGM	100	122	1.00	7
MnRoad Cell 20	PEN 120/150	6.1	6.3	12.5-mm DGM	100	115	0.94	8
ARAC	58-22 (R)	6.8	10.9	19.0-mm GG	100	107	0.88	9
AR-ACFC	58-22 (R)	8.8	17.6	9.0-mm OG	100	101	0.83	10

[1] *Reference Mixture*
[2] *Test Results for frequency of 10 Hz*

Where: DGM = Dense Graded Mixture
CGDM = Coarse Dense Graded Mixture
FDGM = Fine Dense Graded Mixture
GG = Gap Graded Mixture
OG = Open Graded Mixture

Table 2. Summary of the Modular Ratio (R) - Confined Test Results, 20 psi.

(a) Test Temperature 14°F

Mix ID	Binder Type	AC (%)	Va (%)	Nominal Aggregate	Temp (°F)	E*[2] (ksi)	R	Rank
ARAC[1]	58-22 (R)	6.8	10.9	19.0-mm Gap Graded	14	1498	1.00	1
AR-ACFC	58-22 (R)	8.8	17.6	9.0-mm Open Graded	14	1615	1.08	2
ALF Lane 3	AC-5	4.8	7.7	19.0-mm DGM	14	1947	1.30	3
ALF Lane 8	Novophalt	4.7	11.9	19.0-mm DGM	14	2351	1.57	4
WesTrack Section C2	64-22	4.8	9.3	12.5-mm FDGM	14	4233	2.83	5
WesTrack Section C24	64-22	5.8	7.5	12.5-mm CDGM	14	4601	3.07	6
ALF Lane 4	AC-20	4.9	9.7	19.0-mm DGM	14	6137	4.10	7

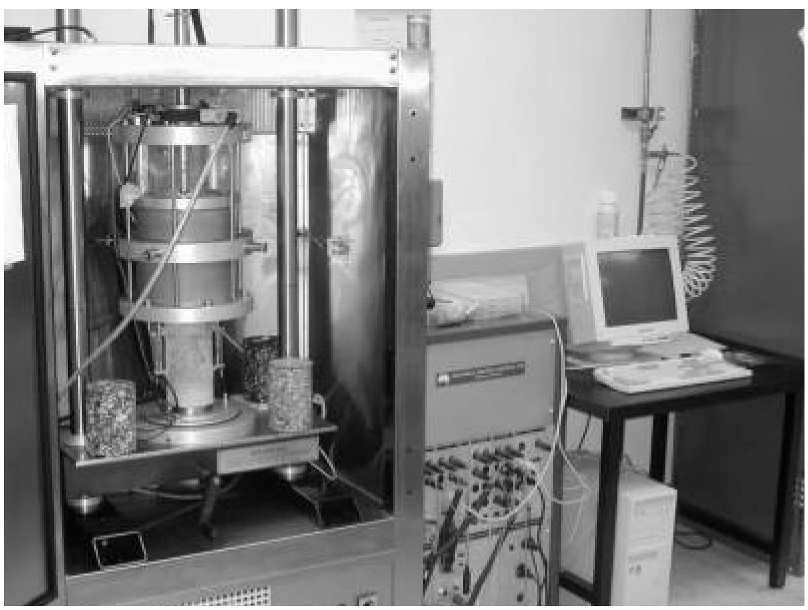
(b) Test Temperature 100°F

Mix ID	Binder Type	AC %)	Va (%)	Nominal Aggregate	Temp (°F)	E*[2] (ksi)	R	Rank
AR-ACFC	58-22 (R)	8.8	17.6	9.0-mm Open Graded	100	875	1.02	1
ARAC[1]	58-22 (R)	6.8	10.9	19.0-mm Gap Graded	100	862	1.00	2
WesTrack Section R4	64-22	5.2	6.6	19.0-mm FDGM	100	812	0.94	3
ALF Lane 12	AC-20	4.1	7.4	37.5-mm DGM	100	664	0.77	4
WesTrack Section R23	64-22	5.8	4.9	19.0-mm CDGM	100	518	0.60	5
ALF Lane 8	Novophalt	4.8	7.7	19.0-mm DGM	100	314	0.37	6

[1] *Reference Mixture*
[2] *Test Results for frequency of 10 Hz*

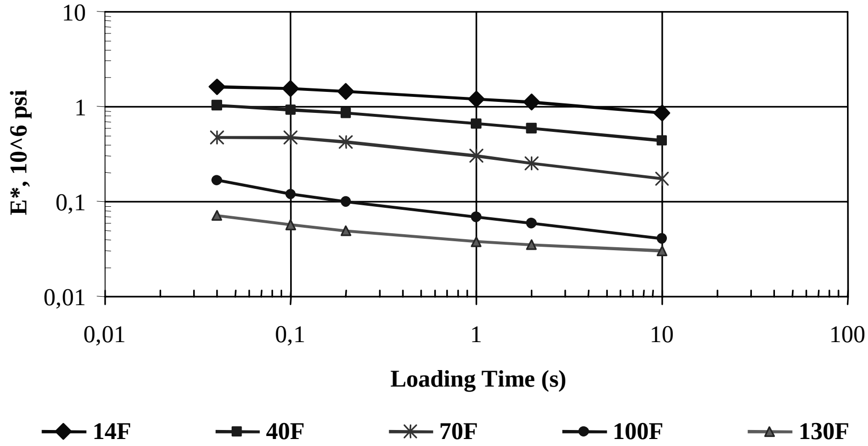
Where: DGM = Dense Graded Mixture
CGDM = Coarse Dense Graded Mixture
FDGM = Fine Dense Graded Mixture
GG = Gap Graded Mixture
OG = Open Graded Mixture

(a)

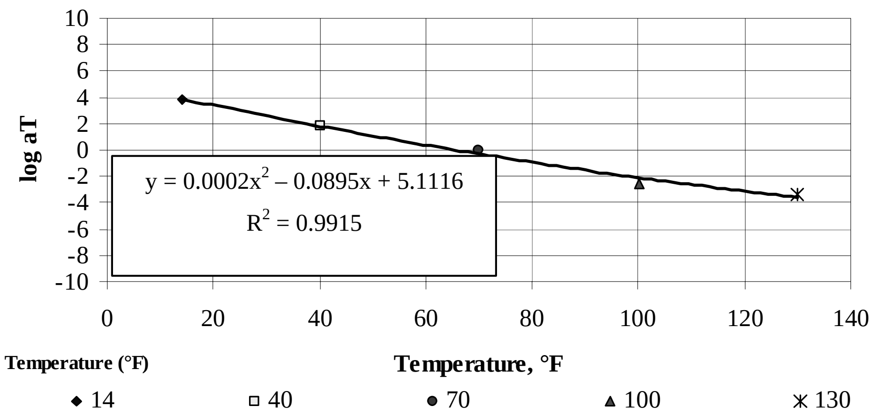


(b)

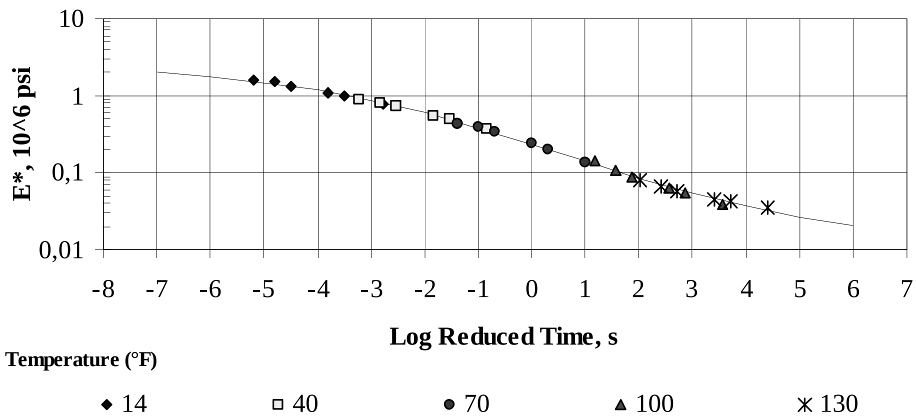
Figure 1. (a) Typical Test Instrumentation (ARAC Test Specimen) (b) Typical Confined Test Set-Up



a) Effect of Loading Time and Temperature on Measured Dynamic Modulus E* - Replicate #2

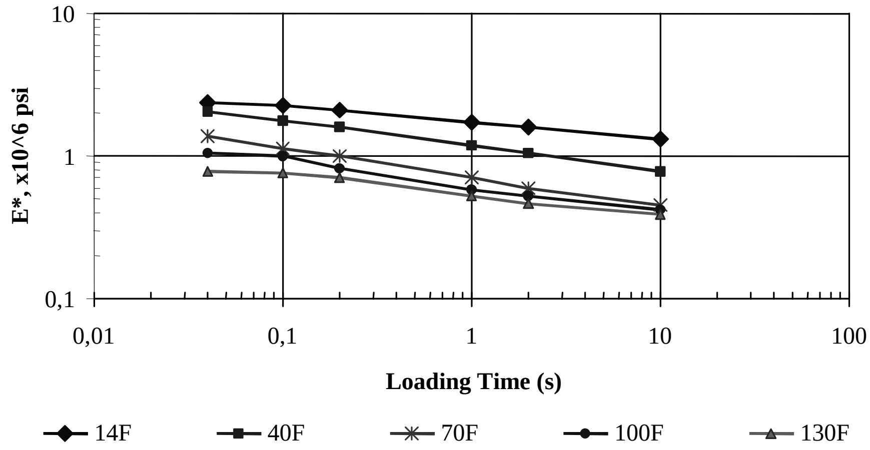


b) Shift Factors for ARAC GAP Graded Mixture (Average of three replicates)

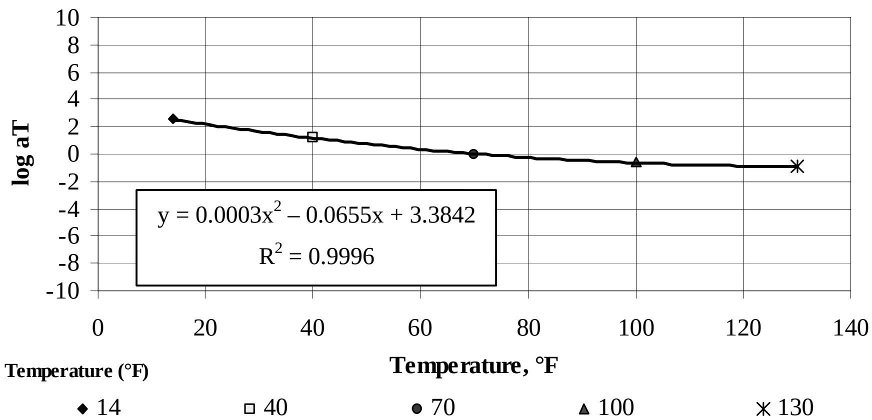


c) Master Curve for ARAC Gap Graded Mixture (Average of three replicates)

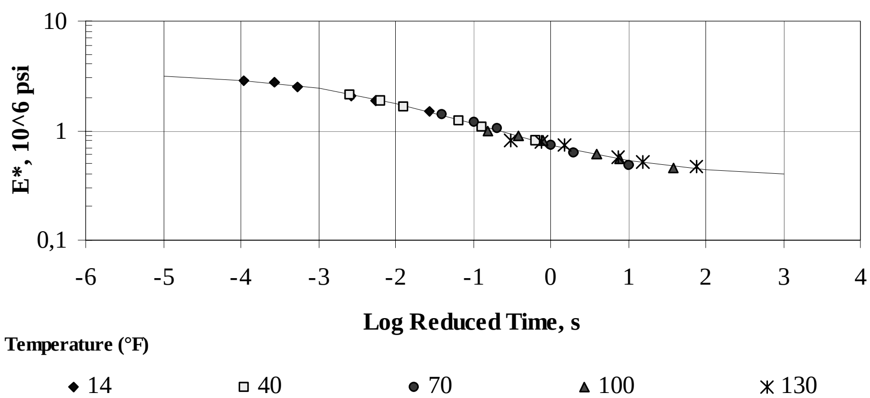
Figure 2. ARAC Gap Graded Mixture – Unconfined Test Results



a) Effect of Loading Time and Temperature on Measured Dynamic Modulus E* - Replicate #3



b) Shift Factors for ARAC GAP Graded Mixture (Average of three replicates)



c) Master Curve for ARAC Gap Graded Mixture (Average of three replicates)

Figure 3. ARAC Gap Graded Mixture – Confined Test Results, 30 psi.

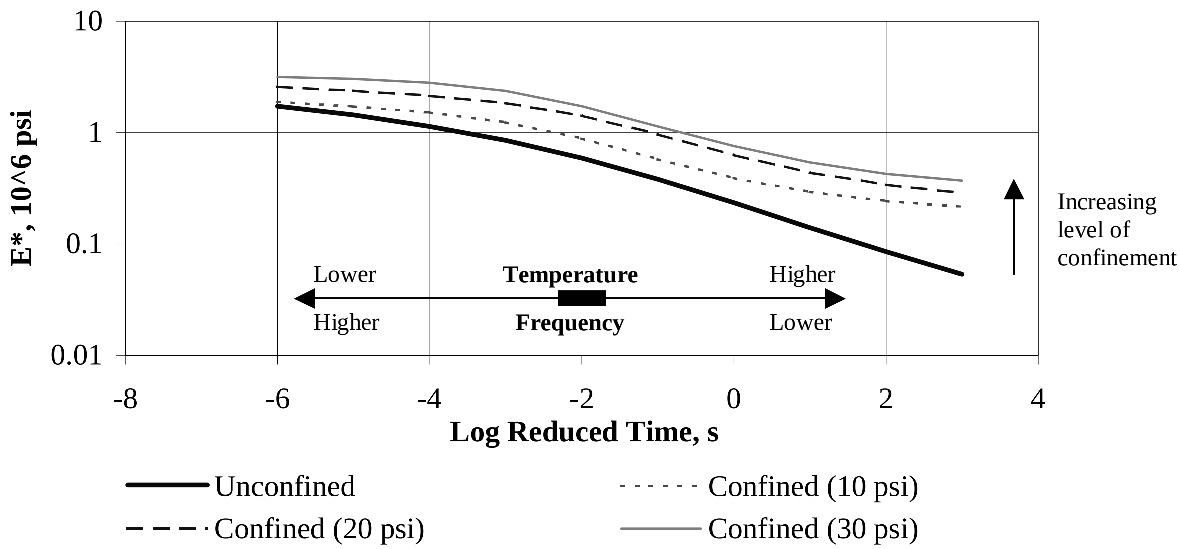
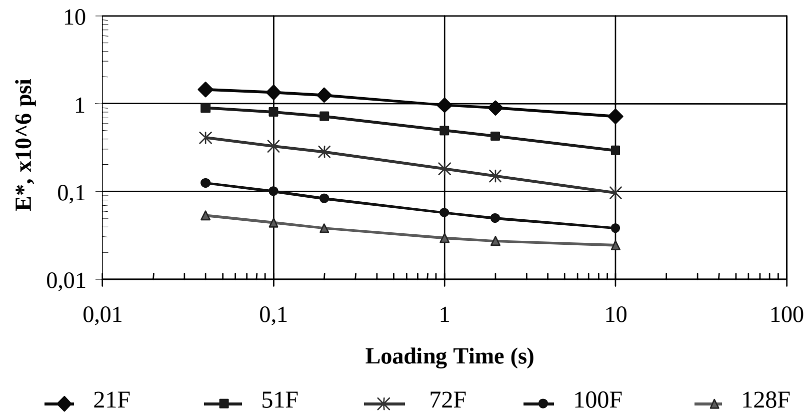
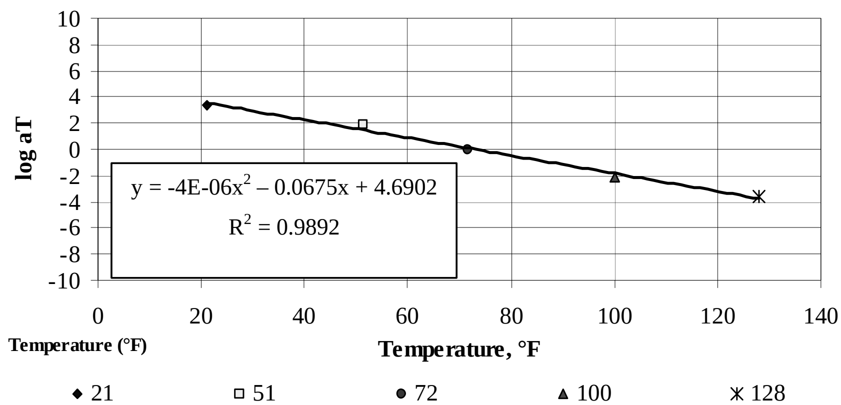


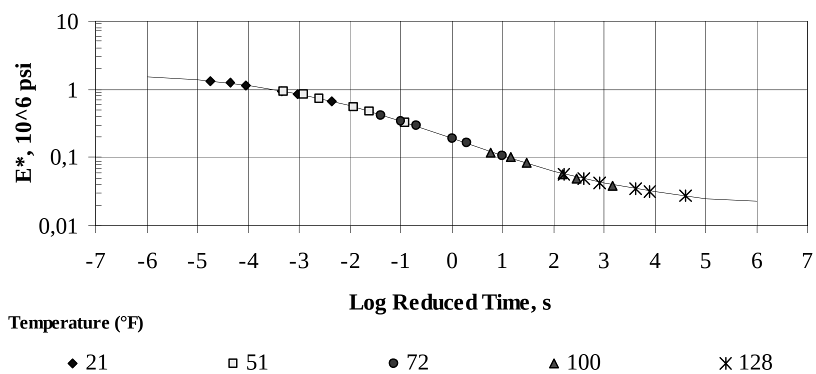
Figure 4. E* Master Curves for the ARAC Gap Graded Mixture.



a) Effect of Loading Time and Temperature on Measured Dynamic Modulus E* - Replicate #2

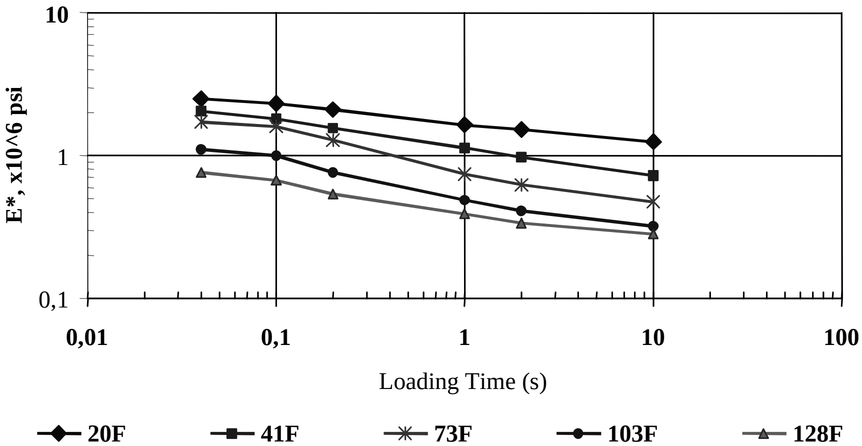


b) Shift Factors for AR-ACFC Open Graded Mixture (Average of three replicates)

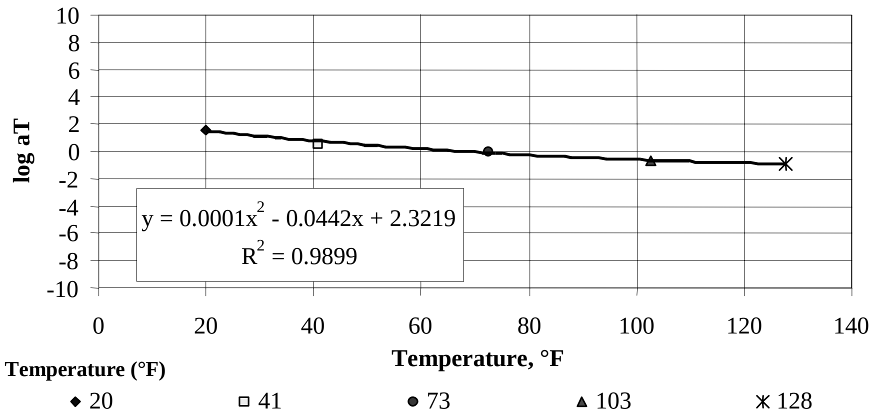


c) Master Curve for AR-ACFC Open Graded Mixture (Average of three replicates)

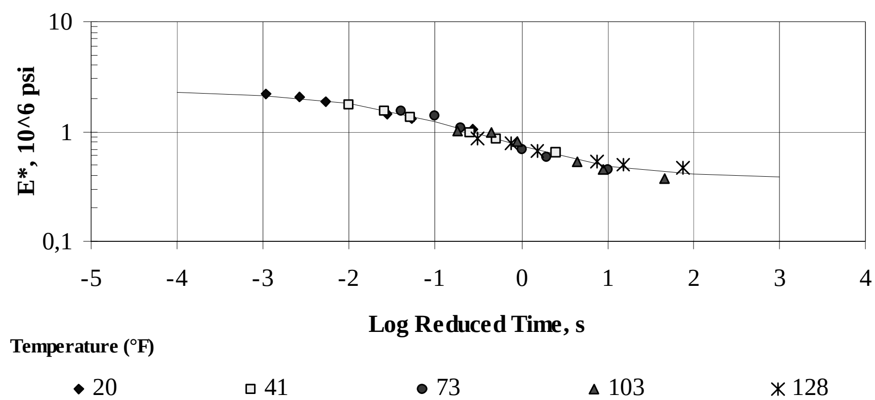
Figure 5. AR-ACFC Open Graded Mixture - Unconfined Test Results.



a) Effect of Loading Time and Temperature on Measured Dynamic Modulus E* - Replicate #1



b) Shift Factors for AR-ACFC Open Graded Mixture (Average of three replicates)



c) Master Curve for AR-ACFC Open Graded Mixture (Average of three replicates)

Figure 6. AR-ACFC Open Graded Mixture - Confined Test Results, 30 psi.

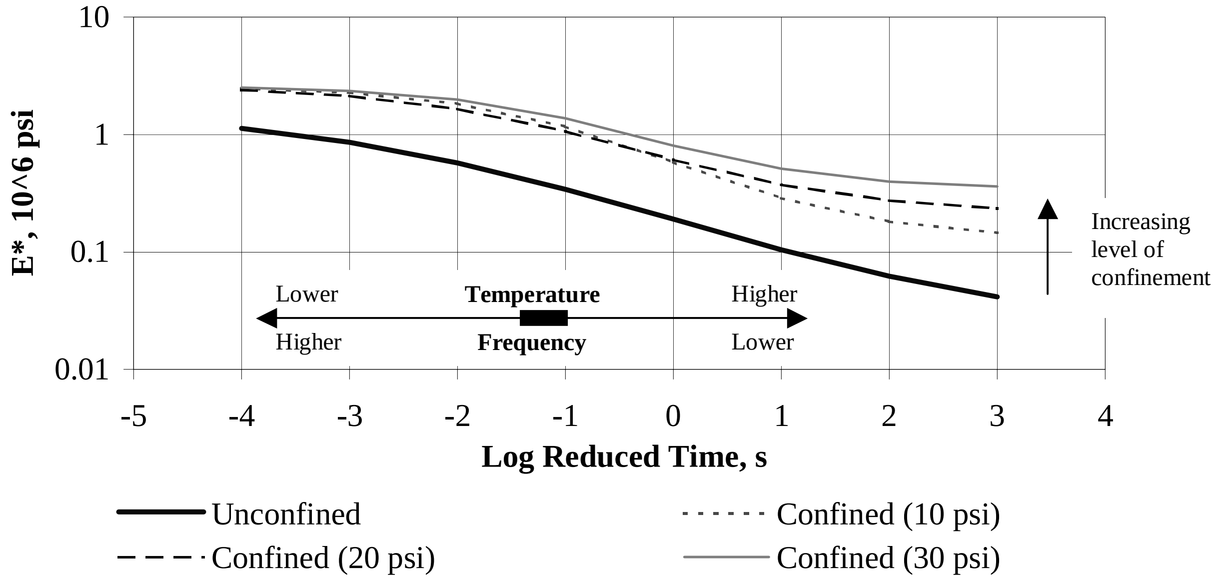


Figure 7. E* Master Curves for the AR-ACFC Open Graded Mixture.

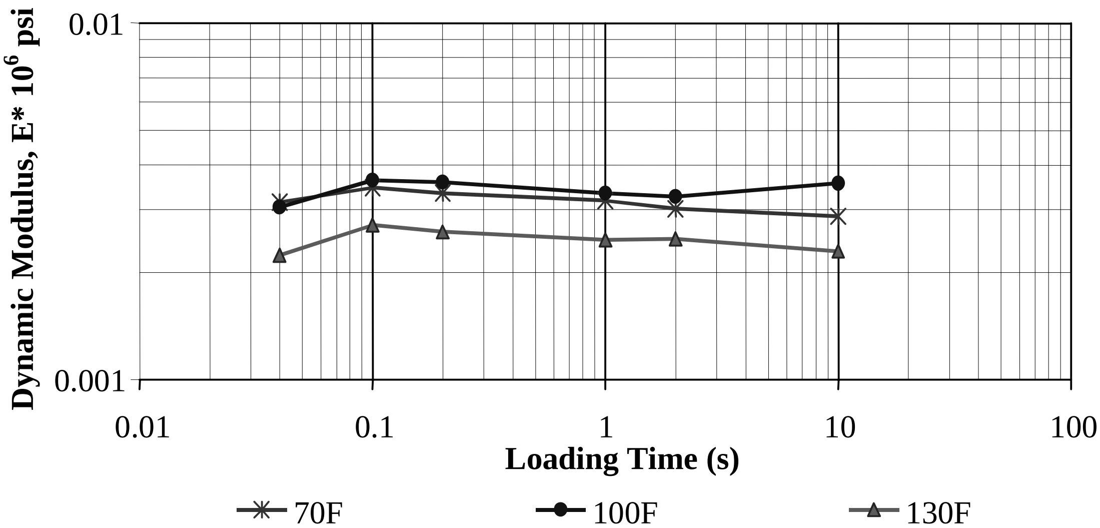


Figure 8. Crumb Rubber Specimen (Molded Using 80% Crumb Rubber and 20% Urethane) – Unconfined Dynamic Modulus Test Results.

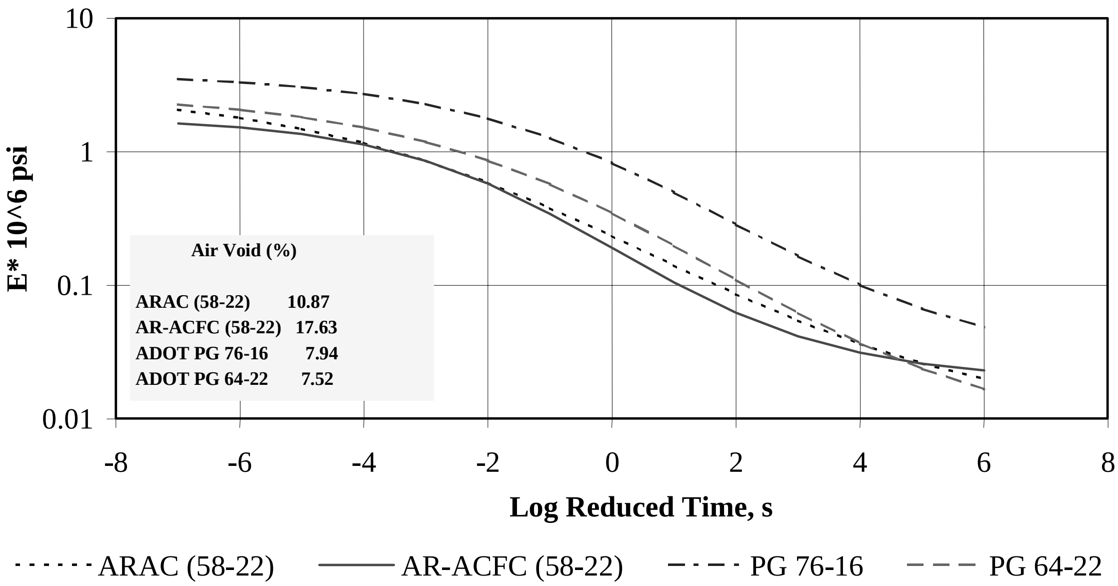


Figure 9. Unconfined Dynamic Modulus Master Curves for ARAC, AR-ACFC and ADOT Dense Graded PG 76-16 and PG 64-22 Mixtures