distresses. END is the equivalent number of distresses and ADV is the adjusted distress value. Only the three surface mixes were evaluated during the VCI determination.

TABLE 24 Astec DBG Summary of Visual Condition Index

	Distress		
	Astec DBG 15% RAP	**DBG 15% RAP - 5% RAS**	**DBG 50% RAP**
DV-Low	10	21	28
DV-Medium	17	0	4
DV-High	0	0	0
TDV	27	21	32
END	1.3	1.8	2.7
ADV	25	18	21
VCI	7.5	8.2	7.9

Laboratory testing was conducted on six inch cores that were taken after two years of trafficking. Testing included air void determination, tensile strength ratio, resilient modulus, and rut testing. Binder tests were also conducted on recovered binders from the cores. From the testing performed on the cores, it was found that the WMA mixtures were all performing along typical behavioral patterns historically seen in conventional HMA. It was also observed that the addition of recycled materials enhanced the performance of the WMA over the virgin WMA mix. This can be seen, for instance, in the tensile strength ratio results (TABLE 25). The inclusion of recycled material allowed the WMA to meet the TSR minimum requirement of 80 percent.

TABLE 25 Astec DBG Tensile Strength Ratio Test Results (*39*)

Mix Type	Average Air Void Content Dry (%)	Dry Indirect Tensile Strength (kPa)	Average Air Void Content Conditioned (%)	Conditioned Indirect Tensile Strength (kPa)	Tensile Strength Ratio (%)
Astec DBG Virgin	7.60	729.9	7.70	510.4	69.9
Astec DBG 15% RAP	6.63	1194.2	6.83	1005.9	84.2
Astec DBG 15% RAP - 5% RAS	5.87	1199.2	5.87	1036.5	86.4
Astec DBG 50% RAP	7.33	860.8	7.30	703.1	81.7

Asphalt binder testing was performed for all four WMAs to evaluate the effect the inclusion of recycled materials on asphalt binder stiffness. The results of the asphalt binder testing on a conventional HMA mix and the extracted four Astec DBG process WMA mixes are shown in TABLE 26. The results indicate that less age hardening of the asphalt binder occurred over time. The authors believe this is due to the light ends contained in the asphalt binder are not being driven off during the production of WMA. They also reference recent research, which indicates that the light ends not evaporated during the mix production are driven off during the first two years of road service.

In order to evaluate the rutting behavior of the extracted asphalt binders at high temperature, values of G*/sin(δ) were plotted at different temperatures. Results are shown in FIGURE 60. Notice the increase in G*/sin(δ) with the higher contents of recycled materials. This also suggests that the inclusion of a higher percentage of recycled materials (Astec DBG 15 percent RAP-5 percent RAS and Astec DBG 50 percent RAP) significantly change the asphalt binder properties at high and low temperatures.

TABLE 26 Astec DBG Recovered Asphalt Binder Characteristics (*39*)

Tests on Recovered Asphalt Binder		Binders extracted from core samples				
		HMA 80/100A Binder Virgin - RTFOT	Astec DBG Virgin	Astec DBG 15% RAP	Astec DBG 15% RAP / 5% RAS	Astec DBG 50% RAP
Dynamic Shear Rheometer						
G*/Sin δ, KPa	@ 64°C	3.872	-	-	-	-
>=2.2 KPa	@ 70°C	1.775	2.076	2.676	5.615	5.209
	@ 76°C	-	0.959	1.213	2.773	2.510
	@ 82°C	-	0.470	0.581	1.388	1.229
Predicted Failure Temperature (°C)		68.40	69.00	71.03	78.01	77.11
Pressure Aging Vessel Residue (AASHTO R28)						
Dynamic Shear Rheometer						
G*/Sin δ, KPa	@ 28°C	-	-	-	4050	2388
<=5000 KPa	@ 25°C	4079	4881	4157	5584	3238
	@ 22°C	5658	6737	5773	-	-
Predicted Failure Temperature (°C)		23.13	24.78	23.31	26.03	20.72
Bending Beam Rheometer						
Creep Stiffness, MPa	@ -6°C	-	-	-	76	90.7
<=300 MPa	@ -12°C	156	161	163	163	143
	@ -18°C	287	323	316	-	-
Slope, m - value, MPa	@ -6°C	-	-	-	0.330	0.316
>=0.300	@ -12°C	0.302	0.311	0.316	0.293	0.301
	@ -18°C	0.259	0.270	0.270	-	-
Predicted Failure Temperature (°C)		-22.30	-23.61	-24.09	-20.86	-22.40
Performance Grade (PG)		*PG 64-22*	*PG 64-22*	*PG 70-22*	*PG 76-16*	*PG 76-22*
Initial Performance Grade (PG) Construction stage		*PG 64-22*	*PG 70-22*	*PG 70-22*	*PG 76-16*	*PG 72-16*

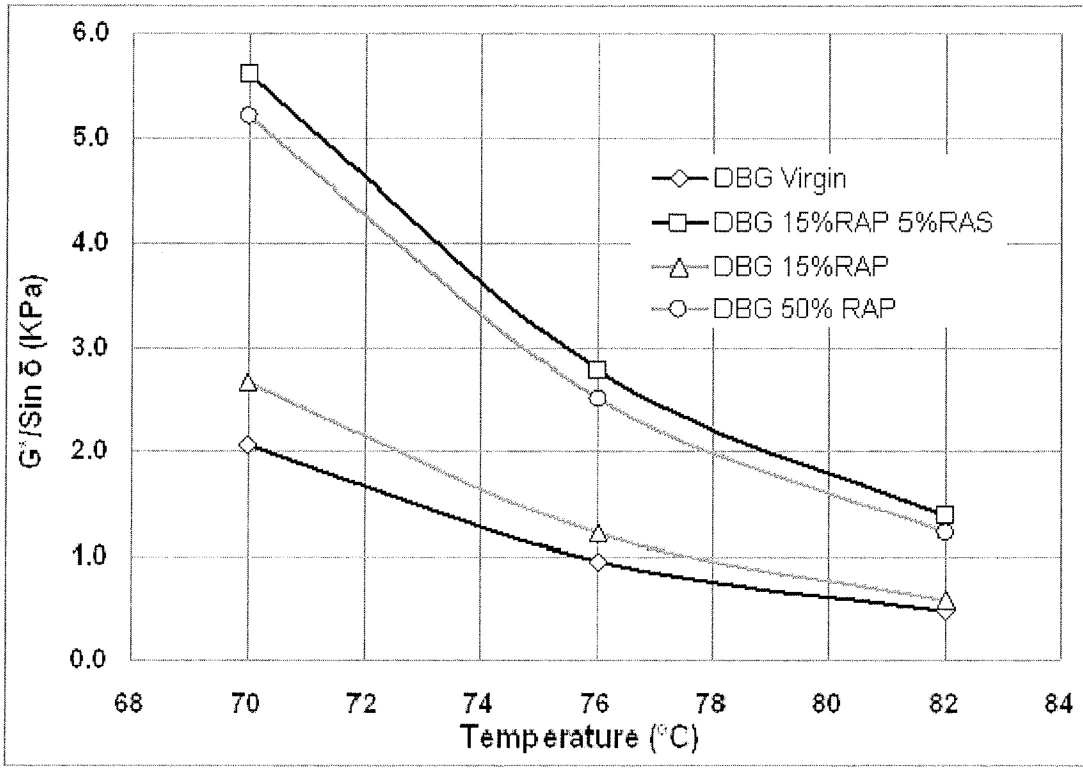

FIGURE 60 Recovered Asphalt Binder G*/Sin (δ) at Different Temperatures

Sasobit Warm Mix Asphalt Technology: Victoria Street in the City of Ottawa (Aurilio and Michael) (40)

A pilot project using Sasobit® was constructed in 2007 after Bitumar had constructed several initial trial projects using Sasobit® to demonstrate its effectiveness. This pilot project used approximately 950 tonnes of WMA, and was used as a rehabilitation project. The asphalt mixture was a 12.5 mm Superpave mix, containing 15 percent RAP, and was placed at a thickness of 50 mm over 100 mm of in-place recycled foamed asphalt.

The WMA was produced on October 23, 2007, and initially used production temperatures of 266 and 230°F (130 and 110°C) as mixing and compaction temperatures, respectively. These temperatures were used for the first 450 tonnes of WMA, when it was decided to decrease the production temperature to 239°F (115°C) for the remaining tonnage based on the success of the placement of the WMA.

Quality control testing was conducted on both the control mix and the Sasobit® WMA for compliance to the City of Ottawa End Result Specification (ERS). Results indicated that the WMA was representative of the job mix formula and volumetrics met the required specifications. TABLE 27 presents the results for the recovered asphalt binder testing on both the control and WMA mixtures. Based on the testing conducted, the binder recovered from the HMA had aged more than the Sasobit® WMA binder.

TABLE 27 Performance Graded Binder Test Results (*40*)

Tests on Recovered Asphalt Binder	PG 58-34	PG 58-34 Modified with 1.5% Sasobit	12.5 mm Superpave Control Mix, Recovered	12.5 mm Superpave WMA, Recovered	Specified
Tests on Original Asphalt					
Rotational Viscosity, Pa.s, @ 135°C	0.321	0.322			3.0 max
@ 165°C	0.101	0.100	N/A	N/A	
G*/Sin δ, KPa @ 52°C	-	-	-	-	1.0 min
@ 58°C	1.13	-	-	-	
@ 64°C	-	1.22	-	-	
RTFO Residue (AASHTO T240)					1.0 max
Mass Change, %	0.646	0.880	-	-	
DSR, G*/Sin δ, KPa @ 58°C	4.77	-	6.53	10.2	2.2 min
@ 64°C	-	3.41	3.21	5.31	
@ 70°C	-	-	-	-	
Predicted Failure Temperature (°C)	23.13	24.78	23.31	26.03	20.72
PAV Residue (AASHTO R18)					
DSR, G* x Sin(δ), kPa @ 22°C	-	2849	-	-	5000 max
@ 16°C	2983	-	-	-	
Bending Beam Rheometer					
Creep Stiffness, MPa @ -12°C	-	-	-	-	300 max
@ -18°C	-	113	108	133	
@ -24°C	199	205	225	216	
Slope, m-value, MPa @ -12°C	-	-	-	-	0.300 min
@ -18°C	-	0.315	0.329	0.314	
@ -24°C	0.307	0.292	0.280	0.258	
Continuous Grading Temperatures	59.3 – 35.4	66.0 – 31.6	65.8 – 31.6	67.8 – 29.5	-
Penetration @ 25°C, 100g, 5 sec	160	120	74	72	-

During the placement of the WMA, adequate compaction was achieved at temperatures as low as 194°F (90°C), and generally ranged from 194 to 230°F (90 to 110°C). In-place density for the WMA ranged between 93 and 94 percent of the maximum theoretical density. It was commented that the angle of attack on the screed had to be slightly adjusted, but the WMA was easy to work with in all other aspects of placement, including handwork.

Evaluating Warm Asphalt Technology as a Possible Tool for Resolving Longitudinal Joint Problems (Tighe et. al) (41)

The authors presented a summary of findings in an attempt to examine the potential benefits and advantages of warm asphalt as a solution to longitudinal joint problems. Test results presented included dynamic modulus, resilient modulus, longitudinal joint permeability testing, and results from surface distress surveys. Additional testing to be completed as part of this study will include in-place density measurements of the longitudinal joint and Portable Falling Weight Deflectometer testing.

Common belief among researchers is that WMA may construct a much tighter joint than conventional HMA due to the reduction in the temperature differential between paving lanes. Therefore, a field trial was conducted in June of 2007, in the City of Hamilton, Ontario, to evaluate if WMA could be used as a possible solution to longitudinal joint cracking. Evotherm™ was used as the WMA technology, and a control HMA section was placed prior to the WMA field trial.

After the field trial was completed, several pavement distress surveys have been conducted, from which no major distresses have been identified. Field permeability testing was conducted at three locations across the mat; longitudinal joint, wheel paths, and center of the mat. Permeability testing was based on the falling head principle. Results indicate that both test sections are generally impermeable; additional permeability testing will be performed over the course of the evaluation.

During construction of the test sections, samples of loose mix were obtained and used to prepare gyratory samples in order to conduct performance testing. Samples were compacted at temperature of 230°F (110°C) and then trimmed to the appropriate testing sample size. Laboratory testing included Thermal Stress Restrained Specimen Tension (TSRST) testing, dynamic modulus, and resilient modulus testing. Samples for resilient modulus testing were prepared in several thicknesses to evaluate the effect of lift thickness on resilient modulus values.

The authors note that for typical HMA asphalt mixtures, resilient modulus values are approximately 14,000 MPa at 32°F (0°C). Results from the WMA samples tested at a temperature of 41°F (5°C) were significantly lower, indicating that WMA would be more resistant to low temperature cracking than HMA due to the lower production temperatures.

Preliminary Results from the California Warm-Mix Asphalt Study (Jones) (43)
The California Department of Transportation (Caltrans) expressed interest in WMA as a way to reduce stack emissions at plants, allow longer haul distances between asphalt plants and construction projects, improve construction quality (especially during night paving), and extend the annual period for paving. However, the use of WMA technology requires the addition of additives into the mix, and/or changes in production and construction procedures, specifically related to temperature, which could influence performance of the pavement. Therefore, Caltrans initiated a phased research study to assess concerns related to these changes before statewide implementation of the technology is approved. This summary report describes the first two phases of the study *(44* and *45)*.

The research is being conducted for Caltrans by the University of California Pavement Research Center (UCPRC), with the objective of determining whether the use of additives (including water) introduced to reduce production temperatures of asphalt concrete, influence mix production processes, construction procedures, and the performance of HMA. Research tasks included:

1. Construction of the following four test sections (subgrade preparation, aggregate base-course, tack coat, and asphalt wearing course) in September 2007:
   A. Conventional dense-graded HMA serving as the control section.
   B. Dense-graded WMA with chemical foam additive (Advera®).
   C. Dense-graded WMA with chemical emulsion additive (Evotherm™ DAT).
   D. Dense-graded WMA with organic wax additive (Sasobit®).
2. Test each section with the HVS in separate phases, with later phases dependent on the outcome of earlier phases and laboratory tests *(Phase 1 [rutting] completed in April 2008 and Phase 2 [moisture sensitivity] completed in June 2009)*.
3. Evaluate the rutting, fatigue, and moisture resistance of field-mix, field-compacted (Phase 1), field-mix, laboratory-compacted (Phase 2a) and laboratory-mixed, laboratory-compacted (Phase 2b).

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4. Monitor the construction and performance of warm-mix technologies against conventional hot-mix asphalt in pilot studies on in-service pavements.

The Phase 1 test sections were located at a quarry and commercial asphalt plant near Aromas, California. The test pavement is 262 ft by 26 ft (80 m by 8.0 m) divided into four test sections. The pavement structure consists of the existing subgrade/subbase material overlying bedrock, with 12 in. (300 mm) of imported aggregate base, and two 2.4 in. (60 mm) lifts of asphalt concrete. A Caltrans Type A 19 mm Hveem mix design was used and no adjustments were made to accommodate the additives. Target production temperatures for the Control mix were set at 310°F (155°C) and at 250°F (120°C) for the WMAs. The mixes were produced with a drum plant at the quarry. The recommended bitumen content was 5.1 to 5.4 percent by mass of aggregate, which was based on the minimum air-void content under standard kneading compaction. TABLE 28 summarizes the quality control data of the mixes. The mix design had very high Hveem stabilities.

TABLE 28 Quality Control of Mix after Production (*43*)

Parameter	Target	Range	Control	Advera	Evotherm	Sasobit
AC Binder Content (%)[1]	5.2	5.1 - 5.4	5.29	5.14	5.23	4.48
Max. Specific Gravity[2]	-	-	2.567	2.581	2.596	2.606
Marshall Compaction[3]						
Compaction Temperature (°C)	-	-	139	115	112	124
Blows per face	-	-	75	75	75	75
Bulk Specific Gravity	-	-	2.511	2.474	2.493	2.464
Air-void Content (%)	-	-	2.18	4.15	3.97	5.45
Gyratory Compaction[3]						
Compaction Temperature (°C)	-	-	139	115	112	124
Number of Gyrations	-	-	100	100	100	100
Bulk Specific Gravity	-	-	2.526	2.522	2.528	2.510
Air-void Content (%)	-	-	1.60	2.29	2.62	3.68
Marshall Stability (lbs)[4]	1,800 min	-	4,267	3,030	3,320	3,307
Marshall Flow (0.01 in.)	-	-	11.8	10.8	10.2	12.1

[1] AASHTO T-308 [2] AASHTO T-209 [3] AASHTO T-166 [4] AASHTO T-245

Marshall compacted quality control tests for the Control mix yielded a higher bulk specific gravity and lower air-void content, compared to the WMA mixes. It was not clear whether this was a testing inconsistency or was linked to the lower production and specimen preparation temperatures. The maximum specific gravities of the four mixes were within a relatively close range, but showed an increase of between 0.010 and 0.015 with each subsequent mix produced. The bulk specific gravities of the four mixes, determined from Marshall-compacted specimens, were within a relatively close range (difference of 0.047 between highest and lowest). The Control mix had the highest bulk specific gravity of the four mixes and the Sasobit mix the lowest. The air-void contents of the four mixes, determined from Marshall-compacted specimens, were notably different, with the Control mix having a significantly lower air-void content than the mixes with additives. The Control mix had the lowest air-void content (2.18 percent) and the Sasobit mix the highest air-void content (5.45 percent). It is not clear whether this was a testing inconsistency, or a result of the warm-mix production process. This will be assessed in the proposed Phase 2b laboratory testing program *(46)*. [Marshall compaction is more sensitive to binder stiffness than SGC compaction. This data may suggest that the binders in the WMA mixes at the lower compaction temperature were stiffer/more viscous than the control mix binder at the higher temperature. However, there were also differences in measured asphalt contents for the mixes which confounds the comparisons.]

The bulk specific gravities of the four mixes, determined from gyratory-compacted specimens, were within a closer range compared to the Marshall-compacted specimens (difference of 0.018 between highest and lowest). The Control and Advera® and Evotherm™ mixes essentially had the same bulk specific gravity, with the Sasobit® mix having a slightly lower value. The air-void contents of the four mixes, determined from gyratory-compacted specimens, were also notably different, with the Control mix again having a significantly lower air-void content than the mixes with additives. The Control mix had the lowest air-void content (1.60 percent) and the Sasobit® mix the highest (3.68 percent).

The Marshall stability of the Control mix was significantly higher than the mixes with additives (approximately 450 kg [1,000 lb] higher). However, the stabilities of all the mixes were well above the minimum limit. The Marshall flows did not follow similar trends. The Advera® and Evotherm™ mixes had the lowest Marshall flows (10.8 and 10.2 respectively) followed by the Control mix (11.8) and the Sasobit® mix (12.1). The Sasobit® mix was expected to have the lowest flow, given that it had the lowest binder content. There was some variability in the moisture contents of the aggregate just prior to it entering the drum, with the material used in the Control mix having the lowest moisture content (0.24 percent) and that used in the Advera® mix the highest moisture content (0.41 percent). The moisture contents of all four aggregate runs prior to entering the drum were well below the Caltrans maximum specification of 1.0 percent *(47)*.

Phase 1 laboratory testing was conducted on specimens sawn or cored from slabs that were sawn from the test track after construction. Phase 2a laboratory testing was conducted on specimens that were prepared adjacent to and at the same time as test pavement construction, but using laboratory compaction equipment. Phase 2b laboratory testing, which was started late due to funding constraints, was still in progress at the time of preparing the report. This work is being conducted on specimens sawn or cored from slabs prepared in the laboratory using aggregates and binder sampled on the day of construction.

Tests included shear (AASHTO T-320 [Permanent Shear Strain and Stiffness Test]), fatigue (AASHTO T-321 [Flexural Controlled-Deformation Fatigue Test]), and moisture sensitivity (AASHTO T-324 [Hamburg Wheel Track Test] and Caltrans CT-371 [Tensile Strength Retained, similar to AASHTO T-283]). Test plans for each mix included 18 shear tests, six shear frequency sweep tests (both incorporating a range of temperatures and stresses), 36 fatigue beam tests, and 12 flexural fatigue frequency sweep tests (both incorporating a range of temperatures and strains, and tested in dry and wet condition).

Resilient shear modulus was not influenced by stress, but was influenced by temperature, with the modulus increasing with decreasing temperature. The variation of resilient shear moduli at 45°C was higher compared to the results at 55°C. The Sasobit® mix specimens had the highest resilient shear modulus, as expected, due to the lower binder content. The Control and Advera® and Evotherm™ mix specimens had essentially the same shear modulus indicating that the use of these additives and lower production and compaction temperatures did not significantly influence the performance of the mix in this test.

The number of cycles to five percent permanent shear strain provides an indication of the rut-resistance of an asphalt mix, with higher numbers of cycles indicating better rut-resistance. As expected, the rut-resistance capacity decreased with increasing temperature and stress level. The Sasobit® mix had the highest number of cycles to five percent permanent shear strain, as expected. With the exception of Evotherm™ at 45°C and 70 kPa stress level, no significant difference was noted between the Control and Advera® and Evotherm™ mixes, despite specimens from these mixes having higher air-void contents than the Control (± 2.0 percent). This indicates that the use of these additives and lower production and compaction temperatures did not significantly influence the performance of the mixes in this test.

The measurement of permanent shear strain (PSS) accumulated after 5,000 cycles provides an alternative indication of the rut-resistance capacity of an asphalt mix. The smaller the permanent shear strain the better the mixture's rut-resistance capacity. The PSS results indicate that:

- In general, the Sasobit® mix accumulated the least permanent shear strain when compared with the other mixes at the same stress level and temperature.
- Evotherm™ was the most stress-sensitive mix.
- There was no significant difference between the Control and Advera® mixes.

The average complex shear moduli (G^*) and average phase angle of three replicates tested at the two temperatures were used to develop master curves for these two parameters. The shifted master curves were fitted with modified Gamma functions. The following observations were made from the shear frequency sweep test results:

- There was no apparent difference between the complex modulus master curves of the Control and Advera® and v mixes although the modulus of the Control mix was slightly higher than the other two mixes. The master curve of the Sasobit® mix was above those of the other three mixes.
- Phase angle increased with increasing loading frequency for all mixes.
- There was no apparent difference in the phase angle master curves for the Control and Advera® and Evotherm™ mixes. The master curve of the Sasobit® mix crossed the other three master curves approximately between 2.0 Hz and 5.0 Hz; hence, at higher loading frequencies the Sasobit® mix appears to have smaller phase angles than the other three mixes and higher phase angles at lower loading frequencies. This is probably a function of the lower binder content.

Initial stiffness from fatigue testing was compared at various strain levels, temperatures, and conditioning for the different mix types. Moisture sensitivity was not influenced by any of the additives. There was no significant difference between the four mixes in terms of initial stiffness indicating that the use of the additives and lower production and compaction temperatures did not significantly influence the performance of the mix in this test.

The fatigue failure was defined as a 50 percent reduction in stiffness. Soaking generally resulted in a lower fatigue life compared to the unsoaked specimens. Inconsistent results were obtained across the mixes at the higher temperatures (i.e., 200 microstrain and 30°C). There was no significant difference between the four mixes in terms of fatigue life at 50 percent stiffness reduction indicating that the addition of the additives and lower production and compaction temperatures did not significantly influence the performance of the mix in this test.

The average stiffness values of the two replicates tested at the three temperatures were used to develop the flexural complex modulus (E^*) master curve. This is considered a useful tool for characterizing the effects of loading frequency (or vehicle speed) and temperature on the initial stiffness of an asphalt mix (i.e., before any fatigue damage has occurred). The temperature-shifting relationships were obtained during the construction of the complex modulus master curve and can be used to correct the temperature effect on initial stiffness. The following observations were made from the frequency sweep test results:

The temperature-shifting relationships were obtained during the construction of the complex modulus master curve and can be used to correct the temperature effect on initial stiffness. The following observations were made from the frequency sweep test results:

- Dry Tests
  - There was no apparent difference between the complex modulus master curves of the Control and Advera® and Sasobit® mixes. The curve for the Evotherm™ mix was below those of the other three mixes, possibly due to the higher air-void contents of the tested beams.

- The temperature-shifting relationships indicate that the Advera® mix was the most temperature-sensitive in extreme temperatures and that the Control mix was the least temperature-sensitive on average. Higher temperature-sensitivity implies that a per unit change of temperature will cause a larger change of stiffness (i.e., larger change of lnaT).

- Wet Tests
  - The complex modulus curves of the Control and Sasobit® mixes were essentially the same, while the curves for the Advera® and Evotherm™ mixes showed lower stiffness.
  - There were no apparent temperature-sensitivity differences between the four mixes at higher temperatures (i.e., higher than 20°C). At lower temperatures (i.e., lower than 20°C), there was no significant difference in temperature-sensitivity between the Control and Advera® mixes, but some temperature sensitivity in the Evotherm™ and Sasobit® mixes.
  - A loss of stiffness attributed to moisture damage was apparent in all four mixes.

Hamburg wheel track testing was conducted to evaluate rutting and moisture resistance. The average results for the maximum rut progression curve are summarized in Table 3. Rut depths at 20,000 passes were linearly extrapolated for tests terminated before the number of wheel passes reached this point. The results indicate that there is no significant difference between the Control mix and the mixes with Advera® and Evotherm. The Sasobit® mix appeared less moisture sensitive than the Control mix, however these results were probably influenced by the lower binder content in the Sasobit® mix, which would be expected to increase the rut resistance as well as increase the moisture sensitivity.

TABLE 29 Test Result Summary of Hamburg Wheel Track Average Rut Progression Curves (*43*)

Specimen	Creep Slope (mm/pass)	Stripping Slope (mm/pass)	Inflection Point	Rut Depth @ 10,000 passes (mm)	Rut Depth @ 20,000 passes (mm)
Control	-0.0009	-0.0017	8,177	12.9	30.9
Advera	-0.0009	-0.0019	7,487	15.1	33.0
Evotherm	-0.0010	-0.0023	7,041	16.3	38.5
Sasobit	-0.0006	-0.0015	9,543	9.1	25.9
Note: results are an average from four specimens tested per mix.					

Laboratory Evaluation of WMA Mixture on Chism Street in Reno Nevada (Hajj et al.) (48)

On June 11, 2009 a WMA demonstration was conducted in Reno, Nevada using the Gencor Ultrafoam GX system. The mix produced was a 50 blow Marshall mix that contained 15 percent RAP, 1.5 percent hydrated lime, and a PG 64-22 binder. The rate of the water injection was 1.25 percent by weight of the binder. Approximately 900 tons were produced. The production temperature of the mix ranged between 265 and 270°F (129 to 132°C). The average compaction temperature of the mix was 250°F (121°F).

Plant mix was sampled and a portion of the sampled mix was compacted without allowing the material to cool to ambient temperatures and another portion was reheated for compacting specimens. The process employed to reheat the mix consisted of reheating the mix for four hours at 275°F, splitting the material, and then continued heating the material for 1.5 hours at 250°F [It is felt that a lower temperature should have been used to reheat the mixture and that the additional heating at 1.5 hours should have been eliminated. If the material had been laboratory produced mixes it would have been appropriate to age the material to simulate plant production aging, however these mixes were plant produced therefore not plant aging simulation was needed.]. The samples were made to evaluate compactability, moisture susceptibility, stiffness, permanent deformation resistance, and thermal cracking resistance.

Specimens for evaluating compactability were compacted after 0, 2, 4 and 15 hours using a Marshall hammer and after 4, 6, 8, and 24 hours using a SGC. The evaluation indicated that the air voids increased with curing time. It was found that to attain the target air void content the number of gyrations increased with curing time. The authors noted that substantial changes in the compactive effort stabilized after 8 hours; which the authors interpreted as an indication that after 8 hours the foaming effect was lost.

Moisture susceptibility was evaluated via dynamic modulus testing of specimens that underwent 0, 1, and 6 freeze-thaw cycles. The measured dynamic moduli decreased with increasing freeze-thaw cycles. The authors also noted that the dynamic modulus specimens compacted from reheated mix exhibited slightly lower dynamic modulus values than those from specimens compacted without reheating.

The resistance of the mix to permanent deformation was evaluated using the flow number test. The reheated specimens exhibited a higher flow number value than the non-reheated specimens. The plant produced WMA specimens were compared to laboratory produced HMA, and the HMA specimens exhibited higher flow number values than the plant produced WMA.

TSRST testing was conducted in accordance with AASHTO TP 10-93 to evaluate resistance to low temperature cracking. The plant produced WMA specimens, both reheated and non-reheated, exhibited better fracture resistance than the laboratory produced HMA. The authors concluded that WMA would generate fewer thermal cracks per mile than HMA.

Evaluation of Warm Mix Asphalt (Russell et al.) (49)

A WMA demonstration was conducted in the state of Washington on I-90 west of George, Washington. A section of the road was constructed with the Sasobit® WMA technology and another section was constructed as a HMA. Both mixes contained a PG 76-28 binder and 20 percent RAP. The Sasobit® was added at 1.6 percent by weight of the mix. The recovered HMA binder was classified as a PG 78-28 and the recovered WMA binder was classified as a PG 80-28. Volumetric properties were determined for both the HMA and WMA. Both mixes met the required air voids. The HMA average air void content (4.9 percent) was higher than the WMA average air void content (4.5). The VMA of the HMA was 0.1 percent higher than the WMA VFA, and both were within tolerance. Dynamic modulus testing was conducted by FHWA. The Sasobit® WMA E* results were higher than the HMA. Flow number testing was also conducted by FHWA and suggested that the WMA was more resistant to permanent deformation. Hamburg testing was also conducted by FHWA and there was no substantial difference between the WMA and HMA.

Warm Mix Asphalt Yellowstone National Park (Neitzke) (50)

Two WMA technologies and an HMA control were placed on the east Entrance Road to Yellowstone National Park in August 2007. A 2-inch thick overlay was placed on 6.93 miles of the two-lane road. The overlay required 12,200 tonnes of HMA; 8,750 tonnes of Advera WMA; and 7,450 tonnes of Sasobit WMA. The HMA control was a 19.0 mm Hveem design with an optimum asphalt content of 5.3 percent at 4.0 percent air voids (12.6 percent VMA). The mix used a PG 58-34 binder. Testing was conducted by the FHWA Mobile Asphalt Pavement Mixture Laboratory (Mobile Asphalt Lab). Since the Mobile Asphalt Lab does not contain a Hveem compactor, samples were compacted with 75 gyrations of the SGC at 5.2 percent asphalt by weight of mix. The volumetric properties of the control mix were similar (4.0 percent air voids and 12.4 percent VMA). The WMA mixes produced slightly lower air voids (3.2 to 3.4 percent) and VMA (12.0 to 12.1 percent). All of the mixes contained 1 percent hydrated lime.

The HMA was produced at approximately 325°F (163°C) with placement temperatures of approximately 315°F (157°C). The one-way haul time was approximately 90 minutes. The mix was windrowed. Compaction consisted of seven vibratory passes with an Ingersoll Rand DD-130 and three static finish passes with an Ingersoll Rand SD-77.

Advera was added at 0.3 percent by weight of mix. The Advera was blow into the plant at the same point the binder was added. The initial placement temperature was approximately 275°F (135°C) and was eventually lowered to approximately 250°F (121°C). The same roller pattern was used for compaction.

Sasobit was added at 1.5 percent by weight of binder. The Sasobit was blow into the plant at the same point that the Advera was added. The initial placement temperature was approximately 275°F (135°C) and was eventually lowered to approximately 245°F (118°C). The same roller pattern was used for compaction. Visually, smoke, evident during the HMA placement, was eliminated during the placement of both WMA technologies.

Binder samples were graded by FHWA. The grading data is summarized in TABLE 30.

TABLE 30 Yellowstone Binder Grades (*50* and *51*)

Binder	M320 Continuous Performance Grade	M320, Table 1 Performance Grade	M320, Table 2 Performance Grade	Additive Rate by Weight of Binder
Base	60.2-34.1	58-34	58-28	0
Sasobit	65.1-32.0	64-28	64-28	1.5%
Advera	61.2-33.2	NA	58-28	5.2%

Production samples were compacted in the SGC to determine volumetric properties. The control samples were reheated to 280°F (138°C); WMA samples were reheated to 230°F (110°C). The average volumetric properties are shown in TABLE 31. The measured VMA of the WMA samples was 0.7 to 0.8 percent lower than the HMA even at reduced compaction temperatures. This suggests the WMA allows better aggregate orientation. The asphalt content of the WMA mixes appears to have been adjusted to maintain laboratory air voids at a level comparable to the HMA. All of the laboratory air voids are higher than that determined during the SGC design verification.

Minimum in-place density requirements were 91 percent of theoretical maximum density. The average in-place densities were approximately the same. The averages and standard deviations were slightly higher for the WMA mixtures, even though the compaction temperature and asphalt content were reduced.

TABLE 31 Production Volumetric Properties (*50*)

Property	HMA (Control)	Advera	Sasobit
Number of Tests	12	12	10
Average Asphalt Content, %	5.26	5.16	4.88
Average VMA, %	15.0	14.3	14.2
Average SGC Air Voids, %	5.7	5.1	5.7
Average In-Place Density, %[1]	93.2	93.9	93.4
Standard Deviation In-Place Density	1.07	1.40	1.16

A number of performance tests were performed by FHWA, including TSR and Hamburg to assess moisture damage potential, APA and Flow number to assess rutting potential and dynamic modulus. The TSR, Hamburg, and APA results are reported in

TABLE 32. Conditioning (aging) procedures, if any, are not reported. All of the mixes produced similar tensile strengths and TSR values which exceeded 80 percent. The Hamburg tests were performed wet at 104°F (40°C). Numerically, the Hamburg rut depths for the WMA mixes were slightly less than for the HMA mix. APA tests were conducted dry at 136°F (58°C). Again, the values are approximately the same for all three mixes.

TABLE 32 Production Performance Tests (*50*)

Property	HMA (Control)	Advera	Sasobit
TSR			
Dry Tensile Strength, psi	67	69	76
Wet Tensile Strength, psi	57	56	64
TSR, %	85	81	84
Hamburg			
Avg. Rut Depth after 20,000 passes, mm	3.9	3.5	2.9
Avg. Sample Air Voids, %	7.2	7.2	7.1
APA			
Avg. Rut Depth after 8,000 cycles, mm	2.5	2.7	1.9
Avg. Sample Air Voids, %	7.2	7.1	7.5

Paugh and Corrigan (*51*) indicate that flow number tests were performed with a 100 psi deviator stress and 10 psi confining pressure at three temperatures: 115, 126, and 136°F (46, 52, and 58°C). However, the data are not reported. Dynamic modulus tests were performed at four temperatures (40, 70, 100, and 130°F (4.4, 21.1, 37.8, and 54.4°C)) and six frequencies (0.1, 0.5, 1, 5, 10, and 25, Hz. FIGURE 61 shows master curves based on the average WMA production. The two WMA mixes have lower stiffness at lower frequencies and higher temperatures. This does not match the results from the APA or Hamburg rut tests.

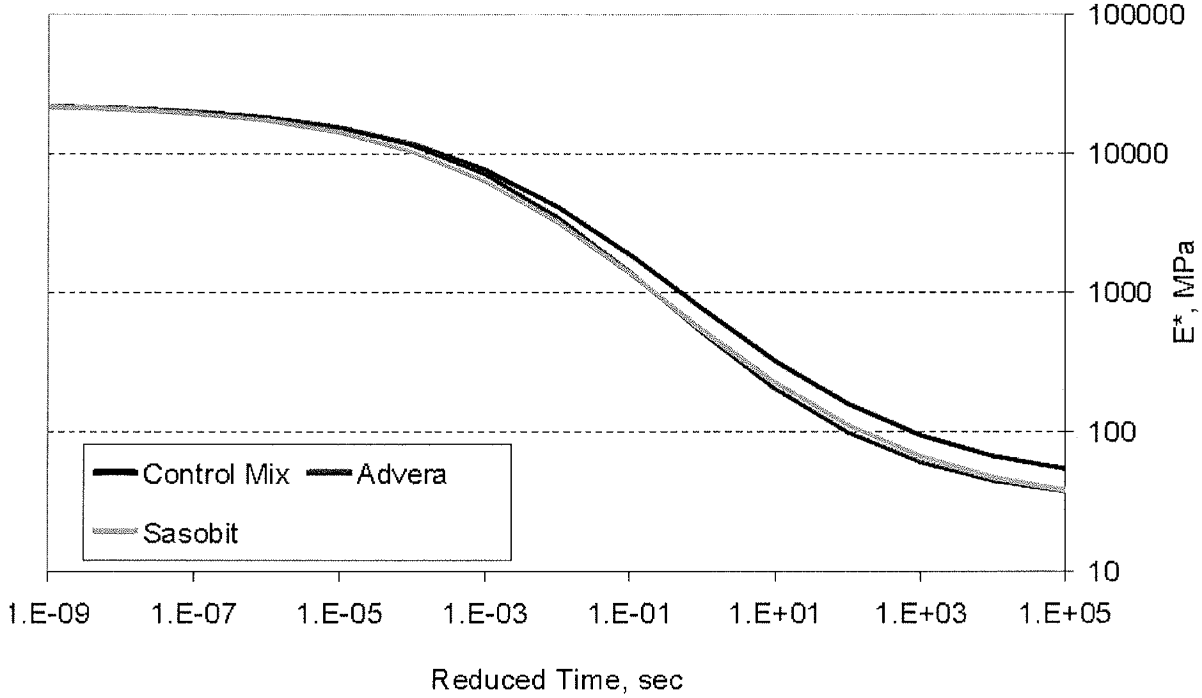

FIGURE 61 Entrance Road, Yellowstone WY, Average WMA Production mater Curves

Warm Mix for a Cold Climate (Scheibel) (52)

Three WMA technologies and an HMA control were placed on I-70 westbound, just west of the Eisenhower Tunnel in July and August 2007. The interstate consists of three lanes in each direction. The WMA was placed in the middle lane. The design traffic for a ten-year period is 4.85 million ESALs.

The existing pavement was milled to a depth of 2.5 inches and overlaid with 2.5 inches of a ½ -inch NMAS Superpave mix with a PG 58-28 binder. Approximate 1,000 tons of each of three WMA technologies, Advera-WMA, Evotherm and Sasobit were placed. Testing was conducted by Colorado DOT and the FHWA Mobile Asphalt Lab. NCAT assisted with field data collection.

The HMA was produced and tested at 280°F (138°C); the WMA technologies were produced and placed at 250°F (121°C). The mix was produced in an Astec Double Barrel plant. The Advera and Sasobit were blown into the mix at the same point the binder was added. Binder samples were graded by FHWA. The grading data is summarized in TABLE 33.

TABLE 33 Colorado I-70 Binder Grades (*52*)

Binder	M320 Continuous Performance Grade	M320, Table 2 Performance Grade	Additive Rate by Weight of Binder
Base	59.9-30.3	58-28	
Sasobit	64.2-29.2	64-22	1.5%
Advera	61.1-30.9	58-28	4.33%
Evotherm	No Data Obtained Due to Schedule		

Production samples were compacted in the SGC using 4-inch diameter molds to determine volumetric properties. Samples were compacted to 75 gyrations using the production and testing temperatures indicated above. Production volumetric targets were: air voids = 3.6 ±1.2 percent, VMA = 16.8±1.2 percent and asphalt content = 6.3±0.3 percent. HMA was produced and placed each night prior to the production of the WMA. The average volumetric properties are shown in TABLE 34. The measured VMA and air voids for the WMA mixes were lower than for the control. The air voids for all three WMA mixes were out of specification.

TABLE 34 Colorado I-70 Production Properties (*52*)

Property	7/24/2007		7/26/2007		8/13/2007	
	HMA	Advera	HMA	Sasobit	HMA	Evotherm
Asphalt Content, %	6.23	6.38	6.41	6.32	6.04	6.38
VMA, %	16.5	15.7	16.5	15.9	16.3	15.8
SGC Air Voids, %	3.8	1.8	3.0	2.4	3.6	2.2
Low Air Temperature,°F						
Avg.Temperature Behind Screed,°F	NR	243	NR	230	NR	235
Average In-Place Density, %[1]	93.8	93.3	95.7[2]	93.2	93.7	94.7

NR = Not Recorded
[1]Percent of theoretical maximum density
[2]Single data point

In-place density requirements were 92 to 96 percent of theoretical maximum density. The average in-place densities were approximately the same, except that the Evotherm in-place densities were slightly higher.

A number of performance tests were performed by Colorado DOT and FHWA, including TSR and Hamburg to assess moisture damage potential, Flow number to assess rutting potential and dynamic modulus. The TSR and Hamburg results are reported in TABLE 35. Conditioning (aging) procedures, if any, are not reported. All of the mixes produced similar TSR values which exceeded the 70 percent required by Colorado DOT for production samples (80 percent required for design). All Hamburg samples were produced from rehaeated mix at a compaction temperature of 280°F (138°C). The Hamburg tests were performed wet; the test temperature was not reported. Colorado DOT does not normally perform Hamburg testing on 75 gyration mixes. For 100 gyration mixes, the failure criteria is 4 mm of rutting after 10,000 cycles. Numerically, the Hamburg rut depths for the Advera and Evotherm mixes reached approximately 10 mm at a lower number of cycles than the control mix. The Sasobit WMA performed comparably to the HMA control in terms of rut depth. The stripping inflection points for the WMA mixes were generally lower than for the HMA.

TABLE 35 Colorado I-70 Production Performance Tests (*52*)

Property	7/24/2007		7/26/2007		8/13/2007	
	HMA	**Advera**	**HMA**	**Sasobit**	**HMA**	**Evotherm**
TSR, %	100	83	NA	111	94	80
Hamburg						
Rut Depth, mm	9.0	9.5	16.0	10.0	10.0	13.5
Cycles tested	9,700	5,100	7,650	9,400	9,650	7,750
Stripping Inflection Point, cycles	7,800	3,300	5,000	5,700	8,400	6,200

Paugh and Corrigan (*51*) indicate that flow number (FN) tests were performed with a 100 psi deviator stress and 10 psi confining pressure at three temperatures: 97, 108, and 118°F (36, 42, and 48°C). The data are shown in FIGURE 62. The three WMA mixes produced slightly lower FN than the HMA. The Evotherm result at 108°F (42°C) is questionable.

Dynamic modulus tests were performed at four temperatures (40, 70, 100, and 130°F (4.4, 21.1, 37.8, and 54.4°C)) and six frequencies (0.1, 0.5, 1, 5, 10, and 25, Hz). FIGURE 63 shows master curves based on the average WMA production. The Advera WMA has lower stiffness at lower frequencies and higher temperatures. The Sasobit has lower stiffness at intermediate frequencies/temperatures than the HMA.

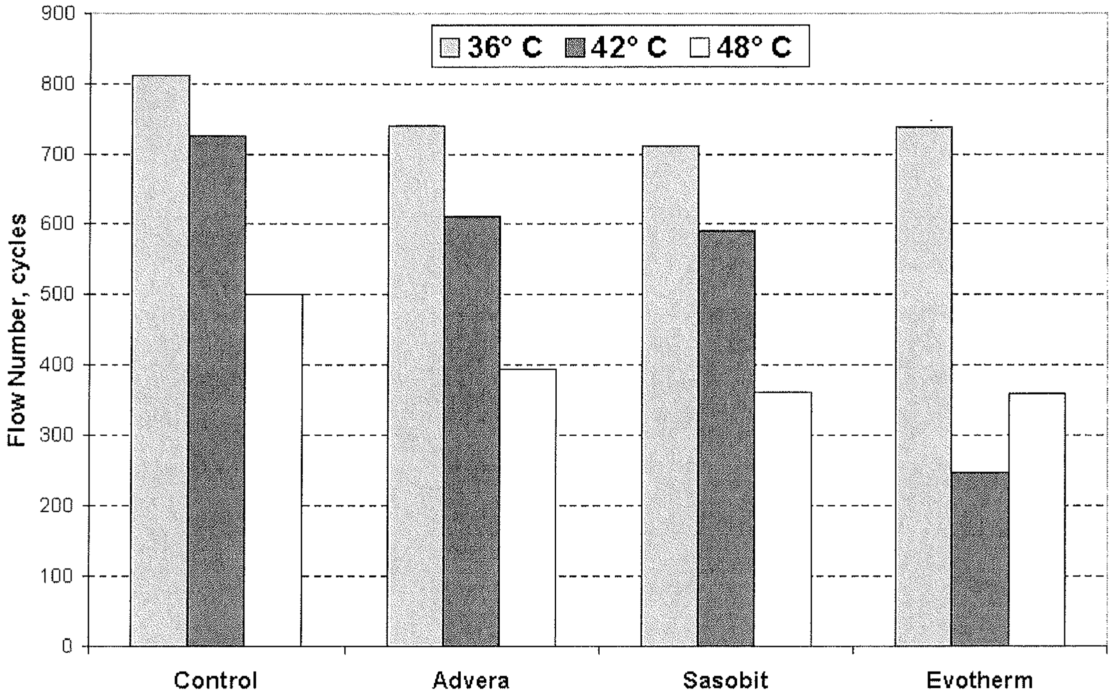

FIGURE 62 I-70 Colorado Average FN Results (*51*)

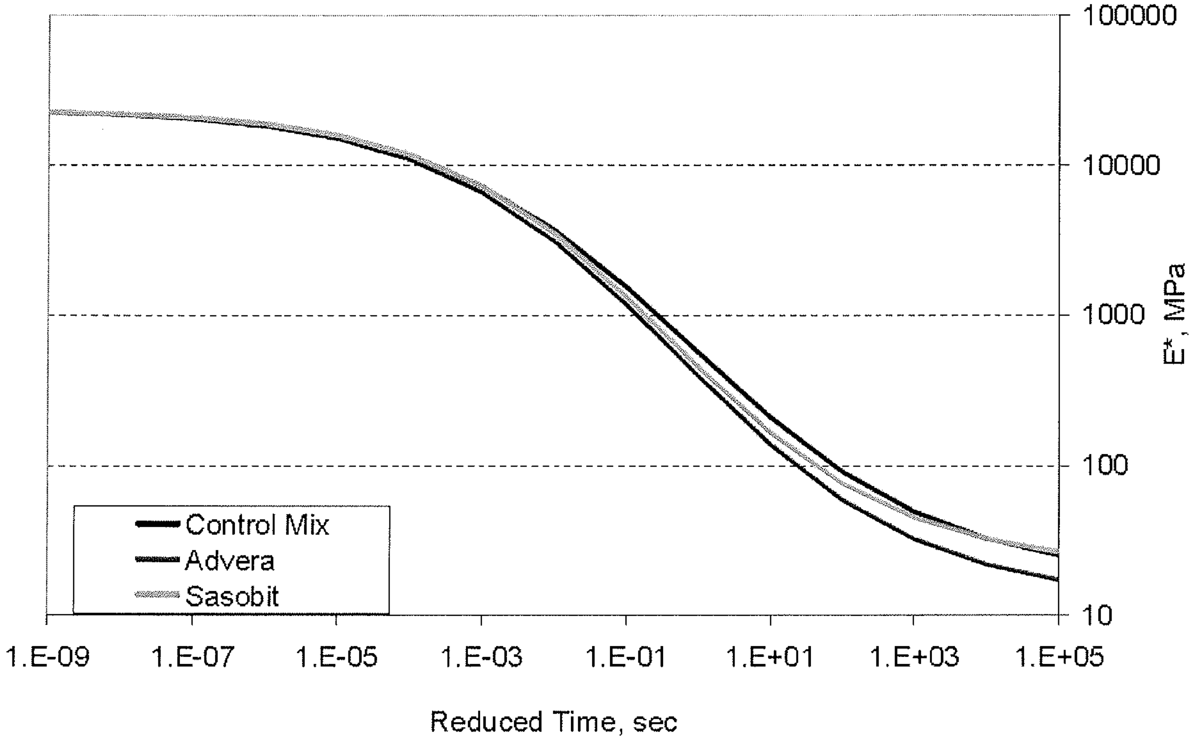

FIGURE 63 I-70 Colorado, Average WMA Production master Curves (*51*)

Field performance monitoring was conducted after one-year of service. All of the sections had less than 5 mm of rutting. Transverse cracks, approximately three to four per mile, were observed in both the HMA and WMA sections. Weathering and raveling were rare and may result from workmanship. Monitoring is scheduled for a three-year period.

Interim Report for NCHRP 09-43: Mix Design Practices for Warm Mix Asphalt (Bonaquist) (52)

Material was obtained from four WMA demonstrations as part of NCHRP 09-43. The material that was collected from each site included plant produced mix and mix components. The four sites were:

- I-70 in Silverthorne, Colorado: The mixes obtained were a control, Sasobit®, Advera®, and Evotherm™ DAT mixes.
- Yellowstone National Park, Wyoming: The mixes obtained were a control, Sasobit®, and Advera® mixes.

- Route 96B, New York: The mixes obtained were a control and LEA.
- Pennsylvania: The mixes obtained were a control and Evotherm™ DAT mixes.

One task in the study was to determine if reheating significantly effects the WMA mechanical properties. Dynamic modulus testing was used to assess the effects of reheating on the binder properties. Specimens were compacted at the time of construction and from reheated material. Half of the specimens compacted at the time of construction were tested immediately and the other half were tested after several weeks. The reheating evaluation indicated that both WMA and HMA mechanical properties are affected in the same manner.

The second task of the study was to evaluate if method for selecting the appropriate binder grade since the use of WMA often results in a softer binder. Work from FHWA was used in the evaluation of the effects of WMA on binder properties. The study at FHWA consisted of aging binders in a Rolling Thin Film Oven (RTFO) at 325, 266, and 230°F (163, 130, and 110°C). The complex shear modulus and phase angle of the aged binders were measured to determine the high temperature grade of each sample. The high temperature grades were compared to ascertain if plant mixing temperatures substantially affects the binder grade. It was determined that plant mixing temperatures do affect the high temperature grade of a binder and it was recommended that an aging index be used to assess if a different binder should be used in a mix. A preliminary aging index table was developed to assist in determining if the lack of aging during production is a concern.

Another mini-study was conducted in NCHRP 09-43 that evaluated the appropriate short term aging of WMA for volumetric and performance specimens. The study compared laboratory produced mix to plant produced mix. The measures for comparison were maximum specific gravity, dynamic modulus, and tensile strength. The results of the aging evaluation indicated that two hours at the compaction temperature is appropriate.

The fourth mini-study evaluated the blending of RAP and virgin binders in WMA. Part of this study consisted of measuring the interfacial mixing that occurs in thin films. The interfacial evaluation indicated that blending can occur at lower temperatures.

The second part of the mini-study compared measured dynamic modulus results of mixes containing RAP to estimated dynamic modulus results of fully blended virgin and RAP mixes. The dynamic modulus testing confirmed that blending of virgin and RAP binder does occur in WMA.

Summary of Laboratory Results

Laboratory and plant produced WMA has been evaluated by several researchers. The main focus of many studies has been on moisture susceptibility followed by permanent deformation. Typically for the moisture susceptibility evaluations, the researchers found that both the ITS and TSR WMA values were lower than those of HMA. The exception to that trend were Sasobit® WMA results, which tended to have ITS and TSR values equal or better than HMA. In a few cases Aspha-min® WMA also resulted in equal or higher ITS and TSR values than HMA. The stripping inflection points of Hamburg testing were also used to evaluate moisture susceptibility. In many of the cases for both laboratory and plant produced mix, WMA stripping inflection points were lower than those for HMA. Similar to the TSR results, Sasobit® WMA stripping inflection points in several cases were the exception and in some cases were equal to or better than the HMA results.

Permanent deformation was another focus of many WMA studies. The typical tests conducted were APA and Hamburg; however, flow number was evaluated in a few cases. For APA results, Sasobit® and occasionally Aspha-min® WMAs tended to result in rut depths equal to or better than HMA for both laboratory and field produced mixes. Thiopave® and Cecabase® also resulted in equal or better rutting resistance; however the results are based one study per technology. The laboratory produced WMA Hamburg results varied. Several of the researchers evaluated different mixing temperatures and found that the rutting of the WMA decreased with increasing mixing temperature. The field produced WMA Hamburg results often indicated that the WMA, with the exception of Sasobit®, tended to rut more than the HMA. However, it should be noted that in many cases where the HMA passed the WMA still passed the criterion established in each study despite the increased rutting in the WMA.

Dynamic modulus testing was conducted in several studies to compare the stiffness of WMA to that of HMA. Most of the studies found WMA to be less stiff than HMA, with the exception of Sasobit®, the Aspha-min®, and Thiopave®.

Fatigue resistance testing was conducted in a limited number of studies using the four point beam fatigue test. The laboratory produced WMA often exhibited a lesser fatigue life than HMA, while the plant produced WMA often resulted in a greater fatigue life.

The thermal cracking testing that has been reported for WMA and HMA comparisons has been indirect tensile creep compliance and TSRST. The comparisons indicated that the use of a WMA technology did not affect the thermal cracking resistance in most cases. However, BBR results indicated that most WMA additives improved the thermal cracking resistance of an asphalt with the exception of Sasobit® and the zeolite additives.

The continuous binder grade of WMA was compared to HMA in numerous studies. Sasobit® tended to stiffen a binder blended in the laboratory. Aspha-min in some cases stiffened the laboratory binder, but in others had no effect on the binder properties. The majority of the recovered WMA binder comparisons to recovered HMA binder indicated that WMA technologies resulted in a softer binder.

FIELD PERFORMANCE

While laboratory testing is a valuable tool to analyze WMA, corresponding field performance is needed to verify that the lab results are reasonable. While many trial sections have been constructed in the U.S. and abroad using WMA in recent years, long-term performance of the projects is not yet available to be able to compare to conventional hot mix. However, other issues regarding warm mix are of interest to many researchers, including ease of construction, field compaction levels, appearance, smoothness, etc.

Innovative Process in Asphalt Production and Application to Obtain Lower Operating Temperatures (Koenders et al. 2002) (3)

Several field demonstrations were constructed in Europe using WMA technologies from 1996 to 1999. A summary of the field demonstrations, including location, year constructed, the metric tonnes placed and the mix types are shown in TABLE 36. Mix details such as aggregate type, anti-strip additives and binder content were not provided. Nuclear density gauge readings were used to estimate the initial air voids, and then cores were taken six weeks after construction and one year after construction to measure air voids again. The air void results are shown in TABLE 36.

TABLE 36 Results from European Field Demonstrations (after *3*)

Location, Date, Tonnes Placed, Mix Type	Voids range %	Cores Taken After	Voids in Mix %
Norway, 1996, 190 t, Agb11[1]			
emulsion 180/200 pen WMA	2.7-5.2	6 wks	5.0
80/100 pen HMA	4.2-7.5	6 wks	4.5
emulsion 180/200 pen WMA	-	1 yr	2.6 / 3.8
80/100 pen HMA	-	1 yr	4.5 / 5.2
Norway, 1997, 450 t, Agb 11			
emulsion 50/60 pen WMA	6.0-7.0	6 wks	7.0 / 6.8
emulsion 60/70 pen WMA	4.7-8.6	6 wks	5.0
emulsion 80/100 pen WMA	3.8-5.3	6 wks	3.8 / 4.9
Norway, 1999, 200 t, Agb 11			
foam 180/200 pen WMA	2.5-3.6	6 wks	2.9±0.5
U.K., 1997, 150 t, DCM 0/14			
emulsion 80/100 pen WMA	9.0-12.6	3 mths	9.0-12.6
80/100 pen HMA	7.9-11.5	3 mths	7.9-11.5
Netherlands, 1999, 400 t, DAC 0/11			
emulsion 80/100 pen WMA	4.0-8.2	6 wks	4.0 / 5.7
80/100 pen HMA	2.8-3.7	6 wks	3.4 / 3.7

[1] Agb 11 is a dense graded asphalt

From the production and placement of these field trials, the authors made the following conclusions:

- The properties of the final binder (when combining hard and soft binders in the WAM Foam process) should be analyzed after the combination has been made. Asphalt mixture testing with the blended binders was recommended.
- The use of emulsions in asphalt plants may cause a problem because of the water evaporation that occurs during production. [This is likely a batch plant issue. Steam explosions in the pugmill can affect the weigh hopper scales and clogging of dust feed lines.] This could create issues with the weighing and dust collection systems, and this problem should be addressed.
- No major problems were encountered during the placement and compaction operations. The air voids of the WMA were comparable to HMA.
- The WMA sections were exposed to traffic very soon after construction with no problems.
- Visual observation of the sections immediately after construction and three years

later showed comparable performance to that of HMA with no visible distresses.

Warm Asphalt Mixes by Adding Aspha-min, a Synthetic Zeolite (von Devivere et al.) (54)

In 2003, a field demonstration was constructed in France to compare a WMA with Aspha-min® to HMA. Both mixtures were identical except for the mixing and compaction temperatures. The HMA was produced at 284 and 338°F (140 and 170°C), and the WMA was produced at 284°F (140°C). Aspha-min® was added at a rate of 0.3 percent by weight of mixture. The mixtures were produced in a batch plant, and were identified as French designation BBSG 0/10 mixes [a dense-graded mix having 25 to 45 percent passing the 2 mm sieve and a maximum aggregate size of 10 mm]. The binder had a penetration grade of 35/50. The binder content was 5.6 percent. No other mixture details were provided. The mixture was hauled for approximately one hour to the paving site. The mat temperature behind the screed for the HMA produced at 284°F (140°C) was 203°F (95°C), and the HMA produced at 338°F (170°C) had a recorded temperature of 291°F (144°C). The WMA temperature behind the screed was 235°F (113°C). Air void results for the HMA and WMA are shown in TABLE 37. It rained periodically during the paving of the WMA section, and air voids measurements were taken separately for when it rained and when it did not rain. The authors did not state why this was done. The method used for measuring air voids was not specified, but it is assumed that they are from nuclear gauge readings.

TABLE 37 Air Voids Results (after *54*)

Mix Type	Compaction	Air Voids (%)
HMA at 140°C	--	8.5
HMA at 170°C	--	6.7
WMA at 140°C	With rain	5.5
WMA at 140°C	Without rain	6.6

Based upon their results, the authors concluded that using Aspha-min® does not affect the production or construction procedures commonly used for HMA. They did not provide any conclusions based upon the air void data provided which seems to indicate better compaction with the WMA.

Binder Characterization for Latex Polymer Modified Evotherm® Warm Mix (Takamura) (55)

A field demonstration was performed using Evotherm™ ET warm mix technology in October 2005. A HMA section was placed for comparison. To create the mixtures, an unmodified PG 58-28 binder was used. The aggregate type was not identified. No further mixture information was provided. During construction, the haul time for the mixtures was 20 minutes. Asphalt cement was recovered from field samples and tested for penetration at 77°F (25°C). The virgin asphalt had a penetration of 124 dmm. When compared to the virgin binder, the WMA had a penetration that was 86 percent of the original value, and the HMA had a penetration that was 63 percent of the original value. There was a 140°F (60°C) reduction in compaction temperature for the Evotherm™ ET mixture when compared to the control (from 293°F to 185°F (145°C to 85°C)). The mix behaved similarly to HMA during construction, and was placed with no issues.

Evotherm Trial in Aurora, Ontario on August 8, 2005 (Davidson) (56)

In August 2005, the first Evotherm™ ET WMA was placed in Canada in Aurora Ontario. The paving site was at the marketing office of Miller Paving, a local contractor. One area that was paved included an employee parking lot, and the other area was the main exit for concrete trucks. An HMA mixture was placed for comparison. The Marshall Mix

Design method was used to design the mixtures. In the parking area, an HL3 surface course was placed, and HL3 and HL8 surface and base courses, respectively were used in the exit area. The HL8 base mix had a maximum aggregate size of 19.0 mm, and the HL3 surface mix contained aggregates of up to 9.5 mm. The aggregate type was limestone. A PG 58-28 binder was used in the HMA mixtures. The Evotherm™ ET was delivered to the drum plant at approximately 190°F (88°C) and was stored in an asphalt storage tank until use at 185°F (85°C). The Evotherm™ ET technology was 6.82 percent of the mix. The mixing and compaction temperatures for the HMA were 302 and 280°F (150 and 138°C), respectively. The mixing and compaction temperatures for the WMA were 248 to 266°F (120 to 130°C) and 203 to 208°F (95 to 98°C), respectively.

The mixtures were hauled for 30 minutes to the paving site, and cooled an estimated 9°F (5°C) during the trip. There were no major problems with producing or placing the Evotherm™ ET mixtures. For the HL8 mixture, the mat texture was uniform, and the mat did not tear behind the screed. There was also no evidence of segregation in the mixture. Joint locations were very smooth, and in some cases were hard to locate to even analyze the appearance. Nuclear readings indicated that the average density of the mixture was 92.5 percent of G_{mm}, which the author stated was exceeded the minimum target density the contractor desired for the parking lot. For the HL3 mixture, there were no problems with paving, and the average nuclear density of the sections was 95.0 percent. The range of nuclear densities was 92.5 percent to 97.0 percent of the theoretical maximum.

During construction of both mixtures, field samples were collected and then taken to the laboratory for compaction and testing. Additionally, moisture contents were recorded for the mixtures in the field [the author did not specify how]. The moisture contents ranged from 0.55 to 1.53 percent, but no correlation could be found between the mix temperatures and the moisture contents. QC test results for the HL8 mixture showed that the field mix was on average about 5 percent finer than the target gradation. All other properties met the Ontario Provincial Standards for the HL8 base mixture. The authors noted that recovered penetration values for the Evotherm™ ET mixtures were approximately 90 percent of the original penetration values. The HL3 mixtures were also tested in the laboratory, and similar issues were found with the finer gradation. However, all other properties met the specifications for the mixture. The recovered penetration values were also high for the HL3 mixtures (85 to 93 percent of original). The author stated that based upon the Marshall properties (stability, flow, etc.), there was no noticeable difference between the HMA and WMA.

TSR test results were presented for each of the mixtures, but test specifications and descriptions were not provided. For the HL8 WMA mixture, a TSR of 73.2 percent was presented, and a value of 82.3 percent was provided for the HL3 WMA mixture. [TSR values for plant produced HMA were not reported.] The author did not state what the minimum criterion was for TSR.

Field cores were also taken for evaluation of field density. For the HL8 mixtures, the average density was 96.7 percent of the maximum. For the HL3 mixtures, the average density was 96.7 percent of the maximum. The author stated that the data indicate that there were no issues with compactability of WMA; however, the authors also stated that there were some issues with tenderness.

Asphalt was extracted from the Evotherm™ emulsion and the Evotherm™ ET mixtures in accordance with ASTM D 1856 (Abson recovery method). The author stated that the asphalt was tested according to SHRP protocols, but did not specify a certain test standard that was used. Testing was conducted to find the continuous grade of the binders. The continuous grade of the residual binder was 59.2-29.3. The recovered binder from the WMA graded as a 55.3-29.3. The penetration at 77°F (25°C) of the base binder was 118 dmm, and was 105 dmm for the extracted binder.

Based upon the results of this field demonstration, the author made the following conclusions:

- There were no major issues with the production of the Evotherm™ ET WMA.
- During paving, there was no evidence of the mat tearing behind the screed.
- Longitudinal joints had a very smooth appearance.
- The Evotherm™ ET mixture stayed tender after construction for an extended period of time. It appeared to cool at a slower rate than HMA.
- The density of the WMA was easily met and was comparable to HMA.

Evotherm Trial in Ramara Township, Road 46 on October 4 and 5, 2005 (Davidson) (57)

In October 2005, an Evotherm™ ET trial was constructed in the Township of Ramara, Canada on Road #46. The mixture placed was a HL4 surface mix (Marshall mix design) with a maximum aggregate size of 16.0 mm. Limestone aggregate was used. A control HMA was placed for comparison. The binder used for the HMA was a PG 58-28. The mixing and compaction temperatures for the HMA were 302 and 280°F (150 and 138°C), respectively. For the Evotherm™ ET mixture, the mixing and compaction temperatures were 257 and 194°F (125 and 90°C), respectively.

The Evotherm™ ET was delivered to the drum plant at approximately 201°F (94°C) and was stored in an asphalt storage tank until use at 199°F (93°C). There were no major problems with producing or placing the Evotherm™ ET mixtures. Nuclear density readings estimated the average density after compaction to be 97.0 percent for the WMA, and 97.5 percent for the HMA. [These are believed to be based on percent Marshall density.] Both exceeded the minimum requirement for density.

Samples were obtained during the production of the Evotherm™ ET and HMA mixtures and taken to a laboratory for testing. The HMA exceeded the minimum requirement for Marshall Stability (8,900 lbs) with values ranging from 10,106 to 13,238 lbs. The WMA samples did not meet the minimum criterion for Marshall Stability (ranged from 8,114 to 8,535). A TSR of 78 percent was presented for the HMA, and a value of 87 percent was presented for the WMA. The minimum criterion for TSR was not provided. The penetration for the base asphalt was 124 dmm. The recovered asphalt from the Evotherm™ ET was an average of 107 dmm. TABLE 38 summarizes the average mix properties.

TABLE 38 Average Mix Properties (*57*)

Property	HMA	WMA
Moisture Content, %	0.13	0.17
Asphalt Content, %	4.83	4.96
Theoretical Maximum Specific Gravity	2.490	2.473
Air Voids, %	4.63	3.63
TSR, %	78	87

Cores were extracted from the field sections and tested for in-place density. The HMA and WMA had average densities of 94.8 and 94.9 percent of theoretical maximum density, respectively. The author stated that this indicates that there were no issues with compaction of the Evotherm™ ET mixture, even at the reduced temperature.

Asphalt was recovered from the Evotherm™ ET sampled from the tank and the Evotherm™ ET mixtures. The author stated that the asphalt was tested according to SHRP protocols, but did not specify a certain test standard that was used. Testing was conducted to find the continuous grade of the binders and the results are listed in TABLE 39. The base binder graded as a continuous grade 59.7-28.1 based on the BBR test, and as 59.7-25.8 based on the results from direct tension testing. The Evotherm™ ET residue graded as 60.2-30.2 based upon BBR testing, and graded as 60.2-25.0 based upon direct tension testing. The recovered binder from the WMA graded as a 57.9-29.0 based upon BBR testing, and as 57.9-27.4 based upon direct tension testing. The penetration at 77°F (25°C) of the base binder was 129 dmm, and was 124 dmm and 107 dmm for the emulsion residue and extracted binder, respectively.

TABLE 39 Binder Results on Lab and Field Samples, Ramara (57)

Sample	Base Asphalt Cement	Emulsion Residue	Recovered Asphalt Cement (HMA)	Recovered Asphalt Cement (WMA)	Spec
Tests on Original AC					
Rotational Viscosity @ 135°C, Pa.s	0.285	NA	NA	NA	3.0 max
@ 165°C	0.088	NA	NA	NA	
Dynamic Shear Rheometer G*/sin δ, kPa, @ 52C					1.0 min
@ 58C	1.250	1.410	NA	NA	
@ 64C	0.570	0.650	NA	NA	
RTFO Residue (AASHTO T240)					
Mass Change, %	0.400	NA	NA	NA	1.0 max
Dynamic Shear Rheometer G*/sin δ, kPa, @ 52C	NA	NA	NA	4.810	2.2 min
@ 58C	3.000	3.030	2.800	2.170	
@ 64C	1.300	1.290	1.280	NA	
PAV Residue (AASHTO R18) C	100	100	100	100	
Dynamic Shear Rheometer G* x sin δ, kPa, @ 19C	4367	3043	3319	2598	5000 max
@ 16C	6562	4760	4957	3913	
Bending Beam Rheometer					
Creep Stiffness @ -12C, Mpa	NA	NA	NA	NA	300 max
@ -18C, Mpa	252.0	204.0	228.0	209.0	
@ -24C, Mpa	482.0	474.0	493.0	520.0	
Slope, m-value @ -12C, Mpa	NA	NA	NA	NA	.300 min
@ -18C, Mpa	0.301	0.326	0.314	0.309	
@ -24C, Mpa	0.241	0.256	0.255	0.256	
PGAC Temperature Range (BBR Basis)	**59.7 - 28.1**	**60.2 - 30.2**	**59.8 - 29.4**	**57.9 - 29.0**	
PGAC Temperature Range (Direct Tension)	**59.7 - 25.8**	**60.2 - 25.0**	**59.8 - 26.2**	**57.9 - 27.4**	
Penetration @ 25C, 100g, 5 sec	129	124	81	107	

Based upon the results of this field demonstration, the author made the following conclusions:

- There were no major issues with the production and placement of the Evotherm™ ET WMA.
- The density of the WMA was easily met and was comparable to HMA.

The author recommended that the Evotherm™ ET should be manufactured to a range of 67 percent to 69 percent residue to prevent pumping issues that could occur from using a mixture with a viscosity that is too high.

Evotherm Trial in the City of Calgary on September 28, 2005 (Davidson) (58)

On September 30, 2005 an Evotherm™ ET WMA was placed in a residential subdivision in northeast Calgary, Canada. The mixture was classified as a Type B mix with a penetration grade asphalt of 150/200A. The maximum aggregate size was 16.0 mm, and the type of aggregate used was not specified. A control HMA mixture was placed for comparison. The mixing and compaction temperatures for the HMA were 302 and 275°F (150 and 135°C), respectively. For the Evotherm™ ET mixture, the mixing and compaction temperatures were 248 and 162°F (120 and 90°C), respectively.

The Evotherm™ ET was manufactured at the Calgary facility the day before production. It was stored in an asphalt storage tank until use at 194°F (90°C). During production, the mixture was not stored in a silo because the conveyor slats were not heated, and the plant operator thought the mix might stick. Therefore, 11 trucks were used to constantly transport the material to the job site. However, mix production was halted 4 times because trucks had not returned to the plant. These production breaks ranged from 15 to 45 minutes, and caused the aggregates and equipment to cool. Sometimes after the breaks the first batch would not have completely coated aggregates, and would be discarded. A total of two truck loads (approximately 28 tons) were discarded during production. The author noted that there were no issues encountered regarding mix sticking in the trucks or in the plant.

At the paving site, the recorded mix temperatures for the WMA were approximately 158°F (70°C) in the spreader box. Some minor tearing was observed at the screed, and the production temperature was increased so that the temperature during placement would be approximately 185°F (85°C). However, the sections placed that had the lower placement temperatures still had densities of 96 to 98 percent of lab compacted (Marshall) density, according to nuclear gauge readings.

Samples were obtained during the production of the Evotherm™ ET mixture and taken to a laboratory for testing. The WMA samples did not meet the minimum criterion for Marshall Stability (ranged from 6,380 to 7,824). The author stated that while these values were low, the values were still higher than the stabilities found from laboratory produced samples during mix design. Those values were not provided for comparison. The gradation, air voids and asphalt content of the samples were all within acceptable levels for the given mixture. The asphalt contents were higher than the design value for all the samples tested (by a maximum of 0.49 percent). The recovered penetration values were approximately 85 percent of the original penetration value.

Based upon the results of this field demonstration, the author made the following conclusions:

- There were no major issues with the production and placement of the EvothermTMET WMA.
- The density of the WMA was easily met and was comparable to HMA.

Low-Energy Asphalt with Performance of Hot-Mix Asphalt (Romier et al.) (59)

In November 2003, a field section was constructed using LEA. No control HMA section was placed. The mixtures were a semigranular bituminous concrete (French designation BBSG) and GB3 (road base material) types. The binder for both mixtures had a penetration grade of 35/50. The aggregate was diorite. No further mixture information was provided. A total of 150 tons were placed. The mixture was stored in a hopper for over an hour before hauling. The WMA was placed using the same procedures as HMA. Placement temperatures ranged from 140 to 158°F (60 to 70°C). Once compacted, the LEA had the same surface appearance of HMA, including at joint locations. The authors did not provide any density or performance information.

Assessing Potential for Warm-Mix Asphalt Technology Adoption (Kristjánsdóttir et al.) (60)

In June 2005, two demonstration projects were constructed in Maryland using Sasobit® WMA technology as a workability and compaction aid for high RAP mixtures. The first demonstration involved the patching and overlaying of a seven mile stretch of SR-28 near the Frederick County line. The project required the placement of several deep patches, followed by a two inch overlay over the entire length of the roadway. The three day demonstration used HMA and WMA, both with 45 percent fractionated RAP. Properties of the RAP were not provided. Both mixtures were Superpave 19 mm NMAS designs made with PG 64-22 virgin binder. The aggregate type was not specified. Sasobit® was added to the WMA at a rate of 1.5 percent by weight of the virgin binder. The production temperatures for the HMA and WMA were 166 and 157°C, respectively. Both mixtures were compacted at temperatures ranging from 135 to 149°C.

Plant-produced samples were collected for laboratory testing. The results showed that the addition of Sasobit® did not have an adverse effect on the overall performance. No specific laboratory data were provided. According to the authors, the high temperature stiffness increased slightly, but the intermediate and low temperature stiffnesses were the same as the control. Testing for rutting, fatigue cracking and thermal cracking showed that there was no significant difference when comparing the warm mix to the control. The mixtures with Sasobit® demonstrated a slightly better resistance to moisture damage than the control. The mixture tested was considered to be of an average risk to moisture damage. Field testing results showed that all WMA patches met the minimum requirement for density (92 percent). Overall, there was an average 40 percent reduction in the number of roller passes required to meet compaction. Again, no raw data was provided to support these findings. It was noted during placement that the HMA was very difficult to work with and the WMA was more workable but still stiff.

The second demonstration took place on SR-925 in Charles County, Maryland in September 2005. A 2.5 mile stretch was overlaid with a half inch leveling course with 15 percent RAP and a one inch surface course with 35 percent RAP. Properties of the RAP were not provided. Both mixtures were Superpave 9.5 mm designs made with PG 64-22 virgin binder. The aggregate type was not specified. Sasobit® added at 1.5 percent by weight of binder. The production temperatures for the HMA and WMA were 320°F (160°C) and approximately 286°F (141°C), respectively. The HMA was compacted at 309°F (154°C), and the WMA at 270°F (132°C). The same laboratory analysis was conducted on these mixtures, and the authors reported identical results to those mentioned for the first demonstration. The average field density was 94.1 percent for the HMA and 92.6 percent for the WMA; however, the HMA required more compactive effort to achieve the desired density. The HMA mat was tearing in the field, and the production temperature had to be increased from 350°F (177°C). The Sasobit® section did not exhibit any similar issues.

A Synthesis of Warm Mix Asphalt (Button et al.) (11)

As mentioned in the Laboratory Performance section, in August and September of 2006, a field trial was performed on Loop 368 in San Antonio, Texas using Evotherm™ ET warm mix technology and a control HMA section. The binder used for the HMA was a PG 76-22. The modifier used for the binder was not identified. The WMA binder started as a PG 64-22, but was modified to become a PG 76-22. No additional anti-stripping agent was used for the Evotherm™ ET mixture since the chemical package contains one, but the HMA contained Pre-Tech Pave Grip 400 anti-stripping agent. Both mixtures were designed as Type C dense-graded mixes, which require the use of the Texas gyratory compactor. The target density was 96.5 percent. The WMA was produced at 219°F (104°C), and the HMA was produced at 320°F (160°C). Both mixtures used the same aggregate source, which was a crushed limestone. The Evotherm™ ET was introduced to the mix by being pumped from tanker trucks into the end of the drum through the plant metering system. Before loading into the truck, the warm mix was stored in a silo for two hours. After construction, nuclear density readings indicated that the density of the warm mix section ranged from 92 to 95 percent. The average density for the HMA section was 94 percent. Traffic was allowed on the warm mix section two hours after construction completion. After one month in service, cores were extracted from both the WMA and HMA sections. The average densities for both were approximately 93 percent. The authors noted that there were no signs of distress on the section after one month in service.

Field Performance of Warm-Mix Asphalt at National Center for Asphalt Technology Test Track (Prowell et al.) (61)

Three sections were constructed at the NCAT Test Track to evaluate Evotherm™ ET WMA rutting performance in late October and early November of 2005. Superpave 19.0 mm NMAS mixes with PG 67-22 binder were placed in two lifts in each of the sections. The aggregate used included a blend of granite, limestone and coarse sand. The surface layers placed were Superpave 9.5 mm mixes also made with PG 67-22 binder (or the equivalent Evotherm™ ET grade). One of the sections was topped with a control HMA lift (section N2), and the other two were topped with Evotherm^{TM} ET mixtures (sections N1 and E9). One top lift of Evotherm^{TM} ET included 3 percent latex by weight of binder residue in the mixture (section N1).

The mixing temperature of the WMA was 239°F (115°C), and the desired compaction temperature was 225°F (107°C). However, equipment problems were encountered during paving the surface of section N1 and the warm mix had to remain stored in a silo for 17 hours. By the time it was placed, the mix had cooled to 205°F (96°C). Once paving was completed, images from an infrared camera showed that there was much less thermal segregation with the warm mix sections than that of HMA. All the in-place densities (based on nuclear readings and cores) of the Evotherm^{TM} ET mixtures were higher than 96 percent G_{mm}. The base layer was 3.1 percent higher, the binder layer was 2.1 percent higher and the surface layer was 1.3 percent higher. These results show that Evotherm^{TM} ET improves compaction even though the production and placement temperatures are lower than conventional hot mix. After 43 days in service (to the end of the test cycle), the maximum value of rutting present in any of the sections was 1.1 mm. During the 43-day time span, 515,333 ESALs (equivalent single axle loads) were applied to the sections.

Plant-mixed laboratory-compacted specimens were obtained for volumetric, APA and TSR testing during construction. Air void results indicated that the Evotherm^{TM} ET improved the compaction almost 40 percent at a temperature 68°F (38°C) lower than that of the HMA. Asphalt contents were determined in accordance with ASTM D 2172. The WMA base and binder layers had asphalt contents that were on average about 1.1 percent higher than that of the control. The gradations were determined in accordance with ASTM C 117 and ASTM C 136. The results indicated that the gradations for the WMA base and binder layers were finer than the control. Both the increased asphalt content and finer gradation contribute to increased densification.

APA testing was performed on the plant-mixed laboratory-compacted specimens at 147°F (64°C) with a hose pressure of 120 psi and a wheel load of 120 lb. The HMA and WMA (without latex) surface mixtures had average rut depths of 7.56 and 7.85 mm, respectively. The WMA surface mixture with latex had an average rut depth of 5.14 mm, which shows that the addition of the latex made the mixture more rut resistant. The

HMA and WMA binder layers had average rut depths of 5.84 and 5.71 mm, respectively. Finally, the HMA and WMA base layers had average rut depths of 5.84 mm and 7.40 mm, respectively.

Moisture resistance was evaluated in accordance with ASTM D 4867 including one freeze-thaw cycle. The samples were prepared without reheating. The ITS and corresponding TSR values are shown in TABLE 40. Results were not presented for the Evotherm™ ET surface mixture with latex. As seen in the table, the control HMA was the only mixture to meet the minimum criterion of 0.80 for TSR. However, the authors stated that typically the freeze-thaw cycle is not used for pavements in Alabama to test moisture resistance, and therefore the test was more severe. Preliminary testing was conducted on laboratory-produced samples before construction (without the freeze-thaw cycle), and those results for the WMA and HMA were comparable.

TABLE 40 TSR Results for Laboratory Compacted Samples (*61*)

Mix Type	Average Air Voids Unconditioned (%)	Average Air Voids Conditioned (%)	Indirect Tensile Strength Unconditioned (psi)	Indirect Tensile Strength Conditioned (psi)	TSR
HMA control	4.6	4.4	104.1	98.0	0.94
Evotherm ET surface	6.2	6.2	118.0	52.9	0.45
Evotherm ET base	7.6	7.7	98.1	32.4	0.33
Evotherm ET binder	8.0	8.1	106.9	40.6	0.38

After the test cycle was completed and the sections were no longer exposed to traffic, cores were extracted to evaluate the possibility of in-place moisture damage. The cores were wrapped in plastic and not allowed to dry, and were taken to the NCAT laboratory for testing. The specimens were cut to separate layers, and then some were conditioned to 77°F (25°C) before determining the indirect tensile strengths. The rest were dried at 122°F (50°C) until they reached a constant mass. They were then tested in accordance with ASTM D 4867. The results are shown in TABLE 41. The Evotherm™ ET surface course without latex was not included in the results. As seen in the table, the TSRs of the WMA improved significantly when compared to the laboratory-compacted samples. The authors stated that the improved in-place density may have contributed to the higher TSR values.

TABLE 41 TSR Results for Field Core Samples *(61)*

Layer	Field Compacted Samples After Traffic				
	Dry Tensile Strength (psi)	**Wet Tensile Strength (psi)**	**In Situ Tensile Strength (psi)**	**TSR**	**In Situ TSR**
HMA control	127	76	103	0.60	0.81
Evotherm™ ET surface + latex	139	103	107	0.74	0.77
Evotherm™ ET base	135	95	105	0.70	0.77
Evotherm™ ET binder	132	91	135	0.69	1.02

From the results of this field study, the authors concluded:

- The WMA produced using Evotherm™ ET was successfully compacted after 17 hours of storage in a silo.
- The in-place densities of the surface layers of WMA were equal to or better than the HMA, and the compaction temperatures were decreased by 14 to 76°F (8 to 42°C).
- For the base and binder layers, the in-place densities of the WMA were significantly greater than those of the HMA. However, the asphalt contents for these warm mixtures were higher than anticipated.
- Rut depths from the APA test were similar for HMA and WMA.
- The three sections paved incorporating Evotherm™ ET technology all had excellent rutting performance after the 43 days of heavy traffic.
- The WMA placed in section N1 was opened to traffic 1.75 hours after paving and still had good rutting performance.
- TSR results indicated an increased potential for moisture damage for the Evotherm™ ET mixtures.

Installation of Warm Mix Asphalt Projects in Virginia (Diefenderfer et al.) (9)

Three trial sections of WMA were constructed in Virginia in late 2006. Two of the sections were constructed using Sasobit® additive, and the other was constructed using Evotherm™ ET. Each demonstration was constructed with a complimentary HMA section for comparison.

Trial 1 was constructed in August 2006 as a 1.5 inch overlay placed on Route 211 in Rappahannock County, Virginia. The mixture was a Superpave 9.5 mm NMAS mix with a PG 64-22 binder with 20 percent RAP. The type of aggregate and RAP properties were not provided. Morelife antistripping additive was used at a dosage of 0.5 percent by weight of binder, and Sasobit® was added at a rate of 1.5 percent by weight of binder. Weather conditions were good during paving, but it had rained the day before and the aggregates were damp. The production temperature for the WMA was 250°F (121°C), and the HMA was produced at 300°F (149°C). Approximately 775 tons of the Sasobit® mixture was placed for the demonstration.

Once placed, the mat temperature for the warm mix ranged from 215 to 225°F (102 to 107°C) behind the screed. Three rollers were used for breakdown, intermediate and finish rolling. The roller pattern remained constant for both HMA and WMA mixtures. The paving crew noted that the warm mix felt slightly stiffer than the HMA. However, other than the difference in stiffness and temperature, the warm mix was constructed the same as hot mix with no issues.

In-place density measurements were taken using a nuclear density gauge. The estimated air voids for the control section was 8.3 percent with a standard deviation of 2.4 percent. The WMA section had an estimated 7.6 percent air voids with a standard deviation of 2.7 percent. Six cores were also extracted from each section and tested for air voids. The average air voids from the HMA and WMA cores were 7.7 percent and 6.7 percent, respectively. The standard deviation for the WMA was higher than the control, at 1.84 compared to 1.11 percent.

Trial 2 was also a 1.5 inch overlay placed using Sasobit®. The section was constructed on August 15, 2006, and approximately 320 tons of warm mix was placed. The mixture placed was a Superpave 12.5 mm mix with a PG 64-22 binder and 10 percent RAP. The authors did not specify any properties of the RAP or the aggregate type that was used. Sasobit® was added at a dosage of 1.5 percent, and hydrated lime was also added. The authors did not specify the dosage rate of the anti-strip additive. The warm mix was hauled from a location that was around one hour and 45 minutes from the construction site. Weather conditions were sunny and clear during paving of the control section. The high temperature was approximately 14°F (8°C) cooler and skies were overcast with occasional light drizzle during placement of the WMA. Due to the long haul time, the HMA was produced at approximately 325°F (163°C) and the WMA was produced at 300°F (149°C). Behind the screed at the paving site, the HMA temperature was around 290°F (143°C) and the WMA was around 262°F (127°C). Two rollers were used for breakdown and finish rolling.

Cores were extracted after construction and analyzed to determine air voids. The HMA had an average air void content of 9.2 percent with a standard deviation of 1.3 percent, and the WMA had an average air void content of 8.1 percent with a standard deviation of 2.5 percent.

Trial C was the construction of an Evotherm™ ET WMA section, and was completed on October 26 and November 2, 2006. This project was also a 1.5 inch overlay, and approximately 520 tons of WMA were placed. The base mix was a Superpave 9.5 mm mix with a PG 70-22 binder and 20 percent RAP. Adhere HP Plus anti-strip additive was added to both the control HMA and WMA at a dosage rate of 0.3 percent by weight of binder. The authors did not specify the aggregate type used. The base binder for the Evotherm™ ET was also a PG 70-22. Weather conditions on the day of paving were windy and cool (30 to 60°F (17 to 33°C)) with clear skies. The warm mix was produced at a counterflow drum plant at approximately 225°F (107°C). Two rollers were used for mat compaction.

After construction, six cores were taken from both the control and Evotherm™ ET WMA sections. The HMA control section had an average air void content of 7.6 percent with field cores and 8.5 percent with nuclear measurements. The Evotherm™ ET section had an average air void content of 9.4 percent with field cores and 11.1 percent with nuclear measurements. The asphalt content of the control mixture was lower and the SGC air voids higher than that of the Evotherm™ ET mixture. All other volumetric properties were similar. The authors stated that after these field trials, they concluded that warm mix can be placed using the same equipment and methods used to place hot mix, and the only difference in the two is the temperature reduction of the warm mix.

A Review of Warm Mix Asphalt (Chowdhury and Button) (62)

Chowdhury and Button reported that as of the writing of their report in 2008, nearly seventy field test sections had been constructed in the United States using WMA. The authors stated that no negative performance had been reported on as of their writing, and that overall the sections are performing well. However, most of the sections that have been reported on have been in service for less than five years (Chowdhury and Button, 2008).

Field Performance of Warm Mix Asphalt (Hurley and Prowell) (6)

As discussed previously in the Laboratory Performance section, field trials were constructed in St. Louis, Missouri and Milwaukee, Wisconsin using the warm mix technologies Aspha-min®, Evotherm™ ET, and Sasobit®. Data were obtained from the test sections in each location to determine the air voids immediately after construction and 6 months after construction. The results from the Milwaukee field trial are shown in FIGURE 64, and the results from the St. Louis field trial are shown in FIGURE 65. No data were collected for the control section after 6 months in Milwaukee, and for the control section immediately after construction in St. Louis.

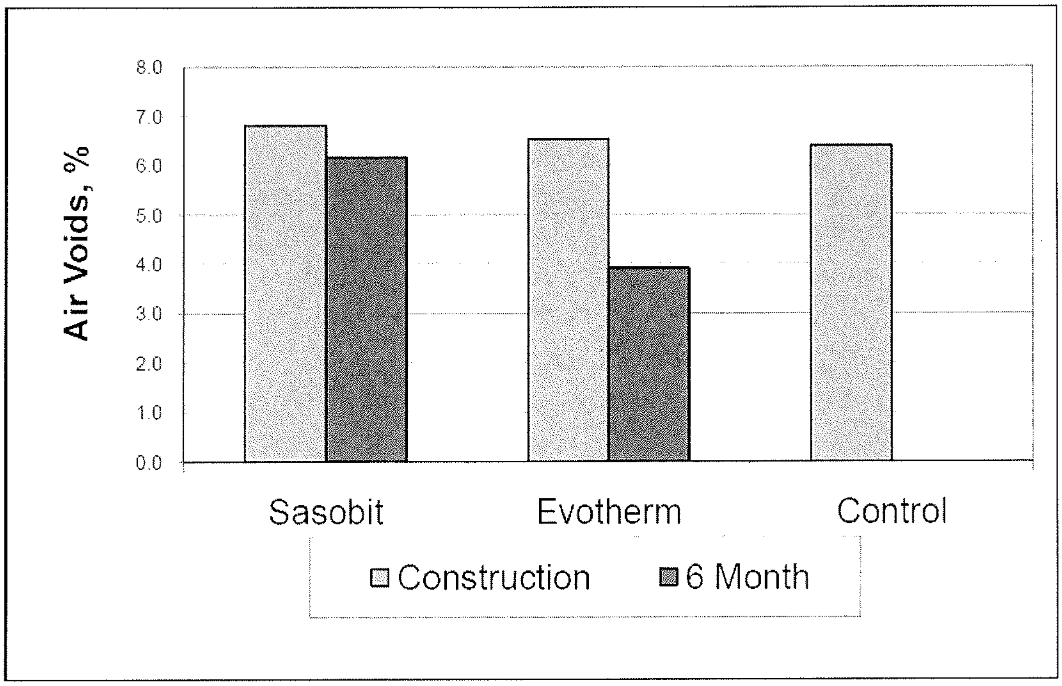

FIGURE 64 In-place Air Voids, Milwaukee Trial (*6*)

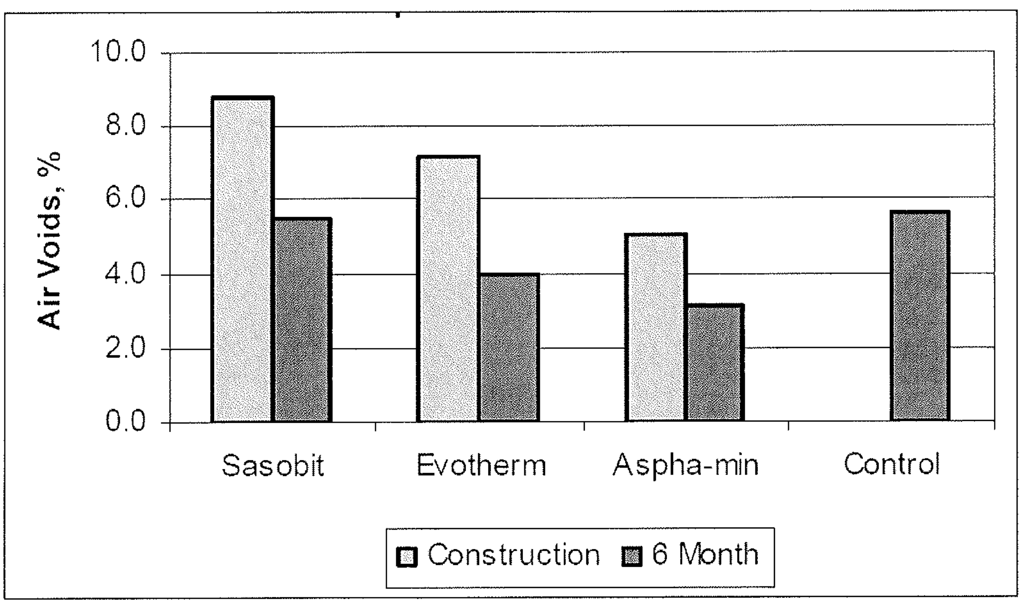

FIGURE 65 In-place Air Voids, St. Louis Trial (*6*)

Immediately after construction in the Milwaukee trial, the WMA sections and the control all had similar air voids. For the St. Louis trial, the warm mix sections had lower in-place air voids than that of the control section. After the St. Louis sections had been trafficked for four summer months (May through October), field rut depth measurements were taken. For all sections, the maximum rut depth was 1.1 mm. In Milwaukee, the average rut depths for the WMA sections were below 1 mm. Therefore, at the time of the report, the field performance indicates that the sections are rut resistant.

Warm Mix Asphalt: European Practice (D'Angleo et al.) (64)

Many field demonstrations have been constructed in Europe over the last decade. In 2007, a scan team from the United States went to Europe to evaluate their progress with warm mixes. The scan tour visited Belgium, France, Germany and Norway. The representatives in each country implied that WMA should perform the same if not better than HMA. The European representatives all stressed the importance of removing the moisture from the coarse aggregates to mitigate moisture problems. The European restrictions on moisture were more stringent than the United States: only aggregates with water absorptions of less than two percent are allowed, and the United States typically allows aggregates with up to five percent absorption.

In France, a number of trials have been constructed. A toll road southwest of Paris was constructed in 2003 using Aspha-min®, and the performance (as of time of the scan tour) was comparable to that of HMA. Six technologies have been trialed on small projects in Paris, including a bus lane. Projects built with the technologies are monitored for three years prior to approving the technology. Projects were built in Eure-et-Loir with Aspha-min® and ECOMAC. No performance data was presented on the latter projects.

In Germany, seven field test sections constructed between 1998 and 2001 were visited. Six of the mixtures were stone matrix asphalts (SMA) and the other was a dense-graded mixture. Four warm mix technologies were used for the construction of these sections, including Sasobit®, Asphaltan® B (not used in the United States), Aspha-min® and Sübit® (asphalt modified with Licomont® BS 100). Each test section constructed was accompanied by a companion HMA section for performance comparisons. Each section visited exhibited the same or better performance than the HMA sections.

In Norway, 28 sections were analyzed that ranged in age from two to eight years.

All the WMA sections used WAM-Foam. Some sections showed considerable deterioration, but the authors attributed this to damage from studded tires. It was noted that similar damage was observed in HMA sections.

From their visit, the scan team observed the following key features about European methods for warm mix asphalt design, production and construction:

- Differences were noted in the design, production and placement of WMA between the European agencies visited. The European methods also had several differences from the methods used in the United States.
- In general, the aggregates used to produce WMA in the European countries visited had absorptions of less than two percent. The maximum absorption for aggregates in France was one percent. In the United States, this number can typically be as high as five percent
- All agencies visited stressed the need to ensure that the coarse aggregates are completely dried. In the United States, this may be more difficult due to the higher absorption percentage.
- European contractors blend and modify binders on a routine basis. In the United States, the performance grading system (with required supplier certification) hinders this possibility.
- While in the United States it is important to know if the warm mix additive changes the grade of the binder, European countries focus more on performance test results.
- Placement of HMA and WMA were the same in the countries visited. The only difference was the lower placement temperatures of the WMA.
- When compared to U.S. contractors, European contractors are better equipped to research and develop new WMA technologies.

Cold Weather Paving Using Warm Mix Asphalt Technology (Manolis et al.) (65)

A more recently developed warm mix technology called HyperTherm was used to conduct field demonstrations in Ottawa, Canada. HyperTherm is a non-aqueous liquid additive that was developed by LaFarge North America.

For the first demonstration, a surface mixture designated as a FC1 mix with a

NMAS of 4.75 mm was created with a PG 58-28 binder. The aggregates were a blend of dolomitic sandstone and sand. The HyperTherm additive was added to the mixture at a dosage rate of 0.2 percent by weight of binder. The section was 25 mm thick, and was designed for between 3 and 10 million ESALs. The mixture was produced at the asphalt plant at 248°F (120°C) and compacted at temperatures ranging from 167 to 194°F (75 to 90°C). A control HMA mixture was produced for comparison. Both the HMA and WMA were dosed 0.5 percent HyperStick anti-stripping additive in order to meet the minimum TSR requirement of 83 percent for the city of Ottawa. Laboratory TSR results for the HMA and WMA were 86.3 and 86.0 percent, respectively. The authors did not provide a test method that was used to determine the TSRs, nor any information on the indirect tensile strengths. APA results were also provided with no further details, and the HMA and WMA rut depths were 13.2 and 14.5 mm, respectively. The virgin binder and the HyperTherm modified binder were evaluated to determine the difference in PG characteristics. The rheological properties were only slightly changed, and both binders still graded as PG 58-28 in accordance with AASHTO M 320.

During construction, the WMA was placed and compacted without issues, and the paving crew noted that it was easier to work with than conventional hot mix. The final product had the same appearance as HMA and had a uniform texture throughout. After five months in service, the sections were revisited and were performing well (no distresses present).

The second demonstration was placed on Oxford Road 4 in the County of Oxford. The mixture was similar to the one used in the first demonstration; however, this mixture was produced at conventional hot mix production and laying temperatures (311 and 293°F (155 and 145°C), respectively) because it was placed in very cold weather. The mixture was a HL8 Marshall Mix design, and included 3 percent modified shingles in the mixture. The aggregate type was not specified. HyperTherm was added at a dosage rate of 0.2 percent by weight of mixture. The binder was a PG 58-28, and the design asphalt content was 5.2 percent. The subgrade was frozen and the ambient air temperature ranged from -13 to 2°C. The mixture was placed without issues and compacted adequately despite the cold weather. The compacted layer thickness was 100 mm. Nuclear density gauge readings indicated that compaction levels were in the range of 92 percent to 98 percent. The authors did not specify whether compaction levels were percent of laboratory or maximum density. This project was meant to be a temporary fix for a roadway until HMA could be used to pave in the warmer months. The road was used for 4 months and generally performed well. A slightly rippled appearance was noted for some portions of the roadway, but the authors attributed this to poor base compaction.

Warm Mix Asphalt Technology: An Overview of the Process in Canada (Davidson) (66)

According to Davidson (2008), there are five warm mix processes that are currently being evaluated in Canada. Three of the processes are relatively new to Canada and have plans for field trials include Sasobit®, WAM Foam and foamed asphalt using the Astec Double Barrel Green system. The other two technologies, Aspha-min® and Evotherm™ ET and DAT, are more common in Canada and have had multiple field trials constructed (six for Aspha-min® and eleven for Evotherm™ ET as of this writing).

Three of the Aspha-min® trials were placed on roads in the city of Montreal in 2005. Two different binder grades were used to create the mixtures, including a PG 64-28 and a PG 70-28. No additional mix information was provided. Hot mix sections were also placed in the trials for comparison. The HMA was mixed at 320°F (160°C) and the WMA was mixed at approximately 275°F (135°C). The laydown temperature for the HMA was between 284 and 302°F (140 and 150°C), and between 230 to 257°F (110 to 125°C) for the Aspha-min® mixtures. After one year the sections were revisited, and no distresses were present in any of the sections.

The other three Aspha-min® trials were completed in 2006. Two of the trials were placed in November during cold weather. The contractor responsible for the construction of the sections stated that the warm mix was easier to compact than conventional hot mix, and that there were no issues with construction.

From 2005 to 2006, four Evotherm™ ET trials were conducted in Canada. A PG 58-28 binder was used for all four mixtures. One of the trials used mixtures that contained 15 percent RAP. Additional mix information was not provided in this paper, but further details can be found in other references by Davidson (*56, 57,* and *58*). The mixtures were produced at temperatures around 45 to 54°F (25 to 30°C) lower than HMA. The production temperature of the HMA was not provided. The WMA compaction temperatures ranged from 185 to 203°F (85 to 95°C). Recovered binder penetration values were analyzed for one of the field trials to quantify the reduced aging of the binder when using warm mix technologies. The WMA binder averaged a penetration of 80 while the HMA averaged 48. PG binder gradings were also performed.

In 2007, Evotherm™ DAT was used for two WMA paving demonstrations. One of the demonstrations was conducted in December 2007 because the road could not be paved with conventional hot mix during such cold weather. Since no asphalt plants were open near the paving site, the mix was produced and hauled 460 km (eight hours) to the jobsite. The ambient temperature was 14°F (-10°C), and the mixture arrived at the jobsite at temperatures ranging from 194 to 266°F (90 to 130°C). No additional mixture information was provided. At the time the article was written, the warm mix was performing well, with no distresses. In an Evotherm™ ET trial, samples of loose mix and cores were obtained and tested to determine the resilient and dynamic moduli. Statistical testing showed that there was no significant difference between the HMA and WMA for both values.

Davidson stated that thus far, no issues have been encountered while paving with warm mixes in Canada. Many of the trial sections were three years old, and all were still performing well.

Case Study of Warm Mix Asphalt Moisture Susceptibility in Birmingham (Kvasnak et al.) (18)

As discussed in the Laboratory Performance section, a field demonstration was conducted in Birmingham, Alabama using Evotherm™ DAT technology. While laboratory results showed that the mixtures used might be susceptible to moisture damage, the authors noted that as of their writing, the field section had not exhibited any sign of moisture damage based on tensile strengths of field cores and visual inspections.

Investigation of Foamed Asphalt (Warm Mix Asphalt) with High Reclaimed Asphalt Pavement (RAP) Content for Sustainment and Rehabilitation of Asphalt Pavement

(Hodo et al.) (24)

A pavement built with Astec's DBG foaming WMA technology was constructed in Chattanooga, Tennessee in June of 2007 as discussed in the Laboratory Performance section. The WMA test section was constructed the day prior to mainline paving. Cores were extracted from the test section for laboratory testing. The in-place density of both mixtures from the test section was approximately 2 percent lower than desired (average of 91 percent). The authors stated that this could have been prevented with more passes of the roller. There were no issues during the production of the warm mix at the plant, and the mixture had good workability except when the placement temperature dropped below 230°F (110°C). The authors recommended keeping the mixture above this temperature to ensure proper handling and compaction. After compaction, the sections had appearances similar to that of HMA, and had no signs of distress after one year in service.

Incorporating High Percentages of Recycled Asphalt Pavement (RAP) and Warm Mix Asphalt (WMA) Technology into Thin Hot Mix Asphalt Overlays to be Utilized as a Pavement Preservation Strategy (Mogawer et al.) (25)

As discussed in the Laboratory Performance section, a WMA field trial was constructed in October 2007 in Massachusetts using Sasobit® at a dosage of 1.5 percent by weight of binder. A Superpave 4.75 mm NMAS mix with a PG 52-33 binder with 30 percent fractionated RAP was used. The extracted binder from the RAP graded as a PG 94-4. The aggregates were a blend of crushed stone (unknown type), manufactured sand and natural sand. Latex was also added to the mixture at a dosage rate of 1.5 percent by weight of virgin binder to protect against cracking. The WMA was placed on a road that serves as the entrance to a recycling center, and heavy traffic loads were anticipated for the section. There were no issues with laydown, compaction or workability of the mixture. The authors stated that after almost a year of trafficking, there were no visible distresses on the warm mix section.

Laboratory and Field Evaluations of Foamed Warm Mix Asphalt Projects (Wielinski et al.) (26)

Two WMA paving demonstrations were performed in Indio, California in 2008. Both projects were paved using foamed asphalt produced using the Astec Double Barrel Green system. Both demonstrations consisted of a Hveem half inch mixture with a target stability of 39, asphalt content of 5.5 percent and air voids of 4.4 percent. No anti-stripping agent was used. A PG 70-10 binder was used for the mixture as well as 15 percent RAP. The authors did not specify what aggregate type was used. HMA control mixtures were constructed for each demonstration. The target plant discharge temperatures for the WMA and HMA were 275 and 330°F (135 and 166°C).

The first demonstration placed in February 2008was the entrance to a Granite Construction plant and used both HMA and WMA sections for comparison. The location of the demonstration was chosen because of the steep grades present and the heavy traffic (1.3 million tons of materials hauled annually).

The second demonstration was placed on Avenue 40 in March 2008. Approximately 1,050 tons of warm mix were placed for this project. The asphalt contents for both the WMA and the control were consistent, and ranged from 5.3 to 5.5 percent. The moisture contents of both the WMA and HMA ranged from 0.02 percent to 0.08 percent, and there was not a significant difference between the two. The authors did not explain how they measured the moisture content values. Aggregate samples were obtained during production, and the moisture contents ranged from 1.1 to 1.7 percent. On the second and third days of production, there was a considerable increase in sand equivalency (from an average of 55 to an average of about 70). This was not anticipated because the P_{200} ranged from 5.9 percent to 6.3 percent throughout the project.

For the first demonstration, field cores were extracted and tested for density. The WMA was compacted to about 93 percent of G_{mm}, and the HMA was about 92 percent of G_{mm}. These results indicate that warm mix has better density than HMA using the same compactive effort. However, in the second demonstration the HMA had a higher in-place density (94 percent) than the WMA (93 percent). After a year of trafficking, the authors stated that both sections were performing well, and that no visible distresses were present.

Warm Mix Asphalts with Low Dosage Chemical Additives (González-León et al.) (28)

Many field tests have been conducted in Europe using the Cecabase RT chemical additive. In 2005, four lanes were paved to evaluate mixtures created using warm mix techniques. One lane was a control HMA mixture, one lane was a warm asphalt mixture with no additive (just a reduced temperature), one lane was a WMA created using 0.5 percent Cecabase RT and the final lane was a WMA created using paraffin wax at a dosage rate of 2.5 percent by weight of binder. The mixtures had a French designation of BBSG 0/10. The binder had a penetration grade of 35/50, and comprised 5.8 percent of the mixture. Limestone aggregate was used. The Cecabase RT was manually added to the binder storage tank two hours before being injected into the mixer.

All mixtures were constructed using the same equipment and application methods, and were placed on the same day. After construction, air voids measurements were taken in accordance with NF P98-241-1 (French standard). The warm mixture created without an additive had significantly higher air voids when compared to the control (7.9 percent and 4.1 percent, respectively). The Cecabase RT mixture had air voids closer to that of the control (5.3 percent). The mixture with paraffin wax had unacceptably high air voids of 8.5 percent. The authors attributed this to the crystallization of the paraffin wax at temperatures below 212°F (100°C). Roughness measurements were obtained in accordance with NF EN 13036-1. All four lanes had statistically equivalent roughness values.

Other field tests with Cecabase RT have been conducted in Spain, Poland, Italy and Denmark. In all tests, similar density levels were achieved with the warm mixes and HMA, and no problems were encountered during mixture laydown and compaction. In one of the field trials, Duriez test ratios (a direct compression test performed on moisture conditioned and unconditioned samples) were determined for the field mixtures, and the WMA TSR was 81 percent, and the minimum requirement was 75 percent.

Weather-Mix Asphalt: Warm Approach Works in California, Where Climates of All Kinds Play (Barros and Dmytrow) (67)

At the time of the writing of the report, seven warm mix asphalt projects had been conducted in the state of California and were being evaluated by CalTrans. Four of the seven were open graded friction course mixtures with polymer-modified binders, two included rubberized asphalt concrete (RAC) and one was a standard dense-graded material. Additional warm mix projects are planned for 2009 and 2010 using open-graded rubberized asphalt concrete.

In 2006, a gap-graded RAC WMA trial section was conducted using Sasobit®. [No mix information was provided.] The WMA trial is located on a shoulder of Highway 152 near Gilroy, California. After over two years, the section is still performing well.

In 2007, CalTrans began performing accelerated testing on WMA mixtures using a heavy vehicle simulator at the University of California Pavement Research Center. The manufacturers of three warm mix technologies participated in the study: the PQ Corporation (Advera®), MeadWestvaco (Evotherm™ DAT) and Sasol Wax (Sasobit®). [The mix information and dosage rates of the warm mix additives were not provided.] The first phase of testing began in October 2007 and was completed in June 2008. Based on the results, it appears that WMAs can perform the same as conventional hot mix. The second phase of testing to evaluate moisture susceptibility is still underway.

A temporary detour was constructed using Evotherm™ DAT warm mix technology while State Route 70 was being realigned. The mixture was a dense-graded material made with a PG 64-16 binder. [The aggregate type was not specified.] The section had high truck traffic (15 percent) and was located on an incline. After four months, the section was performing well with no signs of distress when it was removed.

A warm mix demonstration project was conducted on Highway 1 near Morro Bay using an OGFC with a PG 58-34 polymer-modified binder in May 2008. Three warm mix technologies were used, including Advera, Evotherm™ DAT and Sasobit. The aggregate type was not specified. A control HMA section was constructed as well. The haul time for the mixtures was one hour. After nine months in service, all sections were performing well and will be re-evaluated after the winter.

In Point Arena, California a warm mix section was constructed using Evotherm. [The authors did not specify the Evotherm™ technology used, or any mix information.] The warm mix was hauled between three to four hours to the jobsite, yet still was produced at temperatures 20 to 30°F (11 to 17°F) lower than conventional hot mix. In general, the OGFC warm mix had an improved appearance and was easy to compact.

Another warm mix technology was tested in California on the shoulder of I-5 also in May 2008. The Astec DBG system was used to produce the WMA, [No further mix information was provided.] The production and placement temperatures were lowered by 25 to 35°F (14 to 19°C). Two weeks later, another warm mix asphalt was constructed and the Astec DBG system was used in conjunction with Evotherm^{TM} DAT. The production and placement temperatures were lowered by an additional 30°F (17°C) by using both technologies together.

Development of Recommendations for Compaction Temperatures in the Field to Achieve Density and Limit As-Built Permeability of HMA in Wisconsin (Schmitt et al.) (68)

During 2007, compactive effort testing was performed for a field demonstration of WMA. Additionally, a laboratory study was conducted to further evaluate the compaction of WMA versus HMA. [The authors did not identify a specific warm mix technology, but did state that a surfactant-based additive (most likely Revix) was used to create the WMA.] The field demonstration was constructed in September 2008 on County Highway E in Adams County, Wisconsin. The mix was identified as an E-1 mixture, a typical surface mixture used in Wisconsin. Three percentages of RAP were used in the warm mix: 30, 35, and 40 percent. [Specific properties of the RAP were not provided.] Crushed gravel and sand were used as the aggregates. [The specific type of gravel was not identified.] The mixing and compaction temperatures for the warm mix were 235 and 196°F (113 and 91°C), respectively. Control HMA sections were constructed for comparison. Field data collected included roller passes, roller type, vibratory setting, nuclear and field core density readings. Loose mix samples were collected and compacted in the laboratory using the Superpave gyratory compactor at two pressure settings (300 and 600 kPa) and three temperatures (194, 230, and 275°F (90, 110, and 135°C)). FIGURE 66 and FIGURE 67 show the resulting air voids using the compaction pressures of 300 kPa and 600 kPa, respectively. As seen in the figures, the control HMA and 30 percent RAP WMA mixtures have similar air voids (do not vary more than one percent) regardless of the compaction temperature. Both HMA and WMA with 30 percent RAP mixtures met the Superpave criteria of four percent air voids. The specimens with 40 percent RAP had air voids that were significantly less than the target of four percent. The authors believe this was due to the higher percentage of dust present in the 40 percent RAP mixture.

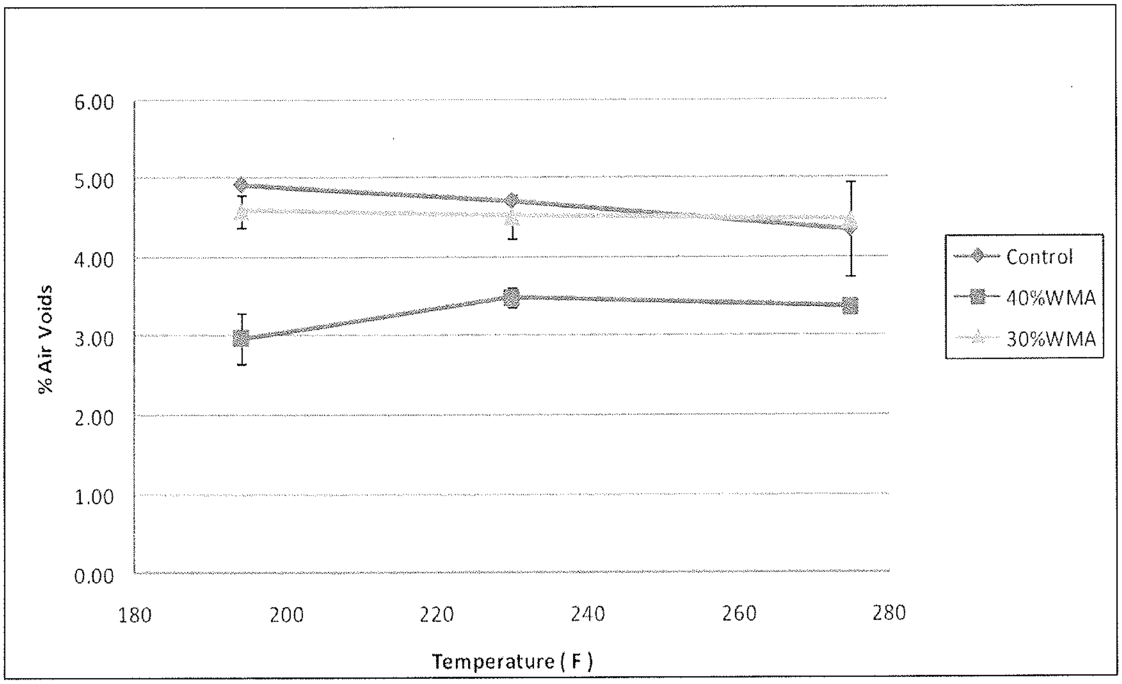

FIGURE 66 Air Voids for N_{des} = 60 Gyrations at 300 kPa (*67*)

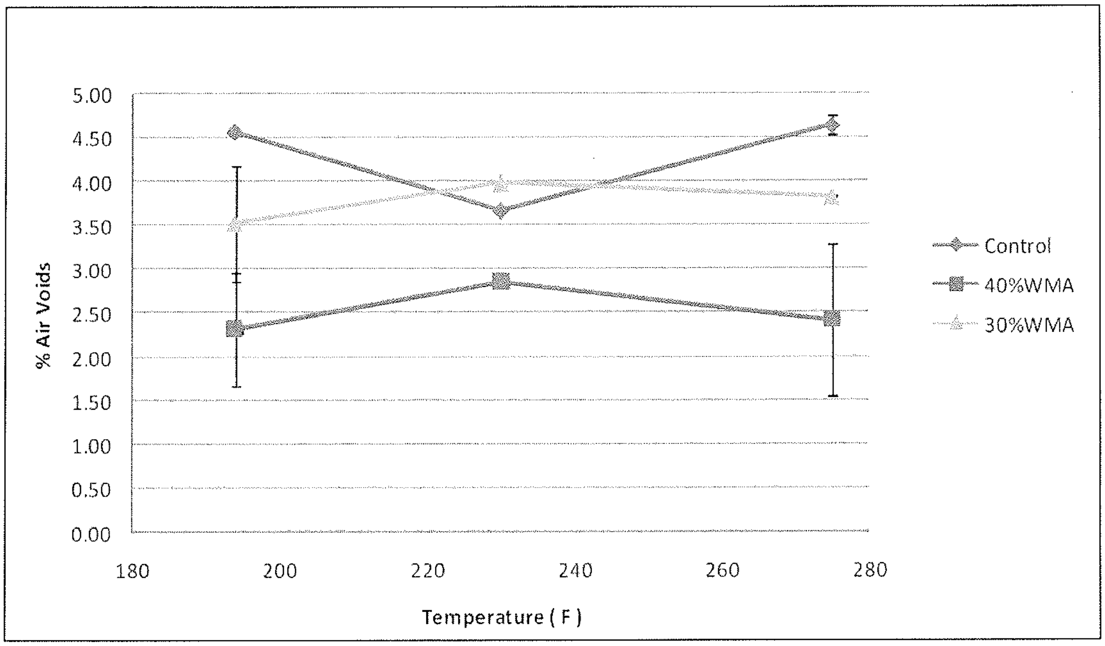

FIGURE 67 Air Voids for N_{des} = 60 Gyrations at 600 kPa (*67*)

From the construction of the field demonstration, nuclear density readings showed that the final density was nearly identical to that of conventional hot mix (approximately 92 percent). Large variability existed in the field densities of the warm mixes as shown in FIGURE 68. The authors attributed this to the varying levels of RAP used. With similar compaction efforts, the WMA with 30 percent RAP had an average of 2.6 percent greater density than the mixture with 40 percent RAP. The authors recommended that lower RAP contents be used to ensure the proper density level is achieved (30 percent or less).

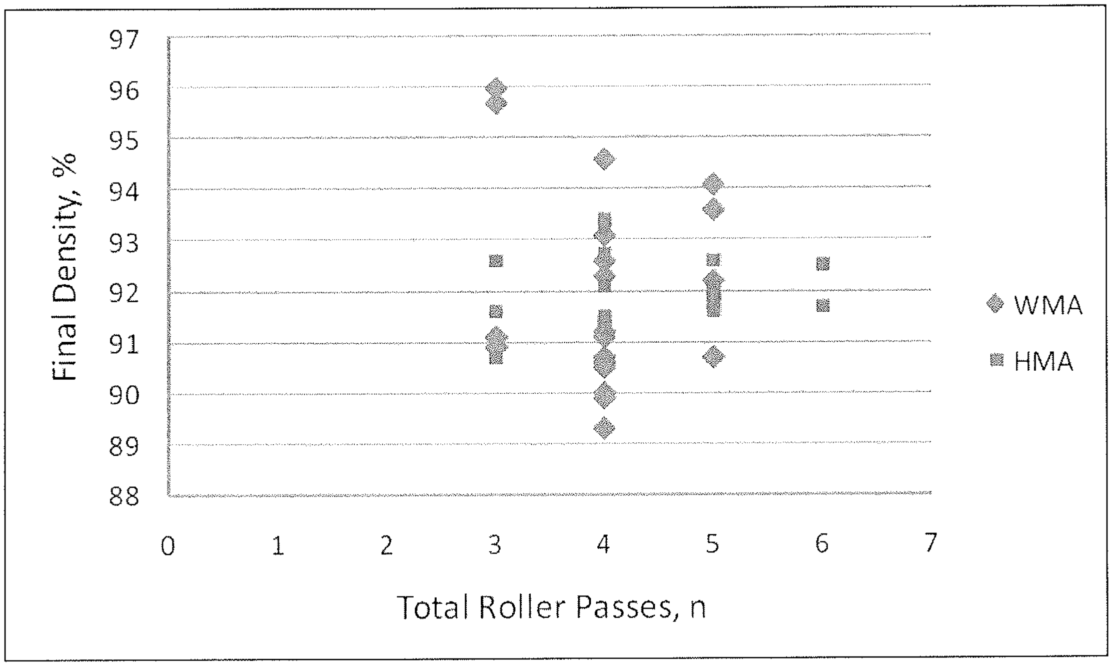

FIGURE 68 Final Densities of HMA and WMA (*67*)

Field Testing of Warm Mix Asphalt (West 2009) (69)

The findings for several WMA field projects monitored by NCAT were presented at the WMA & Recycling Symposium in June 2009. The findings included data from 13 projects. These projects occurred from October 2005 to October 2008, and included demonstrations in Opelika and Birmingham, Alabama; St. Louis, Missouri; San Antonio, Graham and Bridgeport, Texas; Iron Mountain, Michigan; Milwaukee, Wisconsin; Daytona, Florida; Nashville, Tennessee; Kimbolton, Ohio; Rock Hill, South Carolina, and Royal, Nebraska. Mixture information, lift thicknesses, WMA technology, dosage rates, weather, production temperatures, tonnage, production rates and paving rate data were collected for each project, but were not provided in the presentation. This presentation represented an initial attempt to synthesize data from several of the projects previously presented individually in this literature review.

For one project, the rate of cooling of WMA and HMA were recorded over time using a temperature gun. The HMA appeared to cool at a faster rate than WMA due to its larger difference from ambient temperatures.

Mix testing was conducted on plant-produced, laboratory-compacted materials, generally both with- and without reheating. The mix testing included tensile strength, Hamburg wheel tracking device and APA rutting results, IDT creep compliance, dynamic modulus and flow number testing.

Tensile strength ratios were determined in accordance with AASHTO T 283 at 77°F (25°C). The TSR values for both HMA and WMA from the NCAT field projects are shown in FIGURE 69. As seen in the figure, WMA consistently had lower TSR values than HMA at compaction temperatures below 240°F (116°C). However, for temperatures greater than 245°F (118°F), there was no consistent trend between TSRs of HMA and WMA. A paired t-test showed that for temperatures less than 240°F (116°C), the TSR values of the WMA were significantly less than the HMA. At temperatures greater than 245°F (118°C), the TSR values of the HMA and WMA were not statistically different.

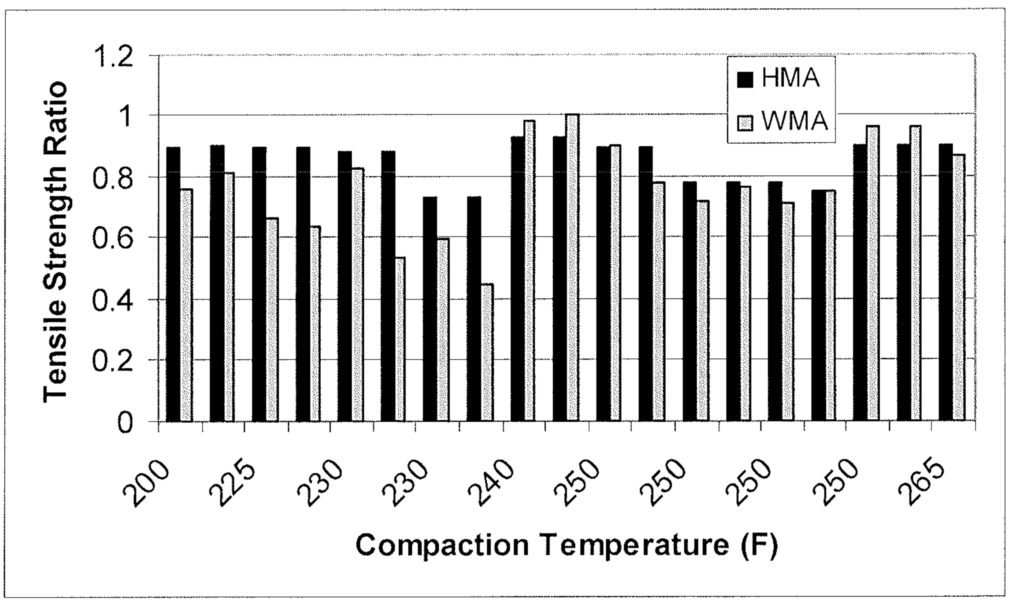

FIGURE 69 TSR Results for HMA and WMA (*69*)

Hamburg wheel tracking device testing was performed on the samples in accordance with AASHTO T 324 at 122°F (50°C). The stripping inflection point results are shown in FIGURE 70 with the red line indicating a stripping inflection criterion of

5,000 cycles. Statistical testing showed that the stripping inflection points for HMA and WMA were not significantly different for either of the same temperature groupings mentioned previously (less than 240°F (116°C) and greater than 245°F (118°C)). The rut depths from the Hamburg test are shown in FIGURE 71. Again, statistical testing showed that the rut depths for HMA and WMA were not significantly different for either of the temperature groupings. However, the rut depths for the WMA are slightly higher when compared to the HMA. Rutting rates were also compared for HMA and WMA, and the differences between them were not significant.

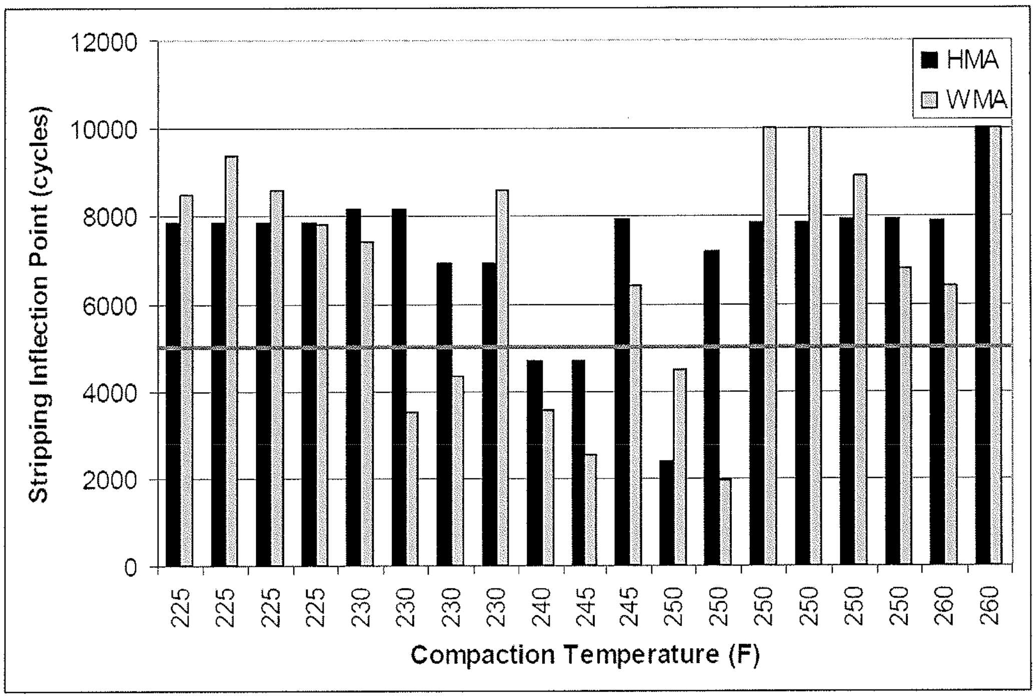

FIGURE 70 Hamburg Stripping Inflection Points for HMA and WMA (*69*)

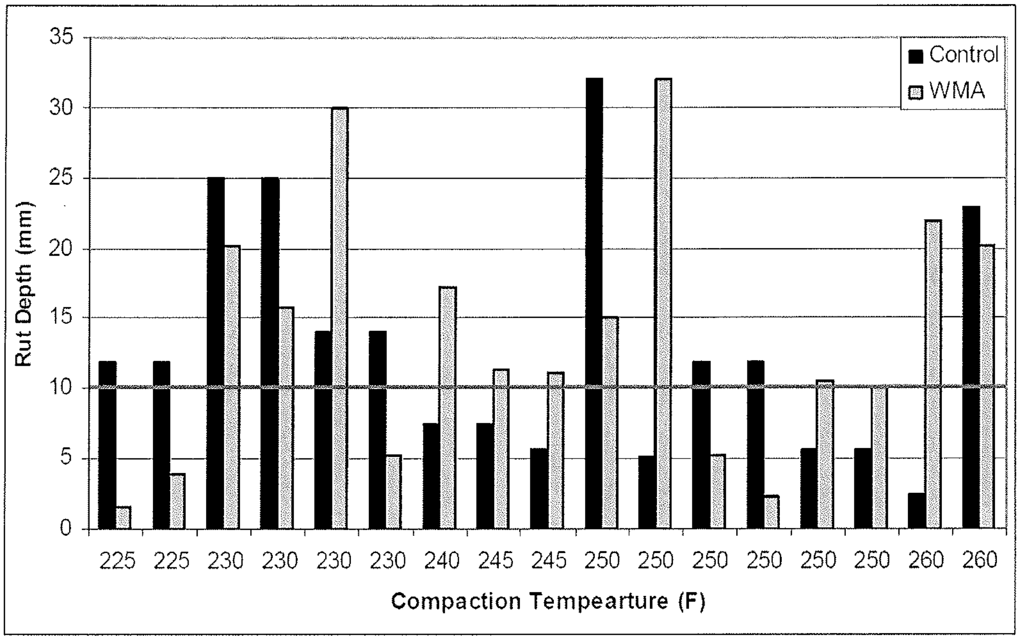

FIGURE 71 Hamburg Rut Depths for HMA and WMA (*69*)

APA testing was performed on the samples in accordance with AASHTO TP 63 at the climatic base PG high temperature. Rut depth measurements for HMA and WMA are shown in FIGURE 72. The results were divided into the same compaction temperature groups as before and tested with a paired t-test. The results showed that for temperatures less than 240°F (116°C), the WMA rut depths were significantly greater than the HMA rut depths. At temperatures above 245°F (118°C), there was no significant difference between the rut depths of the HMA and WMA. As for overall results, most WMA mixes met the maximum 5.5 mm rut depth criterion, but typically did have higher rut depths than HMA.

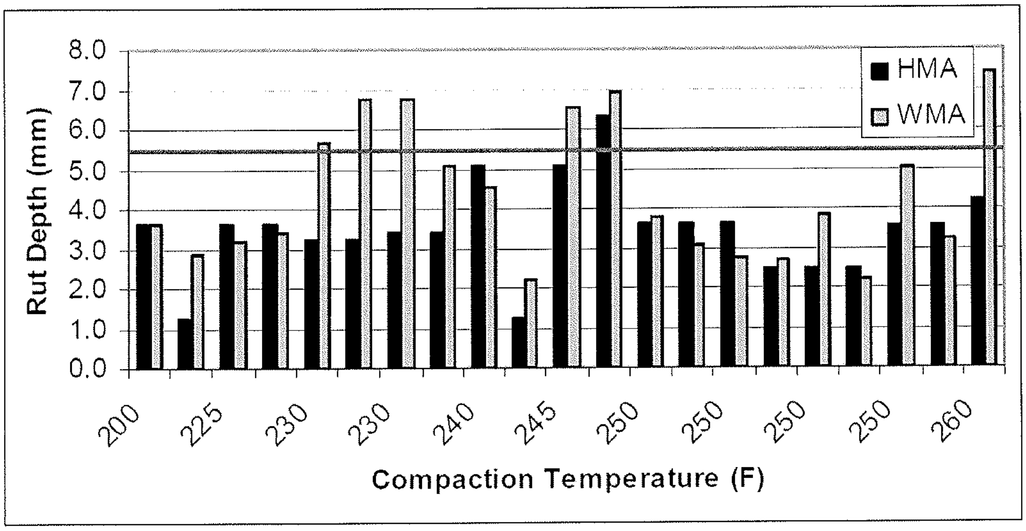

FIGURE 72 APA Rut Depths for HMA and WMA (*69*)

Solvent extractions and recoveries were performed to determine the continuous grades of the HMA and WMA after production. The high and low continuous grades of the HMA and WMA binders are shown in FIGURE 73 and FIGURE 74, respectively. The original binder grades were not provided. From these results, it is apparent that the WMA mixtures did not age and harden as much as the HMA. However, in some cases the difference was not substantial.

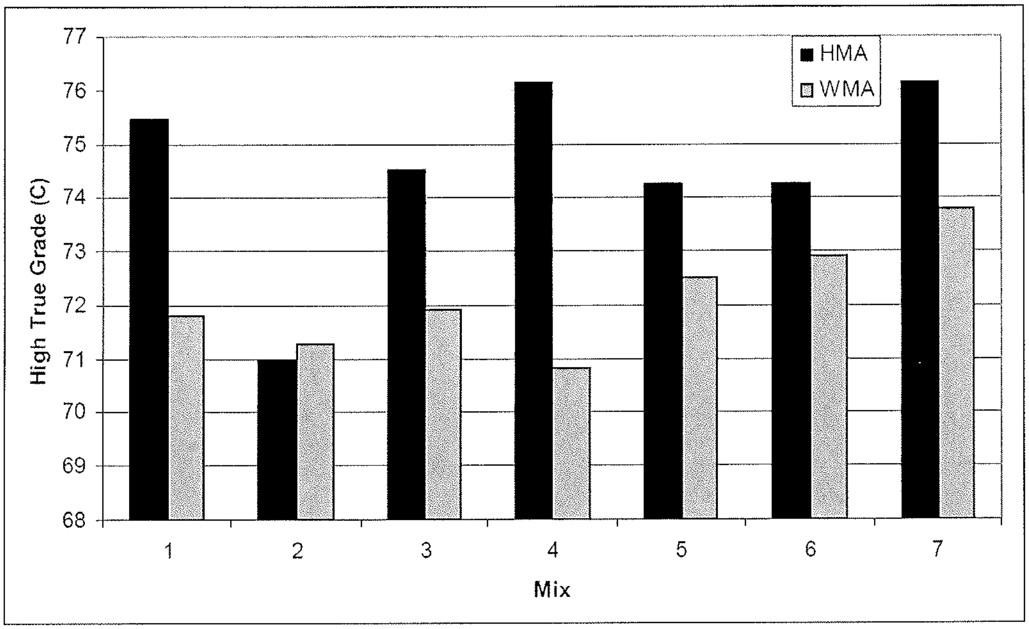

FIGURE 73 High Continuous grades for HMA and WMA (69)

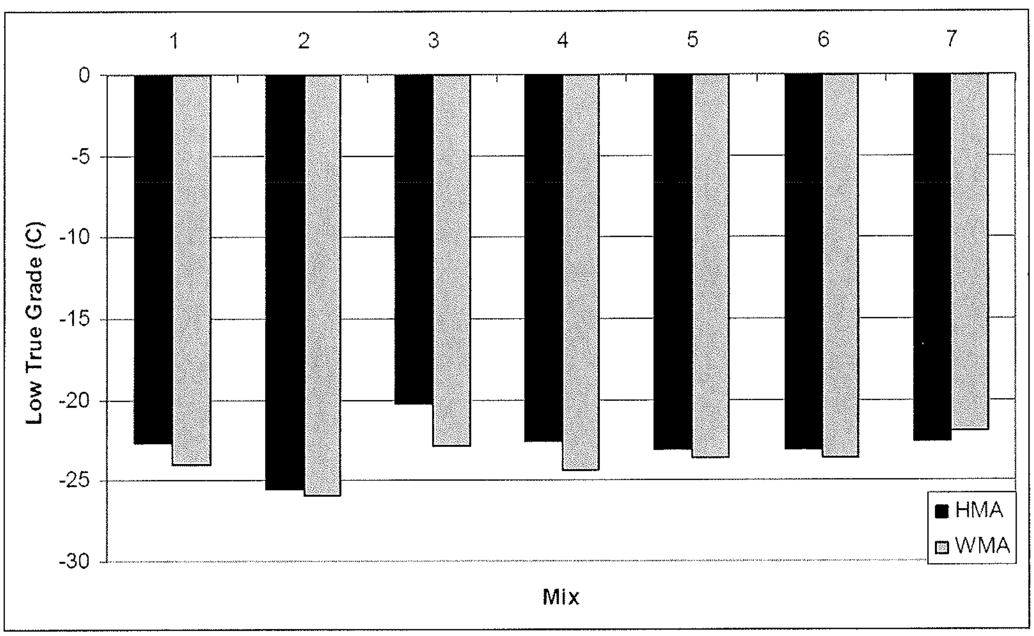

FIGURE 74 Low Continuous grades for HMA and WMA (*69*)

Cores were obtained from three of the field demonstration locations and tested for indirect tensile strength. The oldest site where cores were extracted was approximately two-years old. The tensile strength results showed that the WMA strengths improved over time as the binders oxidized and some degree of curing occurred. After two years in service, the WMA and HMA had similar tensile strength values. Additionally, core analysis showed that the majority of densification of WMA occurs in the first six months in service.

From simple visual inspection of the paving sites, it appeared that HMA and WMA had the same amount of rutting, and that the crack resistance of the WMA is at least equal to (and in some cases better) than HMA. Most importantly, none of the field trials had shown any signs of moisture damage thus far.

LEA Half-Warm Mix Paving Report – 2007 Projects for NYSDOT, (Harder) (70)

In 2006 and 2007, twelve projects consisting of 35,510 tons of LEA were constructed in Region 3 (Syracuse) in New York State. The project locations, dates, and tonnages are documented elsewhere in this report. McConnaughay conducted laboratory testing and monitored various plant production aspects during construction.

In 2006, 1000 tons of a 9.5 mm NMAS LEA mixture was placed as a 1.5-inch thick overlay on Route 11. An HMA control was also placed. In the spring of 2007, cracking was measured as 842 linear feet per lane mile in the HMA and 125 linear feet per lane mile for the WMA, an 85 percent reduction.

Experiments were conducted to determine if a curing period was required for quality control volumetric samples. Initial work indicated that LEA specimens compacted immediately after sampling tended to have lower air voids than corresponding HMA samples. However, if the LEA samples were allowed to completely cool down and then were reheated the LEA sample air voids tended to be higher than the corresponding HMA samples. The reheating process had virtually no effect on the HMA samples. The variances in sample density for the LEA samples were believed to be related to mix moisture content.

LEA samples were prepared at various moisture contents, (coarse aggregate) mix temperatures, and mixing times. These samples were held in an oven at 203°F (95°C) and then tested at various times for residual moisture content (FIGURE 75). The author concluded that the residual moisture contents converged after two-hours of aging. Two-hours of aging at 203°F (95°C) were adopted for conditioning volumetric samples.

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Additional testing was conducted on plant samples to compare the bulk density (G_{mb}) after 30 minutes and two hours at 203°F (95°C) (FIGURE 76).

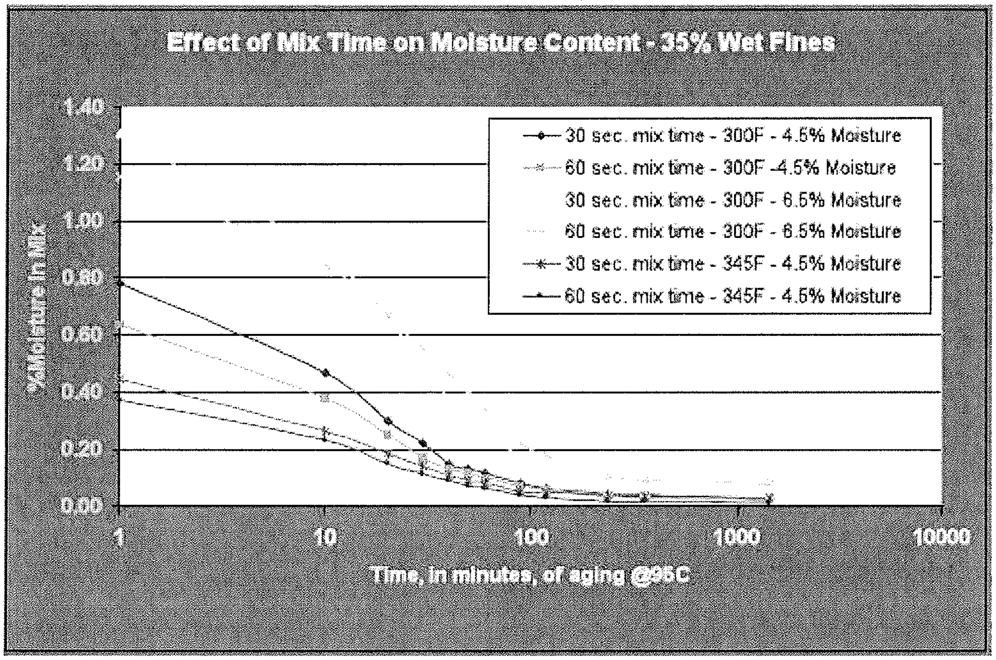

FIGURE 75 Residual Moisture as a Function of Aging Time for LEA (*70*)

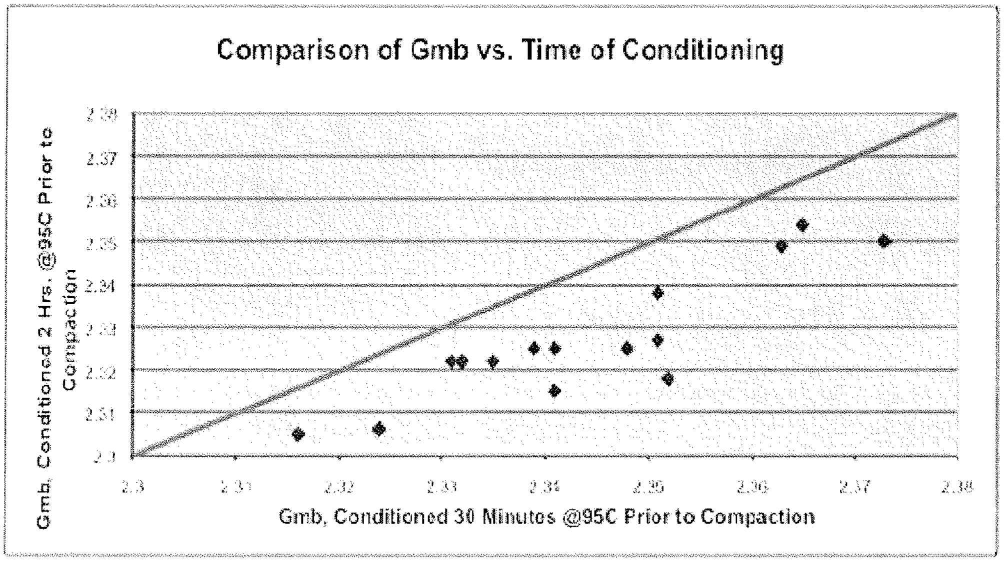

FIGURE 76 G_{mb} as a Function of Aging Time (*70*)

Using a two hour aging period, consistent results were obtained for the volumetric properties of LEA field samples. Incentive was received on 23 of 29 production days. No penalties were incurred.

The theoretical maximum specific gravity (G_{mm}) was determined on each production day for the LEA and HMA. The data are reported in the text. The NCHRP 9-47A team performed some additional analyses which indicate the average G_{mm} of the LEA samples are 0.019 less than the average of the HMA samples (29 and 7 tests, respectively). An F- and t-test were performed on the data. The variances were not statistically different, but the means were statistically different (p = 1.39 E-08). The author theorized that the foaming may reduce the amount of binder absorbed in the sand fraction, resulting in the lower G_{mm}. Personal communication with the author confirmed that the samples were aged for two-hours at 203°F (95°C) prior to testing.

TSR tests were performed on each day's production. Initially the samples were prepared after two-hours aging at 203°F (95°C). After eight days of production, an unaged set was added. Both the dry and wet tensile strengths were higher for the aged as compared to the unaged samples, as was expected. The author reports the resulting TSR values are not different. However, the NCHRP 9-47A team performed an F-test and paired t-test on the data. The F-test indicated the sample variances were not different but the paired t-test indicated the TSR values were significantly different with 95 percent confidence ($p = 0.04$). The mean TSR for the unaged samples was 91.1 percent and the mean TSR for the aged samples was 97.2 percent.

Dynamic modulus testing was performed on each mixture according to the NCHRP 9-29 test protocol. The results indicate a slight decrease in the modulus of the LEA samples compared to the HMA samples produced with the same binder grade. LEA samples were tested with a one-grade bump. The LEA samples produced with PG 70-22 were stiffer than the virgin HMA samples produced with PG 64-28. The addition of 10 percent RAP increases the modulus of LEA samples tested at 40°F (4°C).

Mix moisture content was determined for one sample of LEA per day. Samples A and B were taken from the truck at the plant. Sample A was tested according to AASHTO T 329. AASHTO T 329 specifies drying the sample to a constant mass at a temperature within the recommended mixing temperature for the mixture. Sample B was tested by drying in a 325°F (163°C) oven for four hours. A field sample was taken at the paver and tested in the same manner as Sample B. The results are summarized in

FIGURE 77. With the exception of two samples, the field moisture contents were less than New York DOT's maximum allowable limit of 0.5 percent. FIGURE 78 indicates that the two methods of determining moisture content produce approximately identical results. The method used for Sample B could result in significant time savings in a field lab. FIGURE 79 shows a comparison between the moisture contents of the plant and field samples. In general, there appears to be a reduction in moisture content between the plant and field, as would be expected.

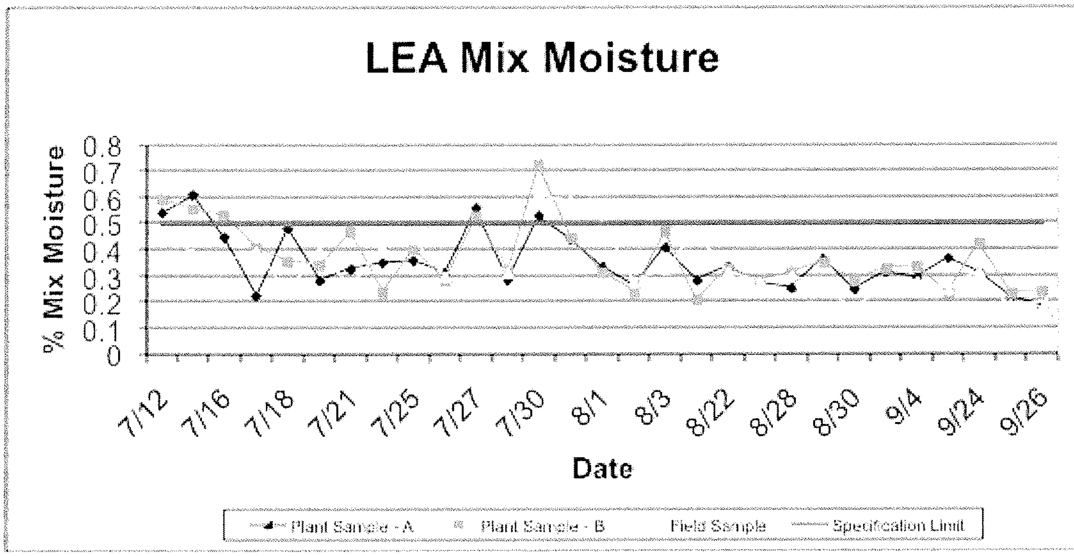

FIGURE 77 LEA Mix Moisture Contents (*70*)

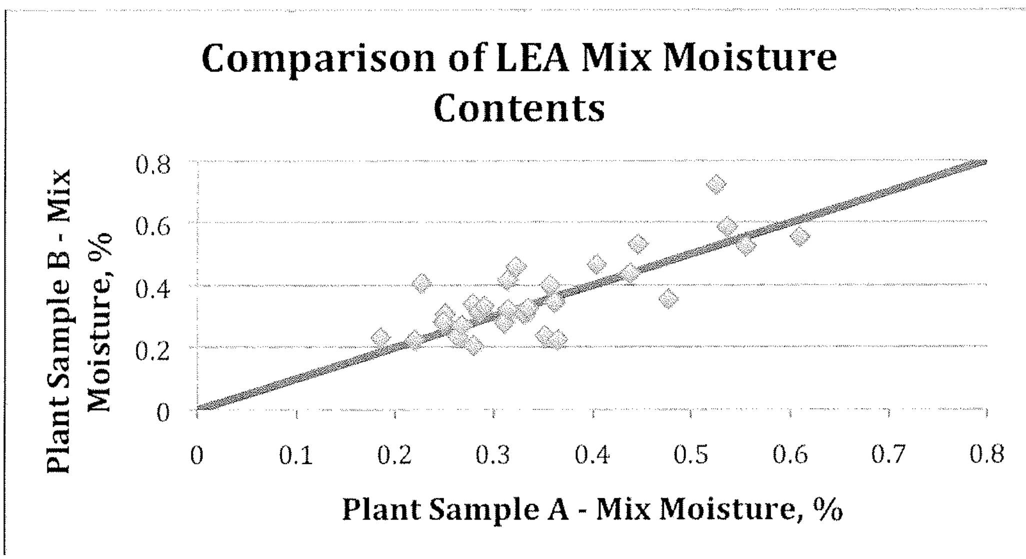

FIGURE 78 Comparison of Measured Moisture Content by Two Methods (*70*)

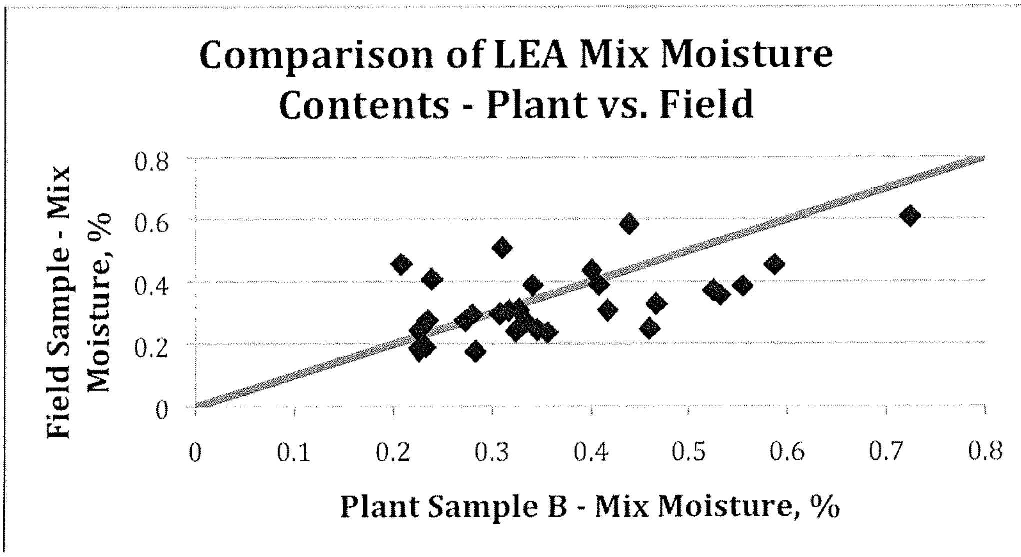

FIGURE 79 Comparison of Plant and Field Moisture Contents (*70*)

The asphalt content of the moisture content samples was determined according to AASHTO T 329. The corrected asphalt contents from both methods of drying were higher than expected. The author proposed that steam in the drum combined with additional aggregate breakdown from not having fines during drying results in a higher portion of very fine dust which would normally be collected in the baghouse. It is believed that this dust is released during the ignition furnace testing.

For the 2007 LEA production, the pugmill discharge temperature ranged from 185 to 228°F (85 to 109°C) with a target of 212°F (100°C). A total of 34,210 tons of LEA were produced in 2007 using natural gas as fuel.

Baghouse temperatures were monitored throughout the 2007 season (TABLE 42). If the baghouse temperature drops below 212°F (100°C), condensation can occur. [Plant manufacturers recommend baghouse temperatures greater than 220°F (104°C) for low sulfur fuels and greater than 240°F (116°C) for high sulfur fuels.] The baghouse temperatures remained high enough to prevent caking or blinding of the bags. This may not be indicative of the baghouse temperatures of other technologies operating in a similar temperature range since the coarse aggregate in the LEA process is heated to a higher temperature. The slat conveyor and pugmill amperages were monitored. The data indicated the amperages for HMA and LEA were the same when the same binder grade was used.

TABLE 42 Comparison of Baghouse Temperatures (*70*)

Mix Type	Baghouse Temperatures,°F	
	Inlet	Outlet
LEA	295 – 335	225 – 275
HMA	345 - 385	260 - 305

Reducing Paving Emissions Using Warm Mix Technology (Davidson and Pedlow) (71)

Two adjoining roads were paved in the City of London, Ontario, Canada, one with conventional HMA and one with WMA. Each road received two lifts of an HL8 binder course with 15 percent RAP on a prepared granular base followed by an HL3 surface course, also containing 15 percent RAP. The WMA was produced using Evotherm™ emulsion. HL8 and HL3 are approximately 19.0 and 12.5 mm nominal maximum aggregate size (Superpave definition) mixes, respectively. Both were Marshall mixes produced according to Ontario's Provisional Standard Specifications.

In the laboratory, the HMA was mixed at 302°F (150°C) and compacted at 280°F (138°C). By comparison, the WMA was mixed at 275°F (135°C) and compacted at 212°F (100°C). The mix was produced in a 200 tonnes per hour batch plant with a dry dust collection system (baghouse). For the HL8 mix, the burner temperatures were 450 and 379°F (232 and 193°C), respectively, for the HMA and WMA. For the HL3 WMA mix, the burner temperature was increased to 396°F (202°C) due to its higher asphalt content. The HMA reportedly left the plant at 302°F (150°C) and the WMA at 212°F (100°C). Compaction temperatures were reportedly 194 to 203°F (90 to 95°C) for the WMA (HMA were not reported). Haul distance reported to be 20 km (25 minutes) and paving occurred in July.

Hand work was reported to be more difficult due to the cooler mix temperatures. The paver reportedly had to work harder, but the WMA had good texture behind the screed. The same roller pattern was used for both the HMA and WMA. The rolling train consisted of a 12 ton double-drum vibratory roller, 20 ton pneumatic roller and one ton static steel-wheel finish roller. Roller passes were not reported.

Samples of both the HMA and WMA mixes were taken during production. Of interest is the recovered binder data, presented in TABLE 43. Asphalt binder was recovered using the Abson method. For the HMA, the high temperature RTFO DSR indicates the stiffening effect of the RAP. For the WMA, the reduced aging resulting from reduced production temperatures offset the stiffening effect of the RAP. This was also evidenced by the retained penetration values, an average of 41 percent for the HMA and 65 percent for the WMA. Neither the inclusion of the RAP or the use of warm mix greatly altered the low temperature properties over those of the base binders.

TABLE 43 Recovered Binder Data (*71*)

Sample	PG 58-28	HMA HL8	HMA HL3	Base Binder for Emulsion	Emulsion Residue	WMA HL8	WMA HL3
Tests on Original Binder							
Rotational Viscosity, Pa·s,135°C 165°C	0.300 0.088	NA	NA	0.321 0.109	0.325 0.155	NA	NA
DSR, G*/sinδ, kPa, 58°C 64°C	1.25 0.57	NA	NA	1.27 0.58	1.28 0.59	NA	NA
RTFO Residue (AASHTO T240)							
Mass Change, %	0.62	NA	NA	0.25	0.37		
DSR, G*/sinδ, kPa, 58°C 64°C 70°C	3.22 1.44	4.00 1.77	 2.81 1.30	3.03 1.34	2.58 1.15	3.05 1.38	2.45 1.10
PAV Residue (AASHTO R18)°C	100	100	100	100	100	100	100
DSR, G*sinδ, kPa, 19°C 16°C	3982 6142	4758 6938	4604 6601	3333 5107	3433 5347	4577 6647	4541 6776
Bending Beam Rheometer (BBR) Creep Stiffness, MPa, -12°C -18°C -24°C	 104.0 225.5 476.0	 99.4 210.5 456.0	 139.0 247.0 487.0	 89.0 195.0 439.0	 73.3 179.0 469.0	 99.1 227.0 446.0	 102.0 218.0 467.0
m-value, -12°C -18°C -24°C	0.371 0.316 0.255	0.356 0.315 0.262	0.322 0.292 0.244	0.364 0.318 0.269	0.385 0.333 0.268	0.364 0.314 0.258	0.371 0.315 0.231
Continuous grade (BBR Basis)	59.7 -29.3	62.4 -29.7	65.9 -27.0	59.8 -30.2	59.2 -31.2	60.5 -29.5	58.8 -29.1
Continuous grade (Direct Tension)	59.7 -28.7	62.4 -28.5	65.9 -28.1	59.8 -29.1	59.2 -27.6	60.5 -28.4	58.8 -29.1
Penetration, 25°C, 100g, 5 sec.	116	49	45	121	118	77	81

Ohio Field Trial of Warm Mix Asphalt Technologies: Construction Summary, (Hurley et al.) (35)

A WMA demonstration was conducted in Ohio on State Route 541 (SR 541).

Compaction and plant discharge temperatures for each of the test section are presented in

FIGURE 80, indicating WMA compaction temperatures ranged from approximately 230 to 261°F (110 to 127°C). The haul distance for the mix was approximately 25 minutes from the plant to the paving site. There was some sticking of all of the WMAs to the truck beds and hopper. The handwork appeared to be more difficult with the WMAs.

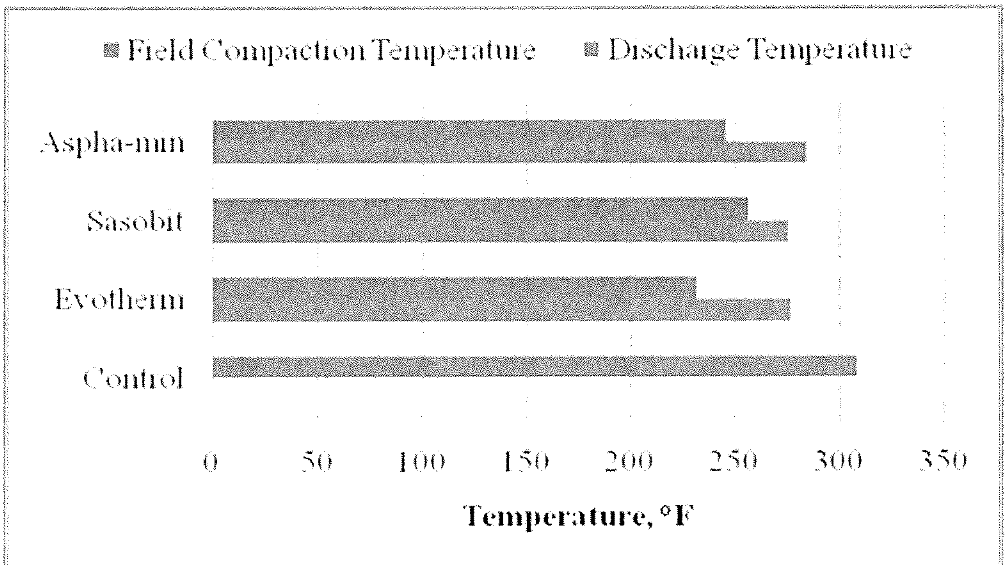

FIGURE 80 Average Compaction Temperature (*35*)

The in-place densities were monitored over time by Ohio University. FIGURE 81 illustrates the average air voids of cores obtained by Ohio University. After 18 months the sections are exhibiting similar air voids. Ohio University also evaluated the condition of the pavement and noted that there is some raveling in all of the WMA sections.

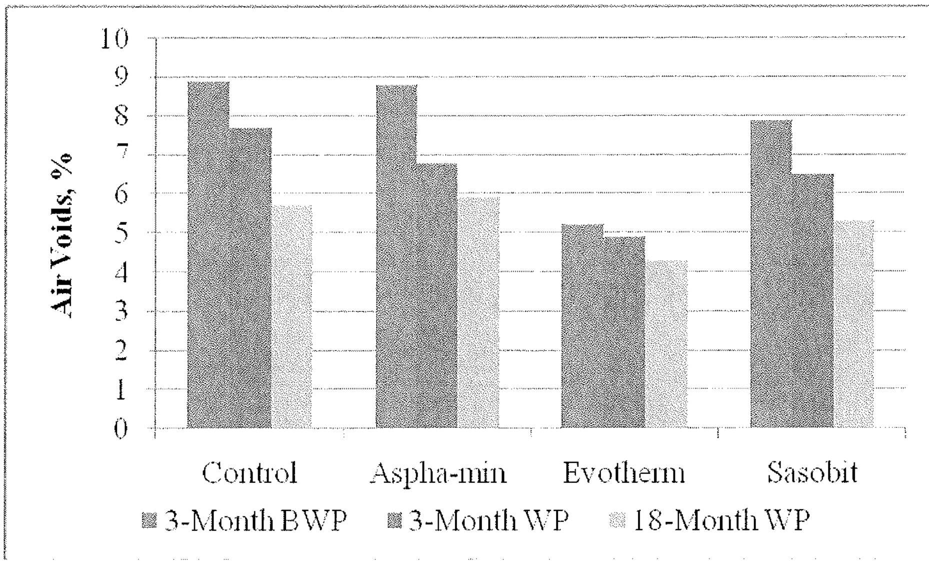

FIGURE 81 In-Place Air Voids with Time (*35*)

Michigan Field Trial of Warm Mix Asphalt Technologies: Construction Summary, (Hurley et al.) (23)

Sasobit® was evaluated as part of a WMA demonstration in Michigan on M95 as mentioned in the laboratory performance literature review.

The condition of the pavement was assessed after two years of trafficking. Visual inspections were conducted to evaluate cracking, and no cracking was observed. String line measurements were taken to determine the extent of rutting. Rutting was non-existent to minimal. Cores were obtained from both the WMA and HMA sections. FIGURE 82 illustrates the change in air voids from the time of construction through two years of trafficking. FIGURE 83 illustrates the average indirect tensile strengths of the field cores.

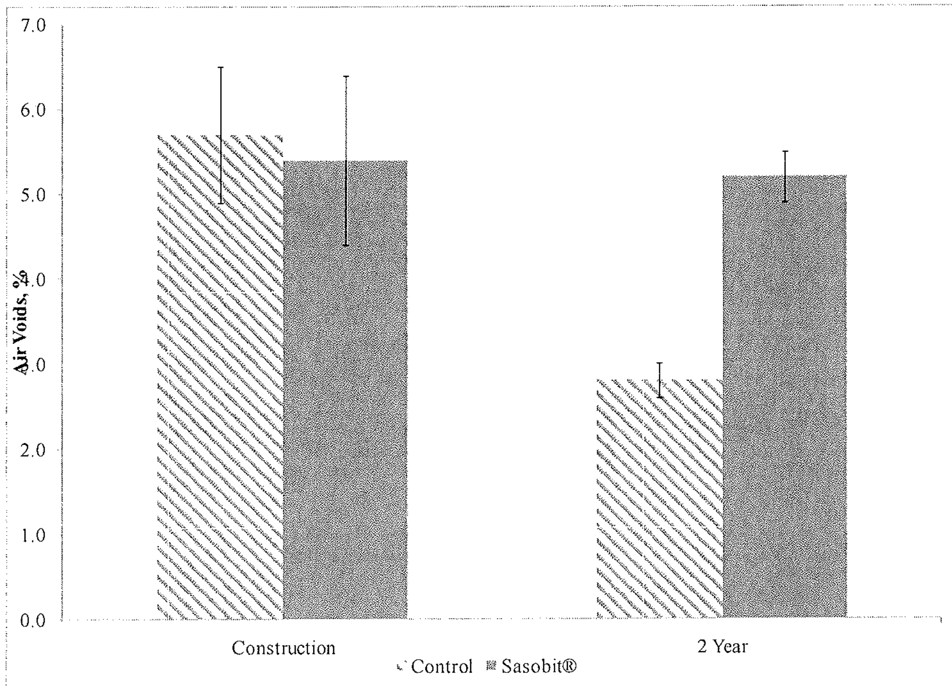

FIGURE 82 In-place Air Voids Through Two Years of Traffic (*23*)

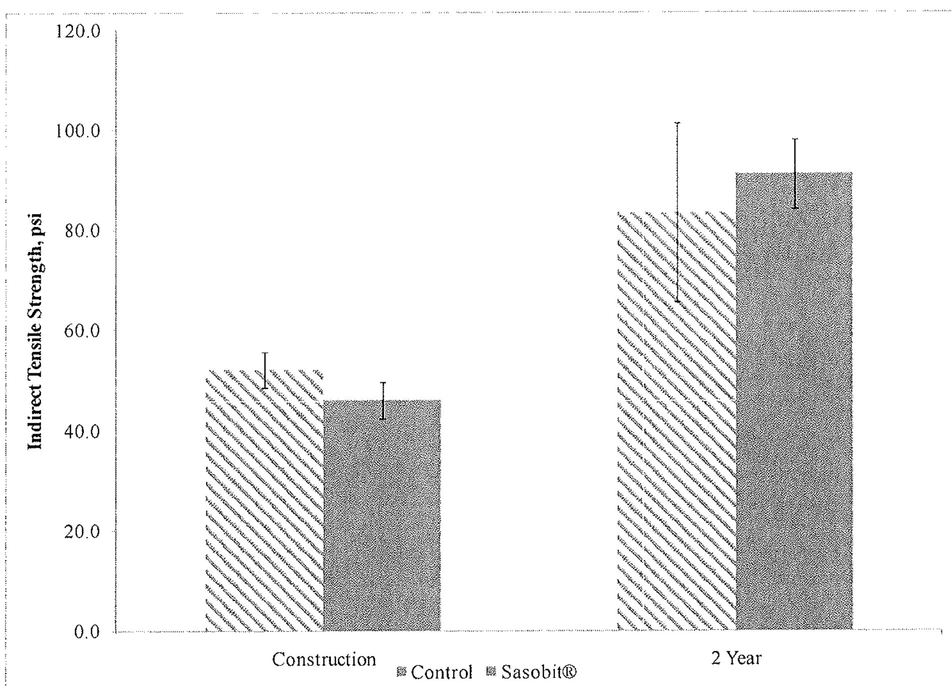

FIGURE 83 Indirect Tensile Strength Results Through Two Years of Traffic (*23*)

Missouri Field Trial of Warm Mix Asphalt Technologies: Construction Summary, (Hurley et al.) (37)

A WMA demonstration was conducted in St Louis, Milwaukee on Hall Street in May 2006. The demonstration evaluated three WMA technologies; Evotherm™ ET, Sasobit®, and Aspha-min®. A control HMA section was also constructed. The mix design used for all four mixes was a 12.5 mm NMAS surface Superpave mix that contained 10 percent RAP. The base binder was a polymer PG 70-22. An anti-stripping agent, ARR MAZ Ad-here HP Plus, was added to the virgin binder.

Construction occurred at night over a ten day period. The control mix was produced at 320°F (160°C) and compacted at around 300°F (149°C). The WMA target compaction temperatures ranged between 200 and 250°F (93 and 121°C). The mixes were hauled approximately 25 minutes from the plant to the paving site. Paving and compacting operations were the same for all four mixes.

The performance of the sections was monitored through two years of trafficking. String line rut measurements were obtained to quantify the extent of rutting. The average rutting ranged from 0.5 to 1.1mm. Small reflective cracks were observed in the sections. Field cores were obtained and the air void content and ITS of each core was determined. FIGURE 84 illustrates the average air void content of the cores. The average air void content after two years was similar for the Aspha-min®, control, Evotherm™ ET, and Sasobit® mixes. FIGURE 85 depicts the average ITS values of the field cores. Overall, the WMA had lower ITS values at the time of construction compared to the control mix, but gained strength within the first two years to be comparable to the control mix. The ITS for two technologies, Aspha-min® and Evotherm™ ET, decreased between 6-months and two-years. This could be testing variability or an indication of the beginning of moisture damage.

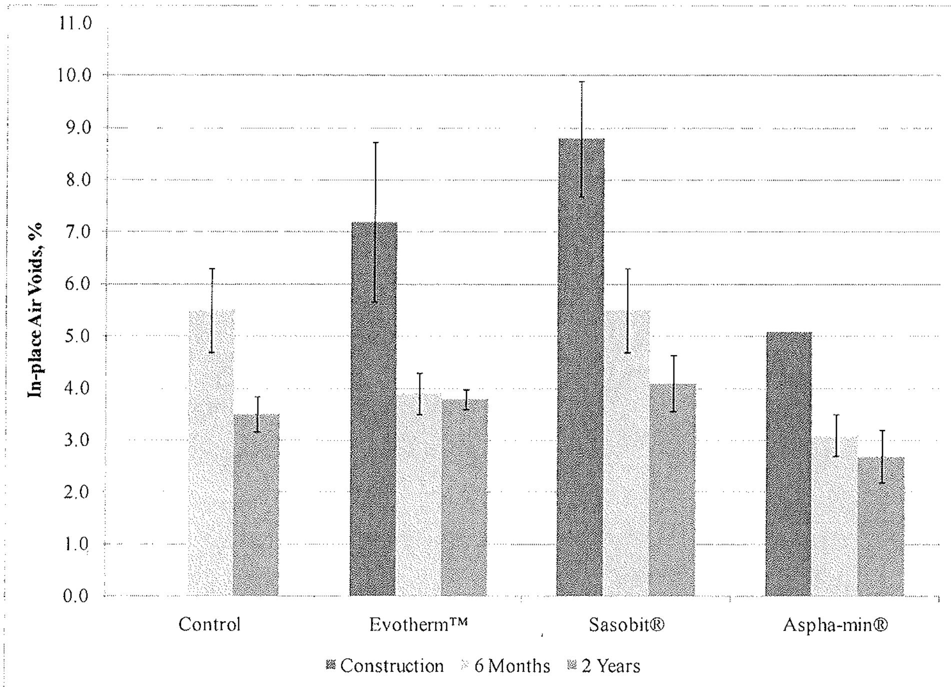

FIGURE 84 In-place Air Void Results, Construction Through Two Years (*37*)

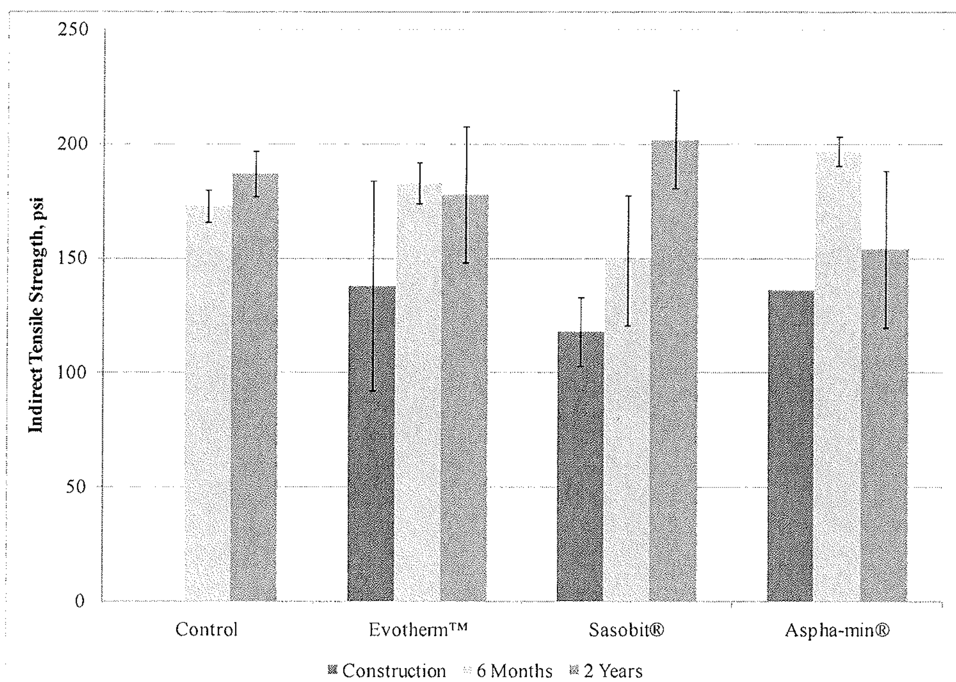

FIGURE 85 Indirect Tensile Strength Results, Construction Through Two years (*37*)

Preliminary Evaluation of Warm mix Asphalt Field Demonstration: Franklin, Tennessee (Kvasnak et al.) (38)

In October 2007, a WMA demonstration was conducted in Franklin, Tennessee on SR 46. Four WMA technologies were evaluated. The four WMA technologies were Astec DBG, Evotherm™ DAT, Sasobit®, and Advera® WMA. Three plants were used to produce the WMA mixes, and so three Marshall mix designs were used. All three of the designs were 12.5 mm nominal maximum aggregate size 75 blow Marshall mixes. An SBS modified PG 70-22 asphalt used in all of the mixes.

The Astec DBG was produced at 260°F (126°C). The Advera® WMA and Sasobit® were produced at 250°F (121°C). The Evotherm™ DAT was produced at 239°F (115°C). There were equipment issues on the job that were not related to the mix that slowed down paving (i.e. rollers breaking down). There were no observed issues with paving any of the sections. Field cores were obtained from the WMA sections. FIGURE 86 illustrates the density results of the field cores. The first set of field cores obtained for all of the WMA sections failed to meet the density requirements. A second set of field cores were obtained for each section and those average densities did meet the field density requirements.

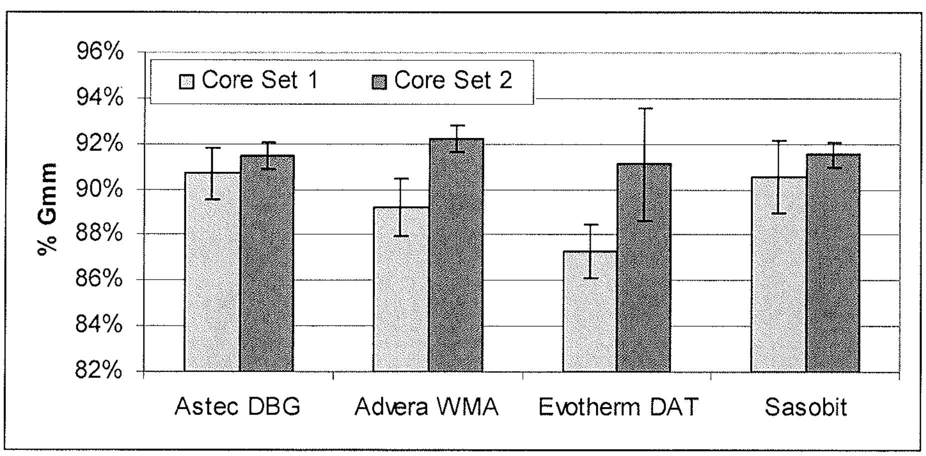

FIGURE 86 Field Densities After Construction (*38*)

The condition of the pavement was assessed after one year of trafficking. There were some spots in the control and Advera® WMA sections where asphalt was pooling on the surface of the pavement. The pools were about a half-dollar size. There was some raveling exhibited in all of the sections. Cores were obtained from each section. FIGURE 87 and FIGURE 88 illustrate the densities and ITS for each section. WP stands for cores taken from in the wheelpath while BW stands for cores taken from between the wheelpaths. From these figures, it can be seen that the core densities have a substantial impact on the tensile strengths.

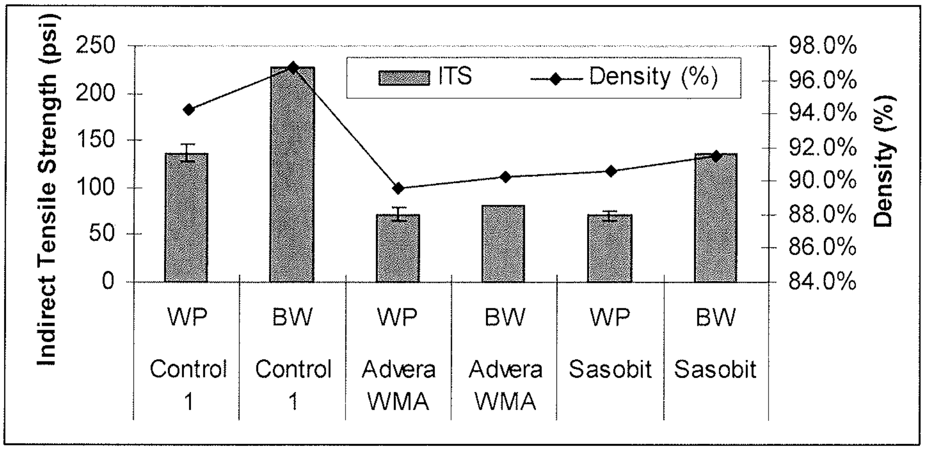

FIGURE 87 Indirect Tensile Strength of Cores for Franklin Plant Mixes (*38*)

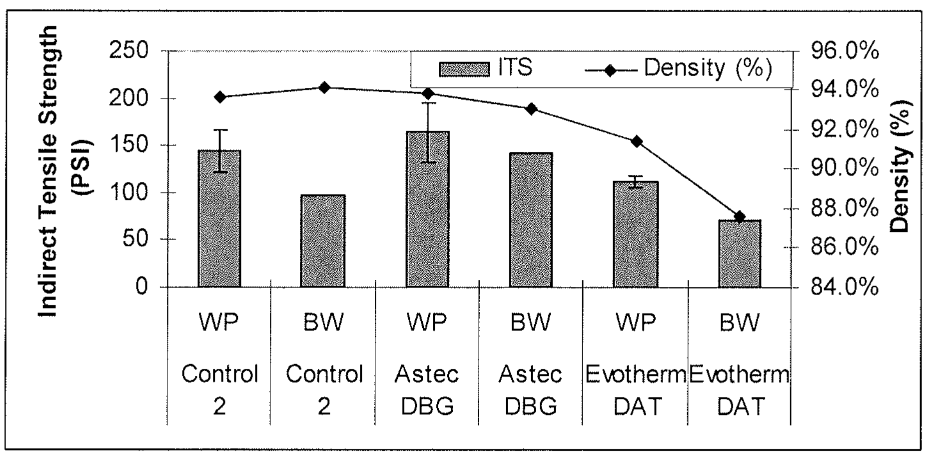

FIGURE 88 Indirect Tensile Strength of Cores for Danley and Murfeesboro Plant Mixes (*38*)

I-90 West of George Paving - Warm Mix Asphalt (--) (*42*)

In June 2008, 10.6 miles of I-90 West near George, Washington were paved with Sasobit® WMA and HMA. The mixes placed were 12.5 mm Superpave mixes containing

20 percent RAP. The binder was a PG 76-28. The WMA binder was modified with 2.0 percent Sasobit® by weight of the binder. The compaction of the HMA and WMA were 93.6 and 93.7 percent G_{mm}, respectively. The fuel usage of the HMA and WMA were 1.4 and 1.07 gal/ton, respectively. The authors attributed the fuel savings to the reduced mixing temperatures for the WMA.

Preliminary Results from the California Warm-Mix Asphalt Study (Jones) (43)

The Phase 1 test sections were located at a quarry and commercial asphalt plant near Aromas, California. Each sections included two 2.4 in. (60 mm) lifts of asphalt concrete. A standard Hveem mix design was used and no adjustments were made to accommodate the WMA additives. Target production temperature for the Control mix was set at 310°F (155°C) and 250°F (120°C) for the WMAs. The test sections were constructed in September 2007, using a drum plant at the quarry. TABLE 44 summarizes the quality control data for the mixes.

TABLE 44 Quality Control of Mix after Production

Parameter	Target	Range	Control	Advera	Evotherm	Sasobit
AC Binder Content (%)[1]	5.2	5.1 - 5.4	5.29	5.14	5.23	4.48
Moisture (before plant) (%)	-	-	0.24	0.41	0.37	0.31
Moisture (after silo) (%)	<1.0	-	0.09	0.25	0.32	0.25
[1] AASHTO T-308						

The moisture contents of all four aggregate runs prior to entering the drum were lower than the Caltrans end-of-drum moisture content specification of 1.0 percent *(47)*.

Modifications to the asphalt plant to accommodate the warm-mix additives were overseen by the warm-mix technology providers. The Advera® and Evotherm™ were added to the mix through pipes placed immediately below and above the asphalt binder supply line respectively, while the Sasobit® was blended with the asphalt binder in a tank prior to mix production. The following observations from the mix production were made *(44)*:

- No problems were noted with producing the asphalt mixes at the lower temperatures. The target mix production temperatures (i.e., 310°F and 250°F [155°C and 120°C]) were achieved.

- The aggregate gradations of the four mixes were similar, generally met the targets, and were within the required ranges.
- Although a PG 64-16 asphalt binder was specified in the work plan, subsequent tests by the Federal Highway Administration indicated that the binder graded as PG 64-22. After blending, the Sasobit® binder graded as a PG 70-22.
- The binder contents of the Control and Advera® and Evotherm™ mixes were similar and all close to the target. The binder content of the Sasobit® mix was 0.72 percent below the target and 0.62 percent below the lowest permissible content. This discrepancy was considered likely to influence behavior of the mix. The problem was attributed to a binder feed rate problem from the tanker during mix production.
- Moisture contents of the mix samples collected at the silos showed a more interesting trend. The moisture content of the Control mix was just 0.09 percent, considerably lower than those of the mixes with additives, which had moisture contents of 0.25 percent (Advera® and Sasobit® mixes) and 0.32 percent (Evotherm). Although moisture contents in all mixes were well below the minimum specified limit, the higher moisture contents of the WMA mixes indicates that less moisture evaporates from the aggregate at the lower production temperatures.

The test sections were constructed using conventional equipment and followed conventional procedures. Some haze/smoke was evident on the Control mix during transfer of the mix from the truck to the paver. No haze or smoke was observed on the mixes with additives. Construction procedures and final pavement quality did not appear to be influenced by the lower construction temperatures. The Advera® mix showed no evidence of tenderness, and acceptable compaction was achieved. Some tenderness was noted on the Evotherm™ DAT and Sasobit® mix sections resulting in shearing under the rollers at various stages of breakdown and/or rubber-tired rolling, indicating that the compaction temperatures were still higher than optimal. No problems were observed after final rolling at lower temperatures. Tenderness on the Evotherm™ and Sasobit® mix sections was not considered as being significantly different from that experienced with conventional mixes during normal construction activities.

Average air-void contents on the Control and Advera® mix sections were 5.6 percent and 5.4 percent respectively. Air void contents for the Evotherm™ and Sasobit® mix sections, which both showed signs of tenderness during rolling, were approximately 7.0 percent, with the caveat that the Sasobit® mix binder content was lower than the target while that for the Evotherm™ mix section was not. Based on these observations, it was concluded that adequate compaction could be achieved on warm-mixes at the lower temperatures. Optimal compaction temperatures are likely to differ between the different WMA technologies.

Heavy Vehicle Simulator (HVS) test section layout, test setup, trafficking, and measurements followed standard UCPRC protocols for the first and second phases of testing. An average maximum rut of 0.5 in. (12.5 mm) over the full monitored HVS test section was set as the failure criteria for the experiments.

The pavement temperature at 2.0 in. (50 mm) was maintained at 122±7°F (50±4°C) in both phases to assess rutting potential under typical pavement conditions. Infrared heaters inside a temperature control chamber were used to maintain the pavement temperature. The pavement surface received no direct rainfall as it was protected by the temperature control chamber.

During Phase 1, the sections were tested predominantly during the wet season (October through March); however, it is unlikely that any water entered the pavement structure due to the confinement on both sides of the test sections. During Phase 2, each section was presoaked with water for a period of 14 days prior to testing. A 6 in. (150 mm) high dam was constructed around each test section and a row of 1.0 in. (25 mm) diameter holes was drilled to the bottom of the upper lift of asphalt away from the section and 10 in. apart. During testing, a constant flow of preheated water (122°F [50°C]) was maintained across the section at a rate of 15 L/hour to try to induce moisture damage.

The HVS loading program for each section is summarized in TABLE 45. All trafficking was carried out with a dual-wheel configuration, using radial truck tires (11R22.5- steel belt radial) inflated to a pressure of 720 kPa (104 psi), in a channelized, unidirectional loading mode. Load was checked with a portable weigh-in-motion pad at the beginning of each test and after each load change.

TABLE 45 Summary of HVS Loading Program

Phase	Section	Wheel Load[1] (kN)	Repetitions	ESALs[2]
1	Control	40	185,000	239,900
		60	10,000	
	Advera	40	170,000	170,000
	Evotherm	40	185,000	185,000
	Sasobit[3]	40	185,000	734,014
		60	100,000	
		Sub-Total	**835,000**	**1,328,914**
2	Control	40	185,000	185,000
		60	80,000	439,200
		90	106,000	3,195,000
	Advera[3]	40	157,000	157,000
		60	32,000	175,700
		90	431,500	13,006,100
	Evotherm	40	166,000	166,000
		60	118,000	647,800
		90	68,000	2,049,600
	Sasobit[3]	40	152,000	152,000
		60	137,000	752,000
		90	175,500	5,289,900
		Sub-Total	**1,807,500**	**26,200,400**

[1] 40 kN = 9,000 lb. 60 kN = 13,500 lb
[2] ESAL: Equivalent Standard Axle Load
[3] Testing terminated before failure criteria was reached

Rutting was measured with a laser profilometer and pavement temperatures were monitored using thermocouples imbedded in the pavement. A dedicated nearby weather station monitored ambient temperature, rainfall, relative humidity, wind speed and direction, and solar radiation. The duration of the tests on the four sections varied from 170,000 load repetitions (Evotherm) to 285,000 load repetitions (Sasobit®). A range of daily average temperatures was therefore experienced; however, the pavement temperatures remained constant throughout HVS trafficking.

Rutting behavior (average maximum rut and average deformation) for the four sections was compared and is shown in FIGURE 89 and FIGURE 90. The duration of the embedment phases on Section B (Advera®) and Section C (Evotherm) were similar to that of the Control; however, the depth of the ruts at the end of the embedment phases on these two sections was slightly higher than the Control. In both instances, this was attributed to less oxidation of the binder during mix production because of the lower plant temperatures and is unlikely to relate to early rutting on in-service pavements with typical highway traffic volumes. Additional binder testing to study effects of the additives on binder properties was beyond the scope of this phase of the study. The slightly greater moisture contents of these mixes may also have had an influence. Rutting behavior on the WMA sections followed trends similar to that of the Control in terms of rut rate (rutting per load repetition) after the embedment phase.

Although the Sasobit® performance cannot be directly compared against the Control due to the lower asphalt content of the Sasobit section, it was concluded that the three WMA additives tested in this experiment will not significantly influence the rutting performance of the mix.

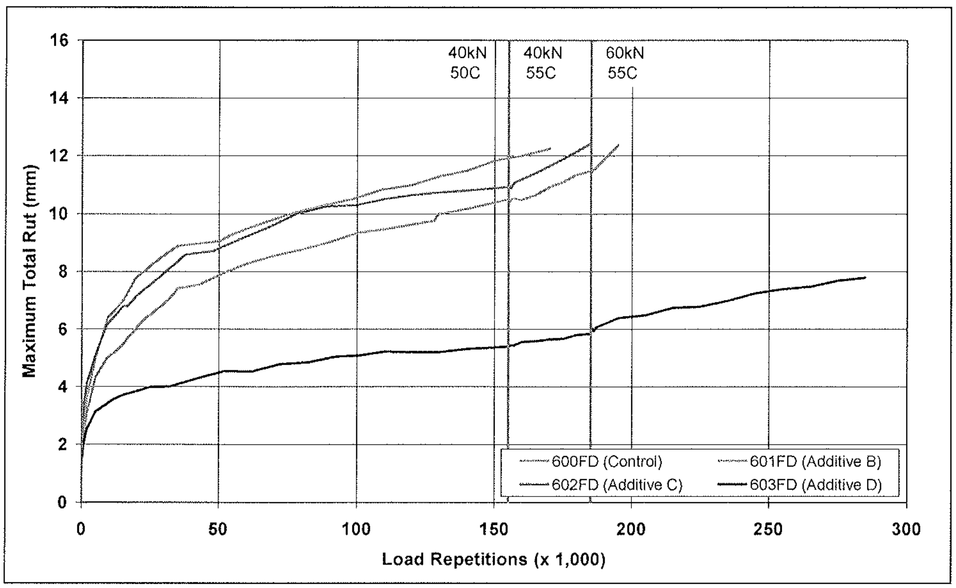

FIGURE 89 Compariosn of Average Maximum Rut for Phase 1 HVS Testing

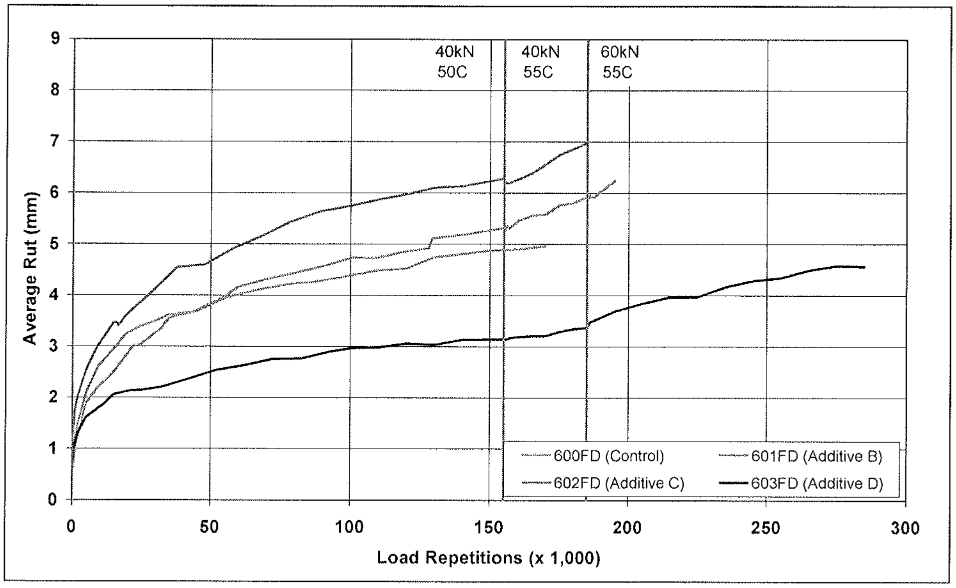

FIGURE 90 Comparison of Average Deformation for Phase 1 HVS Testing

The Phase 2 testing on the four sections was started in the summer of 2008 and ended in the spring of 2009. The duration of the tests on the four sections varied from 352,000 load repetitions (Evotherm) to 620,000 load repetitions (Advera®).

Deformations (average maximum rut) for the four sections measured in Phase 2 are compared in FIGURE 91. The duration of the embedment phases on the warm-mix asphalt sections were shorter than the control, opposite to the behavior in the first phase. Binder extractions and testing is currently underway to better understand this observation. Embedment phases were noted at each load change on all sections. There was a distinct difference in performance of the Advera® and Sasobit® sections compared to the Control and Evotherm™ sections, in that the latter two sections rutted at a notably faster rate than the former two sections. The Control and Evotherm™ sections were shaded by an adjacent shed for much of the day, while the Advera® and Sasobit® sections had sun for most of the day. Binder testing will is underway to determine if different aging played a role in this behavior. Trafficking was terminated on the Advera® and Sasobit® sections before the failure criterion was met in the interests of completing the study. None of the sections showed any indication of moisture damage on completion of testing.

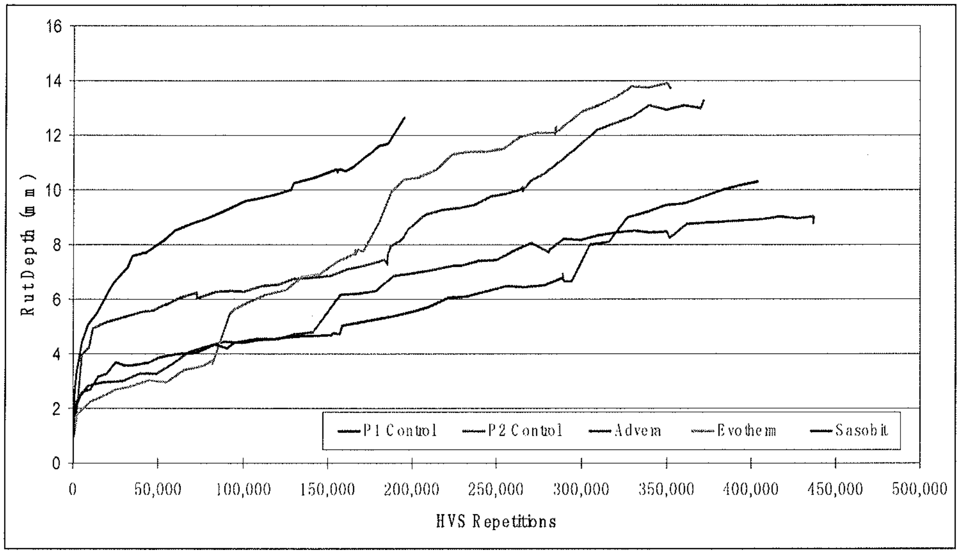

FIGURE 91 Comparison of Average Maximum Rut for Phase 2 HVS Testing

Top-down cracking was observed in all four sections, with no significant difference in the crack patterns, crack length, or crack density between the sections. Cracks did not appear to penetrate below the top lift of asphalt on any of the sections.

A forensic investigation, consisting of core and test pit assessments provided no indication of moisture damage in any of the sections. Rutting on all four sections was confined to the top lift of asphalt only. Debonding of the top and bottom lifts of asphalt was observed on the Control section only. Determining the reason for this was beyond the scope of this phase of the study, but may be investigated at a later stage. A tack coat was used between lifts.

Although the lower asphalt content of the Sasobit® section confounded its comparison to the control HMA, this phase of testing further reinforced findings from the first phase that the three warm-mix asphalt additives do not negatively influence the rutting performance of the mix. The results also indicate that the three warm-mix additives did not increase the moisture sensitivity of the mixes compared to the Control. Binder aging of the warm and hot mixes and its effect on performance over time deserves further investigation.

Summary of Field Performance

The construction and field performance of several WMA pavements has been documented and compared to HMA pavements. The construction conclusions have indicated that with the exception of plant modifications for introducing a WMA technology the production and placement equipment for WMA is the same as those used for HMA. Several reports on construction did indicate that the rate of production was reduced when a WMA technology was produced. It was also emphasized in some of the reports from contractors that the flighting in a drum plant was adjusted to increase the aggregate dwell time in the drum.

Most studies reported that WMA was placed without any issues. In a few cases there were issues with material sticking to truck beds and compaction. Comparisons of in place WMA to HMA have indicated that despite concerns about moisture damage and rutting, the WMA pavements are performing similar to that of the HMA. Field cores of WMA pavements at the time of construction through two years indicate that WMA pavements rapidly increase in tensile strength and often result in similar ITS values to that of HMA after two years. The results of the literature review suggest that WMA is performing at least as well as the HMA.

EMISSIONS AND ENVIRONMENTAL ASSESSMENT

This section provides a literature review of fuel usage, stack emissions, and industrial hygiene tests conducted on WMA field projects. Techniques for industrial hygiene measurements which may provide better discrimination between WMA and HMA, as well as between warm mix asphalt technologies, are presented. Comparisons between U.S. and international industrial hygiene test results are also included. Background information on life-cycle assessments are provided together with limited cost estimates for warm mix technologies.

Fuel Usage and Stack Emissions

Unpublished Data from Heritage Research on Evotherm™ Trial in Boone County, Indiana

The project location was county road 900 E just south of SR-32 in Boone County, Indiana (North of Indianapolis). The average daily traffic (ADT) for the project was 1000 vehicles. ADT is used by the county to determine the type and strength of asphalt to be used for projects. A conventional Superpave 12.5 mm HMA and a Superpave 12.5 mm Evotherm™ mix were placed on the project for comparison.

Milestone Contractors L.P. in Whitestown, IN produced the Evotherm™ warm mix using an H & B drum aggregate drier followed by a Gen-Tech mini drum for mixing the aggregate and asphalt. The silos were Gencor Industries, Inc. products. The plant is rated at 400 tons / hour. The plant ran approximately 600 tons in three and a half hours. There were no problems operating the aggregate drier drum at temperatures of 300°F (149°C). Normal drum operating temperatures are 400°F (204°C) when RAP is added. The WMA mix temperatures at the discharge chute from the drum were between 200 and 212°F (93 and 100°C). The typical target for hot mix is 300°F (149°C) at the chute. Low temperatures in the baghouse was a concern due to the possibility of blinding of the bags. Baghouse temperatures of 200°F (93°C) were observed. Condensation of moisture in the bag house can cause bags to clog or "blind" and therefore not function properly. The bag house temperature was monitored throughout production and checked for "blinding" at the end of production. No evidence of filter clogging was observed after the 600 tons of WMA were produced.

Industrial hygiene tests were conducted for worker exposure to fumes at the roadway. Air samples during placement of the Evotherm™ WMA had a higher total particulate matter (TPM) than the HMA TPM. However, TPM is affected by the surroundings at the job site. Dust and other foreign matter can cause elevated results. The Benzene soluble matter (BSM) is a better indicator of the worker fume exposure. Air samples during placement of the Evotherm™ had results that were BDL while the HMA had a trace amount. The total organic matter (TOM) was also lower during construction of the Evotherm™ mix. Lower HMA placement temperatures have been determined to lower worker exposure to asphalt fume.

Evotherm™

- TPM = 0.76 mg/m^3
- BSM = BDL
- TOM = .988 mg/ m^3

HMA

- TPM = 0.25 mg/ m^3
- BSM = 0.10 mg/ m^3
- TOM = 1.69 mg/ m^3

Evotherm™ warm mix was produced for the project without significant production or placement issues. Longer runs will be necessary to determine if conventional hot mix plants can produce Evotherm™ without bag house clogging. Longer runs will also be necessary to estimate energy savings for Evotherm™ compared to HMA.

Worker exposure to fumes was low in both the HMA and Evotherm™ mixtures. However, the TOM exposure, which is a good measure of total exposure to organics in the work place, was significantly lower (42% lower) with the Evotherm™ WMA.

Evotherm™ Trial – Ramara Township, (Davidson) (57)

A WMA field trial using Evotherm™ emulsion was conducted in October of 2005. Approximately 1,100 tons of Evotherm™ were placed along a two-mile section of Road #46 in the Township of Ramara, Ontario Canada. A control HMA section was also placed so comparisons could be made.

The mixtures were produced in a 2-ton batch plant with a baghouse. A dry mixing cycle of 5 seconds followed by a wet mixing cycle of 28 seconds was reported for the HMA control. The author notes that the Evotherm™ did not cause any problems with the plant mixing process. The production rate for the Evotherm™ WMA was 125 tonnes per hour. The plant operator noted the emulsion took longer to weigh-up due to the volume of emulsion required and that the batch size needed to be reduced due to the capacity of the asphalt binder weigh hopper. Since the emulsion residue was approximately 69 percent asphalt binder, the total quantity of liquid (emulsion) required was increased by 46 percent. The HMA control was mixed at approximately 150°C while the WMA was mixed at between 125 and 130°C. During construction, the control HMA was compacted at a temperature of 293°F (145°C), while the WMA, was compacted at a temperature of 199°F (93°C), representing a decrease of 94°F (52°C). Stack emissions testing was conducted in conjunction with the Ramara Township Evotherm® field trial. Testing was conducted according to U.S. EPA 40 CFR 60 Appendix A. The results comparing the HMA and WMA production are summarized in TABLE 46.

TABLE 46 Combustion Gas Sampling Results (*57*)

Combustion Gas	Concentration		Percent Reduction
	HMA	*WMA*	
Oxygen	14.6 %	17.5 %	
CO_2	4.8 %	2.6 %	45.8
CO	70.2 %	25.9 %	63.1
SO_2	17.2 ppm	10.1 ppm	41.2
NO_x	62.2 ppm	26.1 ppm	58.0
Emissions Corrected for Dilution at 0% Oxygen by NCHRP 9-47A team			
SO_2	57 ppmvd	62 ppmvd	-8.8
NO_x	206 ppmvd	160 ppmvd	22.2
Avg. Gas Temperature	162 °C	121 °C	

Warm Mix Asphalt: The International Technology Scanning Program Desk Scan, (Prowell) (72)

Prowell summarized the early European data on fuel usage, emissions, and fumes in preparation for the U. S. International Scan Tour on Warm Mix Asphalt. Koenders et al. (*3*) reported fuel savings of 24 to 38 percent on two WAM-Foam projects. The projects ranged in size from 130 to 590 tons. Koenders et al. did not report the type of fuel used or the method used to measure fuel consumption. The authors note that the moisture content of the aggregate can have a dramatic influence on fuel usage, increasing fuel consumption almost 10 percent for every one percent increase of moisture in the aggregates. Von Devivere et al. (*54*) reported a fuel savings of 30 percent with a 54 to 63°F (30 to 35°C) decrease in production temperatures when using Aspha-min® zeolite. If all of Germany's HMA, approximately 65 million tons per year, were produced as WMA, the annual production of CO_2 would be reduced by 400,000 tons.

One of the driving factors in the organization of the Bitumen Forum in Germany, was the exposure levels for Gussaphalt or mastic asphalt workers. The Bitumen Forum was a driving force in the initial development of WMA. The most significant reductions in worker exposure resulting from the use of WMA have occurred for mastic asphalt workers (FIGURE 92). Peak exposures for mastic workers were reported as 56.7 mg/m^3 of fumes and aerosols for mastic workers as compared to a maximum of 10.4 mg/m^3 for workers laying HMA. It should be noted that mastic asphalt is placed at much higher temperatures than HMA. The use of WMA has reduced mastic workers exposure to that of workers placing conventional HMA (*50*). A reduction in worker exposure of 90 percent was reported with a decrease of 63°F (35°C) at the paver during Aspha-min® trials (*54*).

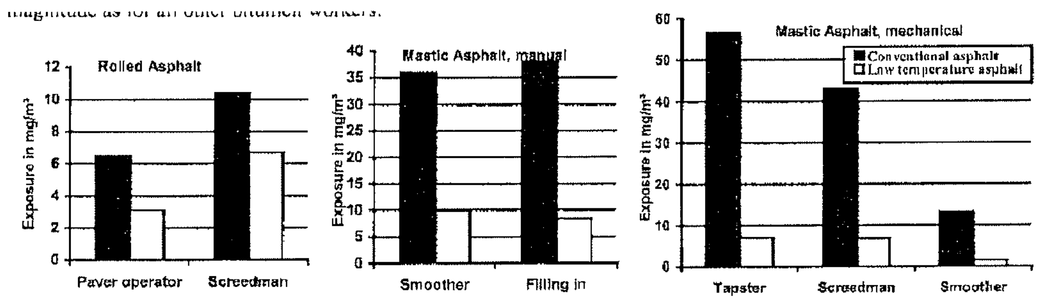

FIGURE 92 Comparison of Worker Exposure for Hot and Warm Mix Asphalt (*63*)

Warm-Mix Asphalt: European Practice (D'Angelo et al.) (64)

In 2007, a team of U.S. paving materials experts visited Belgium, France, Germany, and Norway to evaluate various WMA technologies through the Federal Highway Administration's International Technology Program. Since WMA was initially developed in Europe, the team travelled to Europe to assess what had been learned to date. Fuel savings, emissions and worker exposure were of interest, as well as performance.

Reports indicate typical burner fuel savings of 20 to 35 percent. Certain "half-warm" processes, which do not dry a portion of the aggregate, may produce savings of 50 percent or more. Asphalt plant stack emissions tests performed on projects in several countries are summarized in TABLE 47. Some of these results are reported on a project basis as part of this literature review.

TABLE 47 Observed Reductions in Plant Emissions (Percent) with WMA

Emission	Norway	Italy	Netherlands	France
CO_2	31.5	30-40	15-30	23
SO_2	NA	35	NA	18
VOC	NA	50	NA	19
CO	28.5	10-30	NA	NA
NO_x	61.5	60-70	NA	18[1]
Dust	54.0	25-55	NA	NA

[1]Reported as NO_2

French, German, and Italian worker exposure data were reported. Direct comparisons with U.S. data are difficult due to differences in sampling and testing procedures. All exposure data for HMA was below acceptable exposure limits. Tests for WMA fumes and polycyclic aromatic hydrocarbons (PAH) indicated significant reductions compared to HMA. German data indicated 30 to 50 percent reductions. Data for the Italian study is presented in (*73*), below. The French worker exposure data was not summarized in the report.

Emission and Occupational Exposure at Lower Asphalt Production and Laying Temperatures, (Lecomte et al.) (73)

In October 2006, an 870 ton trial section of WAM Foam WMA was constructed on the high-speed road Firenze-Pisa-Livorno near Florence, Italy by the contractor Conglobit. Conglobit refers to the WAM-Foam process as "Greenfalt." Both stack emissions and industrial hygiene tests were conducted as part of the construction.

The mixing temperatures were 356°F (180°C) for the conventional HMA and 248 to 257°F (120 to 125°C) for the WAM-Foam. The plant used natural gas fuel. Fuel consumption was measured at different levels of the plant's production capacity, ranging from 60 to 100 percent. The results indicated a 35 percent reduction in fuel savings.

Plant stack emissions were measured by Det Norske Veritas AS. The test protocols were not reported. It appears that one to three measurements each were taken from the HMA and WAM-Foam production. At a production rate of 140 tonnes per hour, the following reductions were observed:

- CO_2 – 35 percent
- CO – 8 percent
- NO_x – 60 percent

SO_2 and dust emissions were low for both the HMA and WAM-Foam production. The authors state reductions of 25 to 30 percent can be obtained. Asphalt fume measurements were made at six locations around the plant using closed-faced 37-mm cassettes equipped with a polytetrafluoroethylene (PTFE) filter, which are typically used for industrial hygiene studies. These non-standard measurements indicated that the benzene soluble fraction (BSF) was 200 times higher and the volatile fraction (VF) was six times higher for the HMA as compared to the WMA.

Five members of the paving crew were fitted with personal pumps used for fume sampling at a 2 liter/minute flow rate. Two static (area) samples were also taken to measure background fumes at the site. The fume was collected on 2 µm PTFE filters in a 37-mm cassette. Sampling and analysis of the collected fume were conducted according to National Institute for Occupational Safety and Health (NIOSH) 5042 NMAM (NIOSH Manual of Analytical Methods), with some minor changes [not described]. TABLE 48 presents the eight-hour time-weighted average values for mineral fraction (MF), BSF, and VF.

TABLE 48 Eight-Hour Time-Weighted Average WAM-Foam® Fume Measurements

Sampler	MF, mg/m^3	BSF, mg/m^3	VF, mg/m^3
Paver Driver	0.22	0.05	3.45
Screedman 1	0.19	0.08	2.40
Screedman 2	0.19	0.07	1.18
Raker	0.16	0.14	2.93
Roller Operator	0.13	0.03	0.79
Static 1	0.97	0.02	0.32
Static 2	0.14	0.01	0.23

The authors stated that based on previous exposure measurements conducted by Shell on HMA projects, the above measured fume values are in the lower range, commonly 0.05 to 0.60 mg/m^3 BSM. In 2003, Italy adopted the American Conference of Governmental Industrial Hygienist's recommendations for bitumen fume exposure (0.5 mg/m^3 BSF) into national legislation. PAHs were measured from the BSF fraction from the HMA samplers. The collected organic content of the WAM-Foam samples was too low for this analysis. The measured PAH concentrations, summed from both BSFs and VFs are shown in FIGURE 92.

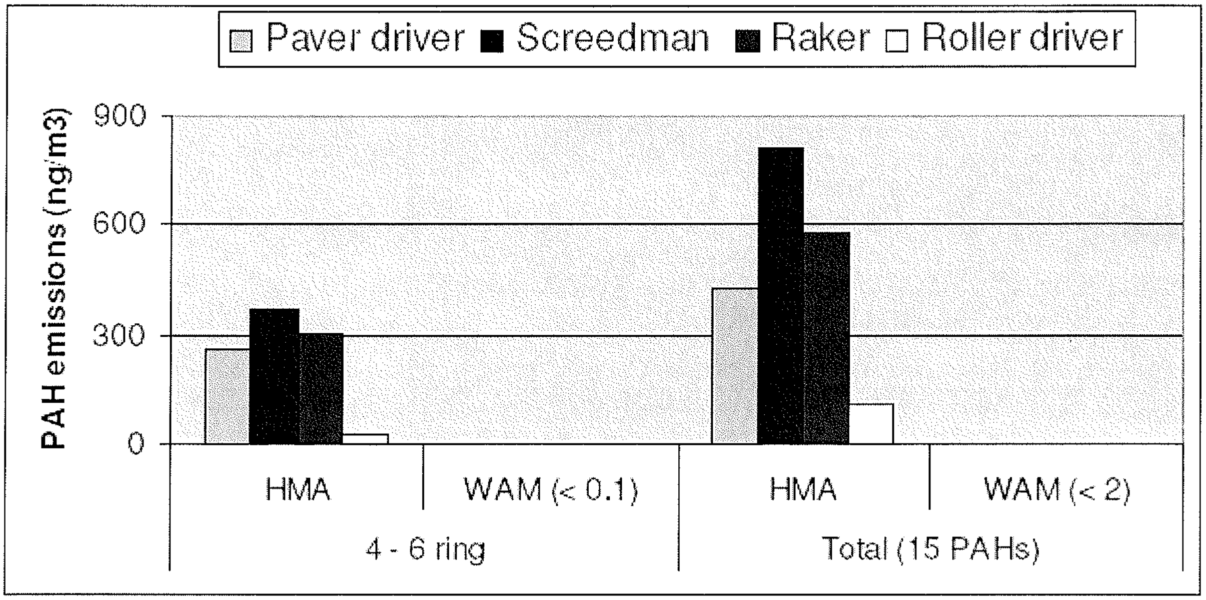

FIGURE 93 PAH Concentration (*73*)

The authors note that for both hot and warm mix production, the values measured were well below all environmental and occupational exposure limits, which demonstrates that both conventional HMA and WAM-Foam production are fully acceptable from an occupational and environmental standpoint.

Unpublished Data from Heritage Research on Indiana WAM Foam Trial

The goal of the project was to produce an asphalt pavement at temperatures lower than typical Hot Mix Asphalt (HMA) and evaluate it against a conventional HMA. Heritage Research was contracted by BP to aid in project logistics, sampling, data collection, and a final report.

WAM Foam® uses a two part binder system. The first part is a soft binder which required less heat to achieve the desired viscosity and coating. The second part is a harder binder, which is injected with cold water and foamed to create the desired viscosity at temperatures lower than typical HMA.

The WAM Foam® and control HMA sections were placed at three separate locations in Hendricks County, Indiana. All of the sections were low volume county roads with minimal truck traffic.

The WAM Foam® system was installed at Milestone's Plant 10, in Whitestown, IN. Plant 10 uses an H & B drum aggregate drier followed by a Gen-Tech mini drum for mixing the asphalt with the aggregate. The plant production rate for the WAM Foam® was 240 tons/hour. The plant is rated at 400 tons/hour. A separate GENCOR Industries, Inc. tank was brought in to hold the soft component asphalt. One of the existing vertical asphalt tanks was used for the hard binder component. The foaming system was installed inside the mixing drum.

The lower production temperatures were a concern in terms of potential bag house mudding and incomplete aggregate coating. The average WAM Foam® mixer discharge temperature was 250°F (121°C). The average stack temperature was 208°F (98°C). The plant's typical stack temperature is 240°F (116°C). The average WAM Foam® temperature at the plant sampling rack was 237°F (114°C). After three full days of production, the bag house showed no signs of mudding. Complete aggregate coating was achieved during all three days.

Stack emissions were measured for both the control and WAM Foam® sections. Five parameters were of interest for the comparison: Carbon monoxide, carbon dioxide, nitrous oxides, sulfur dioxide, and volatile organic compounds. Each of the emissions were reduced compared to the HMA control. TABLE 49 shows the percent reduction for each of the emissions.

TABLE 49 WAM Foam Emissions

Emission	HMA	WMA	% Reduction
CO, ppm	455	365	19.5
CO_2, ppm			
NO_x, ppm	69	59	15.6
SO_2, ppm	4.1	2.6	38.1
VOC, ppm as carbon	175	130	25.4

The worker fume exposure was monitored during the placement of the WAM Foam®. The fume exposures were compared to an average hot mix asphalt fume exposure data from Heritage Research Group (HRG). HRG has over twenty years of asphalt fume monitoring and data analysis experience. The worker fume exposure for the WAM Foam® was lower than that of typical HMA. The lower worker exposures when placing WAM Foam® result from lower placement temperatures. Total Particulate Matter (TPM) is the amount of material collected on a filter that is placed in the workers breathing zone. The TPM material is then extracted with benzene to obtain the benzene soluble material (BSM). Gas Chromatography with Flame Ionization Detection (GC/FID) is used on the BSM to obtain total organic matter (TOM) data and the boiling point range as a simulated distillation. TOM is a measurement parameter that is not regulated, but is monitored to estimate the total organic exposure in the workplace environment. The following three Figures show the WAM Foam® worker exposures compared with the HMA average exposures. The minimum detection limits are 0.095 mg/m^3 for the BSM and 0.108 mg/m^3 for the TOM. All of results for the BSM were below the detection limit.

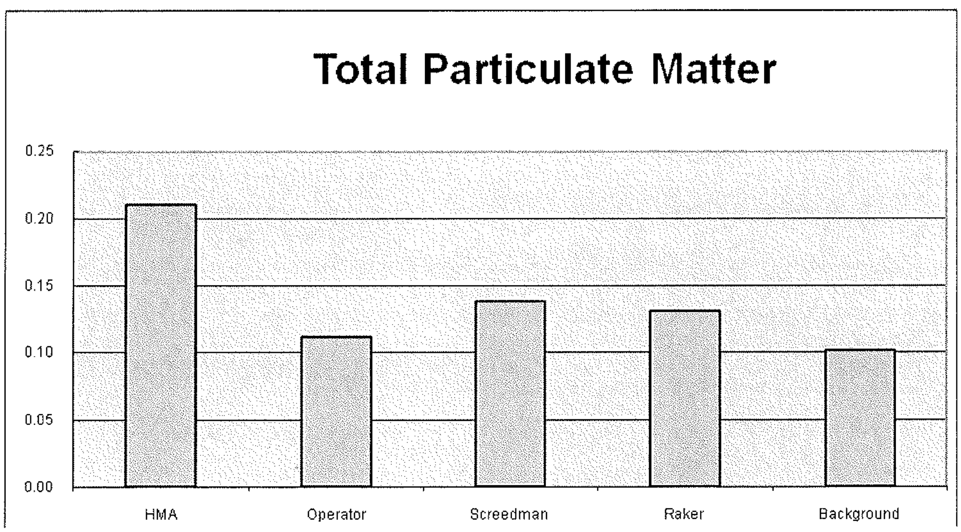

FIGURE 94 WAM Foam TPM

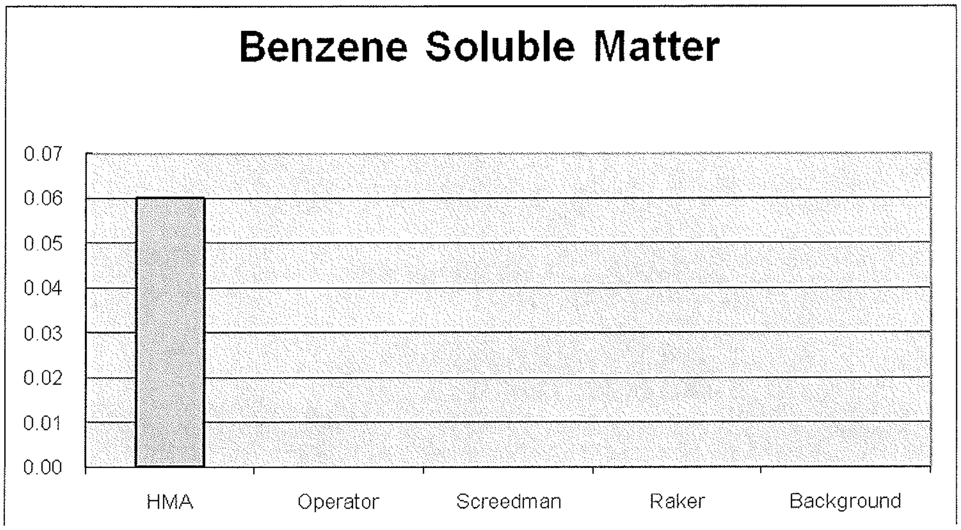

FIGURE 95 WAM Foam BSM

All of results for the BSM were below the detection limit.

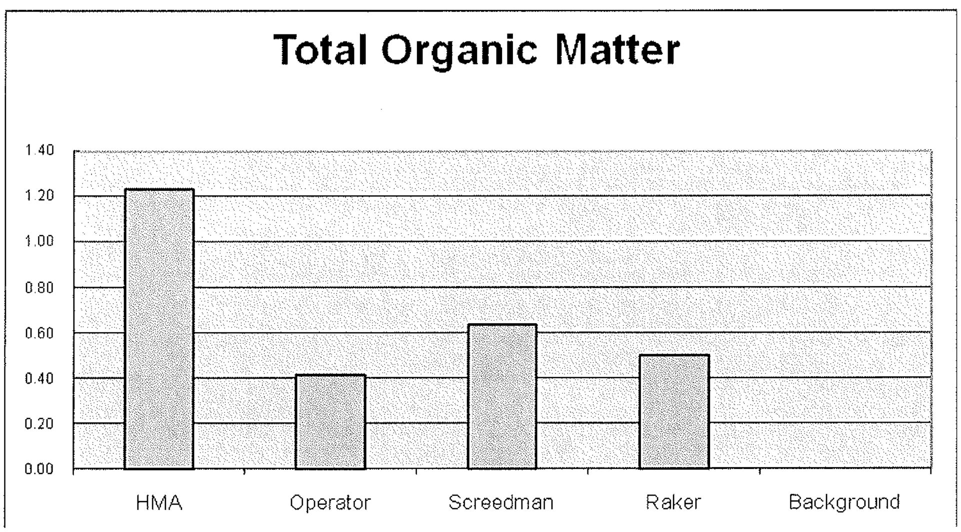

FIGURE 96 WAM Foam TOM

Plant stack emissions for the WAM Foam® mix were lower for all of the parameters monitored. Reducing stack emissions may be critical in the future as regulations are getting tighter.

Worker exposure to fumes was lower for the WAM Foam® mix. However, the TOM exposure, which is a good measure of total exposure to organics in the work place, was significantly lower (66% lower) with WAM Foam®.

Ohio Field Trial of Warm Mix Asphalt Technologies: Construction Summary, (Hurley et al.) (35); Asphalt Emission Study, (EES Group, Inc.) (75); Emission Test Results for: Warm Mix Asphalt Trial Project Mar-Zane Materials, Inc. Asphalt Plant #13 Byesville, Ohio, (Chief Environmental Group, LTD) (76)

Hurley et al. (*35*) present a summary of the latter two reports. All three reports were reviewed, but are presented together for brevity. A field trial was conducted on State Route 541 (SR 541), a two-lane rural highway with limited traffic running near Kimbolton, Ohio. Three WMA processes were used on the project: Evotherm™ emulsion, Sasobit®, and Aspha-min® as well as an HMA control. The project consisted of the construction of a two course pavement overlay. The first course was a standard HMA leveling course placed at an average thickness of 0.75 inches. The wearing surface was placed in four sections, one HMA control section and the three WMA test sections. The wearing course was placed at an average compacted thickness of 1.25 inches, for a total overlay thickness of approximately 2.0 inches. Each test section was approximately three miles in length.

The average measured plant discharge and field compaction temperatures are shown in TABLE 50. The WMA discharge (mixing) temperatures were higher than anticipated. The plant utilized a vertical bucket elevator to convey mix from the mixer to the silos. The WMA tended to back up entering the vertical bucket elevator if the temperature was too low. Discharge temperatures were not recorded for the HMA control.

TABLE 50 Compaction and Discharge Temperatures

Mix	Control	Evotherm™ Emulsion	Sasobit®	Aspha-min®
Discharge Temperature,°F	NA	277	276	285
Field Compaction Temperature,°F	309	232	257	246

TABLE 51 presents the plant's burner fuel usage results for each of the mixes used in this evaluation. During the production of the Aspha-min® and Sasobit® mixtures, fuel usage was reduced 8.8 and 17.9 percent, respectively. Fuel usage increased for the Evotherm™ mixture. It is believed that this is due to the water in the emulsion which increased the energy required to evaporate the moisture.

TABLE 51 Fuel Usage Results for Kimbolton, Ohio WMA Demonstration

Mix	Initial Natural Gas Reading, cf (thousands)	Final Natural Gas Reading, cf (thousands)	Daily Tons Produced	Natural Gas Used per Ton, cf/ton	Percent Change from Control, %
Control	557,015	557,402	1367.24	288	
Evotherm™	558,171	558,583	1207.05	341	+ 15.4
Aspha-min®	559,174	559,457	1139.22	263	- 8.8
Sasobit®	559,832	560,030	835.11	237	- 17.9

During construction of each test section, EES Group, Inc. performed industrial hygiene testing at several points on the paver, as well as a few background locations. This was done to perform a comparative analysis between the control mixture and the different WMA technologies. The results from the industrial hygiene survey are presented in TABLE 52. All three WMA technologies drastically reduced both the total particulates and benzene soluble matter when compared to the control mixture, averaging close to 75 percent reduction in emissions around the paving operations.

TABLE 52 Industrial Hygiene Results for Total Particulate and Benzene Soluble Matter

Mixture	Total Particulate, mg/m^3	Percent Reduction, Total Particulate	Benzene Soluble Matter (BSM), mg/m^3	Percent Reduction, BSM
Control	1.25		1.05	
Evotherm™	0.29	77	0.29	72
Sasobit®	0.33	74	0.21	80
Aspha-min®	0.41	67	0.20	81

TABLE 53 presents the results from asphalt plant stack emissions testing performed during construction of the control and WMA test sections. Testing was conducted by Chief Environmental Group, LTD. Data were obtained for several criteria pollutants emitted from a typical HMA plant: SO_2 (sulfur dioxide), NO_x (oxides of nitrogen), CO (carbon monoxide), and VOCs (volatile organic compounds). As would be expected with natural gas combustion and limestone aggregates, SO_2 emissions were negligible making differences between mixes inconclusive. However, that SO_2 was reduced with Sasobit® and Aspha-min® suggests that warm mix technologies could produce meaningful SO_2 reduction with high sulfur aggregates.

Both Sasobit® and Aspha-min® had significant reductions in CO, NO_x and VOC emissions as compared to the control. For Evotherm™, VOC results were 159% higher than the control mixture while CO and NO_x emissions were reduced. This solitary VOC increase exceeds that accountable to increased fuel usage (+15.4%), discussed previously, attributed to vaporizing emulsion water. Twenty pounds of VOC emissions per hour is four times the State of the Art performance requirements in some states and would exceed permit limits at many plants.

One would expect CO emissions to track natural gas used per ton and any CO reduction to reflect lower fuel usage attributed to reduced mix temperature. That CO dropped with Evotherm™ (-20.3%) even as fuel use increased (+15.4%) suggests that the burner was tuned after the control runs. It is highly unlikely that a 9 to 18% reduction in fuel use with Sasobit® and Aspha-min® would result in a 60% reduction in CO. Consequently, the reported reduction in CO emissions cannot be completely attributed to warm mix technology.

TABLE 53 Asphalt Plant Stack Emissions Results (*35*)

	Control	**Evotherm™**	**Aspha-min®**	**Sasobit®**
Date	8/30/2006	9/7/2006	9/11/2006	9/16/2006
Production Rate, TPH	165	167	168	167
Fuel	Natural Gas	Natural Gas	Natural Gas	Natural Gas
Calculated Stack Moisture, %	22.3	29.5	24.4	24.8
Carbon Dioxide, %	3.5	4.2 (+ 20.0%)	2.8 (- 20.0%)	2.0 (- 42.9%)
Oxygen, %	15.7	15.0	15.8	15.7
Sulfur Dioxide, lbs/hr	0.24	0.37	0.04	0.04
Nitric Oxide, lbs/hr	5.2	5.1 (- 1.9%)	3.6 (- 30.8%)	4.1 (- 21.2%)
Carbon Monoxide, lbs/hr	63.1	50.3 (- 20.3%)	24.0 (- 62.0%)	23.2 (- 63.2%)
VOC, lbs/hr (USEPA Method 25A)	7.8	20.2 (+159%)	2.9 (- 62.8%)	3.8 (- 51.3%)

Wisconsin Field Trial of Warm Mix Asphalt Technologies: Construction Summary, (Hurley et al.) (36); Warm Mix Stack Emission Test, (Environmental Technology & Engineering Corporation) (77); and Industrial Hygiene Survey at Ryan Road Warm Mix Paving Project, (Chojnacki) (78)

Hurley et al. (*36*) presented a summary of the latter two reports. All three reports were reviewed, but are presented together for brevity. State Highway 100 (Ryan Road) was widened to four lanes. Two WMA technologies, Sasobit® and Evotherm™ emulsion were used. A total of 1,270 tons of Evotherm™ WMA and 1,000 tons of Sasobit® WMA were produced. A production temperature of 300°F was targeted for the HMA and 250°F for the WMA. Production temperatures were lowered for the WMA during production. Compaction temperatures as low as 215°F were observed.

TABLE 54 presents the results from the stack emissions testing at the asphalt plant. Data shows an overall decrease in emissions for the WMA production, from 5 percent lower carbon CO_2 to 14 percent lower nitrous oxides NO_x. Also, nine percent less fuel was used during the production of Evotherm™. TABLE 54 also shows that there was a 313 percent increase in the production of VOCs. Other test data and observations from the project suggest that unburned fuel was being released into the asphalt drum, increasing the amount of VOCs emitted. Proper burner tuning should reduce or eliminate the unburned fuel.

TABLE 54 Stack Emissions Test and Fuel Usage Results, Milwaukee, Wisconsin (*36*)

Emission	Avg. WMA	Avg. HMA	Reduction, %	Increase, %
NO_x, lb/ton	0.058	0.068	14.0	
VOC, lb/ton	0.097	0.024		313.0
CO_2, lb/ton	50.4	53.0	5.0	
Fuel Usage, gal/ton	1.79	1.98	9.0	

At the request of the asphalt contractor, an industrial hygiene survey was conducted during the construction of the WMA test sections and the control section. Among the items evaluated during the survey was asphalt fume collection, both at the paver and from personnel monitors. A stack emissions test was also conducted at the asphalt plant to measure emissions produced from the WMA mixtures. FIGURE 97 shows some of the asphalt fume collection pumps placed on the asphalt paver during the construction of the test sections.

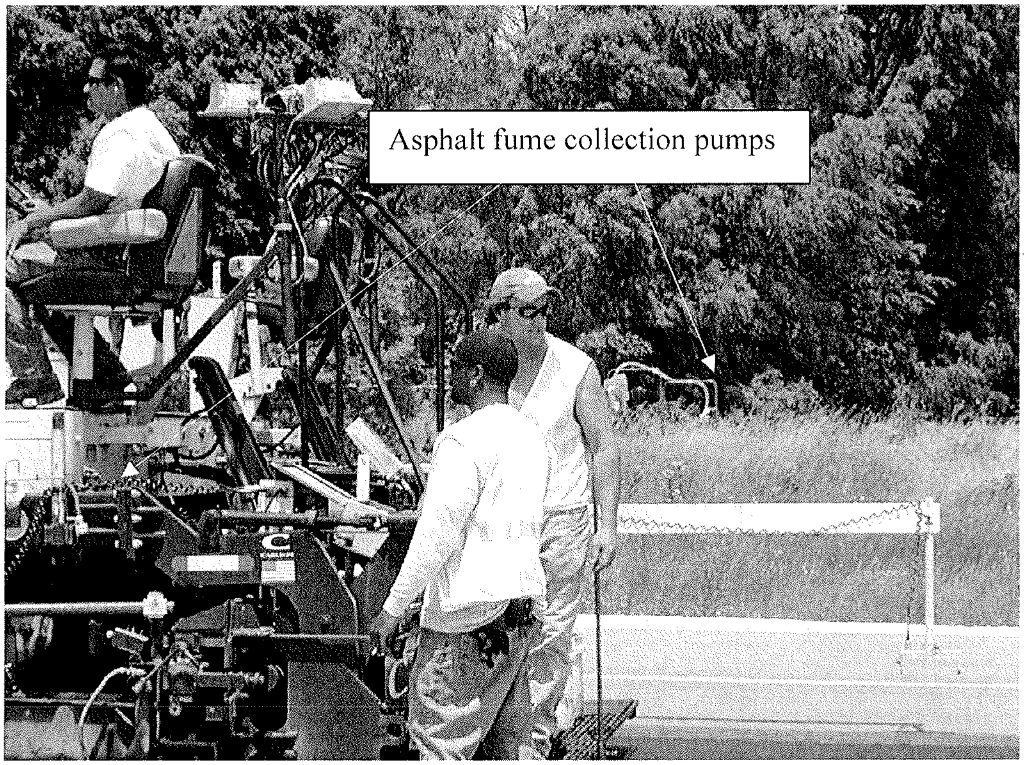

FIGURE 97 Example Locations of Asphalt Fume Collection Pumps (*36*)

NIOSH Method 5042 was used for analysis of the asphalt fume samples collected. The asphalt fume concentration collection devices were located in areas where maximum fume exposure was assumed. This allowed for a better comparison of fume reduction between the control and WMA mixtures following the recommendations of the WMA Technical Working Group's Guidelines for Documenting Emissions and Energy Reductions. Asphalt fume results for the Sasobit® mixture at the paver were 43 to 91 percent lower than for the control test section. For the Evotherm™ mixture, the asphalt fumes were 22 to 82 percent lower than for the control mixture.

An industrial hygiene survey for worker exposure to asphalt fume was conducted according to OSHA Method 58. Based on the personal sampling results, seven of the eight samples taken over the two-day testing period were below detectable limits. The one sample that was detectable had a test result of 0.42 mg/m^3 (inhalable fraction). This sample was from the screed operator during the paving of the control section, and was 84 percent of the ACGIH TLV (American Conference of Governmental Industrial Hygienists Threshold Limit Values) of 0.5 mg/m^3 (inhalable fraction).

Approximately 45 lbs of water per ton of WMA were introduced into the drum as part of the Evotherm™ emulsion. A significant amount of fuel is required to heat aggregate to convert this water into steam. This would tend to increase the amount of fuel used, offsetting savings from lower production temperatures.

Michigan Field Trial of Warm Mix Asphalt Technologies: Construction Summary, (Hurley et al.) (23)

A WMA trial section was constructed on State Highway 95 (M95) near Iron Mountain, Michigan. WMA utilizing Sasobit® was placed. A total of 1000 tons of the Sasobit® WMA were placed. The HMA was compacted at approximately 300°F and the WMA at 250°F. The mix was produced with a portable, parallel flow plant incorporating an Adeco drum, Gencor burner, and a Cedar Rapids silo.

Stack emissions testing was conducted for both the Sasobit® and Control sections to determine how much, if any, the use of Sasobit® reduced the emissions produced during construction. The results from the emissions testing, presented in TABLE 55, show an overall decrease in emissions for the Sasobit® WMA. CO_2 was reduced 18 percent and NO_x was reduced 34 percent. Also, ten percent less fuel was used during the production of Sasobit® WMA. TABLE 55 also shows that there was an eight percent increase in the production of VOCs. Due to the results from the stack emissions testing for the Wisconsin WMA field trial (*36*) produced by the same contractor, the burner and drum flighting were adjusted in. However, the increase in measured VOCs, and carbon monoxide (CO) indicate that additional fine tuning was needed. Both measures are indicators of incomplete fuel combustion.

TABLE 55 Stack Emissions Results

Emission	Reduction, %	Increase, %
NO_x, lb/ton	34.0	
VOC, lb/ton		8.0
CO_2, lb/ton	18.0	
Fuel Usage, gal./ton	10.0	

Installation of Warm Mix Asphalt Projects in Virginia, (Diefenderfer et al.) (9)

Three trial sections were constructed using WMA technologies between August and November 2006. Two projects utilized Sasobit® and one project used Evotherm™ emulsion. During the Evotherm™ trial, Virginia Department of Transportation's (VDOT's) Employees Safety and Health Division conducted asphalt fume (industrial hygiene) sampling to evaluate differences in worker exposure between HMA and WMA laydown operations.

Production temperatures for the Evotherm™ WMA ranged from 220 to 230°F. The HMA control was produced at temperatures ranging from 300 to 310°F. Compaction temperatures were not reported.

Asphalt fume sampling was conducted in accordance with the NIOSH Method 0500/5042 using SKC Aircheck 52 air pumps. The air pumps were calibrated to 2.0 liters per minute with a pre-weighed Teflon filter cassette in-line. Two samples each were collected for the Evotherm™ WMA and HMA control for a three-hour period. The air pumps were worn by the paver operator and screed person. The collected fumes were analyzed for airborne particulates and benzene soluble aerosol.

Three of the four results for total dust (particulate) were less than the detectable limit of 0.28 mg/m^3. The measurement for the screed person during the WMA paving was 0.35 mg/m^3, well below the NIOSH recommended exposure level (REL) of 5 mg/m^3. All four readings for the benzene soluble fraction were less than the detectable limit of 83.4 $\mu g/m^3$. The American Conference of Governmental Industrial Hygienists (ACGIH) threshold limit value is 0.5 mg/m^3 (500 $\mu g/m^3$).

Energy and Environmental Gains of Warm and Half-Warm Asphalt Mix: Quantitative Approach, (Harder et al.) (70)

A manufacturing temperature of 100°C separates warm mix from half-warm mix. The aggregates in the former should be dry while the latter mix retains some moisture in the form of foam or emulsion to aid in workability. For conventional HMA and WMA, heat is applied to increase the temperature of the aggregate and any internal moisture, but also to change the phase of the water from liquid to steam. The latter is known as the latent heat of vaporization and represents a significant amount of energy. Finally, heat is lost in the process due to inefficiencies.

Six processes were compared on this basis:

1) HMA, reference,
2) WMA, coating with binder including wax or foaming agent, such as zeolite,
3) WMW, double coating soft binder and foamed hard binder (WAM Foam),
4) Half-warm, coating with emulsion,
5) Half-warm, coating with foamed asphalt, and
6) Half-warm sequential coating one part of dry hot aggregate and then a second part of cold wet (fine) aggregate (LEA).

Heat losses during manufacture, for a given installation, depend on the difference between the production and ambient temperatures. An approximate proportionality rule suggests that with an ambient temperature of 15°C (59°F), the heat losses at a production temperature of 160°C are approximately twice those at 90°C. Measurements at a batch plant indicate losses at a production temperature of 160°C and an ambient of 15°C equivalent to 3 kg of fuel oil per tonne of mix. [In the NCHRP 9-47A team's opinion, this is unreasonably high as it represents 0.9 gal./ton of fuel oil or about 50 percent of typical fuel consumption of 1.6 to 2.0 gal./ton.]

All of the assumptions and differences between the six manufacturing examples are documented in the paper. FIGURE 98 shows a comparison of the estimated fuel usage for the six processes described above. As can be seen in the figure, not drying the fine aggregate (Case 6) results in significant energy savings compared to HMA. Further, the impact of the water in the emulsion (Case 4) can be seen as an increase in energy consumption compared to other half-warm processes.

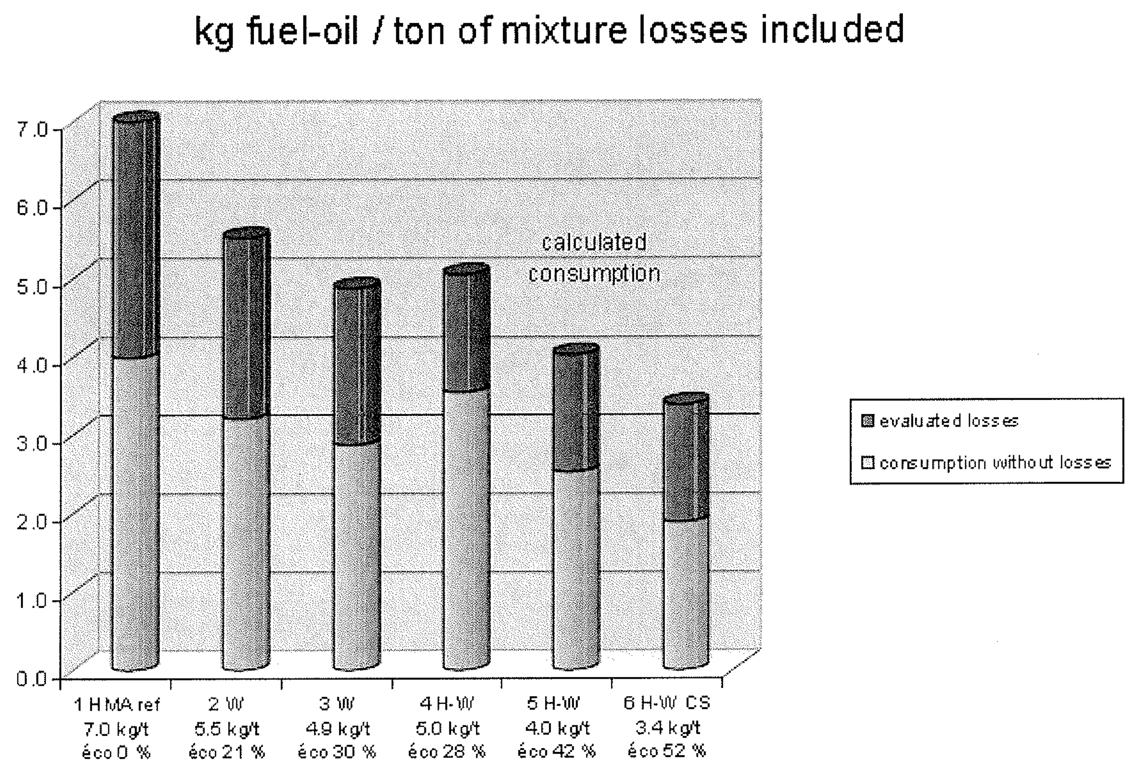

FIGURE 98 Calculated Fuel Consumption Including Expected Losses (*70*)

The authors also demonstrate that natural gas is a more efficient fuel than fuel oil and produces less greenhouse gases. A simple computer model has been developed which can be adjusted for different plant types and operating processes. This model allows optimization of energy consumption.

LEA Half-Warm Mix Paving Report – 2007 Projects for NYSDOT, (Harder) (74)

The LEA process was developed in France. McConnaughay Technologies introduced the process in New York State. As described previously, the hot, coarse (primarily) aggregate is mixed with the asphalt binder containing a chemical additive (believed to be a surfactant and adhesion agent). The coated hot coarse aggregate are then mixed with cold, wet fine aggregate. The moisture in the fine aggregate foams the asphalt binder. The resultant mixture temperature must be less than 212°F (100°C). A small amount of residual moisture is necessary to ensure workability.

In 2006 and 2007, twelve projects consisting of 35,510 tons of LEA were constructed in Region 3 (Syracuse) in New York State. The project locations, dates, and tonnages are documented in the report. McConnaughay conducted laboratory testing and monitored various plant production aspects during construction.

Productions samples were tested for moisture content and asphalt content. The corrected asphalt contents from both methods of drying were higher than expected. The author proposed that steam in the drum combined with additional aggregate breakdown from not having fines during drying results in a higher portion of very fine dust which would normally be collected in the baghouse. It is believed that this dust is released during the ignition furnace testing. This hypothesis may explain the reduction in particulate matter in stack emissions observed for several WMA projects.

For the 2007 LEA production, the pugmill discharge temperature ranged from 185 to 228°F (85 to 109°C) with a target of 212°F (100°C). A total of 34,210 tons of LEA were produced in 2007 using natural gas as fuel. TABLE 56 summarizes the 2007 natural gas usage and fuel savings. Fuel savings of approximately 47 percent were reported in 2006. Production temperatures for the 1,300 tons produced in 2006 were slightly lower, typically 194 to 203°F (90 to 95°C). Calculations suggest that higher mix temperature reduces moisture content, which actually decreases workability, while using more fuel.

TABLE 56 2007 LEA Natural Gas Usage and Fuel Savings

Mix Type	Natural Gas Usage per metric tonne of mix produced, cf	Average Natural Gas Usage	Fuel Savings, %
LEA	204 – 236	213	33
HMA	300 – 329	318	NA

Baghouse temperatures were monitored throughout the 2007 season (TABLE 42). If the baghouse temperature drops below the dew point, condensation can occur. The baghouse temperatures remained high enough to prevent caking or blinding of the bags. This may not be indicative of the baghouse temperatures of other technologies operating in a similar temperature range since the coarse aggregate in the LEA process is heated to a higher temperature. The slat conveyor and pugmill amperages were monitored. The data indicated the amperages for HMA and LEA were the same when the same binder grade was used.

TABLE 57 Comparison of Baghouse Temperatures

Mix Type	Baghouse Temperatures,°F	
	Inlet	*Outlet*
LEA	295 – 335	225 – 275
HMA	345 – 385	260 – 305

Stack emissions testing was conducted by O'Brien and Gere Engineers to compare stack emissions from LEA and HMA. Emissons monitored included: particulate matter (PM), NO_x, CO, SO_2 VOC, and formaldehyde. A total of two test runs were conducted for each mix. EPA Method 5 was used for PM, 7E for NO_x, 10 for CO, 25A for VOC, and 18 for formaldehyde. Percent O_2 and CO_2 were evaluated in the exhaust gas according to EPA method 3A. The results are summarized in TABLE 58.

TABLE 58 Average LEA Stack Emissions

Property	HMA	LEA	Percent Reduction
Exhaust Gas Temperature,°F	271	231	NA
Exhaust Gas Moisture, volume %	24.3	29.0	NA
O_2, dry volume %	13.7	14.0	NA
CO_2, dry volume %	4.02	3.81	NA
Particulate Matter, lbs/hr	23.6	11.6	51
CO, lbs/hr	11.6	2.15	82
NO_x, lbs/hr	6.98	5.13	26
VOC (as propane), lbs/hr	7.1	28.9	-306
SO_2, lbs/hr	0.17	0.09	46
Formaldehyde, lbs/hr	0.0217	0.0012	95

Environmental Comparison at Industrial Scale of Hot and Half-Warm Mix Asphalt Manufacturing Processes, (Ventura et al.) (80)

Data were collected and a life-cycle assessment conducted to compare the environmental impacts of a half-warm asphalt process, LEA, with conventional HMA. The energy consumption used to heat and mix HMA can account for up to 60 percent of the total energy input into the construction and maintenance of a road over a 30-year period. Half-warm processes, with final mix temperatures below 212°F (100°C) reportedly result in a reduction in energy consumption of up to 50 percent, compared to 10 to 30 percent for warm mix processes produced at 54°F (130°C). Measured savings can be higher than those calculated due to inevitable heat losses for processes performed at higher than ambient temperatures.

LEA is based on the hot asphalt foaming/emulsifying when it comes into contact with moisture from aggregates at temperatures below 212°F (100°C). The volume expansion of the foamed binder aids coating and workability. A chemical additive is added at an addition rate less than 1 percent by weight of asphalt binder. Microscopic images of binder films show dispersed craters from evaporated water ranging in size from 2 – 50 μm. The process requires residual moisture at plant discharge (< 212°F (100°C)) of 0.5 to 0.7 percent until final lay down at which point moisture content is less than 0.5 percent. At the time the article was written, 30 plants were reportedly equipped to use this process in Europe and the U.S.

An experimental site was constructed on RD 231 in France's Seine-Marne jurisdiction in October 2007 over a three-day period. Two lanes of the 2 km section of road were paved in eight sections equally divided between HMA and LEA. Each production run lasted at least one hour. Natural gas usage, electrical usage and airborne emissions were monitored. Emissions from the main stack included: O_2, CO_2, NO_x, CO, non-methanic gaseous organic compounds (NMGOC), and CH_4 were measured. Gaseous organic compounds were also measured from a second stack used only with the LEA to protect dust filters from steam. Operating times for the rollers were also measured at the paving site. TABLE 59 summarizes the energy consumption and emissions. Emissions and fuel consumption from hauling and placing the asphalt were calculated from published values. A greater compactive effort was required for the LEA resulting in higher fuel usage for the rollers.

TABLE 59 Consumption and Emissions per Functional unit (*80*)

Consumption and Emissions		Unit	Asphalt Plant Production		Road Works (Paving)		Transport (Haul) (40 km)	
			Hot	Half-warm	Hot	Half-warm	Hot	Half-warm
Energy Consumption	Natural Gas	MJ/FU	102,240	45,990	0	0	0	0
	Diesel		0	0	6,060	6,160	20,660	20,660
	Electricity		3,630	3,130	0	0	0	0
Airborne (Stack) Emissions	CO_2	Kg/FU	5,020	1,780	310	320	1,500	1,500
	CO		37	37	1	1	4	4
	NMGOC		4.7	2.2	0.6	0.5	1.9	1.9
	NO_x		1.5	0.4	4.0	4.0	19.2	19.2
	CH_4		0.6	0.9	0	0	0	0
	N_2O	g/FU	nm	nm	43	44	211	211
	Particles		nm	nm	218	222	1,055	1,055
	SO_2		nm	nm	72	74	349	349
Materials	Additive	t/FU	0	0.200				
	Aggregate		529	529				
	Binder		31	31				
	Mix (Total)		560	560				

Note: (nm) – not measured; the functional unit in this table is 560 metric tons. To evaluate on a per metric ton basis, the energy consumption and emission values need to be divided by 560.

A life-cycle assessment was conducted with the above data using a systematic approach that closely resembles the *Guidelines for Life-Cycle Assessment: a code of practice* by the Society of Environmental Toxicology and Chemistry. The boundary conditions included the production and placement of the HMA or WMA. Crude oil extraction, transportation, and refining as well as aggregate extraction and transport were assumed to be identical and not included. The production of the additive was not included due to lack of validated data. Energy production and transport (natural gas, electricity, and diesel) were identical for both and therefore excluded. Equipment production and wear was excluded. Waste and water treatment amounts were assumed identical.

The life-cycle assessment indicated significant reductions for greenhouse effect, energy equivalent and summer smog (reductions of 60.3, 50.6, and 34.7 percent, respectively). Although HMA is not a major contributor to either acidification or eutrophication, the use of LEA resulted in reductions of 71.7 and 71.4 percent, respectively.

The authors noted several limitations to their study. No information on the additive(s) was included. Toxicity and ecotoxicity factors could therefore not be calculated. The consideration of additives may alter the results. The service-life of half-warm and HMA mixes was excluded. The performance of both pavement types would need to be compared (or forecast) over the relevant period.

Reducing Paving Emissions Using Warm Mix Technology (Davidson and Pedlow) (71)

Two adjoining roads were paved in the City of London, Ontario, Canada, one with conventional HMA and one with WMA. Each road received two lifts of an HL8 binder course with 15 percent RAP on a prepared granular base followed by an HL3 surface course, also containing 15 percent RAP. The WMA was produced using Evotherm™ ET. HL8 and HL3 are approximately 19.0 and 12.5 mm nominal maximum aggregate size (Superpave definition) mixes, respectively. Both were Marshall mixes produced according to Ontario's Provisional Standard Specifications.

The mix was produced in a 200 tonne per hour batch plant with a dry dust collection system (baghouse). For the HL8 mix, the burner temperatures were 450 and 380°F (232 and 193°C), respectively for the HMA and WMA. For the HL3 WMA mix, the burner temperature was increased to 396°F (202°C) due to its higher asphalt content. The HMA reportedly left the plant at 302°F (150°C) and the WMA at 212°F (100°C). Compaction temperatures were reportedly 194 to 203°F (90 to 95°C) for the WMA (HMA were not reported). Haul distance reported to be 12.4 mi (20 km), 25 minutes, and paving occurred in July.

Stack emissions tests were performed according to the test methods shown in TABLE 60. Triplicate one-hour tests were performed during the production of the HL8 mix for both the HMA and WMA. The HMA data was collected on a continuous basis. However, another plant owned by the contractor had mechanical problems, which necessitated HMA for another paving project to be intermittently produced during the WMA production to meet customer's needs. Testing was stopped and started on numerous occasions and may have affected the results. The results are summarized in TABLE 61. Decreases were noted in all gaseous emissions except SO_2.

TABLE 60 Emissions Sampling Methods (*71*)

Combustion Gas	Test Method
Oxygen (O_2)	US EPA Method 3A
Carbon Dioxide (CO_2)	US EPA Method 3A
Carbon Monoxide (CO)	US EPA Method 10
Sulphur Dioxide (SO_2)	US EPA Method 6C
Nitrogen Oxides (NO_x)	US EPA Method 7E
Total Hydrocarbons (THC) as Methane	US EPA Method 25A

TABLE 61 Combustion Gas Sampling Results (after *71*)

Combustion Gas	Concentration		% Reduction
	HMA	WMA	
Particulate Matter Concentration	379 mg/Rm^3 (1)	403 mg/Rm^3 (1)	
Oxygen (O_2)	15.85%	16.48%	
Carbon Dioxide (CO_2)	2.19%	1.81%	
Carbon Monoxide (CO)	41 ppm	33 ppm	
Sulphur Dioxide (SO_2)	2.9 ppm	3.4 ppm	
Nitrogen Oxides (NO_x)	30 ppm	24 ppm	
Total Hydrocarbons (THC) as Methane	91 ppm (2)	68 ppm (2)	
Emissions Corrected for Dilution @ 0% Oxygen (by NCHRP 9-47A Team)			
Carbon Monoxide (CO)	170 ppm	156 ppm	8.3
Sulphur Dioxide (SO_2)	12.0 ppm	16.1 ppm	-34.2
Nitrogen Oxides (NO_x)	124 ppm	118 ppm	8.9
THC	377 ppm	322 ppm	14.6

(1) Dry at 77°F (25°C) and 1 atmosphere
(2) Dry by volume
Note: ppm is concentration in parts per million volume.

Fuel consumption was monitored during construction. Fuel type was not reported, but is believed to be natural gas based on the units for fuel used. The fuel consumption data is shown in TABLE 62. Slight decreases were noted. The contractor noted that this plant is generally efficient. As noted under stack emissions, the HL8 WMA was not produced continuously. Starting and stopping may have affected the fuel economy. Although not mentioned by the authors, the water in the emulsion, approximately 42 lbs/ton for HL8 and 45 lbs/ton for HL3, must be flashed off as steam, which requires additional energy.

TABLE 62 Energy Consumption Data (*71*)

Fuel	HL8 15% RAP		HL3 15% RAP	
	WMA	HMA	WMA	HMA
m^3/tonne	7.649	7.783	8.705	9.129
% Change	-1.75		-4.87	

An Evaluation of Warm Mix Asphalt Produced with the Double Barrel Green Process (Middleton and Forfylow), (21)

The authors provide a general overview of six WMA processes. TABLE 63 summarizes the estimated costs of the technologies.

TABLE 63 Summary of Potential WMA Technology Costs (Canadian Dollars) (after *21*)

Economic Component	WMA Technology					
	Evotherm™	Sasobit®	Aspha-min® (Zeolite), Advera (Zeolite)	Low Energy Asphalt (LEA)	WAM Foam®	Astec DBG™
Equipment Modification or Installation Costs	\$1,000-\$5,000	\$5,000-\$40,000	\$5,000-\$40,000	\$75,000-\$100,000	\$60,000-\$85,000	\$100,000-\$120,000
Royalties	None	None	None	N/A	\$15,000 first yr / \$5,000 per plant/ \$0.35 per ton	None
Cost of Material	\$35-\$50 premium on Binder	\$1.75/kg	\$1.35/kg	None	\$75 premium on Soft Binder	None
Recommended Dosage Rate	30% Water / 70% AC	1.5-3% by weight of Binder	0.3% by weight of Mix	0.5% Coating additive weight of Binder	1.5% weight of Mix	2% Water to Binder
Approximate Increased Cost of Mix	\$3.50-\$4.00	\$2.00-\$3.00	\$3.60-\$4.00	\$0.50-\$1.00 (depending on use of coating additive)	\$0.27 + \$0.35 Royalty	None

Four warm mixes were produced using the Astec DBG™ process. The mixes produced were a virgin mix, a mix with 15 percent RAP, a mix with 15 percent RAP and 5 percent MSM™ (manufactured shingle modifier), and a mix with 50 percent RAP. However, stack emissions tests were performed only on the WMA with 15 percent RAP and 5 percent MSM™ and HMA production with a similar mix. The plant used natural gas for burner fuel. Stack emissions tests conducted with a flue gas analyzer are reported in TABLE 64.

TABLE 64 Astec Double Barrel Green Stack Emissions (after *21*)

Combustion Gas	HMA Production	WMA with 15% RAP and 5% MSM™	% Reduction
Oxygen (O_2)	15.2%	15.8%	--
Carbon Dioxide (CO_2)	4.6%	4.1%	10.9
Carbon Monoxide (CO)	154 mg/m^3	138 mg/m^3	10.4
Sulfur Dioxide (SO_2)	2.1 mg/m^3	2.4 mg/m^3	-14.3
Nitrogen Oxides (NO_x)	24 mg.m^3	22 mg.m^3	8.3
Emissions Corrected for Dilution @ 0% Oxygen (by NCHRP 9-47A Team)			
Carbon Monoxide (CO)	565 mg/m^3	566 mg/m^3	-0.2%
Sulfur Dioxide (SO_2)	8 mg/m^3	10 mg/m^3	-2.5%
Nitrogen Oxides (NO_x)	88 mg/m^3	90 mg/m^3	-27.7%
Avg. Mix Temperature	168°C	128°C	24.2%
Avg. Stack Temperature	109°C	92°C	15.6%

The energy consumption data for the same two mixes are shown in TABLE 65. A drop in production temperature of 106°F (41°C) resulted in a 24 percent reduction in burner fuel usage. At the time of production, this resulted in a savings of $0.76 per tonne (Canadian) based on gas prices of $9.50/m^3

TABLE 65 Double Barrel Energy Consumption (after *21*)

Mix	Aggregate Moisture, %	Mix Temperature,°F (°C)	Asphalt Produced, tonnes	GJ Used	GJ per tonne	Energy Savings, %
HMA – 15% RAP, 5% MSM	4.5	336 (169)	250	83.5	0.33	24.2
WMA – 15% RAP, 5% MSM	4.2	128 (128)	460	116.1	0.25	

A Laboratory Study on CO_2 Emission Reductions Through the Use of Warm Mix Asphalt (Mallick et al.), (14)

CO_2 is produced from burning fuel to dry and heat the aggregates when producing asphalt mixtures and from the oxidization of the asphalt binder. As the hydrocarbons in asphalt binder oxidize or age to higher molecular weight compounds, CO_2 is emitted. A laboratory study was conducted to evaluate the effect of temperature, asphalt content, and Sasobit® on CO_2 emissions. An additional experiment was conducted to determine if

Sasobit® influenced binder absorption and therefore the effective asphalt content of a mixture.

A 200g sample of binder was heated at the specified temperature for three hours in a sealed flask. A rubber stopper was pushed through the seal which allowed CO_2 concentration measurements to be taken with a Dräger CO_2 tube and Dräger Accuro Pump. The measured CO_2 concentrations were corrected for the background (laboratory) CO_2 concentration. Tests without Sasobit® were conducted at 257, 311, and 347°F (125, 155, and 175°C). Tests with Sasobit® were conducted at 230, 257, 311, and 347°F (110, 125, 155, and 175°C). Asphalt contents ranging from 4 to 7 percent were considered. Based on statistical analyses, mix temperature and Sasobit® content were significant factors in the amount of CO_2 produced. Asphalt content did not have a strong correlation with emissions over the range tested. The relationship between temperature and mixture emissions is not linear. Exponential and power models provide better fits to the measured data. From the exponential model, it is estimated that a 54°F (30°C) drop in temperature with a PG 64-28 binder could reduce CO_2 emissions resulting from binder oxidation by approximately 69 percent. Additional calculations were presented to demonstrate the potential reduction in CO_2 from the reduced energy input required to heat the WMA to a lower production temperature. A 54°F (30°C) reduction in mix temperature should reduce CO_2 production resulting from burning fuel by approximately 24 percent. This reduction should parallel reduced fuel savings. The authors note that in terms of total pounds of CO_2 produced per ton of asphalt concrete, the CO_2 reduction from energy savings could be far larger than that from oxidation of the asphalt binder.

Warm Mix Asphalt Yellowstone National Park (Neitzke) (81)

Two WMA technologies and an HMA control were placed on the east Entrance Road to Yellowstone National Park in August 2007. A 2-inch thick overlay was placed on 6.93 miles of the two-lane road. The overlay required 12,200 tonnes of HMA; 8,750 tonnes of Advera® WMA; and 7,450 tonnes of Sasobit® WMA. The HMA was produced at approximately 325°F (163°C) with placement temperatures of approximately 315°F (157°C). The one-way haul time was approximately 90 minutes. For Advera®, the initial placement temperature was approximately 275°F (135°C) and was eventually lowered to approximately 250°F (121°C). For Sasobit®, the initial placement temperature was approximately 275°F (135°C) and was eventually lowered to approximately 245°F (118°C).

Fuel savings were monitored by FHWA. The fuel usage is summarized in TABLE 66. The actual mixing temperatures were not reported for the Advera® and Sasobit®. Although not in the written presentation, it has been noted that the plant production temperatures were higher than what normally might be expected for WMA due to the 90-minute haul. The 40 to 70°F (22 to 39°C) drop in laydown temperature resulted in fuel savings of 15 to 24 percent.

TABLE 66 Yellowstone Fuel Usage

	HMA (Control)	Advera	Sasobit
Total Tonnes	12,200	8,750	7,450
Fuel Usage, gallons/ton	2.12	1.62	1.80
Reduction, %	NA	23.6	15.1

The WMA additive costs (including plant addition) were approximately $3.30 for Advera® and $2.30 for Sasobit®. The reduction in fuel usage would result in savings of approximately $1.00 per ton at August 2007 prices.

Industrial Hygiene

Luminescence Spectroscopy as a Screening Tool for the Potential Carcinogenicity of Asphalt Fumes (Osborn et al.), (83)

In 1981, the NIOSH completed an animal skin painting study of asphalt fume. The fume was divided into five fractions, A through E, with A being least polar and E being most polar. Fractions B and C, and combinations containing fractions B and C were determined to be carcinogenic. Fractions B and C contained virtually all of the 4-6 ring polycyclic aromatic compounds (PACs). The fumes used in the NIOSH study were not representative of fumes from asphalt paving projects.

A laboratory technique using luminescence spectroscopy was developed to maximize the response of the carcinogenic fume fractions and minimize the response of other PACs, which are not carcinogenic. This study presents the development and validation of the technique. The coefficient of determination for the relation between emission units (EU) per gram from luminescence testing and carcinogenic index (CI) per gram was 0.98 based on data from 62 petroleum samples. In addition to investigating asphalt fumes from field samples, this technique also appeared to be able to detect confounding materials in the workplace, such as diesel exhaust and fuel.

Evaluation of Worker Exposure to Asphalt Paving Fumes Using Traditional and Nontraditional Techniques (Kriech et al.), (84)

A review of the available data indicated asphalt fumes can be respiratory irritants. For this reason, NIOSH established a recommended exposure limit of 5 mg/m^3 total particulate. What is uncertain, however, is whether or not asphalt fume is carcinogenic. Most studies evaluate endpoint, such as TPM or BSM, which generally occur in sufficient quantities (above detection limits) to be reliably measured. Although these endpoints provide information on total exposure, they provide little or no information on the carcinogenic potential of the fume. Further, studies are confounded by possible concurrent exposure to coal tar, diesel exhaust, and cigarette smoke. As noted in previously discussed studies, warm mix appears to lower fume production, resulting in measurements below detectable limits. This prevents quantitative assessment of the true reduction in fume.

This study included industrial hygiene monitoring at eleven paving projects across the United States. Sites were located in Arizona, Florida, Indiana, Kansas, Minnesota, Mississippi, New York, and Oregon. Binder grades included PG 58-28, PG 64-22, PG 64-28 (neat), AC 20, and AC 30.

Workers were fitted with monitoring devices to collect asphalt fume. Each sample was collected on a 37-mm PTFE membrane filter in a closed 37-mm cassette. A sorption (XAD-2) tube was used to collect volatile compounds from the air which had previously passed through the filter cartridge.

TPM was conducted on the filters using NIOSH Method 5042. After the TPM determination, BSM testing was performed according to NIOSH Method 5042. Finally, the XAD-2 sorption tube was washed and eluted with methylene chloride. Following a cyano-propyl clean-up, the sorption tube samples were analyzed using a luminescence spectrometer with an excitation wavelength of 385 nm and an emission wavelength of

415 nm. Estimates of potentially cancer causing 4- to 6-ring PACs were made after accounting for contributions from 2- to 3-ring non-cancer causing PACs. Results are reported as mg/m^3 as DPA (diphenylanthracene).

The data from the eleven paving sites indicated a range of individual exposure of 0.03 to 0.64 mg/m^3 of TPM with an average exposure of 0.25 mg/m^3. BSM exposure ranged from non-detectable to 0.31 mg/m^3 with an average of 0.10 mg/m^3. These data compare well with previous studies. Total organic matter (TOM) determined from luminescence spectrometer tests, ranged from 0.15 to 8.32 mg/m^3. Comparison of TOM and BSM suggests that BSM captures less than 10 percent of total organic exposure.

The fluorescence data is a valuable tool for quantifying exposure to four- and higher ring PACs determined to be carcinogens in previous animal skin painting studies. This technique allows small quantities of fume from worker exposure studies to be accurately quantified. The fluorescence tests indicate that the fume collected in this study pose low, if any, carcinogenic hazard to workers.

International Studies to Compare Methods for Personal Sampling of Bitumen Fumes (Ekström et al.) (85)

In January 2000, the ACGIH enacted a new TLV for asphalt fumes. The previous limit was 5 mg/m^3 of TPM; the new limit was 0.5 mg/m^3 measured as BSM. This had international implications since ACGIH TLVs are referenced by other countries. Typically, BSM ranges from 10 to 100 percent of TPM depending on a variety of factors. Typical BSM values from asphalt paving are 0.3 mg/m^3 BSM.

A study was conducted to compare asphalt fume collected and analyzed using samplers from five countries plus the Institute of Occupational Medicine (IOM) personal sampler. IOM samplers are believed to better represent the inhalable fraction and collect 1.2 to 3 times the organic material collected in closed-face samplers which are typically used. Inhalable fraction is based on what would enter the mouth or nose during normal breathing. Total aerosol is defined as that which enters a 37-mm closed face cassette typically used in the U.S.

The samplers were exposed to laboratory generated fume. Three replicates each were tested at two exposure levels. The collected samples were refrigerated and returned to the particular country/lab for analyses. TPM results showed small deviations between laboratories except for the German results, where this test is not typically performed. The range of BSM results was 43 to 55 percent of the mean. The relative range of TOM collected from adsorbent tubes was larger, ranging from 63 to 73 percent of the mean. It is believed that differences in TOM were exacerbated by differences in the adsorbent tube media and differences in extraction and analysis procedures. This demonstrates the difficulty in directly comparing international data, other than for TPM, and the need for standardized analysis procedures.

LIFE-CYCLE ASSESSMENT

Road Rehabilitation Energy Reduction Guide for Canadian Road Builders (Natural Resources Canada), (86)

A survey was performed of five Canadian road builders about their energy use and conservation practices. Two scenarios were included; a rural secondary road and an urban arterial. Asphalt overlays are typically applied to rural secondary roads after 25 years and urban arterials after 18 and 35 years. The rural road received a single-lift mill and overlay and the urban arterial a two-lift mill and overlay.

Average production for the seven plants included in the survey ranged from 12,000 to 250,000 tonnes annually. The most prevalent burner fuels were natural gas and waste oil. Diesel-fuelled generators were used to supply portable plants, accounting for the low average level of electrical use (2.12 kWhr/tonne). The average total energy usage was calculated as 406 megajoules (MJ) per tonne of HMA, with a range of 356 to 443 MJ/tonne. It should be noted that most asphalt plants in Canada are reported to be batch plants, typically over 30-years in age, with capacities of 180 to 240 tonnes per hour. New portable drum plants with production capacities of 400 tonnes per hour average approximately 300 MJ/tone, using 7.4 l/tonne of waste oil or heavy fuel, when running aggregates with 5 percent moisture content. Fuel usage is also provided for transport of liquid asphalt, aggregate, HMA, millings, and workers to and from the two types of projects (rural and urban) as well as on-site heavy equipment. TABLE 67 summarizes the energy use for the two rehabilitation strategies.

TABLE 67 Total Rehabilitation Energy by Road Type (per lane-km) (*86*)

Roadway Class	Units	Average	%	Range	
Rural Secondary Highway[1]				**Low**	**High**
Asphalt Plant		180,728	73	161,637	194,744
Transportation	MJ	48,031	19	26,443	66,166
On-Site Heavy Equipment Use	MJ	18,756	8	14,713	23,301
Total	MJ	247,516	100	239,178	252,792
Urban Arterial Road[2]					
Asphalt Plant	MJ	369,620	69	323,275	389,488
Transportation	MJ	136,735	25	104,867	213,094

On-Site Heavy Equipment Use	MJ	31,765	6	24,099	50,110
Total	MJ	538,120	100	520,243	586,479

[1]40 mm mill and 50 mm overlay, total 431 tonnes/km [2]80 mm mill and 100 mm overlay, total 863 tonnes.

Based on TABLE 67, the production of the HMA is the most energy intensive activity in road rehabilitation.

The authors cite a study completed by COLAS comparing the energy use from HMA and various alternatives including WMA and HMA with RAP. To extract raw materials, manufacture, and place one tonne of conventional HMA requires 680 MJ/tonne. WMA is estimated to require 654 MJ/tonne, a 3.8 percent decrease. No data was provided as to how energy use for WMA was estimated. HMA with 20 percent RAP requires 538 MJ/tone, a 20.9 percent decrease.

The Environmental Road of The Future, (Dorchies et al.) (82)

COLAS conducted a study to compare the energy used and greenhouse gases produced from the road construction techniques principally used in France, including:

Portland cement concrete, HMA, WMA, and emulsion processes. The techniques were compared with life-cycle assessment including extraction of raw materials, transport, manufacture, and placement. The techniques are compared to the impact of 30-years of traffic. FIGURE 99 shows a comparison of the amount of energy required to manufacture and lay one tonne of material from extraction of raw materials to placement on the site.

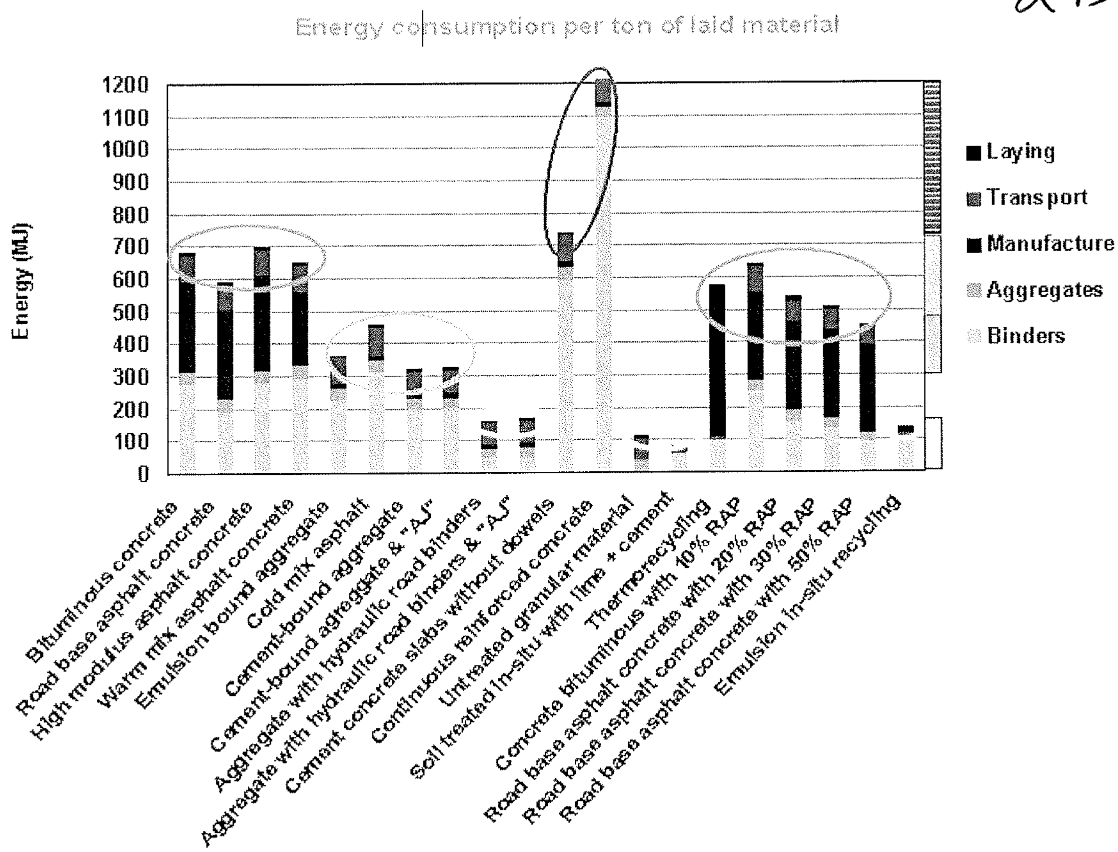

FIGURE 99 Energy Consumption per 1000 tons of Material Laid

Notes accompanying FIGURE 99 include:

- "Binders" are counted as the energy consumed in order to extract and transport raw materials and manufacture binders (asphalt, cement, modified asphalt, etc.)
- "Aggregates" are counted as the energy consumed in order to extract and manufacture aggregates at the quarry.
- "Manufacture" is counted as the energy consumed in order to manufacture mixes in a plant or a production unit.
- "Transport" is counted as the energy consumed in order to transport the constituents and mixes from the plants where the constituents are manufactured to the work site.
- "Laying" is counted as the energy consumed in order to lay the material.

- Hydraulic road binder is a mix consisting of 80 percent crushed blast furnace slag which is considered a waste product and therefore does not consume energy or emit greenhouse gas emissions.
- Cement concrete corresponds to non-dowelled concrete slab pavements.
- As road materials, in particular asphalt mixtures, can be recycled, the energy contained in the binder used in the pavement is not considered as being lost.
- RAP refers to reclaimed asphalt pavement.

The authors suggest that these techniques can be broadly classified from most to least energy intensive as concrete pavements, HMA or WMA pavements, cold (emulsion) mixes, and in situ stabilized soils. Only the first three can be utilized to carry 30-years of traffic. Over a 30-year period, the authors calculate that traffic consumes 10 to 345 times more energy than that used to construct and maintain the roadway.

FIGURE 100 shows the greenhouse gas (GHG) emissions per tonne of material laid. The same notes are applicable as for FIGURE 99, above. The authors conclude that there are three broad groupings for GHG emissions from most to least: Portland cement concrete (140 to 200 kg/tonne); hot, warm, or cold asphalt mixtures, recycled or not (30 to 60 kg/tonne); and in-place stabilization with emulsion or cement or special ground blast furnace slag binder (10 to 20 kg/tonne).

These analyses suggest that although WMA reduces energy consumption in manufacture and greenhouse gas production, other asphalt technologies, such as recycling, offer greater potential benefits.

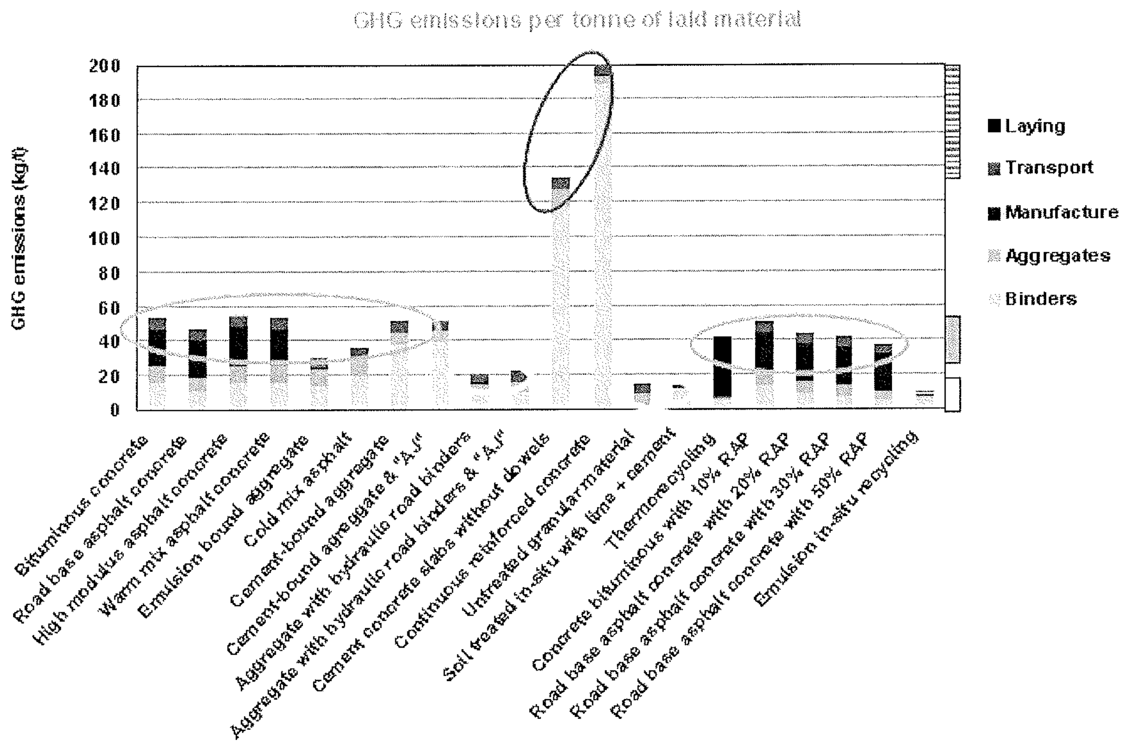

FIGURE 100 Greenhouse Gas Emissions per Tonne of Material Laid

Incorporating Sustainability Considerations into the Transportation Asset Management Process, (Flintsch et al.) (88)

To support sustainable development, the authors state that transportation asset management decisions should be constructed over three pillars: economic development, ecological sustainability, and social desirability. Performance and economics are addressed through life-cycle cost analysis. Environmental aspects are addressed through life cycle assessment. The National Environmental Policy Act of 1969 [U.S. Act] requires the assessment of the social, economic, and environmental impact of all federally funded projects. The scope of the assessment varies with the scale of the project and has often focused on environmental impacts to human health and natural ecosystems.

Life-cycle cost analysis accounts for costs associated with infrastructure investment, including: construction, operation, maintenance, renewal, retirement and any other requirement over the expected service life. Many agencies only include direct project costs since user costs such as vehicle operating cost, travel time (delay) costs, accident costs, and environmental costs are more difficult to quantify. Probabilistic methods or simulations, such as Monte Carlo simulation are used to address uncertainties in the economic analyses, such as performance period.

Life-cycle assessment considers impact on the environment, human health, and depletion of natural resources. One of the first steps is to define the boundaries of the process to be evaluated. Then a life-cycle inventory is developed to estimate the consumption of resources, both materials and energy, and the quantities of waste flows and emissions caused by or attributed to a product's life-cycle. The life-cycle inventory may include: acquisition of raw materials, manufacturing, transportation, use, recycling and disposal. The life-cycle inventory is then used in a life-cycle impact assessment. Potential impacts commonly considered include: ozone depletion, acid rain potential, photochemical oxidant impact, global warming potential, toxic waste, both solid and liquid, human health and ecological risks, and natural resource depletion. The total impact is generally determined by normalizing the various indicators through assignment of weights to the various impacts. The authors state, "Currently, there is no consensus on the types of models/tools appropriate for use in life-cycle impact assessment; rather choosing the appropriate models/tools depends on the use of the analysis results and is preferably based on the judgment of experts familiar with modeling exercises for each media." Life-cycle assessment does not account for product performance, cost, or social acceptance. Combining life-cycle assessment and life-cycle cost analysis for asset management helps to address environmental, economic and performance aspects simultaneously.

Integrating Environmental Perspectives into Pavement Management: Adding PaLATE to the Decision Making Toolbox, (Nathman et al.)(89)

The Pavement Life-cycle Assessment Tool for Environmental and Economic Analysis (PaLATE) can be used to perform an environmental life-cycle assessment and life-cycle cost analysis at the project level. This paper provides an overview of PaLATE, a discussion on integrating environmental life-cycle assessments into pavement management decisions, and two examples comparing, one comparing an emulsion based treatment with a thin HMA treatment, and the other comparing recycled materials options.

PaLATE was developed by a team led by Professor Horvath at the University of California at Berkeley. It is implemented in a multi-page Excel spreadsheet and is available as freeware. PaLATE is a streamlined life-cycle assessment tool. Life-cycle inventory addressed by PaLATE include energy, water consumption, emissions, and generated hazardous waste.

Generally, PaLATE's environmental outputs are based on U.S. government reports. However, the same data source is not used for every material/process. The majority of the emission factor outputs come from an economic input-output life-cycle assessment using a tool developed by Carnegie Mellon University. Economic input-output life-cycle assessments assign emissions per dollar amount for an industry. Asphalt cement would have contributions from the petroleum refining, water and wastewater, and energy industries. Other emission factors come from transportation energy data, the U.S. Environmental Protection Agency (EPA), and equipment manufacturers. PaLATE uses the U.S. EPA Emission factors for HMA plants. Some of the outputs include: energy, CO_2, NO_x, PM-10, SO_2, and CO. Although the data used for the emission factors are stored in PaLATE, it could not be determined from this paper whether or not the user could alter emission factors for new technologies such as WMA.

Environmental Impact Analysis of Pavement Maintenance Using Life Cycle Assessment and Micro-simulation, (Huang et al.) (90).

FIGURE 101 provides an overview of life-cycle assessment as outlined in ISO 14040. The authors note that recycling or reuse of pavement materials for road construction and maintenance require up-to-date studies on the associated environmental impacts, energy usage, emissions, etc. One would assume that there are similar needs for new technologies such as WMA. A life-cycle assessment model is described which is implemented in an Excel spreadsheet. The model gathered data from a number of United Kingdom and European sources. Certain parameters are specifically adjusted to represent typical construction practices, such as trucks are assumed full when travelling to the site and empty returning (this might not be the case if they were back-hauling millings).

Micro-simulation using VISSIM was used to calculate traffic delays due to construction. Two models were then used to estimate the increased emissions from the construction delays. These increases appear relatively small, with increases from 0.1 to 5.5 percent, although over time they could accumulate. The authors conclude that given the long service life of pavement layers (12 years for wearing surface), the majority of fuel use and green house gases comes from traffic on rather than the construction of the road.

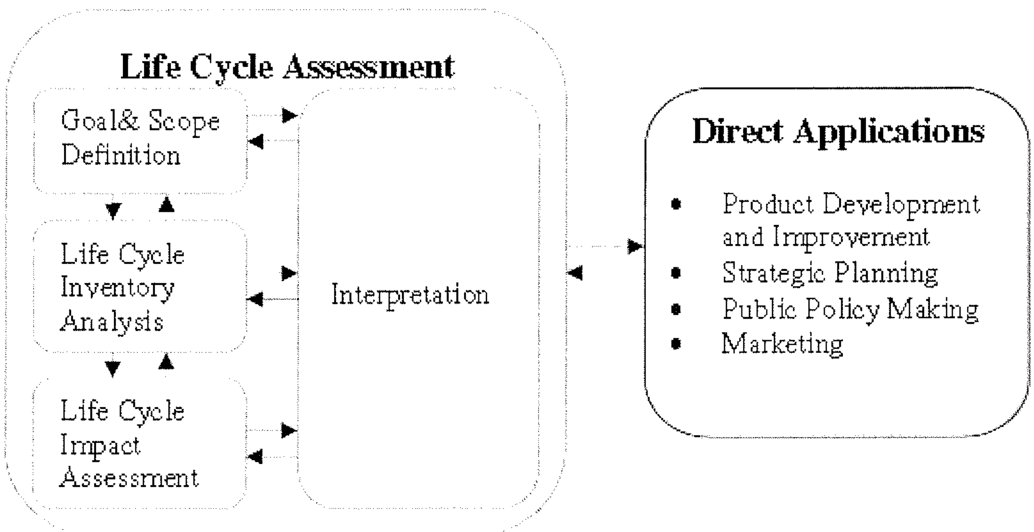

FIGURE 101 Framework of Life Cycle Assessment (*90*)

Life-Cycle Assessment of Warm-Mix Asphalt: An Environmental and Economic Perspective, (Hassan) (92).

A life-cycle assessment was performed to compare WMA versus conventional HMA. The life-cycle inventory provided in BEES 4.0 was used for the HMA. BEES was developed by the National Institute for Standards and Technology (NIST). The life-cycle inventory provides environmental impacts per unit (ton) of production. The life-cycle inventory includes a "boundary" to describe the processes accounted for in the evaluation. The BEES HMA system boundary includes:

- Asphalt binder manufacture and transportation to HMA plant,
- Aggregate production and transportation to plant,
- Plant operations to produce the HMA,

- Transportation of the HMA to the project site, and
- On site equipment and operations to place the HMA.

Impacts resulting from the production of fuels or the tack coat are not included in the evaluation. The life-cycle inventory includes energy usage, emissions to water (13 items), and emissions to air (64 items). The BEES life-cycle inventory for HMA was modified (reduced) based on the findings from Lecomte et al. (*73*). [Although the original BEES inventory is presented in the paper, the modified inventory is not presented.]

Using the BEES model, environmental impacts were calculated for HMA and WMA. Impacts were observed in five of ten categories including: global warming, fossil fuel depletion, criteria air pollutants, and ecological toxicity. The author notes that WMA is really only expected to impact the production of the asphalt mix. None of the other processes described in the boundary are impacted. The author also notes that 51 percent of the energy consumption associated with a ton of HMA comes from its production at the asphalt plant. Based on the adjustments to the life-cycle inventory, the following impacts were reduced: air pollutants (24 percent), fossil fuel consumption (18 percent), smog production (10 percent) and global warming (approximately 4 percent) for an overall reduction of 15 percent in environmental impacts. [It must be noted that the life cycle inventory for WMA was only based on the fuels savings and emissions reductions from one project.]

BEES also includes a life-cycle cost analysis. WMA costs were increased over HMA costs by $0.43 per ton. This was based on a $0.33 per ton royalty and amortization of plant modifications over a 20-year period based on 127,000 metric tons of WMA production per year. [A 20-year amortization period is not realistic. Contractors will want to recoup their investment sooner (five to seven years).] BEES combines the environmental and economic life-cycle assessment using the methodology outlined in ASTM E 1765.

Evaluation of Warm Asphalt Technology – Feasibility Study (Bennert) (91)

This study summarizes warm mix technologies available in the United States. Advanced Materials Services, LLC performed a cost comparison between WMA technologies based on two scenarios for this study. The first scenario examined limited use of WMA with 5,000 tons being produced in a 5-day period with a total production of 15,000 tons of WMA per year. The second scenario considered full implementation of WMA with an annual production rate of 350,000 tons per year. A three-year amortization period was used for equipment purchases and plant modifications with a 12 percent compounded expected rate of return. Equipment rental was considered as an alternative. Equipment and additive costs were provided by the vendors. Freight costs to New Jersey were reported for WMA additives. Cost savings for fuel reductions were not considered but are expected to be approximately $1.00 per ton based on a 30 percent fuel savings. [This would be less based on the median 18 percent savings indicated by the data collected to date.] Savings for the inclusion of anti-stripping agents in some of the WMA technologies were considered. These are required in New Jersey. The results are summarized in TABLE 68.

TABLE 68 WMA Cost Comparison (*91*)

Technology	Scenario	Equipment Purchase Cost	Equipment Rental and mobilization cost for one week	Additive cost per ton with freight	Anti-stripping agent deduct?	Estimated cost increase per ton
Advera®	1	NA	$6,900	$2.01	No	3.39
	2	$130,000	NA	$1.45	No	1.62
Double Barrel Green	1	$90,000	NA	$0.00	No	2.81
	2	$90,000	NA	$0.00	No	0.12
EvothermTM DAT	1	$3,500	NA	$2.25	Yes	1.86
	2	$3,500	NA	$2.25	Yes	1.75
Low Energy Asphalt	1	$72,000	NA	$0.88	Yes	2.63
	2	$72,000	NA	$0.88	Yes	0.48
Rediset Terminal Blend	1	NA	NA	$3.48	Yes	2.98
	2	NA	NA	$3.48	Yes	2.98
Rediset Blown into Plant	1	NA	$5,250	$2.85	Yes	3.40
	2	$55,000	NA	$2.85	Yes	2.42
Sasobit® Terminal Blend	1	NA	NA	$2.88	No	2.88
	2	NA	NA	$2.88	No	2.88
Sasobit® Blown into Plant	1	NA	$5,250	$2.28	No	3.33
	2	$55,000	NA	$2.28	No	2.35
WAM-Foam	1	$100,000	NA	$0.00	No	3.12
	2	$100,000	NA	$0.00	No	0.13

[1] Advera® addition rate is 0.25 percent by total weight of mix (5 lbs per ton).

[2]EvothermTM DAT addition rate is 0.25 percent by weight of binder.

[3]Rediset addition rate is 1.5 percent by weight of binder.

[4]Sasobit® addition rate is 1.5 percent by weight of binder.

[5]Typical liquid anti-stripping additive addition rates are 0.25 to 0.50 percent by weight of binder.

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LIST OF ACRONYMS

AASHTO – American Association of State Highway and Transportation Officials

AC – Asphalt Cement

ACGIH - American Conference of Governmental Industrial Hygienists

APA – Asphalt Pavement Analyzer

AWD – Asphalt Workability Device

BBR – Bending Beam Rheometer

BSF – Benzene Soluble Fraction

BSM – Benzene Soluble Matter

CEI – Compaction Energy Index

cf – cubic feet

CFR – U.S. Code of Federal Regulations

CO – Carbon Monoxide

CO_2 – Carbon Dioxide

DAT – Dispersed Asphalt Technology

DBG – Double Barrel Green

DOT – Department of Transportation

DSR – Dynamic Shear Rheometer

EPA – U.S. Environmental Protection Agency

ET – Emulsion Technology

G_{mm} – Theoretical Maximum Density

HMA – Hot Mix Asphalt

IOM – Institute of Occupational Medicine

ITS – Indirect Tensile Strength

LEA – Low Energy Asphalt

m – BBR m-value

MF – Mineral Fraction

M_r – Resilient Modulus

MSM™ Manufactured Shingle Modifier

NCAT – National Center for Asphalt Technology

NIOSH – National Institute for Occupational Safety and Health

NMAM – NIOSH Manual of Analytical Methods

NMAS – Nominal Maximum Aggregate Size

NO_x – oxides of Nitrogen

PAC - Polycyclic Aromatic Hydrocarbon

PAH – Polycyclic Aromatic Hydrocarbon

PG – Performance Grade

PM – Particulate Matter

PMA – Polymer Modified Asphalt

PPA – Polyphosphoric Acid

ppm – Parts per million

ppmvd – Parts per million volume diluted

PSS – Permanent Shear Strain

PTFE - Polytetrafluoroethylene

RAP – Reclaimed Asphalt Pavement

RAS – Reclaimed Asphalt Shingles

RTFO – Rolling Thin-Film Oven

S – BBR creep Stiffness

SBS – Styrene-Butadiene-Styrene

SFE – Surface Free Energy theory

SGC – Superpave Gyratory Compactor

SO_2 – Sulfur Dioxide

TDI – Traffic Densification Index

TLV – ACGIH Threshold Limit Value

TOM – Total Organic Matter

TPM – Total Particulate Matter

TSR – Tensile Strength Ratio

TSRST – Tensile Stress Restrained Specimen Test

VF – Volatile Fraction

VMA – Voids in Mineral Aggregate

VOC - Volatile Organic Compound

WMA – Warm Mix Asphalt

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NCHRP PROJECT 9-49

PERFORMANCE OF WMA TECHNOLOGIES: STAGE I—MOISTURE SUSCEPTIBILITY

PHASE I INTERIM REPORT
EXCERPTED LITERATURE REVIEW

Prepared for
Transportation Research Board
Of
The National Academies

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CHAPTER 2.0 BACKGROUND

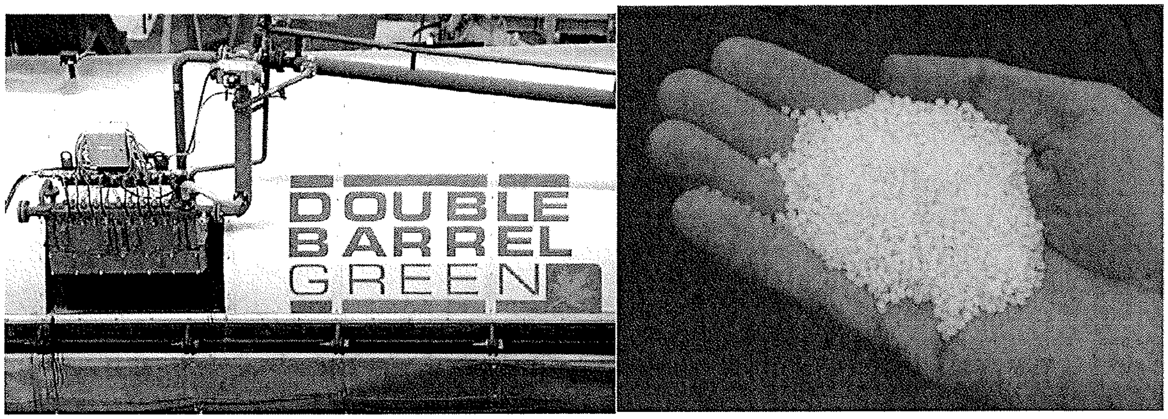
This chapter provides the results of the information search completed in Task 2 that included a review of written documentation on WMA technologies, moisture susceptibility characterization of asphalt concrete mixtures, previous research on moisture susceptibility of WMA, and previous field experience with WMA in terms of moisture susceptibility. The focus of the background provided is limited to results on stiffness as an indicator of moisture damage, moisture susceptibility including retained properties after moisture conditioning or performance measured in the presence of water, and the effects of aging and specimen type to align with the Phase II work plan provided in Chapter 4.

2.1 WMA Technologies

WMA technologies allow for the production and placement of asphalt concrete paving materials at temperatures approximately 50°F (28°C) cooler than the temperatures typically used in the production of HMA. Table 2.1 shows a number of technologies that satisfy this definition through different mechanisms and provide economic, environmental, and engineering benefits in terms of reduced viscosity of the binder and/or mix to allow for complete coating of the aggregate by the binder, sufficient adhesion between the aggregate and binder, and mix compactability at lower temperatures (Diefenderfer et al., 2007). WMA technologies as described in this section can be classified by process type as those where water is introduced (foaming) or those where water is typically not utilized (additive). Reductions in viscosity at lower temperatures are realized with the foaming technologies through the expansion of water as it turns to steam. The additive technologies rely on surfactants, rheology modifiers, and/or other organic material or waxes alone or combined with each other. More detailed information on each of the WMA technologies, including necessary plant modifications and experience/usage in the United States can be found elsewhere (NAPA, 2008; Prowell et al., 2011). Of the WMA technologies listed in Table 2.1, the majority of large volume field sections in the United States utilize Double Barrel® Green, Evotherm®, Sasobit®, and Advera® WMA, since these were the first available WMA technologies (Prowell et at., 2011). Figure 2.1 shows the equipment used for one of the common foaming processes [Double Barrel Green® (DBG®)] and one of the common additives (Sasobit®).

Table 2.1. WMA Technologies

Process	Category	Technology Brand	Brief Description	Recommended Quantity
Foaming	Hydrophilic Materials	Advera® WMA/ Aspha-min® (PQ Corporation)	Synthetic zeolite composed of both aluminosilicates and alkali metals with 20% water (mostly chemically combined)	0.25% by total weight of mixture
	Wet Aggregate	Low Emission/Energy Asphalt (LEA) (McConnaughay Technologies)	Binder with additive coats coarse aggregate at high temperatures plus cold, wet fine aggregate (3-4% water)	0.5% by total weight of binder
	Free Water System	Double Barrel Green® (Astec Industries, Inc.)	Water microscopically added to binder using a multi-nozzle system	1 lb of water per ton of mix
		Terex® WMA System (Terex® Roadbuilding)	Expansion chamber provides binder/water mixture at desired production rate	N/A
		Ultrafoam GX™ System (Gencor Industries, Inc.)	Water injected into binder using only energy of pump supplying binder and water	1.25~2.0% water by weight of total binder
		AquaBlack™ WMA System (Maxam Equipment Company, Inc.)	Foaming gun with nozzle designed to provide binder foaming	About 1/4 cup of water per ton of WMA
		Accu-Shear™ (StanSteel)	Shearing process to force binder and water to mix together to produce foam	N/A
		WAM Foam® (Shell Bitumen)	Soft binder coats aggregate with harder binder infused with a small quantity of cold water	Soft Binder: 20~30% Hard Binder: 2.0~5.0%
		Eco-Foam II (AESCO/MADSEN)	Shear zone turbulence to enhance mixing/foaming process	1.0~2.0% of the liquid asphalt flow rate
Additive		Evotherm™ (MeadWestvaco Asphalt Innovations)	Various forms including an emulsion (with water) plus a chemical package	Approximately 5% by weight of binder
		Rediset™ WMX (Akzo Nobel Surfactants)	Rheology modifiers and surfactants that may provide anti stripping effect	1.5~2.0% by total weight of binder
		Cecabase RT® (Arkema Group)	Surfactant package directly injected into binder	0.3~0.5% by total weight of binder
		QualiTherm/HyperTherm™ (Coco Asphalt Engineering)	Non-aqueous, fatty-acid based chemical additive	0.2~3.0% by weight of the total binder
		SonneWarmmix™/ ECOBIT™ (Sonneborn, Inc.)	High melt point, paraffinic hydrocarbon blend (wax)	0.5~1.5% by weight of the total binder weight
		Revix™ (Mathy Technology and Engineering Services, Inc. & Paragon Technical Services)	Chemical package to reduce internal friction between binder and aggregate under high shear during production and placement	1.5~2.5% by weight of asphalt binder
		Sasobit® (Sasol Wax Americas, Inc.)	Synthetic long-chain paraffin wax reduces binder viscosity above wax melting point and solidifies at lower temperatures after placement	0.8~4% by total weight of binder
		TLA-X™ Warm Mix (LakeAsphalt of Trinidad and Tobago)	Natural asphalt emulsion plus rheology modifying agents	N/A
		Shell Thiopave™ (Shell Sulphur Solutions)	Additive based on sulfur-extended asphalt technology plus compaction aid	2-2.5% by mass of the total mixture



(a) (b)

Figure 2.1. Examples of Common WMA Technologies: (a) Foaming Equipment (Double Barrel® Green) and (b) Additive (Sasobit®) (Astec, 2011; Graniterock, 2011)

2.1.1 Foaming Processes

Foaming processes can be further categorized by how water is introduced, through hydrophilic materials, wet aggregates, or free water systems. All of these processes utilize water to create foam to reduce binder and/or mixture viscosity and improve coating and compactability. When small amounts of water are added to heated asphalt binder, the water vaporizes and the vapor is encapsulated in the binder. This process causes a foaming in the binder, temporarily increasing its volume and lowering its viscosity, which improves coating and compactability.

Hydrophilic materials can be utilized as foaming admixtures to introduce the small amount of water needed to produce the steam required to foam the asphalt binder and reduce its viscosity. These delivery systems release water gradually as steam at temperatures above 212°F (100°C). The most common hydrophilic material used as a foaming admixture is Advera® WMA/ Aspha-min®, which is a synthetically manufactured zeolite that is approximately 20% water by mass. The water is released when pre-blended with heated binder just prior to mixing with aggregate at a high temperature of 250°F (121°C).

Wet aggregates can also be utilized to introduce water into WMA. Low Emission/Energy Asphalt (LEA) is an example of this type of WMA technology. Here, the mixture viscosity is reduced by introducing cold, wet fine aggregates (3-4% moisture) to coarse aggregates that were coated with binder modified by a coating and adhesion additive at high temperatures just prior to mixing with the coarse aggregates. Again, the binder is foamed as the moisture from the fine aggregates turns to steam.

Free water systems use a foaming nozzle, a series of nozzles, or some other mechanical means of injecting the water required for foaming directly into the heated binder just prior to entering the mixing drum. Each system is designed to provide the appropriate water to binder ratio that governs the properties of the resulting foam. These systems rely on the fact that when water turns to steam at temperatures above 212°F (100°C), it expands and results in a reduction of viscosity of the binder. Many different WMA technologies use the free water system (Table 2.1) including Double Barrel® Green, Terex® WMA System, Ultrafoam GX™ System, AquaBlack™, Accu-Shear™, and WAM Foam®. These various free water systems are a popular choice for WMA production due to relatively low cost as compared to other technologies.

2.1.2 Additives

WMA additives are chemical packages that are incorporated during mixing or added to the binder before mixing with aggregate. Detailed information concerning the exact mechanisms these additives use to produce WMA is not available due to proprietary limitations, but in general, surfactants and/or rheology modifiers and/or other organic material and waxes provide complete coating and improved adhesion and compactability.

Some chemical packages added to WMA include surfactants that work at the microscopic interface of the aggregates and the binder, and control and reduce the internal friction when the mixture is subjected to high shear rates and high shear stresses during production and placement. These surfactants enhance the wetting action of the binder on the aggregate surface to facilitate complete coating and improved adhesion and compactability. Other chemical packages include waxes that reduce binder and mix viscosity when heated above the melting point of the wax, and solidify at temperatures below their melting point. Some additives such as Revix™ provide a reduction in internal friction for effective aggregate coating and compaction (Reinke et al., 2008). Other organic material such as natural occurring lake asphalt and sulfur are also included in some WMA additives.