The Use of Recycled Asphalt Products in Asphalt Pavements

Prepared by: Scott Zinke and
James Mahoney

Report Number: CT-2278-F-15-8

June 3, 2015

FINAL REPORT

Project No. SPR 2278

Connecticut Advanced Pavement Laboratory
Connecticut Transportation Institute
School of Engineering
University of Connecticut

Prepared for:
Connecticut Department of Transportation
Bureau of Policy and Planning
Research Implementation Unit

Michael Connors
Assistant Planning Director

Disclaimer

This report [article, paper or publication] does not constitute a standard, specification or regulation. The contents of this report [article, paper or publication] reflect the views of the author(s) who (are) responsible for the facts and the accuracy of the data presented herein. The contents do not necessarily reflect the views of the Connecticut Department of Transportation or the Federal Highway Administration.

Acknowledgements

This report was prepared by the University of Connecticut, in cooperation with the Connecticut Department of Transportation and the United States Department of Transportation, Federal Highway Administration. The opinions, findings and conclusions expressed in the publication are those of the author(s) and not necessarily those of the Connecticut Department of Transportation or the Federal Highway Administration. This publication is based upon publicly supported research and is copyrighted. It may be reproduced in part or in full, but it is requested that there be customary crediting of the source.

Standard Conversions

SI* (MODERN METRIC) CONVERSION FACTORS				
APPROXIMATE CONVERSIONS TO SI UNITS				
Symbol	**When You Know**	**Multiply By**	**To Find**	**Symbol**
		LENGTH		
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		AREA		
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yard	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
		NOTE: volumes greater than 1000 L shall be shown in m^3		
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
		TEMPERATURE (exact degrees)		
^oF	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	^oC
		ILLUMINATION		
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
		FORCE and PRESSURE or STRESS		
lbf	poundforce	4.45	newtons	N
lbf/in^2	poundforce per square inch	6.89	kilopascals	kPa
APPROXIMATE CONVERSIONS FROM SI UNITS				
Symbol	**When You Know**	**Multiply By**	**To Find**	**Symbol**
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
		AREA		
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2
		VOLUME		
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.314	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000 lb)	T
		TEMPERATURE (exact degrees)		
^oC	Celsius	1.8C+32	Fahrenheit	^oF
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m^2	0.2919	foot-Lamberts	fl
		FORCE and PRESSURE or STRESS		
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2

*SI is the symbol for the International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380.
(Revised March 2003)

Technical Report Documentation Page

1. Report No. CT-2278-F-15-8	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle The Use of Recycled Asphalt Products in Asphalt Pavements Final Report		5. Report Date June 3, 2015 6. Performing Organization Code
7. Author(s) Scott Zinke, James Mahoney		8. Performing Organization Report No.
9. Performing Organization Name and Address University of Connecticut Connecticut Transportation Institute 270 Middle Turnpike, U-202 Storrs, Connecticut 06269-5202		10 Work Unit No. (TRIS) N/A 11. Contract or Grant No. N/A 13. Type of Report and Period Covered Final Report
12. Sponsoring Agency Name and Address Connecticut Department of Transportation 2800 Berlin Turnpike Newington, CT 06131-7546		14. Sponsoring Agency Code SPR-2278
15. Supplementary Notes Prepared in cooperation with the U.S. Department of Transportation, Federal Highway Administration		

16. Abstract

Reclaimed asphalt pavement (RAP) and recycled asphalt shingles (RAS) are two of the most commonly used recycled materials in the world. Recommendations as to their use and handling in CT need to be made in order to increase the amount of RAP that may be introduced into the mixture and also to make determinations as to the benefits and total quantity of RAS that should be used. CTDOT constructed three pilot projects utilizing RAS, RAS with RAP and then varying quantities of RAP from 15%-40%. The projects are summarized in this research. Performance tests show comparisons between the test sections and control sections. Density analysis shows that increasing RAP quantities beyond 20% should be avoided at this time. Recommendations are made to continue monitoring these pilot sections in order to determine the longer term effects of the recycled products.

17. Key Words	18. Distribution Statement No restrictions. This document is available to the public through the National Technical Information Service, Springfield, Virginia 22161. The report is available on-line from National Transportation Library at http://ntl.bts.gov.		
19. Security Classif. (of report) Unclassified	20. Security Classif. (of this page) Unclassified	21. No. of Pages 71	21. Price
Form DOT F 1700.7 (8-72)	Reproduction of completed page authorized		

Table of Contents

List of Tables

List of Figures

Executive Summary

Reclaimed asphalt pavement (RAP) and recycled asphalt shingles (RAS) are two of the most commonly used recycled materials in the world. Recommendations as to their use and handling in CT need to be made in order to increase the amount of RAP that may be introduced into the mixture and also to make determinations as to the benefits and total quantity of RAS that should be used. Utilizing RAP and/or RAS can mean reductions in mining and processing of aggregates as well as reductions in the use of virgin asphalt resulting in both environmental and economic benefits. Other benefits of using these recycled products include the reduction in landfilling of these products. Connecticut Department of Transportation (CTDOT) constructed three pilot projects utilizing RAS, RAS with RAP and then varying quantities of RAP from 15%-40%. These projects are summarized in this research. As these projects were constructed, materials were collected at the respective production facilities for fabrication of test specimens. Performance testing included moisture susceptibility via tensile strength ratio, Hamburg wheel track testing and rutting susceptibility. Performance tests show comparisons between the test sections and control sections. With the exception of the base mix on the RAP/RAS project performance testing results show no obvious disparities among the mixes on the three different projects. Research team personnel monitored the construction of the projects in an effort to determine of there were any construction related problems that may have impacted the quality of the pavement. Nothing of consequence was noted. Results of density testing which was performed by CTDOT for acceptance purposes were collected for analysis. Density analysis shows that increasing RAP quantities beyond 20% should be avoided at this time. Recommendations are made to continue monitoring these pilot sections in order to determine the longer term effects of the recycled products.

Introduction and Background Summary

There are two major material waste streams that contain asphalt binder. These include flexible pavement materials that are milled from roadways prior to resurfacing and asphalt shingles that are removed from the roofs of residential and commercial structures at the end of their service life.

Materials milled from flexible pavement surfaces are generally referred to as Reclaimed Asphalt Pavement (RAP). RAP represents the most recycled material in the United States. At a recycling rate of 99%, the amount of RAP that was incorporated into pavements nationwide in the year 2012 was 68.3 million tons, accounting for about 19 million barrels of conserved asphalt binder (assuming a 5.0% asphalt content) [1].

Processed waste from asphalt shingles is generally referred to as Recycled Asphalt Shingles (RAS). RAS accounts for much less (by weight, versus RAP) of the generated waste that can be recycled into asphalt pavements, however, the recycling rate and amount of used recycled RAS is significant. The amount of RAS that was incorporated into pavements nationwide in the year 2012 was approximately 1.9 million tons, accounting for about 2.2 million barrels of conserved asphalt binder (assuming a 20.0 % asphalt content) [1].

RAP is generated when the roadway surface is milled prior to placing the new asphalt pavement as the wearing surface. Milling has become a standard practice prior to paving for many reasons, which include: removing surface distresses, maintaining clearances under structures, improving the overall cross-section of the road, as well as maintaining roadside curb reveal. These practices lead to the generation of significant quantities of RAP throughout the construction season.

The use of RAP in new asphalt pavements has been a standard practice for many years in Connecticut by some Hot-Mix Asphalt (HMA) Producers. The incorporation of RAP into the new asphalt pavement has several benefits, all stemming from the fact that the RAP contains aggregate and asphalt binder. Assuming that the RAP was derived from a CTDOT roadway and that source material property requirements such as LA Abrasion, Soundness, etc. are not apt to change significantly over the service-life of a pavement, the aggregate contained in the RAP is likely to meet CTDOT aggregate requirements, which have not changed significantly over the years. Recycling of the aggregate in the RAP greatly reduces the amount of virgin material required to produce asphalt pavements. The RAP also contains asphalt binder, which can reduce the amount of new asphalt binder that is required to make the asphalt pavement. This can translate into significant cost savings as liquid asphalt remains the most expensive component.

When utilizing RAP in new asphalt pavements, consideration must be given to the fact that asphalt binder becomes much stiffer during its service-life in asphalt pavement due to oxidation. Therefore, depending on the quantity of RAP being used, the PG Grade of the new asphalt binder in the mixture may need to be adjusted to compensate for the stiffer asphalt binder that is present in the incorporated RAP. It may be necessary to utilize a softer grade liquid binder than would normally be used if no RAP (or a lesser quantity) were incorporated into the new asphalt pavement mix. If elevated percentages of RAP are used and no adjustments made for the stiffer asphalt binder, the end result will be an inferior pavement with a greater susceptibility to cracking. This would result in a greatly reduced service-life, particularly in the northeastern United States where temperatures can reach the limits of the PG binder specifications.

The second material waste stream, asphalt roofing shingles, contains a high percentage of asphalt binder, along with a mineral coating and a backing material made up of either an organic material or fiberglass. At the end of their useful service life, asphalt shingles are removed (often referred to as tear-offs) and are either landfilled or reused in other applications. The quantity of tear-off asphalt shingles that is generated far exceeds the demand for this material.

The use of RAS in asphalt pavements represents another outlet to reduce the quantity of tear-offs being landfilled. In addition, as RAS is high in asphalt binder content, a reduction in the amount of new asphalt binder required to produce new HMA pavements can be realized. This, in turn, could potentially result in cost savings assuming the service life of the pavement was not negatively affected.

The processing of the tear-offs is very important for their use in asphalt pavements. The processing must include the removal of virtually all of the nails and wood contained in this waste stream. In addition, all other deleterious materials (e.g., metal flashing, brick, etc.) must also be removed. Following the removal of all deleterious materials, the shingles must be reduced to a small and uniform size (usually 100% passing either the 3/8” or #4 sieve) before they can be included in a mixture.

One challenge in incorporating RAS into asphalt pavements is that the asphalt binder used in roofing shingles is much stiffer than typical asphalt binders used in asphalt pavements. Therefore, the quantity of RAS that can be incorporated in pavements needs to be limited so as not to adversely affect the performance of the pavement.

The use of RAS in combination with RAP in asphalt pavements presents several issues. As indicated above, both RAP and RAS contain stiffer asphalt binder than what is desired in asphalt pavements in the northeastern region of the U.S. Therefore, particularly when used in combination with one another, the new asphalt binder in the mix must be softer than what would normally be used in order to compensate for the stiffer binder from the recycled materials. There is uncertainty as to the actual amount of asphalt binder that is available, referred to as effective asphalt, particularly from the RAS, for combining with the new asphalt binder in the pavement. Of concern is how much of the liquid asphalt in the recycled products actually blends with the virgin asphalt and contributes to the total effective asphalt content of the mix.

During the 2012 construction season, CTDOT placed a section of HMA containing 5% RAS with no RAP. The project specification was developed by the CAP Lab as part of a research project so that CTDOT and contractors could gain experience using RAS and identify any issues associated with its use. Moving forward, the use of RAS while excluding the use of RAP is not practical, since incorporating RAP into new HMA pavements has proven to be a technique for successfully recycling pavement millings.

Therefore, a need to develop a comprehensive specification that allows the use of both in the same mix exists. This presents a challenge as the asphalt binder contribution of both materials is uncertain. Many states are moving toward using a binder replacement specification that puts restrictions on the amount of new asphalt binder that can be replaced with recycled asphalt binder. State DOTs are also considering limiting the amount of RAS asphalt binder that can be counted toward the total asphalt content of the asphalt pavement.

In addition, current CTDOT specifications limit the amount of RAP in asphalt pavements to a maximum of 20% of the total mix. The Federal Highway Administration is urging states to increase the amount of RAP being used in their asphalt pavements. In order to increase the amount of RAP routinely allowed in CTDOT's asphalt pavements, the specification must be adapted to account for increased percentages of the stiffer RAP binder. The use of high RAP contents in asphalt pavements (higher than the CTDOT standard 20%) would preclude the use of RAS as the final product would have an asphalt binder that is much stiffer than desired and would ultimately shorten the service-life of the pavement.

The use of RAP and RAS in asphalt pavements have both an environmental and economic benefit, but this requires a comprehensive approach so as not to negatively impact the asphalt pavement's performance.

Problem Statement

There are two major items to address with this research. The first is the incorporation of RAS into asphalt pavements that already routinely include a percentage of RAP. The second item is the potential increase in the amount of RAP incorporated into CTDOT mixes.

There are many agencies in the U.S. that allow the incorporation of RAS into asphalt pavements however; these percentages vary greatly from state-to-state. The development of a comprehensive specification that allows the use of RAS along with RAP is needed to maintain the quality of paving construction materials being used in Connecticut. Maintaining the quality of these materials ensures the continued desired length of service from asphalt pavements.

The construction of pilot projects under controlled conditions will allow CTDOT to develop a specification allowing both RAS and RAP without compromising the integrity of the asphalt pavement. These pilot projects will allow CTDOT to establish confidence that the use of RAS will not reduce the service-life of the pavements being placed, as well as to develop protocols for its use.

In addition, CTDOT's specification for the use of RAP limits the amount that can be incorporated into new asphalt pavements to a maximum of 20%. Research from around the country shows that this maximum amount can be increased to maximize the benefits of using RAP without compromising the performance of the pavement. The placement and monitoring of pilot projects containing high RAP contents could be performed to ensure that the recommended changes to the CTDOT specification will not have an adverse impact on the pavement's performance.

Objectives and Work Plan

The objective of the research was to make recommendations regarding specification and quality assurance guidelines for asphalt pavement containing RAS and RAP, as well as for mixes containing high RAP content (greater than 20%). In order to achieve these objectives, the following work plan was proposed and approved by CTDOT. A review of regional and non-regional specifications was conducted along with a literature-based review of current practices. CTDOT HMA suppliers were surveyed to gain insight as to the maximum amount of RAP their respective production facilities can accommodate. Material samples and construction data were collected at the time of placement of pilot projects containing varying RAP contents, as well as one project containing strictly RAS, followed by one project utilizing both RAS and RAP. Results of laboratory testing on collected mixes were analyzed. Specifically, the mixes were subjected to moisture susceptibility testing via tensile strength ratio and Hamburg Wheel-track testing, as well as rutting susceptibility testing via the Asphalt Pavement Analyzer (APA). Follow-up condition surveys of the test sections were performed as well.

Reviewed Literature

A State of the Practice report published by the Federal Highway Administration in 2011 [2] states that the two most influencing factors guiding the increased use of RAP are economic and environmental benefits. The report author A. Copeland states that the reason for this is the conservation of raw materials in addition to the conservation of energy it takes to mine and process those raw materials and to produce asphalt pavement using solely virgin materials. From a production cost perspective, the report indicates that obtaining and processing the materials constitutes 70% of the cost of the production of HMA. The report goes on to state that generally, in the past, state DOTs have specified the maximum amount of RAP allowed in the mix by percent of the weight of the aggregate or by weight of the total mix. It is stated, however, that the major issue with higher RAP percentages is the amount of binder replacement that is needed to develop a viable asphalt pavement.

The author cites an article by the National Center for Asphalt Technology (NCAT) that surveyed 18 states across the country utilizing information from the Long Term Pavement Performance (LTPP) program [3]. The projects referred to in the article focused on the comparison of asphalt pavements constructed in the same areas containing 30% RAP and 100% virgin asphalt. The projects were placed between 6 and 17 years prior to the time of the report. International Roughness Index (IRI), fatigue cracking, longitudinal cracking, transverse cracking, rutting, raveling and block cracking were the distress parameters used for the analysis. The conclusions presented by NCAT indicated that in most cases, the sections with 30% RAP provided the same overall performance as the control mixes containing no RAP. Copeland [2] concluded the same.

Connecticut HMA Supplier Survey

Suppliers of HMA to CTDOT were surveyed with respect to their current usage of RAP. There are approximately 12 suppliers of HMA that provide nearly all of the HMA purchased by CTDOT. Nine of these suppliers responded to the survey prepared by the CAP Lab. The questions posed in the survey are listed in Table 1.

Table 1. Supplier Survey Questions

1. Does your company use RAP (or anticipate using RAP in the future) in the production of HMA? (If you don't use RAP, you don't need to go any further in the questions.)
2. In your opinion, what is the maximum percentage of RAP that you can handle in your plants? Please specify between drum plants and batch plants.
3. In your opinion, what is the maximum percentage of RAP that is cost effective for you to use? If you have multiple plants, please specify between drum plants and batch plants.
4. Based upon the availability of RAP from Connecticut projects that you receive, what is the maximum percentage of RAP that you could run so that the amount used on CTDOT projects is relatively consistent throughout the construction season? (In other words, it would not be desirable to have major changes in the RAP content throughout the season for mixes coming from the same HMA plant. Also, it is not desirable for RAP to be imported from other states just to keep the RAP percentages up.)
5. Would you be opposed to having varying RAP percentages allowed depending on if the mix is being used for base course, intermediate course or wearing surface?

The entire survey and responses are shown in Appendix A. A bulleted summary of the responses is shown below:

- Seven (7) of the 9 suppliers that responded indicated that they are currently using RAP.
- Four (4) suppliers indicated that a range of 20% to 50% RAP is possible in drum plants.
- Six (6) suppliers indicated that between 15% and 30% RAP is possible in batch plants, with one supplier indicating that up to 40% is possible in batch plants.

- The maximum amount of RAP that is estimated by the suppliers that could be used while remaining cost effective ranged from 15% to 30% for batch plants. For drum plants, the responses ranged from 20% to 50%.
- Three (3) respondents indicated that utilizing 15% RAP would keep their RAP supply consistent throughout the construction season at batch facilities.
- One (1) respondent indicated that 20% would keep their RAP supply consistent throughout the construction season at drum facilities. Another respondent indicated that 40% RAP would allow for a consistent supply.
- Two (2) respondents do not utilize RAP and 2 respondents do not receive RAP millings from Connecticut projects.
- Five (5) respondents either did not respond or indicated they would have no objections to varying the allowable RAP percentages between pavement layers.
- One (1) respondent indicated no objection to varying allowable RAP contents so long as the percentage did not drop below 15%.
- Two (2) respondents cited logistics concerns as the cause for objecting to varying allowable RAP contents between mixes.

Based on the responses, it is fair to conclude that the current maximum percentage of allowable RAP (20%), <u>when considering production at batch plants</u>, is consistent with what is desirable from a cost effectiveness standpoint as well as RAP availability and consistency. The responses from suppliers with drum facilities would seem to indicate that the use of higher percentages of RAP may be acceptable.

Varying the allowable percentages of RAP does not seem to present a production problem for most suppliers. However, as a consequence, this may result in material management as well as mix design management and logistics issues.

Review of Specifications

CalTrans RAP Usage Survey

The California Department of Transportation (Caltrans) conducted a survey [4] of state transportation agencies to gain insight as to how RAP was being utilized throughout the country. It is the opinion of this research team that this survey is the best reference to use to gain a national perspective as to the use of RAP as 33 out of 50 states responded. The CalTrans survey questions are shown in Table 2.

Table 2. Caltrans RAP Usage Survey

1. Do you allow RAP in HMA?
2. If yes, please note the maximum amount allowed and how it is expressed (i.e., by percent mass or by percent binder replacement).
3. If you allow RAP in the production of HMA, do you specify a maximum mix temperature, maximum aggregate temperature?
4. Do you use aggregate gradation as an acceptance criterion for HMA?

It should be noted that for purposes of this research, the responses to only Questions 1 and 2 were summarized to gain familiarity with what other states around the country specified. Results of the survey are summarized below:

- Thirty three (33) states responded to the survey.
- All 33 responding states allow the use of RAP in HMA.
- Seven (7) of the surveyed states specify tolerances based on binder replacement.
- States with a binder replacement specification range from 25% to 42% total binder replacement depending on the layer in the pavement structure.
- One (1) surveyed state is making a switch from a mass specification to a binder replacement specification.

- Twenty (20) of the surveyed states specify maximum RAP percentage strictly by weight. These percentages vary greatly from state-to-state; from as little as 15% to no specified limit in base courses.
- Six (6) of the surveyed states have a specification that employs restrictions based on both total mass of RAP as well as total binder replacement. Most of these specifications are dependent on whether or not RAS is used in combination with RAP in the mix.

AASHTO SOM RAS Usage Survey

In November of 2014, the AASHTO Subcommittee on Materials (SOM) completed a survey of state transportation agencies regarding their usage of RAS [5]. The questions which were posed through the AASHTO SOM survey are shown in Table 3.

Table 3. AASHTO SOM RAS Usage Survey

1. Do you allow RAS?
2. How do you determine the maximum acceptable limits and what are the values?
3. Project Selection Guidelines for use of limitations?
4. Do you allow RAP and RAS combined?
5. Current performance with RAS?

The relevant summary of the RAS survey is shown in Table 4. Table 4 is a direct extraction from the SOM spreadsheet of complied results.

Table 4. AASHTO SOM RAS Usage Survey Summary*

State	Do you allow RAS?	How do you determine the maximum acceptable limits and what are the values?	Project selection guidelines for use of limitations	Do you allow RAS and RAP combined?	Current pavement performance with RAS
Summary	33 Responses	Max Total % - 46% (11) Most have 5% max	Not in specialty mixes - 11 Grade bumping - 9	YES: Total % changes - 1	Great and pleased - 5
	YES - 73% (24)	No maximum % - 4% (1)	Surface and binder lifts different - 6	BR changes - 4	Acceptable (making changes) - 11
	NO - 27% (9)	Max Binder Ratio (BR) - 21% (5)	Only in maintenance or lower traffic mixes - 6	No change - 16	Somewhat less than acceptable (making changes) - 6
		Both Total % and BR - 25% (6)	Performance testing - 3	Grade bumping added - 3	Not enough information - 3
		Min total virgin binder - 4% (1)	Experimental - 3		

* Table is a direct extract from the SOM Compiled results spreadsheet [5]

Additional RAP Use Specifications

The research team also looked into specifications from agencies that did not participate in the RAP usage survey [4]. Three (3) of the 4 specifications below came from agencies that did not participate in the RAP survey, but did participate in the RAS survey.

Idaho Transportation Department

Idaho [6] allows RAP to be used as an additive to granular sub-base as well as in asphalt pavement mixtures. When RAP is used in pavement mixtures, there is a prescribed virgin binder adjustment above 17% RAP binder (by weight) of the total binder in the mix. Between 17% and 30% RAP binder, the prescribed virgin binder must be either one grade softer than the high and low standard designated temperatures or a blending chart is used. Beyond 30% contribution of the RAP binder, blending charts are required to determine what the virgin binder grade would be.

Colorado Department of Transportation

Colorado [5, 7] allows the use of RAP in HMA up to a limit of 23% binder replacement in all pavement layers, as long as all volumetric and other HMA specifications are met. No RAS is permitted for use in pavement mixtures in Colorado.

Oregon Department of Transportation

Oregon [5, 8] allows the use of RAP in porous asphalt pavements and standard asphalt pavements at a rate of not more than 30% by weight of the mix. RAS is also allowed at no more than 5% by total weight of the aggregate when used without RAP, as long as the binder replacement does not exceed 20% in base courses and 15% in surface mixes. RAP and RAS are also allowed in combination, providing the maximum binder replacement of the combination does not exceed 30% in base mixes and 25% in surface mixes.

Missouri Department of Transportation

Missouri [5, 9] allows the use of RAP in asphalt mixtures (except for stone matrix asphalt mixtures) at a maximum of 30% virgin binder replacement with no change in the prescribed binder grade. RAP may also be used in excess of 30% binder replacement, as long as proof of testing that the binder meets specified requirements accompanies the provided job mix formula. RAS is also allowed to be incorporated into asphalt mixes in Missouri that have a prescribed PG binder grade of 64-22. There is a requirement, however, that if the ratio of virgin binder to total binder in the mixture is between 60.0%

and 70.0%, then the prescribed PG grade of the virgin binder will be softened to either PG 52-28 or PG 58-28. It should be noted that this document does not contain a statement regarding the use of RAP and RAS in combination.

Based on the responses to the CalTrans Survey [4] and the additional reviewed specifications, agencies expressed concern with respect to the use of increased quantities of recycled products. The concern is what effect the recycled binder will have on the expected longevity of the mix.

Pilot Project Sections

This report addresses three different pilot projects that took place in Connecticut. All three projects utilized recycled materials. The three projects differ not only by location but also by traffic level and finally, by the combinations of recycled products that were used. Table 5 describes each of the projects and their uniqueness relative to one another.

Table 5. Recycled Products Pilot Projects

Project/Route #	Town	ADT	Technologies & Products Used
220	Enfield	10,400	RAS
Lenox Street	Manchester	**	RAP, RAS
I-395	Norwich	43,600	Varying RAP Content, Polymer Modified Asphalt, Warm Mix Asphalt

*** ADT Courtesy CTDOT [14]**
**** Residential Street Connecting State Routes of 6600 and 9600 ADT**

Construction of these surfaces was monitored when possible by the research team. CAP Lab personnel were on hand at the production facility during production of these mixes. The mixes, along with the control mixes, were sampled for each one of these pilot projects. The mixes were sampled for the purposes of performance testing at the

CAP Lab. Each sample was collected at a sampling stand from the back of the haul units in accordance with AASHTO T 168 [9]. Enough material was collected for fabrication of specimens for testing of:

- Moisture Susceptibility via Tensile Strength Ratio (TSR) - AASHTO T283 [11]
- Moisture Susceptibility and Rut Depth via the Hamburg Rut Tester- AASHTO T324 [12]
- Rutting Susceptibility via Asphalt Pavement Analyzer (APA) – AASHTO T340 [13]

A description of each of the three performance tests are given in the following subsections.

Laboratory Performance Test Descriptions

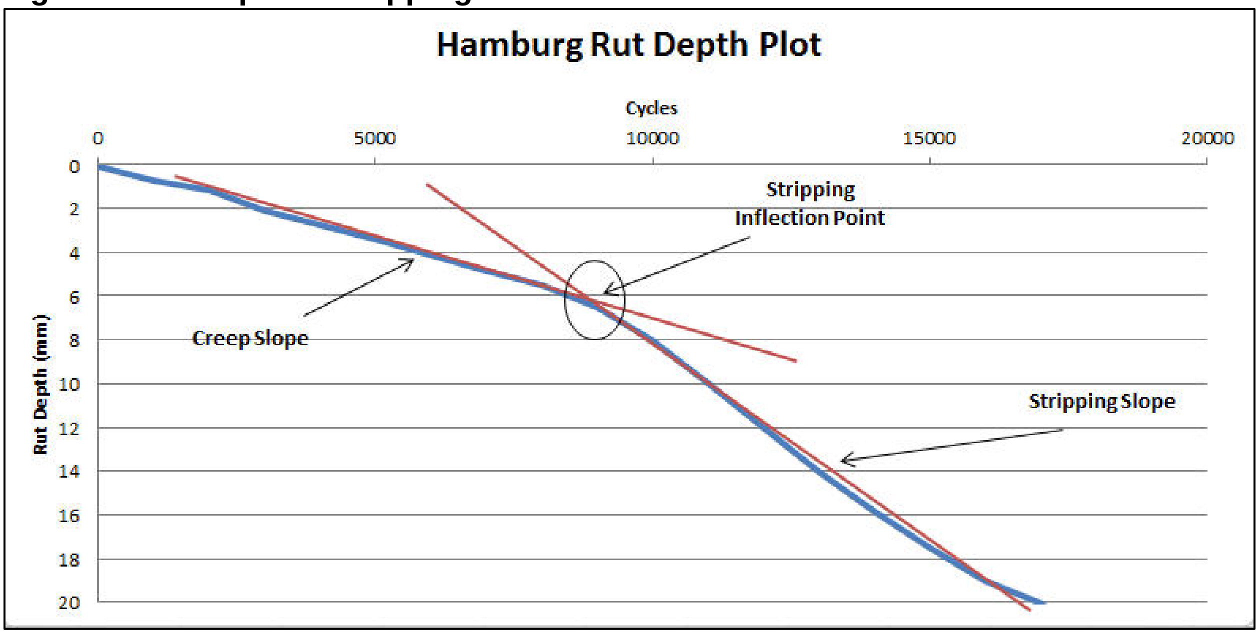
Tensile Strength Ratio Testing (AASHTO T 283)

The tensile strength test measures the potential of a sample for stripping and moisture damage. Freeze/thaw cycling tends to weaken the cohesive bond between the asphalt binder and the surface of the aggregate. The propensity of the mix to strip due to the effects of water is directly related to the strength (specifically tensile strength) of the mix. The TSR is the ratio of the tensile strength of a conditioned set of specimens to that of a set that has not been subjected to moisture or freezing. A high TSR value would be indicative of mix that is not very susceptible to moisture-induced damage, while a lower value would be indicative of a mix that is susceptible to moisture damage. CTDOT specifications currently require a TSR value of no less than 80%, which is also the Superpave standard. This test also serves as a good comparative or relative test when investigating differences in performance between two mixes.

Hamburg Wheel Track Testing (AASHTO T 324)

The Hamburg test is a destructive test, which is used to indicate the mixture's structural integrity in the presence of water and repeated loading. The primary concern with respect to the Hamburg test is the determination of the stripping inflection point. The stripping inflection point is the point at which damage to the specimen is due to the asphalt binder stripping from the aggregate as a result of moisture and repeated loading. The stripping inflection point is evident when viewing the plot of rutting versus the number of passes of the wheel over the specimen. As damage becomes permanent, the slope of rutting depth versus the number of passes changes. An example of this is shown in Figure 1.

Figure 1. Example of Stripping Inflection Point

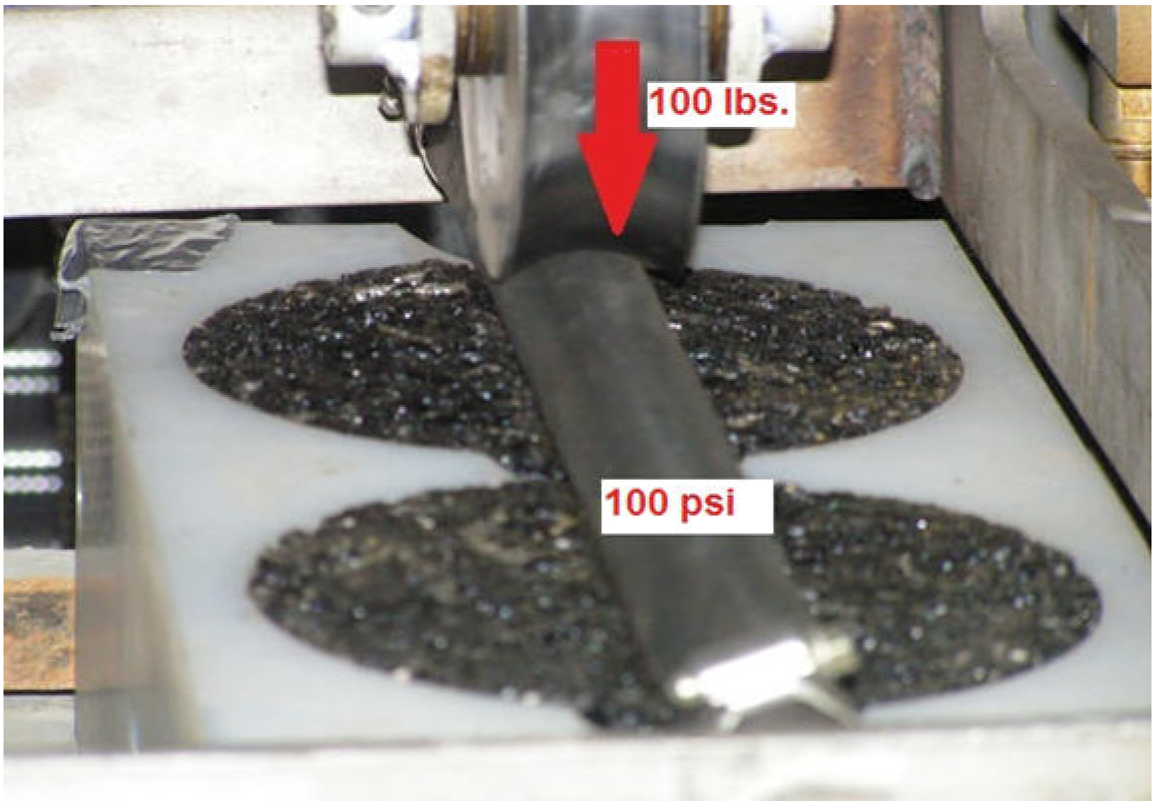


As seen in Figure 1, damage accrues at an increased rate when the slope of rutting (creep slope) changes and is elevated (stripping slope). This point on the plot coincides with the point during testing, when damage increases due to stripping. The longer a specimen lasts without this slope increase taking place, the less prone to moisture-induced damage the mixture will be in place in the field.

Determining the Rutting Susceptibility of Hot Mix Asphalt (HMA) Using the Asphalt Pavement Analyzer (APA) (AASHTO T340)

The APA test involves laying a rubber pneumatic tube, which is pressurized to 100 psi, across the top center of the test specimens as shown in Figure 2. The APA test allows the asphalt mixture to be tested for its likelihood to deform plastically under repeated wheel loads.

Figure 2. APA Test Configuration

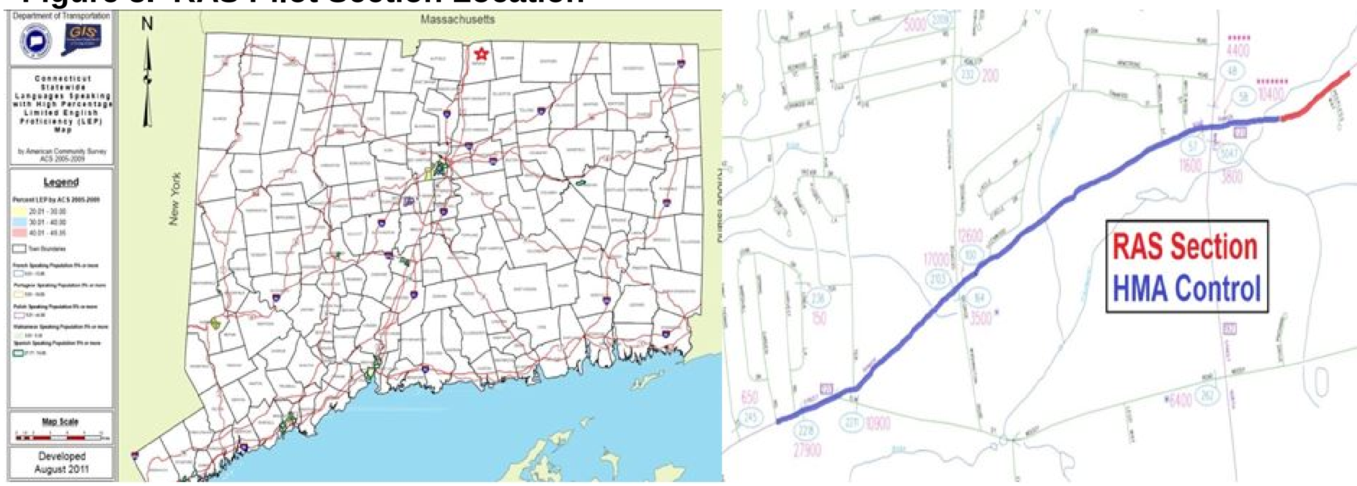


The specimens are conditioned to temperature inside the unit for 6 to 24 hours. Once this has been achieved, the testing consists of applying a 100 pound downward force onto the overlying pneumatic tubes via the wheels as shown in Figure 2. The wheels are then passed across the hoses a maximum of 8000 cycles. Rut depth measurements in millimeters are made via Linear Variable Displacment Transformers (LVDT) at different locations on the specimen.

RAS-only Pilot Section

During October 2012, a resurfacing project took place on Route 220 in Enfield, Connecticut (Figure 3).

Figure 3. RAS Pilot Section Location



A small section of this project, approximately one quarter of a mile (one night of paving), was constructed incorporating RAS in the HMA mix. The exact CTDOT mile points are shown in Table 6.

Table 6. RAS Project Mile Points*

Pavement Section	Starting Milepoint	Ending Milepoint
RAS	2.51	2.78
HMA Control	2.78	4.68

***Mile points in west bound direction**

As this was the first time HMA with RAS had been used in Connecticut, it was determined that it would be best to use it once without the addition of RAP or any Warm Mix Asphalt (WMA) technologies in an effort to minimize the number of variables. The maximum amount of RAS allowed in the mix was 5.0% by weight of the total mix. The intention was to adjust the PG binder grade of the virgin asphalt from 64-22 to 58-28 to account for the stiffer asphalt binder contribution of the RAS. The producer was unable to meet the CTDOT volumetric specifications of the mix at 5.0% RAS. Because of this, adjustments were then made and 3.0% RAS by total weight of the mix was incorporated for the pilot section as volumetrics were met at this rate. 3.0% RAS did not require a binder grade adjustment as a lesser quantity of the new binder would be replaced at 3.0% RAS. CAP Lab personnel were on hand for a portion of the construction of the pilot section. There were no noticeable deviances from a standard HMA paving operation and there were no reported issues with placement on the part of the contractor.

Performance Testing of RAS Mix

Samples of the mix were collected at the production facility to run the following performance tests as described above:

- Moisture Susceptibility via Tensile Strength Ratio (TSR) - AASHTO T283 [11]
- Moisture Susceptibility and Rut Depth via the Hamburg Rut Tester- AASHTO T324 [12]
- Rutting Susceptibility via Asphalt Pavement Analyzer (APA) – AASHTO T340 [13]

RAS Tensile Strength Ratio Testing Results

Table 7 shows the results of the TSR testing of both the HMA control section and the RAS section mixes. The RAS had a 4.5% higher TSR than the HMA control mix. Both values were higher than the Superpave and CTDOT standard minimum value of 80.0%, indicating that damage due to moisture susceptibility is not likely to occur for this mix.

Table 7. RAS TSR Results

Section / Mix	HMA Control	RAS
TSR Value	**87.3**	**91.8**

RAS Hamburg Wheel Track Testing Results

Table 8 shows the results of the Hamburg Wheel Track testing of the RAS and HMA control section mixes. When examining the final rut depth alone, it is evident that the two mixes performed similarly. The RAS mix rutted 0.46 mm more than the HMA control, which can be considered a negligible difference.

Table 8. Rt. 220 Hamburg Wheel Track Testing Results

Section / Mix	HMA Control	RAS
Rut Depth (mm)	**6.14**	**6.60**

Another important consideration with the results of the Hamburg testing is that upon plotting the results (Figures 4, 5), there is no apparent stripping inflection point for either the RAS or the HMA control mix. This reinforces the TSR testing results, which indicate that damage due to moisture susceptibility for this mix is not likely to occur.

Figure 4. Rt. 220 HMA Control Hamburg Plot

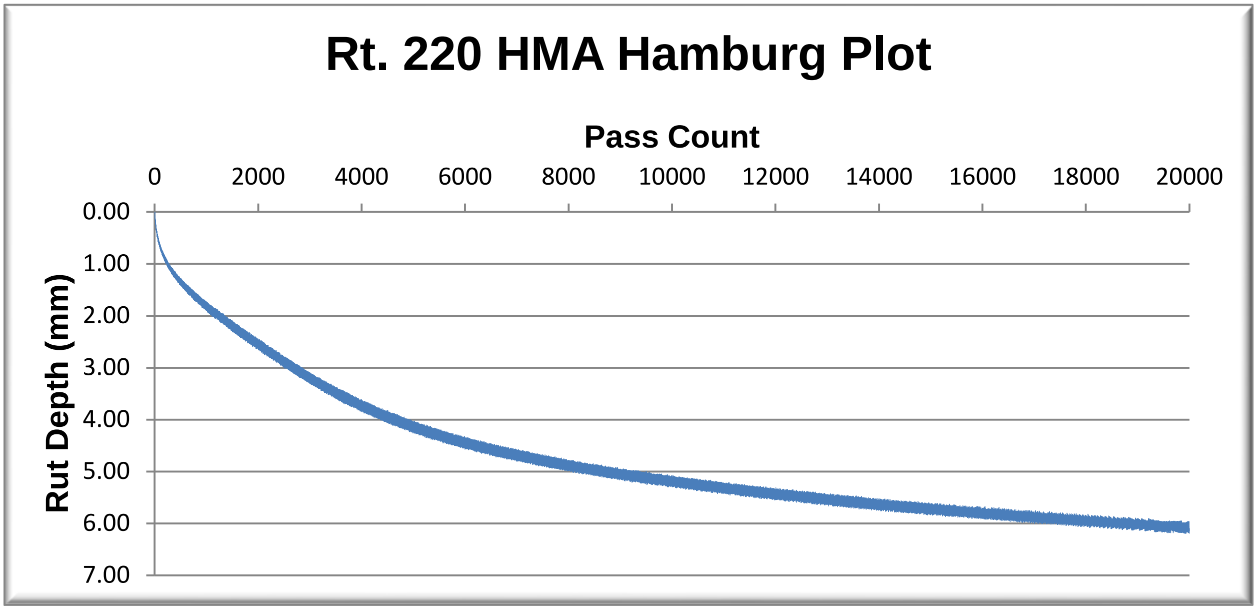
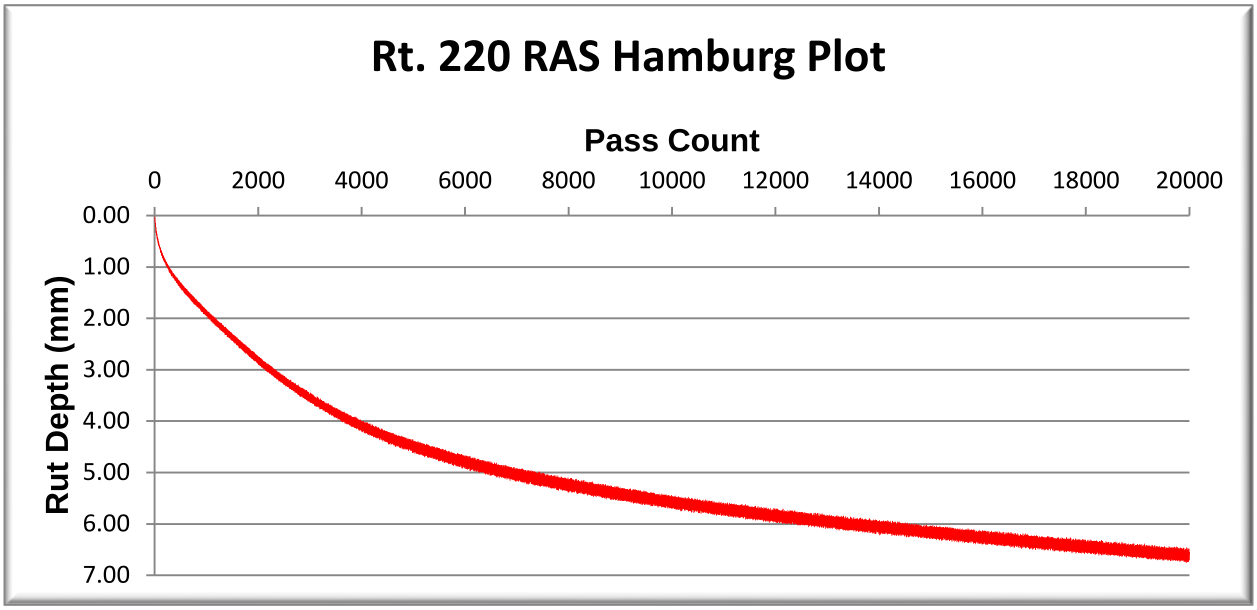


Figure 5. Rt. 220 RAS Hamburg Plot



APA Rut Testing Results

Table 9 shows the results of the APA Rut testing of the RAS and HMA control section mixes.

Table 9. Rt. 220 APA Rut Testing Results

Section / Mix	**HMA Control**	**RAS**
APA Rut Depth (mm)	**3.89**	**4.35**

When comparing the performance results of the two mixes in the rut tester, the RAS mix rutted slightly (approximately 12%) more than the HMA control mix. Without a binder adjustment for the RAS mix, one might expect it to be stiffer and not rut to the degree of the control HMA mix. The difference in the average rut depths is 0.46 mm; coincidently the same as the difference reported for the Hamburg test results. As of the publication of the 2014 AASHTO standard, there was no precision and bias statement for the T 340 designation. Because of this, the research team cannot make a validated statement as to whether the difference in the lab results will translate to different performance in the field.

Figure 6 shows the condition of the 3.0% RAS wearing surface nearly a year following placement. Based on the absence of cracks, raveling and any other indication of distress, the surface appears to be performing well.

Figure 6. 3.0% RAS 1 Year Following Construction

***Image Courtesy CTDOT 2013 Photo log**

As a follow-up, CAP Lab personnel performed pavement distress surveys at the site during the Summer of 2014 to determine if there were any performance differences between the RAS section and adjacent HMA control section. No significant differences were observed. Figures 7 and 8 show both the RAS section and the HMA control section surface conditions in the summer of 2014. The lines in the RAS section image are shadows from overhead power lines. The reader should note that this survey took place only two years following construction and no determinations can yet be made regarding potential long-term disparities between them.

Figure 7. Rt. 220 HMA Control Section Summer 2014

Figure 8. Rt. 220 3.0% RAS Section Summer 2014

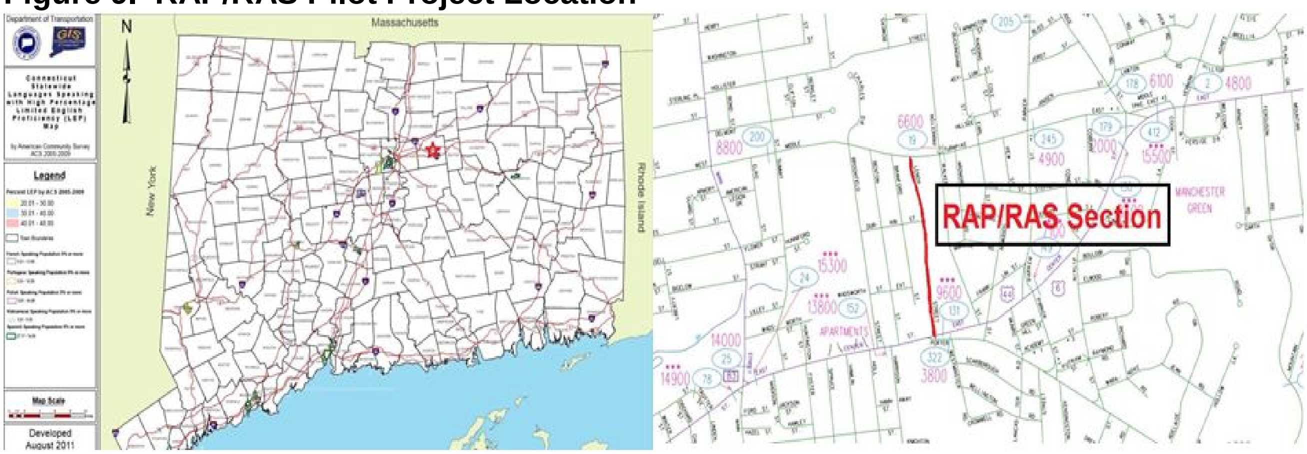
RAP & RAS Pilot Project

The incorporation of RAS into HMA without the use of RAP will not be a practical application in the future based on the following. Most contractors are already using RAP with success and the use of RAP is standard practice for most producers in Connecticut. Also, RAP can be used in much larger quantities than RAS, thereby replacing a much larger portion of the total mix. The use of RAS and RAP in combination needed to be examined in addition to the use of RAS as the sole recycled product in the mix. Finding the balance between the amount of RAP and RAS that can be incorporated into a new mix involves many variables. These variables include the following:

- whether the production facility can handle both RAP and RAS at the same time;
- whether the two products will be mixed and entered in the same location within the plant;
- the total contribution of binder from each recycled product constituent in the mix;
- the total effective contribution of binder from each recycled product constituent in the mix; and
- the required performance grade of the binder in the mix.

During the Summer of 2013, there was a full depth reconstruction of a municipal street, Lenox Street, in the Town of Manchester, Connecticut (Figure 9). The length of the project was 2,160 feet (~0.41 miles).

Figure 9. RAP/RAS Pilot Project Location

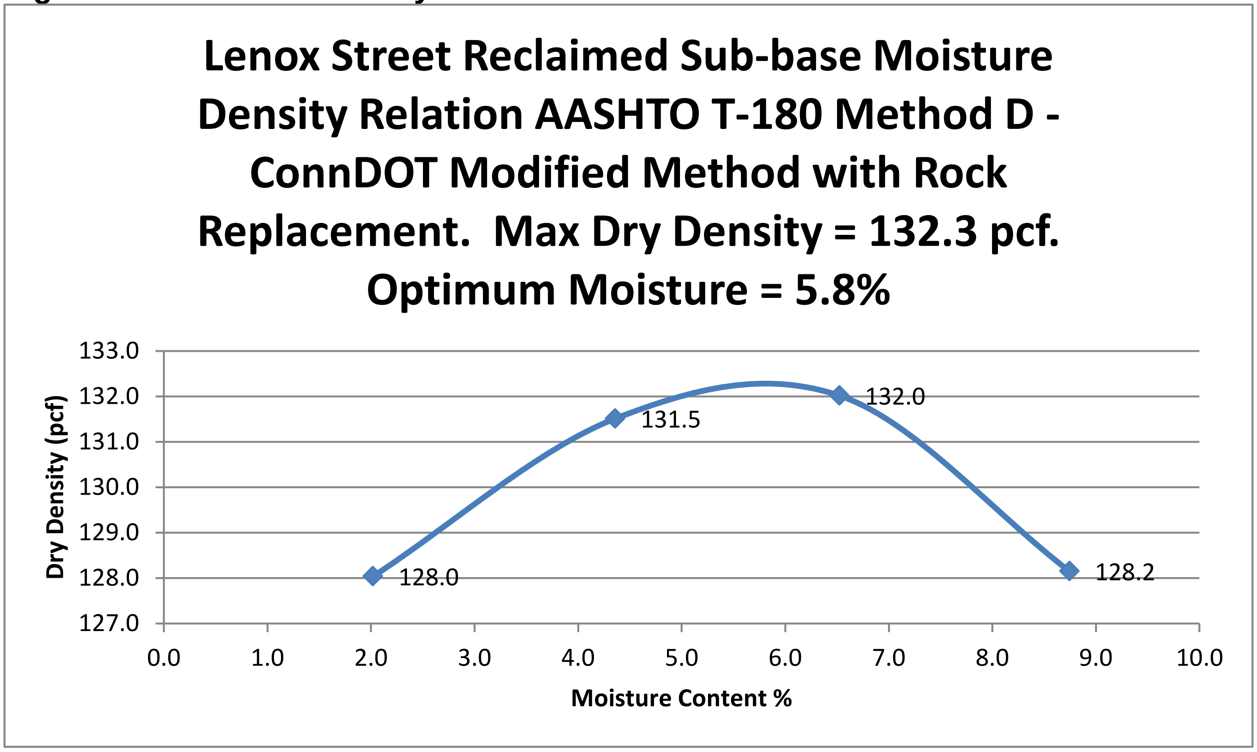


The town of Manchester agreed to specify that the contractor incorporate both RAP and RAS in the wearing surface mix. CAP Lab personnel were on hand to provide some in-place testing results in exchange for permission of the trial on Lenox Street. The testing results included particle size distribution (AASHTO T11, T27) and in-place density monitoring of the gravel base (AASHTO T180 Method D, AASHTO T 191, AASHTO T310 DT), as well as density monitoring of the HMA base and wearing surface (AASHTO T310 BS).

Two particle size distributions were conducted in accordance with AASHTO T11 and T27. The results of the gradation analyses are provided in Appendix X.

In order to establish an optimum moisture content and theoretical maximum value, to which to compare the in-place gravel base densities, CAP Lab personnel collected the necessary materials and ran an AASHTO T 180 (Modified Proctor) Method D. Results of the proctor are shown in Figure 10.

Figure 10. Moisture Density Relation Lenox Street



In-place density testing was conducted via the sand cone (AASHTO T191). Three random locations were selected for sand cone testing due to time constraints. As the resulting values were high relative to the maximum dry density values obtained in the lab, the research team does not have confidence in the sand cone results.

Nuclear density testing (AASHTO T310) was performed in direct transmission mode to gain insight as to the level of density achieved on the base. There was RAP incorporated as aggregate in the base, which tends to increase water content readings with the nuclear gauge. As such, the moisture contents, which were obtained via the T191 testing, were used in lieu of the gauge moisture readings, and those values were corrected. Eleven (11) readings were taken in stratified random locations along the length of the project. Table 10 shows the corrected density percentages of the compacted base.

Table 10. Lenox Street In-Place Density Values

Location	% Maximum Density
1	96.8
2	92.3
3	96.3
4	98.2
5	95.1
6	94.1
7	95.4
8	97.5
9	98.2
10	99.0
11	92.5

The average in-place density of the base was 96.0%. Given these values, the research team has concluded that the base was adequately compacted and that if any problems should arise with the roadway in the future, the base density should not be considered a contributing factor.

With respect to the previous statement, there are exceptions that should be noted. There were three water main breaks during construction/compaction of the sub base. There was one water main break following compaction of the final wearing surface. There was a patched section consistent with the noted water main breaks observed on a follow up survey. These required excavations of the wearing surface, base and sub base. These five excavated sections are all in the northern half of the project. Two of these excavated and patched sections are shown in Figures 11 and 12. The exact locations and detail of these sections are shown in Appendix C. Future analysis/surveys of the RAP/RAS section should take place on the southern half of Lenox Street.

Figure 11. Lenox Street Water Main Break Patch Section

Figure 12. Lenox Street 2014 – 2015 Patched Section

CAP Lab personnel performed density testing in back scatter mode on the HMA base layer. The CAP Lab tested the mix to determine the maximum theoretical density in the lab (AASHTO T209) and to verify the Maximum Theoretical Specific Gravity (G_{mm}). The producer provided their G_{mm} test results for the base material. Because the producer's results and the CAP Lab's testing results for maximum specific gravity varied by more than the tolerance published in the AASHTO T209 precision and bias statement, the producer's G_{mm} was used as it was derived from a larger dataset. A total of 38 readings were recorded at stratified random locations on the base course. The CAP Lab also conducted nuclear density testing of the wearing surface, which contained both RAP and RAS. The G_{mm} used, came from the producer's results and was successfully verified by the CAP Lab. A total of 51 readings were recorded at stratified random locations on the wearing surface. The average results for density testing of the base course and the RAP/RAS wearing surface are shown in Table 11.

Table 11. Nuclear Density Testing Results Lenox Street

Course	Base Course	Wearing Surface
# of tests	38	51
G_{mm}	2.635	2.662
Average Density	89.5	91.1

The CAP Lab also conducted testing of both the base and wearing surface mixtures for total asphalt content. CAP Lab personnel noticed during placement that the base mixture appeared to have a higher than expected amount of asphalt (i.e., the mix appeared rich). This was verified through testing of the asphalt content by means of the ignition oven (AASHTO T 308). Testing of the base material resulted in a 6.2 % asphalt content. Testing of the wearing surface resulted in a 5.5% asphalt content. The CAP Lab conducted PG Binder Grade verification on the RAP/RAS mix as well. The binder was recovered via AASHTO R59. True grading was conducted on the recovered binder and the resulting true grade was PG 81.5-14.1.

Performance Testing of RAP/RAS Mix

Mix was collected at the production facility to run the following performance tests:

- Moisture Susceptibility via Tensile Strength Ratio (TSR) - AASHTO T283 [11]
- Moisture Susceptibility and Rut Depth via the Hamburg Rut Tester- AASHTO T324 [12]
- Rutting Susceptibility via Asphalt Pavement Analyzer (APA) – AASHTO T340 [13]

RAP/RAS Tensile Strength Ratio Testing Results

Table 12 shows the results of the TSR testing of both the HMA base layer and the RAP/RAS surface mix. Both values were above the Superpave and CTDOT standard minimum value of 80.0%, indicating that damage due to moisture susceptibility need not be a concern for this mix.

Table 12. RAP/RAS TSR Results

Section / Mix	**HMA Base**	**RAP/RAS**
TSR Value	**99.2**	**90.5**

RAP/RAS Hamburg Wheel Track Testing Results

Table 13 shows the results of the Hamburg Wheel Track testing of the RAP/RAS and HMA base mixes. When examining the final rut depth alone, it is evident that there was an issue with the HMA base mix. The RAP/RAS mix rutted moderately and withstood the entirety of the test while the HMA base mix rutted heavily and reached the machine's maximum limit of deflection on all three wheels.

Table 13. Rt. 220 Hamburg Wheel Track Testing Results

Section / Mix	**HMA Base**	**RAP/RAS**
Rut Depth (mm)	**17.12**	**6.17**
Avg. Pass Count	**10,074**	**20,000**

Examination of the individual rutting plots (Figure 13) of the HMA Base shows the behavior of the mixture during the test. All of the Hamburg specimens for the HMA base mix rutted heavily. The specimen under the right wheel failed at 4,227 passes. While the mix certainly rutted in an unfavorable manner and to an unfavorable depth, there is no evident stripping inflection point on any of the curves, which indicates that the problem is not related to moisture susceptibility, but to another cause. The likely cause is the high (6.2%) asphalt content in the mix.

A look at the same type of plot for the RAP/RAS mix (Figure 14) shows more consistency and a far lesser degree of rutting. There is also no apparent stripping inflection point on the RAP/RAS plots. This reinforces the TSR testing results, which indicate that damage due to moisture susceptibility for this mix is not a concern.

Figure 13. Lenox Street HMA Base Hamburg Plot

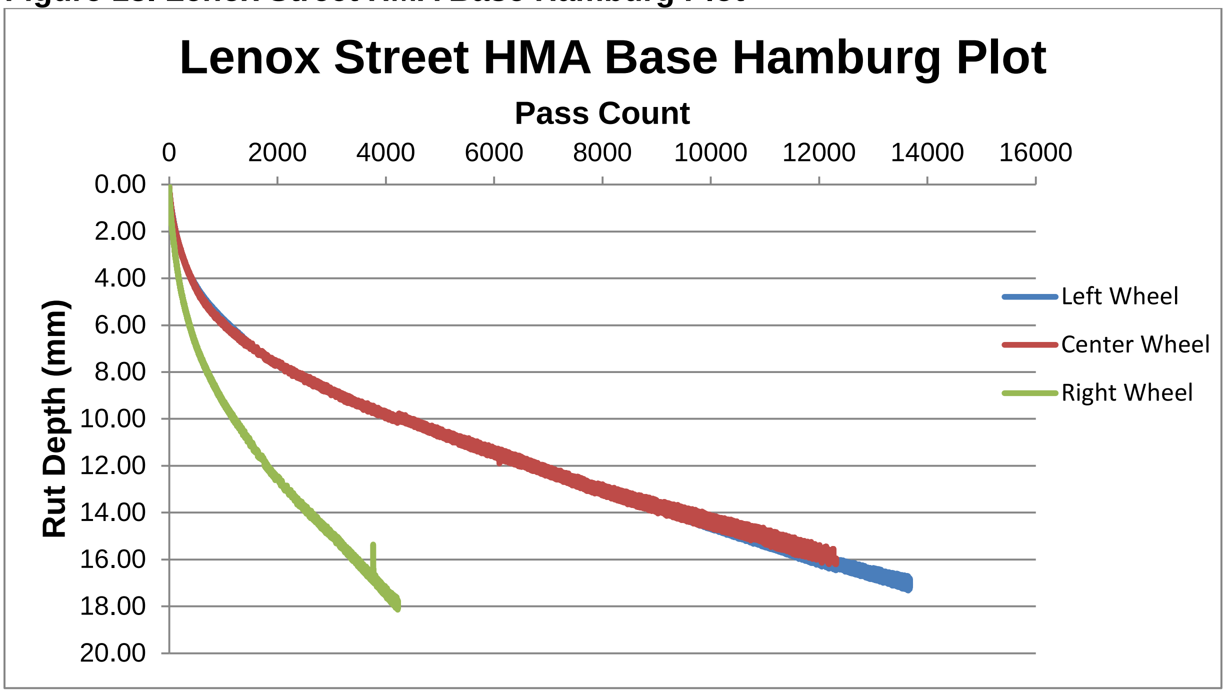
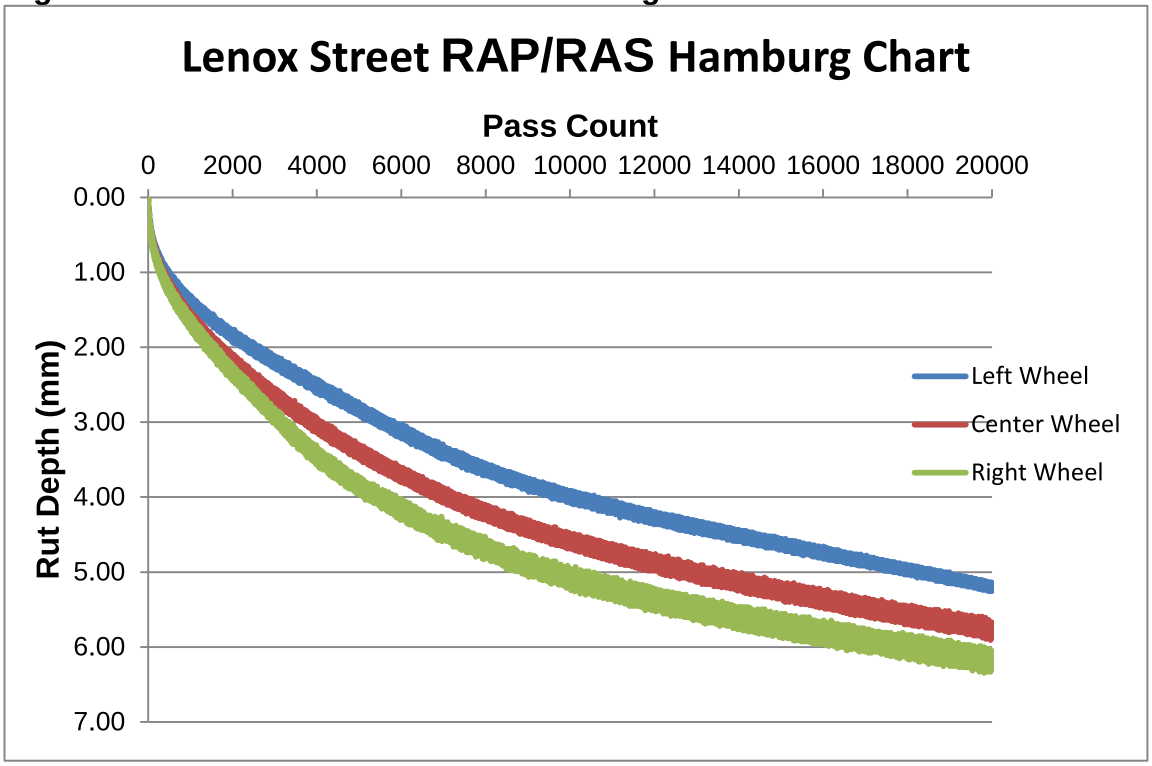


Figure 14. Lenox Street RAP/RAS Hamburg Plot



APA Rut Testing Results

Table 14 shows the results of the APA Rut testing of the RAP/RAS and HMA base mixes.

Table 14. Lenox Street APA Rut Testing Results

Section / Mix	**HMA Base**	**RAP/RAS**
APA Rut Depth (mm)	**10.07**	**3.30**

When comparing the performance results of the two mixes in the rut tester, the RAP/RAS mix rutted 6.77mm less than the base mix. It was expected that the RAP/RAS mix would rut less in the APA test with the stiffer binder in the mix.

The HMA base mix rutted heavily similarly to the same mix in the Hamburg test. The average rut depth of 10.07 mm of the base course is significantly higher than that of the surface mix. It is the opinion of the research team that this is a product of the rich asphalt content (6.2%). The potential for rutting of this mix due to its richness is evident in the results of both the APA and Hamburg tests. That being stated, the base HMA layer is not directly subject to the effects of wheel-loading from traffic. The point load from a wheel is somewhat dispersed by the time it reaches the base layer.

Revisiting Lenox Street

CAP Lab personnel revisited the Lenox Street RAP/RAS project in June 2014 to conduct a visual survey of the overall condition of the surface. With the exception of the excavated/patched portion(s) previously mentioned, the surface appeared to be performing well as there was an absence of surface distress (cracks, raveling etc…). A general condition image of the pavement is shown in Figure 15.

Figure 15. Lenox Street June 2014 General Surface Condition

As the Lenox Street surface is new, it was not expected that any significant distresses would be exhibited after just one year. The surface condition of this roadway should be assessed in person at least yearly, as this is a municipal street that is not photo-logged annually by CTDOT. Without in-person visits, there is no way to monitor and document the condition of the RAP/RAS wearing surface over time.

Lenox Street (RAP/RAS) Discussion

The Lenox Street RAP/RAS pilot project provided some interesting benefits from a research perspective, as well as highlighted a few issues that should be considered if the pavement is going to be monitored for long-term performance. The fact that the sub-base compaction could be verified prior to laydown of the HMA is a benefit that does not often exist when researching pavement overlays. Because it is not always possible to verify the extent of sub-base compaction, an under-compacted sub-base is always considered a potential root-cause variable should premature failure of the pavement structure occur. Another benefit identified during this work was being able to document the properties of the base HMA layer. This information is not typically available when researching overlays, therefore, knowledge of what is taking place below the RAP/RAS wearing surface is valuable from a research perspective in that some of the variable causes of future distresses may be dismissed.

There are a few issues specific to this project that need to be kept in mind upon future analysis of this surface:

- First, it is not known if the backfills, which took place as a result of water main breaks and the other patched section, which was discovered during winter 2014/2015, were properly compacted, as no testing took place on these sections during repair. If there are any early pavement distresses in the general vicinity of these areas, the inclusion of RAP/RAS in the wearing surface should be precluded as a primary cause. It should also be noted that all of these areas are on the northern ~ 900 feet of the project. Consideration should be given to conducting future analysis of this surface on the southern portion of Lenox Street.

- The second issue is the high asphalt content of the HMA base layer. As previously mentioned, the asphalt content was 6.2% in the base layer. This asphalt content combined with the lower (89.5%) base density could be a potential cause of rutting in the future if traffic loading is drastically increased in this area. Both APA and Hamburg testing results indicated the propensity for rutting. Conversely, there may be a potential benefit to this asphalt content. The 6.2% asphalt content may mask issues with the wearing surface as distresses may be absorbed by this layer of rich HMA. It is premature to forecast what effect the rich asphalt base layer will have on this new pavement structure.

- The third issue pertains to the binder grade in the surface mix, which was discussed above. The addition of the RAP and RAS to this mix called for a virgin PG Binder grade of 58 – 28. The softer binder was intended to account for the stiffer binder in the RAP and RAS. It was made known to the research team that an error occurred and the virgin binder in the mix was actually a PG 64-22. The resulting true grade of PG 81.5-14.1 is cause for concern with future premature failure of this surface, specifically, cracking. It will be difficult to assign the cause of any cracking to the addition of the recycled products, as a softer virgin binder would have resulted in a much less stiff true grade in the wearing surface.

Additional Discussion on the Use of Recycled Asphalt Shingles (RAS)

On December 11, 2014, a memorandum [15] regarding the use of RAS in asphalt pavements was sent from the FHWA Associate Administrator for Infrastructure to (among others) FHWA Division Administrators. This memorandum stated the FHWA position of ensuring that any materials used in the construction of public infrastructure whether recycled or virgin, shall not have a negative impact on the highway system. The memorandum went on to indicate that there was an increasing number of state departments of transportation that have observed premature cracking in newer pavements and that a similarity of these failing projects was the use of RAS to replace significant amounts of total binder in the mix. The memo cites the AASHTO SOM survey on the use of RAS, which was previously summarized in this report [5]. The memorandum reported that at least 14 states have a maximum limit on the use of RAS of up to 5.0% by weight of the total mix and that this can translate to a 25.0% replacement of total binder in the mix. It is acknowledged that states with warmer climates will be less prone to the possible effects of aged binder. The memorandum states that agencies currently using or planning to develop specifications for the use of RAS should use the AASHTO PP 78-14 [14] provision as the standard guideline.

The AASHTO provision PP 78-14, Section 6, Note 6 makes the assumption that the available asphalt from the use of RAS is in the range of 0.70 to 0.85. This would then preclude the use of the total asphalt content in the RAS for use as effective asphalt in the design of the mix. This may, in turn, help to reduce the possibility that mixtures designed with RAS have a lower total available asphalt content making them dry and more prone to cracking.

Varying RAP Pilot Sections

Another objective of this research project was to investigate higher total RAP contents in surface mixes in Connecticut than are currently allowed. During the Summer and Fall of 2013, trial mixes were placed on I-395 with varying RAP contents. Table 15 gives the locations along with the placement dates, varying RAP contents and asphalt binder grades for each of the test sections along with the control section. It should be noted that the mix for the control section and the first trial section (15% to 20% RAP) was produced at a batch facility utilizing Advera® as the warm mix technology. The other three sections were produced at a drum facility utilizing a mechanical foaming technology.

Table 15. Varying RAP Pilot Sections

Placement Dates	Section	Binder Grade	WMA Technology	Route	Lane	Beginning Milepoint	Ending Milepoint	Total Mileage	Tons Placed
	Control 15% RAP	PG 76-22	Advera®	I 395 SB	Left/Shoulder	16.88	16.44	0.44	
8/24/2013 - 8/27/13	Control 15% RAP	PG 76-22	Advera®	I 395 SB	Right	16.88	16.45	0.43	**1094.77**
	Control 15% RAP	PG 76-22	Advera®	I 395 SB	Right Shoulder	16.88	16.37	0.51	
	15% - 20% RAP	PG 76-22	Advera®	I 395 NB	Left/Shoulder	15.40	16.00	0.60	
9/29/2013 - 10/1/13	15% - 20% RAP	PG 76-22	Advera®	I 395 NB	Right	15.40	16.00	0.60	**1520.24**
	15% - 20% RAP	PG 76-22	Advera®	I 395 NB	Right Shoulder	15.40	16.00	0.60	
	25% - 30% RAP	PG 76-22	Foaming	I 395 NB	Left/Shoulder	16.00	16.67	0.67	
10/3/2013 - 10/5/13	25% - 30% RAP	PG 76-22	Foaming	I 395 NB	Right	16.00	16.67	0.67	**2326.25**
	25% - 30% RAP	PG 76-22	Foaming	I 395 NB	Right Shoulder	16.00	16.67	0.67	
	25% - 30% RAP	PG 76-28	Foaming	I 395 NB	Left/Shoulder	16.67	17.33	0.66	
10/3/2013 - 10/6/13	25% - 30% RAP	PG 76-28	Foaming	I 395 NB	Right	16.67	17.33	0.66	**1815.21**
	25% - 30% RAP	PG 76-28	Foaming	I 395 NB	Right Shoulder	16.67	17.33	0.66	
	35% - 40% RAP	PG 76 - 28	Foaming	I 395 NB	Left/Shoulder	17.33	18.16	0.83	
10/4/13 - 10/8/13	35% - 40% RAP	PG 76 - 28	Foaming	I 395 NB	Right	17.33	18.16	0.83	**2233.83**
	35% - 40% RAP	PG 76 - 28	Foaming	I 395 NB	Right Shoulder	17.33	18.16	0.83	

***Foaming technology was Iowa Parts Mad Dog® Foaming System**

Varying RAP Tensile Strength Ratio Testing Results

As shown in Table 16, there were no mixes that exhibited TSR percentages less than the Superpave and CTDOT requirement of 80.0%.

Table 16. Tensile Strength Ratio Results of Varying RAP Sections

Mix/RAP %	Tensile Strength Ratio (%)
Control 15% RAP	93.9
20% RAP	107.0
30% RAP (PG 76-22)	97.8
30% RAP (PG 76-28)	88.5
40% RAP	92.8

I-395 Varying RAP Hamburg Wheel Track Testing Results

Table 17 shows the results of the Hamburg Wheel Track testing of the varying RAP and control mixes. Evaluation of the final rut depths indicate that there is no cause for concern with any of the mixes. It should also be noted there were no stripping inflection points on any of these five (5) mixes and all specimens lasted the full 20,000 pass duration of the test.

Table 17. Hamburg Wheel Track Testing Results of Varying RAP Sections

Mix/RAP %	Hamburg Rut Depths (mm)
Control 15% RAP	7.1
20% RAP	7.5
30% RAP (PG 76-22)	8.0
30% RAP (PG 76-28)	7.2
40% RAP	5.9

I-395 Varying RAP APA Rut Testing Results

Table 18 shows the results of the APA rut testing of the varying RAP and control mixes. Evaluation of the final rut depth results indicates that there is no cause for concern with any of the mixes with respect to rutting. Similarly to many mixes containing polymer, which the CAP Lab has tested in the APA, there is very little rutting when compared with traditional mixes containing unmodified asphalt.

Table 18. APA Rut Testing Results of Varying RAP Sections

Mix/RAP %	APA Rut Depths (mm)
Control 15% RAP	4.5
20% RAP	6.3
30% RAP (PG 76-22)	4.0
30% RAP (PG 76-28)	3.4
40% RAP	3.6

Density - Varying RAP Sections

Densities for each section are shown in Table 19. It should be noted that the limited number of cores measured for some of the trial sections owed to where those cores fell in relation to the lots, which were laid out for purposes of acceptance testing.

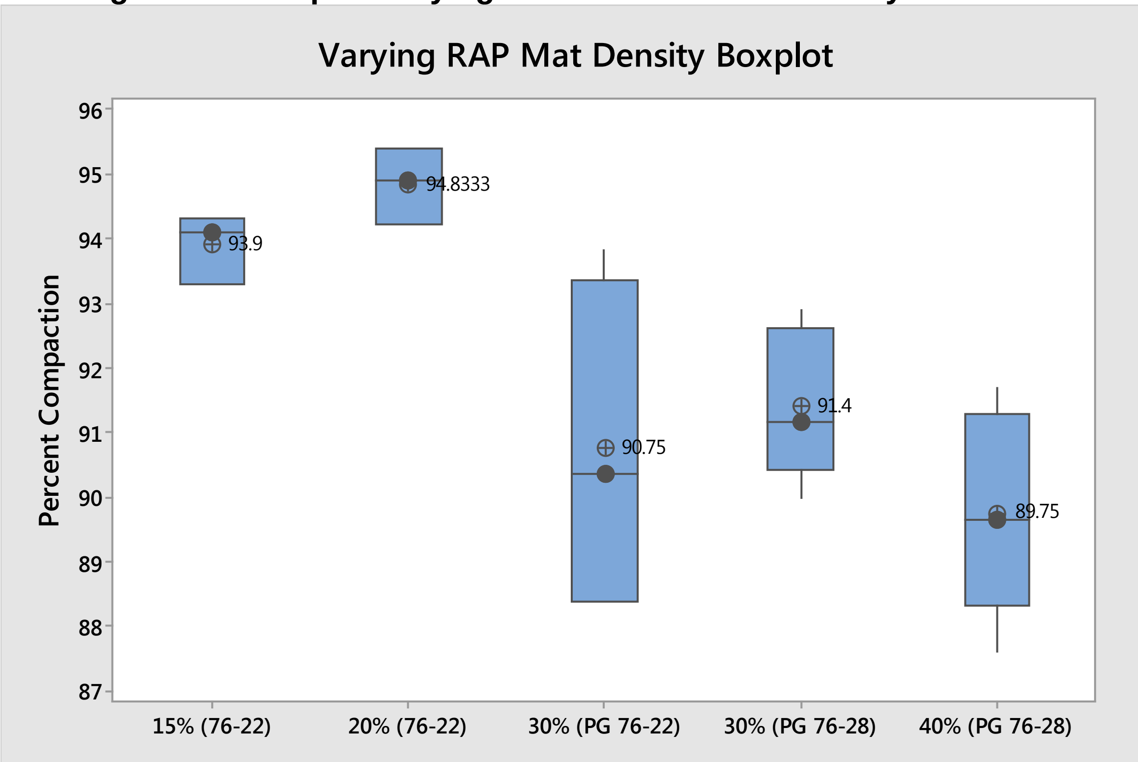
Table 19. Density of Varying RAP Sections

Mix/RAP %	Density (% Compaction)	# Cores
Control 15% RAP (Mat Cores)	93.9	3
Control 15% RAP (Joint Cores)	90.6	6
20% RAP (Mat Cores)	94.8	3
20% RAP (Joint Cores)	91.9	3
30% RAP PG 76-22 (Mat Cores)	90.8	6
30% RAP PG 76-22 (Joint Cores)	88.0	6
30% RAP PG 76-28 (Mat Cores)	91.4	8
30% RAP PG 76-28 (Joint Cores)	88.0	8
40% RAP (Mat Cores)	89.8	8
40% RAP (Joint Cores)	90.3	8

Mat Density Analysis

It was necessary to determine if the differences between the average density values in the trial sections and the control section were statistically significant. Figure 16 shows the boxplot analysis of the mat density data set.

Figure 16. Boxplot Varying RAP Sections Mat Density



A first glance at the boxplot analysis indicates there is a significant difference between the 30% RAP with 76-28 and the control as well as between the 40% RAP with 76-28 and the control. This along with the fact that the average densities of those two sections are less than that of the control indicate those differences may have a negative impact. To supplement that analysis, the research team then compared the density of each of the varying RAP sections with the density of the control section using a two-sample t-test also known as a Student's t-test. There were a total of four comparisons made. The numerical details of each of the individual comparisons are shown in Appendix D. The outcomes are listed in Table 20.

Table 20. Mat Density Comparisons with Control

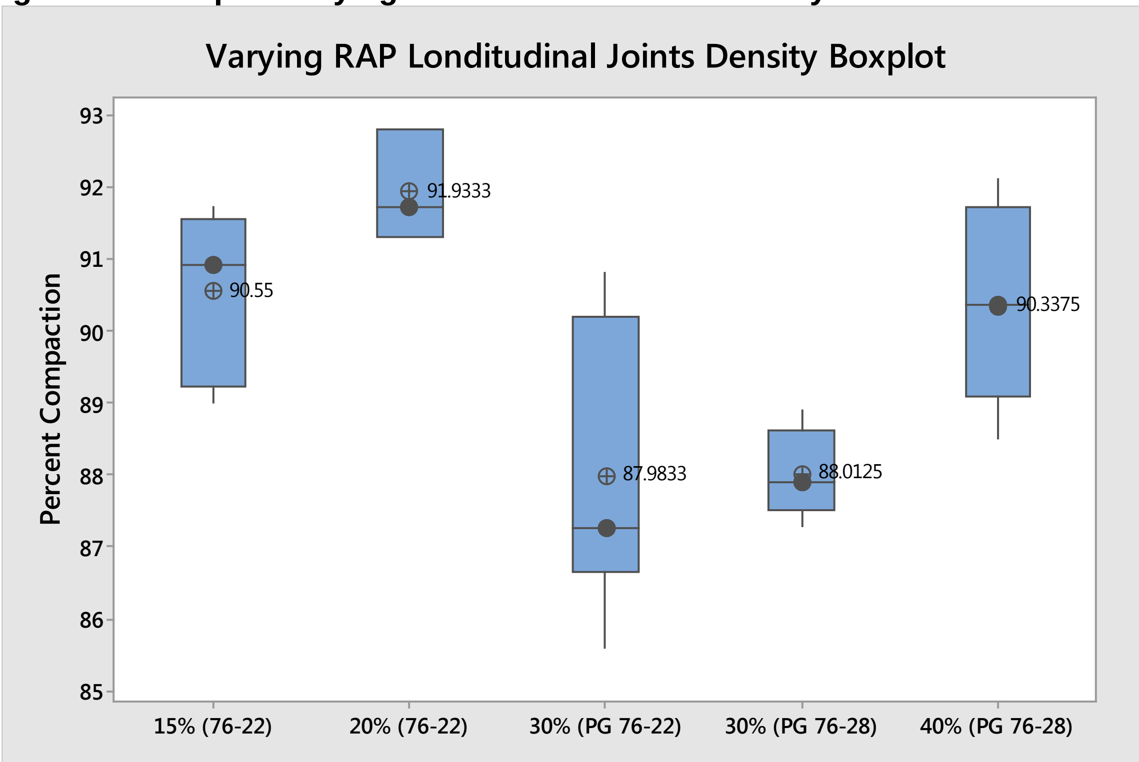
Section	Density	Statistically Different from Control (93.9%)?
20% RAP	94.8	No
30% RAP (76-22)	90.8	No
30% RAP (76-28)	91.4	Yes
40% RAP	89.8	**Yes**

The 40% RAP section yielded the lowest in-place density value. The 30% RAP section with PG 76-28 and the 40% RAP section both show a statistically significant difference from the control section mat density. The lower density could possibly be the result of the stiffer binder at the increased RAP percentages giving way to compaction difficulties in the field.

Joint Density Analysis

It was then necessary to determine if the differences between the average density values in the trial sections and the control section were statistically significant along the longitudinal joints. Figure 17 shows the boxplot analysis of the mat density data set.

Figure 17. Boxplot Varying RAP Sections Joint Density



A first glance at the boxplot analysis indicates there is a significant difference between the 30% RAP with PG 76-28 and the control and no significant difference between the control and any other section. Of note and concern, is the low average value of the 30% RAP with PG-76-22. The average is the same as the 30% RAP with PG 76-28 (88.0%). The boxplot does however, show the large spread in the 30% RAP with 76-22 data which the reader should take into consideration. In order to further examine these differences two-sample t-tests were conducted between the varying RAP sections and control. There were a total of four comparisons made. The details of each of the individual comparisons are shown in Appendix E. The outcomes are listed in Table 21.

Table 21. Joint Density Comparisons with Control

Section	Density	Statistically Different from Control (90.6%)?
20% RAP	91.9	No
30% RAP (76-22)	88.0	**Yes**
30% RAP (76-28)	88.0	**Yes**
40% RAP	90.3	No

The 30% RAP sections yielded the lowest in-place density values of all the sections and they were both 88.0% as previously discussed. They were statistically lower than the control section density. Although the boxplot indicates no statistical difference between the 30% RAP with PG 76-22 and the control, the t-test indicates that those averages are not the same. The 40% RAP section did not exhibit joint density issues however it should have a stiffer binder than all the others making it the most difficult to compact. The decrease in density in both of the 30% RAP sections is less likely due to chance than the satisfactory (90.3%) value of the 40% RAP section. The reader should take into consideration the small sample sizes used for the statistical analysis.

Conclusions and Discussion

In light of the findings of the research conducted as part of this project, there are a number of ways in which the use of recycled products can be viewed. Because the three different projects in this study utilized three different recycling processes (or combinations of processes) in differing quantities on different types of roads with differing traffic levels, it is appropriate to separate the discussions of conclusions and recommendations. It is noteworthy that these pilot projects took place, as the recycling of recycled asphalt shingles (RAS) and Reclaimed Asphalt Pavement (RAP) is becoming a prominent topic and that the recycling of these materials offer benefits from both a cost standpoint as well as an environmental standpoint [1,2].

The RAS project, which took place on Rt. 220 in Enfield, Connecticut was important as it gave confidence that the shingles were not going to present issues as far as production, laydown and compaction were concerned. With respect to any future use of the same quantity of RAS without RAP, the research team is of the opinion that there is reason (to date) that this can take place with confidence that the pavement will perform satisfactorily. The primary issue is that this project contained RAS with no RAP, which is not likely to be feasible going forward, as most producers for CTDOT are already outfitted for the use of RAP. The use of RAP exclusively presents a cost saving benefit over using RAS, as a much larger quantity of RAP (versus RAS) can be incorporated into new pavements.

The RAP/RAS project that took place on Lenox Street in Manchester, Connecticut was an important first look into the use of a combination of both recycled materials. As mentioned earlier, this was a full-depth reclamation project that offered knowledge of underlying layers, such that variables, which may be common alternative causes for future distress, may be dismissed if deemed appropriate. There were some issues that took place during and after the construction of this project, which the reader and any surveyor that observes the project in future years should bear in mind. These include the excavations/back-fills that took place on the northern end of the project, the higher-than-normal asphalt content in the asphalt base layer and the stiffer-than-desired true asphalt binder grade in the surface mix, which was due to the lack of a grade bump to the virgin binder.

The RAP sections that were constructed on I-395 are important as they offer comparisons of varying RAP content with nearly everything else being held constant. There was an important benefit in that the sections were all constructed curb-to-curb and adjacent to each other. Performance testing on the mixes in the laboratory did not reveal any significant disparities between them. It remains to be seen if the sections perform similarly as time advances.

The density analysis of the varying RAP sections yielded little confidence that CTDOT should proceed with specifications allowing for RAP in excess of 20% in HMA mixtures at this time. The 40% RAP section had an average mat density value of 89.8%. Not only is this statistically lower than the control section density, but also lower than the CTDOT specification minimum of 92.0% of maximum theoretical density. The 30% RAP sections both had an average joint density of 88.0% of maximum theoretical density. Given the core sample population of the two 30% RAP sections combined, there is reason to suggest that achieving the CTDOT joint density specification minimum values at RAP contents exceeding 20% RAP may be difficult. The 40% RAP average joint density value was considerable higher (90.3%) however this is more likely due to chance since the mat average density value was significantly lower, as stated.

Finally, these roadway surfaces are still in their infancies so making statements regarding their future performance would not be prudent as the stiffer asphalt binders make these pavements more susceptible to distresses commonly seen in older pavements.

Recommendations

- RAS in the quantity in which it was used on the Route 220 project (3%) should be allowed if a contractor has a desire to do so, as there are no foreseeable detriments with its use.
- The Route 220 pilot project section should be monitored on a yearly basis to verify and ensure the performance of the RAS section as compared to the control section.
- Any future premature distress on the northern ~900 feet of Lenox Street needs to take into consideration the excavations that took place as a result of water main breaks. Future analysis of this section should focus primarily on the southern half of the project.
- Lenox Street should be monitored on a yearly basis. Consideration should be given to the fact that Lenox Street is not a State road and therefore is not photo-logged yearly.
- Additional pilot projects containing both RAP and RAS should be considered, ensuring the specified materials are used, such as a softer asphalt binder and available binder content from RAS in the asphalt binder calculations.
- CTDOT should develop a binder replacement calculation methodology and base future requirements on it, as sources and combinations of recycled materials are subject to change.
- The FHWA memorandum [15] regarding the use of limited binder availability in AASHTO PP 78-14 [16] for use in mix designs containing RAS should be strongly considered.
- Total allowable RAP contents should not be adjusted until further work proves beneficial and/or the determination of the effects of the varying RAP contents on the I-395 sections is complete.
- The high RAP sections on I-395 should be monitored on a yearly basis at least via photo-logging in order to determine any performance inconsistencies.
- RAP content in excess of 20% should not be allowed until there is confidence in achieving at least minimum compaction specification requirements on both the mat and the joint.

- Consideration should be given to constructing additional varying RAP content roadway pilot sections in order to increase the knowledge base and data pool of pavement surfaces with varying RAP contents in Connecticut.
- Producers should be encouraged to follow recycled products management practices, which promote the desired integrity, uniformity and quality of RAP and RAS with respect to processing, storage and handling.

References

1. Hansen, Kent R., Audrey Copeland. *Annual Asphalt Pavement Industry Survey on Recycled Materials and Warm-mix Asphalt Usage: 2009 – 2012*. Information Series 138. National Asphalt Pavement Association. December 2013.

2. Copeland, Audrey. *Reclaimed Asphalt Pavement in Asphalt Mixtures: State of the Practice.* Office of Infrastructure research and Development. Federal Highway Administration. Report No. FHWA-HRT-11-021. April, 2011.

3. National Center for Asphalt Technology. (2009). *"LTPP Data Shows RAP Mixes Perform as Well as Virgin Mixes*." Asphalt Technology News, 21, 2. NCAT. Auburn, AL.

4. Stolarski, Phil. *Caltrans Survey on Reclaimed Asphalt Pavement (RAP) in Hot Mix Asphalt (HMA).* California Department of Transportation. May 16th, 2014.

5. AASHTO Subcommittee on Materials. Reclaimed Asphalt Shingles Usage Survey. Compiled by Hood, Woody, Maryland SHA. November 2014.

6. Standard Specification for Highway Construction. Idaho Transportation Department. P.185. 2012. http://itd.idaho.gov/newsandinfo/docs/2012SpecBook.pdf

7. Revision of Section 401. Reclaimed Asphalt Pavement. May 2, 2013. Standard Specification for Road and Bridge Construction. Colorado Department of Transportation. http://www.coloradodot.info/business/designsupport/construction-specifications/2011-Specs/standard-special-provisions/sections-200-500-revisions/401rap.doc/view

8. *Part 00700 – Wearing Surfaces*. Oregon Standard Specifications for Construction. 2015. Oregon Department of Transportation. http://www.oregon.gov/ODOT/HWY/SPECS/docs/15book/2015_STANDARD_SPECIFICATIONS.pdf

9. *Section 403 Asphaltic Concrete Pavement*. Missouri standard specification for Highway Construction. October, 2014. Missouri Department of Transportation. http://www.modot.org/business/standards_and_specs/Sec0403.pdf

10. *Standard Test Method for Sampling Bituminous Paving Mixtures*. AASHTO Designation :T 168. Standard Specifications for Transportation Materials and Methods of Sampling and Testing. 33rd Edition. Part 2A. American Association of State Highway and Transportation Officials. 2013.

11. *Resistance of Compacted Hot Mix Asphalt (HMA) to Moisture-Induced Damage*. AASHTO Designation: T283-07. Standard Specifications for Transportation Materials and Methods of Sampling and Testing. 33rd Edition. Part 2B. American Association of State Highway and Transportation Officials. 2013.

12. *Hamburg Wheel-Track Testing of Compacted Hot Mix Asphalt (HMA)*. AASHTO Designation: T324-11. Standard Specifications for Transportation Materials and Methods of Sampling and Testing. 33rd Edition. Part 2B. American Association of State Highway and Transportation Officials. 2013.

13. *Determining Rutting Susceptibility of Hot Mix Asphalt(HMA) Using the Asphalt Pavement Analyzer(APA)*. AASHTO Designation: T340-1. Standard Specifications for Transportation Materials and Methods of Sampling and Testing. 33rd Edition. Part 2B. American Association of State Highway and Transportation Officials. 2013.

14. Traffic Monitoring Volume Information ADT I-395. Connecticut Department of Transportation. http://www.ct.gov/dot/cwp/view.asp?a=3532&q=330402. 2015

15. Waidelich, Walter C. Jr. ACTION: Recycled Asphalt Shingles Used in Asphalt Pavements. Memorandum. Federal Highway Administration, U.S. Department of Transportation. December 11, 2014.

16. *Design Considerations When Using Reclaimed Asphalt Shingles (RAS) in Asphalt Mixtures.* American Association of State Highway and Transportation Officials Designation: PP78-14. Provisional Standards. AASHTO 2013.

Appendix A.

2012 Connecticut HMA Producer Survey (RAP Use)

1. Does your company use RAP (or anticipate using RAP in the future) in the production of HMA? (If you don't use RAP you don't need to go any further in the questions)

1	Yes
2	Yes
3	No
4	Yes
5	We are using RAP in our state mixes. 9.5mm, 12.5mm and 1"mixes
6	We do not use RAP
7	Yes
8	Yes
9	Yes, in one facility

2. In your opinion, what is the maximum percentage of RAP that you can handle in your plants? If you have multiple plants please specify between drum and batch plants.

1	15% maybe more
2	25%
3	N/A
4	Drum plants 35-40%, batch plants 15-18% maybe 20%
5	We can probably do 20% in our batch plant. Maybe 25% with a warm mix additive
6	N/A
7	Have done 50% in Drum Plants. 30-40% achieveable in Batch Plants.
8	Drum plants 50%. Batch plants 30%
9	Batch 15%, Drum 20%

3. In your opinion, what is the maximum percentage of RAP that is cost effective for you to use? If you have multiple plants please specify between drum and batch plants.

1	15%
2	20%
3	N/A
4	As much as the type of plant can handle. Drum plants 35-40%, batch plants 15-18% maybe 20%
5	20% without warm mix is roughly our max for cost. As an aside, this is what makes RAS so attractive. The ac gained with 4-5% RAS is equivalent to 15-20% RAP but the fuel usage is less because the agg temp does not have to be as high for the RAS vs the RAP.
6	N/A
7	There isn't one
8	Drum Plants 50%. Batch plants 30%
9	See answer to question #2 but answer depends on specification requirements of higher

RAP %.

4. Based upon the availability of RAP from Connecticut projects that you receive, what is the maximum percentage of RAP that you could run so that the amount or RAP used on CTDOT projects is relatively consistent throughout the construction season? (in other words – it would not be desirable to have major changes in the RAP content throughout the season for mixes coming from the same HMA plant. Also, it is not desirable for RAP to be imported from other states just to keep the RAP percentages up.)

1 15% Runs us close on any given year to equal our intake from state projects

2 15%

3 N/A

4 Our only HMA plant that services CT recieves no millings from CT. The RAP used at the plant utilizes RAP made from millings from NYSDOT Projects

5 As far as the availability, we keep our RAP piles separated by the job it came from. It is very rare I have to switch RAP piles between jobs. When we do I make sure to choose a similar specific gravity RAP supply pile and run that till that pile is exausted. At 15% RAP we see little crossover between RAP supply. Also helps that the majority of our RAP comes from large jobs. So the incoming RAP piles are quite large.

6 N/A

7 N/A

8 Drum plants 40%. Batch plants 30%

9 Batch 15%, Drum 20%

5. Would you be opposed to having varying RAP percentages allowed depending on if the mix is being used for base course, intermediate course or wearing surface?

1 No Objections

2 No

3 N/A

4 Currently that is the standard in NYS. Max RAP in 37.5mm is 30%, 25MM, 19MM, 12.5MM, 9.5MM and 6.3MM all have a maximum of 20%

5 As for varying the RAP amount per what course the mix is being placed I wouldnt mind as long as the RAP amounts allowed do not go below 15%.

6 N/A

7 No answer

8 Yes because it increases the number of mix designs and production logistics

9 Yes, managing material quality and meeting varying specifications for outside customers becomes incredibly difficult if different percentages are allowed

Appendix B. Lenox Street Gradations

Lenox Street Gradation #1

Sieve Analysis Test Report (T 27, T 11 , T 255)

Date/Time:	7/2/2013 0:00	Lab/Location:	CAP Lab		
Weather:		Date Rec'd #:		Random Sample:	No
Project:	Lenox St.	Lab Login #:		Lot #:	
Contract #:		Material ID:	Sub base	Sublot #:	
Contractor:	Tilcon	Material #:		Sample Location:	1
Pay Item #:		Sample #:		Station:	
Source:		Sample Type:	Other	Offset:	
Plant Type:		Sampled By/Cert. #:			

Total Moisture Content by Drying (T 255)

Wet Mass(W):	
Original Dry Mass(D):	3542.1
Moisture Loss (W - D):	
% Moisture (100 x (W - D) / D):	

Materials Finer than 75 µm Sieve by Washing (T 11)

Dry Mass after wash (Dw):	3450.9
Mass of Fines lost by washing (D - Dw):	91.2
% -75 µm Sieve (100 x (D - Dw)/D):	2.6

Sieve Analysis of Fine and Coarse Aggregates (T 27)

	Mass per Sieve		% Retained per Sieve		% Passing		Specification %	
Sieve, in. (mm)	Unwashed	Washed	Unwashed	Washed	Unwashed	Washed	Unwashed	Washed
2 1/2 (63)					100.0	100.0		
2 (50)					100.0	100.0		
1 1/2 (37.5)		72.1		2.0	100.0	98.0		
1 (25)		476.5		13.5	100.0	84.5		
3/4 (19)		103.9		2.9	100.0	81.6		
1/2 (12.5)		492.4		13.9	100.0	67.7		
3/8 (9.5)		237.0		6.7	100.0	61.0		
#4 (4.75)		555.2		15.7	100.0	45.3		
#8 (2.36)		298.1		8.4	100.0	36.9		
#16 (1.18)		254.7		7.2	100.0	29.7		
#30 (600 µm)		286.1		8.1	100.0	21.6		
#50 (300 µm)		317.8		9.0	100.0	12.6		
#100 (150 µm)		199.9		5.6	100.0	7.0		
#200 (75 µm)		90.2		2.5	100.0	4.5		
Pan		66.9		1.9	Calculate Fineness Modulus?			Yes
Sub Total		3450.8			Fineness Modulus (FM) =		4.859	
Loss on Washing (D - Dw)		91.2						
Total		3542.0						

Lenox Street Gradation #2

Sieve Analysis Test Report (T 27, T 11 , T 255)

Date/Time:	7/2/2013 0:00	Lab/Location:	CAP Lab		
Weather:		Date Rec'd #:		Random Sample:	No
Project:	Lenox St.	Lab Login #:		Lot #:	
Contract #:		Material ID:	Sub base	Sublot #:	
Contractor:	Tilcon	Material #:		Sample Location:	7
Pay Item #:		Sample #:		Station:	
Source:		Sample Type:	Other	Offset:	
Plant Type:		Sampled By/Cert. #:			

Total Moisture Content by Drying (T 255)	
Wet Mass(W):	
Original Dry Mass(D):	3483.4
Moisture Loss (W - D):	
% Moisture (100 x (W - D) / D):	

Materials Finer than 75 µm Sieve by Washing (T 11)	
Dry Mass after wash (Dw):	3411.1
Mass of Fines lost by washing (D - Dw):	72.3
% -75 µm Sieve (100 x (D - Dw)/D):	2.1

Sieve Analysis of Fine and Coarse Aggregates (T 27)

	Mass per Sieve		% Retained per Sieve		% Passing		Specification %	
Sieve, in. (mm)	Unwashed	Washed	Unwashed	Washed	Unwashed	Washed	Unwashed	Washed
2 1/2 (63)					100.0	100.0		
2 (50)					100.0	100.0		
1 1/2 (37.5)		127.0		3.6	100.0	96.4		
1 (25)		70.3		2.0	100.0	94.4		
3/4 (19)		175.2		5.0	100.0	89.4		
1/2 (12.5)		129.6		3.7	100.0	85.7		
3/8 (9.5)		208.0		6.0	100.0	79.7		
#4 (4.75)		639.6		18.4	100.0	61.3		
#8 (2.36)		491.7		14.1	100.0	47.2		
#16 (1.18)		401.3		11.5	100.0	35.7		
#30 (600 µm)		369.4		10.6	100.0	25.1		
#50 (300 µm)		406.9		11.7	100.0	13.4		
#100 (150 µm)		228.7		6.6	100.0	6.8		
#200 (75 µm)		81.1		2.3	100.0	4.5		
Pan		19.0		0.5	Calculate Fineness Modulus?			Yes
Sub Total		3347.8			Fineness Modulus (FM) =		4.308	
Loss on Washing (D - Dw)		72.3		Sum of washed weights TOLERANCE ERROR				
Total		3420.1						

Appendix C. Lenox Street Northern Section Details

There were three water main breaks during construction of the sub-base. The first water main break took place approximately 1,350 feet north of the beginning of the project. This was in the vicinity of the intersection with Durkin Road. The other two water main breaks took place north of the Durkin Road intersection. These areas required excavation of the compacted granular base material to repair the main. No density testing was conducted on these sections after the water main repairs were made.

There was a fourth water main break following completion of the project. This required excavation of the wearing surface, the base layer and the sub-base to repair the main. This section is located 1,248 feet north of the beginning of the project. This break was repaired and there was no subsequent density testing of backfill or either of the HMA layers in that location. An image of this patched repair section is shown in Figure 11. It should also be noted that another patched section of the roadway was observed during the Winter of 2014/2015. This patched section is shown in Figure 12 and is located 1,735 feet north of the beginning of the project. It is not known what occurred in this area.

Therefore, there is a total of 5 different excavated sections of the roadway. It is not known how much of an effect the water main breaks or the other occurrence had on the surrounding sub-base and HMA layers. Future analysis of this roadway should take these factors into consideration. It should be noted as well, that these issues all took place in the northern half of the project.

Appendix D. T-Test between Varying RAP Sections and Control (Mat Densities)

t-Test: Two-Sample Assuming Equal Variances

	15%	*20%*
Mean	93.9	94.83333333
Variance	0.28	0.363333333
Observations	3	3
Pooled Variance	0.321667	
Hypothesized Mean Difference	0	
df	4	
t Stat	**-2.01548**	
P(T<=t) one-tail	0.057042	
t Critical one-tail	2.131847	
P(T<=t) two-tail	**0.114083**	
t Critical two-tail	**2.776445**	

t-Test: Two-Sample Assuming Equal Variances

	15%	*30% (PG 76-22)*
Mean	93.9	90.75
Variance	0.28	5.359
Observations	3	6
Pooled Variance	3.907857	
Hypothesized Mean Difference	0	
df	7	
t Stat	**2.253493**	
P(T<=t) one-tail	0.029447	
t Critical one-tail	1.894579	
P(T<=t) two-tail	**0.058894**	
t Critical two-tail	**2.364624**	

t-Test: Two-Sample Assuming Equal Variances

	15%	*30% (PG 76-28)*
Mean	93.9	91.4
Variance	0.28	1.32
Observations	3	8
Pooled Variance	1.088889	
Hypothesized Mean Difference	0	
df	9	
t Stat	**3.538812**	
P(T<=t) one-tail	0.003163	
t Critical one-tail	1.833113	
P(T<=t) two-tail	**0.006326**	
t Critical two-tail	**2.262157**	

t-Test: Two-Sample Assuming Equal Variances

	15%	*40% (PG 76-28)*
Mean	93.9	89.75
Variance	0.28	2.231428571
Observations	3	8
Pooled Variance	1.797778	
Hypothesized Mean Difference	0	
df	9	
t Stat	**4.571823**	
P(T<=t) one-tail	0.000672	
t Critical one-tail	1.833113	
P(T<=t) two-tail	**0.001343**	
t Critical two-tail	**2.262157**	

Appendix E. T-Test between Varying RAP Sections and Control (Joint Densities)

t-Test: Two-Sample Assuming Equal Variances

	15%	*20%*
Mean	90.55	91.93333333
Variance	1.287	0.603333333
Observations	6	3
Pooled Variance	1.091667	
Hypothesized Mean Difference	0	
df	7	
t Stat	**-1.87239**	
P(T<=t) one-tail	0.051657	
t Critical one-tail	1.894579	
P(T<=t) two-tail	**0.103314**	
t Critical two-tail	**2.364624**	

t-Test: Two-Sample Assuming Equal Variances

	15%	*30% (PG 76-22)*
Mean	90.55	87.98333333
Variance	1.287	3.953666667
Observations	6	6
Pooled Variance	2.620333	
Hypothesized Mean Difference	0	
df	10	
t Stat	**2.746324**	
P(T<=t) one-tail	0.010304	
t Critical one-tail	1.812461	
P(T<=t) two-tail	**0.020608**	
t Critical two-tail	**2.228139**	

t-Test: Two-Sample Assuming Equal Variances

	15%	*30% (PG 76-28)*
Mean	90.55	88.0125
Variance	1.287	0.378392857
Observations	6	8
Pooled Variance	0.756979	
Hypothesized Mean Difference	0	
df	12	
t Stat	**5.400335**	
P(T<=t) one-tail	8E-05	
t Critical one-tail	1.782288	
P(T<=t) two-tail	**0.00016**	
t Critical two-tail	**2.178813**	

t-Test: Two-Sample Assuming Equal Variances

	15%	*40% (PG 76-28)*
Mean	90.55	90.3375
Variance	1.287	1.876964286
Observations	6	8
Pooled Variance	1.631146	
Hypothesized Mean Difference	0	
df	12	
t Stat	**0.308084**	
P(T<=t) one-tail	0.38165	
t Critical one-tail	1.782288	
P(T<=t) two-tail	**0.763301**	
t Critical two-tail	**2.178813**	