IMPACT OF LOOSE MIX AGING TIME AND TEMPERATURE ON THE MECHANISTIC PERFORMANCE OF HOT AND WARM BITUMINOUS MIXTURES PRODUCED AS VIRGIN MIXES OR MIXES CONTAINING 20% RAP

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ABSTRACT

Binders recovered from warm mix asphalt (WMA) exhibit lower rheological stiffness than binders recovered from the same mixes produced at traditional hot mix temperatures. Additionally WMA mixes generally exhibit lower modulus values than their HMA counterparts. However, to date WMA mixes have performed comparably to their HMA counterparts. The present study, investigates the rate at which warm mixes develop strength relative to hot mixes using the same binder and aggregate when those mixes are conditioned at their respective warm and hot mix compaction temperatures. Virgin PG 58-28 warm mixes were conditioned for 2, 4 and 8 hours at 104°C while virgin hot mixes were conditioned for 0.5, 2, and 4 hours at 135°C. Counterparts to these mixes were investigated using a 20% RAP substitution. AMPT testing to determine E and Flownumber creep strain and the Hamburg Wheel Tracker (both dry and wet mode) were performed. Dry Hamburg and E* results for all virgin mixes were strongly dependent on aging temperature and aging time. Accumulated strain results from the Flownumber test using confining pressure indicate that the impact of binder stiffness properties in the mix may not be as important as previously considered. The 20% RAP mixes aged 4 hours at 104°C exhibited similar modulus and dry Hamburg performance as mixes aged 2 hours at 135°C. Low temperature recovered binder stiffness properties exhibited minor variations for all warm mixes, whereas HMA mixes exhibited approximately a 3°C increase in low temperature PG grade between 0.5 and 4 hours of aging.*

Keywords: Warm Mix, WMA, HMA, AMPT, complex modulus

1. INTRODUCTION

Warm mix asphalt (WMA) has become a very hot topic within the bituminous paving industry both within the United States and in Europe. Two Scan tours of US technical experts have visited Europe to study approaches to warm mix production and implementation and numerous reports have been written and presentations made at a variety of industry meetings (1). What originally began as three warm mix technologies in Europe (2, 3) has quickly grown into more than 13 technological approaches (4) with more to come one would assume. There is a general consensus at least within the US paving industry that binders recovered from warm mixes are noticeably less stiff than binders recovered from hot mixes produced with the same binder and aggregate (5). Several reports demonstrate that warm mix mechanical properties exhibit lower moduli, greater rutting on wheel tracking tests, lower tensile strengths (although not necessarily lower TSR values). Results from the NCAT test track (5), and California Heavy Vehicle Simulator (6) however, have shown that even with these reduced stiffness properties there does not seem to be any loss of performance with respect to permanent deformation at least in the short term. The bituminous paving industry is therefore left with the conundrum of binder properties and laboratory mixture test properties that predict poor performance if not outright failure and in service results that argue against that conclusion. The study, which is the subject of this paper, is an effort to understand in detail the impact of aging time and temperature on the mechanistic properties of both warm and hot mixes as well as the impact of aging time and temperature on the high and low temperature rheological properties of binders recovered from those warm and hot mixes. Currently NCHRP 9-43 is underway with a goal of determining appropriate methods of mix design for warm mix asphalt (7). Additionally this research will endeavor to provide some insight into why warm mixes perform in the field when laboratory test properties indicate that they should not.

2. STUDY DESIGN

The project used a mix designed for a 10 million Equivalent Single Axel Loads (ESAL) pavement with a limestone aggregate. Both a virgin and a 20% RAP design were investigated. The gradations are shown in Table 1 along with some additional aggregate properties. The mix design binder content was 5.6% for the virgin blend and the design binder content for the RAP mix was 5.5% with a 4.6% virgin add. An unmodified PG 58-28 binder was used to produce the mixes. The following conditions were used to produce the hot mix (HMA) test specimens:

1. RAP content of the mixes was 0% and 20%
2. All mixes were blended at 135°C (275°F) and cured at 135°C (275°F)
3. Loose mix was cured at 135°C (275°F) for 0.5, 2 and 4 hours prior to compaction

For the warm mix (WMA) specimens the following conditions were employed:

1. RAP content of the mixes was 0% and 20%
2. For the initial study 0.5% Evotherm® 3G was blended by weight into the PG 58-28.
3. All mixes were produced at 110°C (230°F) and cured at 104°C (220°F)
4. Loose mix was cured at 104°C (220°F) for 2, 4 and 8 hours prior to compaction.

Additional warm mix specimens were produced according to the following formulations. These additional warm mix specimens were only aged for 4 hours in the loose condition.

1. The addition of water only at 2% water by weight of binder to simulate water only foaming process. Two sets of warm mix specimens were produced. One set was mixed and cured at 121°C (250°F) and another set was mixed and cured at 113°C (235°F).
2. Sasobit® wax at 0.5% by weight of binder pre-blended into the PG 58-28 binder, warm mix produced at 110°C (230°F) and cured at 104°C (220°F). Two separate 0.5% wax blends were produced and cured at these conditions.

TABLE 1—AGGREGATE GRADATIONS AND OTHER PROPERTIES

VIRGIN BLEND			**RAP BLEND**		**OTHER PROPERTIES, Virgin**	
Sieve	% Passing		Sieve	% Passing	Crushed 2 face	97.4 %
19 mm	100		19 mm	100	Flat & Elongated	1.6%
12.5 mm	94.4		12.5 mm	93.0	Fine Agg Angular	45.7
9.5 mm	86.7		9.5 mm	85.7	Filler to Binder ratio	0.8
4.75 mm	69.7		4.75 mm	72.2		
2.36 mm	49.0		2.36 mm	52.8	OTHER PROPERTIES, RAP Mix NOTE 1	
1.18 mm	34.8		1.18 mm	38.0	Crushed 2 face	93.3 %
0.6 mm	24.0		0.6 mm	27.2	Flat & Elongated	0.85%
0.3 mm	17.1		0.3 mm	19.9	Fine Agg Angular	ND
0.15 mm	8.5		0.15 mm	10.6	Filler to Binder ratio	1.0

0.075 mm	3.9		0.075 mm	4.8		

NOTE 1—For RAP mix the natural sand was reduced by 2% compared to the virgin blend and the 12.5 mm crushed limestone was replaced by the 20% RAP. The F&E on the 12.5 mm limestone was 2.7% compared to 1.1% for the RAP

TESTS CONDUCTED ON MIX SPECIMENS AND BINDERS

The following tests were conducted on the virgin and RAP mixes from the original design portion of the study. The additional mixes noted above were only tested in the Hamburg dry at 58°C.

1. Hamburg tests at a target of 58°C dry, with a 703 N (158 lb) load at 52 passes per minute
2. Hamburg tests at a target of 50°C wet, with a 703 N (158 lb) load at 52 passes per minute
3. AMPT testing at 4°C, 20°C and 40°C to determine E* modulus values and generate mastercurves for the mixes. Tests conducted on triplicate specimens.
4. AMPT testing for Flow Number and percent strain were conducted at 52°C, with a 69 kPa (10 PSI) confining pressure at 400, 600 and 800 kPa axial stress levels. One of each of the triplicate E* specimens was tested at each stress level after completion of the E* tests and one fresh specimen was tested at each stress level. The duplicate test results were averaged to yield a strain versus test stress result.
5. The binders from the dry Hamburg samples (including the additional specimens noted above) were extracted with toluene and recovered using ASTM D5404. The true PG grades of the recovered binders were determined and Multiple Stress Creep Recovery (MSCR)[8] tests to determine the non-recovered compliance (Jnr) were performed on the recovered binders.

3. TEST RESULTS

3.1 HAMBURG DRY RUT TEST RESULTS

The dry Hamburg test results for the original hot and warm mixes, both virgin and RAP are shown in Figures 1 and 2. Figure 1 is a linear plot of rut depth versus linear loose mix curing time and Figure 2 is logarithmic plot of rut depth versus loose mix curing time.

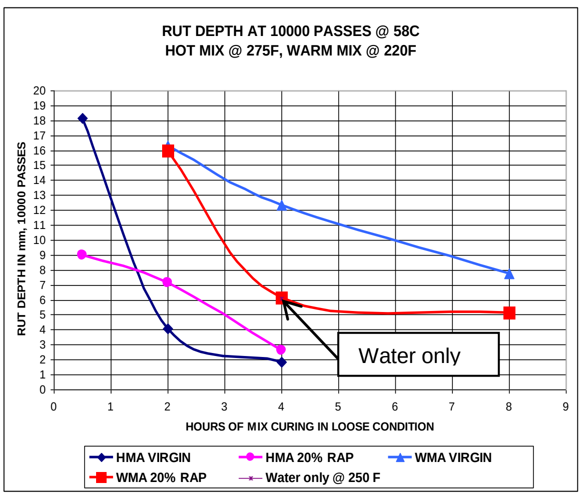


Figure 1: Linear Scale plot of Rut Depth Resulting From Loose Mix Curing Time

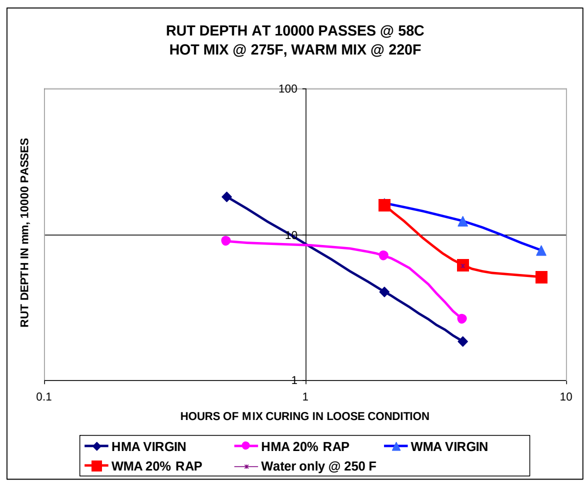


Figure 2: Log-Log plot of Rut Depth Resulting From Loose Mix Curing Time

The log-log plot shows that as the loose mix cure time increases there is a log proportional decrease in rut depth for the virgin mixes. This is true for both the HMA and WMA mixes and is what one would typically expect. For the 20% RAP mixes however there are two factors to consider; one is the actual stiffening of the binders with curing time and the other is the impact of virgin binder interacting with the RAP binder. Examination of the HMA mixes establishes that the initial impact of the RAP binder at 0.5 hours results in less rutting than the virgin mix at the same time. This is most likely due to the overall drier mix that results from less virgin binder present in the mix. After 2 hours of curing there is little change in the rut depth of the RAP HMA mix relative to the 0.5 hour cure time and the rut depth of the 2 hour HMA RAP mix is now greater than that of the 2 hour virgin mix. This could be attributed to the interaction of the virgin and RAP binders beginning to occur, but whatever the cause no apparent binder aging had occurred which would lead to binder stiffening and a decrease in rutting. By the 4 hour cure period the rut depths are nearly identical between the virgin and the RAP mixes, which could indicate RAP and virgin binder interaction as well as similar binder aging in both virgin and RAP mixtures. Figure 3 shows that by the 4 hour time period the binder recovered from the virgin HMA mix and the binder recovered from the RAP HMA mix are nearly identical. There is always a danger in drawing conclusions about the actual binder stiffness of the in place mix for RAP containing mixes, but the 4 hour data shown in Figure 3 would argue that nearly full interaction has taken place and the binder in the RAP mix has aged to the same level as the virgin binder. Another point to consider is that at 0.5 and 2 hours the DSR stiffness of the recovered HMA/RAP binders is such that the rut depth of those mixes, compared to the DSR stiffness of the similarly aged virgin mixes, should have been greater than they were if the recovered HMA/RAP mix binders represented the actual in place stiffness of the binders. Based on these data it is reasonable to conclude that at 0.5 and 2 hours of mix aging the complete interaction of the virgin and RAP binders had not occurred and the rut depths reflect that lack of aging. Looking further at Figure 3 reveals that the recovered binders from the virgin WMA mixes show a minor increase in DSR stiffness even at the 8 hour curing time. The 2 hour cure time for the 20% RAP WMA mix is nearly identical to the virgin WMA mix even though the recovered DSR value is about 2 kPa higher. Again, this indicates a lack of intermingling between virgin and RAP binders. By 4 hours the rut depth of the WMA RAP mix has dropped to half of the rut depth of the 4 hour aged virgin WMA mix (Figures 1, 2), but the recovered DSR is about the same as that of the 2 hour aged RAP WMA mix. This reflects an intermingling of the RAP and virgin binders after 4 hours of curing such that at this time period the DSR stiffness is more representative of the actual binder that is acting in the mix. Further aging of the RAP WMA mix doesn't lead to an appreciable decrease in rut depth (Figures 1, 2) although the DSR stiffness does increase by about 2 kPa as a result of the additional 4 hours of curing time at the warm mix temperature (Figure 3). The DSR stiffness decreases by less than 1 kPa between 4 and 8 hours of curing for virgin WMA and by 2 kPa for the WMA RAP binder. The 4 hour WMA RAP rut depth suggests substantial interaction of RAP and virgin binder which the additional 4 hours of curing at 104°C (220°C) does not enhance given the minor change in rut depth after 8 hours of curing.

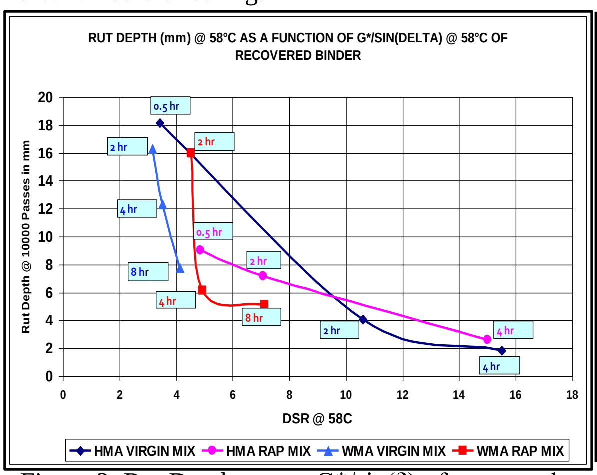


Figure 3: Rut Depth versus G*/sin(δ) of recovered Binder

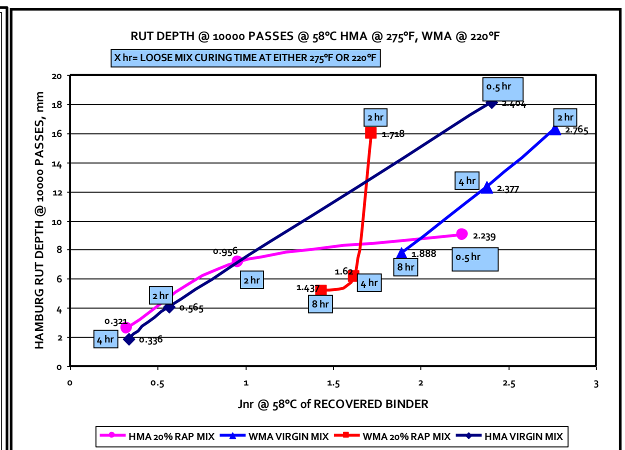


Figure 4: Rut Depth @ 10000 passes versus Jnr of Recovered Binder

Figure 4 is a plot of rut depth versus non-recovered compliance (Jnr) of the binders recovered from the HMA and WMA mixes. The information in Figure 4 can be interpreted in a manner similar to the DSR stiffness data. There are however several interesting observations. Jnr of the binders recovered from the virgin HMA mixes plot a straight line versus rut depth and additionally the Jnr of the binders recovered from the RAP HMA mixes at 2 and 4 hours of aging fall very close to the virgin binder line. This observation lends additional credence to the conclusion that by 2 hours of aging at 135°C (275°F) some intermingling of RAP and virgin binders has taken place. The same observations can be made with respect to the binders recovered from the virgin WMA mixes and the RAP WMA mixes aged at 4 and 8 hours. The lack of a linear fit for the HMA RAP mix at 0.5 hours and the WMA RAP mix at 2 hours further emphasizes that the RAP/virgin binder interaction is not appreciable at those time periods for those mixes. However the lack of RAP/virgin interaction manifests differently for the HMA than the WMA. The HMA rut depth is reasonable given the recovered binder DSR probably due to a dry mix, while the RAP WMA rut depth is very high given the DSR value indicating aging of the virgin binder but no real benefit of a RAP/virgin interaction. Inspection of Figure 4 suggests that the HMA and WMA mixes rut at different rates. Examining the rutting rate as a function of Jnr in Figure 5 shows that the rutting rate behavior of both the HMA and WMA mixes is well explained by the Jnr values of the recovered binders. The rutting rate collapses the rutting data for all four mixes onto one plot.

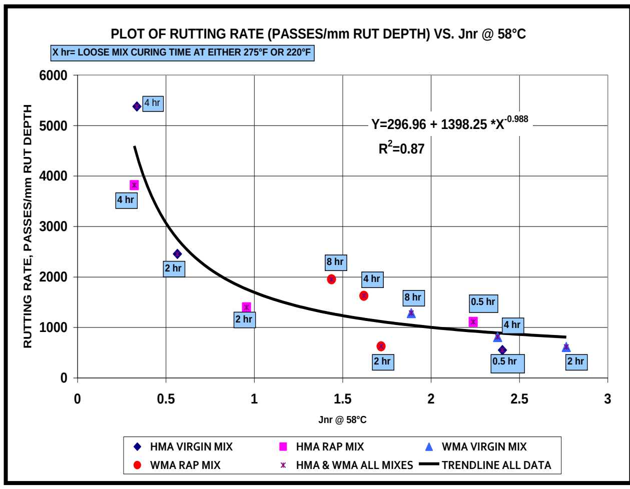


Figure 5:Rutting Rate as a Function of Jnr @ 58°C

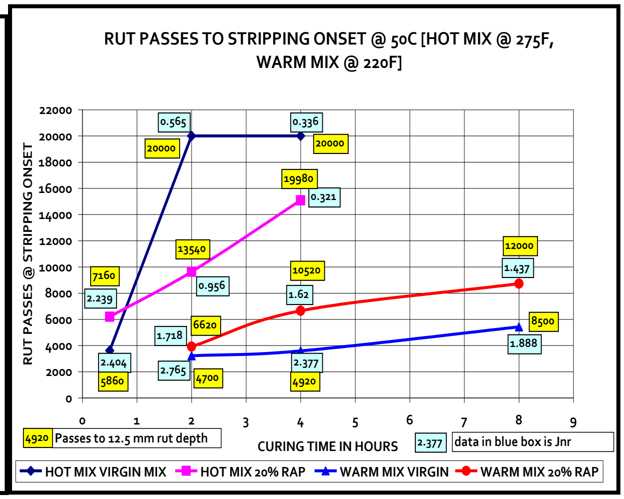


Figure 6: Hamburg Rut Passes to Stripping Onset

3.2 HAMBURG WET TEST RESULTS

Hamburg wheel track testing of mixtures under water were conducted at 50°C. The results plotted as Hamburg wheel passes to the point of stripping onset are shown in Figure 6. Also shown on the plot in Figure 6 are the rut passes to 12.5 mm of rutting and the Jnr values of the binders recovered from the dry Hamburg rut samples previously discussed. There is no specification for the minimum number of wheel passes to 12.5 mm of rutting for a mix produced with a PG 58-28 binder, but since one state (Texas) considers that a minimum of 10000 passes is acceptable for HMA mixes produced with a PG 64-22, then it would be reasonable to use 7500 wheel passes as a minimum number of wheel passes for a PG 58-28 binder. Using the 7500 wheel pass criteria as an acceptable value the 8 hour cured virgin WMA mix would be an acceptable mix and the 4 and 8 hour cured RAP WMA mixes would also be acceptable mixes from a moisture sensitivity point of view.

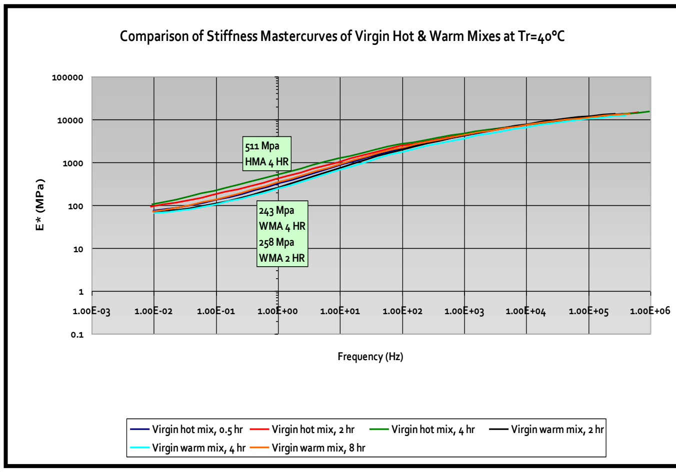
3.3 E* MODULUS TEST RESULTS

Temperature frequency data were collected on all of the mixes using the AMPT. The temperatures selected were 4°C, 20°C and 40°C covering the range of 0.1 to 25 Hz in 10 steps. From these data mastercurves were generated at the 20°C and 40°C reference temperatures. The 40°C mastercurves for all virgin mixes are plotted in Figure 7 and for all RAP mixes in Figure 8. As reduced frequency increases to 1000 Hz and higher the stiffness moduli of all the mixes converge to the same value. However at frequencies below approximately 1 Hz the warm mix specimens exhibit about half the stiffness of the HMA specimens, thus leading to potential permanent deformation concerns for WMA relative to HMA. In Figure 7 the bounding E* values for the HMA and WMA mixes are shown at a frequency of 1 Hz. As expected, the 4 hour cured HMA mix has the highest stiffness value (511 MPa), while the 2 and 4 hour cured WMA mixes have nearly identical modulus values of approximately 250 MPa. The E* data for all of the mixes at 1 Hz and 0.1 Hz at 40°C are shown in Table 2. t 1 Hz and 40°C the 4 hour cured HMA mix has approximately twice the modulus value as the 2 hour cured WMA mix. An examination of Figure 8 shows that at these lower frequencies the 4 hour cured HMA RAP mix is noticeably stiffer than all of the other mixes. The 2 hour cured HMA and 4 hour cured WMA mixes differ in modulus by a little over 100 MPa. At the lower frequency of 0.1 Hz these two mixes differ in stiffness by about 40 MPa.

TABLE 2—E* VALUES FOR ALL MIXES at DIFFERENT TEMPERATURES AND FREQUENCIES

MIX TYPE	CURE TIME, hrs	E*, 1 Hz, 40°C, MPa	E*, 0.1 Hz, 40°C, MPa	E*, 0.001 Hz, 20°C, MPa	Jnr of recovered binder
HMA VIRGIN	0.5	325.6	131.4	131.6	2.404
HMA VIRGIN	2	416.0	179.7	217.2	0.565
HMA VIRGIN	4	511.0	224.4	285.7	0.336
HMA RAP	0.5	379.6	146.1	163.0	2.239
HMA RAP	2	507.6	200.0	223.8	0.956
HMA RAP	4	739.0	308.6	376.5	0.321

MIX TYPE	CURE TIME, hrs	E*, 1 Hz, 40°C, MPa	E*, 0.1 Hz, 40°C, MPa	E*, 0.001 Hz, 20°C, MPa	Jnr of recovered binder
WMA VIRGIN	2	259.1	109.6	106.7	2.765
WMA VIRGIN	4	243.2	105.0	113.6	2.377
WMA VIRGIN	8	339.5	137	150.8	1.888
WMA RAP	2	360.7	144.8	143.6	1.718
WMA RAP	4	392.9	161.5	167.8	1.62
WMA RAP	8	447.5	187.0	207.6	1.437



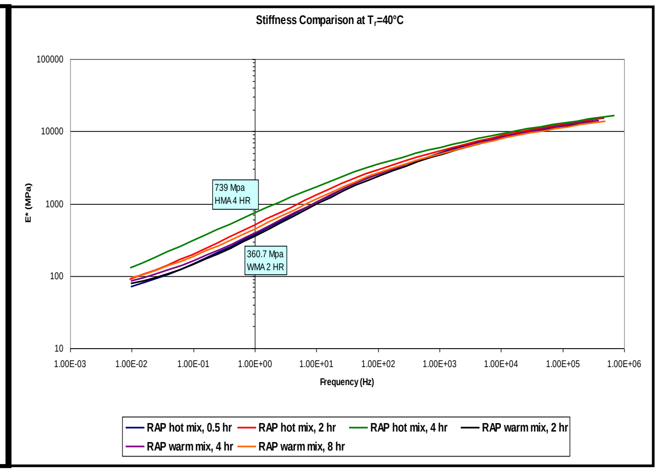


Figure 7: E* Modulus for HMA & WMA @ 40°C

Figure 8: E* Modulus for HMA & WMA @ 20°C

Evaluation of E* as a function of recovered binder Jnr (Figures 9 and 10) shows that Jnr is a reasonably good predictor of mixture modulus at all curing times for both the virgin and RAP mixes. Figure 9 is a plot of E* determined at 0.001 Hz from the 20°C mastercurve and thus the moduli are better correlated because the mix is inherently stiffer due to the lower temperature and the RAP binder properties plays less of a role.

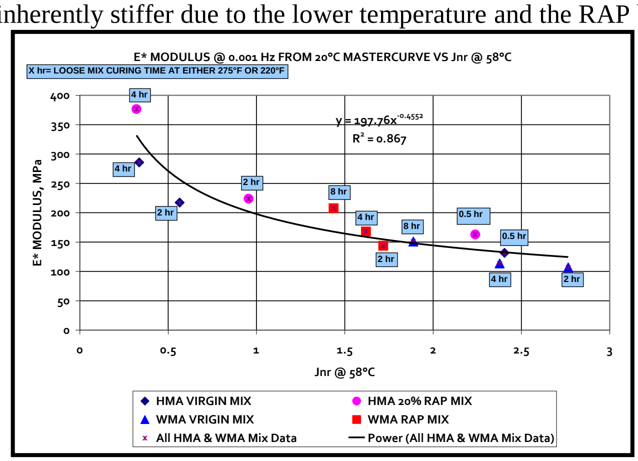


Figure 9: E* @ 0.001 Hz, 20°C as Function of binder Jnr

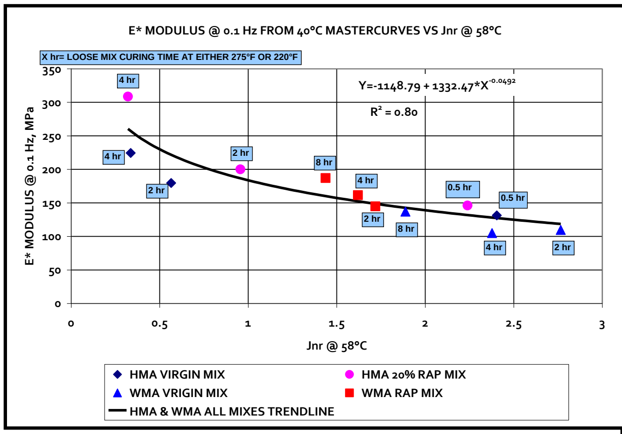
When Jnr is evaluated against the moduli from the 40°C mastercurve (Figure 10) the R^2 drops from 0.88 to 0.80, which based on an examination of the plots is a result of the RAP and cure time exerting their influence on the modulus values of the mixes at the warmer temperature. Nearly all of the E* values for the RAP mixes fall above the line of best fit in Figure 10, indicating that some other factor(s) beyond the binder Jnr is driving the mixture stiffness. As further evidence that the recovered Jnr values don't reflect the actual *in situ* binder stiffness properties resulting in E* modulus in the RAP mixes, consider that when E* at 0.001 Hz from the 20°C mastercurve, for only the virgin mixes, is evaluated as a function of recovered binder Jnr the R^2 value jumps to 0.977 (graph & data not shown). For the virgin mixes it would appear that binder stiffness is the main factor controlling mix stiffness at the lowest frequencies. Figure 11 shows that the development of mixture stiffness is influenced by mix curing time as well as the presence of RAP. The HMA RAP mix shows a slight non-linear increase in modulus at 2 hours of aging and a more substantial increase in modulus at 4 hours of aging compared to a direct linear response for the virgin HMA mixes. The WMA mixes, both the virgin and RAP mixes show very moderate increases in modulus with aging time. The data in Figure 11 supports the conclusion that by 2 hours of conditioning at 135°C (275°F) the interaction of RAP binder and virgin binder has begun and by 4 hours of conditioning at 135°C (275°F) substantial interaction between RAP and virgin binder has occurred. It is not clear just how much interaction is occurring in the WMA RAP mix by 8 hours of conditioning at 104°C (220°F). Since the slope of the change in

E* with conditioning time is moderate, one could conclude that there is some interaction. Overall the 8 hour WMA RAP mix has a stiffness modulus mid-way between the 2 and 4 hour cured virgin HMA mix. The 4 hour cured WMA RAP mix is comparable to the 2 hour cured virgin HMA mix and the 8 hour cured virgin WMA is comparable in stiffness to the 0.5 hour cured HMA.

Figure 10: E* @ 0.1 Hz 40°C as Function of Binder Jnr Figure 11: E* at 1 Hz at 40°C versus Mix Cure Time

3.4 CUMULATIVE STRAIN RESULTS FROM FLOW NUMBER TEST

Flow Number tests at 52°C were conducted in duplicate at three different axial stress levels with a confining stress of 69 kPa. Most of the samples tested did not reach tertiary flow in the 10000 second time period of the test. The one parameter that was captured that yielded valuable information was the total accumulated percent strain at the end of the test. That data is shown in Table 3, which is an average of duplicate tests at each stress level.



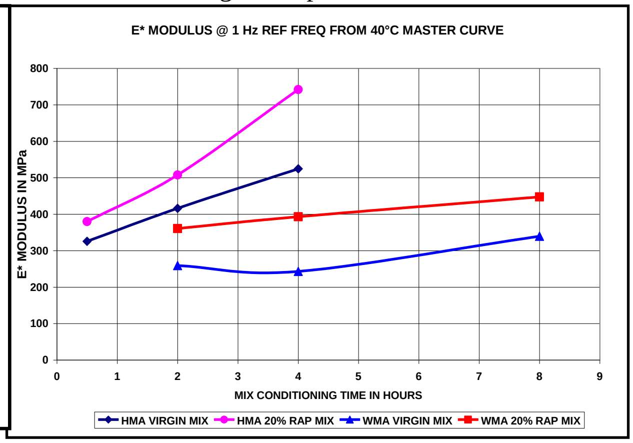
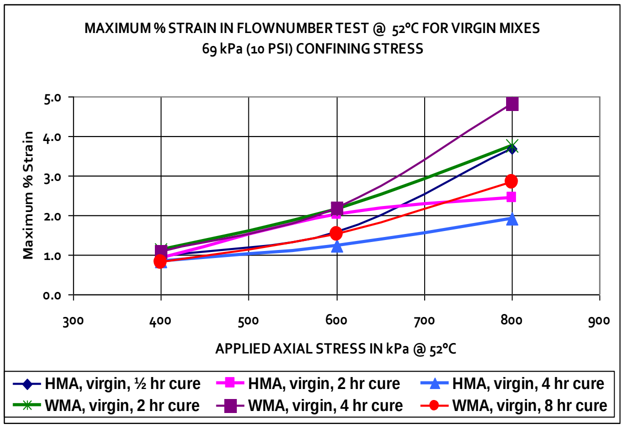


TABLE 3—MAXIMUM PERCENT STRAIN FROM FLOW NUMBER TESTS

Hot/Warm Mix Overall Comparison - Maximum % Strain, 69 kPa CONFINING STRESS at THREE AXIAL STRESS LEVELS						
Sample Type	**AXIAL STRESS, kPa, Virgin**			**AXIAL STRESS, kPa, RAP Mix**		
	400	**600**	**800**	**400**	**600**	**800**
HMA-0.5 hour cure	0.95	1.57	3.67	0.92	1.69	2.81
HMA-2 hour cure	0.92	2.04	2.44	1.08	1.87	3.46
HMA-4 hour cure	0.83	1.24	1.91	0.83	1.39	2.56
WMA-2 hour cure	1.13	2.17	3.77	1.11	1.88	4.24
WMA-4 hour cure	1.08	2.18	4.81	0.97	1.53	3.47
WMA-8 hour cure	0.83	1.53	2.84	0.88	1.52	2.85



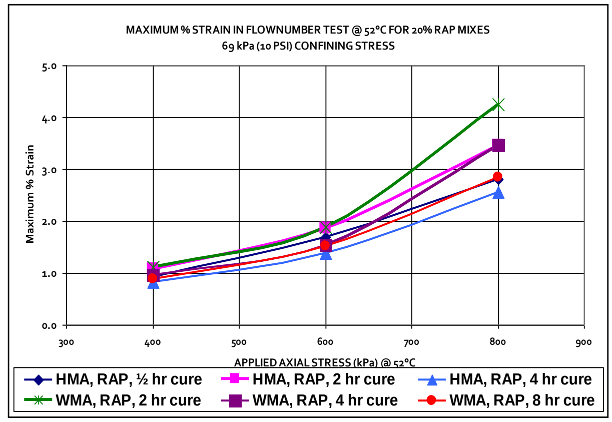
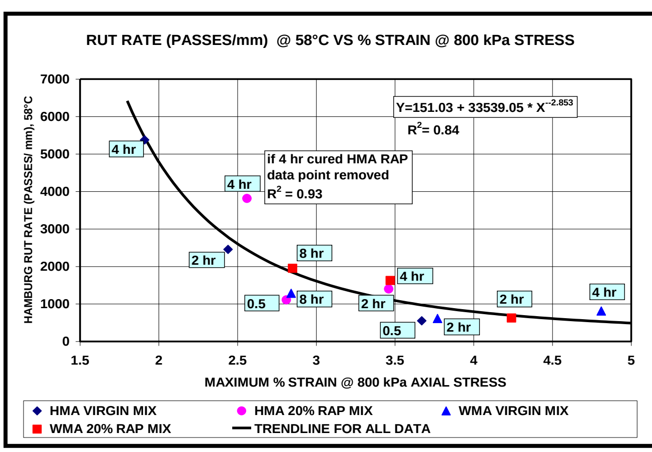


Figure 12: Maximum Strain @ 52°C for Virgin Mixes Figure 13: Maximum Strain @ 52°C for RAP Mixes

The percent strain results at each axial stress level for the virgin and RAP mixes are shown in Figures 12 and 13 respectively. Three axial stress levels were chosen because it was felt that just determining the strain at one stress level (typically 600 kPa) would provide little information about the impact that different in-service stresses would have on mixture performance. A confining stress was chosen based on a desire to better simulate the conditions in the pavement structure. Much of the warm mix work that has been performed to date has been on secondary or lower volume state routes. Clearly, a very high stress condition is not appropriate to model traffic on those pavements and just as clearly, a low stress test condition would not be applicable to model traffic on high volume interstate routes. Figures 12 and 13 show the maximum strain at 400 kPa is both very low and undifferentiated between HMA and WMA regardless of the RAP loading. Similarly, the maximum strain at 600 kPa is quite low but for the virgin mixes there is some differentiation between WMA and between curing times; the 4 hour and 0.5 hour HMA and 8 hour cured WMA exhibiting the lowest strains. At 600 kPa both the HMA and WMA RAP mixes fall within a very narrow strain range. At 800 kPa there is noticeably more strain with approximately a 4 to 5 fold increase in strain compared to the strain at 400 kPa for some of the virgin mixes. At 800 kPa the 2 and 4 hour cured HMA and 8 hour cured WMA have the lowest accumulated strain results (Figure 12). For the RAP mixes total accumulated strain values are lower, but there is still noticeable differentiation of the mixes. The 4 hour and 0.5 hour cured HMA RAP mixes and the 8 hour cured WMA RAP mix have accumulated strain values of less than 3%.



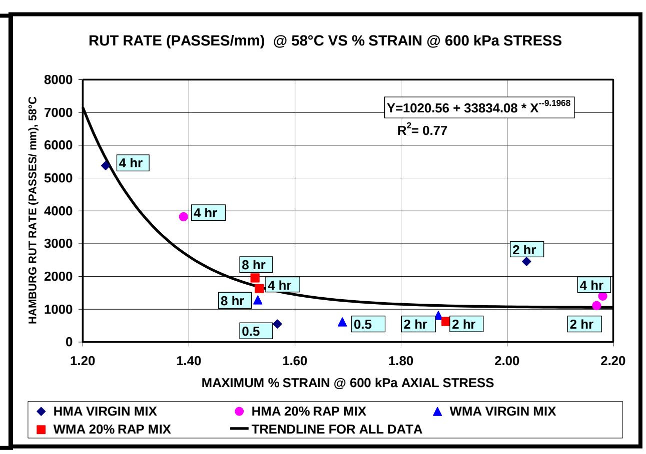


Figure 14: Rut Rate as a Function of Strain @ 800 kPa Figure 15: Rut Rate as a Function of Strain @ 800 kPa

The rutting rate of the dry Hamburg test at 58°C is plotted versus the maximum percent strain for the 800 kPa Flow Number test in Figure 14. The fitted curve for all the HMA and WMA virgin and RAP data yields a R^2 value of 0.84 and if the single data point for the 4 hour cured HMA RAP mix is eliminated the R^2 increases to

0.93, indicating that the E* value for that particular mix may not be correct. These results provide a strong argument that using an 800 kPa axial stress for the Flow Number creep test is appropriate for the high stress environment to which the Hamburg tester subjects mixtures. Using an 800 kPa stress level for predicting mix performance on high ESAL pavements would also seem to make sense. When an evaluation of Hamburg rutting rate is computed as a function of percent strain for the 600 kPa Flow Number test (Figure 15) the correlation (R^2=0.77) is reduced compared to the fit for the 800 kPa stress values although it is still quite good. It should be noted that the E* result for the 4 hour cured HMA RAP mix lies much closer to the line of best fit. The rutting rate data is the same for the plots in Figures 14 and 15. This further suggests that the accumulated strain data for the 800 kPa test is suspect. Obtaining a strong level of correlation between two different types of mixture tests, both designed to provide information about permanent deformation performance is encouraging. None of the data for one set of specimens is influenced by the results of the other specimens.

3.5 LOW TEMPERATURE PG GRADE RESULTS OF RECOVERED BINDER

The low temperature PG grade of the binders recovered from the dry Hamburg test specimens was determined. The results of low temperature PG grade are plotted versus loose mix curing time in Figure 16. As would be expected the HMA binder samples, both virgin and RAP, exhibit a continuing increase in low temperature grade with aging time, although the 4 hour HMA RAP binder has the same grade as the 4 hour cured virgin binder. The more important results are found in the WMA mixes. The WMA virgin mix binders exhibit virtually no increase in low temperature grade over the 8 hour curing period and the WMA RAP mixes exhibit less than a 0.5°C increase in low temperature grade. The 20% RAP addition to the warm mix increases the low temperature PG grade of the recovered binder by about 1.6-1.7°C and after that, no further change is evident.

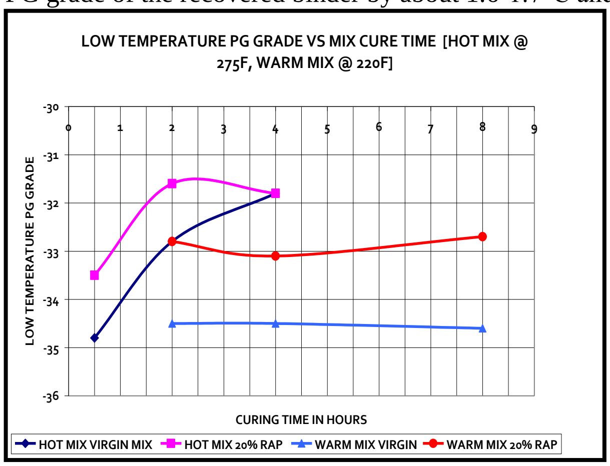


Figure 16:Low Temperature PG Grade of Recovered Binder

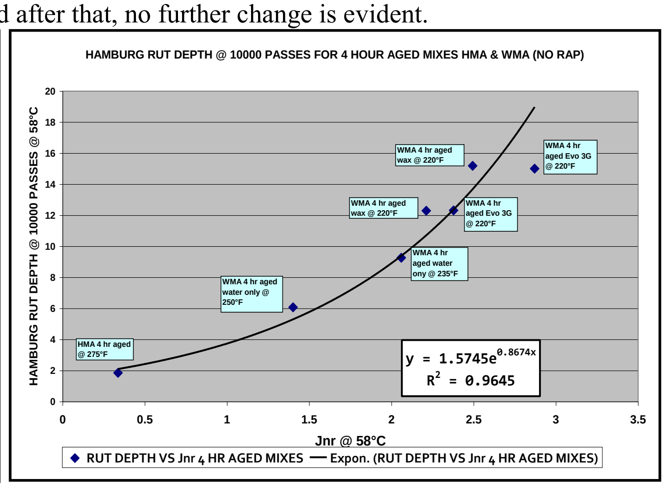


Figure 17: Rut Depth as Function of Jnr of Recovered Binder from 4 hour Cured Mix at Different Temperature

3.5 EVALUATION OF RUTTING AT OTHER WARM MIX TEMPERATURES

As noted in the Study Design some additional warm mixing processes were employed at different temperatures. Samples produced according to these procedures were tested for Hamburg rutting at 58°C dry. The binders were extracted, recovered and high temperature properties were determined. Only the 4 hour curing condition was used on these mixes so that a comparison to the other 4 hour cured mixes evaluated in this study could be compared. The additional mixes produced are described in Table 4.

TABLE 4—ADDITIONAL WARM MIXES PRODUCED & CURED 4 HOURS BEFORE COMPACTION

Additive	Amount	Mix temperature	Cure temperature
Evotherm® 3G (2 sets)	0.5% by wt binder	110°C (230°F)	104°C (220°F)
Sasobit® (2 sets)	0.5% by wt binder	110°C (230°F)	104°C (220°F)
Water	2% by wt binder	121°C (250°F)	104°C (220°F)
Water	2% by wt binder	113°C (235°F)	104°C (220°F)

The result of the evaluation of these additional samples is shown in Figure 17. For this very limited evaluation of alternative approaches for warm mix the take away message is that for a given aggregate and consistent curing time of 4 hours the rutting results and Jnr are governed by the curing temperature. Producing these mixes with water only at 121°C (250°F) proved quite difficult and required twice as long to fully coat the aggregate in the bucket mixer compared to the other warm mix technologies employed. Those difficulties notwithstanding, the value of producing and testing these specimens shows how strongly curing time and temperature impact short term mixture test results and recovered binder properties.

4 DISCUSSION

4.1 SUMMARIZATION OF PERCENT CHANGE IN RUT DEPTH AND Jnr VERSUS CURING TIME

Figures 18 and 19 are graphical summaries of the extent to which the percent change in Jnr of recovered binder and the percent change in rut depth with curing time for the virgin and RAP mixes respectively inform the research as to the mechanisms of binder and mix aging and the extent of virgin/RAP binder interaction. For virgin mixes (Figure 18) mix temperatures and conditioning times drive Jnr of recovered binder. For the HMA the percent reduction in Jnr and rut depth at 2 and 4 hrs as compared to 0.5 hrs is very similar. For the WMA the rut depth is being reduced at a faster rate than the Jnr value and this difference increases with aging time. This work shows how strongly curing time and temperature impact short term results. This work should be repeated and extended to longer conditioning periods; because, if confirmed, there would a more compelling basis for concluding that even though the binder is not aging as rapidly, there is something else happening within the binder/aggregate interaction that is improving rutting resistance besides binder aging.
For the HMA RAP mixes (Figure 19) mxing temperaure and conditioning times drives Jnr. For the 0.5 hr aged mix there can be but minor aging and the Jnr is a product of the extraction and homogenization of the RAP and virgin binders. Even though there is a large change in Jnr at 2 hrs there is only a modest change in rut depth

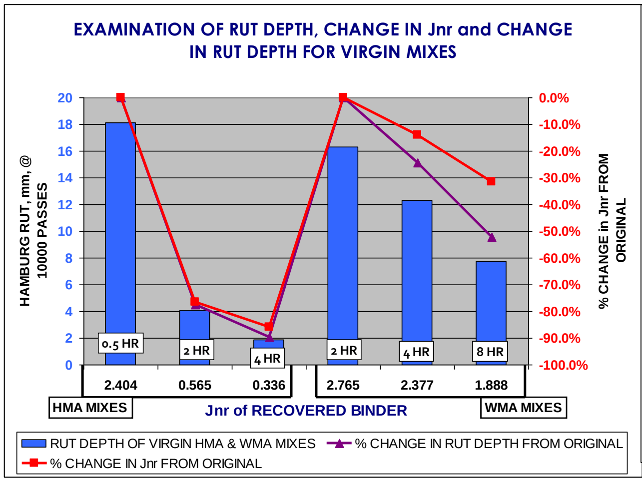


Figure 18: Evaluation of Rut Depth versus Change in Jnr and Change in Rut Depth for Virgin Mixes

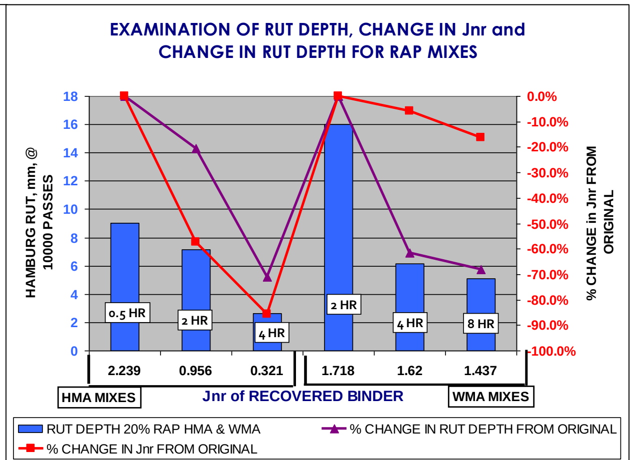


Figure 19: Evaluation of Rut Depth versus Change in Jnr and Change in Rut Depth for RAP Mixes

because of relatively low rut value of the 0.5 hr mix. This low value could be due to an asphalt deficient mix since at 0.5 hrs there would be little opportunity for interaction. For the WMA RAP mixes the 2 hr aged mix has a lower Jnr than the 0.5 hr HMA and yet a much greater rut depth. The Jnr of this recovered sample contributes nothing towards mix deformation reistance. For the 4 and 8 hr aged WMA the Jnr decreases very little as a percent of the 2 hr value, but the rut depths decrease substantially. With only modest evidence of binder aging in the WMA RAP mixes the substantial reduction in rutting (on the order of the change for the HMA RAP mixes) strongly suggests an intereaction of virgin an RAP binders. Further the similarity of the WMA and Virgin mix rut depths at extended curing times and lack of similarity of Jnr values suggest that RAP plays a role beyond just stiffening the binder.

4.2 SUMMARY DISCUSSION

An in depth study of the mechanistic properties of laboratory produced hot and warm mixes was undertaken. Virgin mixes and mixes containing 20% RAP were produced using a conventional PG 58-28 binder. Both HMA and WMA mixes were cured in the loose condition for 3 different time periods prior to compaction. Compacted specimens were tested in the Hamburg rut tester in the dry condition at 58°C and in the wet condition at 50°C. Additional specimens were prepared and tested in the AMPT for E* modulus and Flow Number properties. E* data was collected at 4°C, 20°C and 40°C from which modulus mastercurves were produced. Flow Number tests were conducted at 3 different stress levels, 400, 600 and 800 kPa with 69 kPa confining stress. The main parameter evaluated from the Flow Number creep test was the maximum percent strain which each specimen attained over the 10000 second time period of the test. Hamburg rutting data and E* data plotted against curing time showed that higher temperatures and longer curing times produced stiffer mixes with less rutting. The Jnr of binders recovered from all mixes was well correlated to the E* modulus results especially at the 20°C reference temperature. While Jnr of the recovered binder did not correlate well to the rut depth at 10000 wheel passes for all the mixes, it was found that Jnr did correlate quite well with the rutting rate of all the mixes tested. It was further found that the maximum percent strain accumulated in the mixes as determined on the AMPT at 800 kPa and to a lesser extent at 600 kPa correlated very well with the dry Hamburg rutting rate expressed in wheel passes per mm of rutting. The low temperature PG grade of the recovered binders showed that for the both the virgin and RAP mixes there was almost no change in the grade as determined by BBR as curing changed from 2 hours to 8 hours. The HMA mixes exhibited approximately 3°C increase in low temperature grade as curing moved from 0.5 hours to 4 hours.

5 CONCLUSIONS

Conclusions that can be drawn from this study are:

1. The Hamburg rutting results, both wet and dry; and the E* results are strongly driven by aging temperature and aging time especially for the virgin mixes.
2. Four hours of aging at 104°C (220°F) with RAP was roughly equivalent in terms of performance to 2 hours of aging at 135°C (275°F) with RAP. Further study will be needed to ascertain whether this relationship holds for other mixes and temperature ranges.
3. Conditioning at 135°C (275°F) resulted in an 11° increase in high temperature PG grade when the conditioning time changed from 0.5 hours to 4 hours.
4. Conditioning at 104°C (220°F) resulted in a 2° increase in high temperature PG grade when the conditioning time changed from 2 hours to 8 hours.
5. Conditioning at 135°C (275°F) resulted in a 3° increase in low temperature PG grade when the conditioning time changed from 0.5 hours to 4 hours for virgin HMA mixes.
6. Conditioning at 135°C (275°F) resulted in a 2.5° increase in low temperature PG grade when the conditioning time changed from 0.5 hours to 4 hours for HMA RAP mixes.
7. Conditioning at 104°C (220°F) resulted in a 0° increase in low temperature PG grade when the conditioning time changed from 2 hours to 8 hours for all WMA mixes.
8. Flow Number creep test accumulated strain results at 800 kPa axial stress using 69 kPa confining stress shows that 8 hours of warm mix conditioning time is equivalent to 2 to 4 hours of hot mix conditioning time for virgin mixes.
9. Flow Number creep results at 400 kPa and 600 kPa with 69 kPa confining stress exhibited low levels of accumulated strain and minor differentiation between different mixes and conditioning times. Perhaps there has been good warm mix performance despite the lack of binder aging because the pavements which have been studied are adequately modeled by axial stresses in the 400 to 600 kPa range with confining stress.
10. Comparison of changes in rut depth and Jnr of recovered binder suggests that RAP interacts with virgin binder in both hot and warm mixes albeit at differing rates based on cure time. The percent decrease in WMA RAP mix rutting is greater than the percent decrease in the Jnr of the recovered binder thus providing evidence that for RAP containing warm mixes binder stiffening due to aging may not be necessary for long term permanent deformation performance.

6 RECOMMENDATIONS

More study should be conducted looking at the impact of different axial stress levels on mixture performance and especially attempt to correlate accumulated strain at different stress levels to mixture performance. There must be some rational explanation for the successful field performance of warm mixes in the face of laboratory test results that indicate these mixes are not stable. More in depth study of fatigue behavior must be performed. The limited data of this study indicates similar fatigue behavior for mixes that have undergone short term aging. Longer term aging of both hot and warm mixes followed by fatigue testing must be performed. Based on results presented in this research it is suggested that when performing mechanistic tests on warm mix the mix should be conditioned for 8 hours at the target compaction temperature if the warm mix compaction temperature is 50°F below the HMA compaction temperature for a comparable mix. As the differential between the conventional HMA compaction temperature and the WMA compaction temperature decreases of increases the conditioning time may have to decrease or increase accordingly. More in depth evaluation of the impact of conditioning time and temperature on mix performance is needed.

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