Investigation of Low and High Temperature Properties of Plant-Produced RAP Mixtures

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INTRODUCTION

Recycling of asphalt mixtures became widely practiced in the United States in the 1970s, spurred on by high petroleum prices and limited availability caused by the oil embargo of 1973. The increased availability of cold milling machines also promoted recycling in some areas of the country. By the late 1970s, technology had developed to allow recycle ratios of as high as 100%, although typically hot mix contained at most 25% to 40% reclaimed asphalt mixture. In today's climate of high petroleum prices, recycling is becoming even more attractive. There is interest in using higher RAP contents and in using RAP in more mixtures.

Effects of RAP

The presence of RAP binder in a mixture increases stiffness at all temperatures and frequencies of loading. At high temperatures, this increase is considered advantageous because it helps to resist permanent deformation. At low temperatures, however, an increase in stiffness may reduce resistance to cracking. At low RAP contents, the amount of stiffening may be negligible.

The actual blending of the virgin and RAP binders will have a direct effect on stiffness. If the new and old asphalt binders are homogenized, the mixture will have increased stiffness and may crack at low temperatures. If poor blending occurs, the mixture may behave as if it contained only the virgin binder. As a result, low temperature cracking might not occur, but the lack of stiffening by the RAP binder may contribute to high temperature rutting.

Background

The current specifications in Indiana and most other states conform to the requirements of AASHTO M323, *Standard Specification for Superpave Volumetric Mix Design*, and PP28, *Standard Practice for Superpave Volumetric Mix Design for Hot Mix Asphalt*. Both standards were revised to incorporate RAP mixes based on the results of an NCHRP project (9-12), *Incorporation of Reclaimed Asphalt Pavement in the Superpave System*, which was concluded in 2000 (*1*). That study was undertaken to develop guidelines for how to incorporate RAP in Superpave mixes.

When Superpave was implemented beginning in the mid-1990s, the use of RAP decreased markedly as contractors learned to work with the new system. Interim guidance on the use of RAP in Superpave mixes had been developed through the Asphalt Mixture Expert Task Group (*2*) based on experience and the performance of Marshall mixes with RAP. The need for additional guidance prompted the NCHRP project, which addressed two asphalt binder considerations:

- Does the RAP binder act as part of the cohesive binder or is it inert (i.e., a "black rock")?
- How do the aged properties of the RAP binder influence the properties of the composite binder?

The results indicated that the RAP binder did commingle with the new binder to a significant extent. Binder and mixture testing showed negligible to small effects of 20% RAP and some effect at 40% RAP. Linear blending appeared to be applicable to the higher RAP content mixes.

The current specification, based on that research, prescribes that up to 15% RAP by weight of mix may be added without changing the virgin binder grade. At RAP contents higher than 15% but less than 25%, the virgin binder grade must be adjusted one grade softer to account for the stiffening effect of the hardened RAP binder. At RAP contents above 25%, a detailed design is necessary to select properties of the virgin binder.

The standards do assume that a significant amount of blending does occur during production, as evidenced in the NCHRP study. The guiding principle of the interim guidance and the current AASHTO standards is that mixtures with and without RAP should meet the same requirements. The aggregate provided by the RAP is included in determination of the mixture gradation and fine aggregate angularity, coarse aggregate angularity, and flat and elongated content. The asphalt binder contributed by the RAP is considered a part of the total binder content of the mixture.

A regional pooled fund study in the Midwest looked at three more RAP sources at contents up to 50%. This study showed that the NCHRP results generally held true for the materials tested (*3*). This study included a comparison of plant produced mixes to a linear blending chart. In two of the three cases, linear blending worked very well. In the third case, however, the mixture was consistently stiffer than expected based on linear blending, perhaps showing the effects of plant production variables.

Current Issues

The break points above correspond to the middle column of a recommended table of break points based on the performance grade of the recovered RAP binder from the NCHRP study. There was some evidence that the RAP contents at which the virgin binder grade should be changed varied depending on the grade of the RAP binder, but there were too few data points to support including this in the specifications. The asphalt binder requirements that were adopted in the specifications represent a "middle ground" based on the results of the laboratory testing; they also agree well with the interim recommendations made by the FHWA Asphalt Mixture Expert Task Group based on extensive experience with Marshall mixes.

Anecdotal evidence to date suggests that these recommendations generally work well in many cases; there is also some evidence that these break points may not be appropriate in all cases. The actual amount of blending that happens in a mixture depends on many factors including the stiffness of the RAP binder, the compatibility of the virgin and RAP binders, and specifics of the hot mix production including plant type (batch or drum), type and amount of mixing (pugmill or drum), mixing temperature, mix handling (live bottom trucks or dump trucks, shuttle buggies, windrow and pickup or dumping straight into the paver hopper) (*3*). Laboratory-produced mixtures may not reflect the effects of all of these factors, so testing of plant-produced mixtures would be more realistic.

As contractors endeavor to use more RAP, two issues have become increasingly important. The effects of RAP on the low temperature grade are a concern, particularly to agencies that may have to deal with increased cracking later in the service life of the pavement. The increased stiffness of the mix generally provided by the addition of RAP is beneficial at high temperatures, but may be detrimental at low temperatures. On the other hand, there is some evidence that the addition of RAP may not have as great an effect on low temperature properties as it does on high temperature properties. Experiences in Missouri and Minnesota suggest that recycled shingles do not have as great an effect on low temperature properties as on high temperature; the effects of RAP may be similar since both may contain highly oxidized binders (*4, 5*). Research at Heritage Research Group has also indicated that increasing the RAP content from 25% to 40% only changed the low temperature grade by 2°C.

Another issue for contractors is the RAP content at which the binder grade must be changed. For contractors in Indiana, where this work was conducted, the use of greater than 15% RAP requires the use of a PG58-28 virgin binder. This binder grade is more expensive than the PG64-22 typically used with 15% RAP or less. If the addition of more than 15% RAP does not affect the resulting binder grade to the extent assumed in the specifications, contractors could produce a more economical mix with higher percentages of RAP.

This issue is also of concern to agencies; if RAP does not stiffen the mix to the extent expected, the resulting mixture may be too soft for the intended purpose. Similarly, if there are cases where the plant-produced mix with RAP is stiffer than expected, as seen in the regional pooled fund study, the mix may be even more prone to cracking.

Work by Ray Bonaquist et al. also suggests that there are some cases where RAP and shingles do not blend with virgin materials to the extent expected (*6*). Bonaquist uses the dynamic modulus of plant-produced mix and the predictive equations to back-calculate an effective binder modulus for the mix. This effective binder modulus is compared to the modulus of binder recovered from the mixture, which is completely blended in the process of extraction and recovery. If the two binder modulus curves overlap, the blending of recycled and virgin binders is nearly complete. If the curves do not overlap, there is incomplete blending. Bonaquist has examples of incomplete blending, particularly with shingles, but also with RAP. Since this testing is done on plant-produced mixes, the potential variables introduced by the plant also play a role in the amount of blending that occurs.

So, the degree of mixing of old and new binders, particularly in plant-produced mixtures, warrants further research. The effects of RAP on low and high temperature properties should be evaluated further to determine if the current approach is, perhaps, over-simplified. The experimental project described in this report investigates both high and low temperature properties of six mixtures as a starting point in that further examination.

TEST PLAN

Milestone Contractors, LP, produced six mixes over a period of two days in one plant during the summer of 2006. The plant was a counter-flow drum plant with an embedded burner. Four mixes with 0%, 15%, 25% and 40% RAP were produced with PG64-22 binder; in addition, two mixes with 25% and 40% RAP and PG58-28 were produced. A representative sample of each mix was obtained for testing after 100 tons were produced. Table 1 summarizes the different mixes in this research. RAP used in this study was fractionated into a coarse fraction (plus 12.5 mm) and a fine fraction (minus 12.5 mm); only the fine RAP was used in the mixes. Mix design details are shown in the Appendix (Table A1).

Table 1. Binder grades and RAP contents in mixes tested

Grade	**0% RAP**	**15% RAP**	**25% RAP**	**40% RAP**
PG64-22	✓ (A)	✓ (B)	✓ (C)	✓ (D)
PG58-28			✓ (E)	✓ (F)

Letters shown in parentheses are mix labels.

In addition to the six mixes, Heritage Research Group (HRG) also obtained samples of the RAP and the tank binders used in the mixes. Binder was recovered from the mixes and the RAP samples using the Abson recovery process outlined in AASHTO T170 with methylene chloride as the solvent. To address the objectives of this study, the following binder and mixture properties were determined:

- Complex shear modulus of the binder ($|G^*|_b$)
- Complex shear modulus of the mix ($|G^*|_m$)
- Complex dynamic modulus of the mix ($|E^*|$)
- Indirect tensile strength and creep stiffness of the mix

The complex shear moduli of the recovered binders were determined using a Bohlin Dynamic Shear Rheometer (DSR), in accordance with AASHTO T315. Binder samples were heated in an oven at 285ºC for 30 minutes and stirred for consistency before pouring. Two replicate samples of each recovered binder were tested. A third sample was tested if the two initial tests showed poor repeatability. The complex shear moduli ($|G^*|$) and phase angles (δ) of the binders were determined by conducting a frequency sweep (25, 8.33, 2.75, 0.91, 0.30 and 0.10 Hz) at three test temperatures (20ºC, 37.2ºC and 54.4ºC).

Four replicate samples of each mix were compacted to 7 ± 1% air voids using a Pine Superpave Gyratory Compactor. The complex dynamic moduli ($|E^*|$) and phase angles (ϕ) of the mixes were determined using an IPC Simple Performance Tester (UTM-25). The modulus was determined at three test temperatures (20º, 37.8º and 54.4ºC) at the six frequencies (25, 10, 5, 1, 0.5 and 0.1 Hz). The test procedure followed is outlined in AASHTO TP62. Test data were checked for outliers by examining the trends shown in plots of |E*| versus frequency, |E*| versus phase angle, $|E_1|$ versus $|E_2|$, and phase angle versus frequency (Figures A2 to A5 in the Appendix).

Frequency sweep at constant height tests were conducted on the mixes to determine the complex shear modulus and phase angle at three test temperatures (20º, 37.8º and 54.4ºC), using an Interlaken Superpave Shear Tester. Samples were tested in accordance with AASHTO T320 at 10, 5, 2, 1, 0.5, 0.2, 0.1, 0.05, 0.02 and 0.01 Hz. Three replicates of each mix were compacted to 7 ± 1% air voids and tested.

Creep compliance testing of the HMA samples was conducted on three replicate samples of each mix, compacted to 7 ± 1% air voids. Samples were tested at -20º, -10º and 0ºC for 100 s. These data were processed using the LTSTRESS routine, developed by Don Christensen, to estimate the thermal stresses in the pavement. Each of the three replicates was tested at a different test temperature (-20º or -10º or 0Cº). The intersection of the thermal stress curve, estimated from creep compliance testing, and the indirect tensile strength curve yields the critical cracking temperature of the pavement. The critical cracking temperature of the pavement may be defined as the lowest temperature the material (pavement) can withstand without cracking. A typical example of the thermal stress curve is shown in the Appendix (Figure A1). Creep stiffness was determined by taking the inverse of creep compliance.

After some initial binder testing results were obtained, two blends (C and D) were created in the lab to simulate the expected blended binder in the HMA. Blend C was created by mixing RTFO-aged PG64-22 and binder recovered from RAP, in appropriate proportions to simulate the binder in mix C (25% RAP). Similarly, Blend D was created to simulate mix D. These binders were expected to represent complete blending of the RAP and virgin binders as a point of comparison. The shear moduli of these blended binders were compared with the corresponding moduli of binders recovered directly from mixes C and D, respectively.

RESULTS AND ANALYSIS

Mixture Tests at Low Temperatures

Figure 1 shows the indirect tensile strength of the mixes at the three test temperatures. Two-factor (temperature and mix type) analysis of variance (ANOVA) indicated that temperature was not a significant variable; i.e., the test temperature did not influence the strength of the mixes. Therefore, the three data points were treated as replicates for each mix. The coefficient of variation for the mixes varied between 5.5% and 14.6% (Table A2 in Appendix).

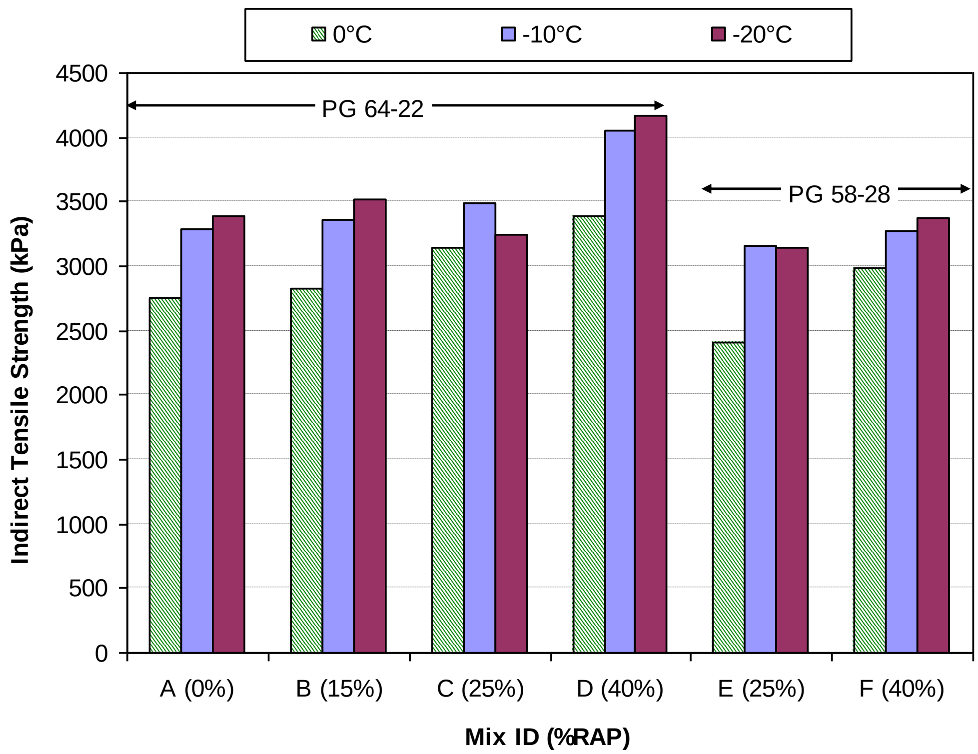


Figure 1. Average indirect tensile strength of the mixes

The addition of 15% RAP (mix A versus B) resulted in a 2 - 4% increase in strength at all test temperatures; while addition of 40% RAP resulted in a 23% increase (mix A versus C). Single factor ANOVA of the "replicate" dataset, however, indicated that the differences in the strengths of the mixes with different RAP contents and PG64-22 binder or with PG58-28 binder were not statistically significant. Two-sample t-test comparisons were conducted to test for differences between specific pairs of mixes. The p-values from these tests are shown in Appendix (Table A3). Comparison of mixes B and C with 15% and 25% RAP, respectively, shows that the higher RAP content did not appear to improve the strength of the mix. Changing to a lower binder grade to account for higher RAP contents lowered the strength of the mixes (mix C versus E and mix D versus F).

Table 2 shows the critical cracking temperature of the pavement along with the estimated creep stiffness (at 60 s) for each mix. The strength at -10ºC was used to determine the critical cracking temperature of the pavement. Increasing the RAP content in a mix resulted in an increase in the stiffness of the HMA due to intermixing of the RAP binder with the virgin binder, as expected (see mixes A through D). However, the increase in stiffness resulted in a corresponding increase in T_c (became less negative). Mix B would be expected to crack at a warmer temperature than mix A, because of the 2.5 GPa increase in stiffness. Mixes B and C showed similar stiffnesses, while mix C showed only a slightly higher strength than mix B. The higher strength of mix C in comparison with mix B was beneficial in lowering the T_c, but not to the same level as the control mix (A) due to the higher stiffness of the RAP mix (C). Increasing the RAP content to 40% increased the stiffness by 4.5 GPa and increased the T_c by 6ºC, i.e., one binder grade.

Table 2. Creep stiffness and critical cracking temperature of the mixes

MIX ID	**RAP %**	**Grade**	**Strength @-10ºC, kPa (psi)**	**Stiffness @ 60 s, GPa**	**T_c, ºC**
A	0	PG64-22	3284 (476)	14.7	-28.9
B	15	PG64-22	3359 (487)	17.3	-23.3
C	25	PG64-22	3498 (507)	17.7	-25.6
D	40	PG64-22	4056 (588)	19.2	-22.8
E	25	PG58-28	3153 (457)	13.1	-27.2
F	40	PG58-28	3272 (474)	16.1	-23.9

Using a softer binder grade was beneficial in improving the low temperature as it lowered the stiffness of the mix and also lowered the T_c of the mix. This is particularly evident when the comparing the stiffness and T_c of mixes A and E. Mix E, with the bumped grade, showed comparable stiffness and T_c to that of the control mix A. Comparison of mixes with same RAP content but with different binder grade (C versus E and D versus F) shows that the mixes with a stiffer binder grade (PG64-22) had higher strength and stiffness, as expected.

Mixture Tests at High Temperatures

Frequency versus modulus data obtained from complex dynamic modulus tests were examined for outliers by plotting |E*| vs. frequency, $|E_1|$ vs. $|E_2|$, ϕ vs. frequency and ϕ vs. log |E*|. Typical examples of these plots are shown in Figures A2 through A5 in the Appendix. The average dynamic moduli of the mixes at the three test temperatures are shown in Figure 2. Table A5 summarizes the average |E*| and coefficient of variation for these mixes.

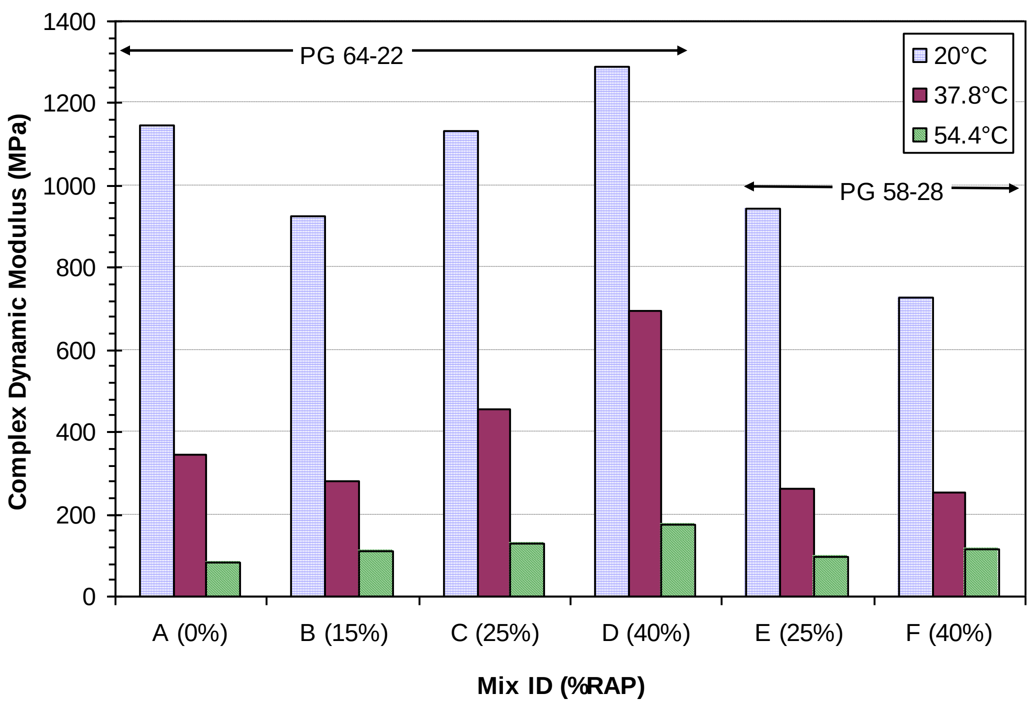


Figure 2. Average complex dynamic modulus of the mixes at 25 Hz

The contribution of RAP binder stiffness to the complex dynamic modulus of the mixes was particularly evident at the higher test temperature (37.8º and 54.4ºC). An increase in modulus of over 100% was observed with the addition of 40% RAP (mix D) compared with the control mix (A). A trend of increasing modulus was observed with increasing RAP contents from 15% to 40% at all temperatures; however, the addition of 15% RAP lowered the modulus at 20º and 37.8ºC when compared with the control mix. Bumping the grade to PG58-28 lowered the stiffnesses of the mixes with similar RAP content at all temperatures. The stiffness of mix with 25% RAP and PG58-28 binder (mix E) was comparable to mix with 15% RAP and PG64-22 (mix B). The addition of 40% RAP with PG58-28 (mix F) did not improve the stiffness of the mix compared with the 25% RAP mix (E), particularly at lower temperature (20ºC).

Results of two-sample comparisons on |E*| mix data at 25 Hz are presented in Table A4. No clear cut statistical inferences could be drawn based on these results, which may be attributed to the large coefficient of variation in the test data. Similar statistical tests were conducted at 10 Hz. The conclusions obtained from p-value at 10 Hz were similar to those obtained at 25 Hz.

The dynamic modulus data obtained at different test temperatures were combined to generate master curves showing the change in log |E*| as a function of log reduced frequency, using 37.8ºC as the reference temperature. The Arrhenius shift factors for these master curves are shown in Figures A5 through A11 in the Appendix. The master curves for mixes with PG64-22 and with PG58-28 are shown in Figures 3 and 4, respectively. Figure 5 shows a comparison of mixes with the same RAP content, but with different binder grades (mixes C, D, E and F).

The trends observed in Figures 3 and 4 correspond with the general observations made earlier from Figure 2 concerning the average dynamic modulus results. No significant improvement in modulus was observed with the addition of 15% RAP. At higher RAP contents, however, the increase in modulus compared with the control mix was more evident, which may be attributed to the contribution of the old binder from the RAP.

Changing the binder grade to PG58-28 at 25% and 40% RAP levels, did not alter the modulus of the mixes significantly compared with the control mix (Figure 4). At high frequencies (lower temperatures), the addition of RAP decreased the dynamic modulus of the mixes with respect to the control mix marginally, while at low frequencies (warmer temperatures), the reverse trend was observed.

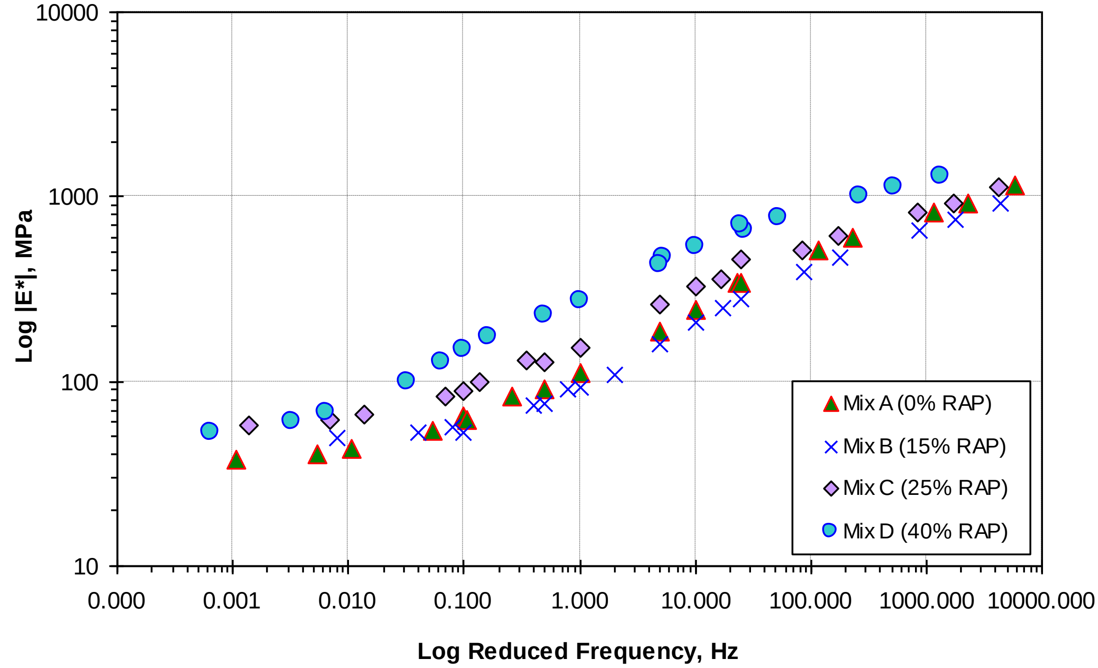


Figure 3. Master curves for mixes with PG64-22 (T_{ref} = 37.8ºC)

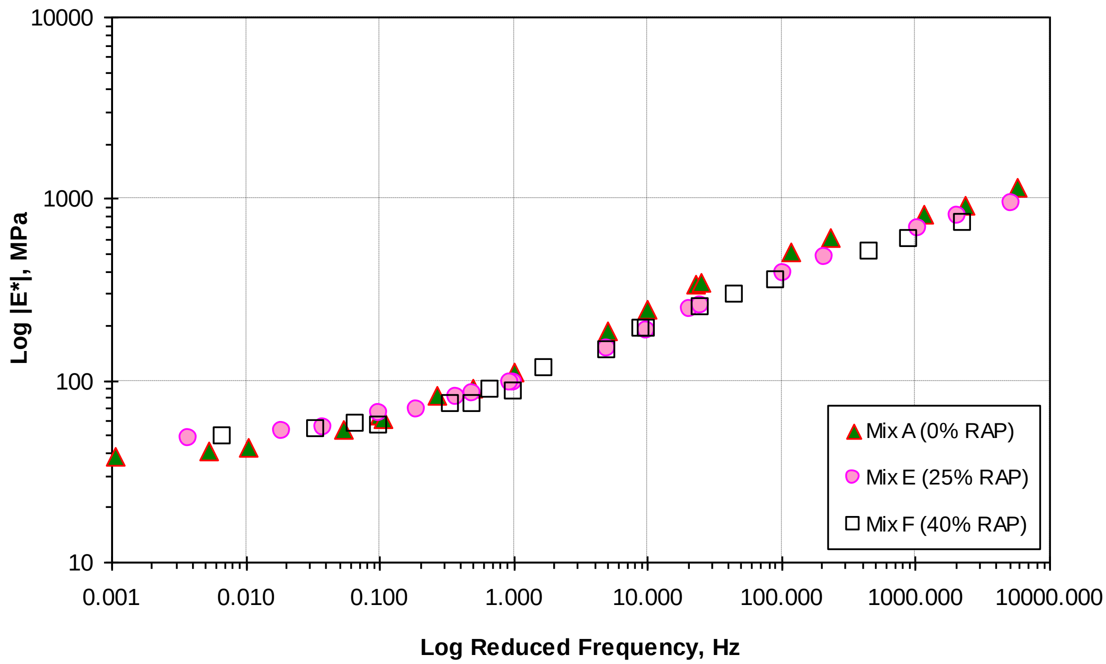


Figure 4. Master curves for mixes with PG58-28 binder and the control mix (T_{ref} = 37.8ºC)

Comparison of mixes C and E, shown in Figure 5, (same RAP content but with different binder grade) shows that the mixes with softer binder had lower modulus; the same was true in the case of mixes D and F (40% RAP), as expected. The moduli of mixes C and D (same grade but with different RAP levels) show a distinct increase when the RAP content was increased from 25% to 40% with PG64-22. In the case of mixes with the bumped grade PG58-28, such an increasing trend was not observed between mixes E and F (25% and 40%, respectively).

Results of the frequency sweep at constant height tests at the three test temperatures are presented in Figure 6. An increase in stiffness was observed at all test temperatures with increasing RAP content. At 54.4ºC, increasing the RAP level beyond 15% did not appear to significantly contribute to further increase in stiffness of the mixes. At 20ºC, the increase in stiffness appeared to be almost linear

Comparison of |G*| and |E*| of the mixes at three test temperatures (shown in Figure 7) shows the highest degree of correlation at the warmest temperatures (R-squared ≈ 82%). However, removing one outlier at 20ºC, gave the highest R^2 of 99% at this lowest test temperature. The coefficient (slope) of line increased with decreasing temperature (1.4 to 2.1).

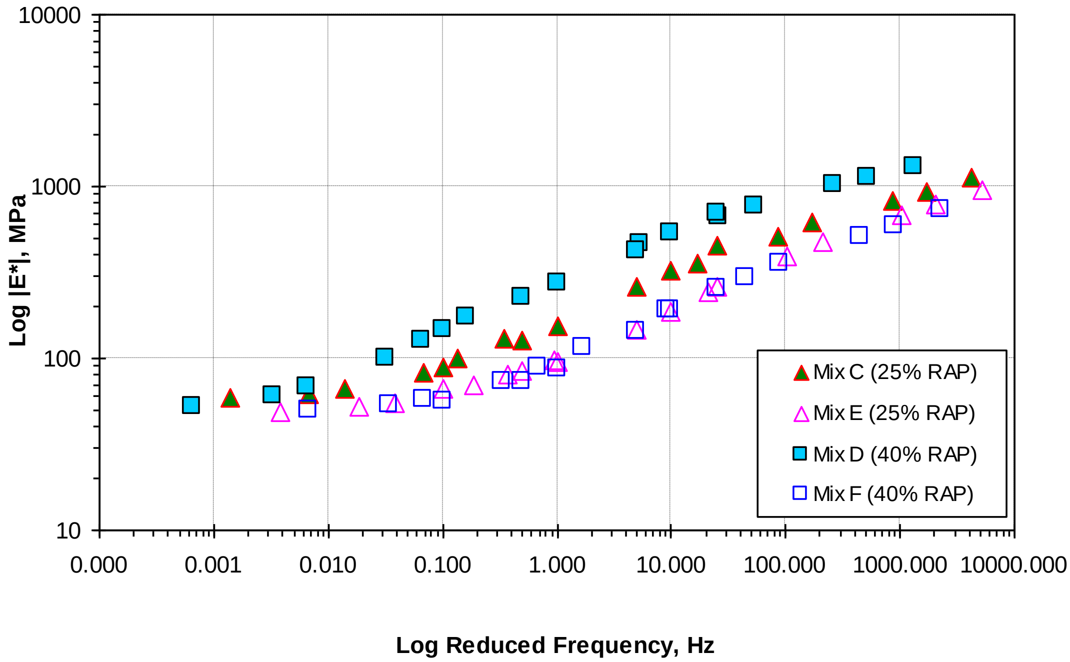


Figure 5. Master curves for mixes with similar RAP contents and different binder grades (T_{ref} = 37.8ºC)

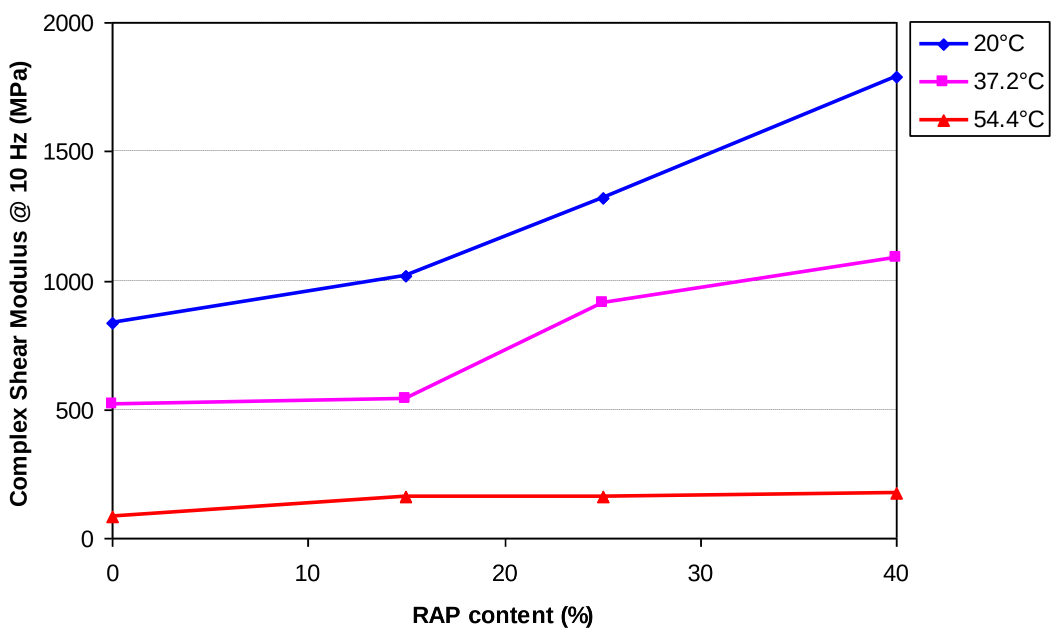


Figure 6. Average complex shear moduli of the mixes

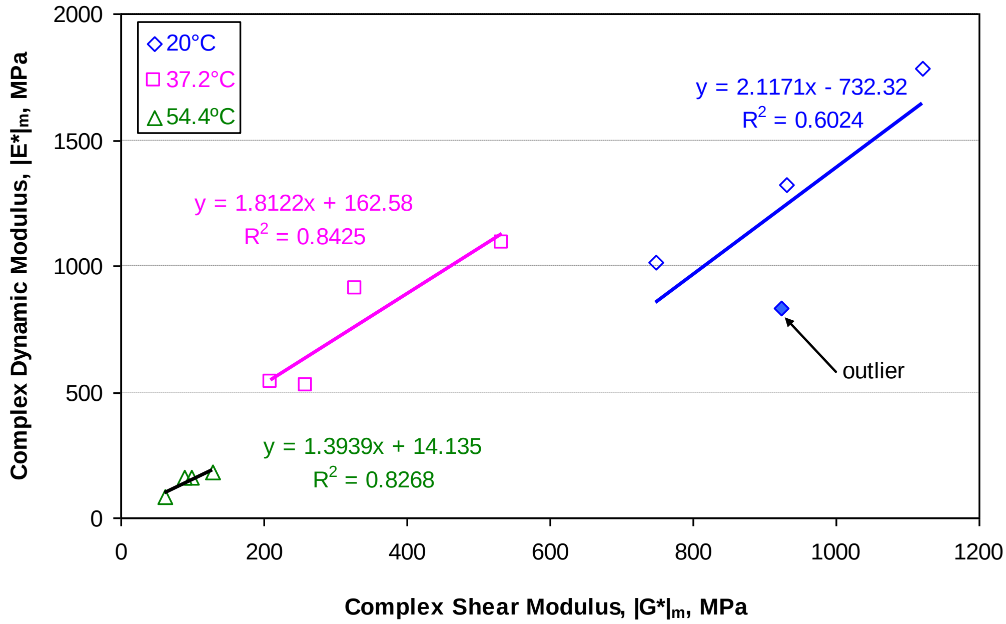


Figure 7. Correlation between complex shear and dynamic moduli at 10 Hz

Binder Tests

The complex shear modulus data obtained from frequency sweep tests conducted at different temperatures on recovered and RTFO-aged tank binder samples were used to generate the master curves shown in Figure 8 (PG64-22) and Figure 9 (PG58-28). As expected the RAP binder was significantly stiffer than all of the other recovered binders. Comparison of the master curves for binders recovered from mixes A through D indicates an increasing trend in stiffness with increasing RAP content, similar to the trend observed in the mixture tests. Binders recovered from the control mix, A, had the lowest shear modulus, while mix D with the highest RAP content had the highest |G*|. Binder recovered from mix A had a lower modulus than RTFO-aged PG64-22 binder, perhaps indicating that there was less aging in this plant than predicted by the RTFOT.

In the case of PG58-28 and binders recovered from mixes E and F, the RFTO-aged binder had the lowest stiffness followed by mixes E (25% RAP) and F (40% RAP), showing a trend similar to the RAP mixes with PG64-22.

Figure 10 shows the master curves for binders recovered from mixes with the same RAP content, but with different binder grade. As expected, binders recovered from mixes with the same binder grade but with higher RAP content (40%) showed higher shear moduli when compared with binders recovered from mixes with 25% RAP. Additionally, recovered binders with PG64-22 were stiffer than recovered binders with PG58-28.

A supplementary study was performed to evaluate blending of the recovered binder. Figures 8 and 9 show that binder recovered from the mixes did not harden as much as expected. For example, based on linear blending, binder recovered from Mix D (40% RAP) would be expected to have a stiffness approximately 40$ of the way from the RTFOT 64-22 to the RAP binder. In fact, the stiffness increased only 8%, about one-fifth of the expected amount.

In the supplementary study, asphalt binder was recovered from the RAP and blended with RTFOT- aged PG 64-22 in proportion for Mixes C and D. Comparison of moduli from the blended binders simulating mixes C and D with binders recovered from the corresponding mixes, shown in Figure 11, indicates similar results. This demonstrates that the stiffening effect of complete blending of these binders did not occur; even when the binders were forced to blend, the RAP binder did not stiffen the virgin binder in proportion to the relative amounts of the two binders (i.e., linearly). This suggests some sort of incompatibility between these two binders that prevented their complete blending or some other effect (see later discussion of colloids).

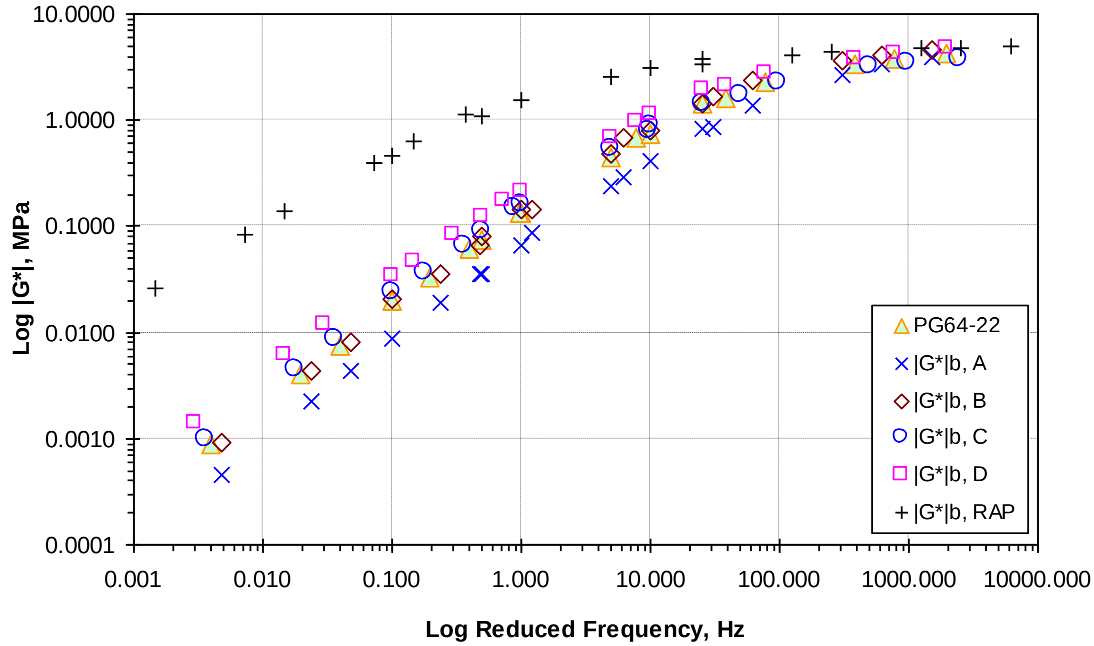


Figure 8. Master curves for binders recovered from mixes with PG64-22 (T_{ref} = 37.2ºC)

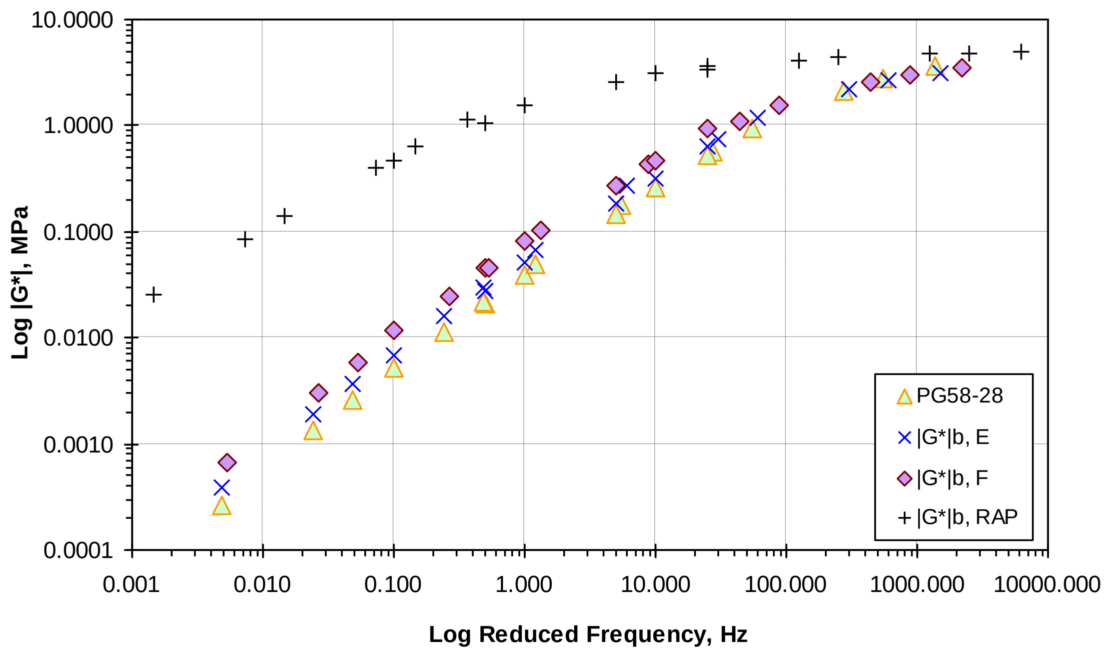
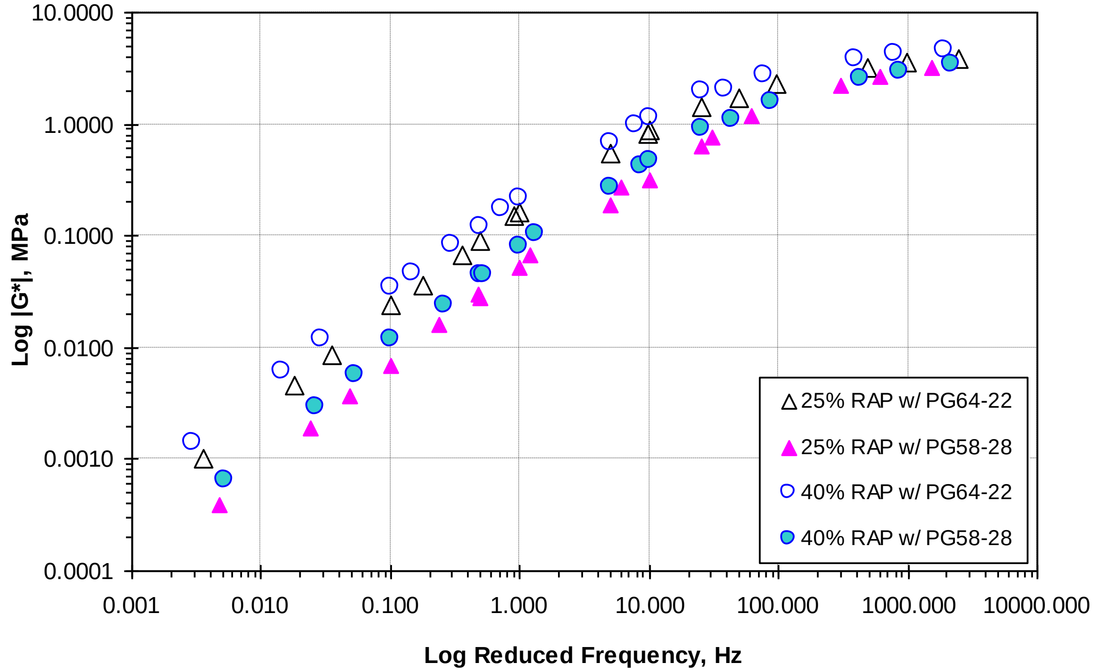


Figure 9. Master curves for recovered binders with PG58-28 (T_{ref} = 37.2ºC)



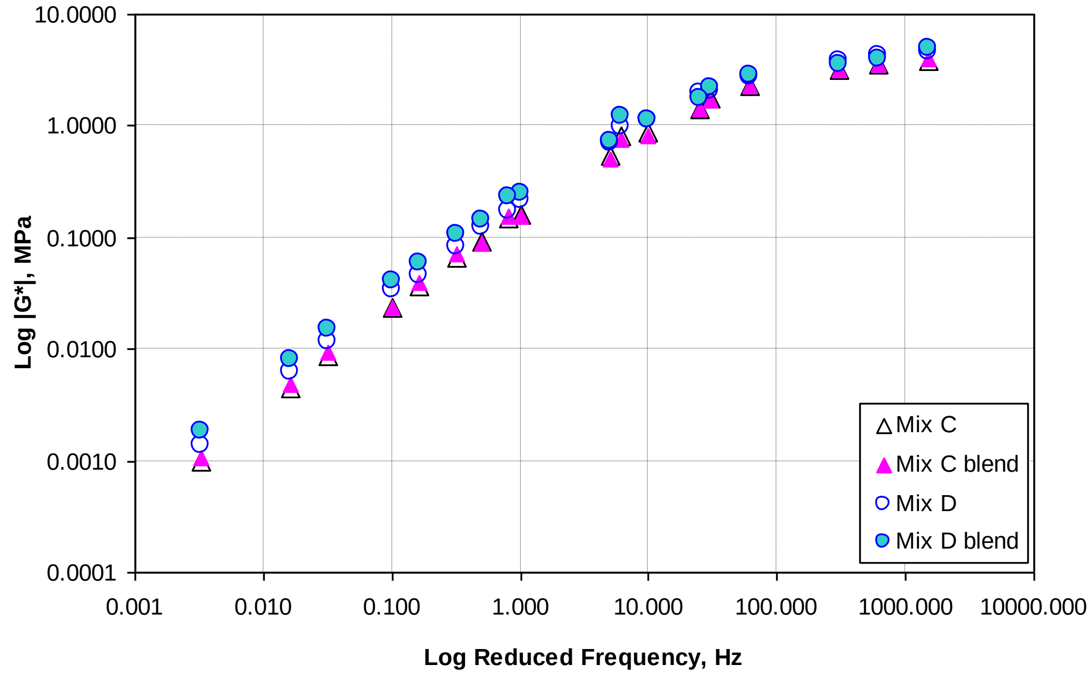


Figure 10. Master curves for recovered binders from mixes C, D, E and F (T_{ref} = 37.2ºC)

Figure 11. Master curves for binder blends C and D (T_{ref} = 37.2ºC)

DISCUSSION

Stiffening of the asphalt binder in mixtures containing RAP did not occur as rapidly in this case as might be expected considering the difference in stiffness between the virgin and RAP binders. The reasons for this are not known. It may be a reflection of the effect of incompatibility of the virgin and RAP binders, or simply poor blending.

One possible explanation may be related to the behavior of colloids. In a colloidal system (a system of dissimilar particles bound together in a matrix), the addition of colloids with different properties may not influence the properties of the matrix in proportion to their presence. Adding a small percentage of a different substance makes a small change to the matrix properties. Increasing the number of colloids will not change the matrix properties to a large degree because the colloids are a minority in the matrix and are not interacting. As the percentage of the differing particles increases, the number of interactions increases and the matrix properties are significantly changed.

An example of this effect can be seen in the SBS modification of asphalt binder. Adding a half percent of SBS changes the binder stiffness only a little. Increasing the addition rate to one percent will have an effect on the binder properties, but will not enhance the properties significantly. As the percentage increases, a network of SBS bonds develops throughout the binder and the properties change quite dramatically.

These data support the hypothesis that adding small amounts of reclaimed asphalt binder may not change the mix properties greatly, at least in most cases. As the percentage increases, some effect on the mixture properties is noted, but not in proportion to the amount being added. When the percentage is high enough, the RAP binder should create a dramatic change in the mixture properties. In colloidal chemistry, the "threshold" value at which each type of colloid begins to have influence on the matrix properties varies with the type of colloid suspended in the matrix. In a similar manner, the influence of RAP on the complete hot mix asphalt sample also varies with the RAP amount. That may explain why some combinations of RAP and virgin binder show the effects of the stiffer RAP binder at lower percentages and some at higher percentages than predicted by linear blending.

Further research is needed to examine additional RAP materials and to evaluate even higher RAP contents to determine when the RAP binder does have a substantial effect on the mixture properties. Three Indiana contractors have agreed to replicate this experiment in 2007 using different RAP sources and plants. There have also been expressions of interest in recreating this experiment on a wider scale to include even more RAPs and plants. Only by collecting more data in a systematic way, will we be able to validate the existing specifications or to determine if modifications are warranted.

Replication of Mix C

Because the results of testing the original mixes did not indicate the level of blending expected, there was concern that perhaps some conditions at the plant were out of the ordinary and might be causing the mixtures to be softer than expected. Therefore, Milestone Contractors produced mix C (25% RAP) again several weeks after the first production. The same binder and virgin aggregate sources were used; the same RAP pile was also used. Tests to determine the indirect tensile strength and complex dynamic modulus were conducted on this mix. No statistically significant differences were obtained between the properties of the original mix C and the replicate run. The repeatability of the results for this mix suggests that random variability is not producing the results observed in the experiment. By extension, the results of the experiment represent actual changes in mix properties.

Another potential source of the difference in results between this experiment and the testing from NCHRP 9-12 and the regional pooled fund study is the asphalt recovery method. Heritage Research Group used Abson recovery whereas the NCSC used the modified SHRP extraction/recovery procedure outlined in AASHTO T319 in the other studies. The Abson recovery was done using reagent grade methylene chloride, whereas the NCSC used n-propyl bromide in the T319 procedure.

Binder was recovered from mixes A and C (old) using both T319 and Abson recovery process for comparison. It was observed that binders recovered using AASHTO T319 had somewhat stiffer moduli compared with the corresponding binder recovered using the Abson process. Table A6 shows the average |G*| for recovered binders from mixes A and C (old) using the two recovery processes. Statistical comparison of complex shear moduli at 25 Hz and 10 Hz showed no significant differences at 20ºC. At 37.2ºC and 54.4ºC, the differences in the mean moduli of the binders were statistically significant.

CONCLUSIONS

Low Temperatures Tests

The addition of recycled asphalt pavement increased the mix stiffness at low temperatures and decreased the thermal cracking resistance, i.e., resulted in warmer (less negative) critical cracking temperatures. With the addition of 40% RAP to the HMA, the observed increase in T_c was about 6ºC, equivalent to one binder grade. At RAP contents where the current specifications would require switching to a softer binder grade, the change in T_c was around 3 to 6°C. Although addition of RAP also increased the indirect tensile strength of the mixes, this increase was not sufficient to counteract the effect of increasing stiffness. Bumping the grade to account for the higher RAP content was beneficial in improving the thermal cracking resistance as it lowered the stiffness of the mixes and the T_c.

High Temperature Tests

An increase in shear and dynamic modulus values was observed with the addition of RAP. No significant increase in moduli was observed with the addition of 15% RAP, but the addition of 40% RAP increased the dynamic modulus by 100% at 54.4ºC. Lowering the binder grade to PG58-28 also lowered the dynamic and shear moduli of mixes. Mix E with 25% RAP and PG58-28 showed similar moduli to mix B with 15% RAP and PG64-22. Strong correlation was found between complex shear modulus and complex dynamic modulus at the three test temperatures.

Tests on recovered binder samples reflected (or reinforced) the conclusions obtained from the mixture tests. Increasing the RAP content increased the binder stiffness of the recovered binder. This was to be expected, as the extraction and recovery process results in a complete mixing of the old RAP binder with the newly added binder added; and increasing the RAP content increases the amount of “stiffer” old binder in the recovered blend, thereby increasing the modulus.

Tests on blended binders confirmed that the solvent used in extraction process was completely removed and did not affect the results. The RTFO-aged binder modulus was higher than the modulus of the binder recovered from the control mix.

FUTURE PLANS

The results of this study raise a number of questions that will require additional testing to resolve. More mixes containing RAP from a variety of sources mixed with different virgin binders in different plants (preferably including different types of plants) should be evaluated.

At least two more Indiana contractors have agreed to essentially replicate this study in their plants with their sources of materials. Heritage Research Group and the NCSC are willing to collaborate with these contractors to continue this study. A work plan describing the testing to be completed will be prepared and submitted to FHWA for possible funding.

The work plan will include securing additional samples for more thorough study. Some of the additional testing that will be done includes the following:

- Binder low and intermediate temperature properties will be determined in addition to the high temperature tests performed here. This will allow determination of the continuous grades of the binders (virgin, RAP and recovered) and comparison of the results to linear blending charts for all three temperature ranges.
- Binders from the RAP and mixes containing RAP will be extracted and recovered using both the Abson and T319 procedures to allow comparison of those methods.
- Samples will be collected to share with other researchers. Dr. Jo Daniel and Mr. Nelson Gibson both expressed interest in sampling and testing the same materials. This will strengthen and expand the results of the research.

The research team is intrigued by the results of this study and is interested in continuing to examine the properties of plant produced mixtures containing RAP.

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2. Federal Highway Administration, Superpave Mixture Expert Task Group, "Guidelines for the Design of Superpave Mixtures Containing Reclaimed Asphalt Pavement (RAP)", Washington, D.C. (1997) 5 pp.

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4. Joe Schroer, Presentation at NCAUPG, January 2007, http://cobweb.ecn.purdue.edu/~spave/NCAUPG/Activities/2007/2007%20HMA%20Conference.html.

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7. Christensen, D. "*LTSTRESS*", English units version, May 1997.

APPENDIX

Table A1. Mixture properties

Average Property	Mixture					
	A	B	C	D	E	F
RAP Content, %	0	15	25	40	25	40
Binder Grade	PG64-22	PG64-22	PG64-22	PG64-22	PG58-28	PG58-28
Total %AC	5.4	5.5	5.6	5.8	5.9	6.2
VMA, %	15.3	14.6	15.1	13.7	14.8	14.1
Air Voids, %	3.6	2.6	3.6	2.5	3.1	2.3
Gradation (Percent Passing)						
12.5	100.0	100.0	100.0	100.0	100.0	100.0
9.5	94.7	97.4	97.4	98.7	98.3	99.3
4.75	61.0	64.9	60.4	63.4	63.5	65.3
2.36	38.5	39.8	33.7	36.5	35.8	38.7
1.18	26.6	28.4	23.1	24.7	24.1	26.2
0.600	17.4	19.6	16.0	17.3	16.4	18.0
0.300	9.1	9.8	9.1	10.4	9.2	10.7
0.150	5.4	5.6	6.3	7.4	6.5	7.6
0.075	3.9	4.1	4.7	5.4	4.8	5.9

Table A2. Mixture strength data

Mix ID	**Specimen No.**	**RAP %**	**Strength, kPa**	**C. V., %**
A	1	0	3284	10.8
	2		3393	
	3		2758	
B	1	15	3359	11.2
	2		3525	
	3		2831	
C	1	25	3498	5.5
	2		3245	
	3		3150	
D	1	40	4056	10.8
	2		4165	
	3		3390	
E	1	25	3153	14.6
	2		3143	
	3		2413	
F	1	40	3272	6.2
	2		3370	
	3		2988	

Table A3. P-values of two-sample t-tests on mixture strength data

Pairs Tested	RAP %	p-value	Conclusion
A vs. B	0 vs. 15	0.7604	NSD
A vs. C	0 vs. 25	0.5399	NSD
A vs. D	0 vs. 40	0.0805	NSD
B vs. C	15 vs. 25	0.8158	NSD
B vs. D	15 vs. 40	0.1197	NSD
C vs. D	25 vs. 40	0.1182	NSD
E vs. F	25 vs. 40	0.3390	NSD
C vs. E	25 vs. 25	0.2348	NSD
D vs. F	40 vs. 40	0.0906	NSD

Table A4. P-values for two sample t-tests on |E*| data

Grade	Pairs Tested	RAP %	T, ºC	p-value	Conclusion
PG64-22	A vs. B	0 vs. 15	20.0 37.8 54.4	0.0431 0.2117 0.0109	SD NSD SD
PG64-22	A vs. C	0 vs. 25	20.0 37.8 54.4	0.8373 0.0616 0.0532	NSD NSD NSD
PG64-22	A vs. D	0 vs. 40	20.0 37.8 54.4	0.0807 0.0034 0.0004	NSD SD SD
PG64-22	B vs. C	15 vs. 25	20.0 37.8 54.4	0.0437 0.0203 0.4481	SD SD NSD
PG64-22	B vs. D	15 vs. 40	20.0 37.8 54.4	0.0098 0.0044 0.0005	SD SD SD
PG64-22	C vs. D	25 vs. 40	20.0 37.8 54.4	0.0487 0.0200 0.0139	SD SD SD

Table A5. Average complex dynamic moduli of the mixtures

Mix	RAP %	Binder	T, ºC	|E*|, MPa	C. V., %
A	0	PG64-22	20.0 37.8 54.4	1145 344 83	7.5 19.7 4.3
B	15	PG64-22	20.0 37.8 54.4	925 282 110	10.6 16.9 6.5
C	25	PG64-22	20.0 37.8 54.4	1221 507 148	10.5 6.8 5.6
D	40	PG64-22	20.0 37.8 54.4	1290 698 173	3.4 11.4 4.4
E	25	PG58-28	20.0 37.8 54.4	946 261 98	8.1 5.7 7.6
F	40	PG58-28	20.0 37.8 54.4	728 254 115	14.1 1.2 6.3

Table A6. Average complex shear moduli of recovered binders

Temperature	Mix	Frequency	Abson Recovery	AASHTO T319	Percent difference
20.0ºC	A	25 Hz 10 Hz	3.95×10^6 3.33×10^6	4.14×10^6 3.94×10^6	4.78 18.31
	C (old)	25 Hz 10 Hz	2.94×10^6 2.64×10^6	4.45×10^6 4.27×10^6	51.49 62.04
37.2ºC	A	25 Hz 10 Hz	8.43×10^5 4.13×10^5	1.36×10^6 7.34×10^5	61.45 77.87
	C (old)	25 Hz 10 Hz	1.22×10^6 7.10×10^5	2.25×10^6 1.45×10^6	84.60 103.62
54.4ºC	A	25 Hz 10 Hz	8.65×10^4 3.56×10^4	1.38×10^5 6.20×10^4	59.04 74.21
	C (old)	25 Hz 10 Hz	1.35×10^5 6.12×10^4	3.34×10^5 1.68×10^5	146.84 174.17

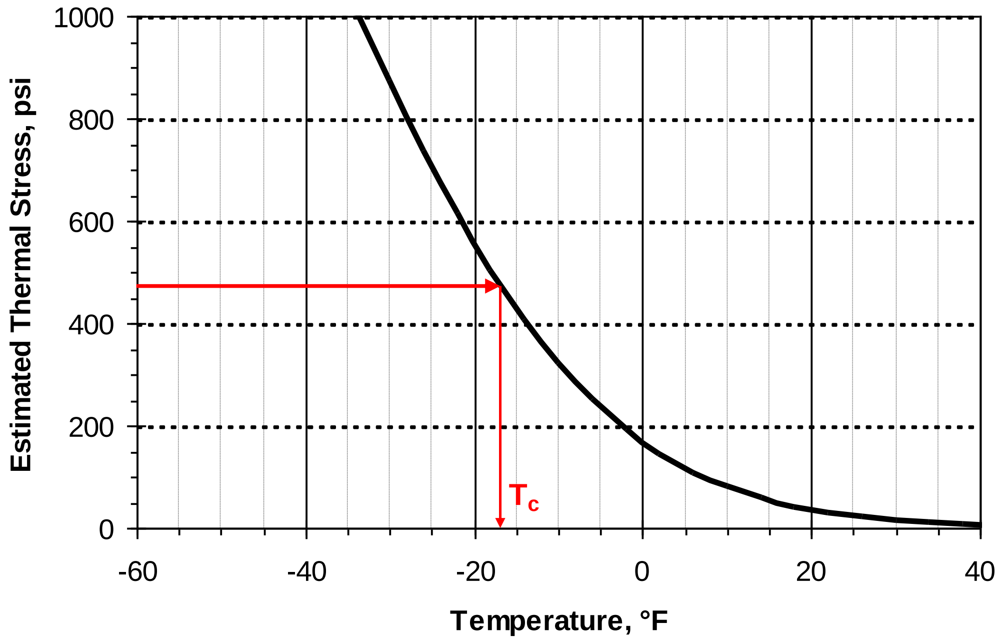

Figure A1. Typical plot of thermal stress versus temperature

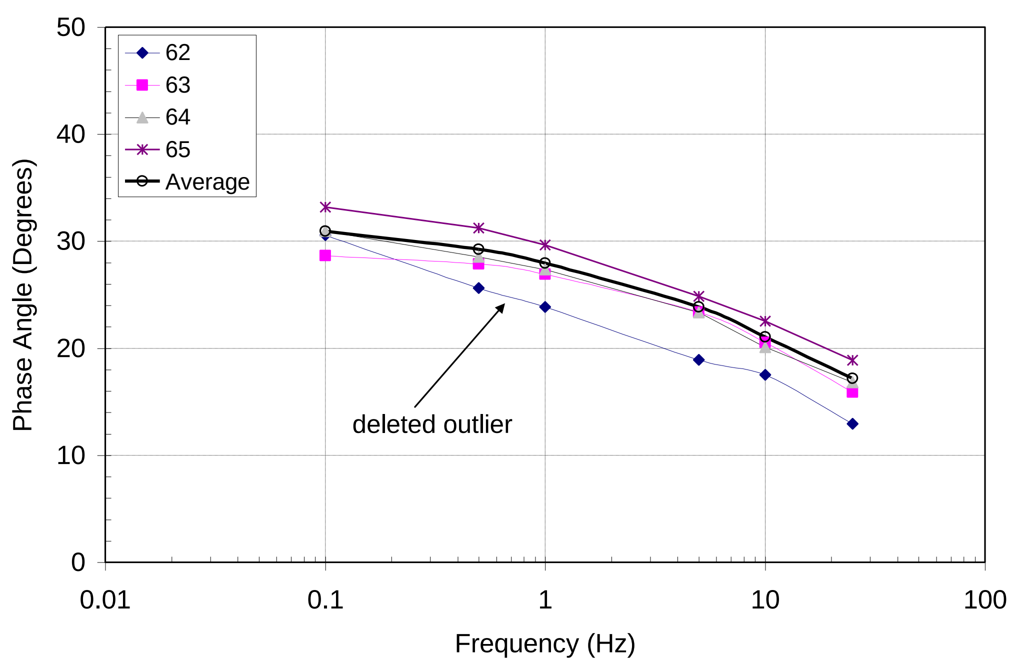

Figure A2. Typical plot of complex modulus versus log frequency

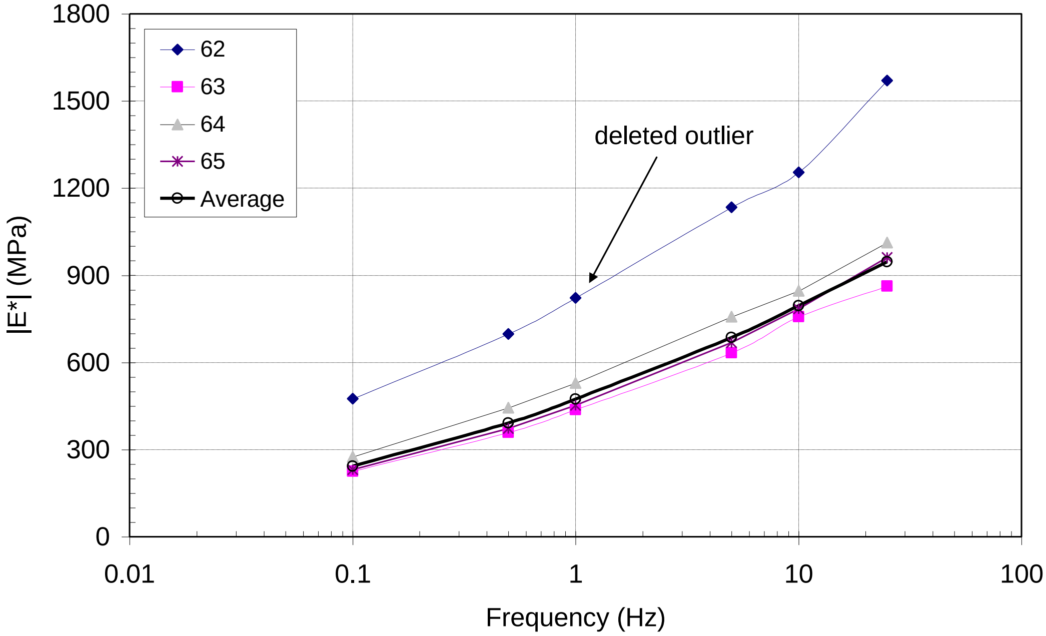

Figure A3. Typical plot of phase angle versus log frequency

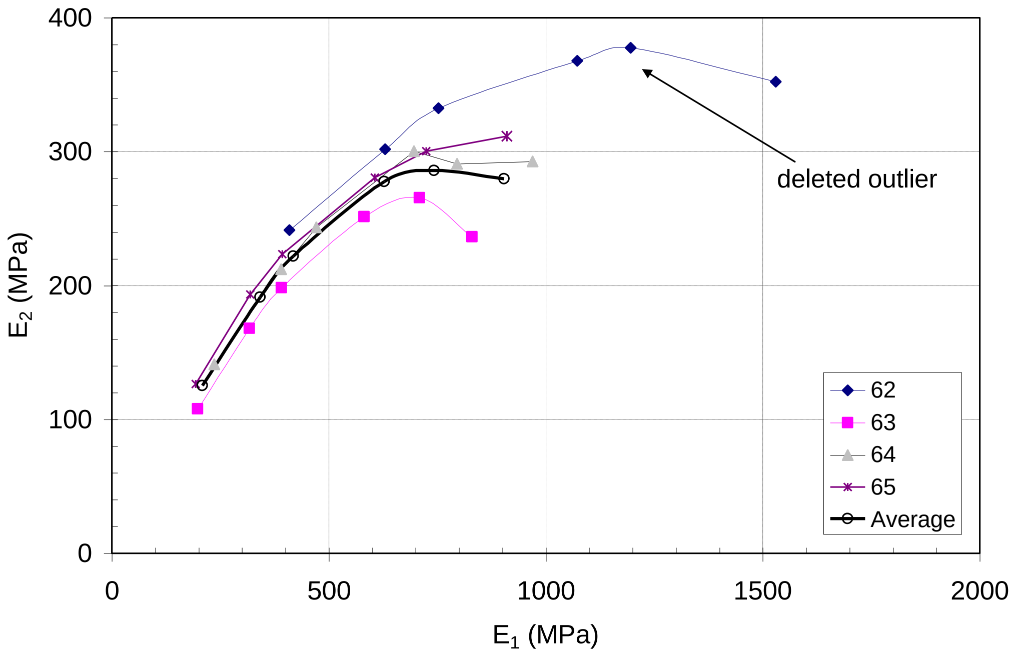

Figure A4. Typical plot of loss modulus versus storage modulus

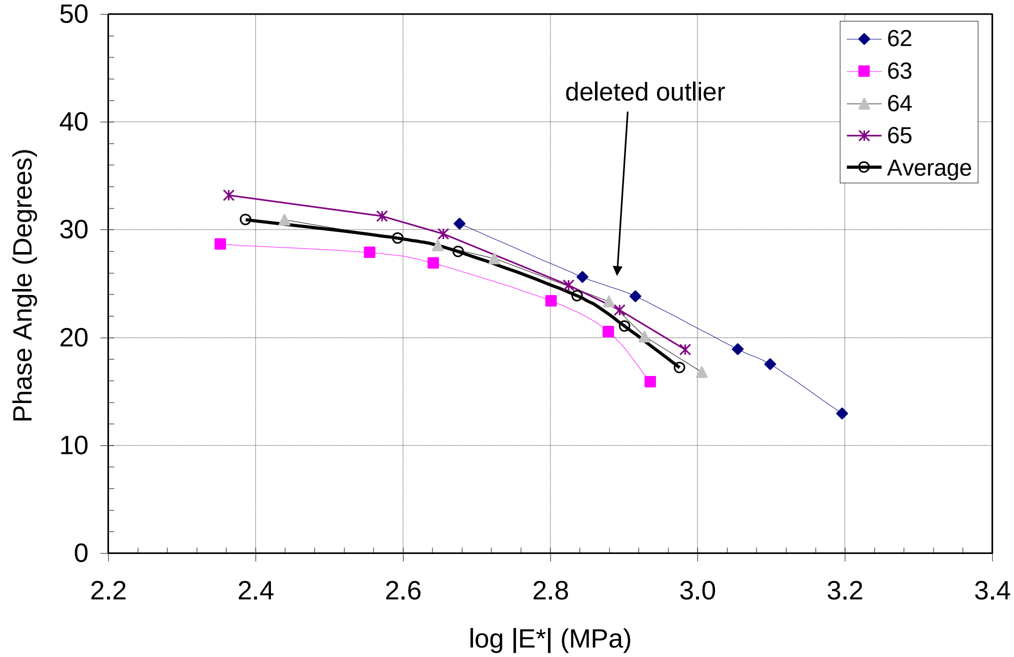

Figure A5. Typical plot of phase angle versus log |E*|

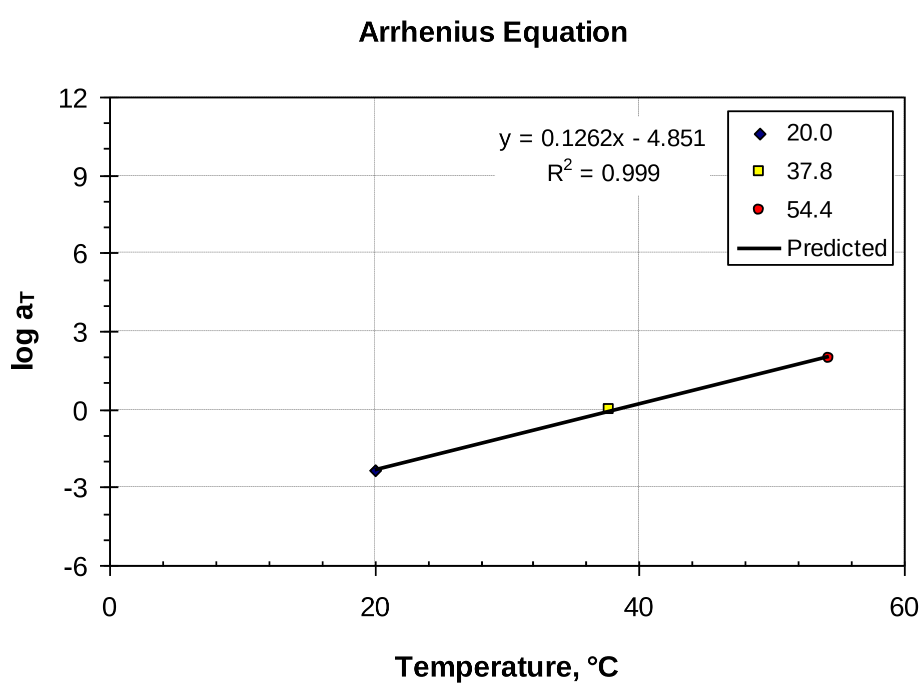

Figure A6. Plot of shift factors for mix A

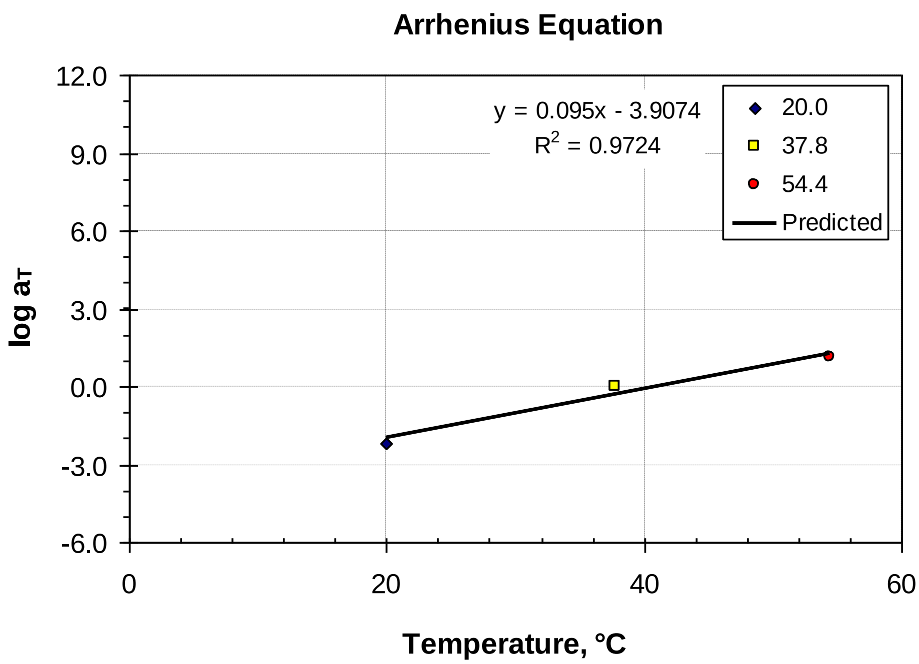

Figure A7. Plot of shift factors for mix B

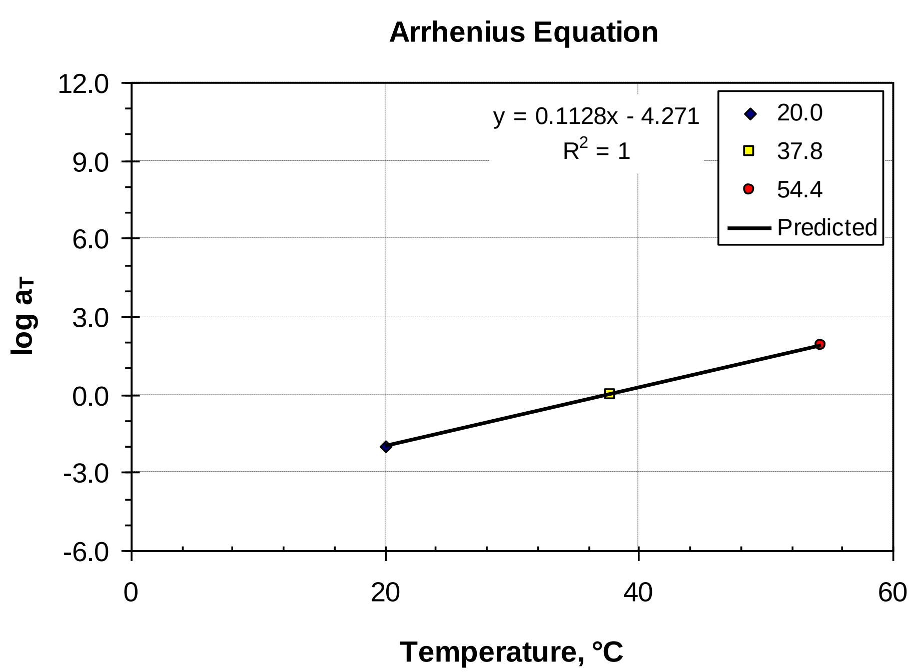

Figure A8. Plot of shift factors for mix C

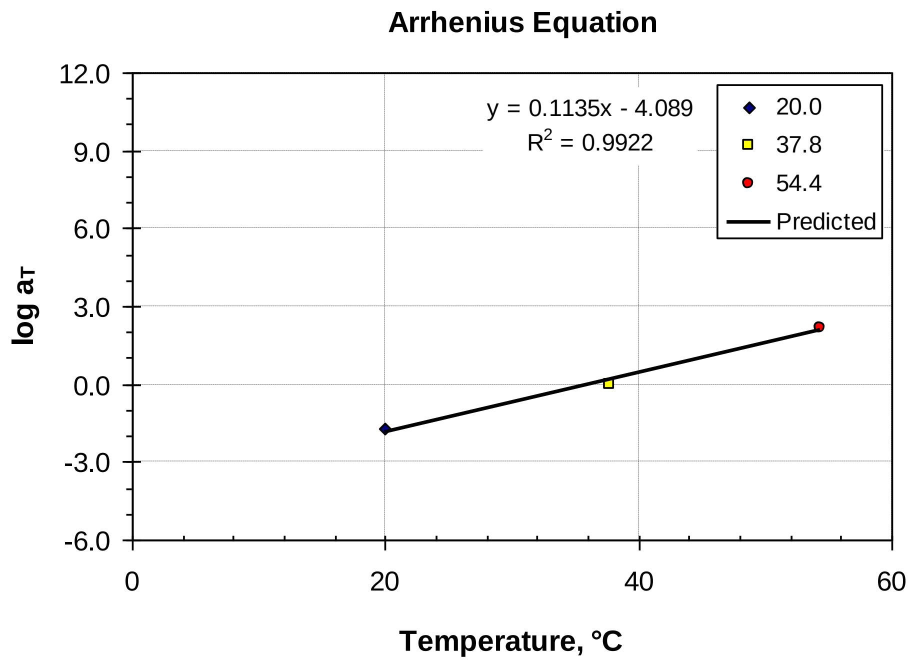

Figure A9. Plot of shift factors for mix D

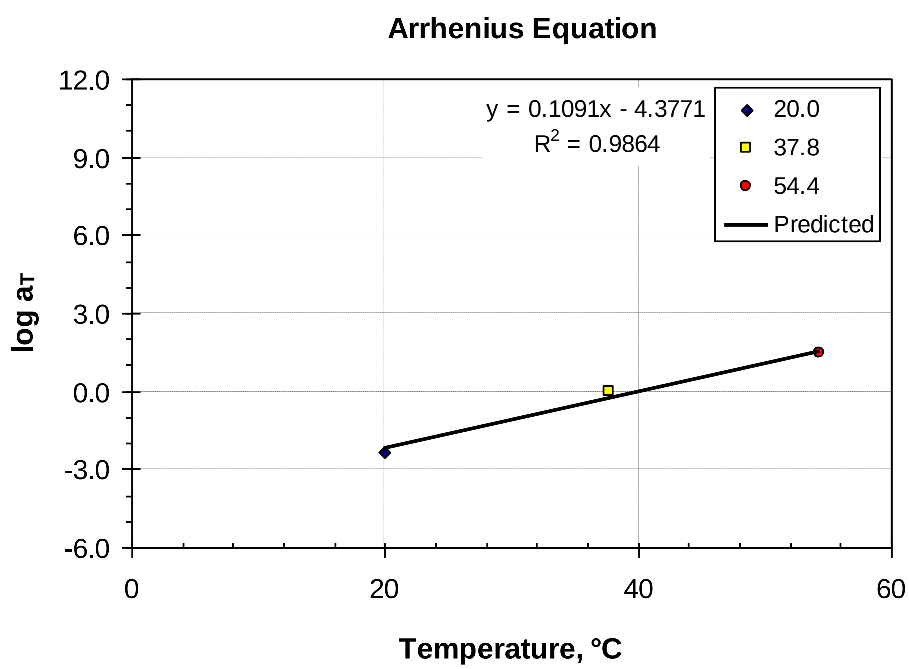

Figure A10. Plot of shift factors for mix E

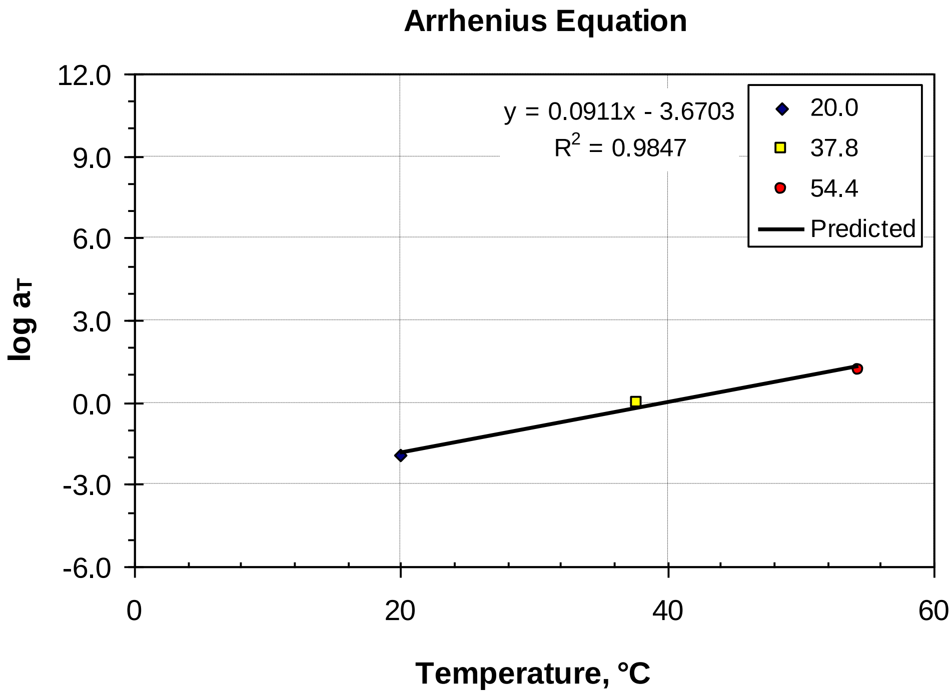

Figure A11. Plot of shift factors for mix F