**Recycling Asphalt Pavements**
**Containing Modified Binders**

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# SI (Modern Metric) Conversion Factors Page

## 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 | mililitres | 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

## Executive Summary

The use of reclaimed/recycled asphalt pavement as a construction material has potentially substantial long-term benefits from both a cost standpoint as well as durability standpoint. RAP has been utilized in increasing amounts by agencies across the United States in recent years.

The use of modified asphalt binder has also been increasing in areas across the US especially in areas where there are large varying climatic cycles such as in the northeastern portion of the country. These modifications to asphalt binder are intended to increase ductility and flexibility in colder temperatures. They are also intended to increase rigidity and resistance to permanent deformation in higher temperatures.

Questions and skepticism as to the benefits of RAP usage along with the use of modified asphalt binder have given rise to this research. It is possible that the incorporation of RAP, particularly in higher quantities, changes the chemistry of the asphalt binder making it unstable and mitigating any benefits associated with its use.

Phase I of this research involved surveying State Transportation agencies in the northeast region of the United States as to which types of modified asphalts are currently being used as well as any RAP usage specification they may have. States were also asked to provide their definition (if any) of what a modified binder is. This information along with information collected from asphalt suppliers was used to develop a regionally accepted, working definition of what a modified binder is.

During Phase II of this research, multiple sources of RAP, aggregates and asphalt binder grades (modified and unmodified) were combined and tested in the laboratory. The materials which were collected and tested, are some of the most commonly used throughout the northeast region of the United States. A single mix design, with slight adjustments for the different materials, was used to fabricate specimens used in this research.

The performance testing which was conducted includes FT-IR testing for binder modification, Multiple Stress Creep Recovery testing of the different binders for rutting susceptibility and rut testing in the Asphalt Pavement Analyzer for rutting susceptibility of the different combinations of materials.

Results show that there is no negative impact on performance caused by the incorporation of RAP into mixes which contain modified binders. For the most part, the incorporation of RAP actually increased the ability of each mix to resist rutting and permanent deformation. Conclusions and recommendations were based on graphical analyses of plotted data as well as statistical analyses and comparisons of results of all of the performance testing conducted over the course of this research.

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## List of Symbols and Acronyms

**RAP –** Recycled (or reclaimed) Asphalt Pavement

**FHWA –** Federal Highway Administration

***APA* –** Asphalt Pavement Alliance

**PM –** Polymer Modified

**PPA –** Polyphosphoric Acid

**CPDM –** Comprehensive Pavement Design Manual

**EB –** Engineering Bulletin

**NCHRP –** National Cooperative Highway Research Program

**SBS –** Styrene-butadiene-styrene

**IDT –** Indirect Tensile Test

**Pb** – Percent Binder

**RAP** pb – Percent Binder in RAP

**Gsb** – Bulk Specific Gravity

**Gmm** – Maximum Theoretical Specific Gravity

**APA –** Asphalt Pavement Analyzer

**DSR –** Dynamic Shear Rheometer

**MSCR –** Multiple Stress Creep Recovery

**psi** – Pounds Per Square Inch

**lbs** – pounds

**N** - Newton

**kPa** – kilopascals

**PG** – Performance Grade

**LVDT** – Load Variable Distance Transducer

**FT-IR** – Fourier Transform Infrared Spectroscopy

**ATR** – Attenuated Total Reflectance

**$cm^{-1}$** – reciprocal centimeter, representing wave number

**RTFO** – Rolling Thin Film Oven

**PB –** Polybutadiene

**PS –** Polystyrene

**Jnr –** Non-recoverable Creep Compliance

**ANOVA –** Analysis of Variance

## 1.0 Phase I Background

The Northeastern States represent the region of the country where the use of modified asphalt binders has been the least prolific. This is due to the availability of crude oils that make high quality asphalt binders without the need for modification. Recent reports and construction utilizing modified asphalts have been shown to increase a pavement's ability to resist rutting and shoving among other various forms of deformation. This has caused many transportation agencies to consider the possibility of using modified asphalts in areas subject to stresses that may cause the pavement to permanently deform. The use of modified asphalts has become commonplace in many other parts of the United States.

The definition of what a modified asphalt binder actually is, has been very elusive and difficult to establish and in most cases an agency will commonly use their own definition or description of what they feel constitutes a modified binder. Modified asphalt binders are most commonly defined as an asphalt binder that has had an additive incorporated into it after leaving the refining tower. This definition creates difficulties and confusion when anti-strip agents are added, polyphosphoric acid (PPA) is used to alter the properties of asphalt binder, the asphalt binder is air blown to increase its stiffness and other aromatic oils are added back into the binder to alter its properties. Most suppliers would not consider these activities to be asphalt modification techniques while many transportation agencies would consider these to be methods of asphalt modification, and thus there is potential for a discrepancy. Identifying the exact methodology used by modified asphalt manufacturers is made more difficult as the manufacturers tend to guard their modification techniques and processes.

Asphalt modification generally takes place on soft virgin asphalts in an effort to make the asphalt binder stiffer at higher temperatures while retaining the asphalt binder's flexibility and ductility at lower temperatures. One of the most common methods of asphalt binder modification is the incorporation of polymers into the asphalt binder. These polymers are long molecular chains which are dispersed homogeneously throughout the binder. Polymer modified asphalts tend to reduce rutting because in order for the pavement to permanently deform, the “internal friction” which is enhanced by these long polymer chains must be overcome.

Modified asphalts do require some special handling requirements. The manufacturers of these modified asphalts must pay special attention to the chemistry of the asphalt binder to be modified to ensure their modification method will be stable. If the base asphalt and the material used as a modifier do not co-exist well together, then the product is likely to be unstable. This instability is likely to reduce the effectiveness of the modification thereby leaving an asphalt binder that is much softer at high temperatures than anticipated and as such, less useful than initially expected. This process can be extremely significant when two modified asphalt binders with the same performance grade but different base crude sources or modification systems are mixed. The final product of this mixing may not be the original performance grade of the two modified asphalts but instead, may be closer to the base grade of the two asphalt binders prior to modification due to an incompatibility between the two asphalts.

## 1.1 Phase I Research Objectives

There are two objectives to this research. One objective is to determine which types of modified asphalt binders are currently being used in the production of hot mix asphalt (HMA) in the Northeast. The approach to accomplishing this was to contact representatives of transportation agencies throughout the region to inquire about their modified asphalt use and specifications. Asphalt binder suppliers to the region were also contacted for inquiry. The second objective was to investigate individual transportation agencies’ definition of what constitutes modified binder and finally provide a working definition that is universally accepted by users of modified binders.

## 1.2 Transportation Agencies’ Responses on Modified Asphalt and RAP

As part of this research, seven State transportation agencies in the Northeast were surveyed about their individual binders, modifier specifications and RAP use. The agencies that were surveyed in no particular order were: Connecticut Department of Transportation, Maine Department of Transportation, MassHighway, New Hampshire Department of Transportation, New York State Department of Transportation, Rhode Island Department of Transportation and Vermont Agency of Transportation. Each agency was asked to answer the following eleven survey questions:

1. What grades of asphalt binder are specified for your state?
2. What companies supply asphalt binders for your state?
3. Does your state intentionally specify modified asphalt binder grades and if so what grades?
4. Does your state have a list of approved asphalt binder modifiers?
5. Does your state prohibit any types of asphalt?
6. Does your state require modified asphalts be labeled as such on the bill of lading and what criteria does your state use for requiring such lading?
7. What definition if any does your state use for what constitutes a modified asphalt?
8. Does your state allow latex injection at the mix plant? If so, what companies/products are approved for this type of modification?
9. Does your state restrict the HMA layers in which RAP can be used? (Such as only allowing it in the base/binder course).
10. What is the maximum percentage of RAP allowed in your state?
11. Has your state had any experience using RAP with a modified asphalt? If so, please provide your impression of how it worked out.

These questions were sent to a representative for each agency via email questionnaire and the responses from each representative for each question are given in Appendix A. The questions precede the responses from each agency. Of the seven agencies surveyed all but one in some way have specified or do specify modified asphalt binder grades however none of the surveyed states has a list of approved modifier materials, although Vermont discourages the use of polyphosphoric acid in their state. The Northeast Asphalt User Producer Group (NEAUPG) agreement asserts that each modified asphalt be labeled on receipt slips as well as test results. Loose definitions of what is described as a modified asphalt are used in the development of a standard working definition as part of this research. RAP, in various percentages is used in all layers of HMA pavements by all agencies surveyed with the exception of Rhode Island DOT. Half of the agencies surveyed indicated they had experience with the use modified binder in a mix containing RAP and reported no problems.

### 1.3 Asphalt Binder Suppliers' Responses Regarding Modified Asphalts

As part of this research, 19 asphalt binder suppliers to the Northeast were surveyed about their individual binders, modifier specifications and RAP use. Of the 19 surveyed, 5 replied. The suppliers that were surveyed in no particular order are labeled as supplier A, Supplier B, Supplier C etc… This was done in an effort to maintain confidentiality with the suppliers. Each supplier was asked to answer the following six survey questions:

1. In order to work towards the best working definition of a modified asphalt, I want to contact suppliers (even if they do not regularly supply modified asphalt) for their definition of a modified asphalt. How does your working definition of a modified asphalt compare to AASHTO's?
2. What quantity of polymer modified asphalt do you sell in the region (New England and New York)?
3. What quantity of acid modified asphalt do you sell in the region (New England and New York)?
4. What quantity of air blown modified asphalt do you sell in the region (New England and New York)?
5. If you sell modified asphalts other than the methods listed in 2A-2C, please list the modification system and approximate quantities sold of each type listed.
6. Would you be willing to provide MSDSs for your products to the research team? If yes, if you would forward them to me at your convenience, it would be appreciated.

The companies that were surveyed were done so via email questionnaire. The responses provided by the representative of each supplier are tabulated in Appendix B. The questions precede the responses from each supplier. The response from the suppliers with respect to the definition of a modified asphalt is broken down in the Chapter of this report entitled "Development of a Working Definition of Polymer Modified Asphalt". The group of suppliers in general does not report to sell a great deal of polymer modified asphalt in the New

England/New York region nor do they sell a great deal of acid modified asphalt. One supplier reported to have sold air-blown asphalt in the past however there were no suppliers planning to sell any air-blown asphalt this coming year. All of the asphalt binder suppliers did contribute their material safety data sheets for all of their products to the research team.

### 1.4 Development of a Working Definition of "Modified Asphalt"

Several documents and research reports have been reviewed in order to synthesize a designation that can be used to define what exactly constitutes a modified asphalt, as well as to characterize which properties and characteristics an asphalt needs to exhibit, to be classified as modified or unmodified. The documents that were reviewed consist of research reports including National Cooperative Highway Research Program (NCHRP) reports, American Association of State Highway and Transportation Officials (AASHTO) designations, and the Association of Modified Asphalt Producers (AMAP) definition, different supplier definitions as well as New England /New York states' transportation agencies definitions. A concluding definition adopted by the research team follows the review.

#### 1.4.1 Modified Asphalt Definitions from Reviewed Literature

AASHTO Designation: R 15-00 (2005): R 15-00 is AASHTO's Standard Recommended Practice for Asphalt Additives and Modifiers. AASHTO gives an interpretation for the meaning of asphalt modifiers as well as asphalt additives and state that the terms are used interchangeably and apply when the intention is to improve the properties of the asphalt binder at hand. It is stated in Section 1 (Scope) as follows:

*1.1 This standard recommended practice covers the laboratory testing required to evaluate asphalt additives and modifiers in both neat asphalt and in asphalt-aggregate hot mixtures. The terms "additive" and "modifier" are used interchangeably and are broadly interpreted to include any materials added to asphalt binder in minor amounts, other than mineral fillers, sand, and aggregates, whose purported effect is to improve the performance and service life of* *pavements or maintenance materials by improving the properties of the asphalt binder and/or hot mix asphalt.*

AASHTO Designation M320 (2005): M 320 is AASHTO's Standard Specification for Performance Graded Asphalt Binder. In section 5, (Materials and Manufacture) of the specification subsections 5.1 and 5.2 are stated as follows:

*5.1 Asphalt binder shall be prepared by the refining of crude petroleum by suitable methods, with or without the addition of modifiers*

*5.2 Modifiers may be any organic material of suitable manufacture that is used in virgin or recycled condition and that is dissolved, dispersed or reacted in asphalt binder to enhance its performance.*

NCHRP 459: Characterization of Modified Asphalt Binders in Superpave Mix Design: p.15

*The Superpave binder test protocols are based on two main assumptions:*

1. *Binder behavior is independent of film thickness and sample geometry;*

2. *The binder is evaluated based on the properties within the linear viscoelastic range in which its behavior is independent of the strain or stress level.*

*The essence of these two assumptions is that the asphalt binder is a simple system that can be characterized using linear viscoelasticity and simple geometry within which stress and strain fields are simple to calculate. To apply the current Superpave binder protocols for modified binders, both of these conditions have to be satisfied. In other words, the modified binders must be rheologically "simple."*

*Modified binders not classified as simple are termed "complex" according to the following definitions:*

- *Simple binders: Asphalt binders with rheologically simple behavior that do not violate the assumptions upon which the PG system is based; these assumptions include independence of strain, non-thixotropy, isotropy, and independence of sample geometry.*

- *Complex Binders: Asphalt binders that cannot be classified as simple binders because their behavior violates one or more of the PG system assumptions.*

The report states that the simple/complex characterization handles the issue of a blind specification well. It is noted that because a reasonable specification would cover all simple binders, the user would by the same cause not need to know the composition of the binder in question as the PG system sufficiently describes its characteristics. It is said then that the only thing a user would need to know is whether the testing protocol used in grading the asphalt at hand is applicable. The only circumstance in which the testing protocol would not apply is when the asphalt is "complex".

Further in the NCHRP 459 report, a similar statement is made on page 86. The statement somewhat suggests that it may not in most cases, be necessary to classify binders as modified or unmodified because with few exceptions, the PG grading system covers most binders used, whether modified or unmodified. The statement is as follows:

*This research indicates that there is no clear definition of what constitutes a modified asphalt. Asphalt modification techniques are expanding to include the use of different additives, refining processes, or both, in order to meet the requirements of the performance-grading system. Establishing criteria to classify asphalts into modified and unmodified is difficult and unnecessary, because, with few exceptions, the performance grading system can be made applicable to all binders, regardless of their composition. Exceptions include multi-phase systems with additives used to modify asphalts. These asphalts with additives need special testing to determine the nature and relative amount of additives. The storage stability of such asphalts also needs to be evaluated.*

Study of Asphalt Cement Additives and Extenders by Haas et al (1982):
*An asphalt cement modifier or additive is a material which would normally be added to and/or mixed with the asphalt before mix production, the resulting binder and/or the mix; or where an aged binder is involved, as in recycling, to improve or restore the properties of the aged binder.*

This definition suggests that cases where asphalt would be considered modified are those cases where the properties of the asphalt in question have been altered by means of an additive prior to HMA production. According to this definition, recycled HMA material where a rejuvenator has been added would be said to contain modified binder as well.

Guidelines for Use of Modified Binders. University of Florida. (2005):

Researchers expanded on the definition from Haas et al and developed the following goals and intentions of a modified binder:

*Based on the definition above (Haas et al.), an ideal asphalt modifier used in HMA aims to the following primary objectives:*

- *To obtain stiffer mixes at high service temperatures to reduce rutting susceptibility*
- *To obtain softer mixes at low service temperatures to minimize thermal cracking*
- *To improve the fatigue resistance of HMA mixes*
- *To improve the asphalt-aggregate bond to improve resistance to stripping or moisture damage*
- *To improve resistance to abrasion which also reduces other forms of surface disintegration*
- *To rejuvenate aged asphalt binders*

In essence, these intentions are to improve on the characteristics which are required of an asphalt binder in order to perform optimally in an HMA paved roadway surface given any set of conditions.

The Association of Modified Asphalt Producers (AMAP): Glossary of terms on the internet defines modified asphalt as follows: *Modified Asphalt* - A modified asphalt cement or binder has one or more additives that have been physically and/or chemically blended to improve overall durability and in-service pavement performance.

### 1.4.2 State Transportation Agency Definitions

The research team for this project surveyed several state transportation agencies in the Northeast and found that some states utilized a definition of modified asphalt while some states did not. The following definitions were reported by their corresponding states and the entire questionnaire with responses is tabulated in Appendix A:

***What definition, if any, does your State use for what constitutes a modified asphalt?***

New Hampshire Department of Transportation – "Anything added to an asphalt after the refining process that is done to change the properties of the binder.

New York State Department of Transportation – "We specify PG binder meeting M 320 regardless of modifier. On some projects we do specify an additional Elastic Recovery requirement".

Connecticut Department of Transportation – "Requirements are listed in a copy of our annual binder letter." Items of pertinence are listed as follows:
*6. Each source of supply of PG binder shall indicate that the PG binders contain no additives used to modify or enhance their performance properties without disclosure to the Department as required herein and as specified in AASHTO R 26-01, Section 9.6.*

Vermont Agency of Transportation – "Vermont likes to define modified asphalt as any product that has been altered physically or chemically from its proposed original state. Even if the modification takes place during the refining cycle Vermont still considers it to be a modified PG Binder."

Rhode Island Department of Transportation – "No definition."

Maine Department of Transportation – "Not sure we have a firm definition. I think we reference AASHTO, etc for testing… NOTE: I personally consider PPA and the other items that we discussed at the Rocky Hill meeting last year as modified asphalts."

### 1.4.3 Modified Asphalt Definitions from Suppliers from Northeast Region

19 suppliers were also surveyed in a similar manner in an attempt to obtain their definitions of modified binders of which only 5 suppliers responded. Along with

the request for their definition of a modified asphalt, they were asked how their working definition of a modified asphalt compared to AASHTO R-15. The definitions and responses provided by the suppliers are listed below and the entire questionnaire is tabulated in Appendix B. Please note that the suppliers' names have been replaced with a generic name to avoid any supplier being connected with any disseminated information as a result of this research.

***In order to work towards the best working definition of a modified asphalt, I want to contact suppliers (even if they do not regularly supply modified asphalt) for their definition of a modified asphalt. How does your working definition of a modified asphalt compare to AASHTO's?***

Supplier – "…would define a modified asphalt as any material or process change which alters the characteristics of the asphalt binder after the refining process."

Supplier – "We have no problem with AASHTO's definition."

Supplier – "Polymer Modified Asphalt (PMA), of which there are two types in general use in this area –

> Terminal blended – SBS which is normally "reacted" with a networking agent to provide a storage stable product.
>
> HMA plant in-line blended – where SBR latex is in-line injected into the asphalt line at the HMA plant.
>
> A ter-polymer may also be available on a limited basis.

Supplier – "… we tend to consider as "modified asphalt" any asphalt that is not a direct extraction of the Vacuum Tower Bottom stream, from crude distillation. We understand the definition provided by AASHTO. As far as we are concerned, the difference with AASHTO may reside in the classification of an asphalt that contains an oxidized component (from our patented "Premium technology" for example). We internally consider as "modified" an asphalt that contains an oxidized component, whereas AASHTO may not consider it as modified, by definition. As far as the other ways of modification (polymer, acid) we agree with AASHTO's classification."

Supplier –"no modified asphalt supplied in 2005"

### 1.4.4 Research Team Working Definition of Modified Asphalt

In conclusion of the reviewed documents and the survey responses from suppliers and state transportation agencies, the research team has developed a working definition of modified asphalt. It is relatively straight forward however encompassing the general scope of the reviewed literature as well as the responses received from the surveys. The definition is as follows:

*An asphalt is considered modified when less than one hundred percent of its constituents are naturally inherent within the crude oil stock(s) from which it originated. A neat asphalt (sometimes referred to as unmodified asphalt) consists solely of the compounds in the crude oil stock used to produce it. Therefore, an asphalt that consists of the blend of two neat asphalts would still be considered neat or unmodified.*

## 2.0 Phase II Background

The original scope of Phase II for this project was to examine the effects of using RAP containing polymer modifiers in hot mix asphalt HMA pavements. After meeting with the technical committee, it was determined that there is very little if any pavement in New England that contained polymer modified asphalt old enough to require milling. In addition, no state transportation agencies were able to identify where any of these sections were along with the type of asphalt modifier used. Therefore, in concert with the project's technical committee, the project scope for Phase II was revised and submitted to NETC for approval. The approved revised scope of work changed the focus of the second phase of the project to investigate the effect of using virgin asphalt binders that contain modifiers when RAP is added to the project. As the cost of modified asphalt binders is considerably higher than neat asphalt binders, it is important to make sure that the addition of RAP does not negate the anticipated performance benefits from the modified asphalt binder.

At the time the revised scope of work was approved, the technical committee also agreed that using 10% RAP by weight would be a good average representation of what was being done across New England. In 2010, the amount of RAP being allowed throughout New England had increased well above the 10% level. The rapid development of warm mix asphalt technologies has made even higher RAP content mixes a possibility that has yet to be fully explored.

## 2.1 Phase II Introduction and Summary of Reviewed Literature

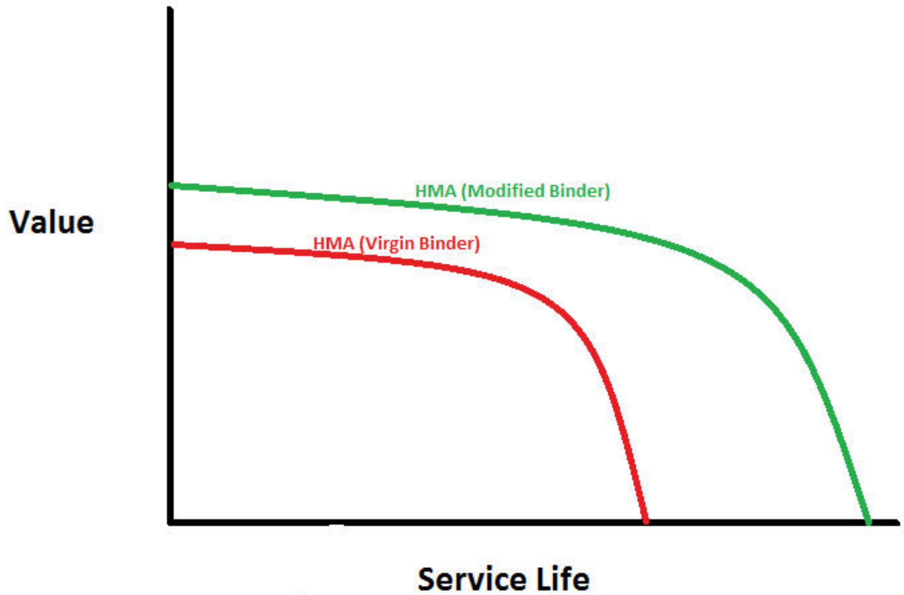
RAP has been seen as a quality construction product/material by many transportation agencies and industry officials. The use of RAP in new HMA pavements has positive implications from both economic and environmental viewpoints. When RAP is incorporated into a pavement, the volume of virgin raw materials needed to be excavated, manufactured and/or purchased is reduced. The Federal Highway Administration (FHWA) Recycled Materials Policy states *"Recycling presents environmental opportunities and challenges, which, when appropriately addressed, can maximize the benefits of re-use. The use of most recycled materials poses no threat or danger to the air, soil, or water. Furthermore, careful design, engineering and application of recycled materials can reduce or eliminate the need to search for and extract new, virgin materials from the land." (FHWA, 2006)*

According to the Asphalt Pavement Alliance (*APA*), the United States asphalt industry reclaims approximately 100,000,000 tons of HMA per year and about 95% of this reclaimed material is reused or recycled. (*APA*, 2010) As the most recycled material in the United States, asphalt pavements are continually changing in constituency. Understanding the interaction of virgin materials and RAP is necessary for predicting and determining a pavement's ability to meet serviceability requirements and withstand loading from both traffic and environmental conditions.

When asphalt pavement surfaces or base courses are milled and then combined with virgin aggregates and asphalt binders (neat or modified) to form new pavement, physical properties as well as performance properties can be expected to differ in comparison with pavements which were constructed with no recycled materials. The quantity of RAP which is incorporated into a new pavement as well as the material properties of the RAP itself are variables which could affect the performance of constructed pavements. The physical properties of RAP and the variation of those properties present numerous possible effects on the performance of a pavement.

Modified asphalt binders are becoming increasingly standard in many areas of the country. In a report Foreword by T. Paul Teng from FHWA Office of Infrastructure Research and Development, he states that the use of polymer modified (PM) asphalt binder is increasing and it is expected that it will continue to increase *(Stuart, 2001)*. Asphalt modifications are intended to enhance neat asphalt binder properties such that they will meet and perhaps exceed standard requirements and perform well under given environmental and traffic loading conditions. These modifications come in several forms from latex to acid and different polymer arrangements intended to enhance the placement, serviceability and performance characteristics of the pavement. While these binder modifications have a significantly higher cost, the expectation is that the added service life of the pavement will more than compensate for the added dollars spent during construction similarly to what is illustrated in Figure 2.1.

**Figure 2.1 Modified Binder Intention**




Because of the numerous different constituent possibilities involved with the production of asphalt pavement, there are as many possible compatibility issues among these different materials which, if exist, need to be identified and addressed.

One such example of a possible compatibility issue which may arise is the use of polyphosphoric acid (PPA) modification in conjunction with limestone aggregates. PPA modification has been used in the Northeastern region of the United States for many years. Polyphosphoric acid is an inorganic polymer that is incorporated into virgin asphalt binders as a means of increasing the high temperature performance grade and there is some conflicting preliminary research that suggests it may or may not help slow aging of the asphalt binder.

The New York State Department of Transportation (NYSDOT) Comprehensive Pavement Design Manual (CPDM) disallows the use of PPA modification in all upstate New York paving projects and includes the following statement regarding downstate New York paving projects *"Use of polyphosphoric acid (PPA) to modify the PG binder properties is prohibited for mixtures containing limestone,*

*limestone as an aggregate blend component, limestone as a constituent in crushed gravel aggregate, or recycled asphalt pavement (RAP) that includes limestone. This prohibition also applies to the use of PPA as a cross-linking agent for polymer modification." (NYSDOT, 2008)* Investigation into the reason for this prohibition lead to Engineering Bulletin(EB) 08-008 and EB08-014, *Replacement Pages for Comprehensive Pavement Design Manual Chapter 6*… and *Performance Graded Binder Requirements for Ongoing Contracts,* respectively. These EBs reveal a compatibility issue between limestone and PPA. The documents refer to several instances of flushing taking place on different projects throughout New York State. In many cases, the bulletins state, the flushing was not evident until several weeks after placement of the pavement. The EBs go on to indicate that these pavements continued to be soft and pliable. Those instances were termed "atypical flushing" by the agency because they could not assign the cause to those factors normally attributed to flushing. The bulletins state that the common factors among these projects exhibiting atypical flushing include the use of limestone and PPA binder modification. *(NYSDOT EB, 2008(1)), (NYSDOT EB, 2008(2))*

As the use of different modification techniques increases, the short term and long term effects they have on pavements which are constructed with differing aggregate sources need to be identified and examined. Styrene-butadiene-styrene or SBS modification of asphalt is another very prolific asphalt modification. The ability of SBS modified asphalt to remain ductile and flexible at low temperatures combined with its tendency to resist permanent deformation at high temperatures make its use very attractive and appealing with respect to gaining the maximum serviceability potential from a roadway. Any potential long-term or short term problems with the incorporation of such modifiers into a pavement containing RAP need to be addressed especially with respect to the increased cost of these modifications. The increasing use and incorporation of RAP into asphalt pavements adds to the complexity of examining when PG binder modification along with the use of different aggregates will have a positive or negative effect on the performance of a pavement.

Possible incompatibilities may exist between the materials present in RAP and the virgin aggregates and asphalt (neat or modified) materials they are combined with. Modified asphalt binders are primarily a chemical package designed such that the modifier remains stable in the asphalt binder. The base asphalt, prior to modification is typically a softer asphalt which the modifying agent causes to be stiffer with the intent of better performance of the HMA at higher temperatures. If the modifier is damaged, possibly due to the inclusion of RAP materials altering the binder chemistry in the mix, there is a chance the asphalt binder will revert to its softer original nature. These compatibility issues may lead to premature failure of the pavement and ultimately mitigate any anticipated monetary savings associated with the use of the RAP.

National Highway Cooperative Research Program (NCHRP) Report 459 states that it may not be necessary to classify binders as modified or unmodified because, regardless of their composition, these binders can be classified according to the PG grading system with few exceptions. The text reads as follows:

"*This research indicates that there is no clear definition of what constitutes a modified asphalt. Asphalt modification techniques are expanding to include the use of different additives, refining processes, or both, in order to meet the requirements of the performance-grading system. Establishing criteria to classify asphalts into modified and unmodified is difficult and unnecessary, because, with few exceptions, the performance grading system can be made applicable to all binders, regardless of their composition. Exceptions include multi-phase systems with additives used to modify asphalts. These asphalts with additives need special testing to determine the nature and relative amount of additives. The storage stability of such asphalts also needs to be evaluated." (Bahia et. al., 2001)*

This notion unfortunately does not address the compatibility issues which may be associated with combining modified or unmodified asphalts with different aggregate sources. It also does not address the possible compatibility issues which may be inherent when combining modified or unmodified binders with RAP containing different binder compositions. This research does, however, introduce the complications of testing HMA materials produced with the numerous variations of modified binders. It is suggested that the traditional PG binder grading system may not be sufficient in determining variations in field performance with respect to modified asphalt binders. Additional research has shown that the PG system does not adequately address modifiers as was originally anticipated.

Regional State Transportation Agencies as well as regional binder suppliers were surveyed as to their views and definitions of modified asphalt binders. (See Phase I) All responses pointed away from potential compatibility issues dealing with combining these binders with RAP containing different binders. Different asphalt-aggregate interactions among these different binders also was not considered or addressed in the responses. As part of this regional transportation agency inquiry, each was questioned as to their RAP usage as well as any restrictions on RAP usage and experience with the use of RAP and modified asphalt. Tables 2.1, 2.2 and 2.3 show the responses to the RAP usage restrictions and the modified asphalt/RAP experience questions posed to each agency. Responses were received in 2007 for Phase 1 of this research. These responses were verified and a few minor updates were included in 2010 for Phase 2 of this research. The results to those specific questions are shown below.

**Does your state restrict the HMA layers in which RAP can be used? (such as only allowing it in the base/binder course).**

**Table 2.1. HMA Layer Restrictions for RAP (Agency 2010 Responses)**

| | |
|---|---|
| RI DOT | Yes. RAP is only allowed in the base and binder courses. |
| NH DOT | No |
| Maine DOT | Not at this time---until a couple years ago we did not allow any RAP in surface mixes. |
| NYSDOT | NYSDOT allows RAP in base, binder, and surface/top course mixes. |
| ConnDOT | No |
| MassHighway | RAP may be used in Class I Bituminous Concrete. The proportion of RAP to virgin aggregate shall be limited to a maximum of 40% for Drum Plants and 20% for modified batch plants. The maximum amount of RAP for surface courses shall be 10% (except in Open Graded Friction Course in which RAP is not allowed.) |
| VAOT | Vermont only limits the percentage used but does not restrict it by location. |

**What is the maximum percentage of RAP allowed in your state?**

**Table 2.2 Allowable RAP Percentages (Agency 2010 Responses)**

| | |
|---|---|
| RI DOT | 30% |
| NH DOT | Up to 1.5% total recycled binder in base and binder courses (equivalent to 37.5% RAP). Up to 1.0% total recycled binder in wearing surfaces (equivalent to 20% RAP). |
| Maine DOT | Maine made a slight change in 2010 to allow a max of 20% RAP in surface, binder, or base courses without a PG binder grade change provided that the RAP is from a "classified" source (taken from a DOT project that had a designed mix with proper aggregate quality). We continue to allow 15% "unclassified" RAP in all mixes without a bump in PG binder. We also can approve a PG 52-34 or the current PG 58-34 for mixes that exceed the above RAP percentages. |
| NYSDOT | NYSDOT allows up to 20% RAP in binder and surface course mixes and up to 30% in base. |
| ConnDOT | Limit of 15% max on all classes for all lifts |
| MADOT | Drum Plants – 40%, Batch Plants 20%. No more than 10% in wearing surfaces. |
| VAOT | 15% for Superpave and up to 20+% for Marshall mix |

**Has your state had any experience using RAP with a modified asphalt? If so, please provide your impressions of how it worked out.**

**Table 2.3. Modified Asphalt and RAP Experience (Agency 2010 Responses)**

| | |
|---|---|
| RI DOT | No. We feel that if we are going to pay a significant premium for a modified binder, we won't risk losing the enhancements we obtain from the binder by introducing RAP. |
| NH DOT | No |
| Maine DOT | No if you define modified as "polymer" but the answer is Yes if you consider PPA as modified. Maine DOT does not have any evidence to show that PPA modified mixes with RAP perform any different than other mixes. |
| NYSDOT | NYSDOT does have locations with both RAP and modified PG binder (primarily polymer modified). No issues were encountered, but an evaluation re: benefits has not been completed at this time. |
| ConnDOT | No |
| MADOT | No response |
| VAOT | 60-70% of Vermont's binder is modified and most of it contains RAP. In my opinion RAP is one of the most consistent "aggregates" in the State and mixes perform very well as long as the percentage of natural is controlled. |

Given the inquiry responses, it is apparent that the use of RAP in both quantity and source vary from agency to agency however there is no indication that any of the polled agencies have experienced problems with the use of RAP in a mix containing modified binder. It should be noted at this time that this inquiry was conducted 2 years prior to the aforementioned Engineering Bulletins describing the experiences and restrictions of NYSDOT with PPA modified asphalt binder and limestone aggregate combinations.

Florida DOT conducted a study entitled *Laboratory Evaluation of Polymer Modified Asphalt Mixture with Reclaimed Asphalt Pavement.* (Kim et al, 2009), state that RAP mixtures have shown good rutting resistance and mixes containing styrene-butadiene-styrene (SBS) polymer modified binders have shown both good rutting resistance as well as cracking resistance. In their research they investigated the performance of the RAP mixes combined with SBS polymer modified binders. These materials were investigated with respect to cracking, rutting and binder properties. The mixes included RAP containing both limestone and granite aggregates. These mixes contained 0%, 15%, 25%, and 35% RAP.

The authors concluded that all of the RAP mixes containing SBS polymer modified binder performed well under the Superpave Indirect Tensile Test (IDT) as well as the APA (Asphalt Pavement Analyzer) which measures susceptibility to rutting. They also concluded that the amount of RAP binder blended with the modified binder had some effect on the performance parameters as measured with the Dynamic Shear Rheometer (DSR). The extent of this effect on mixture performance was not evident.

### 2.2 Phase II Objectives

Phase II of this research is intended to serve multiple functions. The first of those functions is to identify, examine, and address compatibility issues that may be present when RAP is incorporated into HMA, particularly HMA containing modified asphalt binder. It is desired to understand if incorporating RAP into mixes with modified binder changes the chemistry of the virgin binder to a degree that would have a negative impact on mixture performance which would be seen through performance testing of the mix in the laboratory. It is assumed that damage to the modified binder would result in a much softer asphalt binder.

Because RAP may or may not contain asphalt binder which was previously modified, several sources and combinations of RAP, aggregates, as well as modified and unmodified binders were tested and investigated as to their performance under load in the laboratory. The objective was to test different combinations of commonly used liquid asphalt binders and aggregates along with RAP throughout the northeast region of the United States.

One specific purpose of this research is to examine the performance effects of polyphosphoric acid modification with several different commonly used aggregates and RAP in the northeastern region of the United States. Based on findings during the review of literature, the interest is especially focused on limestone aggregates and RAP containing limestone aggregates.

The combinations were to be subjected to performance testing in the laboratory. The performance testing was to be focused primarily around rutting susceptibility in order to gain insight as to a certain material combination's ability to maintain its structural integrity. The assumption is that if the asphalt binder is damaged by the addition of RAP, the rutting susceptibility would increase.

The results of this research will provide insight as to which combinations of RAP, aggregates, binder, and modified binder should be avoided, which combinations perform the best, and which constituents in the mix are the limiting factors to acceptable performance.

## 2.3 Phase II Work Plan

The initial work plan for this research involved collecting several samples of RAP with different binder characteristics. These RAP samples were to contain differing asphalt grades, including modified asphalt binders. The work plan was altered as described in Section 2.0 of this report.

Four RAP sources from the New England Region were sampled with differing aggregates including schist, limestone, basaltic trap-rock and granite. These four aggregates are among the most commonly used for HMA throughout the Northeast. Five of the most commonly used asphalt binders were also used in the study. These were both modified and unmodified. These combinations were selected to examine different asphalt modifications and the differing effects of the inclusion of RAP with each of the binders.

The research team developed a single mix design for use with all combinations of aggregate, binder and RAP. These mixes were then tested in the Asphalt Pavement Analyzer for susceptibility to rutting.

The different asphalt binders were also tested for creep compliance via the Multiple Stress Creep Recovery MSCR test in the DSR. The MSCR test measures the elastic recovery after a series of shear stresses are exerted on the specimen. Superpave binder testing specifications were initially focused around unmodified asphalt binders and the MSCR test was designed to better characterize the performance properties of modified versus unmodified binders particularly with respect to rutting potential.

The final step in the approved work plan was to develop guidelines for the use of RAP with modified binders based on results of testing conducted during this research as well as selected guidelines currently used throughout the region.

### 2.4 Materials

The research team collected asphalt binder and RAP from different sources throughout the northeast. This was done in an effort to cover the broad spectrum of the different aggregates and the most commonly used asphalt binders in the northeastern region of the United States. In all, there were 5 different liquid binders collected and used for testing.

The liquid binders selected and collected for use were:

- PG 58-34
- PG 64-28
- PG 64-28 (ppa)
- PG 70-28
- PG 76-22

All of these binders contained some degree of polymer modification with the exception of the PG 64-28. The PG 64-28 was the only unmodified binder used during the course of this research.

The research team also collected RAP samples from different sources throughout the Northeast. These sources included RAP with differing coarse aggregate morphologies. In all, there were 4 different RAP aggregates which were collected and used for testing.

The RAPs selected were based on coarse aggregate morphology were:

- Basaltic trap-rock – Connecticut
- Schist – Connecticut
- Limestone – Maine
- Granite – Vermont

Each of the individual combinations are shown in Table 2.4. The mix designs for the RAP combinations as well as the recovered RAP aggregate combinations are discussed in the next section.

**Table 2.4. Binder and RAP/RAP Aggregate Combinations**

| PG58-34 | PG64-28 | PG64-28(ppa) | PG70-28 | PG76-22 |
|---|---|---|---|---|
| Schist RAP | Schist RAP | Schist RAP | Schist RAP | Schist RAP |
| Granite RAP | Granite RAP | Granite RAP | Granite RAP | Granite RAP |
| Limestone RAP | Limestone RAP | Limestone RAP | Limestone RAP | Limestone RAP |
| Basalt RAP | Basalt RAP | Basalt RAP | Basalt RAP | Basalt RAP |
| Recovered Schist | Recovered Schist | Recovered Schist | Recovered Schist | Recovered Schist |
| Recovered Granite | Recovered Granite | Recovered Granite | Recovered Granite | Recovered Granite |
| Recovered Limestone | Recovered Limestone | Recovered Limestone | Recovered Limestone | Recovered Limestone |
| Recovered Basalt | Recovered Basalt | Recovered Basalt | Recovered Basalt | Recovered Basalt |

### 2.5 Mix Design

These materials (in their respective different combinations) were incorporated into a mix design from a producer in Connecticut. The virgin aggregates remained constant for each different combination of RAP and binder. These virgin aggregates were comprised primarily of basaltic trap rock from the central region of Connecticut.

#### 2.5.1 10% RAP Mix

The first mix design, which included the RAP added as 10% of the total mix weight, is shown summarized in Table 2.5. Very slight adjustments were made to the constituent virgin aggregate weights and binder weights to accommodate for the amount of binder in the RAP and the different grades of virgin binder such that each mix combination would meet volumetric criteria. The slight differences in each batch are also seen in Table 2.5.

**Table 2.5. 10% RAP Mix Design Summary**

| Mixes With 10 % RAP | Percent (%) Mix | | | |
|---|---|---|---|---|
| | Wallingford (basalt) | Vermont (granite) | Torrington (schist) | Maine (limestone) |
| | | | | |
| 1/2" | 20 | 19 | 22 | 18 |
| 3/8" | 25 | 26 | 28 | 24 |
| Stone Sand | 35 | 35 | 35 | 38 |
| Natural Sand | 10 | 10 | 5 | 10 |
| RAP | 10 | 10 | 10 | 10 |
| | | | | |
| Pb | 5.2 | 5.2 | 5.3 | 5.5 |
| RAP Pb | 5.2 | 5.3 | 5.1 | 5.2 |
| | Specific Gravity | | | |
| Gsb | 2.806 | 2.788 | 2.816 | 2.787 |
| Gmm: | | | | |
| 58-34 | 2.63 | 2.623 | 2.617 | 2.635 |
| 64-28 | 2.647 | 2.633 | 2.645 | 2.621 |
| 64-28 PPA | 2.644 | 2.619 | 2.647 | 2.618 |
| 70-28 | 2.631 | 2.616 | 2.624 | 2.609 |
| 76-22 | 2.655 | 2.640 | 2.651 | 2.638 |

### 2.5.2 10% RAP Aggregate Mix

The second mix design did not include RAP as a constituent in the mix. Instead, the aggregate from the RAP was recovered and added as 10% (compensation was made for the weight as the asphalt binder was no longer present) of the total mix weight. This kept the aggregate structure the same between the specimens containing all virgin binder and a blend of virgin binder and RAP aggregate. The RAP aggregates were recovered by first burning off the RAP binder in an ignition oven. The aggregates were then recovered and added to the virgin binder and virgin aggregates. The summary of that mix design is shown in Table 2.6.

**Table 2.6. 10% RAP Aggregate Mix Design Summary**

| Control mixes | Percent (%) Mix | | | |
|---|---|---|---|---|
| | Wallingford (basalt) | Vermont (granite) | Torrington (schist) | Maine (limestone) |
| 1/2" | 21 | 16 | 20 | 17 |
| 3/8" | 25 | 22 | 27 | 23 |
| Stone Sand | 34 | 37 | 35 | 38 |
| Natural Sand | 10 | 15 | 8 | 12 |
| RAP | 10 | 10 | 10 | 10 |
| | | | | |
| Pb | 5.5 | 5.5 | 5.5 | 5.8 |
| | Specific Gravity | | | |
| Gsb | 2.807 | 2.771 | 2.807 | 2.778 |
| Gmm: | | | | |
| 58-34 | 2.624 | 2.609 | 2.598 | 2.65 |
| 64-28 | 2.621 | 2.610 | 2.620 | 2.599 |
| 64-28 PPA | 2.628 | 2.607 | 2.633 | 2.599 |
| 70-28 | 2.627 | 2.597 | 2.620 | 2.593 |
| 76-22 | 2.619 | 2.605 | 2.621 | 2.593 |

### 2.5.3 Specimen Fabrication

Specimens from each mix combination were then fabricated in a Superpave Gyratory Compactor model Pine AFGC125X at the CAP Lab. The fabricated specimen height was 75 mm to accommodate testing in the Asphalt Pavement Analyzer. The mix specimens were subsequently checked to ensure volumetric properties prior to performance testing.

### 2.6.1 Spectroscopic Verification of Asphalt Binders

Although verification of the binders was outside the scope of the work plan, the technology was available to the research team who decided to include it in this research. The five asphalt binders were analyzed using Fourier Transform Infrared Spectroscopy (FT-IR). Samples of the binder from each RAP source were recovered via AASHTO T170 *Standard Method of Test for Recovery of Asphalt from Solution by Abson Method* and these recovered binders were tested as well. A portable Bruker ALPHA Attenuated Total Reflectance (ATR) FT-IR spectrometer was used. To perform an FT-IR test, about 1 g of binder was put directly on the ATR crystal (diamond) and a fixed load was applied to a sample to ensure its full contact with the crystal. 24 scans were run for each sample within the wave number range of 4000 to 400 $cm^{-1}$ with resolution of 4 $cm^{-1}$, and the resultant averaged spectra was recorded. Three replicates were made for each binder type. The ATR cell was chosen for a multitude of reasons including; the portability of the device, in case of viscous solids/liquid materials such as asphalt binder, ATR does not require any special sample preparation. A quantitative analysis of the FT-IR spectra in this study was performed using Gaussian approximation. This procedure facilitated identification and quantification of the absorbance peaks related to oxygen-containing functional group and, more importantly, polymer components. This testing was conducted to confirm polymer modification of the virgin binders and compare level of oxidation of all binders.

### 2.6.2 Testing of the Asphalt Binders

The testing of the liquid asphalt binders was conducted in a dynamic shear rheometer (DSR). The test protocol was the MSCR test as outlined in AASHTO TP 70, *Multiple Stress Creep Recovery (MSCR) Test of Asphalt Binder Using a Dynamic Shear Rheometer (DSR)*. This test was run on the five asphalt binders which were subjects of this study after they were short-term aged in a rolling thin film oven (RTFO). The RTFO short-term aging is used to simulate that aging of asphalt binder which takes place during production and placement of the HMA. This aging was desired because it is the in place performance of the mix which is of primary concern for this research.

The recovered RAP binders were tested in this manner as well. These recovered binders were also run in the RTFO for purposes of eliminating any remaining trichloroethylene from the samples. The Research Team's previous experience has shown that RTFO conditioning of recovered RAP binder greatly improves the reproducibility of the test results.

The MSCR test repeatedly subjects the asphalt specimens under test to shear loads and measures the percent of both recovered and non-recovered creep. A

0.1 kPa load is applied for 1 second and the zero-stress recovery is then measured over a 9 second recovery period. This sequence is repeated 10 times after which the load is increased to 3.2 kPa. Again, after a 1 second load, measurements are recorded over a 9 second recovery period and this cycle is repeated 10 times at the increased load. Measurements are taken every 0.1 second and stored by the DSR computer data acquisition system.

## 2.7 Testing of Mixes – Asphalt Pavement Analyzer

Performance testing of the different HMA combinations took place in the APA or Asphalt Pavement Analyzer. The test is outlined in AASHTO TP 63 *Determining the Rutting Susceptibility of Hot Mix Asphalt (HMA) Using the Asphalt Pavement Analyzer (APA)*. The APA test is intended to predict the ability of the mix to resist rutting. The APA is shown in Figure 2.2.

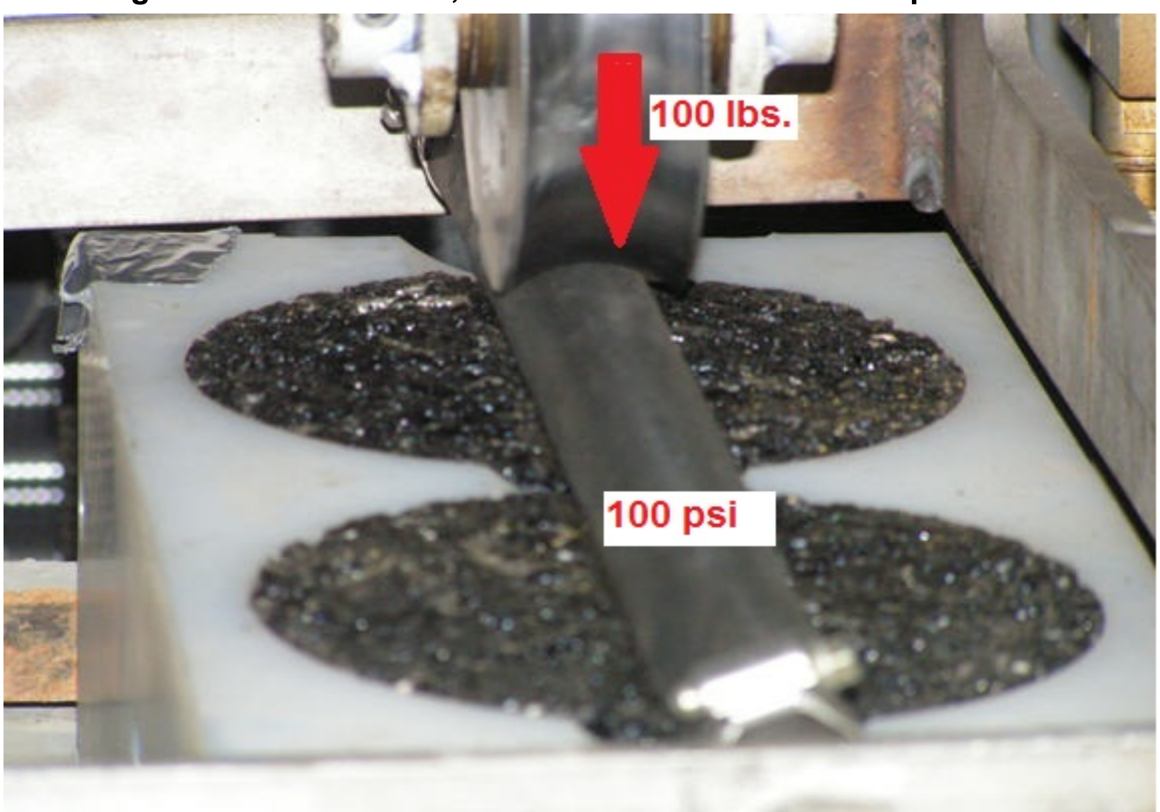
**Figure 2.2 Asphalt Pavement Analyzer**

The APA at the CAP Lab is also capable of several other performance tests including The Hamburg test which tests for stripping due to moisture susceptibility and a flexural beam fatigue test (*Mahoney et al. 2008*). For this research, only the rutting susceptibility was measured using the APA.

Rut testing in the APA involves repeated linear dynamic loading of HMA specimens in a temperature controlled chamber. The HMA specimens are fabricated in a Superpave gyratory compacter to dimensions of 150 mm in diameter by 75 mm in height. The APA allows for 3 sets of specimens to be tested simultaneously. Each set consists of two gyratory specimens which are fitted into a mold as shown in Figure 2.3. The sets are tested side by side. Once the specimens are placed into the machine, a loading rack is placed over the top of them. The loading rack consists of a steel frame with three pressurized rubber tubes which sit atop the specimens. The specimens are then conditioned to the test temperature for at least 6 but not more than 24 hours. The test temperature corresponds to the upper temperature of the PG grade of the constituent binder in the HMA. Once the specimens have been conditioned, the tubes are pressurized to 100 ± 5 psi (690 ± 35 kPa). There is a stainless steel load wheel for each set of specimens which is then set to exert a force of 100 ± 5 lbs (445 ± 22 N) on the pressurized tubes over the specimens as shown in Figure 2.4.

**Figure 2.3. APA Mold with Specimen Set**

**Figure 2.4. Load Wheel, Loaded Pressure Tube and Specimens**



The loaded wheels then oscillate over the pressurized tubes to simulate traffic loading on the HMA specimens. The load wheels are cycled over the specimens 8000 times for a complete test. A test can also be terminated after a certain specified rut depth has been reached on machines with an automatic rut-depth measurement system such as was used during this research.

Rut depths are measured in four locations per specimen set: twice on the front specimen and twice on the rear specimen. Rut depths are measured with load variable distance transducers or LVDTs. These measurements are recorded each time the wheel passes over the specimens. An example of the raw data output is shown in Figure 2.5.

**Figure 2.5 Raw Data Output from APA Test**

| Left Stroke Count | Left Depth Value 1 | Left Depth Value 2 | Left Depth Value 3 | Left Depth Value 4 | Left Depth Value 5 | Center Stroke Count | Center Depth Value 1 | Center Depth Value 2 | Center Depth Value 3 | Center Depth Value 4 | Center Depth Value 5 | Right Stroke Count | Right Depth Value 1 | Right Depth Value 2 | Right Depth Value 3 | Right Depth Value 4 | Right Depth Value 5 | Cabin Temp | Water Temp | Add Stroke | L Avg | C Avg | R Avg |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 73 | 67 | 0 | 0 | 0 | 0 |
| 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 75 | 67 | 0 | 0 | 0 | 0 |
| 3 | 0 | 0 | 0 | 0.029892 | 1.3899422 | 3 | 0 | 0 | 0 | -0.224056 | 0.5227928 | 3 | 0 | 0 | 0 | 0.4500656 | 1.485218 | 74 | 67 | 3 | 0.3549585 | 0.0746841 | 0.4838209 |
| 4 | 0 | 0 | 0 | 0.029892 | 1.3899422 | 4 | 0 | 0 | 0 | -0.224056 | 0.5227928 | 4 | 0 | 0 | 0 | 0.4500656 | 1.485218 | 74 | 67 | 4 | 0.3549585 | 0.0746841 | 0.4838209 |
| 6 | 0 | 0 | 0 | 0.029892 | 2.7051544 | 6 | 0 | 0 | 0 | -0.224056 | 1.4190102 | 6 | 0 | 0 | 0 | 0.4500656 | 2.5653725 | 74 | 67 | 6 | 0.6837616 | 0.2987385 | 0.7538595 |
| 7 | 0 | 0 | 0 | 0.029892 | 2.7051544 | 7 | 0 | 0 | 0 | -0.224056 | 1.4190102 | 7 | 0 | 0 | 0 | 0.4500656 | 2.5653725 | 74 | 67 | 7 | 0.6837616 | 0.2987385 | 0.7538595 |
| 8 | 0 | 0 | 0 | 0.029892 | 2.7051544 | 8 | 0 | 0 | 0 | -0.224056 | 1.4190102 | 8 | 0 | 0 | 0 | 0.4500656 | 2.5653725 | 74 | 67 | 8 | 0.6837616 | 0.2987385 | 0.7538595 |
| 9 | 0 | 0 | 0 | 0.029892 | 2.7051544 | 9 | 0 | 0 | 0 | -0.224056 | 1.4190102 | 9 | 0 | 0 | 0 | 0.4500656 | 2.5653725 | 74 | 67 | 9 | 0.6837616 | 0.2987385 | 0.7538595 |
| 10 | 0 | 0 | 0 | 0.029892 | 2.7051544 | 10 | 0 | 0 | 0 | -0.224056 | 1.4190102 | 10 | 0 | 0 | 0 | 0.4500656 | 2.5653725 | 74 | 67 | 10 | 0.6837616 | 0.2987385 | 0.7538595 |
| 11 | 0 | 0.9565163 | 0 | 0.029892 | 2.7051544 | 11 | 0 | 0.5676041 | 0 | -0.224056 | 1.4190102 | 11 | 0 | 0.6750984 | 0 | 0.4500656 | 2.5653725 | 74 | 67 | 11 | 0.9228907 | 0.4406395 | 0.9226341 |
| 12 | 0 | 0.9565163 | 0 | 0.029892 | 1.5393982 | 12 | 0 | 0.5676041 | 0 | -0.224056 | 1.0157127 | 12 | 0 | 0.6750984 | 0 | 0.4500656 | 1.5902328 | 74 | 67 | 12 | 0.6314516 | 0.3398151 | 0.6788492 |
| 13 | 0 | 0.9565163 | 0 | 0.029892 | 1.5393982 | 13 | 0 | 0.5676041 | 0 | -0.224056 | 1.0157127 | 13 | 0 | 0.6750984 | 0 | 0.4500656 | 1.5902328 | 74 | 67 | 13 | 0.6314516 | 0.3398151 | 0.6788492 |
| 14 | 0.4782562 | 0.9565163 | 0 | 0.029892 | 1.5393982 | 14 | 0.7169762 | 0.5676041 | 0 | -0.224056 | 1.0157127 | 14 | 0.2850418 | 0.6750984 | 0 | 0.4500656 | 1.5902328 | 74 | 67 | 14 | 0.7510157 | 0.5190592 | 0.7501097 |
| 15 | 0.4782562 | 0.9565163 | 0 | 0.029892 | 2.9741745 | 15 | 0.7169762 | 0.5676041 | 0 | -0.224056 | 1.7774963 | 15 | 0.2850418 | 0.6750984 | 0 | 0.4500656 | 2.6253815 | 74 | 67 | 15 | 1.1097097 | 0.7095051 | 1.0088968 |
| 16 | 0.4782562 | 0.9565163 | 0 | 0.029892 | 2.9741745 | 16 | 0.7169762 | 0.5676041 | 0 | -0.224056 | 1.7774963 | 16 | 0.2850418 | 0.6750984 | 0 | 0.4500656 | 2.6253815 | 74 | 67 | 16 | 1.1097097 | 0.7095051 | 1.0088968 |
| 23 | 0.4782562 | 0.9565163 | 0 | 0.029892 | 1.7934723 | 23 | 0.7169762 | 0.5676041 | 0 | -0.224056 | 1.1501465 | 23 | 0.2850418 | 0.6750984 | 0 | 0.4500656 | 1.7552567 | 74 | 67 | 23 | 0.8145342 | 0.5526676 | 0.7913656 |
| 24 | 0.4782562 | 0.9565163 | 0 | 0.029892 | 1.7934723 | 24 | 0.7169762 | 0.5676041 | 0 | -0.224056 | 1.1501465 | 24 | 0.2850418 | 0.6750984 | 0 | 0.4500656 | 1.7552567 | 74 | 67 | 24 | 0.8145342 | 0.5526676 | 0.7913656 |
| 25 | 0.4782562 | 0.9565163 | 0 | 0.029892 | 3.1385765 | 25 | 0.7169762 | 0.5676041 | 0 | [illegible] | [illegible] | 25 | 0.2850418 | 0.6750984 | 0 | 0.4500656 | 2.6853905 | 74 | 67 | 25 | 1.1508102 | 0.7281771 | 1.0238991 |
| 26 | 0.4782562 | 0.9565163 | 0 | 0.029892 | 3.1385765 | 26 | 0.7169762 | 0.5676041 | 0 | [illegible] | [illegible] | 26 | 0.2850418 | 0.6750984 | 0 | 0.4500656 | 2.6853905 | 74 | 67 | 26 | 1.1508102 | 0.7281771 | 1.0238991 |
| 27 | 0.4782562 | 0.9565163 | 0 | 0.029892 | 3.1385765 | 27 | 0.7169762 | 0.5676041 | 0 | [illegible] | [illegible] | 27 | 0.2850418 | 0.6750984 | 0 | 0.4500656 | 2.6853905 | 74 | 67 | 27 | 1.1508102 | 0.7281771 | 1.0238991 |
| 28 | 0.4782562 | 0.9565163 | 0 | 0.029892 | 3.1385765 | 28 | 0.7169762 | 0.5676041 | 0 | [illegible] | [illegible] | 28 | 0.2850418 | 0.6750984 | 0 | 0.4500656 | 2.6853905 | 74 | 67 | 28 | 1.1508102 | 0.7281771 | 1.0238991 |
| 34 | 0.4782562 | 0.9565163 | 0 | 0.029892 | 3.1385765 | 34 | 0.7169762 | 0.5676041 | 0 | -0.224056 | 1.8521843 | 34 | 0.2850418 | 0.6750984 | 0 | 0.4500656 | 2.6853905 | 74 | 67 | 34 | 1.1508102 | 0.7281771 | 1.0238991 |
| 35 | 0.4782562 | 0.9565163 | 0 | 0.029892 | 3.3627625 | 35 | 0.7169762 | 0.5676041 | 0 | -0.224056 | 1.8969917 | 35 | 0.2850418 | 0.6750984 | 0 | 0.4500656 | 2.9554329 | 74 | 67 | 35 | 1.2068567 | 0.7393789 | 1.0914097 |
| 36 | 0.4782562 | 0.9565163 | 0 | 0.029892 | 3.3627625 | 36 | 0.7169762 | 0.5676041 | 0 | -0.224056 | 1.8969917 | 36 | 0.2850418 | 0.6750984 | 0 | 0.4500656 | 2.9554329 | 74 | 67 | 36 | 1.2068567 | 0.7393789 | 1.0914097 |
| 41 | 0.4782562 | 0.9565163 | 0 | 0.029892 | 3.3627625 | 41 | 0.7169762 | 0.5676041 | 0 | -0.224056 | 1.8969917 | 41 | 0.2850418 | 0.6750984 | 0 | 0.4500656 | 2.9554329 | 74 | 67 | 41 | 1.2068567 | 0.7393789 | 1.0914097 |
| 42 | 0.4782562 | 0.9565163 | 0 | 0.029892 | 3.3627625 | 42 | 0.7169762 | 0.5676041 | 0 | -0.224056 | 1.8969917 | 42 | 0.2850418 | 0.6750984 | 0 | 0.4500656 | 2.9554329 | 74 | 67 | 42 | 1.2068567 | 0.7393789 | 1.0914097 |
| 43 | 0.4782562 | 0.9565163 | 0 | 0.029892 | 3.3627625 | 43 | 0.7169762 | 0.5676041 | 0 | -0.224056 | 1.8969917 | 43 | 0.2850418 | 0.6750984 | 0 | 0.4500656 | 2.9554329 | 74 | 67 | 43 | 1.2068567 | 0.7393789 | 1.0914097 |
| 48 | 1.0611382 | 0.9565163 | 0 | 0.029892 | 3.3627625 | 48 | 0.6273537 | 0.5676041 | 0 | -0.224056 | 1.8969917 | 48 | 1.1701698 | 0.6750984 | 0 | 0.4500656 | 2.9554329 | 74 | 67 | 48 | 1.3525772 | 0.7169733 | 1.3126917 |
| 52 | 1.0611382 | 0.9565163 | 0 | 0.8668442 | 3.3627625 | 52 | 0.6273537 | 0.5676041 | 0 | 0.7169762 | 1.8969917 | 52 | 1.1701698 | 0.6750984 | 0 | 1.2601852 | 2.9554329 | 74 | 67 | 52 | 1.5618153 | 0.9522314 | 1.5152216 |
| 55 | 1.2404861 | 0.9565163 | 0 | 0.8668442 | 3.3627625 | 55 | 0.7916603 | 0.5676041 | 0 | 0.7169762 | 1.8969917 | 55 | 1.2901878 | 0.6750984 | 0 | 1.2601852 | 2.9554329 | 74 | 67 | 55 | 1.6066523 | 0.9933081 | 1.5452261 |
| 56 | 1.2404861 | 0.9415703 | 0 | 0.8668442 | 3.3627625 | 56 | 0.7916603 | 0.7468491 | 0 | 0.7169762 | 1.8969917 | 56 | 1.2901878 | 1.2751846 | 0 | 1.2601852 | 2.9554329 | 74 | 67 | 56 | 1.6029158 | 1.0381193 | 1.6952477 |
| 57 | 1.2404861 | 0.9415703 | 0 | 0.8668442 | 3.3627625 | 57 | 0.7916603 | 0.7468491 | 0 | 0.7169762 | 1.8969917 | 57 | 1.2901878 | 1.2751846 | 0 | 1.2601852 | 2.9554329 | 74 | 67 | 57 | 1.6029158 | 1.0381193 | 1.6952477 |
| 58 | 1.2404861 | 0.9415703 | 0 | 0.8668442 | 3.3627625 | 58 | 0.7916603 | 0.7468491 | 0 | 0.7169762 | 1.8969917 | 58 | 1.2901878 | 1.2751846 | 0 | 1.2601852 | 2.9554329 | 74 | 67 | 58 | 1.6029158 | 1.0381193 | 1.6952477 |
| 59 | 1.2404861 | 0.9415703 | 0 | 0.8668442 | 3.3627625 | 59 | 0.7916603 | 0.7468491 | 0 | 0.7169762 | 1.8969917 | 59 | 1.2901878 | 1.2751846 | 0 | 1.2601852 | 2.9554329 | 74 | 67 | 59 | 1.6029158 | 1.0381193 | 1.6952477 |
| 60 | 1.2404861 | 0.9415703 | 0 | 0.8668442 | 3.3627625 | 60 | 0.7916603 | 0.7468491 | 0 | 0.7169762 | 1.8969917 | 60 | 1.2901878 | 1.2751846 | 0 | 1.2601852 | 2.9554329 | 74 | 67 | 60 | 1.6029158 | 1.0381193 | 1.6952477 |
| 61 | 1.2404861 | 0.9415703 | 0 | 0.8668442 | 3.3627625 | 61 | 0.7916603 | 0.7468491 | 0 | 0.7169762 | 1.8969917 | 61 | 1.2901878 | 1.2751846 | 0 | 1.2601852 | 2.9554329 | 74 | 67 | 61 | 1.6029158 | 1.0381193 | 1.6952477 |
| 62 | 1.2404861 | 0.9415703 | 0 | 0.9565163 | 3.3627625 | 62 | 0.7916603 | 0.7468491 | 0 | 0.7617836 | 1.8969917 | 62 | 1.2901878 | 1.6502419 | 0 | 1.305191 | 2.9554329 | 74 | 67 | 62 | 1.8345728 | 1.1016006 | 1.8002634 |
| 64 | 1.3600502 | 1.7785263 | 0 | 0.9565163 | 3.3627625 | 64 | 1.2098923 | 0.9559669 | 0 | 0.7617836 | 1.8969917 | 64 | 1.3802032 | 1.6502419 | 0 | 1.305191 | 2.9554329 | 74 | 67 | 64 | 1.8644638 | 1.2061586 | 1.8227673 |
| 65 | 1.3600502 | 1.7785263 | 0 | 0.9565163 | 3.3627625 | 65 | 1.2098923 | 0.9559669 | 0 | 0.7617836 | 1.8969917 | 65 | 1.3802032 | 1.6502419 | 0 | 1.305191 | 2.9554329 | 74 | 67 | 65 | 1.8644638 | 1.2061586 | 1.8227673 |
| 66 | 1.3600502 | 1.7785263 | 0 | 0.9565163 | 3.7662926 | 66 | 1.2098923 | 0.9559669 | 0 | 0.7617836 | 2.2704163 | 66 | 1.3802032 | 1.6502419 | 0 | 1.305191 | 2.8804207 | 74 | 67 | 66 | 1.9653463 | 1.2995148 | 1.8040142 |
| 67 | 1.3600502 | 1.7785263 | 0 | 0.9565163 | 3.7662926 | 67 | 1.2098923 | 0.9559669 | 0 | 0.7617836 | 2.2704163 | 67 | 1.3802032 | 1.6502419 | 0 | 1.305191 | 2.8804207 | 74 | 67 | 67 | 1.9653463 | 1.2995148 | 1.8040142 |
| 68 | 1.3600502 | 1.7785263 | 0 | 0.9565163 | 3.7662926 | 68 | 1.2098923 | 0.9559669 | 0 | 0.7617836 | 2.2704163 | 68 | 1.3802032 | 1.6502419 | 0 | 1.305191 | 2.8804207 | 74 | 67 | 68 | 1.9653463 | 1.2995148 | 1.8040142 |
| 69 | 1.3600502 | 1.7785263 | 0 | 0.9565163 | 3.7662926 | 69 | 1.2098923 | 0.9559669 | 0 | 0.7617836 | 2.2704163 | 69 | 1.3802032 | 1.6502419 | 0 | 1.305191 | 2.8804207 | 74 | 67 | 69 | 1.9653463 | 1.2995148 | 1.8040142 |
| 70 | 1.3600502 | 1.7785263 | 0 | 0.9565163 | 3.7662926 | 70 | 1.2098923 | 0.9559669 | 0 | 0.7617836 | 2.2704163 | 70 | 1.3802032 | 1.6502419 | 0 | 1.305191 | 2.8804207 | 74 | 67 | 70 | 1.9653463 | 1.2995148 | 1.8040142 |
| 71 | 1.3600502 | 1.7785263 | 0 | 0.9565163 | 3.7662926 | 71 | 1.2098923 | 0.9559669 | 0 | 0.7617836 | 2.2704163 | 71 | 1.3802032 | 1.6502419 | 0 | 1.305191 | 2.8804207 | 74 | 67 | 71 | 1.9653463 | 1.2995148 | 1.8040142 |
| 72 | 1.3600502 | 1.7785263 | 0 | 0.9565163 | 3.7662926 | 72 | 1.2098923 | 0.9559669 | 0 | 0.7617836 | 2.2704163 | 72 | 1.3802032 | 1.6502419 | 0 | 1.305191 | 2.8804207 | 74 | 67 | 72 | 1.9653463 | 1.2995148 | 1.8040142 |
| 73 | 1.3600502 | 1.7785263 | 0 | 0.9565163 | 3.7662926 | 73 | 1.2098923 | 0.9559669 | 0 | 0.7617836 | 2.2704163 | 73 | 1.3802032 | 1.6502419 | 0 | 1.305191 | 2.8804207 | 74 | 67 | 73 | 1.9653463 | 1.2995148 | 1.8040142 |
| 74 | 1.3600502 | 1.7785263 | 0 | 0.9565163 | 3.7662926 | 74 | 1.2098923 | 0.9559669 | 0 | 0.7617836 | 2.2704163 | 74 | 1.3802032 | 1.6502419 | 0 | 1.305191 | 2.8804207 | 74 | 67 | 74 | 1.9653463 | 1.2995148 | 1.8040142 |
| 75 | 1.5244522 | 1.7785263 | 0 | 0.9565163 | 3.7662926 | 75 | 0.9111557 | 0.9559669 | 0 | 0.7617836 | 2.2704163 | 75 | 1.5902328 | 1.6502419 | 0 | 1.305191 | 2.8804207 | 74 | 67 | 75 | 2.0064468 | 1.2248306 | 1.8565216 |
| 76 | 1.5244522 | 1.7785263 | 0 | 0.9565163 | 3.7662926 | 76 | 0.9111557 | 0.9559669 | 0 | 0.7617836 | 2.2704163 | 76 | 1.5902328 | 1.6502419 | 0 | 1.305191 | 2.8804207 | 74 | 67 | 76 | 2.0064468 | 1.2248306 | 1.8565216 |
| 77 | 1.5244522 | 1.7785263 | 0 | 0.9565163 | 3.7662926 | 77 | 0.9111557 | 0.9559669 | 0 | 0.7617836 | 2.2704163 | 77 | 1.5902328 | 1.6502419 | 0 | 1.305191 | 2.8804207 | 74 | 67 | 77 | 2.0064468 | 1.2248306 | 1.8565216 |
| 78 | 1.5244522 | 1.7785263 | 0 | 0.9565163 | 3.7662926 | 78 | 0.9111557 | 0.9559669 | 0 | 0.7617836 | 2.2704163 | 78 | 1.5902328 | 1.6502419 | 0 | 1.305191 | 2.8804207 | 74 | 67 | 78 | 2.0064468 | 1.2248306 | 1.8565216 |

Figure 2.5 shows measurements for just under 80 cycles however because the depths are recorded for each cycle, there are 8,000 rows of output. It should be noted that the center LVDT always reads 0 for each set of specimens as is shown in Figure 2.5. This LVDT was shut off because it would be located directly

at the interface of the two specimens. This LVDT is turned on when compacted beams are being tested.

The APA also generates two summary output sheets: one sheet is graphical and the other summarizes the numerical data. The graphical summary is simply a plot of rut-depth versus cycle number. The graphical summary is updated after each cycle while the test is running. An example of the graphical output is shown in Figure 2.6. The summary of the average rut-depth for each specimen is the other summary output. An example of this numerical summary is shown in Figure 2.7.

**Figure 2.6 Graphical Output from APA Test**

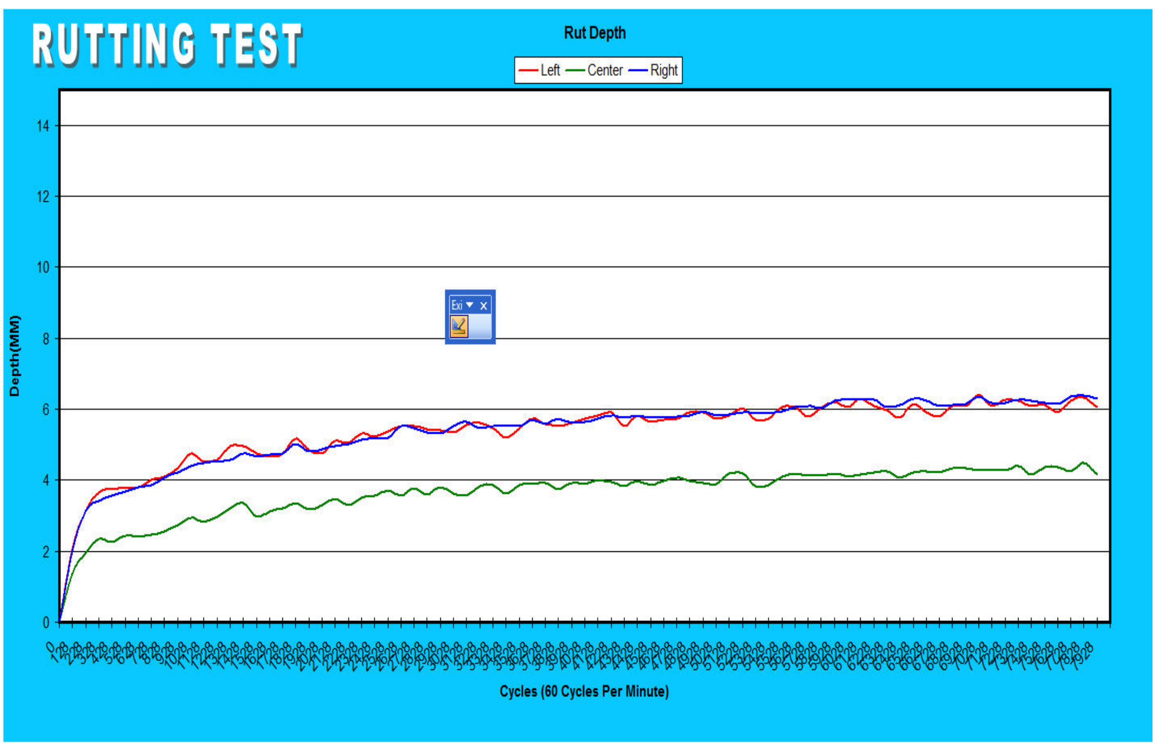


**Figure 2.7 Numerical Summary Output from APA Test**

| | Left Sample ID | 251 268 | | | Bulk S Gravity | | | | % Air Void | 6.7 |
|---|---|---|---|---|---|---|---|---|---|---|
| | Temperature | | Depth Gauge Reading | | | | | | | |
| STROKE COUNT | F | C | 1 | 2 | 3 | 4 | 5 | Man Average Depth | APA Average | Percent Change |
| 0 | 32 | 0 | | | | | | 0 | | |
| 25 | 165.2 | 74 | 0.478256226 | 0.956516266 | 0 | 0.029891968 | 3.138576508 | | 1.150810242 | |
| 4000 | 165.2 | 74 | 4.946994781 | 5.664386749 | 0 | 6.247264862 | 6.14264679 | | 5.750323296 | 79.99% |
| 8000 | 165.2 | 74 | 5.425254822 | 6.471450806 | 0 | 6.770362854 | 6.710578918 | | 6.34441185 | 9.36% |
| 8000 | 32 | 0 | | | | | | 0 | | |

| | Center Sample ID | 270 332 | | | Bulk S Gravity | | | | % Air Void | 6.9 |
|---|---|---|---|---|---|---|---|---|---|---|
| | Temperature | | Depth Gauge Reading | | | | | | | |
| STROKE COUNT | F | C | 1 | 2 | | 4 | 5 | Man Average Depth | APA Average | Percent Change |
| 0 | 32 | | | | | | | 0 | | |
| 25 | 165.2 | 74 | 0.716976166 | 0.567604065 | 0 | -0.224056244 | 1.852184296 | | 0.728177071 | |
| 4000 | 165.2 | 74 | 3.659553528 | 3.614742279 | 0 | 4.227157593 | 4.421337128 | | 3.980697632 | 81.71% |
| 8000 | 165.2 | 74 | 3.868671417 | 3.793987274 | 0 | 4.839572906 | 5.212997437 | | 4.428807259 | 10.12% |
| 8000 | 32 | | | | | | | 0 | | |

| | Right Sample ID | 252 269 | | | Bulk S Gravity | | | | % Air Void | 7.4 |
|---|---|---|---|---|---|---|---|---|---|---|
| | Temperature | | Depth Gauge Reading | | | | | | | |
| STROKE COUNT | F | C | 1 | 2 | 3 | 4 | 5 | Man Average Depth | APA Average | Percent Change |
| 0 | 32 | | | | | | | 0 | | |
| 25 | 165.2 | 74 | 0.285041809 | 0.675098419 | 0 | 0.450065613 | 2.685390472 | | 1.023899078 | |
| 4000 | 165.2 | 74 | 5.355781555 | 5.925865173 | 0 | 5.805847168 | 5.850852966 | | 5.734586716 | 82.15% |
| 8000 | 165.2 | 74 | 5.805847168 | 6.690975189 | 0 | 6.780986786 | 6.645969391 | | 6.480944633 | 11.52% |
| 8000 | 32 | | | | | | | 0 | | |

Depending on the rutting susceptibility of the mix, there may or may not be a significant visual rut in the top of the specimens at the completion of the test. Figure 2.8 shows a specimen after testing has concluded.

**Figure 2.8 Specimen after Testing**

## 2.8. Results of Binder Testing

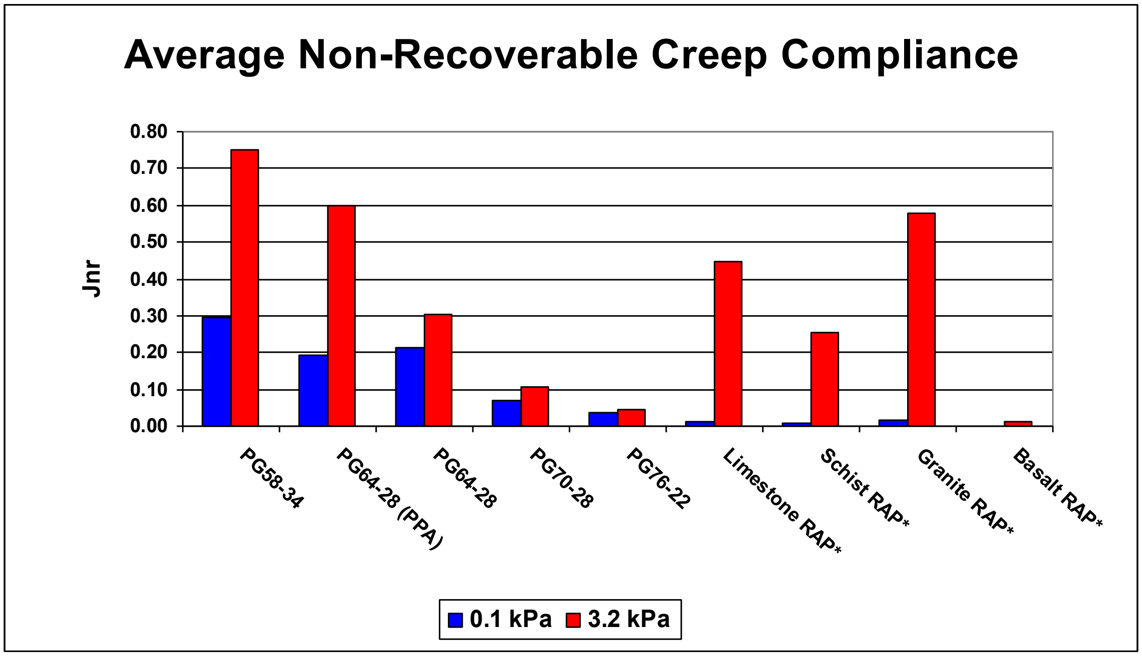
### 2.8.1 FT-IR Testing Results

The FT-IR testing of the 5 binders used for this research verified that they were in fact modified as expected. Detectable levels of polymer modifiers were found in the PG58-34, PG70-28 and PG76-22. PPA was found in the 64-28(PPA) as was expected. A minor amount of polymer was found in the 64-28. The outcome of the FT-IR scans and graphic depictions of the results of this testing are given in Appendix C. There were no polymer modifiers found to be present in the recovered RAP binders.

### 2.8.2 MSCR Testing Results

The higher the performance grade temperature of the binder, the stiffer the binder tends to be at elevated temperatures. Results of the MSCR testing (at 58 or 64° C) of the binders indicated that the higher the performance grade, the less non-recoverable creep compliance the binder exhibited under test. Thus, for this testing, the higher the performance grade of the binder containing polymer modifiers, the less susceptible to rutting the binder would be as non-recoverable creep-compliance (Jnr) is indicative of permanent deformation in the field. This is shown in Figure 2.9. In other words, the smaller the Jnr, the more elastic the material.

**Figure 2.9. MSCR Test Results**




*** Denotes asphalt binder recovered from this RAP**

Of note are the differences in non-recoverable creep under the two different load stresses. It can be seen from Figure 2.9 that the PG58-34 and the PG64-28(PPA) behaved quite differently under the two different loads. Both of these binders exhibited a great deal more non-recoverable creep compliance in the non-linear range than in the linear range. The PG64-28(PPA) also exhibited much more non-recoverable creep than the same grade without the PPA modification in the non-linear range. In the linear range, the PPA modified binder slightly outperformed the 64-28 binder without modification although the difference does not appear significant.

Of the recovered RAP binders, the basalt-based RAP binder appeared to outperform all the other recovered RAP binders in both stress ranges. None of the recovered RAP binders exhibited problems in the linear range while the limestone, schist and granite based RAP binders exhibited significantly higher non-recoverable creep compliance under the higher stress.

## 2.9 APA Rut Testing Results

The average rut depths for each set of specimens as measured in the APA are shown in Table 2.7. The specimens containing RAP are shown first followed by the specimens containing only the aggregates recovered by burning the asphalt off in the ignition oven.

**Table 2.7. Average Rut Depths**

| | 10% RAP Rut Depths (mm) | | | | Average | | 10% RAP Aggregate Rut Depths (mm) | | | | Average |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | Granite | Basalt | Schist | Limestone | | | Granite | Basalt | Schist | Limestone | |
| 64-28 | 5.4 | 3.6 | 3.5 | 3.5 | 4.0 | 64-28 | 4.4 | 5.9 | 4.7 | 5.4 | 5.1 |
| 64-28(ppa) | 4.4 | 3.3 | 3.4 | 3.6 | 3.7 | 64-28(ppa) | 6.3 | 6.0 | 5.5 | 5.6 | 5.9 |
| 70-28 | 5.5 | 5.0 | 4.8 | 4.6 | 5.0 | 70-28 | 5.6 | 5.0 | 5.9 | 6.4 | 5.7 |
| 76-22 | 5.8 | 3.2 | 6.0 | 2.9 | 4.5 | 76-22 | 5.9 | 3.3 | 3.1 | 3.4 | 3.9 |
| 58-34 | 6.1 | 5.1 | 6.0 | 6.3 | 5.9 | 58-34 | 5.7 | 5.9 | 5.9 | 6.8 | 6.1 |

***Green values indicate a lower rut depth than the counterpart on the opposite side of the table either with or without RAP.**

As seen in Table 2.7, the average rut depth across all specimens was higher in the specimens containing no RAP than in the specimens containing 10% RAP. There were two combinations of granite-based RAP and two combinations of schist-based RAP which exhibited higher rut depths than their RAP aggregate counterparts. The higher rut depths are shown in red and the lower rut depths are shown in green. The averages of the rut depths for the different combinations are shown in the last row with the averages for all sets for both groups.

### 2.9.1 Effect of RAP on Rut Depth

Of the most significant concern for this research was the effect that the general addition of RAP would have on the rut depths during APA testing. As discussed previously, a significant increase in rut depth after the incorporation of RAP into the mix would be an indication that the RAP changed the chemistry of the virgin binder such that the integrity of the modified asphalt binder was compromised. Shown in Table 2.8 are the paired rut depths for each combination of RAP aggregate and binder as well as each combination of RAP and binder.

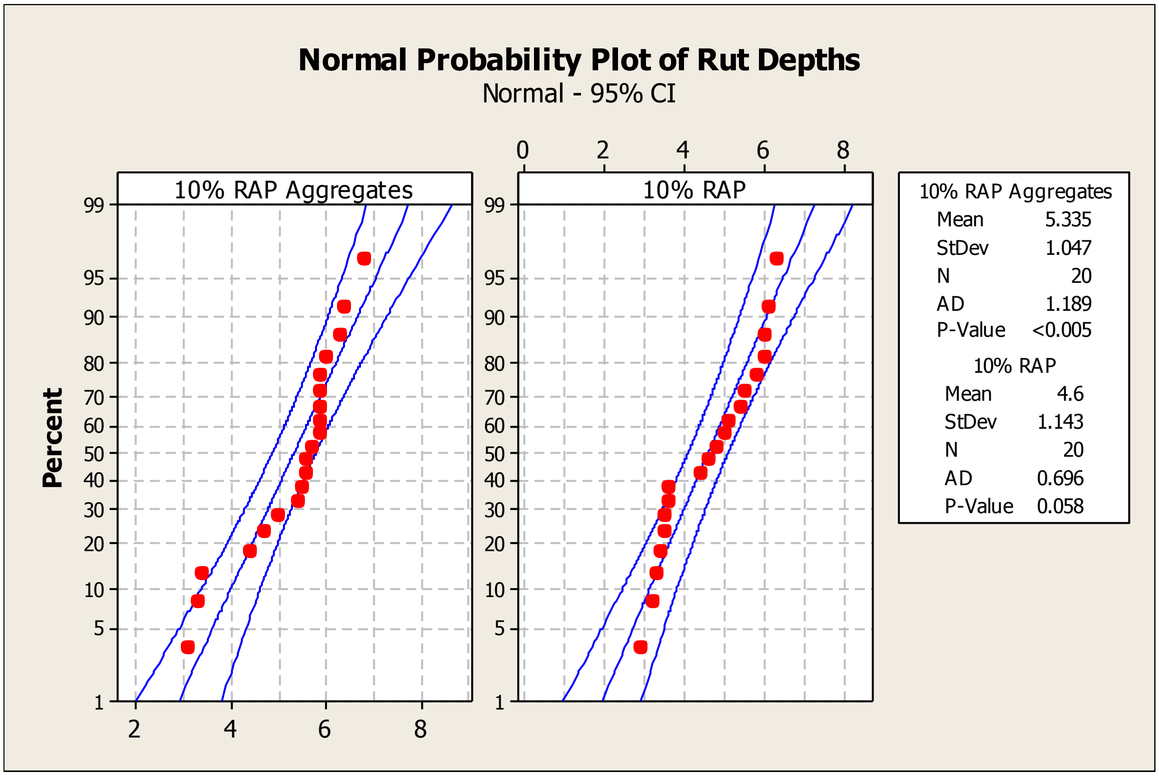
**Table 2.8 Rut Depths – RAP vs. RAP Aggregates**

**Rut Depth (mm)**

| RAP Base | Binder | 10% RAP Aggregates | 10% RAP |
|---|---|---|---|
| Granite | 64-28 | 4.4 | 5.4 |
| | 64-28(ppa) | 6.3 | 4.4 |
| | 70-28 | 5.6 | 5.5 |
| | 76-22 | 5.9 | 5.8 |
| | 58-34 | 5.7 | 6.1 |
| Basalt | 64-28 | 5.9 | 3.6 |
| | 64-28(ppa) | 6 | 3.3 |
| | 70-28 | 5 | 5 |
| | 76-22 | 3.3 | 3.2 |
| | 58-34 | 5.9 | 5.1 |
| Schist | 64-28 | 4.7 | 3.5 |
| | 64-28(ppa) | 5.5 | 3.4 |
| | 70-28 | 5.9 | 4.8 |
| | 76-22 | 3.1 | 6 |
| | 58-34 | 5.9 | 6 |
| Limestone | 64-28 | 5.4 | 3.5 |
| | 64-28(ppa) | 5.6 | 3.6 |
| | 70-28 | 6.4 | 4.6 |
| | 76-22 | 3.4 | 2.9 |
| | 58-34 | 6.8 | 6.3 |

On average, the rut depth decreased by 0.7 mm across all sets of specimens with the use of RAP as opposed to simply the recovered RAP aggregates. Prior to utilizing parametric statistical analyses on these data sets a normality test was conducted to ensure the results would be reliable. The plots for each dataset are shown in Figure 2.10.

**Figure 2.10 Rut Depth Test for Normality**




Although the plot appears to show the vast majority of the data points within the descriptive bounds for normally distributed data, the reader should take into consideration the Anderson-Darling test for normality p-value for the 10% RAP Aggregate. The p-value for that dataset falls below the alpha level of 0.5. Because this is the case, the reader should consider the distribution of the data when analyzing results of any parametric analyses henceforth.

Although the two distributions are not quite similar, a comparison for difference of means assumed that the data was all normally distributed. A paired t-test was conducted on the dependent sets of data in an effort to view whether the addition of the RAP had a significant impact on the susceptibility to rutting. Because the set of data which included 10% RAP had the lower average rut depth, if a significant difference did exist, it would indicate that the RAP had a positive influence on the ability of the mixes to resist rutting. If no significant difference was found then it could be stated that the RAP had no impact on the ability of the mixes to resist rutting. The outcome of the t-test is shown in Table 2.9.

**Table 2.9 Rut Depths - RAP vs. Rap Aggregate Paired T-Test**

**t-Test: Paired Two Sample for Means**

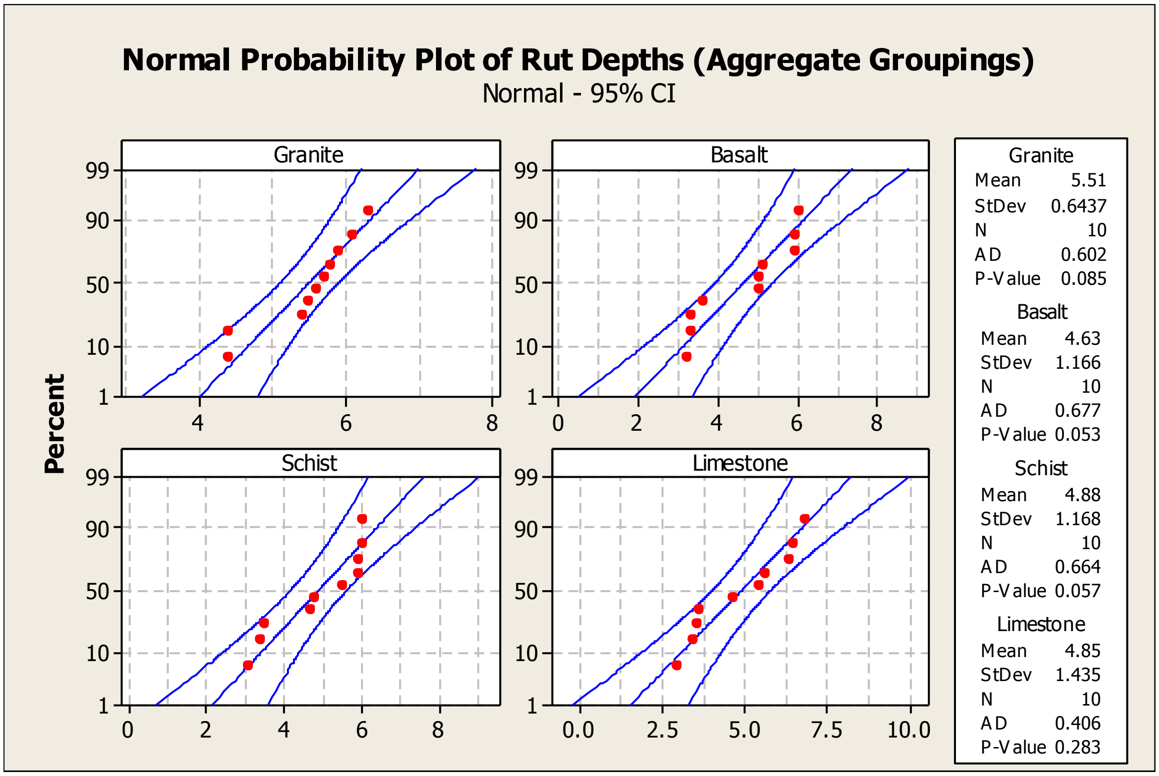
| | ***10% RAP Aggregates*** | ***10% RAP*** |
|---|---|---|
| Mean | 5.3 | 4.6 |
| Variance | 1.1 | 1.31 |
| Observations | 20 | 20 |
| Pearson Correlation | 0.3 | |
| Hypothesized Mean Diff. | 0 | |
| Df | 19 | |
| T Stat | **2.456** | |
| P(T<=t) one-tail | 0.012 | |
| T Critical one-tail | 1.729 | |
| P(T<=t) two-tail | **0.024** | |
| T Critical two-tail | 2.093 | |

Given the results of the t-test, it can be seen that there was indeed a significant performance gap between the sets of specimens. As stated previously, because the set of specimens containing RAP had a lower average rut depth, this significant difference indicates that the impact of the RAP on rut resistance of the mix is positive.

### 2.9.2 Effect of Aggregate on Rut Depth

It was desired to combine both the RAP and RAP aggregate rut depths into groupings according to their aggregate base to get an indication of whether or not the aggregate could be assigned to affect the performance of the mix with respect to rutting. Prior to analyzing these groups they were subjected to a normality test as shown in Figure 2.11.

**Figure 2.11. Rut Depth Test for Normality (Aggregate Grouping)**




The alpha levels for each grouping were not exceeded by the p-value as calculated so it was assumed all groups of data were distributed normally. As such, an Analysis of Variance (ANOVA) was conducted to determine if there was a significant difference between the means of the sets of data. Table 2.10 shows the results of the ANOVA.

**Table 2.10. ANOVA – Rut Depth by Aggregate Groupings**

ANOVA - Aggregate Groups

**SUMMARY**

| *Groups* | *Count* | *Sum* | *Average* | *Variance* |
|---|---|---|---|---|
| Granite | 10 | 55.1 | 5.5 | 0.41 |
| Basalt | 10 | 46.3 | 4.6 | 1.36 |
| Schist | 10 | 48.8 | 4.9 | 1.36 |
| Limestone | 10 | 48.5 | 4.9 | 2.06 |

**ANOVA**

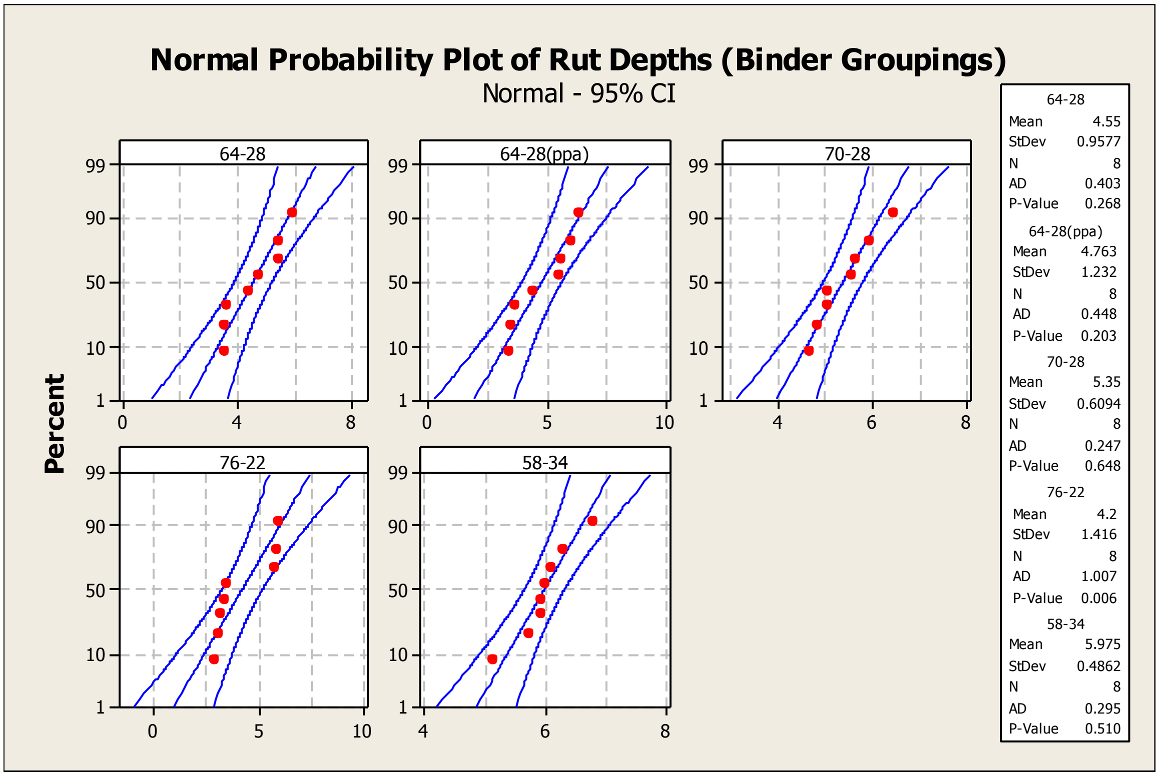
| *Source of Variation* | *SS* | *Df* | *MS* | *F* | *P-value* | *F crit* |
|---|---|---|---|---|---|---|
| Between Groups | 4.30 | 3 | 1.43 | **1.10** | **0.36** | **2.87** |
| Within Groups | 46.77 | 36 | 1.30 | | | |
| | | | | | | |
| Total | 51.07 | 39 | | | | |

As seen in Table 2.10, the p-value far exceeds the null-hypothesis rejection threshold value of 0.05. Another observation from Table 10 is that the calculated F-value does not exceed the critical value for this set of data. This indicates that the four groupings can be assumed to have come from populations with the same mean and there is no significant impact on the performance of the mixes with respect to rutting that can be attributed to type of aggregate base.

### 2.9.3 Effect of Binder on Rut Depth

It was then desired to combine both the RAP and RAP aggregate rut depths into groupings according to their binder grade to investigate whether or not the binder could be assigned to affect the performance of the mix with respect to rutting. Prior to analyzing these groups they were subjected to a normality test similarly to the aggregate groupings. The normality test is shown in Figure 2.12.

**Figure 2.12. Rut Depth Test for Normality (Binder Grouping)**




Although there is a low p-value for the 76-22 grouping, it was assumed normal because the values fell within the graphical bounds on the plot and comparisons could be made among the means for the binder groups. An ANOVA was conducted to determine if any of the binder groupings had rut depths which stood out as significantly different from the rest. Table 2.11 shows the results of the analysis.

**Table 2.11 ANOVA – Rut Depth by Binder Groupings**

Anova: Binder Groups

**SUMMARY**

| *Groups* | *Count* | *Sum* | *Average* | *Variance* |
|---|---|---|---|---|
| 64-28 | 8 | 36.4 | 4.6 | 0.92 |
| 64-28(ppa) | 8 | 38.1 | 4.8 | 1.52 |
| 70-28 | 8 | 42.8 | 5.4 | 0.37 |
| 76-22 | 8 | 33.6 | 4.2 | 2.01 |
| 58-34 | 8 | 47.8 | 6.0 | 0.24 |

**ANOVA**

| *Source of Variation* | *SS* | *Df* | *MS* | *F* | *P-value* | *F crit* |
|---|---|---|---|---|---|---|
| Between Groups | 15.73 | 4 | 3.93 | **3.90** | **0.01** | **2.64** |
| Within Groups | 35.33 | 35 | 1.01 | | | |
| | | | | | | |
| Total | 51.07 | 39 | | | | |

The output from the ANOVA shows that there is indeed a significant difference between these sets of data. It may be stated that there is a chance that the binders themselves contribute significantly to the rutting performances of these different mixes.

## 2.10 Discussion of Results

During this research there were several combinations of RAP, RAP aggregates, and modified binder examined. The goal was to determine which of the different combinations of constituent materials should be considered possibly detrimental to the long term service life of a HMA pavement, which combinations should be considered beneficial and which component(s) of a poorly performing combination is causing the mix to under-perform. To answer these questions, the analyses examined the effects of each individual component in the different combinations of HMA.

The first analysis examined the level of polymer and other possible modifications in each of the sampled asphalt binders. It was expected and found that the highest level of polymer modification was found in the PG76-22 binder. The next grade down was PG70-28 which was found to contain the second highest level of polymer modification followed very closely by the PG58-34. These two binders appear to have nearly the same level of polymer modification and they are both one high-end PG grade away from the PG64-28 which did not appear through testing to contain a great deal of modification comparatively. Finally the PG64-28(ppa) was confirmed to contain polyphosphoric acid. This was important in case there arose a relatively high level of rutting with respect to the PG64-28 binder in combination with the limestone aggregate as was a concern stated in the objectives.

The combination of limestone based RAP or recovered limestone aggregate and the PG64-28(ppa) binder did not stand out in any of the performance testing as exhibiting different behavior than other combinations. It would be desirable to conduct a suite of other types of performance testing to investigate if there are indeed some compatibility issues between these materials as stated in the reviewed literature and experienced by the NYSDOT as previously discussed.

The addition of RAP generally increased the rut-resisting performance of the mixes as illustrated in Section 2.8.3. There was indeed a significant difference between the performance of the control set and the RAP set. This significant difference shows the mixes containing RAP had no negative impact on the rutting of the mixes and indeed the RAP mixes outperformed the control mixes.

In viewing the performance of the binders with respect to the MSCR test and then in the APA, it is clear that the binder which outperformed the others with respect to non-recoverable creep compliance and rut-resistance was the PG 76-22 which also contains the highest level of polymer modification. This may be an indication that the higher level of polymer modification is worth the cost as the resistance to permanent deformation could lead to an increase in the service life of the pavement.

The PG 58-34 binder performed the worst in both the MSCR testing and the APA rut testing. It was also shown to contain less than half the polymer modification of the PG 76-22. As shown in Table 2.11, there is a significant difference in the performance of the binders in the APA and this could indicate the PG 58-34 binder might show higher rutting resistance if it were modified more heavily.

### 2.11. Conclusions

Based on the results of the performance testing of both the asphalt binders, the different combinations of materials in the APA, and the analyses of these results, the research team concludes the following:

- With respect to the MSCR test, the higher PG binders with polymer modification exhibited the least amount of non-recoverable creep compliance in both the linear and non-linear range.
- The binder with the highest amount of polymer modification performed the best under both the MSCR test and APA rut testing.
- The PG 64-28(ppa) exhibited twice the amount of non-recoverable creep compliance than the PG 64-28 in the non-linear range. In the linear range the PG 64-28(ppa) slightly outperformed the PG 64-28.
- The PG 64-28(ppa) combined with limestone aggregate did not show a higher tendency to rut than the other combinations.
- The different aggregates did not have an impact on rutting potential.
- The binders were shown to have the largest impact on the potential for a mix to rut.
- The addition of 10% RAP to mixes with any of the investigated binders, with few exceptions, enhanced the ability of the mix to resist rutting and there is no indication that RAP adversely affects the long term service life of the mix.
- The use of high RAP contents with polymer modified asphalts should be done with caution so as not to risk the higher investment level in the modified asphalt binder.

### 2.12 Recommendations

At this time the research team recommends that RAP continue to be used as a quality material in the construction of new pavements and the rehabilitation of old pavements regardless the PG grade of the binder or type of modification it may contain.

The research team also recommends efforts to locate pavements constructed with varying amounts of RAP with different types and grades of modified and unmodified binders. These pavements should be sampled and compatibility testing in the laboratory should accompany field monitoring of the in-place materials to further identify and quantify compatibility issues with varying pavement construction materials.

The research team also recommends that work commence to test the compatibility of limestone aggregates and asphalt binders containing polyphosphoric acid modification at higher levels. This recommendation comes due to the literature reviewed and experiences from the NYSDOT as previously discussed. This work should involve a host of laboratory performance testing as well as field monitoring of sites identified as having been constructed with this combination of materials.

Finally, in light of the increased interest and use of warm mix asphalt technology across the United States, it is recommended that these compatibility concerns be extended to warm mix technology. There are numerous warm mix methods being experimented with and deployed and there is a seemingly deep lack of knowledge and experience when it comes to recycled warm mix asphalt pavements. Research work should be conducted in an effort to determine what the long term effects of warm mix additives are, whether there are compatibility issues with warm mix additives and modified asphalts, and finally, if recycled warm mix asphalt is a quality construction material.

Research also needs to be conducted as the compatibility issues that may arise from the various warm mix additives when it comes time for milling warm mix pavements currently being placed. The effect of warm mix additives present in future RAP when it is combined with future warm mix additives is completely unknown. There may be incompatibilities when two different types of additives are combined.

### 2.13 General Guidelines for the use of RAP

**1.** Agencies incorporating RAP into their mixes should implement a testing plan consistent with their Quality Assurance program to ensure quality materials.

**2.** RAP should be tested at frequent routine intervals to ensure quality and consistency.

**3.** Routine RAP testing should include the following:

- Gradation
- Binder content

**4.** Periodic RAP testing should include the following:

- Aggregate verification
- Recovery and PG Grading

**5.** Mix design should be conducted any time the following occurs with respect to RAP:

- Change in source
- Change in gradation
- Change in PG Grade
- Noticeable change in consistency
- Desired increase in RAP quantity in HMA

**6.** RAP should be stored under cover to minimize moisture content:

- The cover should be in the form of a shed or other roof structure to allow air circulation and promote water evaporation
- Never cover the RAP pile with plastic as it traps water and will increase the moisture content of the RAP

- Place the RAP on a paved surface with enough slope to allow water to run out of the pile

7. It has been generally found to be easier to incorporate high levels of RAP into HMA mixtures if the RAP is fractionated into a coarse pile and fine pile.

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**Appendix A. State Survey Responses**

**1. What grades of asphalt binder are specified for your state?**

| | |
|---|---|
| RI DOT | PG58-28, PG64-28, PG76-28, PG76-34 |
| NH DOT | Typically PG64-28, PG58-28, PG58-34, Occasionally PG70-28 |
| MaineDOT | PG64-28, PG70-28 (SMA) |
| NYSDOT | Typical Grades used upstate – PG64-28, some PG58-34. Regions may allow PG64-22 for single course overlays (but rarely done). Downstate – PG70-22 and PG 76-22. 6.3mm HMA – upstate requires PG64-28 with 60% min ER; Downstate requires polymer modified PG76-22 |
| ConnDOT | PG64-28, when 10% RAP is used or less. |
| MassHighway | PG64-28 for use on all HMA with less than 25% RAP. For product manufactured with 25% or more, up to 40% RAP MassHighway requires the producer to use a PG52-34. Should the Abson recovery test show the liquid at >25% to <40% doesn't meet 64-28,less RAP is stipulated. |
| VAOT | Vermont specifies PG58-28, PG58-34, PG64-28, PG64-34, and PG70-28 |

**2. What companies supply asphalt binders to your state.**

For confidentiality purposes this information is withheld from this report.

**3. Does your state intentionally specify modified asphalt binder grades and if so what grades?**

| | |
|---|---|
| RI DOT | Yes. PG76-28, PG76-34 |
| NH DOT | NHDOT specified modified asphalt on one project. Littleton Waterford, I-93 was PG58-28 on one barrel and PG58-34 on the other and had to be either SBS or SBR |
| MaineDOT | Yes 70-28 Used in SMA |
| NYSDOT | Sometimes PG64-28 with min. 60% ER is specified for high traffic volume roads; also, binder for 6.3 mm HMA as listed above in response to question 1. |
| ConnDOT | Only one job in the last five years, PG70-22 |
| MassHighway | MassHighway specifies modified material on a project-by-project basis at this time. There may be standard modified binders in the future. At present MassHighway specifies a 3% latex modified PG64-28 binder and also have attempted a PG72-34 modified w/ polymer and 7% rubber |
| VAOT | No. Vermont specifies the PG grade and if it requires modification then that is left up to the supplier |

**4. Does your state have a list of approved asphalt binder modifiers?**

| | |
|---|---|
| RI DOT | No |
| NH DOT | No |
| Maine DOT | No |
| NYSDOT | No, only require PG Binder to meet AASHTO M320 for specified grade. |
| ConnDOT | No |
| MassHighway | No |
| VAOT | No |

**5. Does your state prohibit any types of asphalt?**

| | |
|---|---|
| RI DOT | No |
| NH DOT | No |
| Maine DOT | No |
| NYSDOT | No, only require PG Binder to meet AASHTO M320 for specified grade. |
| ConnDOT | No |
| MassHighway | Not at this time but MassHighway is reviewing options |
| VAOT | Vermont does not prohibit any types but does discourage use of PPA |

**6. Does your state require modified asphalts be labeled as such on the bill of lading and what criteria does your state use for requiring such lading?**

| | |
|---|---|
| RI DOT | Although this is not a requirement the bills of lading always list the grade and type of modifier. |
| NH DOT | Asphalt modifiers. The generic type of each asphalt binder admixture and/or additive shall be identified on the certificate of analysis which will be furnished by the manufacturer for each load of asphalt delivered. |
| Maine DOT | Yes - General type of modification required on either Cert. or BOL |
| NYSDOT | Require labeling per 2005 NEAUPG agreement. |
| ConnDOT | PG binders that are modified with fillers, extenders, reinforcing agents, adhesion promoters, additives, or other types shall disclose percentages and handling specifications |
| MassHighway | Labeling is per the NEAUPG QC plan and is to show on delivery slips and test results. |
| VAOT | Yes. The bill of lading or COA need to state if the binder is modified or neat and if modified the type of modifier needs to be recorded |

**7. What definition, if any, does your state use for what constitutes a modified asphalt?**

| | |
|---|---|
| RI DOT | No Definition |
| NH DOT | Anything added to an asphalt after the refining process that is done to change the properties of the binder. |
| Maine DOT | No firm definition. |
| NYSDOT | We specify PG binder meeting M 320 regardless of modifier. On some projects we do specify an additional Elastic Recovery requirement. |
| ConnDOT | Requirements are listed in a copy of ConnDOT annual binder letter |
| MassHighway | No Definition |
| VAOT | Vermont defines modified asphalt as any product that has been altered physically or chemically from its proposed original state .Even if the modification takes place during the refining cycle Vermont still considers it to be a modified PG Binder. |

**8. Does your state allow latex injection at the mix plant? If so, what companies/products are approved for this modification?**

| | |
|---|---|
| RI DOT | No |
| NH DOT | No |
| Maine DOT | No |
| NYSDOT | NYSDOT has allowed latex injection at the HMA plant, but are waiting to evaluate performance before continuing the practice. Future use of in-line blending will likely require additional QC and QA of the final product. |
| ConnDOT | Not for HMA, only Chip seal. |
| MassHighway | No response |
| VAOT | The only injection allowed at HMA plants are the addition of liquid anti-strip and silicon if proper procedures are followed. |

**9. Does your state restrict the HMA layers in which RAP can be used? (such as only allowing it in the base/binder course).**

| | |
|---|---|
| RI DOT | Yes. RAP is only allowed in the base and binder courses. |
| NH DOT | No |
| Maine DOT | Not at this time---until a couple years ago we did not allow any RAP in surface mixes. |
| NYSDOT | NYSDOT allows RAP in base, binder, and surface/top course mixes. |
| ConnDOT | No |
| MassHighway | RAP may be used in Class I Bituminous Concrete. The proportion of RAP to virgin aggregate shall be limited to a maximum of 40% for Drum Plants and 20% for modified batch plants. The maximum amount of RAP for surface courses shall be 10% (except in Open Graded Friction Course in Which RAP is not allowed.) |
| VAOT | Vermont only limits the percentage used but does not restrict it by location. |

**10. What is the maximum percentage of RAP allowed in your state?**

| | |
|---|---|
| RI DOT | 30% |
| NH DOT | 50% for Drum plants, 35% for Batch plants when using known (DOT) sources. 15% otherwise. No more than 15% in wearing course in any case. |
| Maine DOT | Our spec allows 15% maximum RAP without a change in the PG Binder (We primarily use PG64-28). I believe most RAP mixes use 10% RAP as we try to minimize the number of designs (and lots) used on our QA projects. However, we do allow up to 25% RAP in mixes if the contractor uses PG58-34 binder. I am not aware of any contractors requesting this option. As you may also know, Maine DOT does utilize much of the RAP from our projects for use in Foam, PMRAP, etc. which has reduced the amount of RAP stockpiles that contractors have to use in HMA mixes. |
| NYSDOT | NYSDOT allows up to 20% RAP in binder and surface course mixes and up to 30% in base. |
| ConnDOT | limit of 10% max on all classes for all lifts |
| MassHighway | Drum Plants – 40%, Batch Plants 20%. No more than 10% in wearing surfaces. |
| VAOT | 15% for Superpave and up to 20+% for Marshall mix |

**11. Has your state had any experience using RAP with a modified asphalt? If so, please provide your impressions of how it worked out.**

| | |
|---|---|
| RI DOT | No. We feel that if we are going to pay a significant premium for a modified binder, we won't risk losing the enhancements we obtain from the binder by introducing RAP. |
| NH DOT | No |
| Maine DOT | No if you define modified as "polymer" but the answer is Yes if you consider PPA as modified. Maine DOT does not have any evidence to show that PPA modified mixes with RAP perform any different than other mixes. |
| NYSDOT | NYSDOT does have locations with both RAP and modified PG binder (primarily polymer modified). No issues were encountered, but an evaluation re: benefits has not been completed at this time. |
| ConnDOT | No |
| MassHighway | No response |
| VAOT | 60-70% of Vermont's binder is modified and most of it contains RAP. In my opinion RAP is one of the most consistent "aggregates" in the State and mixes perform very well as long as the percentage of natural is controlled. |

## Appendix B. Binder Supplier Survey Responses

***(Order of supplier responses for each question have been shuffled for purposes of confidentiality)***

**1. In order to work towards the best working definition of a modified asphalt, I want to contact suppliers (even if they do not regularly supply modified asphalt) for their definition of a modified asphalt. How does your working definition of a modified asphalt compare to AASHTO's?**

| | |
|---|---|
| Supplier | …would define a modified asphalt as any material or process change which alters the characteristics of the asphalt binder after the refining process, |
| Supplier | We do not sell PMA. We purchase it, as needed, for a specific project. |
| Supplier | No modified asphalt supplied in 2005 |
| Supplier | …we tend to consider as "modified asphalt" any asphalt that is not a direct extraction of the Vacuum Tower Bottom stream, from crude distillation. We understand the definition provided by AASHTO. As far as we are concerned, the difference with AASHTO may reside in the classification of an asphalt that contains an oxidized component. We internally consider as "modified" an asphalt that contains an oxidized component, whereas AASHTO may not consider it as modified, by definition. As far as the other ways of modification (polymer, acid) we agree with AASHTO's classification. |
| Supplier | I would further divide this into - Polymer Modified Asphalt (PMA) , of which there are two types in general use in this area –1. Terminal blended – SBS which is normally "reacted "with a networking agent to provide a storage stable product.<br>2. HMA plant in-line blended – where SBR latex is in-line injected into the asphalt line at the HMA plant. A ter-polymer may also be available on a limited basis.<br>All of the materials listed above have been supplied to road projects within the NEAUPG region over the last 15 years. Therefore they could have been or will be recycled. |

**2. What quantity of polymer modified asphalt do you sell in the region (New England and New York)?**

For confidentiality purposes this information is withheld from this report. There was one supplier of polymer modified asphalt that responded to the questionnaire.

**3. What quantity of acid modified asphalt do you sell in the region (New England and New York)?**

For confidentiality purposes this information is withheld from this report. There was one manufacturer of acid modified asphalt that responded to the questionnaire.

**4. What quantity of air blown modified asphalt do you sell in the region (New England and New York)?**

For confidentiality purposes this information is withheld from this report. There was one supplier of air blown asphalt that responded to the questionnaire but that supplier has no plans to produce air blown asphalt this year.

**5. If you sell modified asphalts other than the methods listed in 2-4, please list the modification system and approximate quantities sold of each type listed.**

| | |
|---|---|
| Supplier | None |
| Supplier | N/A |
| Supplier | None |
| Supplier | Not applicable to us |
| Supplier | None |

**6. Would you be willing to provide MSDSs for your products to the research team? If yes, if you would forward them to me at your convenience, it would be appreciated.**

| | |
|---|---|
| Supplier | Yes |
| Supplier | Yes |
| Supplier | Yes |
| Supplier | Yes, we have standard MSDS's for unmodified PGAB and those from the manufacturer of the PMA we've used. |
| Supplier | Yes |

## Appendix C. FT-IR Testing of Asphalt Binders

Figure C.1 shows the summary of polymer indices for PMBs. The results indicate that the binders were in fact modified. As an example, the PG 64-28(PPA) has a unique and distinct peak for polyphosphoric acid and lacks any significant amount of styrene-butadiene rubber. This would be expected. The rest of the binders exhibit distinctive polystyrene (PS) and polybutadiene (PB) peaks at 966 $cm^{-1}$ and 700 $cm^{-1}$, which suggest significant presence of Styrene-Butadiene-based polymers in those binders. Inconsistently with the others, the PG 64-28 shows only PB peak at 973 $cm^{-1}$, while the expected PS peak exhibited only a shoulder and could not be identified by Gauss approximation.

**Figure C.1 Summary of Polymer Constituency**