Low Temperature and Moisture Susceptibility of RAP Mixtures with Warm Mix Technology

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16. Abstract

A major concern with the use of Warm Mix Asphalt (WMA) technologies has been their impact on the moisture susceptibility of asphalt paving mixtures. This is due to the lower production temperatures associated with mixtures incorporating these technologies which could lead to inadequate drying of aggregates. The moisture susceptibility concern may be compounded if high amounts of Reclaimed Asphalt Pavement (RAP) are added to the mixture. RAP is mixed with the heated aggregates in an attempt to avoid further stiffening of the binder present in the RAP. Therefore, if the aggregates in a mixture are heated at lower temperatures than the conventional temperatures due to WMA, the RAP will be exposed to less heat which might lead to residual moisture in the RAP being present in the mixture. Residual moisture may lead to adhesive and/or cohesive failures. The purpose of this study was to better understand the influence of moisture on the performance of plant produced high RAP content mixtures incorporating WMA technologies fabricated at reduced mixing temperatures.

Nine 12.5-mm Superpave mixtures were produced in two drum plants using three WMA technologies and three RAP contents. The three WMA technologies were wax-based SonneWarmix™, chemical-based Evotherm®, and the Stansteel ACCU-SHEAR™ foaming process.

Post production moisture in each mixture was negligible which means that moisture had no effect on mixture performance. The quality of blending analyses showed that the majority of the mixtures had poor blending, which would indicate that there should be performance issues with many of these mixtures. However, the quality of blending had no apparent effect on mixture performance. It did not explain any poor performance or any difference in performance.

Overall, some WMA with RAP contents up to approximately 50% RAP provided acceptable performance. Field trials or full-scale pavement accelerated tests with rigorous pavement monitoring are needed to confirm the findings of this study.

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SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	25.4	millimetres	mm
ft	feet	0.305	metres	m
yd	yards	0.914	metres	m
mi	miles	1.61	kilometres	km
		AREA		
in^2	square inches	645.2	millimetres squared	mm^2
ft^2	square feet	0.093	metres squared	m^2
yd^2	square yards	0.836	metres squared	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	kilometres squared	km^2
		VOLUME		
fl oz	fluid ounces	29.57	millilitres	mL
gal	gallons	3.785	Litres	L
ft^3	cubic feet	0.028	metres cubed	m^3
yd^3	cubic yards	0.765	metres cubed	m^3

NOTE: Volumes greater than 1000 L shall be shown in m^3

Symbol	When You Know	Multiply By	To Find	Symbol
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams	Mg
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5(F-32)/9	Celcius temperature	°C

* SI is the symbol for the International System of Measurement

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimetres	0.039	inches	in
m	metres	3.28	feet	ft
m	metres	1.09	yards	yd
km	kilometres	0.621	miles	mi
		AREA		
mm^2	millimetres squared	0.0016	square inches	in^2
m^2	metres squared	10.764	square feet	ft^2
ha	hectares	2.47	acres	ac
km^2	kilometres squared	0.386	square miles	mi^2
		VOLUME		
mL	millilitres	0.034	fluid ounces	fl oz
L	litres	0.264	gallons	gal
m^3	metres cubed	35.315	cubic feet	ft^3
m^3	metres cubed	1.308	cubic yards	yd^3
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.205	pounds	lb
Mg	megagrams	1.102	short tons (2000 lb)	T
		TEMPERATURE (exact)		
°C	Celcius temperature	1.8C+32	Fahrenheit temperature	°F

°F 32 98.6 212 °F
-40 0 40 80 120 180 200
-40 -20 0 20 40 60 80 100
°C 37 °C

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1.0 BACKGROUND & SIGNIFICANCE OF PROBLEM

A major concern with the use of Warm Mix Asphalt (WMA) technologies has been their impact on the moisture susceptibility of asphalt paving mixtures. This is due to the lower production temperatures associated with mixtures incorporating these technologies which could lead to inadequate drying of aggregates and thus residual moisture in the mixture. Some WMA technologies, like foaming technologies, introduce water directly into the binder. Additionally, the type of WMA technology may decrease the stiffness of the asphalt binder which can also affect the moisture susceptibility of the mixture. Literature has indicated that, after coating the aggregate during the mixing process, stiffer asphalts are generally harder to peel from an aggregate or take longer to peel at ambient temperatures and thus have more resistance to moisture damage. Accordingly, if a WMA technology softens the binder, the degree of adhesion between the asphalt and the aggregate and cohesiveness of the mixture can be adversely impacted. Even if there are no problems caused by introduced moisture and no decrease in stiffness, some WMA technologies could still positively or negatively affect the bond strength between asphalt and an aggregate by altering surface chemistry (*1*, *2*).

The moisture susceptibility concern in mixtures incorporating WMA may be compounded if Reclaimed Asphalt Pavement (RAP), especially at high contents, is added to the mixture. RAP is generally introduced during the mixing processes. It is heated via mixing with the heated aggregates in an attempt to avoid further stiffening of the binder present in the RAP. Therefore, if the aggregates in a mixture are heated at lower temperatures than the conventional temperatures due to the incorporation of a WMA, the RAP will be exposed to less heat than in the typical hot mix asphalt (HMA) which might lead to residual moisture being present in the mixture. Residual moisture in mixtures may lead to adhesive and/or cohesive failures. Moreover, lower production temperatures may negatively impact the degree of blending between the aged RAP binder and the virgin binder. However, lower production temperatures may also decrease the amount of mixture aging thereby decreasing the mixture stiffness. This may lead to a mixture less prone to cracking (*3*).

The purpose of this study is to better understand the influence of moisture on the performance of plant produced high RAP content mixtures incorporating WMA technologies fabricated at reduced mixing temperatures associated with WMA. Specifically, the influence of these variables on mixture performance in terms of moisture susceptibility and cracking at low temperature was examined. Additionally, since lower WMA production temperatures may negatively impact the degree of blending between the aged RAP binder and the virgin binder, the degree of blending for each mixture was examined.

2.0 RESEARCH OBJECTIVE

The main objective of this research project was to understand the influence of moisture on the moisture susceptibility and low temperature cracking performance of plant produced RAP mixtures incorporating WMA technologies fabricated at reduced mixing temperatures. Plant produced mixtures were fabricated at different plants using different WMA technologies in combination with varying moisture contents and percentages of RAP. Because of the lower production temperatures associated with WMA and concerns over performance implications due to incomplete blending, additional testing was included to evaluate the degree of blending between the RAP and the virgin binders.

3.0 INTERNET BASED SURVEY

In order to assist in development of the experimental plan for the study, two internet based surveys were developed and distributed to members of state agencies and industry (producers) throughout the Northeast. A copy of each survey is located in Appendix A. One survey was created to solicit feedback from state agency personnel while the other was developed to solicit feedback from industry. The purpose of the agency survey was to determine specification limits for RAP usage, allowable RAP stockpile moisture contents, WMA technologies approved for use, production and placement temperatures for high RAP and WMA mixtures, and approved mixture moisture susceptibility tests. The purpose of the industry survey was to determine typical RAP stockpile moisture contents, typical RAP properties, maximum permissible amount of RAP used in production, WMA technologies utilized, production and placement temperatures for high RAP and WMA mixtures. The complete compilation of the survey results is in Appendix A. Some highlights from the survey results were:

- Drum mix plants can typically be used to produce mixtures up to 50% RAP by weight of aggregate, whereas batch plants are typically used to produce mixtures up to 20% RAP by weight of aggregate.

- The most commonly specified and used wax-based WMA technology among respondents was SonneWarmix™. Similarly, Evotherm® was the most commonly specified and used chemical WMA technology additive. Foaming/moisture-based processes were not commonly specified or used.

- RAP binder content varied from 3 to 8% (See Figure 1 for distribution of responses) and moisture content varied from 0 to 7% (See Figure 2 for distribution of responses).

- Survey responses indicated that HMA mixtures with high RAP had typical production temperatures of 143-168ºC (290-335ºF) and compaction temperatures of 135-149ºC (275-300ºF). WMA mixtures had typical production temperatures of 135-168ºC (275-335ºF) and compaction temperatures of 121-160ºC (250-320ºF).

- The Tensile Strength Ratio TSR (AASHTO T283) and Hamburg Wheel Tracking Device (HWTD) (AASHTO T324) tests were the most commonly identified approved mixture moisture susceptibility tests for state agencies. Mixtures were considered to be acceptable if the TSR result exceeds 80%. For HWTD results a criteria of a maximum rut depth of 12.5mm after 20,000 passes combined with no Stripping Inflection Point (SIP) before 15,000 passes was considered acceptable.

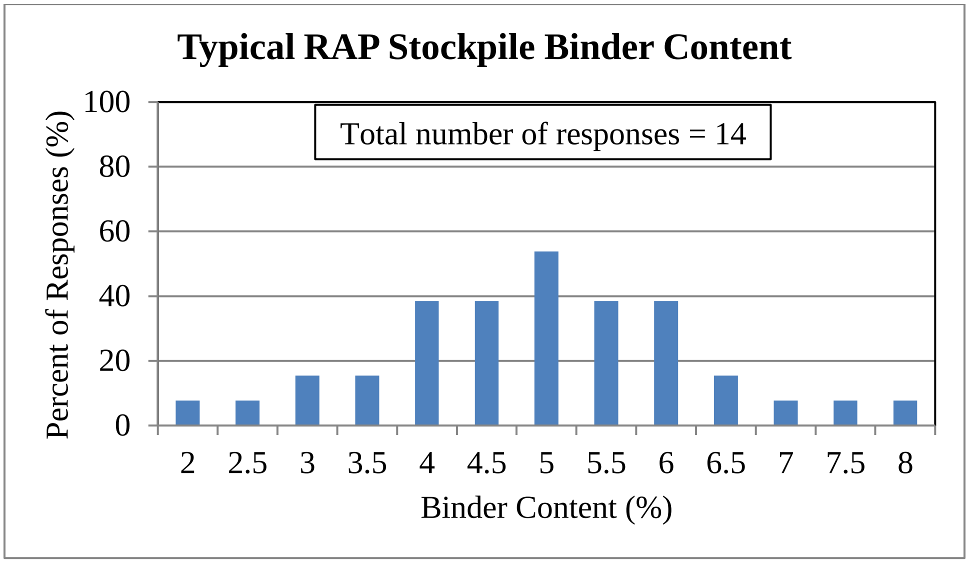

FIGURE 1 Industry Survey Result - Typical RAP Stockpile Binder Content

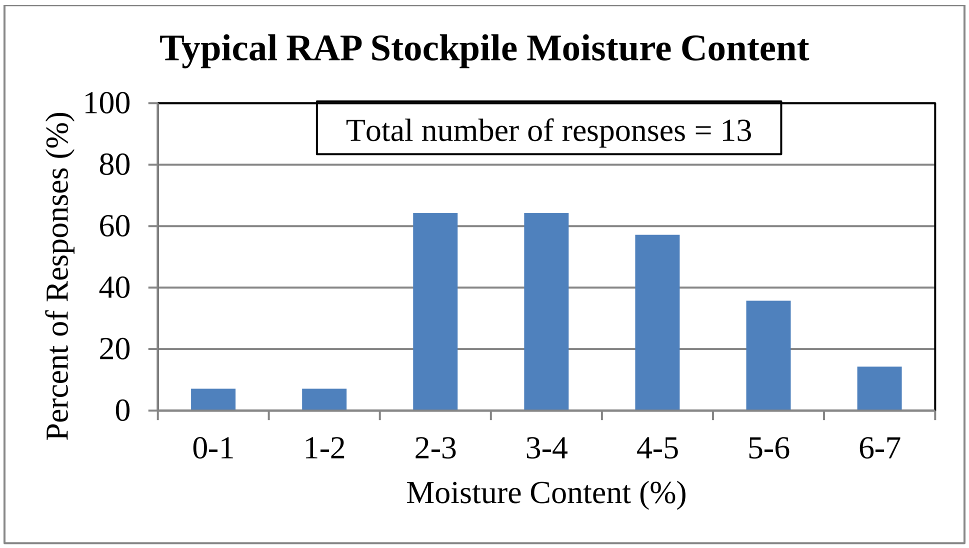

FIGURE 2 Industry Survey Result - Typical RAP Stockpile Moisture Contents

4.0 EXPERIMENTAL PLAN

An experimental plan was developed in order to achieve the objectives of the study as shown in Figure 3.

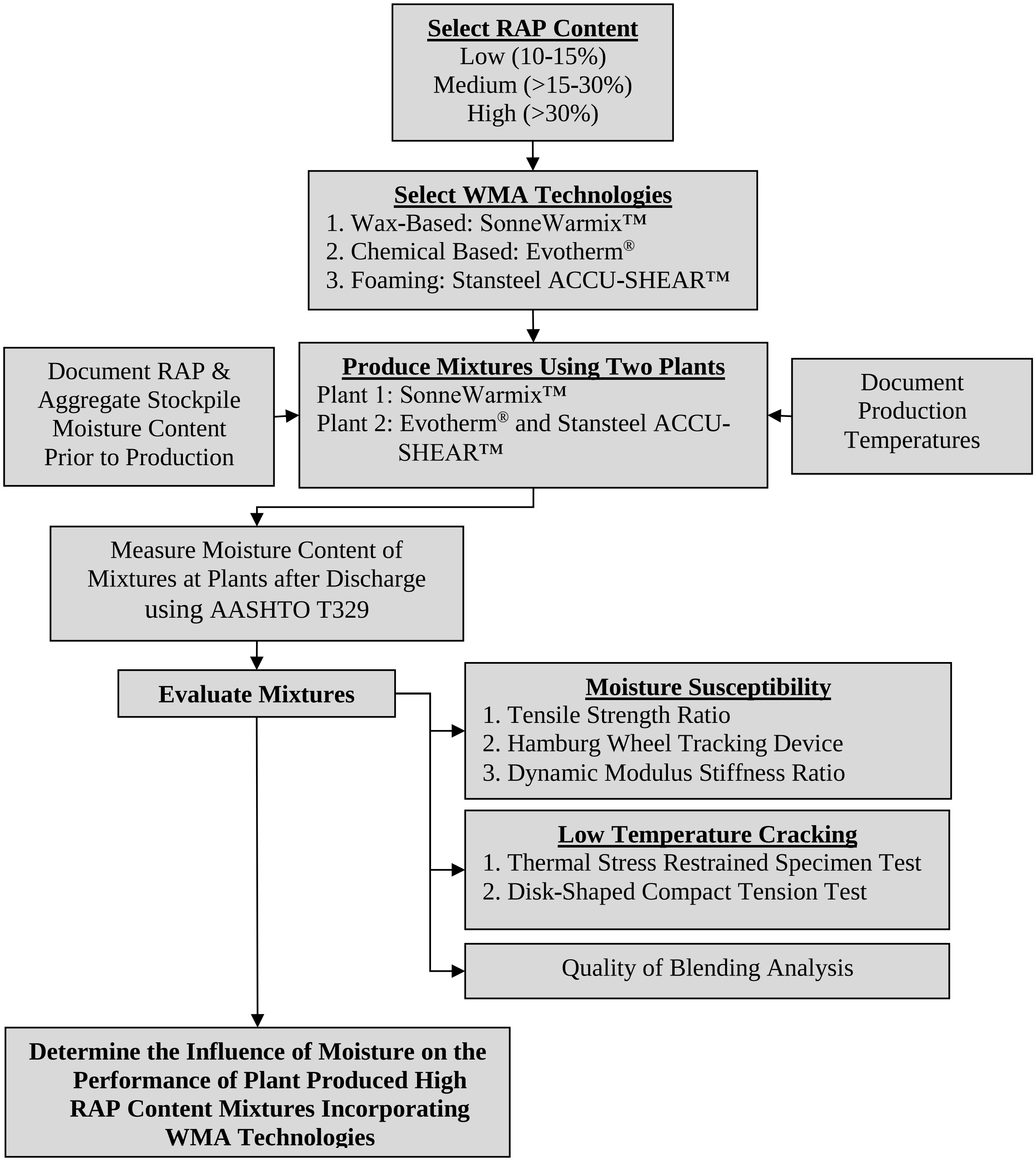

FIGURE 3 Experimental Plan

5.0 WMA TECHNOLOGY SELECTION

An organic wax-based additive named SonneWarmix™, a chemical-based additive named Evotherm®, and a foaming process named Stansteel ACCU-SHEAR™ were selected from the Northeast Asphalt User Producer Group (NEAUPG) approved list of WMA technologies. SonneWarmix™ and Evotherm® were utilized at a dosage of 0.5% per weight of binder which was according to manufacturer's recommendations. The Stansteel ACCU-SHEAR™ foaming process utilized a water content of 3% by weight of binder.

6.0 PLANT PRODUCED MIXTURES

Two Massachusetts approved 12.5-mm Nominal Maximum Aggregate Size (NMAS) Superpave mixtures were selected. Each mixture design gradation was then modified to include the increasing amounts of RAP while keeping the Job Mix Formula constant. Drum plants were selected to produce each mixture in order to accommodate RAP contents greater than 20%. As noted in the survey results, batch plants are typically limited to 20% RAP. The binder remained constant at each plant with no changes in performance grade (PG) as the RAP content was increased. The binders used at both plants were a PG64-28 which have production temperatures around 160℃ when used in HMA. No antistripping agents were used.

The first 12.5-mm mixture was a 100-gyration mixture produced using SonneWarmix™. Three mixtures were produced with RAP contents of 15% (low), 27.8% (medium) and 46.3% (high). The RAP content of 27.8% and 46.3% corresponded to 1.5% and 2.5% virgin binder replaced, respectively. The binder content of the RAP was 5.4% and the moisture content of the RAP was 1.6%. The properties of these mixtures and production temperatures are shown in Table 1. The production temperatures ranged from 133ºC to 134ºC.

TABLE 1 Drum Plant #1 - 12.5-mm Mixture Properties with 0.5% SonneWarmix™

Sieve Size (mm)	% Passing by Weight		
	15% RAP Mixture	**27.8% RAP Mixture**	**46.3% RAP Mixture**
19.0	100	100	100
12.5	98.4	98.2	98.1
9.5	85.9	84.9	83.4
4.75	61.0	60.6	60.2
2.36	41.8	42.0	42.9
1.18	28.2	28.9	31.0
0.60	18.4	18.8	21.1
0.30	11.8	12.0	13.6
0.15	6.7	6.9	8.2
0.075	3.5	3.5	4.3
Total Mixture Binder Content (%)	5.5	5.5	5.5
Mixture Air Voids (%)	4.1	3.4	2.8
Voids in Mineral Aggregate (VMA), %	14.0	14.2	13.7
Voids Filled with Asphalt (VFA), %	71.0	76.1	79.8
Production Temperature (ºC)	133ºC	133ºC	134ºC

The second 12.5-mm mixture was a 75-gyration mixture using Evotherm® and Stansteel ACCU-SHEAR™. Six mixtures, three for each WMA technology, were produced with RAP contents of 29% (medium), 39% (high) and 48% (high), which corresponded to 1.5%, 2.0% and 2.5% binder replaced, respectively. For the 29% and 39% RAP mixtures incorporating Evotherm®, the binder content of the RAP was 5.0% and the moisture content of the RAP was 2.9%. For the 48% RAP mixture incorporating Evotherm®, the RAP binder content was 5.4% and moisture contents was 4.0%. For all three mixtures incorporating the Stansteel ACCU-SHEAR™ foaming process, the binder content of the RAP was 5.9% and the moisture content of the RAP was 4.1%. The properties of these mixtures and production temperatures are shown in Tables 2 and 3. The production temperatures ranged from 135ºC to 143ºC.

TABLE 2 Drum Plant #2 - 12.5-mm Mixture Properties with 0.5% Evotherm®

Sieve Size (mm)	% Passing by Weight		
	29% RAP Mixture	**39% RAP Mixture**	**48% RAP Mixture**
19.0	100	100	100
12.5	97.4	98.5	99.0
9.5	84.1	85.0	88.2
4.75	59.7	59.7	63.5
2.36	47.1	46.7	50.5
1.18	39.9	39.1	38.2
0.60	32.9	32.1	34.0
0.30	21.4	20.9	22.2
0.15	9.8	9.8	11.3
0.075	4.1	4.2	4.8
Total Mixture Binder Content (%)	5.0	5.0	5.0
Mixture Air Voids (%)	4.4	4.3	4.2
Voids in Mineral Aggregate (VMA), %	14.1	14.2	14.4
Voids Filled with Asphalt (VFA), %	69.0	69.6	71.1
Production Temperature	138ºC	135ºC	143ºC

TABLE 3 Drum Plant #2 - 12.5-mm Mixture Properties with ACCU-SHEAR™ Foaming

Sieve Size (mm)	% Passing by Weight		
	29% RAP Mixture	39% RAP Mixture	48% RAP Mixture
19.0	100	100	100
12.5	97.4	98.5	99.0
9.5	84.1	85.0	88.2
4.75	59.7	59.7	63.5
2.36	47.1	46.7	50.5
1.18	39.9	39.1	38.2
0.60	32.9	32.1	34.0
0.30	21.4	20.9	22.2
0.15	9.8	9.8	11.3
0.075	4.1	4.2	4.8
Total Mixture Binder Content (%)	5.0	5.0	5.0
Mixture Air Voids (%)	3.4	3.5	3.8
Voids in Mineral Aggregate (VMA), %	14.1	14.2	14.4
Voids Filled with Asphalt (VFA), %	76.2	75.6	73.5
Production Temperature	138ºC	135ºC	143ºC

7.0 MOISTURE CONTENT

As noted previously, a major concern with using high RAP content with WMA is the potential for residual moisture from the RAP to exist in the mixture after production due to the reduced production temperatures associated with WMA. The moisture contents of all mixtures produced in this study were measured immediately after production (no silo storage) in accordance with AASHTO T329 "Moisture Content of Hot Mix Asphalt (HMA) by Oven Method" (*4*). The moisture of the RAP prior to being used in production in shown in Table 4 along with the moisture remaining in the mixture after production. Based on the results of these moisture measurements, the moisture remaining after production in the mixture was very negligible. This suggests that nearly all of the moisture in the RAP and aggregate was eliminated during plant production.

TABLE 4 Moisture Content Results

Plant	Mixture	Warm Mix Asphalt Technology	RAP Moisture Content Prior to Production	Mixture Moisture Content Post Production
Drum Plant #1	15% RAP	0.5% SonneWarmix™	1.6%	0.2%
Drum Plant #1	27.8% RAP	0.5% SonneWarmix™	1.6%	0.1%
Drum Plant #1	46.3% RAP	0.5% SonneWarmix™	1.6%	0.1%
Drum Plant #2	29% RAP	0.5% Evotherm®	2.9%	0.04%
Drum Plant #2	39% RAP	0.5% Evotherm®	2.9%	0.03%
Drum Plant #2	48% RAP	0.5% Evotherm®	4.0%	0.0%
Drum Plant #2	29% RAP	Foaming	4.1%	0.0%
Drum Plant #2	39% RAP	Foaming	4.1%	0.0%
Drum Plant #2	48% RAP	Foaming	4.1%	0.0%

8.0 LABORATORY TESTING OF PLANT PRODUCED MIXTURES

Mixtures were collected during production and placed into buckets. These buckets were reheated in the laboratory to fabricate specimens for the performance evaluations. The same reheating procedure was used for each mixture and the amount of reheating was minimized. Each bucket was first heated at the post-production temperature for one hour with the lid loosely on it. After this, the lid was removed and the temperature was monitored until it reached 82ºC. The mixture was then removed from the oven and split and quartered manually to the appropriate test specimen weight in accordance with AASHTO T248 “Reducing Samples of Aggregate to Testing Size” (*4*). The spilt and quartered samples were placed back into the oven until the compaction temperature of 121℃ was reached, which is the minimum compaction temperature noted for WMA mixtures from the survey responses. All specimens were compacted using Superpave Gyratory Compactor (SGC).

8.1 Moisture Susceptibility

The Tensile Strength Ratio (TSR), Hamburg Wheel Tracking Device (HWTD), and E* stiffness ratio (ESR) were used to evaluate the moisture susceptibilities of the mixtures. The TSR and HWTD were found to be the most common tests used to evaluate moisture susceptibility according to the internet survey.

8.1.1 Tensile Strength Ratio (TSR) and Percent Area Stripped

A common method to evaluate moisture susceptibility of paving mixtures is the Tensile Strength Ratio (TSR) performed in accordance with AASHTO T283 “Standard Method of Test for Resistance of Compacted Asphalt Mixtures to Moisture-Induced Damage” (*4*). A minimum of six specimens were compacted using the SGC to a height of 95mm at an air void level of 7±1.0%. Mixtures were sorted, conditioned and tested in accordance with AASHTO T283. TSR tests results are shown in Table 5.

TABLE 5 Mixture Moisture Susceptibility – AASHTO T283 TSR Results

Plant	Mixture	Warm Mix Asphalt Technology	AASHTO T283 Tensile Strength Ratio (TSR), %	Area Stripped, %
Drum Plant #1	15% RAP	0.5% SonneWarmix™	92.0	<10%
Drum Plant #1	27.8% RAP	0.5% SonneWarmix™	88.7	<10%
Drum Plant #1	46.3% RAP	0.5% SonneWarmix™	93.9	<10%
Drum Plant #2	29% RAP	0.5% Evotherm®	82.2	<10%
Drum Plant #2	39% RAP	0.5% Evotherm®	77.5 **F**	<10%
Drum Plant #2	48% RAP	0.5% Evotherm®	85.9	<10%
Drum Plant #2	29% RAP	Foaming	94.8	<10%
Drum Plant #2	39% RAP	Foaming	90.1	<10%
Drum Plant #2	48% RAP	Foaming	86.8	<10%

F = Failed the specification.

All mixtures passed except for the 39% RAP mixture with Evotherm® which had a borderline but failing TSR of 77.5%. However, this mixture easily passed HWTD discussed later. None of the mixtures exhibited visual stripping that was more than 10% of the total area.

8.1.2 Hamburg Wheel Tracking Device (HWTD) Test

The HWTD test was conducted in accordance with AASHTO T324 “Hamburg Wheel-Track Testing of Compacted Hot Mix Asphalt (HMA)” (*4*). In this test, the rut depth versus numbers of wheel passes is plotted to determine the Stripping Inflection Point (SIP), which gives an indication of when the test specimen is beginning to exhibit moisture damage.

SGC specimens were fabricated to an air void level of 7.0±1.0% as required by AASHTO T324. The test temperature was 45ºC which is required by the state agency where these mixtures were produced. Testing is terminated at 20,000 wheel passes or sooner if damage is high. Based on the internet survey, the passing criteria for the HWTD is a maximum rut depth of 12.5 mm at 20,000 passes combined with no SIP before 15,000 passes. These criteria are also currently required by the state agency where these mixtures were produced.

The HWTD results are presented in Table 6. All mixtures passed except for the 15% RAP mixture with SonneWarmix™ which means an antistripping agent would be needed for it. The reason for its poor performance is unknown. It is hypothesized that the WMA technology might have softened the virgin asphalt binder and that the low RAP content might not have introduced enough stiff binder to counteract this softening effect. However, the mixture easily passed the other two tests for moisture susceptibility. All rut depths were low except for the mixture which failed from moisture damage.

TABLE 6 Mixture Moisture Susceptibility – HWTD Results

Plant	**Mixture**	**Warm Mix Asphalt Technology**	**Stripping Inflection Point**	**Rut Depth at 20,000 Passes (mm)**
Drum Plant #1	15% RAP	0.5% SonneWarmix™	11,766 **F**	13.4 **F**
Drum Plant #1	27.8% RAP	0.5% SonneWarmix™	NONE	5.1
Drum Plant #1	46.3% RAP	0.5% SonneWarmix™	NONE	4.4
Drum Plant #2	29% RAP	0.5% Evotherm®	NONE	2.8
Drum Plant #2	39% RAP	0.5% Evotherm®	NONE	2.1
Drum Plant #2	48% RAP	0.5% Evotherm®	NONE	2.3
Drum Plant #2	29% RAP	Foaming	NONE	3.0
Drum Plant #2	39% RAP	Foaming	NONE	2.4
Drum Plant #2	48% RAP	Foaming	NONE	1.7

F = Failed the specification.

8.1.3 Dynamic Modulus E Stiffness Ratio (ESR)*

Previous studies showed that the ESR can also be used to evaluate moisture susceptibility (*5,6,7*). For each mixture, three E* specimens were compacted to a height of 170 mm. Test specimens were cored from them at a diameter of 101±0.5 mm which were then cut to a height of 150±2 mm. The air void level was 7±1%. The specimens were conditioned at 20ºC for a minimum of two hours and then tested for E* at 20ºC and loading frequencies of 10, 1, and 0.1 Hz in accordance with AASHTO PP61 "Developing Dynamic Modulus Master Curves for Asphalt Mixtures Using the Asphalt Mixture Performance Tester (AMPT)"(*4*) The same specimens were then freeze thaw conditioned in accordance with AASHTO T283 - Section 10.3 with the exception that the vacuum was applied for 30 minutes regardless of the degree of saturation attained. The specimens were then tested in the AMPT to determine the E* once again at the same temperature of 20ºC and same loading frequencies of 10, 1, and 0.1 Hz. The ESR is the ratio of the E* of the conditioned specimens to the E* of the unconditioned specimens which is computed at each frequency. A minimum ESR in the range of 70% to 80% is generally considered acceptable (*7*).

The ESR results are shown in Table 7. All ESR values were above 70%, suggesting good performance. Even so, the ESR may have further identified the 39% RAP mixture with Evotherm® to be slightly susceptible to moisture damage, having ESR between 73 and 78%. The TSR for this mixture failed at 77.5%. The mixture easily passed the HWTD.

TABLE 7 Mixture Moisture Susceptibility – ESR Results

Plant	Mixture	Warm Mix Asphalt Technology	@10 Hz, %	@1 Hz, %	@0.1 Hz, %
Drum Plant #1	15% RAP	0.5% SonneWarmix™	101.4	95.2	95.1
Drum Plant #1	27.8% RAP	0.5% SonneWarmix™	99.8	92.0	93.3
Drum Plant #1	46.3% RAP	0.5% SonneWarmix™	96.5	89.9	91.6
Drum Plant #2	29% RAP	0.5% Evotherm®	90.4	77.8	92.3
Drum Plant #2	39% RAP	0.5% Evotherm®	89.2	73.2	90.4
Drum Plant #2	48% RAP	0.5% Evotherm®	81.7	74.7	88.4
Drum Plant #2	29% RAP	Foaming	94.6	92.4	92.3
Drum Plant #2	39% RAP	Foaming	94.7	89.3	90.4
Drum Plant #2	48% RAP	Foaming	98.0	94.8	88.4

8.2 Low Temperature Cracking

As discussed previously, lower production temperatures associated with WMA technology use may decrease the amount of mixture aging thereby decreasing the mixture stiffness. This may lead to a mixture less prone to cracking. However, the use of high amounts of RAP in combination with good blending may effectively increase mixture cracking susceptibility due to the increased influence of aged RAP binder which is stiffer than virgin binder. Therefore, in order to understand these effects, tests for low temperature cracking were conducted.

8.2.1 Thermal Stress Restrained Specimen Test (TSRST)

Thermal cracking susceptibility was first measured using the Thermal Stress Restrained Specimen Test (TSRST) in accordance with AASHTO TP10-93 (*8*) with the exception that SGC specimens were utilized.

In this test, an asphalt specimen is cooled at a constant rate of -10ºC/hour while its length is held constant. As the specimen gets colder, it tries to contract but the device restricts this contraction which results in the accumulation of thermal stresses. Eventually the thermal stresses exceed the tensile strength capacity of the specimen resulting in specimen fracture. The temperature at which this fracture occurs is the low cracking temperature of the mixture.

SGC specimens, which were 185 mm tall by 150 mm in diameter, were fabricated for each mixture. TSRST specimens were then cored and cut from them to a height of 160±2 mm by 54±0.5 mm in diameter. The air voids were 7±1%.

The TSRST results are shown in Table 8. The TSRST cracking temperatures ranged from -23.0 to -27.3℃. Since a virgin PG64-28 binder was used in all mixtures, it might be expected that the mixtures would fail at a temperature equal to or colder than -28°C if there was no influence of the aged RAP binder. However, the TSRST often provides a temperature that is warmer than the low-temperature PG. For a low-temperature PG of –28℃, the TSRST usually provides a cracking temperature in the range of -26 to -28℃. Although the potential beneficial effects on thermal cracking performance due to the lower production temperatures associated with WMA were not realized in this study, it was concluded that the thermal cracking performances of the mixtures would be acceptable at temperatures down to -28℃ except for one mixture. The 48% RAP mixture with foaming WMA potentially showed the effect of the aged RAP binder as it had the warmest cracking temperature of -23℃, whereas the rest of the mixtures were between -26 to -28℃.

TABLE 8 Mixture Low Temperature Cracking – TSRST Results

Plant	**Mixture**	**Warm Mix Asphalt Technology**	**Average Failure Temperature (ºC)**
Drum Plant #1	15% RAP	0.5% SonneWarmix™	-27.0
Drum Plant #1	27.8% RAP	0.5% SonneWarmix™	-27.3
Drum Plant #1	46.3% RAP	0.5% SonneWarmix™	-26.6
Drum Plant #2	29% RAP	0.5% Evotherm®	-25.5
Drum Plant #2	39% RAP	0.5% Evotherm®	-26.2
Drum Plant #2	48% RAP	0.5% Evotherm®	-26.8
Drum Plant #2	29% RAP	Foaming	-26.9
Drum Plant #2	39% RAP	Foaming	-25.8
Drum Plant #2	48% RAP	Foaming	-23.0

8.2.2 Disk-Shaped Compact Tension DC(T)

A second test utilized to evaluate thermal cracking performance was the Disk-Shaped Compact Tension DC(T) test. In this test, fracture energy is used to describe the thermal fracture resistance of a mixture. Specimens having a 150-mm height were fabricated, prepared, and tested in accordance with ASTM D7313 "Standard Test Method for Determining Fracture Energy of Asphalt-Aggregate Mixtures Using the Disk-Shaped Compact Tension Geometry" (*9*). As outlined in the method, a test temperature of -18ºC was utilized which is 10ºC warmer than the low-temperature PG of the asphalt binder used in the mixtures, which was –28℃. The crack mouth opening displacement rate was 0.017 mm/s.

Threshold values of DC(T) fracture energy have been developed based on field investigations of thermally-induced cracks under a FHWA Pooled Fund Study (*10*). The thresholds for low, medium, and high traffic asphalt pavement mixtures were set at 400, 460, and 690 J/m2, respectively. Mixtures from drum plant #1 were 100 gyration design mixtures which would be for high traffic, having a minimum criterion of 690 J/m2, whereas, the mixtures from drum plant #2 were 75 gyration design mixtures which would be for medium traffic, having a minimum criterion of 460 J/m2.

The DC(T) results are shown in Table 9. The mixtures from drum plant #1 did not meet the high traffic criteria but passed the medium traffic criteria. The mixtures from drum plant #2 passed the medium traffic criteria. Mixtures from drum plant #1 might exhibit thermal cracking at high traffic levels while all mixtures would be acceptable for medium traffic levels. A final comment is that the TSRST does not consider traffic level. A mixture can be used at any traffic level as long as the pavement temperature will not go below the cracking temperature that the TSRST provides. Thus, the two tests might not always provide an identical conclusion.

TABLE 9 Mixture Low Temperature Cracking – DC(T) Results

Plant	Mixture	Warm Mix Asphalt Technology	Average Fracture Energy (J/m^2)
Drum Plant #1	15% RAP	0.5% SonneWarmix™	499
Drum Plant #1	27.8% RAP	0.5% SonneWarmix™	518
Drum Plant #1	46.3% RAP	0.5% SonneWarmix™	474
Drum Plant #2	29% RAP	0.5% Evotherm®	504
Drum Plant #2	39% RAP	0.5% Evotherm®	562
Drum Plant #2	48% RAP	0.5% Evotherm®	562
Drum Plant #2	29% RAP	Foaming	548
Drum Plant #2	39% RAP	Foaming	517
Drum Plant #2	48% RAP	Foaming	582

9.0 QUALITY OF BLENDING ANALYSIS

Since lower WMA production temperatures might negatively impact the quality of blending between the virgin and aged RAP binders, and thus, possibly, might impact mixture performance, a blending analysis is critical. If no blending occurs, the resultant mixture will contain less than the targeted asphalt binder content which could lead to mixtures which are prone to cracking (*11*,*12*,*13*).

Factors that may affect the quality of blending are plant type, production temperature, mixing time, discharge temperature, RAP source and RAP properties. Several laboratory studies have researched the quality of blending. These studies illustrated that the quality of blending can be evaluated using the dynamic modulus (E*) of the mixtures and the complex shear modulus (G*) of extracted and recovered binders (*11*,*12*).

To evaluate the quality of blending, the first step was to develop a E* master curve for each mixture in accordance with AASHTO PP-61 "Developing Dynamic Modulus Master Curves for Asphalt Mixtures Using the Asphalt Mixture Performance Tester (AMPT)" (*6*). Three 170-mm tall specimens were compacted using the SGC. These specimens were then cored and cut to the final test specimen dimensions of 101±0.5 mm in diameter and 150±2 mm in height. The air voids were 7±1%. Specimens were conditioned overnight at 4ºC and then tested for E* at loading frequencies of 10, 1, and 0.1 Hz. The specimens were next conditioned at 20ºC for a minimum of one hour and tested again at the same loading frequencies of 10, 1, and 0.1 Hz. Finally, the specimens were conditioned at 40ºC between one and two hours and tested at loading frequencies of 10, 1, 0.1, and 0.01 Hz. For each mixture, the E* results were used to develop the master curve.

The second step was to extract and recover the binder from each mixture using toluene in accordance with ASTM D2172/D2172M "Quantitative Extraction of Bitumen from Bituminous Paving Mixtures" (*9*) – Method A. The G* and phase angle (δ) of each binder was then measured using a Dynamic Shear Rheometer in accordance with AASHTO T315 "Determining the Rheological Properties of Asphalt Binder Using Dynamic Shear Rheometer" (*4*) at 10, 22, and

34ºC and strain levels of 0.1, 1, 1%, respectively, and at loading frequencies of 0.1, 1, 10, and 100 Hz.

For each mixture, the Hirsch model (*14*) was used to predict a mixture E* for a fully blended condition at each temperature and loading frequency from the binder G* using Equations 1 and 2:

$$E^* = P_c \left[4{,}200{,}000\left(1-\frac{VMA}{100}\right) + 3 \times G^*\left(\frac{VFA \times VMA}{10{,}000}\right)\right] + \frac{1-P_c}{\left[\frac{\left(1-\frac{VMA}{100}\right)}{4{,}200{,}000} + \frac{VMA}{3 \times VFA \times G^*}\right]} \tag{1}$$

$$P_c = \frac{\left(20+\frac{VFA \times 3G^*}{VMA}\right)^{0.58}}{650+\left(\frac{VFA \times 3G^*}{VMA}\right)^{0.58}} \tag{2}$$

Where:
E* = predicted asphalt mixture dynamic modulus, psi
G* = measured asphalt binder complex shear modulus, psi
P_c = aggregate contact volume

The measured E* master curve for each mixture was then utilized to determine E* at the temperatures of 10, 22, and 34ºC and loading frequencies of 0.1, 1, 10, and 100 Hz used for the binder testing. For each temperature and loading frequency, the mean E* from the master curve and the predicted mean E* from the Hirsch model were statistically compared at a significance level of α=0.05 to determine if the blending was good or poor. If the means were significantly different, blending was poor.

The results are shown in Figure 4 with the shaded areas indicating poor blending. Note that this method does not directly measure the degree of blending in terms of a percentage but is simply an indication of the quality of blending, either good or poor. Because of this, whether there is good or poor blending for a particular mixture often varies with the temperature and loading frequency. When this is encountered, whether there is good or poor blending must be deduced from the overall results.

Figure 4 shows that blending was poor for the majority of mixtures. The 29 and 48% RAP mixtures with Evotherm® provided the best overall quality of blending, although why the quality of blending for them was better than for the 39% RAP content is not known. Why the quality of blending for the 48% RAP mixture with ACCU-SHEAR™ foaming was so imprecise and why it was somewhat better than for the 29 and 39% RAP contents are also unknown.

Drum Plant #1 - 12.5-mm Mixture with 0.5% SonneWarmix™									
Loading Frequency (Hz)	15% RAP			27.8% RAP			46.3% RAP		
	10ºC	22ºC	34ºC	10ºC	22ºC	34ºC	10ºC	22ºC	34ºC
100									
10									
1									
0.1									

Drum Plant #2 - 12.5-mm Mixture with 0.5% Evotherm®									
Loading Frequency (Hz)	29% RAP			39% RAP			48% RAP		
	10ºC	22ºC	34ºC	10ºC	22ºC	34ºC	10ºC	22ºC	34ºC
100									
10									
1									
0.1									

Drum Plant #2 - 12.5-mm Mixture with ACCU-SHEAR™ Foaming									
Loading Frequency (Hz)	29% RAP			39% RAP			48% RAP		
	10ºC	22ºC	34ºC	10ºC	22ºC	34ºC	10ºC	22ºC	34ºC
100									
10									
1									
0.1									

Note: Shading indicates poor blending.

FIGURE 4 Quality of Blending Results

10.0 CONCLUSIONS

Based on the testing and analysis conducted in the study, the following conclusions were made:

1. A major concern with using a WMA technology and RAP is the potential for residual moisture from the RAP to be present in the mixture after production due to the reduced production temperatures associated with WMA and also any residual moisture if a WMA foaming process is used. The residual moisture contents of the mixtures in this study after plant production were negligible, which means that moisture had no effect on mixture performance. The results indicate that moisture can be dried out of these types of mixtures by a drum plant. The moisture contents of the RAP stockpiles ranged from 1.6 to 4.1%.

2. The three moisture susceptibility tests generally indicated acceptable performance regardless of the WMA technology or RAP content. The only significant failure was provided by the low RAP content of 15% RAP in combination with one WMA technology

when tested by the HWTD. However, the mixture easily passed the other two tests. The three tests for moisture susceptibility did not always agree with one another. All rut depths in the HWTD were low except for the mixture which failed from moisture damage.

3. Results from the TSRST and DC(T) did not indicate any influence of moisture on mixture performance in terms of low temperature cracking for all mixtures. The TSRST provided acceptable thermal cracking performances. The DC(T) showed that all mixtures would have acceptable thermal cracking performances for pavements with low or medium traffic levels.

4. The quality of blending analyses showed that the majority of the mixtures had poor blending, which would indicate that there should be performance issues with many of these mixtures. However, the quality of blending had no apparent effect on mixture performance. They did not explain any poor performance or any difference in performance. Perhaps, the method used to determine them is not accurate for these types of mixtures.

5. Overall, some WMA with RAP contents up to approximately 50% RAP provided acceptable performance. Field trials or full-scale pavement accelerated tests with rigorous pavement monitoring are needed to confirm the findings of this study.

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APPENDIX A – INTERNET BASED SURVEYS & SURVEY RESULTS

Appendix A1: State Agency Based Survey

UMassD Surveys

Agency Experience with High Reclaimed Asphalt Pavement (RAP) Mixtures Incorporating Warm Mix Asphalt Technologies

0%
100%

Agency Experience

1. Does your agency allow the use of high RAP mixtures (Generally >25% RAP) for state paving projects? If No, please specify the maximum allowable amount of RAP for state projects in the comment box.

Choose one of the following answers

- ○ Yes
- ○ No
- ● No answer

Please enter your comment here:

2. What is the allowable range of moisture contents in RAP stockpiles utilized for paving mixtures in your state?

Check any that apply

- ☐ 0 – 0.99%
- ☐ 1 – 1.99%
- ☐ 2.0 – 2.99%
- ☐ 3.0 – 3.99%
- ☐ 4.0 – 4.99%
- ☐ 5.0 – 5.99%
- ☐ 6.0 – 6.99%
- ☐ 7% or Greater
- ☐ Not Specified
- ☐ Other:

3.Does your agency have a specification/limitation on the moisture content of the final paving mixture? If Yes, please provide details on how the moisture content is determined in the comment box.

Choose one of the following answers

- ○ Yes
- ○ No
- ● No answer

Please enter your comment here:

4. What is the maximum RAP content allowed for specific mixtures utilized in your state?

5. Please identify the WMA technologies previously/currently approved and utilized in your state. Please indicate the approved dosage in the comment box (if applicable).

Check any that apply

- ☐ SONNEWARMix
- ☐ CWM
- ☐ SONNEWARMixRT
- ☐ CECABASE RT
- ☐ Evotherm
- ☐ Low Emission Asphalt-Lite (LEA-Lite)
- ☐ Rediset LQ
- ☐ Advera
- ☐ ASTEC Double Barrel Green System
- ☐ Low Emission Asphalt (LEA)
- ☐ MAXAM AQUABlack
- ☐ Meeker Warm Mix System
- ☐ Terex Foamed WMA System
- ☐ Stansteel Accu-Shear
- ☐ Mad Dog Warm Mix Asphalt System

Other:

6. What are the common production and placement temperatures for high RAP mixtures (>25%) mixtures in your state?

7. What are the common production and placement temperatures for high RAP (>25%) + WMA mixtures in your state?

8. Which laboratory tests are used to determine the moisture susceptibility of high RAP + WMA mixtures?

Check any that apply

- [ ] AASHTO T283
- [ ] Hamburg Wheel Tracking Device (HWTD) Test - AASHTO T324
- [ ] Other:

9. Does your state have a pass/fail criterion for the tests noted in the previous question? If yes, please list the criteria for each test in the comment box.

Choose one of the following answers

- ○ YES
- ○ NO
- ● No answer

Please enter your comment here:

Resume later

Submit

Exit and clear survey

Appendix A2: Industry Based Survey

UMassD Surveys

Industry Experience with High Reclaimed Asphalt Pavement (RAP) Mixtures Incorporating Warm Mix Asphalt Technologies

0%
100%

Industry Experience

1. Do you produce high RAP mixtures (Generally >25% RAP) for state paving projects? If yes, please list which states in the comment box.

Choose one of the following answers

- ○ Yes
- ○ No
- ● No answer

Please enter your comment here:

2. What are the typical moisture content ranges of your RAP stockpiles? Click all that apply.

Check any that apply

- ☐ 0 – 0.99%
- ☐ 1 – 1.99%
- ☐ 2.0 – 2.99%
- ☐ 3.0 – 3.99%
- ☐ 4.0 – 4.99%
- ☐ 5.0 – 5.99%
- ☐ 6.0 – 6.99%
- ☐ 7% or Greater
- ☐ Other:

3. What is the typical range of binder content in your RAP stockpiles?

4. What types of plants are used in your operation?

Choose one of the following answers

- ○ Batch Plant
- ○ Drum Plant
- ○ Both Batch & Drum Plant
- ● No answer

5. What is the maximum permissible amount of RAP utilized in production (List for both batch and drum plants if applicable)? If producing mixtures in multiple states, please list requirements for each state.

6. If a batch plant is utilized, where is the RAP added? Also, what are the typical wet and dry mixing times when using high RAP?

7. What Warm Mix Asphalt (WMA) processes are your plants capable of utilizing? Please put dosage utilized in comment box (if applicable).

Check any that apply

- ☐ SONNEWARMix
- ☐ SONNEWARMixRT
- ☐ CECABASE RT
- ☐ Evotherm
- ☐ Low Emission Asphalt-Lite (LEA-Lite)
- ☐ Rediset LQ
- ☐ CWM
- ☐ Advera
- ☐ ASTEC Double Barrel Green System
- ☐ Low Emission Asphalt (LEA)
- ☐ MAXAM AQUABlack
- ☐ Meeker Warm Mix System
- ☐ Terex Foamed WMA System
- ☐ Stansteel Accu-Shear
- ☐ Mad Dog Warm Mix Asphalt System
- Other:

8. What production and placement temperatures are utilized for high RAP (>25%) mixtures?

9. What production and placement temperatures are utilized for high RAP (>25%) + WMA mixtures?

10. Would you be available and willing to help the team by producing high RAP content mixtures with and without WMA at different RAP moisture contents?

Choose one of the following answers

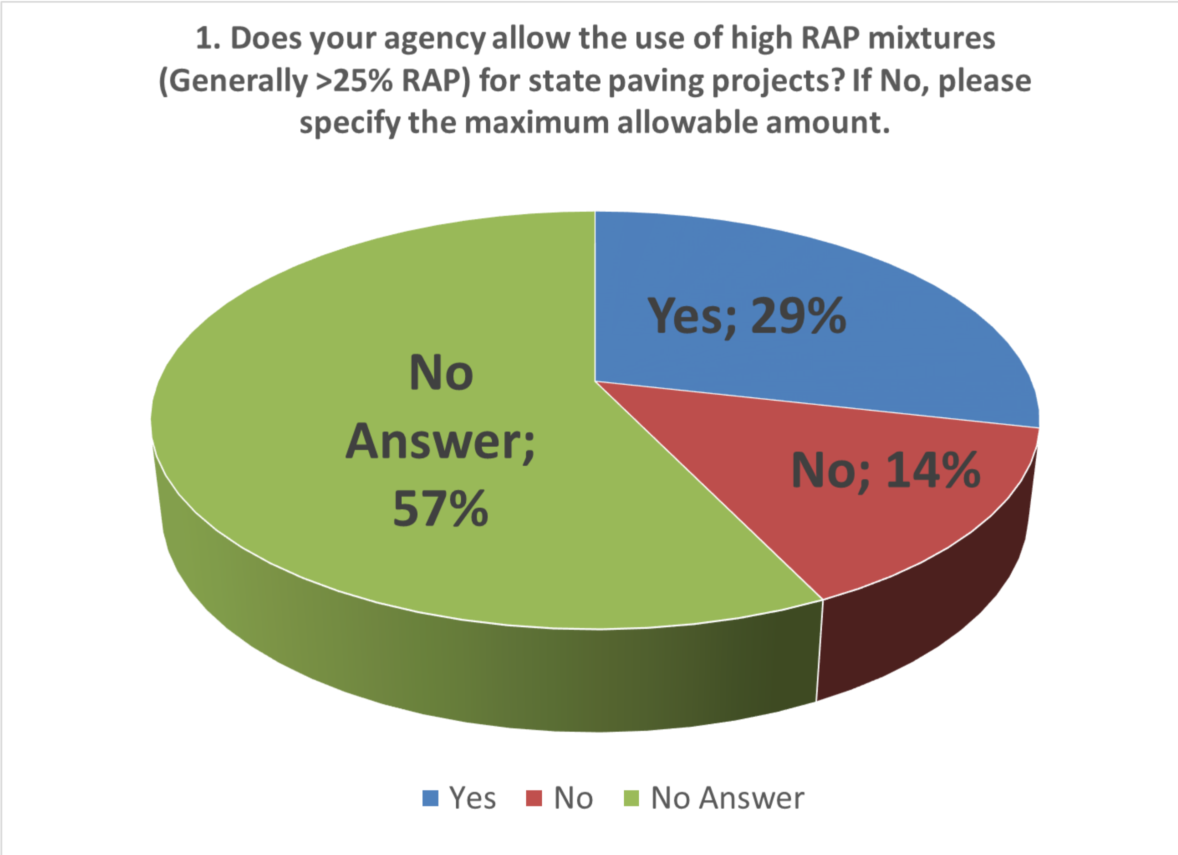
- YES
- NO
- No answer

Please enter your comment here:

Resume later | Submit | Exit and clear survey

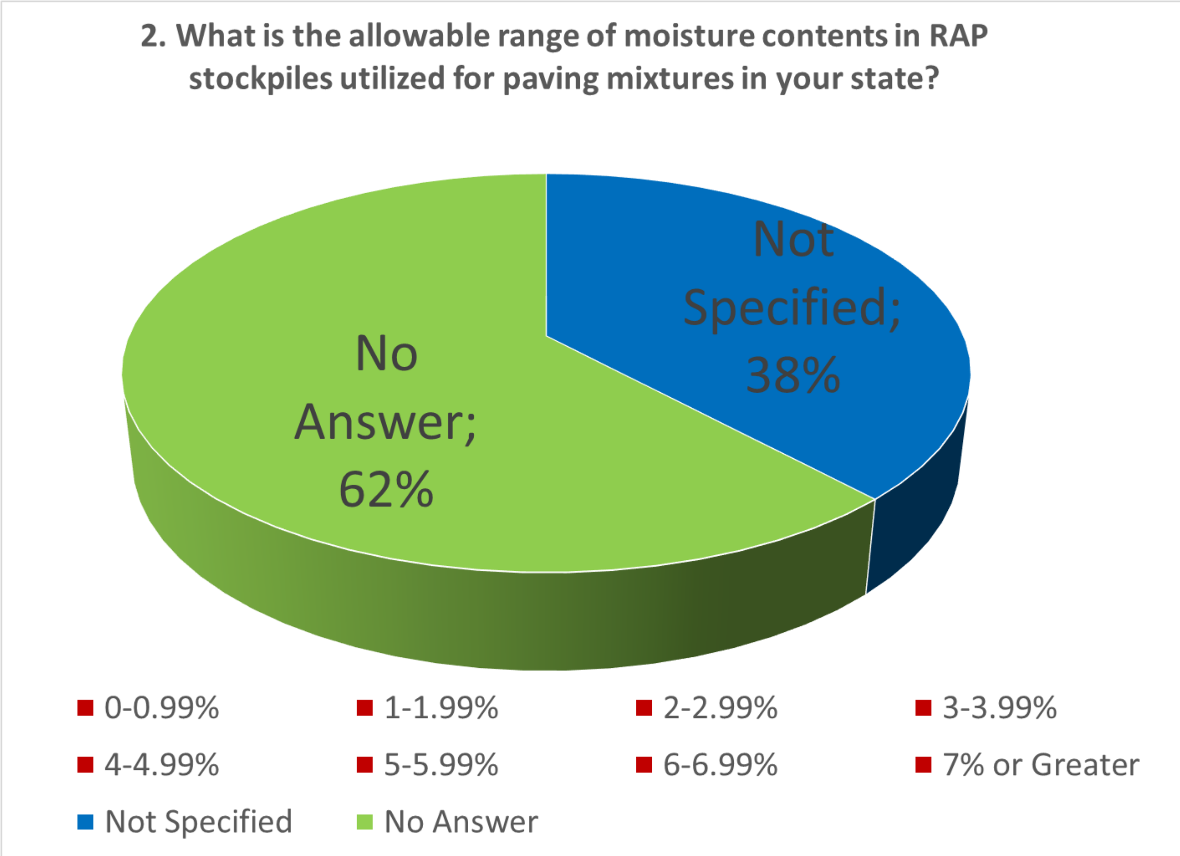
Appendix A3: State Agency Based Survey Results

Total Number of Responses to Survey = 21

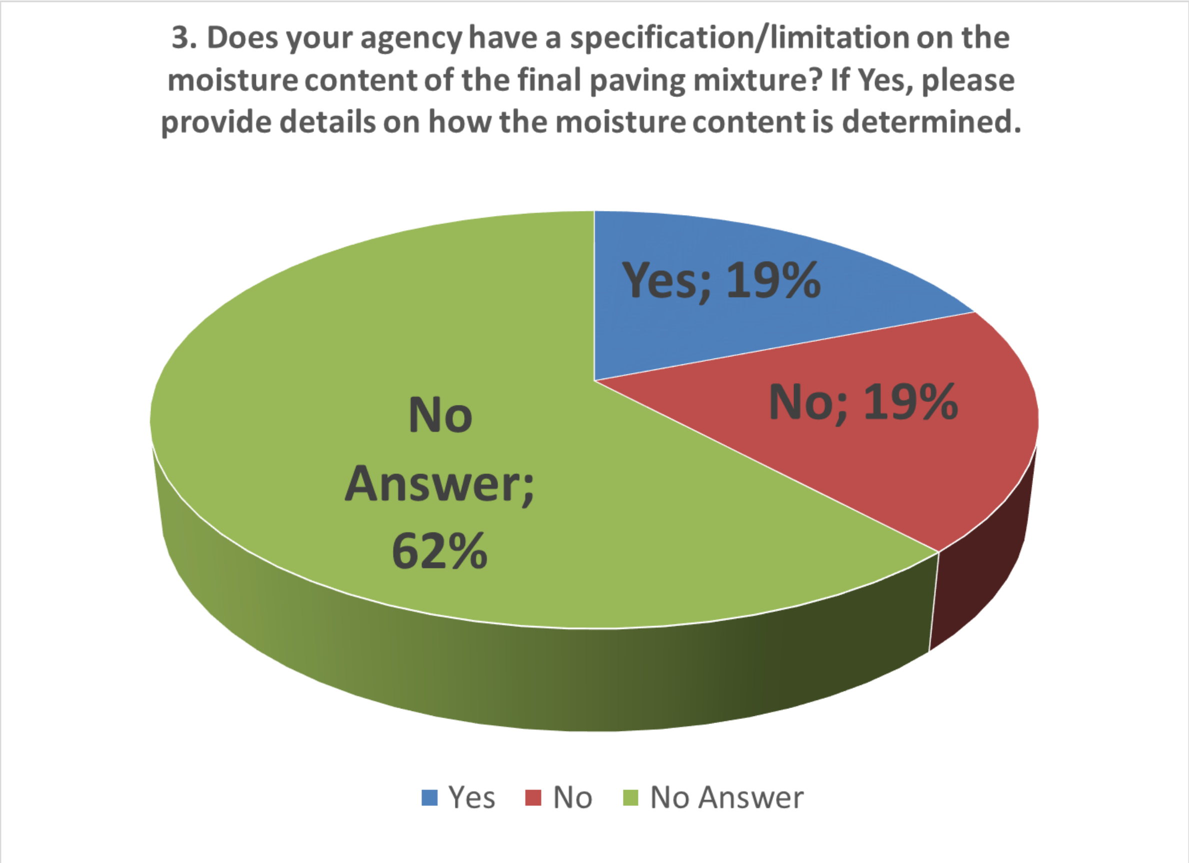


Question 1 Comments:

1. 25% for base course 0% for surface course.
2. Limit at 20%.
3. Up to 30% possible, done very few times in recent years.
4. Currently we do not allow more than 20%. We have done a pilot project that used 25 and 30 percent RAP with WMA.

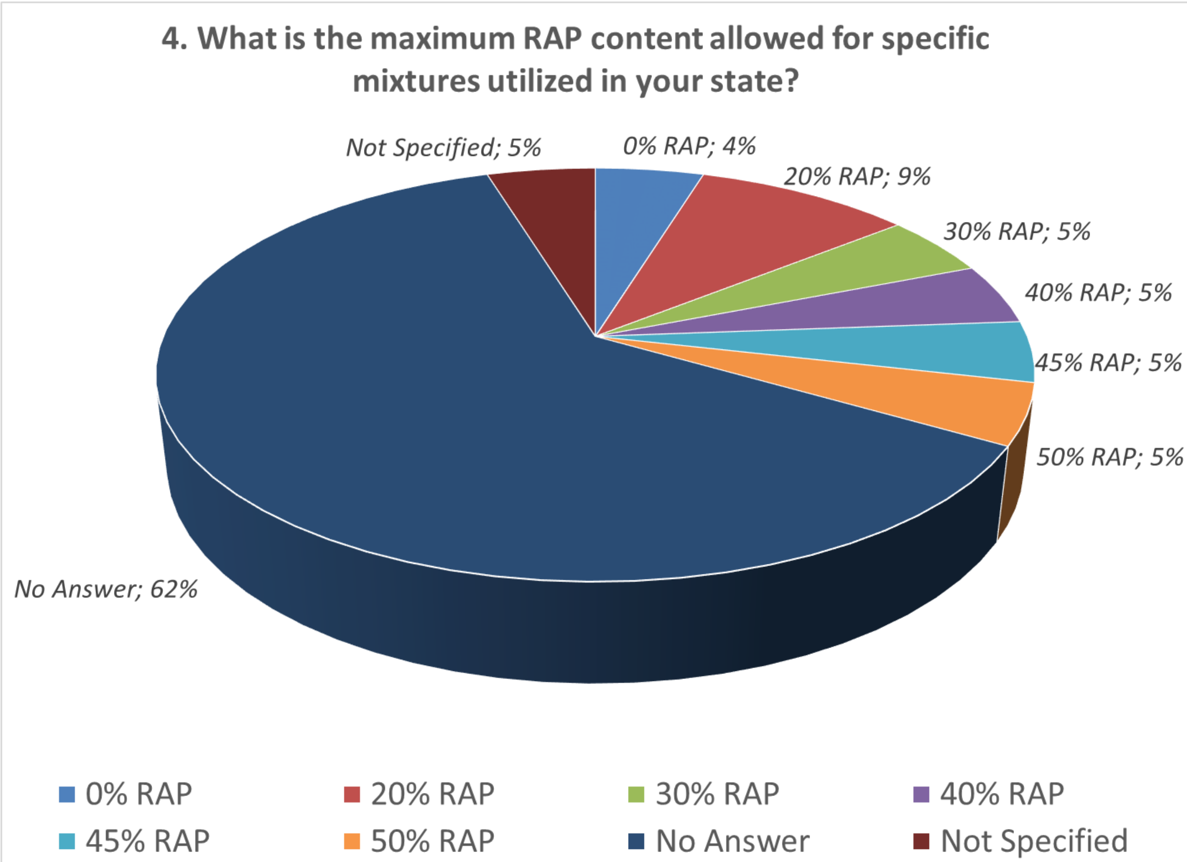


Question 2 Comments:
NONE

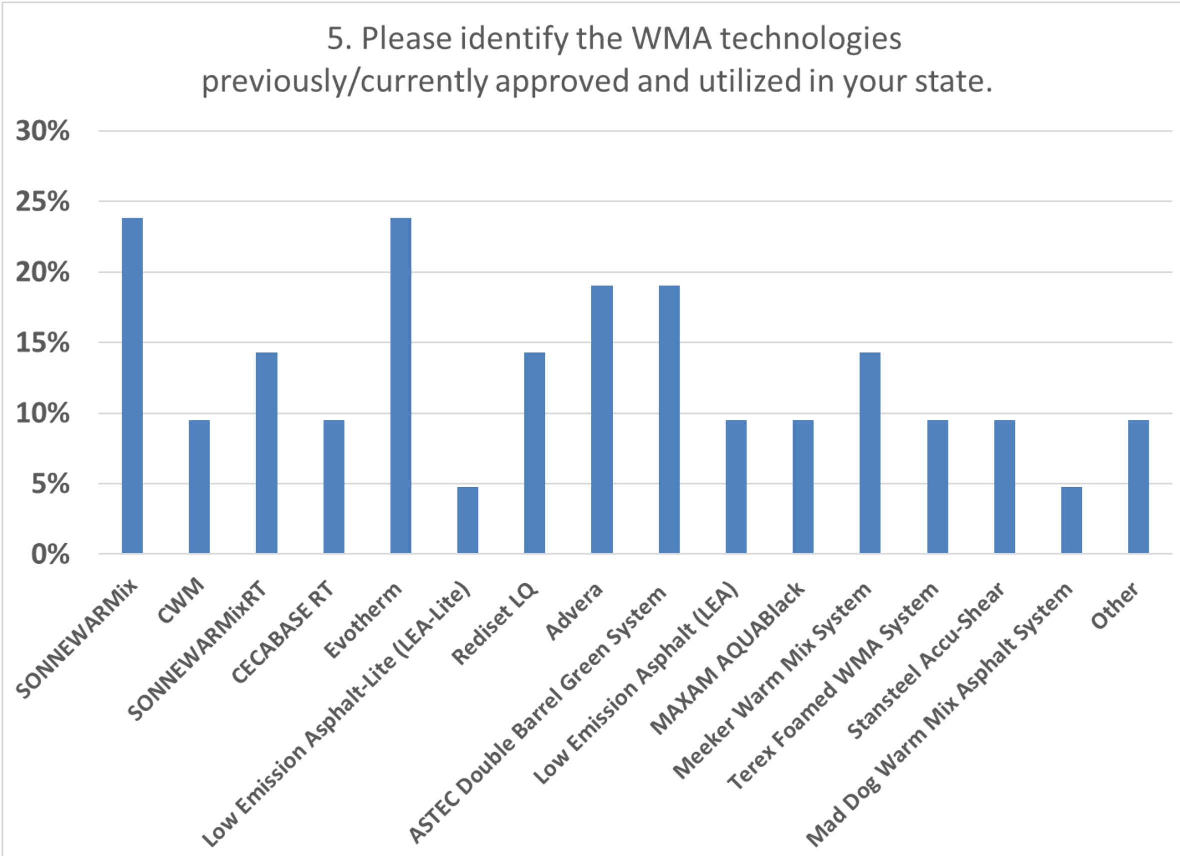


Question 3 Comments:

1. 0.5% AASHTO T 329
2. When coarse aggregate absorption exceeds 2.0% the mix is tested using an oven drying method and the apparent moisture cannot exceed 0.5% in the finished mix.



Question 4 Comments:.
NONE



<u>Question 5 Other:</u>.
1. SMART-FOAM
2. NEAUPG List (2 Respondents)

<u>Question 5 Approved Dosage:</u>
1. Rediset LQ – 0.5%
2. Stansteel Accu-Shear – 1 to 2%
3. At manufacturer's recommendation
4. According to manufacturer’s recommendations

6. What are the common production and placement temperatures for high RAP mixtures (>25%) mixtures in your state?

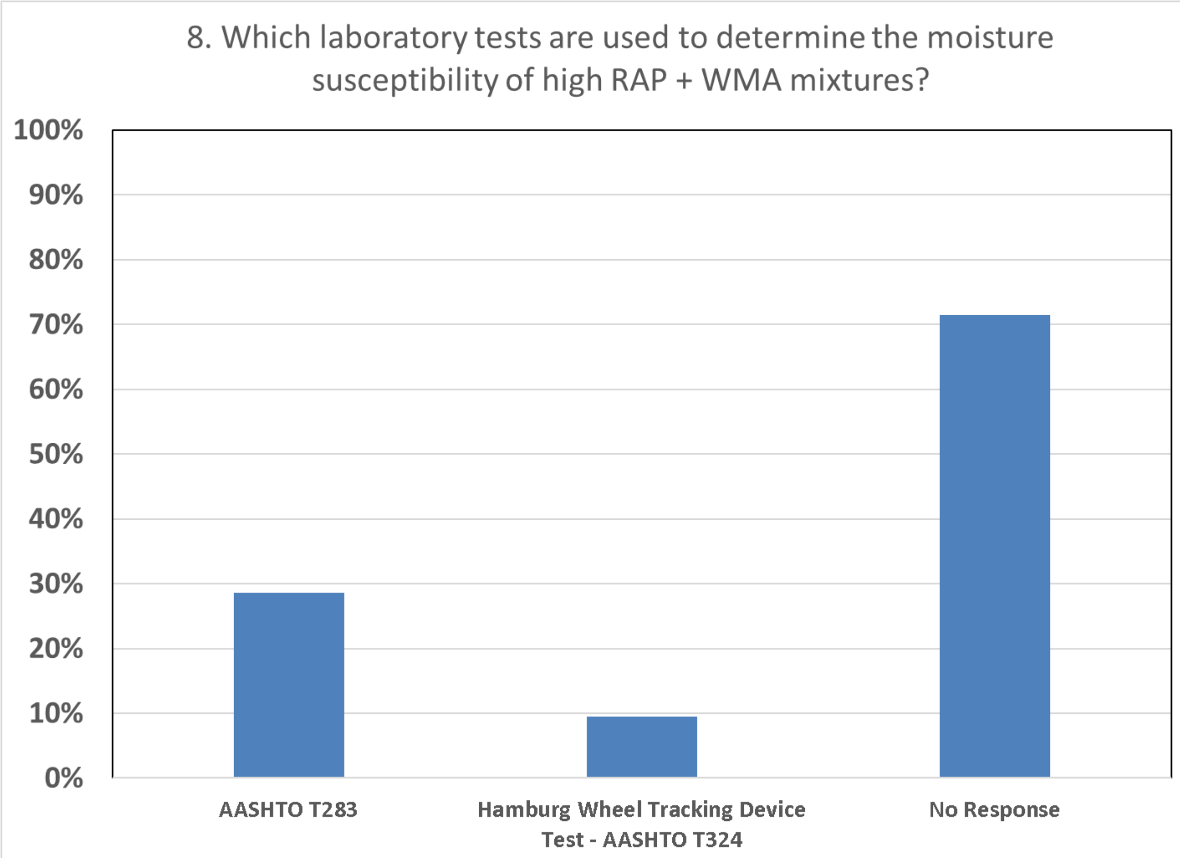
Question 6 Responses:

1. Not Applicable (3 respondents)
2. Production 295-320 / Placement 275-320
3. Currently no one is using more than 25%
4. 290 - 300, generally the same as hot mix or a little below
5. Production - 310-320F / Placement - 290-300F
6. No temperature reduction, 275F-325F

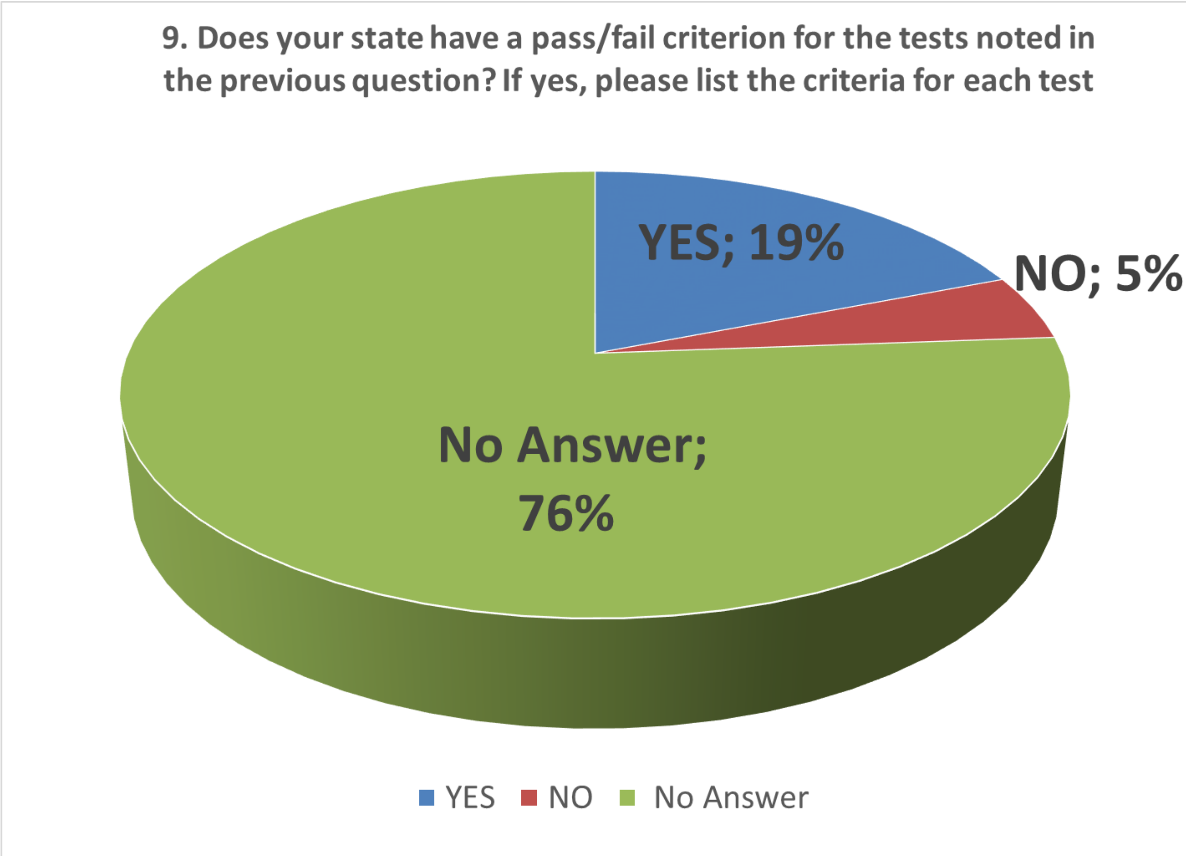
7. What are the common production and placement temperatures for high RAP (>25%) + WMA mixtures in your state?

Question 7 Responses:

1. Not Applicable (3 respondents)
2. Production 275-320 / Placement 250-320
3. Currently no one is using more than 25%
4. 290 - 300, generally the same as hot mix or a little below
5. These mixes are allowed but not common. Have not seen one to date.



<u>Question 8 Comments:</u>
NONE

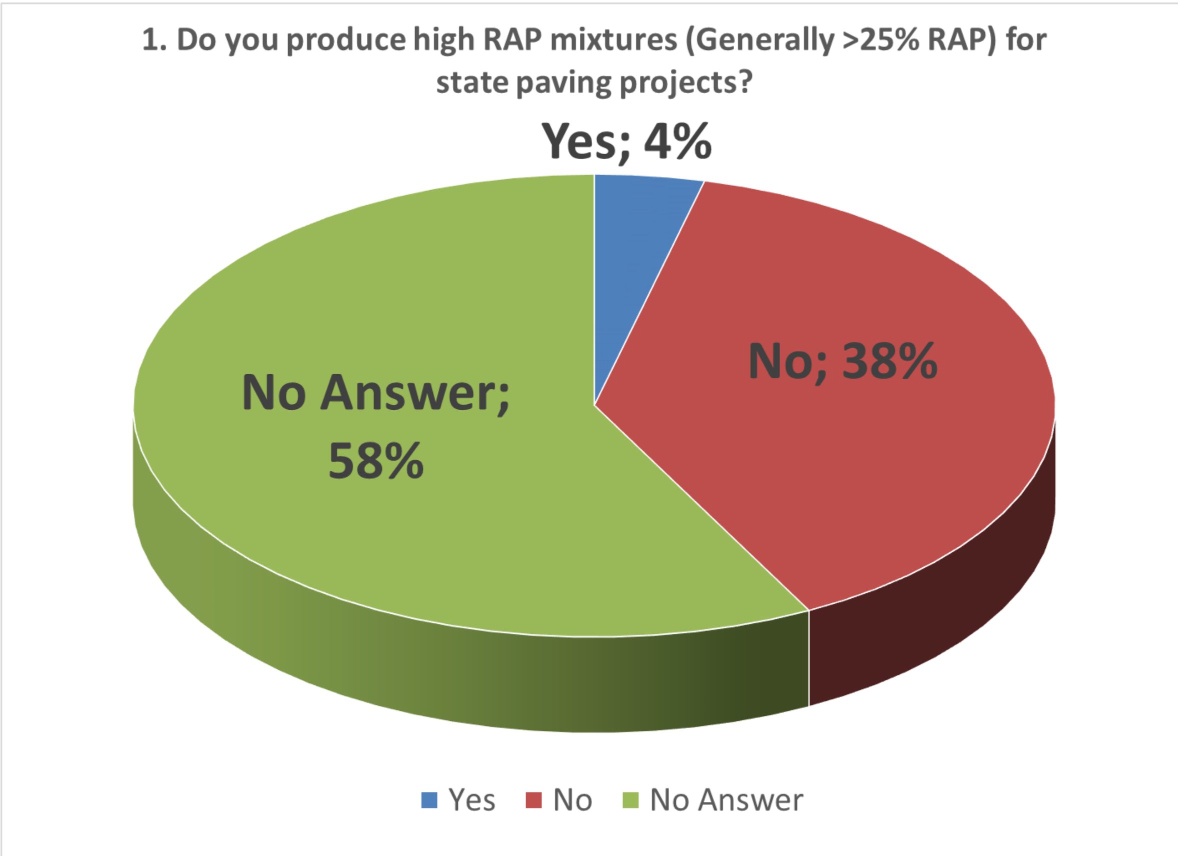


<u>Question 9 Responses</u>:

1. Minimum of 80% TSR value.
2. 80%
3. 80% TSR
4. 80% TSR, we are in the process of making minimum liquid anti-strip usage mandatory.
5. HWTD - SIP above 15,000, max rut 12.5mm at 20,000 TSR greater than 80%

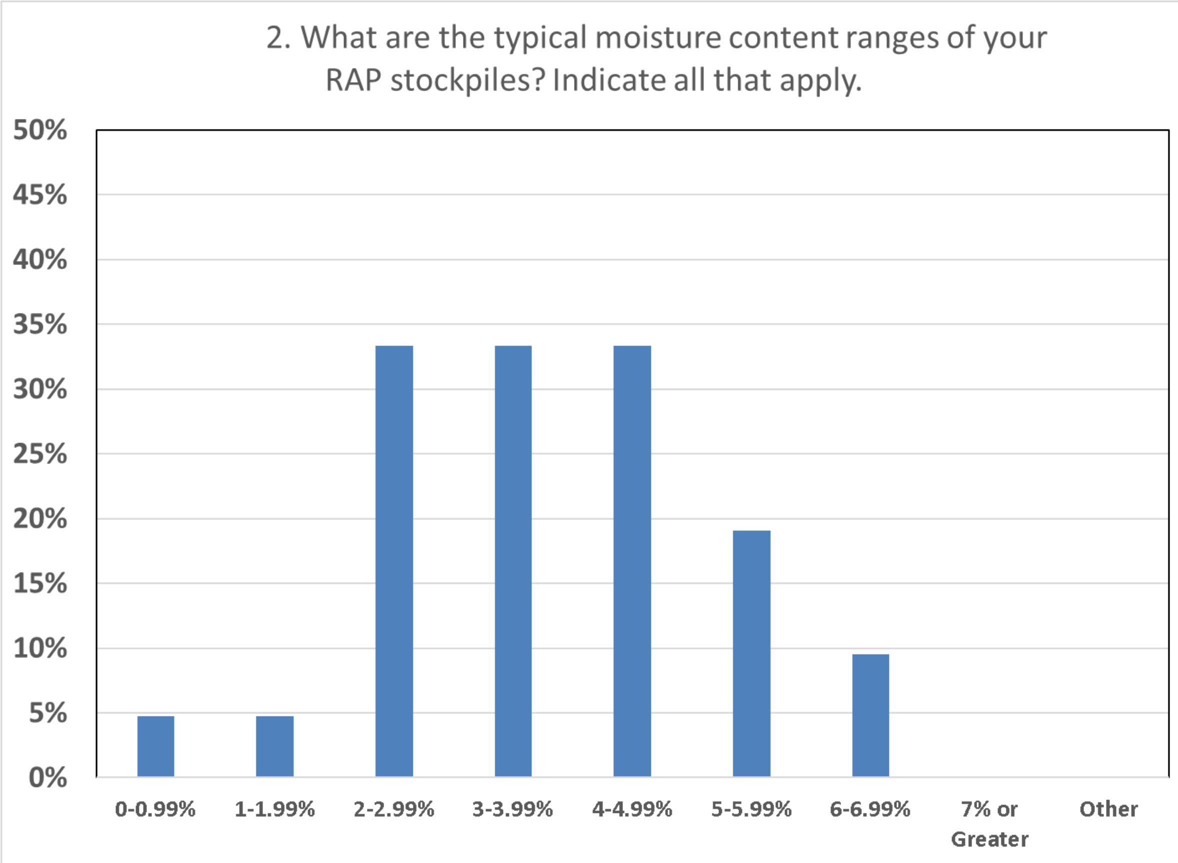
Appendix A4: Industry Based Survey Results

Total Number of Responses to Survey = 26



<u>Question 1 Comments:</u>

1. We operate in approximately 40 states (62 companies) so my answers are averages.
2. Specificity mixes sometimes uses higher rap %



Question 2 Comments:
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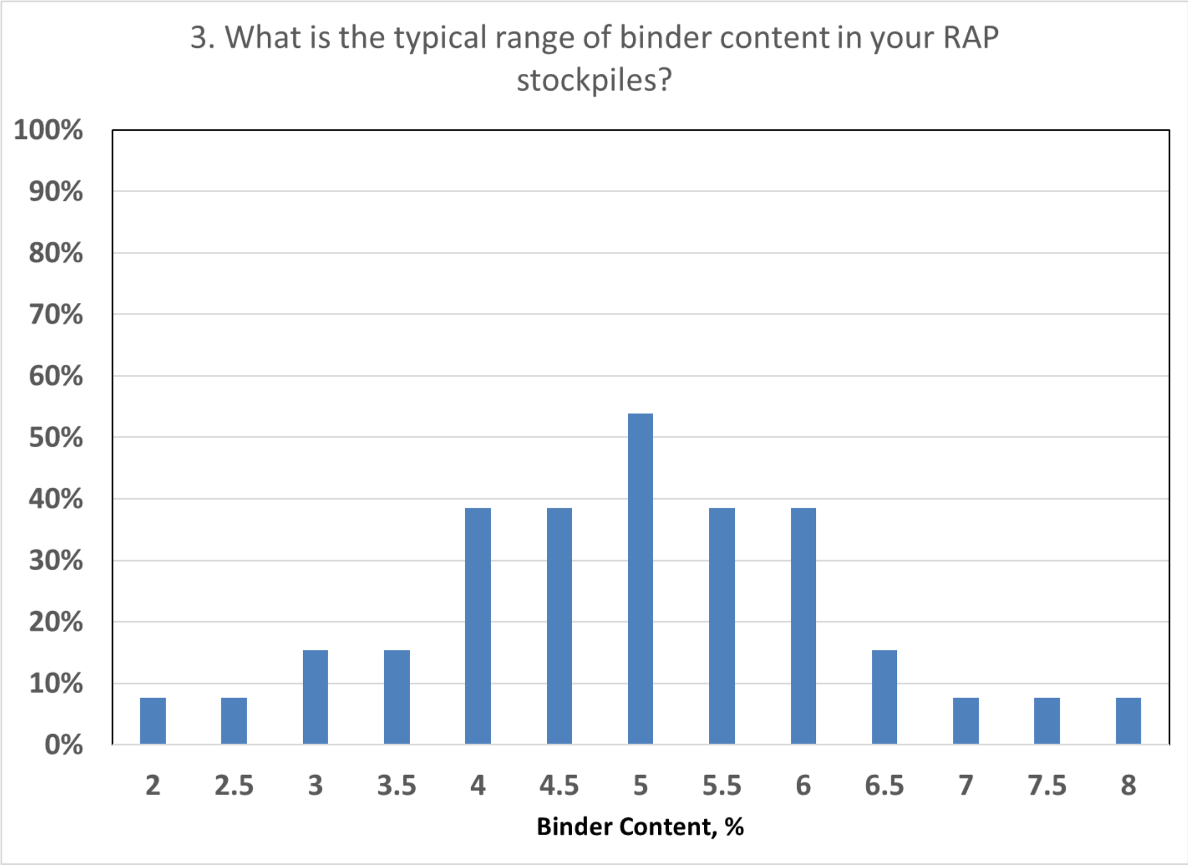
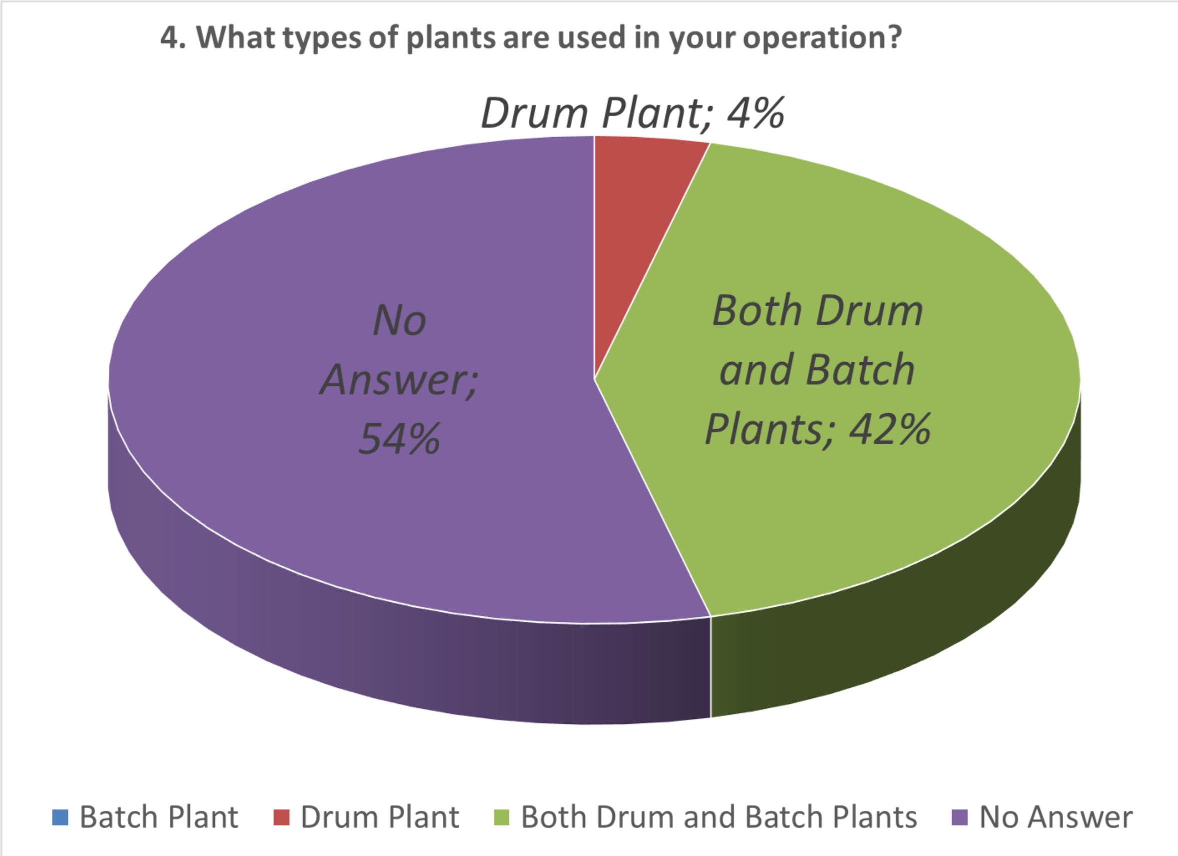


Question 3 Comments:
NONE



Question 4 Comments:
NONE

5. What is the maximum permissible amount of RAP utilized in production (List for both batch and drum plants if applicable)? If producing mixtures in multiple states, please list requirements for each state.

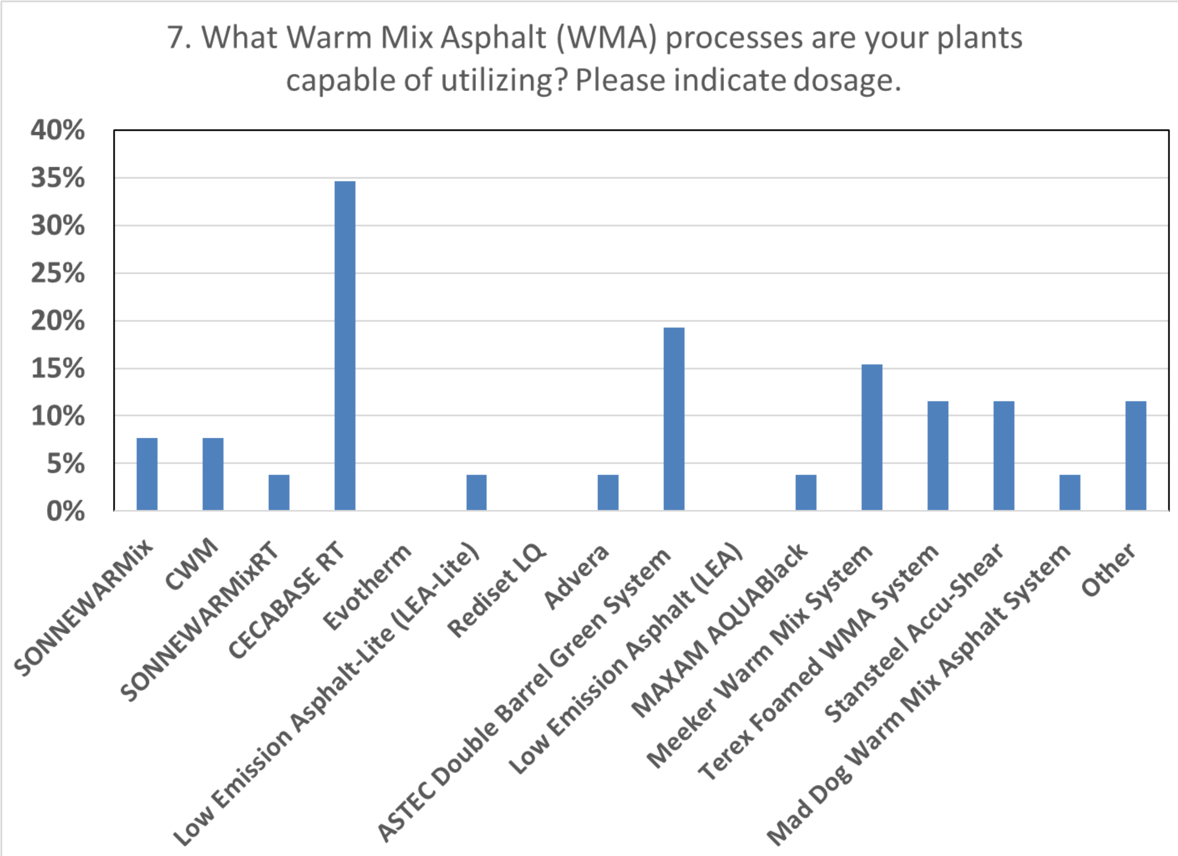
Question 5 Responses:

1. Batch 20% Drum 25%
2. 20% (2 respondents)
3. VT: No more than 50% allowed. 0-20% we need to stay with base grade of binder. 20-25% we need to bump to a lower grade. 25-50 we need to use a blending chart.
4. Varies, generally no difference in what's specified for batch and drum. We are limited in some cases w/ batch plants due to steam issues when adding the wet RAP.
5. 25% rap for Drum plant 20% rap for Batch plant
6. 22% to 25% Based on maximum replacement binder of 1.0%
7. MA - 25% RI - 25%
8. For surface maximum RAP set at 15% for both batch and drum plants; for base and intermediate courses, batch plants limited to 20%, drum plants limited to 40%.
9. RIDOT- 25% max RAP(58-28 PGAB is required for mixes 15% and higher)- no RAP allowed in surface courses. MassDOT - 25% max in base / binder mixes - 15 % in surface - 10% in ARGG.
10. 1.0% TRB without grade bump
11. 15% (internal limit)

6. If a batch plant is utilized, where is the RAP added? Also, what are the typical wet and dry mixing times when using high RAP?

Question 6 Responses:

1. Pugmill Wet 5 seconds Dry 40 seconds
2. pugmill via screw 6 & 22- this is a guess but very close some may be more or less for both depending on the moisture content
3. RAP is typically weighed in an external weigh hopper and fed into the pug mill during the batching process. Typical dry mix times are 5 to 10 seconds and wet mix times range between 25 and 40 seconds.
4. RAP is added in pug mill. dry:10 wet 36
5. Varies
6. Introduced into weigh hopper. we are typically 7 seconds wet and 34 seconds dry for mix times.
7. External weigh box into pugmill 36 to 40 sec
8. RAP is introduced directly into pugmill. Typical dry mix time is 3-5 seconds. Typical wet mix time is 30-40 seconds.
9. The RAP is added to the pug mill. Mixing times vary depending on amount of rap and conditions.
10. Exterior weigh box into pugmill Timers dependent upon mix type
11. Weigh hopper, N/A



Question 7 Other:.
1. ASTEC Green PAC
2. Gencor Green Machine (2 respondents)

Question 7 Dosage:

SONNEWARMix	0.05% (1)
SONNEWARMixRT	0.3-0.5% (1)
CECABASE RT	0.4% (3), 0.5% (3), 0.4-0.6% (1)
Low Emission Asphalt-Lite	0.3-0.75% (1)
ASTEC Double Barrel Green	1% (1), 2% (1), 1-2% (1), 0.5-2% (1)
MAXAM AQUABlack	0.5-2% (1)
Meeker Warm Mix System	0.5-2% (1), 2% (1), 1-2% (1)
Terex Foamed WMA System	0.5-2% (1), 2% (1), 1-2%(1)
Stansteel Accu-Shear	2% (1), 0.5-2% (1), 1.5-5%, Typical 1.3%(1)
Mad Dog Warm Mix Asphalt	2% (1)
Astec Green Pac	1-2% (1)
Gencor Green Machine	2% (1)

(#) = Number of Respondents

8. What are the common production and placement temperatures for high RAP mixtures (>25%) mixtures in your state?

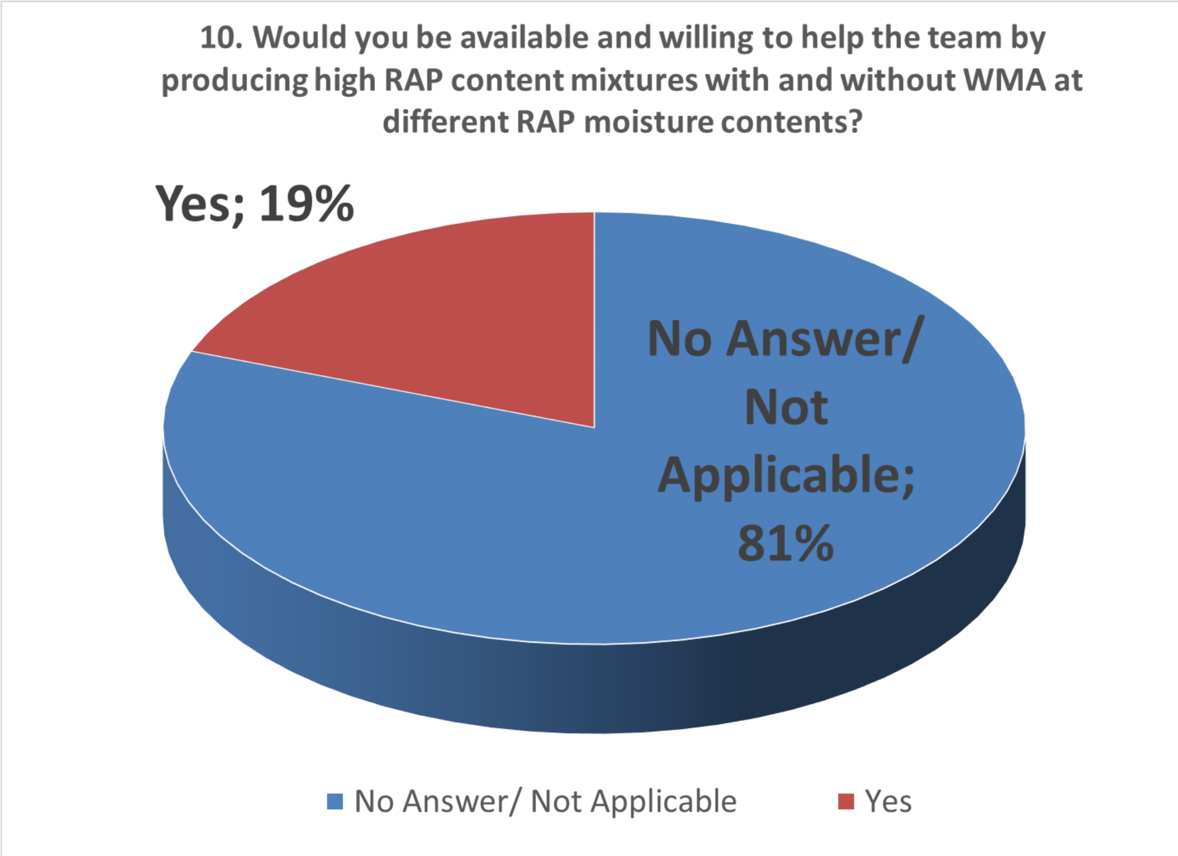
<u>Question 8 Responses</u>:

1. Not Applicable (5 respondents)
2. 300 to 320 degree production. 275 to 300 degree placement
3. ~ 310 to 325F
4. 275-325F
5. Based on conditions. Mixing approx. 335F Placement approx. 290F
6. 275-325F
7. No products utilize >25%

9. What are the common production and placement temperatures for high RAP (>25%) + WMA mixtures in your state?

<u>Question 9 Responses</u>:

1. Not Applicable (5 respondents)
2. 300 to 320 degree production 275 to 300 degree placement
3. Likely similar to HMA. Trend is for less temperature reduction than in the past. Energy savings is not that significant and WMA generally used as compaction aid. Sometimes max temperature is set by DOT at ~275F
4. 250-300F
5. Same
6. 250-300F
7. No products utilize >25%



Question 10 Comments:

1. Jobs in CT that allow high RAP mixes are few making it difficult to support this kind of research.
2. I'm sure we can find some help in the NE area.
3. Will help if possible. One thing to note is all our plants using rap take daily moisture contents and adjust virgin aggregates temperatures accordingly to dry the RAP.
4. As is convenient to our production schedule.
5. NHDOT does not allow at this time.
6. Possibly, but will depend on timing & details.