Evaluation Of Current Practices Of Reclaimed Asphalt Pavement/Virgin Aggregate As Base Course Material

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WSDOT Research Report

EVALUATION OF CURRENT PRACTICES OF RECLAIMED ASPHALT PAVEMENT/VIRGIN AGGREGATE AS BASE COURSE MATERIAL

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Every year Hot Mix Asphalt (HMA) roadways are rehabilitated by milling the existing roadway and replacing the milled portion with new HMA. As a result of this practice, a tremendous amount of reclaimed asphalt pavement (RAP) is created. The Federal Highway Administration estimates that 100 million tons of HMA is milled each year (MAPA, 2007). The Washington State Department of Transportation (WSDOT) currently allows RAP to be recycled into new HMA, but only 20% of the RAP may be used in the new material. Thus, a large portion of the milled asphalt ends up at contractors' pits or landfills. Due to the possible reduction in product and construction cost by using RAP as base course in addition with increasing requests by contractors to do so, WSDOT is investigating the possibility of blending RAP with virgin material for use as a base course material. This report analyzes existing studies that have examined the properties and performances of 100% RAP mixtures as well as RAP/virgin aggregate blends. In addition, this report includes a survey of 12 state DOT's detailing current practices regarding the use of RAP as base course and any corresponding specifications and testing procedures.</td></tr>
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Abstract

Every year Hot Mix Asphalt (HMA) roadways are rehabilitated by milling the existing roadway and replacing the milled portion with new HMA. As a result of this practice, a tremendous amount of reclaimed asphalt pavement (RAP) is created. The Federal Highway Administration estimates that 100 million tons of HMA is milled each year (MAPA, 2007). The Washington State Department of Transportation (WSDOT) currently allows RAP to be recycled into new HMA, but only 20% of the RAP may be used in the new material. Thus, a large portion of the milled asphalt ends up at contractors' pits or landfills. Due to the possible reduction in product and construction cost by using RAP as base course in addition with increasing requests by contractors to do so, WSDOT is investigating the possibility of blending RAP with virgin material for use as a base course material. This report analyzes existing studies that have examined the properties and performances of 100% RAP mixtures as well as RAP/virgin aggregate blends. In addition, this report includes a survey of 12 state DOT's detailing current practices regarding the use of RAP as base course and any corresponding specifications and testing procedures.

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Section 1: Introduction

1.1 Problem Statement

Currently, great emphasis is placed on sustainable construction and infrastructure. The Leadership in Energy and Environmental Design (LEED) program has seen a dramatic increase in prominence in the past few years and public agencies across the country are modifying building construction requirements to lessen the effect of such construction on the environment. Although roadway construction is lagging in this area as compared to the building construction industry, the demand for sustainable and environmentally sound roads will increase in the future. One way to construct environmentally sound roads is through the use of recycled materials. Recycled materials have seen increasingly more use in the past 20 years and state DOTs have subsequently conducted a number of studies to analyze the performance of these recycled materials (Mokwa, 2005).

Reclaimed asphalt pavement (RAP) is one material that has been extensively recycled. RAP is created when existing asphalt concrete surfacing is milled or completely removed. Milling the existing roadway surface and replacing it with a new Hot Mix Asphalt (HMA) is a rehabilitation method utilized throughout the country. The Federal Highway Administration estimates that 100 million tons of HMA is milled each year (MAPA, website). Most, if not all, state DOT's allow a percentage of RAP to be recycled into new HMA in order to reduce product cost.

The Washington State Department of Transportation (WSDOT) currently allows contractors to utilize 20% RAP in HMA production. As a result of allowing only 20% of RAP to be reused in HMA production, the quantity of unused RAP continually increases, creating opportunities for using RAP in other applications. Contractors have frequently inquired about using or at least blending RAP with virgin aggregate for use as base course. Although WSDOT has allowed RAP to be mixed with virgin aggregate base course in the past, the State Materials Lab still has questions regarding this procedure. For example, what is the maximum percentage of RAP that should be allowed in the base course and does the RAP need to be processed prior to blending? As a result of these questions, the Materials Lab is hesitant to allow further use of RAP as a base course material but has an increased interest in determining whether utilization of RAP as a base course material is a viable option for WSDOT. Allowing RAP to be used as base course material would preserve non-renewable aggregate as well as decrease the amount of space needed to store the millions of tons of RAP created each year. But allowing the use of RAP may require new specifications and testing procedures; therefore, WSDOT is interested in reviewing existing research as well as the practices of other state DOTs regarding this material. This report provides a literature review and a survey of 12 state DOT's concerning RAP use as a base course material including specifications and testing procedures.

1.2 Objective and Scope

This research has two primary objectives: (1) review the current research literature on RAP used as a base course material, and (2) review other agency practices in the use of RAP as a base course material. This report will not cover the use of stabilizers (eg., cement) in conjunction with RAP and the use of reclaimed concrete pavement as base course material. The only material discussed herein is RAP and RAP blended with virgin aggregate.

1.3 Method of Research

The literature search focused on studies conducted by state DOTs or studies conducted for state DOTs by outside research facilities. In addition, state material engineers were contacted to determine the current practice of state DOTs regarding the use of RAP as a base course material. The following states were contacted: Colorado, Florida, Illinois, Minnesota, Montana, New Jersey and Utah. Information from California, New Mexico, Rhode Island, South Dakota and Texas is included in this report, however, the state material engineers were not contacted due to lack of contact information or the states were unresponsive. The information for these states was obtained only from their respective standard specifications.

Section 2: Literature Review

2.1 Overview

The majority of the 8 studies discussed in the literature review were conducted for state DOTs from 1993 to 2005. The Taha (1999) and Trzebiatowski (2005) studies were conducted for the Sultanate of Oman and for the State of Wisconsin's Solid Waste Research Program, respectively. All 8 studies tested both similar and different types of engineering properties. In addition, the studies analyzed different types of RAP, at different blends, with different types of virgin aggregate. As a result, no one study can be compared directly with another, but by comparing similar tests from all 8 studies, some general trends appear. Table 1 lists the general trends for five engineering properties from the 8 studies. If the study did not blend virgin aggregate with RAP, the table compares 100% RAP to 100% virgin aggregate.

Table 1: Literature Review Findings

Report	Blended[1]	Dry Density[2]	Moisture Content[3]	Permeability[4]	CBR[5]	Resilient Modulus[6]
Cooley (2005)	Yes	Decreased	Decreased	---	Decreased	---
Garg & Thompson (1996)	No	Decreased	Increased	---	Decreased	---
MacGregor (1999)	Yes	---	---	No Change	---	Increased
Bennert & Maher (2005)	Yes	Decreased	Decreased	Decreased	---	Increased
Papp (1998)	Yes	Decreased	Decreased	---	---	Increased
Sayed (1993)	No	---	Decreased	---	Decreased	---
Taha (1999)	Yes	Decreased	No Change	Increased	Decreased	---
Trzebiatowski (2005)	No	Decreased	---	Increased	---	---

1 Details whether the RAP material was blended with virgin aggregate.
2 Effect on the dry density of the material as the percent RAP was increased.
3 Effect on the optimum moisture content as the percent RAP was increased.
4 Effect on the permeability as the percent RAP was increased.
5 Effect on the California Bearing Ratio (CBR) as the percent RAP was increased.
6 Effect on the resilient modulus as the percent RAP was increased.

As seen in Table 1, three general conclusions can be made in regards to the use of RAP as a base course material: (1) dry density decreases as the percentage of RAP increases in the blend; (2) CBR value decreases as the percentage of RAP increases; and (3) resilient modulus increases as the percentage of RAP increases. Furthermore, these conclusions agree with other studies which will be discussed later.

Section 3: Key Observations

3.1 Not all RAP is the same

RAP derived from different sources can have significantly different gradation, oil content and density. This can be due to the milling process, rock source, type of oil, etc. RAP combined from several sources may change the quality of the product throughout the construction project because of this variation. One effective way to deal with this is to identify and segregate the various types of milled HMA. This can add expense and would require major changes to the current practices for storing RAP.

Cooley (2005) investigated RAP for use in full-depth-reclamation rehabilitation methods. Although this method is not utilized by WSDOT, results are still relevant. Cooley conducted material classification and compaction tests, and evaluated the strength, stiffness and moisture susceptibility on two sources of RAP blended with two types of virgin aggregate at RAP contents of 0, 25, 50, 75 and 100%.

The RAP from the first stockpile was milled from I-84, in Weber Canyon, while the RAP from the second stockpile was milled from a parking lot. Both materials were milled using different pieces of equipment. The I-84 RAP had approximately 8% particles finer than the No. 200 sieve while the parking lot RAP had only 0.45%. This difference could have resulted from a number of different causes, such as rock source, milling machine and the original HMA gradation. The large difference in gradation between the two RAP piles is significant because it affected some of the results between the two materials.

For example, the I-84 RAP had a maximum dry density of 130 lb/ft^3; the parking lot RAP had a maximum dry density of 115 lb/ft^3. It is unknown how this difference will affect the performance of the material, but it reveals that material properties of RAP will vary depending on factors such as, asphalt pavement type and gradation as well as the milling methods used to reclaim the pavement. It is important to note, however, that the large difference in gradation and dry density was found at 100% RAP blends; therefore, by adding virgin aggregate to the RAP, these differences would most likely be reduced.

One solution to achieving a more uniform RAP product is by segregating RAP piles by source. Although this would require most, if not all, contractors in Washington State to change current practices of storing RAP, Illinois DOT does require the contractor to separate the RAP—that is to be used for coarse aggregate in HMA—by aggregate type and to determine the location of the originally placed pavement (Illinois DOT, 2002). RAP piles located at contractors' pits most likely include pavement from a variety of locations. As a result, the various pavements within the RAP pile have different types of aggregate and asphalt that could affect the quality of the base course when blended with virgin aggregate. Determining the type of RAP and its gradation prior to approving its use as a base course material would ensure more consistent test results.

3.2 Weather might affect performance

Weather affects the performance and properties of HMA. Warmer temperatures lead to an increase potential for rutting whereas cooler temperatures cause HMA to stiffen. Consequently, it is realistic that weather will affect a RAP. Although limited studies have analyzed the possible effect temperature may have on RAP base course, two of three studies investigated for this report observed changes in properties of the RAP mixture due to temperature.

Consentino (2001) conducted the most in-depth study regarding the effects of weather and storage time at elevated temperatures on RAP base courses. Both laboratory and field tests were performed. The laboratory tests revealed that increasing the storage temperature from 75 to 100°F increased the maximum principal stress at failure, stiffness and cohesion. Increasing the temperature to 125°F did not cause the properties to change.

The field investigation consisted of constructing a base course of RAP to determine the variations in stiffness due to climatic change. A control section was constructed and consisted of cemented coquina—a typical FDOT base course material. No surfacing was placed over the base course materials. The field investigation lasted for 12 months and revealed the following results: (1) LBR values decreased during warmer summer months and increased during the cooler months and (2) the Impulse Stiffness Modulus (ISM) decreased during the warmer summer months and increased during the cooler months.

Cooley (2005) also noted variations to properties due to temperature. When the stiffness was tested at optimum moisture content, the values decreased as the RAP percentage increased from 0 to 25%. As more RAP was blended into the material, from 25 to 100%, the stiffness values increased. On the other hand, when the RAP was dried for 72 hours at 140°F, then soaked and tested, the trend reversed. Stiffness values increased as the RAP percentage was increased from 0 to 25% and then decreased when the RAP percentage was increased from 25-100%. Cooley stated that the heat from the drying oven softened the asphalt in the RAP samples and, after a cooling period, the asphalt hardened and enhanced the bonding between the aggregates.

In the Garg and Thompson study (1996), an 8-inch, 100% RAP base course was constructed and a 3-inch, dense-graded, AC surface course was placed over the top. Dynatest Falling Weight Deflectometer tests were conducted at various times throughout the following years after construction and Garg and Thompson concluded that the RAP base course does not behave as a bound material and is not temperature sensitive. This disagrees with Consentino's observation, but it should be emphasized that the Consentino study did not cover the RAP base course with an AC surface course. Moreover, Consentino found that below 18-inches, air temperature variations caused little effect on the RAP temperature. Thus, temperature may not have as great as an effect on the performance of the base course material once a surface course is placed overtop. The Garg and Thompson study is notable because an actual RAP base course material was constructed and tested against a virgin-aggregate test section. More of these type of studies need to be conducted because laboratory tests won't determine how the material will perform after years of service in actual weather conditions.

Although the Consentino study was conducted on 100% RAP samples, warmer weather will affect the properties of the asphalt in the RAP base course. Further research is need to determine the extent of the effects of temperature differences in the RAP base course material.

3.3 Hydraulic conductivity is difficult to compare between reports

Factors such as compaction effort, gradation and type of soil affect hydraulic conductivity. The differing asphalt contents of RAP may also affect hydraulic conductivities. Consequently, it is difficult to compare the hydraulic conductivity results of different studies, especially when those studies blend virgin aggregates with RAP. The wide spectrum of virgin aggregates makes it impractical to compare studies, unless the virgin aggregates have similar properties.

MacGregor's (1999) study demonstrates the large effects that can occur when factors are adjusted. MacGregor blended RAP with both dense, graded, crushed stone and gravel-borrow subbase at RAP percentages ranging from 0 to 50%. Hydraulic conductivity tests were conducted using a Constant Head Permeameter.

In the study, no variation in hydraulic conductivity was observed when the RAP/crushed-stone base mixtures were blended (as compared to a 100% crushed-stone blend), but the hydraulic conductivity of the RAP/gravel-borrow subbase mixes increased by nearly an order of magnitude with an increase of RAP from 0 to 50%. Thus, to determine how the addition of RAP to a virgin-aggregate base course will affect the hydraulic conductivity of the blend, it must be done on a material-by-material basis. The results of one study cannot be used to determine whether the addition of RAP will affect the conductivity of the blend unless the aggregates are similar.

Moreover, the level of compaction of the material will largely affect the conductivity of the sample. This is verified by the results of the MacGregor study shown in Table 2.

Table 2: MacGregor (1999) Hydraulic Conductivity Results

RAP/Dense Graded Crushed Stone Base Mixture		
% RAP	Density (Mg/m^3)	Avg. Hydraulic Conductivity (cm/s)
0	1.83	0.73
0	1.9	0.32
10	1.87	0.32
10	2	0.1
30	1.9	0.13
50	1.8	0.24

When performing conductivity tests, it is imperative to ensure the densities are the same to ensure consistent results. For example, the low density, 10% RAP blend shown in Table 2 had a conductivity that is three times higher than the denser specimen.

Section 4: Density and Water Content Testing

One concern of using RAP as base course material is developing a test procedure to test the in-place density and water content of the compacted base course material. Predominately, state DOTs utilize a nuclear gauge to measure the density and water content of the compacted base course. The addition of RAP to the base course material, however, can affect the performance of the gauge. Density measurements are taken when gamma rays are emitted from the end of a retractable rod in the gauge, pass through the pavement and are then counted by a Geiger-Mueller detector located at the opposite end of the gauge. The gauge measures water content by emitting neutrons which collide with nuclei of other atoms. Neutrons that collide with hydrogen atoms slow down much quicker than when they collide with other atoms. By counting the number of slow neutrons, the gauge can determine how many hydrogen atoms are in the material. Since water consists of many hydrogen atoms (H_2O), the gauge can be calibrated to determine the water content of the material (WSDOT, *Pavement Interactive*). It is important to note, though, the gauge is detecting hydrogen atoms in the material, and not specifically water molecules.

The Viyanant, et. al. study (2004) was conducted to analyze the accuracy of nuclear density and water content tests performed on in-place crushed concrete, RAP and crushed limestone (conventional fill material or CFM). A test site was constructed of the three materials and a calibrated nuclear gauge was used to measure density and water content at various locations throughout the site. After a reading was taken by the nuclear gauge, the density was also measured by either the Rubber Balloon Method (ASTM D 2167) or the Test Pit Method (ASTM D 5030). Water contents were checked by oven drying the sample.

RAP moisture contents measured by nuclear gauge were three times as large as the oven-dried moisture contents. Conversely, the nuclear gauge and oven-dried moisture contents were similar for the CFM. The authors concluded that the asphalt cement binder is likely the major hydrogen contributor. This additional hydrogen from the reclaimed asphalt likely caused the high moisture contents seen in the RAP. Test results also showed that the measured, nuclear-gauge density of the RAP was 8% and 3% higher than the Rubber Balloon and Test Pit Method, respectively. The authors noted, however, that the balloon used for the Rubber Balloon Method could only accommodate volumes up to 1420 cm^3 and ASTM D 2167 recommends a minimum excavation volume of 2840 cm^3. In addition, Garg and Thompson (1996) also observed that the nuclear gauge densities were higher than the lab maximum dry densities.

The authors also discussed that the materials used in calibrating the nuclear gauge may have been different from the materials used in the study, causing the discrepancies in the density. On a traditional, virgin-aggregate base course, the material is sampled from a stockpile. It is believed that the aggregate in the stockpile consists of the same type of aggregate and that the compaction curves produced from the samples represent the whole stockpile. But this is not a reasonable assumption to make of a RAP stockpile. As previously discussed, RAP piles usually consist of reclaimed pavement from various locations and the type of aggregate within the pile may vary, producing test results that are not reflective of the sampled material. This problem, however, may be of little concern depending on the percentage of RAP allowed within the mix. Although the Viyanant study conducted tests on 100% RAP base courses, further studies should be conducted with varying percentages of RAP and virgin aggregates. Many states allow RAP in base course material, but few allow 100%. Studies of this nature should reflect this trend and test varying percentages of RAP to provide state DOTs the opportunity to decide what percentage of RAP to allow in base course materials.

In addition, more density test comparisons should be conducted using the Test Pit Method. This method requires 20,000 cm^3 of excavated material rather than 2840 cm^3 required by the Rubber Balloon Method. The Test Pit Method takes longer to perform than the balloon, but the balloon can deform the excavated hole during the application of the operating pressure. More data points are shown on the balloon method graph than the test pit method leading the reader to believe more rubber balloon tests were performed.

The test pit method, however, produced results that were closer to the nuclear gauge and needs to be analyzed further.

Section 5: State DOT Practices

5.1 Overview

State material engineers were contacted to determine the current practice of state DOTs regarding the use of RAP as a base course material. The following states were contacted: Colorado, Florida, Illinois, Minnesota, Montana, New Jersey and Utah. Information from California, New Mexico, Rhode Island, South Dakota and Texas is included in this report, however, the state material engineers were not contacted due to lack of contact information or the states were unresponsive. Information for these states was obtained solely through their respective standard specifications.

Table 3 is a survey of the practices of state DOTs regarding the use of RAP as a base course material.

Table 3: State DOT Survey

State	Rap Allowed[1]	Max %[2]	Processed[3]	Testing[4]
Florida	No	---	---	---
Illinois	No	---	---	---
Montana	Yes	50-60%	No	Corrected Nuclear Gauge
New Jersey	Yes	50%[5]	Yes - Gradation	Corrected Nuc. Gauge + Sample
Minnesota	Yes	3%[6]	Yes - Gradation	Dynamic Cone Penetrometer
Colorado	Yes	50%[5]	Yes - Max Agg. Size	Roller Compaction Strip
Utah	Yes	2%[6]	Yes - Gradation	Nuc. Gauge or Breakdown Curve
Texas[7]	Yes	20%	Unknown	Various (including Nuc. Gauge)
California[7]	Yes	50%	Unknown	No special testing procedure listed
New Mexico[7]	Yes	Unknown	Unknown	Corrected Nuc. Gauge
Rhode Island[7]	Yes	Unknown	Yes - Gradation	Unknown
South Dakota[7]	No	---	---	---

1 Describes whether state allows RAP as a base course material.
2 The maximum percentage of RAP (by weight) allowed.
3 Describes whether the listed state requires the RAP blend to be processed prior to placement and what requirements must be met
4 Describes the type of QA testing required.
5 These are modified values. The current values are 100%, but the materials department is in the process of modifying current values.
6 These values are the maximum AC content allowed in the RAP blend.

7 These states were not contacted and the information listed in the table is from the state's current standard specification.

5.2 Montana

Montana Department of Transportation (MDT) materials engineer, Matt Strizich, provided the following information. MDT does not state in their standard specifications whether RAP may be used as a base course material. Rather, they decide on a project-by-project basis whether or not to use RAP in the base course material and write project-specific specifications in the contract documents. Moreover, MDT blends the RAP with the virgin aggregate in a different manner than is typically seen in other DOTs. Due to vertical and horizontal alignment problems on state highways, MDT reconstructs more roadways than other states. Instead of blending previously milled asphalt with virgin aggregates, MDT mills the top few inches of the asphalt surface, hauls this material away, pulverizes the remaining asphalt and underlying base course and reuses this material as base course. For example, if the existing asphalt depth was 7-inches and MDT specified that 50% RAP would be allowed as base course and 4-inches of base course would need to be removed, the first 3-inches of the asphalt pavement would be milled and hauled off. The remaining 4-inches of asphalt and 4-inches of base would be pulverized, blended and used as base course material for the project. From previous experience, MDT believes the underlying base material is suitable to be reused.

Field compaction testing is followed in the same manner as is for virgin aggregate base course, although some subtle differences exist. Due to the hydrocarbons in the existing asphalt, MDT does not believe the nuclear gauges are accurate in determining density; therefore, a correction factor is added. The correction factor is determined by first testing the density and moisture of the blended material with the nuclear gauge. The material is then sampled and the actual moisture is determined. Actual moistures are used to determine the correction factor which is applied to the recorded density from the gauge.

MDT analyzes each project individually and decides on the percentage of RAP to allow. The depth of the pulverized material is limited to 8-inches to ensure adequate compaction and the total percentage of combined RAP is typically limited to a maximum of 50%. In some instances, the percentage is increased to 60% if it is deemed an economical alternative.

These maximum percentages were established from the results of a study conducted by Mokwa (2005). Mokwa conducted laboratory tests on four different types of virgin aggregates blended with varying percentages of RAP (20, 50 and 75%). The laboratory tests consisted of grain size analyses, specific gravity, modified Proctor compaction, relative density, Los Angeles abrasion, large-sample direct shear, R-value, permeability and X-ray computed tomography scans were conducted on the blends. Mokwa found that blending RAP with virgin aggregate results in only minor changes to the engineering properties of the virgin material.

5.3 Florida

The Florida Department of Transportation (FDOT) allows the use of RAP as a base course material but only in non-traffic applications such as paved shoulders and bike paths. The state's Geotechnical Material Engineer, David Horhota, also stated that no special provision exists within the state allowing the use of RAP as a base course material (Horhota Interview).

FDOT, however, has previously pursued the idea to use RAP as a base course material for roadway bases and subbases. In 2001, Florida Institute of Technology published a study that was conducted in order to develop specifications for using RAP as a base or subbase material (Consentino, 2001). A laboratory and field investigation was conducted to determine strength and deformation properties of RAP, effects of crushing unprocessed RAP, storage time at elevated temperatures and weather on the properties of the RAP. FDOT issued a *Summary of Final Report* in conjunction with the Florida Tech report (FDOT, 2001). A few of the results from the laboratory investigation are listed below:

1) Typical moisture density curves were not realized due to the fact that the dry density was relatively constant at moisture contents greater than 4%. Most of the curves were fairly flat with no distinct peak.

2) Various compaction methods—Proctor, Marshall, vibratory and static—were utilized but none of the methods, except the static at 1,000 psi, met FDOT Limerock Bearing Ratio (LBR) test specifications for base course material (LBR>100).
3) Increasing the temperature of the RAP has a significant effect on most of its triaxial properties.

The Limerock Bearing Ratio (LBR) test—similar to the CBR test but correlated to limerock that is predominantly used in Florida—is the most widely accepted FDOT specification for acceptance of a base course material (Consentino, 2001). As a result of the low LBR test values recorded in the laboratory investigation and during the warmer, summer months of the field investigation, FDOT did not adopt RAP as a possible base course material.

5.4 New Jersey

Currently, the state of New Jersey specifies that any percentage of RAP may be blended with virgin aggregate for base course material. According to the state materials engineer, Eileen Sheehy, however, this specification is being modified to allow a maximum of 50% RAP to be blended with virgin aggregate (Sheehy Interview) based on results from a Rutgers University study by Bennert and Maher (2005). This study will be discussed later.

RAP is utilized as a base course material by the New Jersey Department of Transportation (NJDOT) in the following manner. The standard specification employed by NJDOT allows up to 100% RAP to be used as base course material. The contractor for each project determines whether to incorporate RAP into the base course blend and at what percentage. Base course that consists of RAP shall meet the following requirements: (1) percent loss shall not exceed 50% when tested using the Los Angeles Machine; (2) RAP percentage shall be determined by the contractor and shall not vary by more than plus or minus 15% from the established value when measured at the source;

and (3) the blend shall conform to the gradation listed in Table 4 (New Jersey DOT, 2001).

Table 4: NJDOT Base Course Gradation

Sieve Size	% Passing
2"	100
1.5"	85-100
0.75"	55-90
No. 4	23-60
No. 50	3-25
No. 200	0-10

Although NJDOT does not require the RAP to be processed prior to blending, Sheehy said no contractor has been able to meet gradation requirements without processing. In some instances, the RAP only needed to be run over a scalping screen (Sheehy Interview). Sheehy further stated: (1) recycled concrete (RCA) is the preferred material to blend with virgin aggregate for base course material because RAP is more valuable when recycled for use in HMA and (2) only a few projects in New Jersey had used a RAP blend as a base course, but no failures have been noted for these projects.

Testing the in-place density of the blended material is performed according to AASHTO T191, T205 or T238, Method B and T239. If the nuclear gauge method is used, the procedure is slightly modified. The nuclear gauge is used to determine the in-place, wet density of the base course. Once the wet density is determined, a 1,000-gram sample is collected and taken to a laboratory where the percent moisture value is determined. Using both the field-measured wet density and laboratory-determined moisture content, the dry density is calculated.

The study conducted by Bennert and Maher analyzed the permeability, triaxial shear strength, cyclic triaxial loading, California Bearing Ratio (CBR) and resilient modulus of base and subbase materials as well as RAP and RCA. The study found that permeability decreases as the percentage of RAP increases. This finding further illustrates the inconsistencies of a RAP-blended material between different reports. For the permeability tests—constant and falling head—RAP was blended with New Jersey's

Central Region, naturally graded base (Dense Graded Aggregate Base Course - DGABC) and subbase material (I-3) at four different percentages. The results are listed in Table 5.

Table 5: Bennert and Maher (2005) Permeability Results

	Constant Head (ft/day)		Falling Head (ft/day)	
Blend Percentage	DGABC	I-3	DGABC	I-3
Natural (0% RAP)	172.7	55.8	121.05	43.2
25% RAP	121.4	2.2	27.8	2.4
50% RAP	113.7	8.3	39	7.7
75% RAP	1.7	3	2.1	3.3
100%RAP	16.9	16.9	13.9	13.9

As shown in Table 5, the difference between the permeability of the 100% natural aggregate and the 25% RAP – 75% natural aggregate blend is dramatic. The study conducted by Mokwa (2005), Taha (1999), Trzebiatowski (2005) and others, however, concluded just the opposite. A number of possible reasons exist for this discrepancy between the various studies. Bennert proposes the following possible reasons for those discrepancies (Bennert Interview): (1) level of compaction; (2) quality of virgin aggregate (hard, angular rock for the New Jersey study); (3) higher percent fines of virgin aggregate (10 to 11%); and (4) combining of a highly angular New Jersey DGABC to a more rounded, softer RAP source. The New Jersey study also noted that the RAP used for the various tests throughout the report was too fine to meet specifications for base course material; the percent passing the ¾" sieve was 100% and the specification requires a range between 55-90% (Table 4). This further emphasizes the need for each state to conduct its own testing to determine how that state's aggregates and RAP specifications affect the properties of the blend.

Results from the CBR tests revealed that there was about a 50 and 55% decrease in CBR values when the RAP blend was increased from 0 to 25% RAP and 50 to 75% RAP, respectively. Little change occurred in the CBR value when the RAP percentage was increased from 25 to 50%. In general, as the percentage of RAP increases, the CBR values decrease.

Bennert and Maher also conducted a triaxial test; the test was conducted only on a 100% RAP specimen. The specimen displayed similar results to the subbase material (I-3), but displayed lower shear strength than the base course material (DGABC). For the resilient modulus test, as the percentage of RAP increased, the resilient modulus increased. Permanent deformation, however, increased as the percentage of RAP increased. The 100% RAP mixture experienced the most deformation.

One of the trends that existed throughout the various tests was that a significant difference existed between a 0% RAP and 25% RAP mixture as well as the 50% RAP and 75% RAP mixture. But little difference existed in test results between 25% RAP and 50% RAP. As a result, if the 25% RAP blend is able to meet requirements for base course material, then it is likely that the 50% blend will also meet those requirements. This allows a public agency to set a higher maximum allowable RAP percentage.

5.5 Minnesota

The Minnesota Department of Transportation allows both the asphalt and underlying base course to be reclaimed at the same time—as is done in Montana—as well as stockpile the reclaimed asphalt and mix it with virgin aggregate at a later time. The maximum bitumen content of the composite mixture—reclaimed asphalt and aggregate—shall not exceed 3% by weight. According to the State Grading and Base Engineer, Tim Andersen, this maximum percentage by weight corresponds to a volume percentage of 50-75% RAP due to low asphalt contents of previously placed HMA and degradation of the asphalt binder (Andersen Interview).

If a contractor chooses to use RAP as a base course material, the gradation of the RAP/aggregate blend must meet the gradation of the class of aggregate that was specified for the contract. However, the amount of RAP in the blend must exceed 10% (by volume) to be considered a recycled blend (Class 7). This means that a contractor may add a small percentage of RAP without changing the class of the aggregate. All the quality control specifications that apply to that class of virgin aggregate will apply to the blended mix if the RAP percentage does not exceed 10%. Andersen said this specification is currently being modified and will most likely be increased to allow up to 20-25% RAP to be added to a virgin class of aggregate without being considered a recycled blend. Minnesota requires the contractor to mechanically blend the RAP and virgin aggregate at the crushing site. They do not allow a stockpile of RAP and a virgin aggregate to be blended at the job site, with a grader. Andersen said that this type of blending—mechanically blending the two materials together at the crushing site—usually occurs in urban areas whereas the reclaiming of both the asphalt and underlying base course often happens in rural areas.

Minnesota does not use a nuclear gauge to determine the in-place density of the RAP blend. Instead, the state uses either a Quality Compaction method or the Dynamic Cone Penetrometer (DCP) method. The Quality Compaction method consists of visual inspection by the state inspector and is usually reserved for only small quantities. The DCP method is preferred. Andersen stated the permeability of the blended material decreases as RAP is increased. A typical base course aggregate has a permeability of 0.5 ft/day, but this value is reduced in half when RAP is added to the virgin aggregate.

5.6 Colorado

The Colorado Department of Transportation (CDOT) has lenient requirements with regards to the use of RAP as a base course material. Currently, CDOT allows up to 100% RAP. The State Materials/Geotechnical Engineer, Tim Aschenbrener, said this specification will likely be reduced to 50% due to recent findings (Aschenbrener Interview). Although RAP is not often used as a base course material in Colorado, recent studies have shown that the RAP blend has a high permeability. CDOT has no specific gradation for blended material, but a maximum aggregate size is specified to ensure larger pieces of reclaimed asphalt are not added to the blend. Aschenbrener was unsure of the exact maximum allowable size—either 1 or 2 inches—but he said that this requirement is usually met by running the RAP over a scalper and then re-crushing any of the larger pieces. In addition, RAP origin is not classified and a nuclear gauge is not used to test the in-place density. Rather, a roller compaction strip is completed to determine the roller pattern and visual observation is then used to ensure compaction is met during the construction process.

CDOT is also in the process of performing a material study on various properties of a RAP/aggregate blend. According to CDOT Research Engineer, Roberto de Dios, the study is similar to the one conducted by Bennert and Maher for New Jersey. Roberto de Dios said the study would be published at the end of 2007 or early 2008 (de Dios Interview).

5.7 Utah

The Utah Department of Transportation (UDOT) allows RAP as a base course material but limits the AC content to 2%. According to Tim Biel, a UDOT materials engineer, this maximum AC content equates to 30% RAP and 70% virgin aggregate by weight (Biel Interview). The maximum percentage of RAP allowed into the mix was determined by a research project; the limit was set at 2% because more RAP resulted in difficulty performing the proctor test and also in obtaining accurate nuclear gauge tests. UDOT will occasionally allow more RAP than the 2% AC content based on Value Engineering Ideas and other economic reasons. For example, if the contractor has a large quantity of RAP that could be utilized and the plans require a large amount of base course material, Utah might allow more RAP. This is done on a project-by-project basis.

The gradation that is used for a RAP base course material is the same as used for virgin aggregate which is listed below in Table 6.

Table 6: Utah Base Course Gradation

Gradation Limits – Single Value Job-Mix Formula			
Sieve Size	**Percent Passing of Total Aggregate (Dry Weight)**		
	1-1/2 inch	1 inch	3/4 inch
1-1/2 inch	100	--	--
1 inch	--	100	--
3/4 inch	81 -91	--	100
1/2 inch	67 - 77	79 - 91	--
3/8 inch	--	--	78 - 92
No. 4	43 - 53	49 - 61	55 - 67
No. 16	23 - 29	27 - 35	28 - 38
No. 200	6 – 10	7 - 11	7 - 11

Utah requires the RAP/aggregate blend to be mechanically blended to ensure a homogenous material. Biel said that on a previous job the contractor placed the milled asphalt and dumped it onto base course material already placed. This process caused the base course to separate into lenses. If the material is kept to the maximum AC content of 2%, the material is usually tested as is virgin aggregate base course. A compaction curve is developed from a sample of the blended material and a nuclear gauge is used to measure field density.

However, if more RAP is used in the mix or nuclear gauge is producing results greater than the laboratory maximum density another method is used. A test section is rolled and the densities are taken. Once the base course densities reach a maximum and start decreasing, the maximum density can be determined. This process is conducted several times and an average Breakdown Curve Maximum Density is determined. The required construction density is usually 98% of the Breakdown Curve Maximum Density. Samples will also be taken to determine the moisture content to ensure proper watering if this testing procedure is used. Biel did not know of any previous areas where a RAP base course performed poorly and caused poor performance on the surface course and also said no changes regarding the use of RAP as a base course material would be made in the 2008 standard specifications.

5.8 Illinois

The state of Illinois does not allow RAP to be used as a base course material. Shelia Beshears, the state geotechnical engineer, stated that they sometimes use RAP as a subbase material but virgin aggregate is always placed overtop, prior to placing HMA or concrete (Beshears Interview). She also said that the main hurdle for using RAP as a base course material is the lack of quality control testing procedures for the material.

Section 6: Discussion

6.1 Overview

RAP is a highly variable material due to different gradations, oil contents, milling processes, etc. Blending virgin aggregate with RAP increases this variability causing the wide range of test results observed in the published literature. It is important to determine if these tests are relevant to a RAP/virgin aggregate blend and how these tests correlate to field performance of the base course. For example, three studies analyzed weather/temperature effects on RAP. The one study that did not observe any effect actually constructed an AC-surface course over the base course. Effects from temperature variations can be detected in laboratory tests but those effects are probably less applicable to construction and field performance. Moreover, the RAP blend permeability results produced a variety of results confirming that the addition of RAP will affect each virgin aggregate base course differently. More than likely, though, the gradation of the RAP will have a significant effect on permeability and if the RAP/virgin aggregate blend is similar to the traditional base course blend gradations, similar permeability will be observed.

Two test results, however, never varied between the studies. As the percent RAP increased, the resilient modulus increased and the shear strength decreased. Besides these two results, it appears as if a RAP/virgin aggregate blend will behave similarly in the field to a 100% virgin aggregate base course. If the percentage of RAP is limited—to limit the decrease in shear strength—it is a viable option for use in base course. More observations are discussed below.

6.2 100% RAP should not be allowed

The published literature that examined the properties of 100% RAP blends all agreed that 100% RAP does not produce a product of base course quality. As the percent of RAP increased, the shear strength of the blend decreased below state required levels for base course materials. Studies predominantly used the CBR to measure shear strength and observed that as the percent RAP increased, CBR values decreased. Taha (1999) reported that the CBR value for a 100% RAP blend was 11%, but when the RAP percentage decreased to 80%, the CBR value increased to 26%.

In addition, the states contacted for this report that currently allow 100% RAP as base course material—New Jersey and Colorado—are in the process of modifying state specifications to limit the maximum percentage of RAP due to recent findings from research reports and previous experience. Both of the material engineers from New Jersey and Colorado believe the maximum amount will be set to 50%. The other states contacted, with the exception of Minnesota, that allow RAP in base course material have limits of 50% or less.

6.3 The maximum percentage of RAP is converging towards 50%

As more research becomes available, it appears as though state DOTs will set maximum RAP percentages near or below 50%. These maximum percentages, however, depend on a number of factors such as AC content of RAP, aggregate quality, base course requirements, etc. For example, in Minnesota, previously paved roadways had light AC contents, therefore allowing Minnesota, in their opinion, to increase the percentage of RAP allowed. AC content, as well as the other factors, will vary by state and need to be given consideration. As a result, each state will need to decide what maximum percentage of RAP will meet the needed requirements for base course material. Furthermore, some states allow the blend percentages to vary a certain percentage. If this is done, the maximum percentage of RAP allowed, plus the allowable percentage variance should be less than or equal to 50%. For instance, if the blend percentage variance is 15%, the maximum allowable percentage of RAP should be set to 35%. Once the RAP percentage increases over 50%, the properties of the blend can have sharp, drastic effects. The properties of the blend can also have large changes when increasing the RAP percentage from 0%; but, the changes have been less severe when the RAP content increases from 20 to 50%. More studies need to be conducted to better pinpoint a maximum percentage within this range, but, currently, it is better to maintain the RAP percentage at or below 50%.

6.4 RAP used for base course needs some type of gradation requirements

Of the nine states surveyed that allow RAP as a base course material, four require gradation specifications, one has a maximum allowable aggregate size specification, one does not have a gradation specification and three states are unknown. Requiring RAP used as base course material to meet gradation specifications, though, will prevent contractors from milling HMA on one side of the project and using the RAP for base course on the other side. This practice can greatly reduce cost by limiting the number of trucks needed to haul away milled asphalt and the number of miles traveled. Unfortunately, most milling machines do not produce consistent size pieces of RAP, leading to varying performance results. RAP is a material that is inconsistent, due in part to the many variables associated with the product, as explained above. Consequently, when one of the variables can be controlled, such as gradation, it must be done to ensure more consistent performance results. Whether this gradation can be as minimal as running the material over a scalper to ensure larger pieces are removed—Colorado—or a gradation requirement as strict as traditional base course material—New Jersey and Utah—is still unknown.

6.5 Different virgin aggregates produce varying results

The engineering properties of the RAP/virgin aggregate blends vary depending on the type of virgin aggregate used. Engineering properties of RAP/virgin aggregate blends have little meaning to those states that use different virgin aggregates from those in the study. For instance, limerock used in Florida will vary from the basalt used in Washington, possibly resulting in different properties between the blends. This might be one reason why some of the engineering properties—permeability, for example—display such different results between studies. Individual states need to conduct their own studies or find studies with similar aggregates to that of their own. For example, by comparing the RAP blends to four different types of aggregates found within Montana, Mokwa (2005) produced a valuable report that the Montana Department of Transportation could use to decide whether RAP could be used as a base course material.

Section 7: Recommendations

7.1 Determine if 50% is the correct maximum

According to the states surveyed, 50% is a common maximum percentage, but this does not mean it is the best percentage. The majority of the studies conducted tests on blends of 0, 25, 50 and 100% RAP. Now that more states are converging on 50% as a maximum, more tests, ranging from 0 to 50% RAP, need to be conducted. Although small changes in the RAP percentage will have little effect on field blends due to the imprecise nature of construction, a 10 to 15% change could result in a large effect. Blends at 0, 15, 30 and 50% RAP should be tested to determine if there is a large difference in shear strength between 30 and 50%, for example, as is seen between 50 and 75% in the Bennert and Maher (2005) study.

7.2 Property Tests

The tests used to measure RAP properties were primarily chosen to correspond with the tests used by that state. For example, Consentino (2001) used the Limerock Bearing Ratio test (LBR) because the LBR is the most widely accepted FDOT specification for acceptance of a base course material. And Mokwa (2005) performed the R-value test instead of the preferred resilient modulus test because the funding agencies were interested in the R-value test. These tests, including the CBR test, have been used for many years, but they may not correspond well to field performance. Although triaxial tests are more expensive than the other tests, more research on shear strength should be conducted on 0 to 50% RAP blends.

7.3 More field performance studies are needed

The majority of the research regarding RAP as a base course material thus far is laboratory tests. More research into actual, field-performance of the blended material needs to be completed such as that done by Garg and Thompson (1996) and Maher (1997). Many questions still exist as to how permanent deformation, construction process, etc. will affect performance. Montana DOT is currently conducting a study that will analyze approximately 20 projects that used RAP as a base course material since 1988 (Montana DOT, Implementation Plan). Although Montana mills and places HMA and the existing base course material at the same time, this study will be valuable to better understand how a RAP/aggregate blend will affect surface performance.

7.4 Quality Control testing needs refining

As stated by the Illinois DOT geotechnical engineer, Shelia Beshears, one main hurdle for using RAP as a base course material in Illinois is the lack of testing procedures for the material (Beshears Interview). As detailed above, each state has its own testing procedure; Minnesota does not use a nuclear gauge at all, whereas Montana just adds a correction factor to the density obtained from the nuclear gauge. Only one study (Viyanant, 2004) was obtained that compared the accuracy of densities measured by a nuclear gauge between virgin aggregate and RAP blends. The differences in densities ranged from 3 to 8% between the virgin aggregates and the RAP. These studies, however, were conducted on 100% RAP blends. These differences might decline if the RAP percentage was decreased. Utah State DOT stated that as the RAP percentage increases over 30%, accurate nuclear gauge tests are difficult to obtain (Biel Interview). This information is crucial for states that allow the RAP percentage to vary, such as New Jersey, because varying the RAP content might affect the nuclear gauge results. Therefore, more studies need to be conducted to determine how the nuclear gauge results are affected at varying percentages of RAP.

Section 8: WSDOT Preliminary Specifications

(1) Limit RAP content to 25%. The primary reason for the lower RAP content is quality control testing. New Jersey and Montana allow 50% RAP, but both include a correction factor for the nuclear gauge density results. On the other hand, Utah allows a maximum of 30% RAP to ensure accurate nuclear gauge density tests. Until more research can be conducted on the effects of RAP at higher percentages, the maximum percentage should be limited.

(2) Use the current gradation for base course. As detailed above, RAP is a highly inconsistent material. Producing RAP with a constant gradation will limit this variability and will likely ensure more consistent performance results.

(3) Blending of the RAP and virgin aggregate will occur offsite. Therefore, virgin aggregate cannot be combined with RAP at the construction site and blended with a grader. Utah has allowed this practice in the past but it caused the base course to separate into lenses (Biel Interview).

(4) Conduct current quality control tests used for base course. In addition, add another test similar to Utah's Breakdown Curve Maximum Density in case the nuclear gauge produces densities greater than 100%.

Section 9: Conclusion

Although the majority of states contacted for this report allow the use of RAP/virgin aggregate base course blend, many stated that this blend is not often used. This has not stopped those states from examining the option of RAP as a base course material. Apart from Illinois, all the states contacted have recently or are currently researching the possibility of using RAP as a base course material. Whether this interest is generated from contractors or from within, it demonstrates the importance that other state DOTs are placing on this option.

As more emphasis is placed on environmental awareness in infrastructure construction, contractors and government agencies will look for ways to decrease the environmental impact of such construction. Reusing non-renewable resources and decreasing the size of the stockpiles of RAP can both be accomplished by using RAP as base course and are both beneficial to sustainable construction. Gone are the days when roads were built without a worry about the resources that were being used or the pollution that was being created. Sooner or later government agencies and contractors will be rated by not only the product they produce but also the sustainable construction they provide. Although the use of RAP as a base course material is not completely understood and conflicting reports exist, with more research and testing, it is a viable option for future, sustainable construction.

References

Bennert, Thomas, and Maher, Ali. (2005). The Development of Performance Specification for Granular Base and Subbase Material. (accessed online through http://www.state.nj.us/transportation/refdata/research/reports/FHWA-NJ-2005-003.pdf on June 12, 2007)

Cooley, Dane A. (2005). Effects of Reclaimed Asphalt Pavement on Mechanical Properties of Base Materials. *Master Thesis*. (accessed online at http://contentdm.lib.byu.edu on May 18, 2007).

Cosentino, Paul J, and Kalajian, Edward H. (2001). Developing Specifications for Using Recycled Asphalt Pavement as Base, Subbase or General Fill. (accessed online at www.dot.state.fl.us/research-center/Completed_Proj/Summary_SMO/FDOT_BB892_rpt.pdf on July 12, 2007)

Florida Department of Transportation (FDOT). (2001). Developing Specifications for Using Recycled Asphalt Pavement as Base, Subbase or General Fill Materials. *Summary of Final Report*. (accessed online at www.dot.state.fl.us/Research-Center/Completed_Proj/Summary_SMO/FDOT_BB892.pdf on July 12, 2007).

Garg, Navneet, and Thompson, Marshall R. (1996). Lincoln Avenue Reclaimed Asphalt Pavement Base Project. *Transportation Research Record 1547*. pp. 89-95.

Illinois Department of Transportation. (2002). *Standard Specifications for Road and Bridge Construction*. (accessed online through www.dot.state.il.us/default.asp on April 24, 2007)

MacGregor, Jennifer A.C., et al. (1999). Structural Numbers for Reclaimed Asphalt Pavement Base and Subbase Course Mixes. *Transportation Research Record 1687*. pp. 22-28.

Maher, M.H., et al. (1997). Recycled Asphalt Pavement as a Base and Sub-Base Material. *ASTM Special Publication 1275*. pp. 42-53.

Missouri Asphalt Pavement Association (MAPA) website. *Recycling of Asphalt Pavement*. (accessed online at www.moasphalt.org/facts/environmental/recycling.htm on July 12, 2007).

Mokwa, Robert L, and Peebles, Cole S. (2005). Evaluation of the Engineering characteristics of RAP/Aggregate Blends. *Final Report*. (accessed online at www.mdt.mt.gov/research/docs/research_proj/rap_aggregate/final_report.pdf on July 12, 2007).

Mokwa, Robert L, and Peebles, Cole S. (2006). Strength, Stiffness and Compressibility of RAP/Aggregate Blends. *Pavement Mechanics and Performance – GeoShanghai International Conference*. pp. 247-255.

Montana Department of Transportation. *Implementation Plan: Evaluation of the Engineering Characteristics of RAP/Aggregate Blends*. (accessed online through http://www.mdt.mt.gov/research/projects/mat/rap_aggregate.shtml on November 21, 2007).

New Jersey Department of Transportation. (2001). *Standard Specifications for Road and Bridge Construction*. (accessed online through www.state.nj.us/transportation/ on May 1, 2007).

Papp, W.J., et al. (1998). Behavior of Construction and Demolition Debris in Base and Subbase Applications. *Geotechnical Special Publication, No. 79*. pp. 122-135.

Sayed, S.M., et al. (1993) Construction and Performance of Shoulders Using *UNRAP* Base. *Journal of Materials in Civil Engineering, Vol. 5, No. 3*. pp. 321-338.

Taha, Ramzi, et al. (1999). Evaluation of Reclaimed Asphalt Pavement Aggregate in Road Bases and Subbases. *Transportation Research Record 1652*. pp. 264-269.

Trzebiatowski, Bert D. and Benson, Craig H. (2005). Saturated Hydraulic Conductivity of Compacted Recycled Asphalt Pavement. *Geotechnical Testing Journal, Vol. 28, No. 5*. (accessed online through www.astm.org on May 18, 2007).

Viyanant, C., et al. (2004). Compaction Control of Crushed Concrete and Recycled Asphalt Pavement Using Nuclear Gauge. *Geotechnical Engineering for Transportation Projects*. Pp. 958-966.

Washington State Department of Transportation (WSDOT). *Pavement Guide Interactive*. Module 7, Chapter 6, Nuclear Density Gauge. (accessed through CD-ROM).

WSDOT. *State DOT Search Engine* website. (accessed at http://www.google.com/coop/cse?cx=006511338351663161139%3Acnk1qdck0dc)

Interviews

Andersen, Tim. Minnesota Department of Transportation Grading and Base Engineer. Contact Info: tim.andersen@dot.state.mn.us; 651.366.5455. Contacted June 14, 2007.

Aschenbrener, Tim. Colorado Department of Transportation Materials/Geotechnical Engineer. Contact Info: tim.aschenbrener@dot.state.co.us; 303.398.6501. Contacted June 15, 2007.

Bennert, Tom. Rutgers University. Contact Info: bennert@eden.rutgers.edu. Contacted May 28, 2007.

Beshears, Shelia. Illinois Department of Transportation Geotechnical Engineer. Contact Info: 217.782.7086. Contacted April 30, 2007.

Biel, Tim. Utah Department of Transportation Materials Engineer. Contact Info: tbiel@utah.gov; 801.965.4859. Contacted June 13, 2007.

de Dios, Roberto. Colorado Department of Transportation Pavement and Materials Research Engineer. Contact Info: roberto.dedios@dot.state.co.us; 303.757.9975. Contacted June 15, 2007).

Horhota, David. Florida Department of Transportation Geotechnical Materials Engineer. Contact Info: david.horhota@dot.state.fl.us; 352-955-2924. Contacted April 26, 2007.

Sheehy, Eileen. New Jersey Department of Transportation Materials Engineer. Contact Info: Eileen.Sheehy@dot.state.nj.us; 609.530.2307. Contacted May 25, 2007.

Strizich, Matt. Montana Department of Transportation Materials Engineer. Contact Info: mstrizich@mt.gov; 406.444.6297. Contacted April 20, 2007.