Virginia Center *for* Transportation
INNOVATION
& RESEARCH

Feasibility of Reclaimed Asphalt Pavement (RAP) Use As Road Base and Subbase Material

http://www.virginiadot.org/vtrc/main/online_reports/pdf/15-r6.pdf

EDWARD J. HOPPE, Ph.D., P.E.
Associate Principal Research Scientist

D. STEPHEN LANE
Associate Principal Research Scientist

G. MICHAEL FITCH, Ph.D.
Associate Principal Research Scientist

SAMEER SHETTY
Engineering Associate

Final Report VCTIR 15-R6

VIRGINIA CENTER FOR TRANSPORTATION INNOVATION AND RESEARCH
530 Edgemont Road, Charlottesville, VA 22903-2454

www.VTRC.net

Standard Title Page—Report on State Project

<table>
<tr><td rowspan="2">Report No.:
VCTIR 15-R6</td><td rowspan="2">Report Date:
January 2015</td><td rowspan="2">No. Pages:
40</td><td>Type Report:
Final</td><td>Project No.:
RC00080</td></tr>
<tr><td>Period Covered: March–June 2014</td><td>Contract No.:</td></tr>
<tr><td colspan="4">Title:
Feasibility of Reclaimed Asphalt Pavement (RAP) Use As Road Base and Subbase Material</td><td rowspan="3">Key Words:
RAP, reclaimed asphalt pavement, unbound, base, subbase, road</td></tr>
<tr><td colspan="4">Authors:
Edward J. Hoppe, Ph.D., P.E., D. Stephen Lane, G. Michael Fitch, Ph.D., and Sameer Shetty</td></tr>
<tr><td colspan="4">Performing Organization Name and Address:
Virginia Center for Transportation Innovation and Research
530 Edgemont Road
Charlottesville, VA 22903</td></tr>
<tr><td colspan="5">Sponsoring Agencies' Name and Address:
Virginia Department of Transportation
1401 E. Broad Street
Richmond, VA 23219</td></tr>
<tr><td colspan="5">Supplementary Notes:</td></tr>
</table>

Abstract:

The purpose of this study was to investigate the current state of the practice with regard to the use of reclaimed asphalt pavement (RAP) material for road base and subbase applications and the potential for such use by the Virginia Department of Transportation (VDOT). To achieve the objectives of the study, a comprehensive review of the literature was conducted and the current state of the practice by other state departments of transportation was analyzed.

The results indicated that the use of RAP in road base and subbase materials is viable and has been implemented by a number of transportation agencies. There seemed to be no major environmental concerns associated with using unbound RAP without chemical stabilization agents. Numerous sources of RAP are available in Virginia.

Based on practices adopted by other state transportation agencies, the study recommends that VDOT allow the use of RAP in a road base material on highway construction projects. The study further recommends that the allowable percentage of RAP in a blend be phased in gradually to allow VDOT to gain familiarity with the materials and processes involved. Compaction testing could be performed with current methods while alternative procedures were analyzed for suitability. Once a standard specification has been developed, sites for long-term field studies will be identified to implement further the recommendations stemming from this study.

There is a potential for significant economic benefits if RAP is used in base and subbase applications. Approximately 30% in material cost savings could be realized with a 50/50 blend of RAP and virgin aggregate. In addition, this application would likely result in a substantial reduction in the amount of RAP material currently stockpiled in Virginia.

FINAL REPORT

FEASIBILITY OF RECLAIMED ASPHALT PAVEMENT (RAP) USE AS ROAD BASE AND SUBBASE MATERIAL

Edward J. Hoppe, Ph.D., P.E.
Associate Principal Research Scientist

D. Stephen Lane
Associate Principal Research Scientist

G. Michael Fitch, Ph.D.
Associate Principal Research Scientist

Sameer Shetty
Engineering Associate

Virginia Center for Transportation Innovation and Research
(A partnership of the Virginia Department of Transportation
and the University of Virginia since 1948)

Charlottesville, Virginia

January 2015
VCTIR 15-R6

DISCLAIMER

The contents of this report reflect the views of the authors, who are responsible for the facts and the accuracy of the data presented herein. The contents do not necessarily reflect the official views or policies of the Virginia Department of Transportation, the Commonwealth Transportation Board, or the Federal Highway Administration. This report does not constitute a standard, specification, or regulation. Any inclusion of manufacturer names, trade names, or trademarks is for identification purposes only and is not to be considered an endorsement.

ABSTRACT

The purpose of this study was to investigate the current state of the practice with regard to the use of reclaimed asphalt pavement (RAP) material for road base and subbase applications and the potential for such use by the Virginia Department of Transportation (VDOT). To achieve the objectives of the study, a comprehensive review of the literature was conducted and the current state of the practice by other state departments of transportation was analyzed.

The results indicated that the use of RAP in road base and subbase materials is viable and has been implemented by a number of transportation agencies. There seemed to be no major environmental concerns associated with using unbound RAP without chemical stabilization agents. Numerous sources of RAP are available in Virginia.

Based on practices adopted by other state transportation agencies, the study recommends that VDOT allow the use of RAP in a road base material on highway construction projects. The study further recommends that the allowable percentage of RAP in a blend be phased in gradually to allow VDOT to gain familiarity with the materials and processes involved. Compaction testing could be performed with current methods while alternative procedures were analyzed for suitability. Once a standard specification has been developed, sites for long-term field studies will be identified to implement further the recommendations stemming from this study.

There is a potential for significant economic benefits if RAP is used in base and subbase applications. Approximately 30% in material cost savings could be realized with a 50/50 blend of RAP and virgin aggregate. In addition, this application would likely result in a substantial reduction in the amount of RAP material currently stockpiled in Virginia.

FINAL REPORT

FEASIBILITY OF RECLAIMED ASPHALT PAVEMENT (RAP) USE AS ROAD BASE AND SUBBASE MATERIAL

Edward J. Hoppe, Ph.D., P.E.
Associate Principal Research Scientist

D. Stephen Lane
Associate Principal Research Scientist

G. Michael Fitch, Ph.D.
Associate Principal Research Scientist

Sameer Shetty
Engineering Associate

INTRODUCTION

The recycling of asphalt pavement has become a common practice in the transportation industry. Motivations for recycling typically include the environmental, economic, and social benefits. The use of reclaimed asphalt pavement (RAP) in roadway construction fits with the global objective of sustainable development by the prudent use of natural resources. RAP recycling activities address the issues of reducing use of declining virgin aggregate sources and material storage and disposal of reclaimed asphalt material from paving projects. Further, energy savings can be realized through the use of RAP in roadway construction by reducing the processing and haulage of virgin aggregate materials. Other factors include potentially faster project completion and reduction in construction-related traffic, resulting in less disruption to the traveling public.

For many years, the Virginia Department of Transportation (VDOT) has been at the forefront of research into the increased use of RAP in hot-mix asphalt (HMA) mixtures. It is commonly recognized that using RAP in HMA is a very effective recycling approach. At present, the maximum RAP content allowed by VDOT in asphalt mixtures is 30%. Despite the current recycling efforts, RAP stockpiles in Virginia continue to grow in size. As a consequence, additional uses for the excess material need to be considered. This study was initiated to explore potential alternative applications of RAP in a high-quality use as base or subbase material for roads.

PURPOSE AND SCOPE

With the ever-increasing amounts of stockpiled RAP material, the search for potential alternative recycling applications has intensified. VDOT recognized the importance and urgency of this issue in its *Business Plan for FY14– FY15* (VDOT, 2013). Goal 4 of VDOT's environmental stewardship includes the task of investigating other recycling uses of RAP (Action Item 4.1.4, Objective 4.1).

The purpose of this study was to address Action Item 4.1.4, Objective 4.1, of VDOT’s *Business Plan for FY14-FY15*. The scope of the study was limited to the feasibility of using RAP as base and subbase material in roadway construction. The study focused on the current state of the practice in other transportation agencies.

METHODS

Three tasks were carried out to achieve the study objective:

1. *A literature review was conducted on the current state of the practice with respect to the use of RAP as a base and/or subbase material and the implications of its use.* The review focused on peer-reviewed research and literature sources and was followed up by direct communication with representatives of select departments of transportation (DOTs). Search tools included Engineering Index, TRISWorld, Mechanical and Transportation Engineering Abstracts, and VDOT OneSearch databases.

2. *Specifications by select transportation agencies were analyzed and examined for their potential applicability to VDOT operations.*

3. *Existing source stockpiles of RAP material in Virginia were surveyed, and VDOT’s historical RAP usage was determined.* The information was used to assess the general quantities, types, and availability of RAP within Virginia localities. Mapping of stockpiles was carried out to identify feasible applications by region.

RESULTS

Literature Review

Overview

Over the years, the spiraling costs of asphalt pavement manufacturing have resulted in the increased demand for recycling. Since the 1970s, the Federal Highway Administration (FHWA) has been promoting efficient re-use of RAP materials (Copeland, 2011).

The principal factors behind recycling efforts include reduction of construction waste, preservation of non-renewable natural resources, and lower energy costs. Typically, economic savings and environmental benefits of using recycled materials are balanced by the performance requirements of pavement design. It is commonly acknowledged that the use of recycled construction materials to the maximum extent possible should be carried out in the overall context of maintaining a cost-effective, high-quality, well-performing, and environmentally sound pavement infrastructure.

More than 90% of U.S. roads are constructed with HMA, and as the pavement infrastructure ages, there is a growing need to maintain and rehabilitate these roads. In principle, the same materials used to build the original highway system can be re-used to repair, reconstruct, and maintain it. Integral to pavement maintenance is the milling of the aged asphalt pavement during resurfacing, rehabilitation, and reconstruction operations. The RAP produced in the milling operations is a granular material consisting of the original aggregates from the mixture along with aged asphalt binder.

Although the principal use of RAP is in the production of new asphalt concrete mixtures, there is currently an excess supply of RAP in certain parts of Virginia that could be used in other highway applications where granular materials are needed.

Collins and Ciesielski (1994), in an NCHRP Synthesis of Highway Practice, noted that highway agencies have been proactive in the recycling of reclaimed and byproduct materials into construction materials, with RAP being the material most frequently used. In addition to its use in asphalt mixtures, they identified unbound base and subbase as "proven" applications for RAP, with grading identified as the limiting factor for use. Although 49 states indicated they used RAP, the primary use was in asphalt concrete. Thirteen states, including Virginia, indicated RAP use in base materials; four states used RAP in subbase material, and RAP was used in stabilized base and shoulder aggregate, each in two states. Overall, the performance of granular base and subbase layers containing RAP material has been characterized as satisfactory to excellent (Collins and Ciesielski, 1994).

In a more recent study, Saeed (2007) indicated that 16 state DOTs allowed the use of 100% RAP as aggregate in unbound pavement layers and 5 DOTs restricted the use of RAP to 50% or less by weight.

Aggregate Base and Subbase Material Properties

Subbase is the layer of aggregate material placed directly on the subgrade. Its role is to reduce and spread traffic loads evenly over the subgrade. The quality of subbase material is important to the pavement service life as it provides a foundation for the overlying pavement layers. The materials may be either unbound granular or bound, depending on the requirements for the layer. Base course material, consisting of a specific type of aggregate, is placed on top of the subbase. It supports the bound pavement layer.

According to Tutumluer (2013), some of the most important material characteristics affecting the unbound aggregate behavior include the following:

- mineralogy
- particle size distribution (grading) and fines content
- particle shape, surface texture, and angularity
- durability (soundness, abrasion resistance).

These characteristics play out during construction by affecting the workability of the mixture and controlling the degree of compaction (density) and pore structure of the layer. These in turn impact the layer strength, stability (resistance to deformation), and modulus (stiffness) properties that are relevant to performance and design (Tutumluer, 2013).

Standard methods such as sieve analysis, sulfate soundness, and Los Angeles impact and abrasion are used to assess the suitability of materials for use in granular base applications, but grading is the only universally common method applied by the various states (Tutumluer, 2013). Generally, subbase materials tend to be more coarse-graded than granular base. Both materials are designed to provide the required bearing capacity and drainage for the pavement structure. They are essential to long-term pavement performance.

Index tests such as the California bearing ratio (CBR) and the Hveem R-value are commonly used to characterize the shear strength, resilient modulus, and deformation characteristics of granular layers (Tutumluer, 2013); however, VDOT relies on particle size grading to provide an empirical estimate of layer properties for design purposes in addition to material quality characteristics such as abrasion and soundness. Subbase and aggregate base materials are covered in Section 208 of VDOT's *Road and Bridge Specifications* (VDOT, 2007). VDOT also has requirements for Atterberg limits, soundness, abrasion loss (Los Angeles), and flat and elongated particles as quality measures of these materials.

Section 208 does not include RAP and provides for three sizes of dense-graded aggregate, i.e., 21A, 21B, and 22, with the distinction between sizes being that 21B is somewhat coarser than 21A and 22 is finer than 21A (VDOT, 2007). The VDOT grading ranges are provided in Table 1 along with highway base and subbase grading from ASTM D2940 (ASTM, 2009c) for comparison. The VDOT specification further classifies aggregate base into two types, with the requirement that Type I material have at least 90% by weight of the material retained on the No. 10 sieve having at least one fractured face.

The condition classifications used in Table 2 follow the AASHTO *Guide for Design of Pavement Structures* (AASHTO, 1993b). Generally, locations in Virginia fall into the H (High) moisture and F (Freezing) conditions. With the exception of the criteria for the Micro-Deval test (ASTM, 2010b), the values appear to be a reasonable starting point for consideration, subject to further study. The suggested limits for Micro-Deval test results seem overly restrictive at the high-performance end and too loose at the low-performance end.

In a study focused on Virginia aggregates, Hossain et al. (2008) concluded that coarse aggregates with a Micro-Deval test loss under 15% were suitable for all applications including more critical bound layer applications such as HMA and hydraulic cement concretes. In Ontario, Canada, a locale that is subject to high moisture conditions and freezing conditions more severe than in Virginia, the *Provincial Standard Specification* for granular aggregate materials has Micro-Deval test loss limits of 21% for open-graded aggregate, 25% for dense-graded aggregate used as base or road metal, and 30% for subbase material (Ontario Ministry of Transportation, 2003).

Table 1. Grading Range for Dense-Graded Aggregate Base Materials (% passing by weight)

Sieve Size	VDOT 21A	VDOT 21B	VDOT 22	ASTM D2940 Base	ASTM D2940 Subbase
2 in	100	100	---	100	100
1½ in	---	---	---	95-100	90-100
1 in	94-100	85-95	100	---	---
¾ in	---	---	---	70-92	---
3/8 in	63-72	50-69	62-78	50-70	---
No. 4	---	---	---	35-55	30-60
No. 10	32-41	20-36	39-56	---	---
No. 30	---	---	---	12-25	---
No. 40	14-24	9-19	23-32	---	---
No. 200	6-12	4-7	8-12	0-8	0-12

Table 2. Recommended Tests and Performance Levels

<table>
<tr><th rowspan="3">Condition/
Test</th><th>Traffic</th><th colspan="2">H</th><th colspan="2">M</th><th colspan="2">H</th><th colspan="2">L</th><th>M</th><th>L</th></tr>
<tr><th>Moisture</th><th>H</th><th>L</th><th>H</th><th>L</th><th>H</th><th colspan="2">L</th><th colspan="2">H</th><th>L</th></tr>
<tr><th>Temperature</th><th colspan="4">F</th><th colspan="2">NF</th><th>F</th><th colspan="3">NF</th></tr>
<tr><td colspan="2">Micro-Deval (% loss)</td><td colspan="3">< 5</td><td colspan="4">< 15</td><td colspan="2"><30</td><td><45</td></tr>
<tr><td colspan="2">Tube section (dielectric constant)</td><td colspan="3">≤ 7</td><td colspan="4">≤10</td><td colspan="2">≤ 15</td><td>≤ 20</td></tr>
<tr><td rowspan="2">Static triaxial (Max. deviator stress, psi)</td><td>OMC, 5 psi confinement</td><td colspan="3">≥100</td><td colspan="4">≥60</td><td colspan="2">≥25</td><td>Not required</td></tr>
<tr><td>Sat., 15 psi confinement</td><td colspan="3">≥180</td><td colspan="4">≥135</td><td colspan="2">≥ 60</td><td>Not required</td></tr>
<tr><td rowspan="2">Repeated load triaxial (Failure deviator stress, psi)</td><td>OMC, 15 psi confinement</td><td colspan="3">≥180</td><td colspan="4">≥160</td><td colspan="2">≥90</td><td>Not required</td></tr>
<tr><td>Sat., 15 psi confinement</td><td colspan="3">≥180</td><td colspan="4">≥160</td><td colspan="2">≥60</td><td>Not required</td></tr>
<tr><td colspan="2">Stiffness (Resilient modulus, ksi)</td><td colspan="3">≥60</td><td colspan="4">≥40</td><td colspan="2">≥25</td><td>Not required</td></tr>
</table>

Sources: Saeed, 2008; Saeed and Hammons, 2008.
Traffic: H = >1M equivalent single-axle load (ESAL)/yr; M = 100K-1M ESAL/yr; L = <100K ESAL/yr.; *Moisture:* H = high; L = low; *Temperature:* F = freezing; NF = non-freezing; Max. = maximum; OMC = optimum moisture content; Sat. = saturated.

RAP Stockpiles

Once RAP is delivered to a plant yard, it can be processed in a single pile or segregated based on the source. Some agencies allow only RAP from their projects to be recycled (West, 2010). This limitation is used to control aggregate and binder quality. Most agencies allow the use of RAP from multiple sources, including 'unclassified RAP' that has been combined and processed into a single stockpile. This practice is usually allowed with the stipulation that appropriate aggregate properties meet the required specifications. Some agencies also impose a requirement that no additional material can be added to a stockpile once it is built and tested. A more common approach is to allow stockpiles to be continuously replenished with new material. Delivery of consistent material over time requires regular testing and analysis of RAP samples. Typically, millings from a single project are consistent in gradation, asphalt content, aggregate properties, and binder properties. Currently, there are processes and techniques available to achieve uniform RAP composition from multiple sources.

As with virgin aggregates, there is the potential for segregation of RAP material placed on stockpiles. This is a common problem when stockpiles are built using fixed conveyors that allow particles to drop long distances. The problem can be minimized by using indexing-type conveyors that extend and raise the discharge point as the size of the stockpile increases.

RAP Properties and Behavior

RAP composition is typically characterized using applicable material standards. For example, EN 13108-8: European Standard for Reclaimed Asphalt (European Committee for Standardization, 2005) allowing the use of RAP in the production of new HMA includes the following requirements:

- content of foreign matter
- type of binder
- binder content
- binder properties
- aggregate grading
- maximum particle size
- no tar in the reclaimed asphalt.

Based on laboratory test results, Saeed (2008) reported the following regarding the applicability of RAP in unbound applications.

- *Toughness test.* Results indicate that RAP blends are appropriate for use in high-traffic areas with nonfreezing temperatures or in low and medium traffic areas in freezing climates with low moisture conditions.

- *Frost susceptibility test.* Results indicate RAP blends are appropriate for use in high traffic conditions.

- *Static triaxial test.* Results indicate that RAP is appropriate for use in high traffic areas in nonfreezing temperatures, medium traffic in freezing temperatures in the presence of low moisture, and low traffic areas in freezing temperatures.

- *Repeated loading triaxial test.* Results indicate that RAP is generally appropriate for use on medium traffic areas in nonfreezing temperatures and in low traffic areas.

- *Stiffness test.* Results indicate that RAP blends can be used in high traffic areas in nonfreezing temperatures and in medium and low traffic areas in freezing conditions.

Gradation

RAP is composed of crushed or milled asphalt concrete and as such is analogous to an aggregate produced by crushing stone that happened to be an asphalt-cemented conglomerate. Individual particles will range from those composed wholly of the original coarse aggregate of the asphalt concrete with some adhering asphalt cement and mineral fines to particles composed of the asphalt concrete matrix, agglomerations of fine aggregate, mineral fines, and asphalt

cement. The mix of particles present in the RAP will depend on the nature of the asphalt concrete from which it was produced: open- or dense-graded, coarse or fine, etc.
The gradation of RAP material is comparable to that of a crushed natural aggregate, but, depending on milling and stockpiling operations, it may contain a higher content of fines, with a reported typical range being rather broad (Chesner et al., 2008). In many respects, the physical properties of RAP are similar to those of crushed limestone (Ontario Hot Mix Producers Association, 2010).

Strength and Stiffness

Particles of original coarse aggregate can be presumed to have good strength and be resistant to deformation, whereas agglomerations of fine aggregate and asphalt mastic may tend to be brittle or malleable depending on the asphalt condition (age and oxidation) and temperature.

Bennert et al. (2000) reported that 100% RAP specimens have higher stiffness, higher resilient modulus values, and lower shear strengths than dense-graded aggregate base course specimens. Even though RAP is stiffer than the dense-graded aggregate base course, 100% RAP material accumulates the greatest amount of permanent strain. Several studies have shown relatively high resilient modulus values for RAP, accompanied by large permanent deformations. Bennert et al. (2000) reported that the resulting contrast between the 100% RAP resilient modulus and its permanent deformation might be attributable to the progressive breakdown of asphalt binder under loading. Dong and Huang (2014) also indicated that RAP materials tended to have a higher resilient modulus and larger permanent deformations when tested as unbound aggregates. Triaxial creep test results demonstrated viscous properties and temperature dependency of unbound RAP base mixture. Locander (2009) reported that the shear strength decreases as the quantity of RAP increases. Taha et al. (1999) indicated that the presence of RAP results in the lower bearing capacity of the material as compared to virgin aggregates.

In a study of recycled aggregates for use in unbound subbase, Ayan (2011) reported a decrease in CBR values with increasing RAP content. The results were attributed to sliding of the bitumen-coated aggregates over each other under the load application. Performance was satisfactory with the 50/50 mixture of RAP and recycled concrete aggregate (RCA). The study recommended that shear strength measurements be carried out using a large direct-shear box apparatus. A laboratory and field evaluation of aggregate blends, including RCA, in pavement subbases concluded that RAP/RCA mixture with 15% RAP content meets the repeated load triaxial requirements for use in pavement subbase layers in Australia (Arulrajah et al., 2014). The best results were achieved at moisture contents of 59% to 78% of the optimum value. However, the CBR results for this blend were marginally lower than the required design value of 80.

A study of geotechnical and geoenvironmental properties of construction and demolition waste conducted by Arulrajah et al. (2013) indicated that pure RAP does not meet the CBR and repeated load triaxial test requirements to qualify as an unbound subbase material in Australia. The test provides resilient modulus / permanent deformation parameters that describe the material response to traffic loading. These parameters are used as input to the design and analysis of pavements (AustRoads, 2004). The study recommended blending RAP with high-quality aggregates to achieve the required strength and deformation requirements. Bennert and Maher (2005) confirmed the general trend of larger permanent deformations and lower CBR values as the RAP content was increased in the granular mixture. The authors recommended that RAP blended with virgin aggregate be limited to 50% by weight.

Cosentino et al. (2012) reported that all granular blends containing RAP exhibited some amount of creep. The study recommended that unstabilized RAP material be blended with a minimum of 75% approved aggregate for use in traffic base applications. Alternatively, blends should be proportioned so that the asphalt binder content does not exceed 1.5% by weight. In a study of material properties, Bleakley and Cosentino (2013) concluded that granular RAP and limerock mixtures without a stabilizing agent can meet the strength and creep requirements for base course if blended up to a maximum of 25% RAP and 75% limerock. Blends with a maximum of 50% RAP may be used with a chemical stabilizing agent, such as cement. The amount and type of the stabilizing agent should be determined by a mix design method that results in a blend that meets the required performance specifications.

McGarrah (2007) examined published studies on the properties of RAP blends used in unbound base applications and concluded that 100% RAP does not produce a product of adequate base course quality and should not be allowed. As the RAP content increased, the shear strength of the blend decreased below the required level. McGarrah recommended limiting the RAP content to 25% and blending RAP with the virgin aggregate at the mixing plant. Onsite blending was found to be unsatisfactory, resulting in base course separation into lenses. Dong and Huang (2014) recommended that no 100% unbound RAP base be used under asphalt pavements. Schaefer et al. (2008) concluded that 20% to 50% RAP content is typically used in actual construction.

Ooi (2010) concluded that limiting RAP to 50% may be prudent as long as the material meets all other requirements in the specifications that a virgin aggregate would satisfy. In addition, Ooi recommended minimum CBR values of 80 and 60 for base and subbase aggregate blends, respectively. The intent was to provide performance specifications expressed in terms of CBR test results.

Sayed et al. (2011) reported on Florida field installations of 100% RAP as unbound base aggregate for temporary roadways with positive results. Although limited by the relatively short length of the study period, they found that the performance of the unbound RAP base was at least equivalent to that of control sections constructed with limerock base. Although RAP base material is suitable in a wide range of grain-size distributions, dense gradings provide improved performance. The authors also indicated that falling weight deflectometer and Dynaflect testing methods are suitable for measuring field performance. Standard sampling and testing procedures were recommended, along with a structural coefficient of 0.12 to 0.15 for RAP base (Sayed et al., 2011); however, the authors indicated that tests such as the Florida limerock bearing ratio (and by implication, CBR) may not be relevant for assessing RAP field performance. The authors stated: “In summary, the data suggest that UNRAP [unbound RAP] is a viable alternate materials for base courses, but are we ready for it.”

Binder

Over time, asphalt binders in RAP undergo oxidation, which results in age hardening (Roberts et al., 1996). This change in chemical properties can influence the unbound layer stiffness and shear strength and potentially decreases the resistance to rutting and fatigue cracking.

Compaction

Malleable or brittle particles can lead to post-compaction deformations of the base or subbase layer if sufficient densification is not achieved during construction, which may be the cause of permanent strains sometimes reported when RAP was used as base material. Although construction methods for RAP are generally similar to those for conventional granular materials, field testing of moisture content and density by nuclear gauges is greatly affected by the presence of hydrogen ions in RAP material and requires using correction factors or resorting to other methods of quality control.

The presence of asphalt reduces the amount of water needed to achieve the required compaction level of the RAP mixture, because of the surface coating of stone particles (Stroup-Gardiner and Wattenberg-Komas, 2013). This factor has to be considered when the suitable moisture content for compaction is determined. Locander (2009) observed that as the RAP fraction of the base layer increases, the optimum moisture content (OMC) required to achieve compaction decreases. This trend was confirmed by Guthrie et al. (2007), who found that the increase in RAP content leads to a decrease in the maximum dry density and OMC values.

Observations by the Minnesota DOT (Mn/DOT) indicated that the standard Proctor test does not provide sufficient energy to achieve adequate compaction of RAP blends (J. Siekmeier, personal communication). Kim et al. (2007) reported that the gyratory compaction test method provided a closer correlation with field density measurements than the standard Proctor test. When compared to the Proctor test, gyratory compaction test results showed a large difference in the maximum dry density and a small difference in the OMC. As the RAP content of the blend increased, the OMC decreased for both test methods.

Drainage

RAP tends to behave as a strongly hydrophobic material. With regard to soil-water characteristic curves, RAP exhibited the best ability to drain water when compared to other recycled and natural aggregates (Edil et al., 2012). As a result, RAP is expected to provide more efficient subsurface drainage as compared to hydrophilic materials having the same pore size.

In a study designed to evaluate the suitability of using RAP as an additive to crushed angular aggregate or pit-run granular soils, Mokwa and Peebles (2005) concluded that the use of RAP mixtures in base and subbase courses is viable. The permeability of RAP blends reportedly increased as the percentage of asphalt millings was increased, indicating improved drainage properties.

Volume Change

Volume expansion of RAP material may be a factor if steel slag aggregates are present. These aggregates are used to improve frictional characteristics of the HMA surface course. Considerable volume change has been attributed to the hydration of calcium and magnesium oxides in the recycled steel slag (Collins and Ciesielski, 1994). The potential for expansion depends on the origin of the slag, grain size distribution, and age of the stockpile (Rohde et al., 2003). The expansive characteristics can be assessed by conducting tests in accordance with ASTM D4792 (ASTM, 2013) on the aggregate material. Additional petrographic and chemical analysis of the RAP material can be performed to assess field performance (Deniz et al., 2009).

Proposed Tests

Currently, there are no accepted national specifications for the use of RAP as unbound base materials in the United States (Edil, 2011). ASTM Subcommittee D18.14 on Geotechnics of Sustainable Construction is tasked with developing ASTM WK26824: *Specifications for Recycled Asphalt Pavement Materials for Base or Subbase for Highway or Airports* (ASTM, 2010a).

Saeed and Hammons (2008) recommended the following tests to characterize the field performance of RAP mixtures:

- screening tests (sieve analysis and moisture-density relationship)
- toughness (Micro-Deval test)
- stiffness (resilient modulus test)
- shear strength (static triaxial and repeated loading at OMC and saturated conditions)
- frost susceptibility (tube suction test).

Potential Stabilization Techniques

Typical stabilization techniques available for use with granular materials in highway construction can also be used with RAP. The selection will depend on the characteristics of the RAP material and the demands of the end use. Mechanical (compaction, geotextiles), chemical, and cementitious (including hydraulic, pozzolanic, and bituminous cements) stabilization methods are all potentially viable.

Improving Grading Deficiencies

Apart from site-specific geotechnical and anticipated traffic loading issues, grading is the most important factor influencing the need for stabilization of RAP. RAP that is deficient in fines (<No. 200 sieve) can be difficult to compact and can be blended with fine soil, mineral fines, or fly ash to improve the grading characteristics. In addition to improving the workability of the material, fines create an internal pore structure in the compacted material that improves strength through capillary suction. If sufficient fines are already present in the RAP mixture, simple chemical humectants such as calcium chloride or sodium chloride may provide adequate stabilization.

Addressing Plasticity

If the fines present in the RAP or blending material are plastic, common stabilizers such as lime, lime or cement kiln dusts, or portland cement may be appropriate. ASTM D4609 (ASTM, 2008a) provides general guidance on evaluating the effectiveness of materials for use in stabilizing soils. In Section 240 of VDOT's *Road and Bridge Specifications*, VDOT (2007) specifies that lime for use in soil stabilization should satisfy the requirements of AASHTO M 216 (AASHTO, 2013a) (ASTM C977) (ASTM, 2009b). ASTM D5050 (ASTM, 2008b) provides guidance on evaluating lime kiln and cement kiln dusts for use in stabilization with or without fly ash.

Cementitious Stabilization

Where higher strength levels are needed and/or the fines content is low, portland cement can be used to provide cementitious stabilization. Similar stabilizing benefits can be achieved by using pozzolanic fly ash or other pozzolans with lime or portland cement (or other activators) or with a self-cementing fly ash. VDOT (2007) requires that fly ash for use with lime in stabilization meet the requirements of ASTM C593 (ASTM, 2011a). ASTM C821 (ASTM, 2009a) is a specification for lime for use with pozzolans and may be more appropriate than AASHTO M 216 (AASHTO, 2013a) (ASTM C977) (ASTM, 2009b) to use for lime in lime–fly ash stabilization when pozzolanic activity is intended. Fly ashes from coal-fired power plants generally fall into two categories: pozzolanic or self-cementing (high CaO content). ASTM D5239 (ASTM, 2012) provides a protocol for characterizing fly ashes intended for use in stabilizing soils. To date, self-cementing fly ashes have not been available in Virginia. However, ASTM D7762 (ASTM, 2011b) provides a design methodology for using self-cementing fly ash for soil stabilization should this situation change.

Little and Nair (2009) developed a methodology for the design and selection of stabilization methods for base materials. The focus was on more common practices, such as portland cement and lime-pozzolan stabilization. Asphalt cement is an alternative for open-graded materials, covered in Section 313 of VDOT's *Road and Bridge Specifications* (VDOT, 2007). Recently, the focus on full-depth reclamation processes has sparked interest in the use of foamed-asphalt stabilization (Schwartz et al., 2013).

Miscellaneous RAP Stabilization Studies

Ganne (2009) examined the feasibility of stabilizing Texas RAP materials with portland cement and self-cementing fly ash. Three RAP materials from different locations in Texas were blended in varying percentages with virgin aggregate material. The RAP-base blends were stabilized with varying percentages of portland cement or self-cementing fly ash. The mixtures were evaluated based on unconfined strength and volume stability in a wetting-drying test. Optimal performance was provided by the 75% RAP mixture stabilized with portland cement at 4%. The self-cementing fly ash mixtures exhibited excessive volume change in the wetting-drying test.

A recent study indicated that the stability of RAP aggregate base and subbase mixtures can be markedly improved by adding sawdust ash (Osinubi and Edeh, 2011). This material is a byproduct of burning sawdust. It is normally disposed of at a landfill site.

The addition of fly ash was found to increase the resilient modulus of RAP mixtures (Carmargo et al., 2009). The modulus increased with curing time, with the largest rate of increase taking place between 7 and 28 days of curing. The effectiveness of fly ash is typically less than for a similarly stabilized virgin aggregate.

Bleakley and Cosentino (2013) concluded that blends of 50% RAP and 50% limerock can be effectively stabilized with asphalt liquid emulsion. The resulting mixture had soaked limerock bearing ratio strengths exceeding 100 and acceptable 30-year creep deformations. Similar results were achieved with portland cement stabilization. The addition of 2% to 3% of cement by weight yielded satisfactory strength and deformation properties of the stabilized RAP.

Cosentino et al. (2012) recommended that the asphalt binder content of a blend stabilized with asphalt emulsion not exceed 3.5% by weight. If portland cement is used as a stabilizer, its content should not exceed 2% by weight. Excessive application of cement stabilizer can cause brittle behavior of base material.

In Alaska, base course containing 50% RAP is commonly stabilized with asphalt materials (Li and Liu, 2010). Hot asphalt treatment and emulsified asphalt treatment were found to be the most effective.

A study designed to assess the performance of RAP on gravel roads found that a blend of RAP and virgin aggregate can be effectively used for dust control (Koch and Ksaibati, 2010). The recommendations included blending in a pugmill to prevent segregation, compacting with a roller compactor to improve serviceability, and adding calcium chloride to improve dust control properties further.

Thakur (2010) conducted an experimental study on geocell-reinforced RAP bases. This concept was verified by experimental results of cyclic plate testing (Thakur et al., 2012). The research demonstrated satisfactory performance of a novel polymeric alloy geocell infilled with RAP material. A nonwoven geotextile was placed between the subgrade and the geocell base. The study concluded that 100% RAP with geocell confinement can be used as an effective base course material in roadway construction. An example geocell base design for low-volume roads, including the recommended geocell dimension and layer thickness, was documented by Bortz et al. (2011). Creep deformation behavior of geocell-reinforced RAP bases indicated marked improvement as compared with the unreinforced base (Thakur et al., 2013).

Environmental Considerations

There are important environmental benefits associated with the reuse of RAP in HMA including reduced energy consumption and reduced HMA aggregate and asphalt binder use. Similarly, it is well understood that the use of RAP in base and subbase applications has the potential to reduce the use of virgin aggregate material and the energy consumption associated with production of these materials (Copeland, 2011). There are, however, potential contamination concerns related to the use of RAP in base and subbase applications that are not typically associated with the use of RAP in HMA. These concerns are principally related to the leaching of contaminants resulting from the pulverization of the binder of the old asphalt layer as a result of the milling process. New binder added to the HMA mixture containing RAP serves to encapsulate the old binder, reducing the potential for leaching.

Contaminants of Concern for RAP

Contamination concerns associated with the use of unbound RAP are primarily related to pH, polycyclic aromatic hydrocarbons (PAH), and a variety of metals. These metals include aluminum, cadmium, chromium, lead, silver, and selenium.

pH. Arulrajah et al. (2014) reported an average pH level of 7.6 in 100% RAP samples. Shedivy et al. (2012) reported pH levels ranging from 8.59 to 9.58 for leachate from batch leaching tests done on five RAP sources from Ohio, Wisconsin, California, New Jersey, and Colorado. Edil et al. (2012) found pH values between 6.5 and 8.5 in unbound RAP samples. Hoyos et al. (2008, 2011) tested the pH of free water in accordance with ASTM D1287 (ASTM, 2002) by soaking RAP samples for 28 days and found the values to be neutral. Work performed for Mn/DOT found pH levels in RAP leachate at 7.57 and 9.67 for unsaturated leach tests and batch tests, respectively (Gupta et al., 2009; Kang et al., 2011).

Chemical Oxygen Demand (COD). Hoyos et al. (2008, 2011) performed COD analyses in accordance with ASTM D1252 (ASTM, 2006) and found COD values of approximately 60 mg/L, lower than the U.S. Environmental Protection Agency's (U.S. EPA) (2005) stormwater sampling benchmark of 120 mg/L (Hoyos et al., 2011).

Polycyclic Aromatic Hydrocarbons. Laboratory batch leaching tests using both toxicity characteristic leaching procedure (TCLP) (U.S. EPA, 1992) fluid and deionized water performed by Shedivy et al. (2012) on RAP samples resulted in PAH levels (acenaphthalene, benzo(a)anthracene, benzo(b)fluoranthene, benzo(a)pyrene, benzo(ghi)perylene) very close to or below the U.S. EPA drinking water standards. Similarly, Townsend and Brantley (1998) and Brantley and Townsend (1999) found PAH levels below drinking water standards in laboratory leaching tests.

Metals. Numerous leaching studies have been conducted to determine the potential for metals contamination resulting from the use of RAP. Shedivy et al. (2012) conducted leaching tests using EPA Method 1311 (U.S. EPA, 1992) with both TCLP fluid and deionized water. Even when subjected to the lower pH test using TCLP fluid, all metals except manganese and arsenic were below the maximum contaminant level (MCL) concentration for drinking water. Edil et al. (2012) found that concentrations of arsenic, selenium, and antimony were slightly higher than the U.S. EPA MCL for drinking water. Though the leachate collected from Class 5 virgin aggregate (used as a control for the study) had similar concentrations for these three constituents, based on findings of the associated TCLP tests, the authors assumed that these values were the result of leaching from the asphalt binder (Edil et al., 2012).

Kang et al. (2011) performed leachate tests for an extensive list of inorganic chemicals including aluminum, arsenic, barium, beryllium, calcium, cadmium, chromium, copper, iron, lead, lithium, magnesium, manganese, molybdenum, nickel, phosphorus, potassium, rubidium, silicon sodium, sulfur, strontium, titanium, vanadium, and zinc. Based on the results obtained in batch tests using a 1:20 RAP to water ratio, none of the constituents was found in concentrations above applicable U.S. EPA drinking water standards. Leachate tests run by Gupta et al. (2009) on 100% RAP resulted in aluminum, iron, and lead above the U.S. EPA's drinking water standard.

An extensive field evaluation lasting 10 months was performed by Cosentino et al. (2003) on a base constructed of RAP. This was done in conjunction with laboratory leaching tests. Metals including cadmium, chromium, silver, selenium, and lead were determined to pose no runoff contamination threat. Overall, with the use of four different testing protocols, all levels of these metals in the leachate were below the levels in the U.S. EPA drinking water standards (Cosentino et al., 2003).

Work by Townsend and Brantley (1998) and Brantley and Townsend (1999) at the University of Florida using both the TCLP and synthetic precipitation leaching procedure (U.S. EPA, 1994) tests found that leaching from RAP was unlikely to contribute to groundwater contamination under beneficial reuse conditions. This same work did indicate, however, that lead levels were elevated in older RAP, with lead levels above the primary drinking water standard (15µg/l) in the leachate. This was assumed to be the result of the previous use of leaded gasoline.

Contaminants of Concern for RAP with Stabilizing Agents

Because of decreased strength and stiffness concerns related to the use of RAP as a base/subbase material, various stabilizing agents have been tested to determine the increase in these properties. Similar to the RAP material itself, concerns about potential leaching from these stabilizing agents have resulted in numerous and varied leaching tests being conducted in both the laboratory and the field.

pH. A study evaluating the effects of RCA on the RAP was performed by Arulrajah et al. (2014). Samples composed of 50% RAP and 50% RCA had a pH of 11.37, only slightly lower than that for 100% RCA, but much higher than the 7.6 pH reading for 100% RAP. The authors concluded that this increase in pH was the result of the soluble calcium hydroxide being formed because of the hydration reaction from the RCA cement residual (Arulrajah et al., 2014).

Kang et al. (2011) compared varying percentages of fly ash and RAP with virgin aggregate. pH values of the leachate measured as low as 9.7 (5% fly ash + 25% RAP + 70% aggregate) and as high as 10.99 (15% fly ash + 75% RAP + 10% aggregate). The authors went on to explain how inorganic desorption and dissolution from the fly ash are dependent on pH.

Hoyos et al. (2011) also found pH values above 10 in leachate from cement-treated RAP (both 2% and 4%), but they concluded that even with these pH levels, RAP use as a base or subbase would not be directly exposed to extreme weather cycles.

Li et al. (2007) analyzed leachate from RAP containing Class C fly ash. pH readings for leachate collected from a road base constructed using RAP and 10% fly ash ranged from 6.9 to 7.5.

Chemical Oxygen Demand. Hoyos et al. (2008, 2011) found the COD values dropped with the addition of 2% and 4% portland Type I cement. This reduction was said to be attributable to the reduction of the fine materials coming in from the RAP material as a result of the addition of the cementitious material.

Metals. Kang et al. (2011) concluded that up to 5% fly ash and 75% RAP could be combined with 20% aggregate without substantial leaching of metals except aluminum. It was stated that aluminum leaches from the fly ash because of a drop in pH from the addition of the aggregate and RAP, increasing the formation of amorphous $Al(OH_3)$ (aluminum hydroxide) and $CaAl_2(OH)_8 + 6\ H_2O$. It should also be noted that mixtures containing 15% fly ash resulted in considerable leaching initially, leading the authors to postulate that with increased residence time, the RAP mixture containing this level of fly ash may result in leaching above the U.S. EPA drinking water standards (Kang et al., 2011).

Li et al. (2007) blended 10% Class C fly ash to stabilize RAP in the construction of a flexible pavement in Minnesota. Column leaching tests were performed in the laboratory in addition to collecting leachate from field installations. None of the measured chemical constituents associated with health risks was found in levels exceeding U.S. EPA MCLs, but levels of these constituents were increasing throughout the field monitoring period. Because of this upward trend, the authors stated that additional leachate collection and analyses needed to be undertaken.

Selected Practices of Transportation Agencies in the United States and Abroad

Virginia Department of Transportation

Current VDOT specifications do not address the use of RAP in unbound base and subbase layers.

Colorado Department of Transportation

Colorado DOT (CDOT) specifications pertaining to the use of RAP in base materials were developed following the study by Locander (2009), which concluded that RAP may be substituted for unbound aggregate base course. The “Revision of Sections 304 and 703” of the CDOT specifications, dated October 31, 2013 (CDOT, 2013), includes aggregate base course (RAP) as a separate pay item and allows 100% RAP use. The specification includes allowable gradation ranges for various particle sizes. The acceptable field compaction criterion is specified in terms of a wet density of not less than 95% of the maximum wet density when determined in accordance with one-point AASHTO T 180, Method D (AASHTO, 2010).

Federal Aviation Administration

Airport pavements are fundamentally different from highway pavements. Typically, they have comparatively low volume loading. Weathering, raveling, and cracking are the primary distress types. The Federal Aviation Administration (FAA) allows the use of the AASHTO pavement design method (AASHTO, 2013b) for non-primary public use airports, for runways of 5,000 ft or shorter, and for aircraft of 60,000 pounds gross weight and under (FAA, 2011b).

FAA Specification P-401 allows for the use of RAP in HMA pavement mixtures (FAA, 2011a). It further stipulates that RAP should not be used for surface mixtures except on shoulders. It allows the use of RAP only in lower bound layers and for shoulders. Currently, there are no provisions for the use of RAP in the FAA Specification P-154 (subbase course) and in various granular base course specifications, including P-208, P-209, P-210, P-211, P-213, P-217, and P-219.

Florida Department of Transportation

Florida DOT (FDOT) specifications allow the use of up to 100% RAP only for non-traffic base applications, primarily at paved shoulders and bike paths, as described in Section 283 (FDOT, 2013). The use of RAP in roadway base is not allowed (D. Horhota, personal communication). FDOT's main concerns are low bearing capacity and a high potential for long-term creep deformations. Some districts reported excessive settlements when large trucks were parked on the shoulder overnight.

FDOT specifies the use of the nuclear gauge for compaction acceptance of RAP layers. Moisture content is obtained by use of the Speedy moisture tester.

France

The use of RAP in unbound layers is not a common practice in France (F. Delfosse, personal communication). When used in granular base materials, RAP content is typically kept below 30% by weight. Specifications for unbound mixtures, as defined in NF EN 13285 (European Committee for Standardization, 2010), are followed. RAP is widely used in bound pavement layers, including HMA and warm-mix asphalt, and in cold processes involving foam and emulsion.

Germany

Current practice in Germany focuses on RAP recycling in HMA layers (D. Jansen, personal communication). The use of RAP in unbound base layers is allowed, up to 30% by weight (Road and Transportation Research Association, 2012). RAP materials with binders containing coal tar are excluded. Field compaction is usually tested using the lightweight deflectometer or intelligent compaction method.

Hawaii Department of Transportation

Section 720 of the Hawaii DOT specifications currently under consideration for adoption addresses "Reclaimed Asphalt Pavement (RAP) and RAP-made Materials." Up to 10% RAP content by weight is allowed in unbound base courses. Up to 25% RAP can be used in subbase materials. These proposed amounts represent a substantial reduction from the 50% RAP content for base and subbase layers originally recommended in the study conducted by Ooi (2010).

When RAP is stockpiled from previous DOT projects, the engineer in charge may approve the material on the basis of composition. When the composition is unknown, sampling and testing of RAP stockpile are required. Typically, testing involves gradation analysis and the determination of the percentage of deleterious material. A maximum of 3% and 5% deleterious material is allowed in base and subbase courses, respectively. The contractor is required to submit the means and method for uniform mixing of recycled and virgin aggregates. Blending at the job site is not permitted. The contractor is also required to submit the blended aggregate design prior to use or prior to changing either the source or the amount of RAP originally approved.

Idaho Transportation Department

The Idaho Transportation Department (2012) specifies that RAP can be mixed in approximately equal proportions with granular borrow for subbase applications. RAP is defined as salvaged bituminous pavement that may have minor coatings of dust or aggregate particles adherent from the reclamation process, with no discernible seams, pockets, or amounts of untreated aggregate or soil. A maximum RAP size of 3 in is allowed. Field compaction is governed by the use of the roller pattern (Section 300). In-place, uncorrected density readings are obtained from a nuclear gauge. The required compaction is achieved when the final roller pass adds no more than 0.5 lb/ft^3 to the previous in-place density. For payment, RAP is measured as a portion of granular subbase (no additional compensation).

Iowa Department of Transportation

For the Iowa DOT (2014), the processing requirements for aggregates produced from reclaimed materials are essentially the same as for virgin aggregates. Up to 50% RAP is allowed in the granular subbase. In practice, relatively small quantities of RAP material are actually used in unbound layers, as the contractors prefer to blend it back into HMA mixtures (M. Dunn, personal communication).

Minnesota Department of Transportation

Mn/DOT specifications (2014a) allow up to 3.5% bitumen content in granular bases and up to 3.0% in subbases. Sections 2105, 2211, 3138, and 3149 of the specifications address the material requirements for aggregate bases, subbases, and subgrade. The bitumen content is determined by the solvent extraction method (Mn/DOT, 2014b). The extraction method is the Mn/DOT modification of AASHTO T 164.

Mn/DOT selected the Dynamic Cone Penetrometer (DCP) for use in soil testing. Mn/DOT specifies the DCP for compaction acceptance in terms of maximum seating and Dynamic Penetration Index values, as per Table 2211-3 of the Mn/DOT 2014 standard specifications. Allowable values are based on the grading number and moisture content at the time of testing. The grading number is dependent on the fineness modulus using 1 in, ¾ in, 3/8 in, No. 4, No. 10, No. 40, and No. 200 sieves. The choice of DCP method reflects long-term Mn/DOT research efforts on alternative test methods for compaction control (Siekmeier et al., 1999).

Mn/DOT (2014) specifications do not call for the OMC determination of recycled aggregate bases. Instead, target moisture content values are assigned for various classes of materials. The contractors typically use between 10% and 75% RAP in recycled aggregate base (T. Andersen, personal communication). The actual RAP limit is governed by the amount of bitumen content allowed in the mixture. No evidence of pavement distress was reported when the recycled material met the compaction specifications.

Currently, approximately 60% of roadway bases in Minnesota contain RAP material (T. Beaudry, personal communication). The Mn/DOT specification was recently revised upward from 3.0% to 3.5% allowable bitumen content in unbound base layers. Mn/DOT does not require any quality control tests on RAP materials.

New York State Department of Transportation

Section 304 of the New York State DOT (2008) *Standard Specifications* allows "Alternate C" subbase construction using at least 95% reclaimed bituminous material with a maximum top size of 2 in. No soundness or plasticity index tests are required for this alternate. RAP is approved based on a visual inspection by the regional geotechnical engineer. Testing may be required if there is evidence of a substantial amount of flat or elongated particles. Material with a greater than 30% content of flat or elongated particles is rejected. Grain size distribution requirements are waived when the material consists solely of RAP. If in the opinion of the regional geotechnical engineer the material becomes unstable during construction, it may be necessary to add a mixture of virgin aggregate. RAP is not allowed on roads with a high percentage of truck traffic, defined as 10% or more, unless portland cement concrete pavement is used. For interstates and other freeways, *a high percentage of trucks* is defined as a directional design-hour volume of 250 vehicles per hour or more (M. Mathioudakis, personal communication).

North Carolina Department of Transportation

North Carolina DOT (2012) specifications do not address the use of RAP in unbound base and subbase layers.

Oregon Department of Transportation

The Oregon DOT does not have a standard design policy for the use of RAP in unbound layers (J. Moderie, personal communication). Some of the key concerns include quality assurance / quality control testing and temperature-dependent behavior during compaction. On occasion, RAP was allowed in granular base under a thick pavement section.

Texas Department of Transportation

Texas DOT (TxDOT) specifications allow up to 20% RAP by weight in flexible bases (TxDOT, 2004a). RAP material must pass the 2 in sieve. The compaction specifications call for 100% maximum density, as determined by the Tex-113-E laboratory procedure (TxDOT, 2011). The field density of granular materials is verified by a nuclear density gauge. More common, TxDOT uses RAP in cement-treated base layers, where up to 50% RAP by weight is allowed (TxDOT, 2004b). TxDOT has been using RAP in these applications for more than 10 years (J. Si, personal communication).

The Netherlands

In the Netherlands, with a landfill ban on construction and demolition waste, almost 100% of RAP is recycled in road construction. The recycling is focused primarily on base asphalt pavement layers. Current practice does not allow for use of RAP in unbound granular subbase and base layers (J. van der Zwan, personal communication). In contrast, the RCA is commonly used in unbound layers.

United Kingdom

In the United Kingdom, the requirements for unbound mixtures are listed in Series 800 of *Specification for Highway Works* (Department for Transport, 2014). Up to a maximum of 50% RAP by weight is permitted in Type 1 and Type 2 unbound subbase mixtures. Up to 100% RAP is allowed in Type 4 unbound aggregate mixture. The compaction requirements are defined in terms of a number of passes of a specified type of compaction equipment (type and mass) over a specified loose layer thickness (Table 8/4 of the Series 800 specifications). Contractors are allowed to use an alternative method of compaction if they can prove at site trials that the results are equivalent to or better than those using the specified method. The moisture content of the compacted material is specified within the range of 1% above to 2% below the optimum value. *Specification for Highway Works* is primarily used for main roads, but it is widely adopted by local highway authorities (C. Nicholls, personal communication).

Washington State Department of Transportation

Currently, the Washington State DOT (2012) allows up to 20% RAP by weight to be blended with crushed aggregates in the base materials. Gradation and waste material limits are specified for quality control. A nuclear moisture-density gauge is used for acceptance.

Wisconsin Department of Transportation

Wisconsin DOT (WisDOT) specifications allow the use of RAP in any amount for 1¼-in and 3-in dense-graded base courses (WisDOT, 2014). There are restrictions on the use of RAP in ¾-in dense-graded material and in all open-graded materials.

There are some problems reported with the compaction acceptance, despite use of the moisture corrections (J. Peters, personal communication). WisDOT is routinely using nuclear gauges for compaction testing. False high moisture contents were found because of well-documented issues with the presence of hydrocarbons in RAP. To address this problem, WisDOT is allowing the contractor three different methods of determining target density when the base aggregate material contains more than 20% recycled material. The first option is to carry out the conventional procedure using the moisture bias correction. The second option is to base the acceptance on the wet density target value. The third option, which is likely to be adopted by WisDOT, is to construct a control strip and use the average density of the strip as the target density.

RAP Availability in Virginia and Historical RAP Usage by VDOT

RAP Availability in Virginia

In order to characterize the available RAP materials better, a survey of existing source stockpiles throughout the state was undertaken in coordination with VDOT's Materials Division and VDOT's district materials engineers. This information was used to assess the general quantities, types, and availability of RAP within VDOT districts. A map of stockpiles was created to identify feasible applications by region, as shown in Figure 1.

There is approximately 4.7 million tons of RAP stockpiled in Virginia. Almost one-half of the available RAP is located in the Northern Virginia District, followed by the Richmond (21%) and Hampton Roads (12%) districts, as shown in Figure 2. A majority of the asphalt plants with RAP stockpiles had all the necessary and appropriate processing capabilities for blending RAP materials.

Historical RAP Usage by VDOT

Based on the information obtained from VDOT's Materials Information Tracking System/Producer Lab Analysis and Information Detail (MITS-PLAID) and historical HMA databases, the majority of in-service HMA mixtures had 20% or less RAP content, although the VDOT specification currently allows up to 30% (VDOT, 2007). Figure 3 shows the historical RAP usage on VDOT paving projects in the past 5 years (2009-2013). Data indicate that no clear trend in RAP usage can be established.

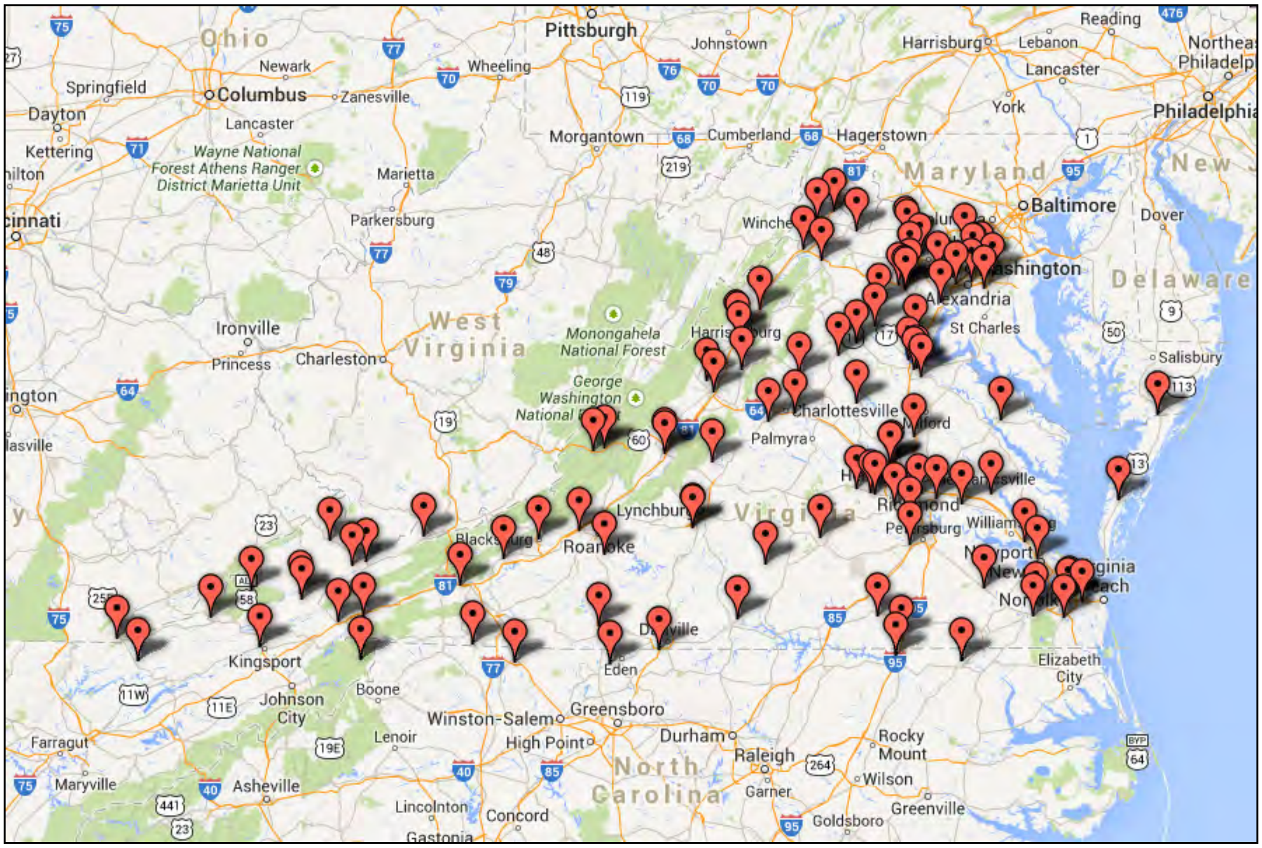

Figure 1. Location of Recycled Asphalt Pavement (RAP) Stockpiles in Virginia

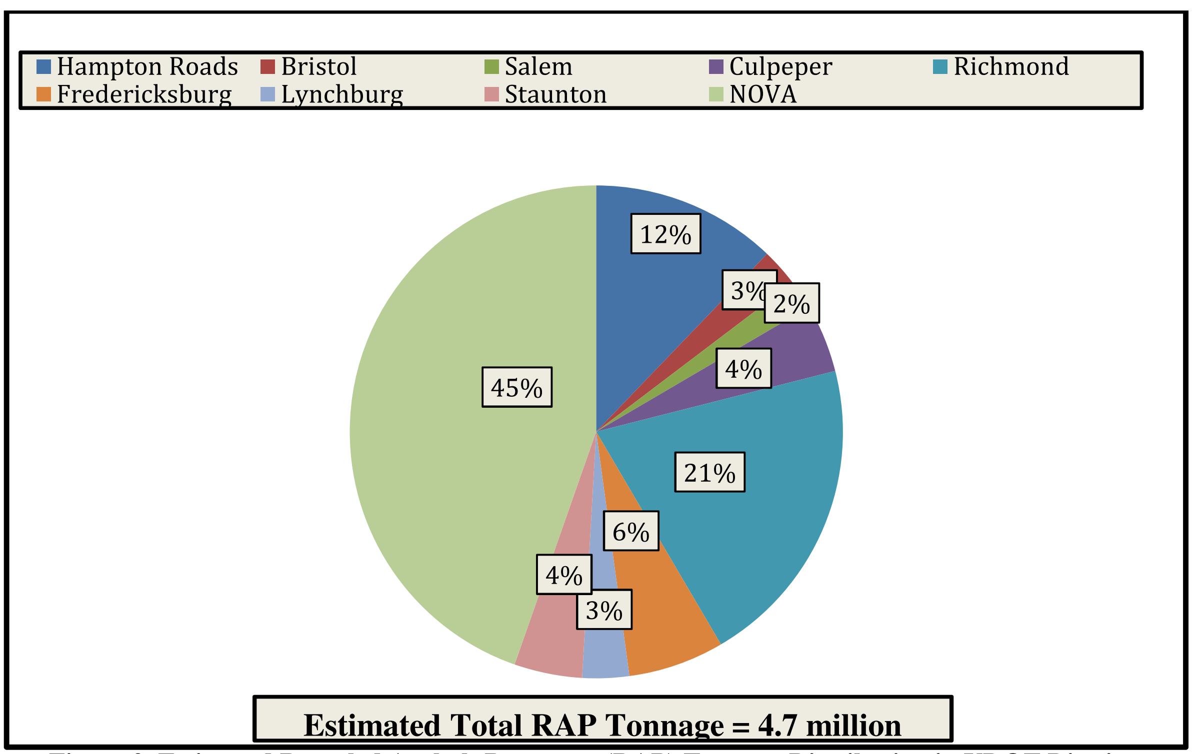

Figure 2. Estimated Recycled Asphalt Pavement (RAP) Tonnage Distribution in VDOT Districts

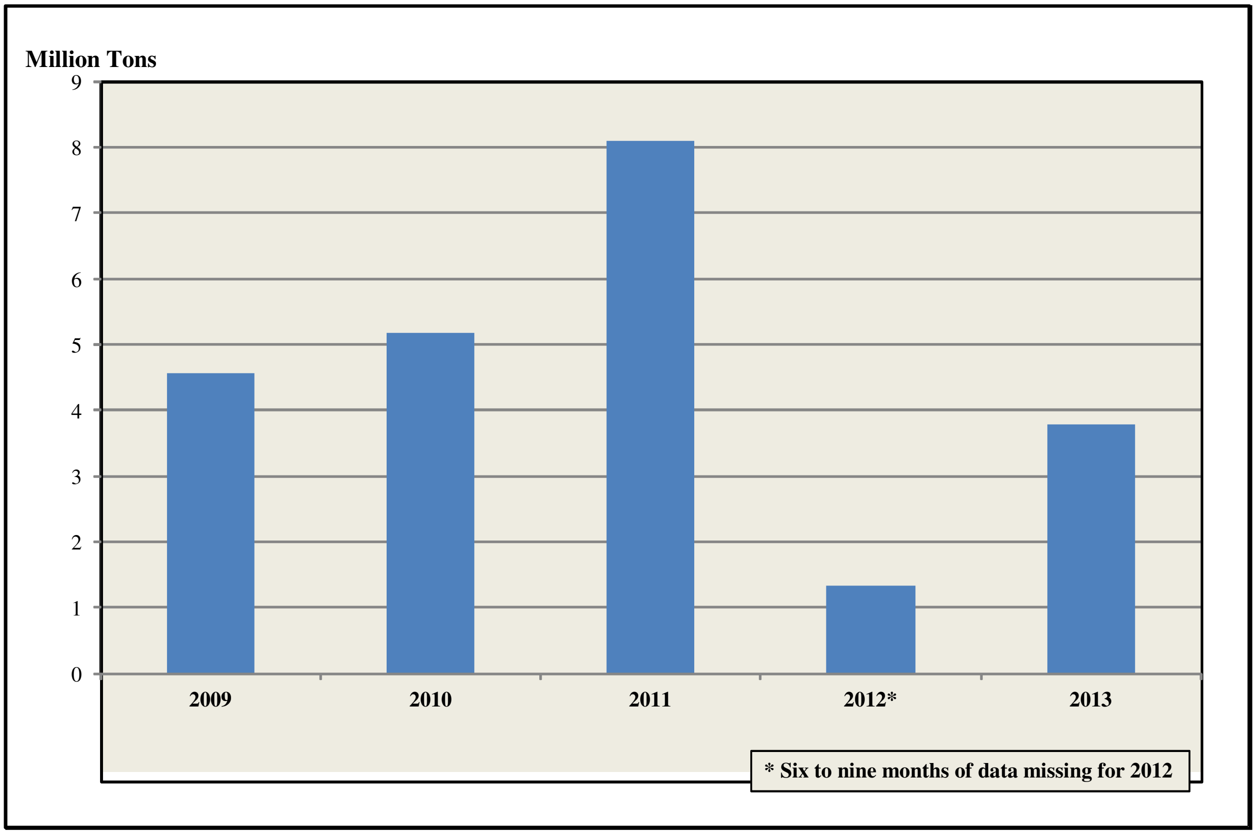

Figure 3. Historical Recycled Asphalt Pavement (RAP) Usage on VDOT Paving Projects From 2009 Through 2013

DISCUSSION

Benefits and Economic Consideration of RAP Use

Some of the environmental and economic benefits of using RAP as a sustainable construction material are as follows (Carswell et al., 2005):

- the use of already existing materials
- the elimination of disposal problems
- conservation of natural resources
- major energy savings, including those related to avoiding processing of additional virgin material and the reduced haulage of materials
- reduction of inconvenience attributable to traffic caused by haulage of materials.

Some asphalt recycling equipment suppliers quoted potential cost savings ranging from $30 to $80 per ton recycled (AsphaltRecycling.com, 2013). It has been estimated that in some areas recycled materials cost less to use than conventional crushed stone base material by as much as 30% (Edil, 2011).

There are wide variations in the amount of RAP allowed in unbound layers by various transportation agencies. Although the use of 100% RAP is not isolated, the general state of the practice appears to be trending toward 50% as the maximum allowable content. Many agencies set limits at well below 50% by weight. The large variability in RAP content in unbound layers allowed by various agencies may indicate that this particular application is not the main focus of RAP recycling efforts. It can be argued that RAP material is too valuable a resource to be used in large quantities in applications other than recycling in bound asphalt mixtures.

The asphalt binder is typically the most expensive component of asphalt pavement construction and thus the most valuable and economically variable material (Copeland, 2011). It is commonly used in the production of intermediate and surface layers of flexible pavements. The focus of RAP research has been traditionally concentrated on asphalt mix design. A mixture with a high RAP content is defined as one that has 25% or more recycled material by weight. Current research efforts in pavement technology are aimed at increasing the asphalt mixture RAP content to above 30% by weight.

Copeland et al. (2010) concluded that the most economical use of RAP is in asphalt mixtures that go into the intermediate and surface layers of flexible pavements, where RAP actually replaces a portion of the more expensive virgin binder.

Material Property Requirements

RAP, being produced from asphalt concrete, is mostly aggregate material and is itself granular and can be used in a variety of applications for which freshly produced natural aggregates have traditionally been used. Highway agencies often require that reclaimed materials satisfy most of the virgin aggregate specifications, with certain tests often relaxed, especially when they are irrelevant or inappropriate for the particular recycled material under consideration.

With regard to RAP intended for use as granular material in base and subbase applications, key factors for good performance are grading, particle toughness as measured by the Micro-Deval test, and the plasticity of fines. Soundness of individual particles could be of concern or discounted depending on the particular original aggregate component of the asphalt concrete and if necessary can be assessed by unconfined freezing and thawing or sulfate solution cycling.

Performance-related parameters to be assessed for the granular mixture include the moisture density relationship, stiffness (resilient modulus), shear strength (static triaxial testing), permanent deformation (repeated load triaxial testing), and frost susceptibility (tube suction). These assessments of the bulk mixture together with the descriptive and quality tests provide up-to-date methods for evaluating and selecting materials for use as granular base and subbase. Table 2 provides recommended tests and performance levels for varying environmental and traffic loading conditions.

In the European practice, recycled unbound aggregates must comply in general with the same criteria as the virgin aggregates, with most countries having no specific requirements for these materials (Thøgersen et al., 2013). In the United States, many state DOTs actively promote the use of recycled materials, allowing the use of RAP in unbound base and subbase layers (Saeed, 2007). RAP materials are often, but not always, subjected to the same tests and specifications as virgin aggregates. It may be argued that RAP material has already passed various quality control tests, although the aggregate can be somewhat degraded and the binder is aged. At a minimum, it may be prudent to enforce limits on grain size distribution and the percentage of deleterious matter.

Existing laboratory studies indicate that as the RAP content increases in the RAP and virgin aggregate blend, the permeability increases, the resilient modulus increases, and the shear strength decreases. There is a clear trend showing that large strains (CBR) lead to substantial permanent deformations, whereas the resistance to small strains (resilient modulus) increases in a RAP blend. Notably absent in these studies are the measurements of actual stress levels in unbound base layers. It is possible that for some pavement sections the resulting traffic-induced stresses in base and subbase materials are inconsequential and the rutting potential may be minimal. The depth of the pavement section and the relative layer stiffness affect RAP material performance in the field.

The pavement design method currently used (AASHTO, 1993b) is not capable of capturing the performance of base material containing RAP (Wu, 2011). Only the resilient modulus value is used in design. The MEPDG procedure (AASHTO, 2008) includes a prediction model for fatigue, rutting, and other performance distresses and can be used to predict the performance of a pavement containing RAP base material. Thus a life cycle cost analysis is possible to evaluate the cost-effectiveness of using RAP. However, the characteristics of RAP are different from those of traditional materials. For instance, the rutting potential of virgin aggregates is negatively correlated with their stiffness. This is not the case for RAP materials (Wu, 2011). Therefore, the rutting prediction model for granular materials in the MEPDG is not directly applicable to base materials containing RAP.

Quality Control and Acceptance

Currently, there is no unified approach to the quality acceptance testing of RAP base courses. The majority of state DOTs use field density and moisture content measurements obtained by the nuclear density gauge for compaction control of unbound materials (Nazzal, 2014). Nuclear gauge test results are affected by the presence of asphalt binder, and moisture content adjustments are required to obtain representative dry density values. Various implemented options for compaction acceptance criteria include the following:

- nuclear gauge providing dry density values adjusted for the presence of binder (gauge moisture correction)

- nuclear gauge providing wet density results only

- nuclear gauge providing wet density measurements and Speedy moisture tester used for dry density determination

- nuclear gauge used with a control strip

- specified number of passes of compaction equipment over a specified layer thickness

- DCP test and a prescribed moisture content

- no field testing.

The use of a test method based on strength/stiffness, such as DCP, has been found to be a viable alternative to nuclear gauges. The DCP is simple, durable, and economical, and its use requires minimum training and maintenance (Nazzal, 2014). There is a standard specification for its use, ASTM D6951 (ASTM, 2009d), and it requires no prior calibration. Various correlations have been developed for the DCP, including the resilient modulus and CBR values.

Environmental Considerations

RAP has been successfully incorporated in bound pavement layers for many years with few concerns about potential environmental contamination. Although the use of RAP as an unbound base layer is not as extensive, the lack of experience has been offset by recent studies examining the leaching potential, indicating no environmental issues of concern. The research results related to the use of stabilizing agents with RAP, however, are not as conclusive. As different stabilization methods begin to be used to a greater extent, undoubtedly more will be learned about additional methods to limit potential contamination concerns.

CONCLUSIONS

- *The use of RAP in road base and subbase layers is technically viable.*

- *Numerous transportation agencies have been recycling RAP in unbound base and subbase layers for many years; however, there is a lack of literature on actual field performance.*

- *Because of concerns related to lower shear strengths and excessive permanent deformations resulting from large strains as RAP content increases, there is a general trend of using up to 50% RAP content by weight in virgin aggregate base and subbase layers.*

- *There is a general lack of uniformity among the RAP use specifications adopted by various transportation agencies.*

- *RAP for use in base and subbase layers can be characterized by performance-related parameters and properties including those needed for pavement design, such as grading,* *resilient modulus, shear strength under static triaxial loading, and permanent deformation under repeated triaxial loading, and those identifying material durability, such as frost susceptibility and abrasion resistance as measured by the Micro-Deval test.*

- *When the nuclear density gauge is used for wet/dry density measurements, the compaction acceptance criteria need to be modified to account for the RAP content.*

- *Current pavement design procedures do not account for RAP material properties.*

- *There do not appear to be substantive leaching concerns related to unstabilized RAP used as base or subbase material.*

- *Use of chemical stabilization agents may require environmental assessment on a case-by-case basis.*

- *Currently, there is reportedly at least 5 million tons of RAP available at various asphalt plants in Virginia. Although nearly one-half of this tonnage is located in Northern Virginia, there are adequate stockpiles of RAP to supply most parts of the state.*

RECOMMENDATIONS

1. *VDOT's Materials Division should consider allowing the use of RAP in road base and subbase layers.*

2. *VDOT's Materials Division should consider limiting the use of RAP to no more than 50% by weight and to low-volume applications to gain familiarity with the materials and processes involved.*

3. *The Virginia Center for Transportation Innovation and Research (VCTIR) in collaboration with VDOT's Materials Division should proceed with long-term field studies involving the performance evaluation of roads containing RAP in bases and subbases. The goal of such studies would be development of criteria for pavement design and quality acceptance.*

4. *Since there seemed to be no major environmental concerns associated with using unbound RAP without chemical stabilization agents, VDOT's Environmental Division should consider not requiring environmental testing when RAP is used without chemical stabilization agents.*

BENEFITS AND IMPLEMENTION PROSPECTS

This study was performed to investigate the state of the practice with regard to the use of RAP materials in road bases and subbases. The recommendations, based on practices adopted by other state transportation agencies, call for allowing the use of RAP in a road base material on

VDOT highway construction projects. The state materials engineer, with support from VCTIR, will review current specifications and determine any additions or modifications that may be needed to implement Recommendations 1 and 2. The state materials engineer, along with VCTIR, will also seek guidance from VDOT's Construction Division in the development of this specification. Once a standard specification has been developed, VCTIR will work with VDOT's Materials Division and the districts to locate sites for long-term field studies to implement further the recommendations stemming from this study.

Increased use of RAP material can generate substantial economic benefits for VDOT. Based on the past 5-year usage, it is estimated that on average VDOT uses approximately 10 million tons of virgin aggregate material annually on projects for base and subbase layer applications. Potential cost savings of up to 30% could be realized with the use of 50% RAP by weight, as shown in Figure 4. These cost estimates are based on the average price of $30/ton for Aggregate Base Material Type 1 (VDOT, 2013b) and $12.50/ton for RAP (Kandhal and Mallick, 1997; Reid, 2008).

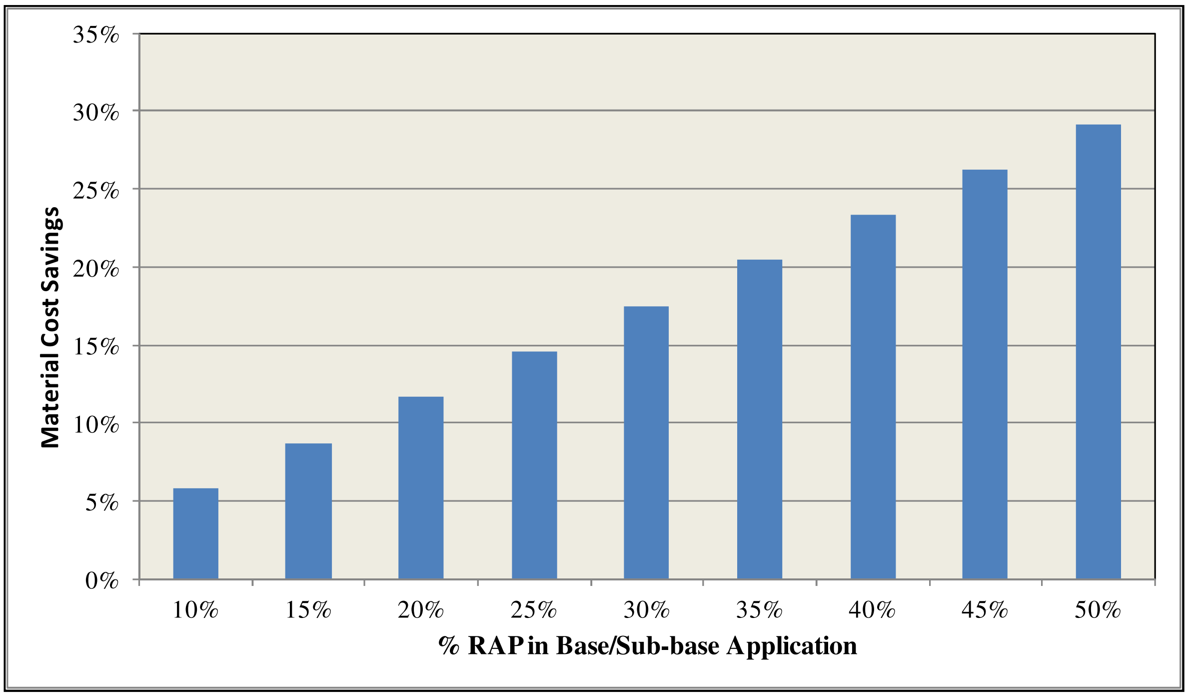

Figure 4. Potential Material Cost Savings to VDOT From RAP Use in Base and Subbase Applications

ACKNOWLEDGMENTS

The authors acknowledge the technical guidance provided by Robert Crandol and John Schuler of VDOT's Materials Division and VDOT's district materials engineers. Ken Winter of VCTIR assisted with the literature search. Linda Evans of VCTIR provided assistance with the editorial process.

REFERENCES

American Association of State Highway and Transportation Officials. *AASHTO T 307-99 (2007): Standard Method of Test for Determining the Resilient Modulus of Soils and Aggregate Materials*. Washington, DC, 2007.

American Association of State Highway and Transportation Officials. *Mechanistic-Empirical Pavement Design Guide: A Manual of Practice*. Washington, DC, 2008.

American Association of State Highway and Transportation Officials. *AASHTO T 180-10: Standard Method of Test for Moisture-Density Relations of Soils Using a 4.54-kg (10-lb) Rammer and a 457-mm (18-in) Drop*. Washington, DC, 2010.

American Association of State Highway and Transportation Officials. *AASHTO M 216-13: Standard Specification for Lime for Soil Stabilization*. Washington, DC, 2013a.

American Association of State Highway and Transportation Officials. *Guide for Design of Pavement Structures.* Washington, DC, 2013b.

Arulrajah, A., Piratheepan, J., Disfani, M.M., and Bo, M.W. Geotechnical and Geoenvironmental Properties of Recycled Construction and Demolition Materials in Pavement Subbase Applications. *Journal of Materials in Civil Engineering,* Vol. 25, No. 8, 2013, pp. 1077-1088.

Arulrajah, A., Piratheepan, J., and Disfani, M.M. Reclaimed Asphalt Pavement and Recycled Concrete Aggregate Blends in Pavement Subbases: Laboratory and Field Evaluation. *Journal of Materials in Civil Engineering,* Vol. 26, No. 2, 2014, pp. 349-357.

AsphaltRecycling.com. FAQ. 2013. http://www.asphaltrecycling.com/display.php?cnt_id=24. Accessed April 5, 2014.

ASTM International. ASTM D1287-91: Standard Test Method for pH of Engine Coolants and Antirusts. In *Annual Book of Standards.* West Conshohocken, PA, 2002.

ASTM International. ASTM D1252-06: Standard Test Methods for Chemical Oxygen Demand (Dichromate Oxygen Demand) of Water. In *Annual Book of Standards.* West Conshohocken, PA, 2006.

ASTM International. ASTM D4609-08: Standard Guide for Evaluating the Effectiveness of Admixtures for Soil Stabilization. In *Annual Book of Standards.* West Conshohocken, PA, 2008a.

ASTM International. ASTM D5050-08: Standard Guide for Commercial Use of Lime Kiln Dust and Portland Cement Kiln Dust. In *Annual Book of Standards.* West Conshohocken, PA, 2008b.

ASTM International. ASTM C821-09: Standard Specification for Lime for Use with Pozzolans. In *Annual Book of Standards.* West Conshohocken, PA, 2009a.

ASTM International. ASTM C977-10: Standard Specification for Quicklime and Hydrated Lime for Soil Stabilization. In *Annual Book of Standards,* West Conshohocken, PA, 2009b.

ASTM International. ASTM D2940-09: Standard Specification for Graded Aggregate Material for Bases and Subbases for Highways and Airports. In *Annual Book of Standards.* West Conshohocken, PA, 2009c.

ASTM International. ASTM D6951-09: Standard Test Method for Use of the Dynamic Cone Penetrometer in Shallow Pavement Applications. In *Annual Book of Standards.* West Conshohocken, PA, 2009d.

ASTM International. Proposed New ASTM Soil and Rock Standard Covers Sustainable Use of Recycled Asphalt Pavement. News Release No. 8493. February 2010a. http://www.astmnewsroom.org/default.aspx?pageid=2066. Accessed September 18, 2014.

ASTM International. ASTM D6928-10: Standard Test Method for Resistance of Coarse Aggregate to Degradation by Abrasion in the Micro-Deval Apparatus. In *Annual Book of Standards.* West Conshohocken, PA, 2010b.

ASTM International. ASTM C593-06-09 (2011): Standard Specification for Fly Ash and Other Pozzolans for Use with Lime for Soil Stabilization. In *Annual Book of Standards.* West Conshohocken, PA, 2011a.

ASTM International. ASTM D7762-11: Standard Practice for Design of Stabilization of Soil and Soil-Like Materials with Self-Cementing Fly Ash. In *Annual Book of Standards.* West Conshohocken, PA, 2011b.

ASTM International. ASTM D5239-12: Standard Practice for Characterizing Fly Ash for Use in Soil Stabilization. *Annual Book of Standards.* West Conshohocken, PA, 2012.

ASTM International. ASTM D4792-13: Standard Test Method for Potential Expansion of Aggregates From Hydration Reactions. In *Annual Book of Standards.* West Conshohocken, PA, 2013.

AustRoads. *Guide to the Structural Design of Road Pavements*. Sydney, NSW, Australia, 2004.

Ayan, V. *Assessment of Recycled Aggregates for Use in Unbound Subbase of Highway Pavement*. Ph.D. Thesis, Kingston University, London, UK, 2011.

Bennert, T., and Maher, A. *The Development of a Performance Specification for Granular Base and Subbase Material*. Rutgers University, Piscataway, NJ, 2005.

Bennert, T., Papp, W.J., Jr., Maher, A., and Gucunski, N. Utilization of Construction and Demolition Debris Under Traffic-Type Loading in Base and Subbase Applications. In *Transportation Research Record: Journal of the Transportation Research Board,* No. 1714, Washington, DC, 2000, pp. 33-39.

Bleakley, A.M., and Cosentino, P.J. Improving the Properties of Reclaimed Asphalt Pavement for Roadway Base Applications Through Blending and Chemical Stabilization. Presented at the Annual Meeting of the Transportation Research Board, Washington, DC, 2013.

Bortz, B.S., Halami, I., Hossain, M., and Gisi, A. Geocell-Reinforced Crushed Stone Base for Low-Volume Roads. In *Proceedings of the 2011 Mid-Continent Transportation Research Symposium,* Ames, IA, 2011.

Brantley, A.S., and Townsend, T.G. Leaching of Pollutants From Reclaimed Asphalt Pavement. *Environmental Engineering Science*, Vol. 16, No. 2, 1999, pp. 105-116.

Carmargo, F., Wen, H., Edil, T.B., and Son, Y.H. Laboratory Evaluation of Sustainable Materials at MnRoad. Paper No. 09-3160. In *Proceedings of the 86th TRB Annual Meeting.* Transportation Research Board of the National Academies, Washington, DC, 2009.

Carswell, I., Nicholls, J.C., Elliot, R.C., Harris, J., and Strickland, D. *Feasibility of Recycling Thin Surfacing Back Into Thin Surfacing Systems*. TRL Report TRL645. Transport Research Laboratory, Wockingham, UK, 2005.

Chesner, W.H., Collins, R.J., and MacKay, M.H. *User Guidelines for Waste and Byproduct Materials in Pavement Construction*. FHWA-RD-97-148. Washington, DC, 1998. http://www.fhwa.dot.gov/publications/research/infrastructure/pavements/97148/index.cfm. Accessed March 29, 2014.

Collins, R.J., and Ciesielski, S.K. *Recycling and Use of Waste Materials and By-Products in Highway Construction*. NCHRP Synthesis 199. Transportation Research Board of the National Academies, Washington, DC, 1994.

Colorado Department of Transportation. *Revision of Sections 304 and 703 – Aggregate Base Course (RAP).* Denver, 2013. http://www.coloradodot.info/business/designsupport/construction-specifications/2011-Specs/standard-special-provisions/sections-200-500-revisions/304abcr.doc/view. Accessed April 30, 2014.

Copeland, A. *Reclaimed Asphalt Pavement in Asphalt Mixtures: State of the Practice*. FHWA-HRT-11-021. Federal Highway Administration, McLean, VA, 2011.

Copeland, A., Jones, C., and Bukowski, J. *Reclaiming Roads*. FHWA-HRT-10-001. Federal Highway Administration, McLean, VA, 2010.

Cosentino, P.J., Kalajian, E., Shieh, C.S., Mathurin, W.J., Gomez, F.A., Cleary, E.D., and Treeratrakoon, A. *Developing Specifications for Using Recycled Asphalt Pavement as Base, Subbase or General Fill Materials, Phase II*. Florida Department of Transportation, Tallahassee, 2003.

Cosentino, P.J., Kalajian, E.H., Bleakley, A.M., Diouf, B.S., Misilo, T.J., Petersen, A J., Krajcik, R.E., and Sajjadi, A.M. *Improving the Properties of Reclaimed Asphalt Pavement for Roadway Base Applications*. Florida Institute of Technology, Melbourne, 2012.

Deniz, D., Tutumler, E., and Popovics, J. S. *Expansive Characteristics of Reclaimed Asphalt Pavement (RAP) Used as Base Materials*. Illinois Center for Transportation, Urbana – Champaign, 2009.

Department for Transport. Specification for Highway Works – Series 800. In *Manual of Contract Documents for Highway Works.* London, UK, 2014. http://www.dft.gov.uk/ha/standards/mchw/vol1/index.htm. Accessed April 28, 2014.

Dong, Q., and Huang, B. Laboratory Evaluation on Resilient Modulus and Rate Dependencies of RAP Used as Unbound Base Material. *Journal of Materials in Civil Engineering,* Vol. 26, No. 2, 2014, pp. 379-383.

Edil, T.B. *Specifications and Recommendations for Recycled Materials Used As Unbound Base Course*. University of Wisconsin-Madison, 2011.

Edil, T.B., Tinjum, J.M., and Benson, C.H. *Recycled Unbound Materials*. Final Report 2012-35. Minnesota Department of Transportation Research Services, Office of Policy Analysis, Research & Innovation. University of Wisconsin-Madison, 2012.

European Committee for Standardization. *DS/EN 13108-8: Bituminous mixtures – Material specifications – Part 8: Reclaimed asphalt.* Brussels, Belgium, 2005.

European Committee for Standardization. *NF/EN 13285: Unbound mixtures – Specifications*. Brussels, Belgium, 2010.

Federal Aviation Administration. *Airport Construction Standards (AC 150/5370-10).* Washington, DC, 2011a. http://www.faa.gov/airports/engineering/construction_standards/. Accessed April 28, 2014.

Federal Aviation Administration. *Development of State Standards for Nonprimary Airports*. Advisory Circular No. 150-5100-13B. Washington, DC, 2011b. http://www.faa.gov/documentLibrary/media/Advisory_Circular/150_5100_13b.pdf . Accessed April 28, 2014.

Florida Department of Transportation. *Standard Specifications for Road and Bridge Construction*. Tallahassee, 2013.

http://www.dot.state.fl.us/specificationsoffice/implemented/SpecBooks/2013/Files/2013eBook.pdf. Accessed May 4, 2014.

Ganne, V.K. *Long-Term Durability Studies on Chemically Treated Reclaimed Asphalt Pavement (RAP) Materials.* M.S. Thesis, University of Texas at Arlington, 2009.

Gupta, S.C., Kang, D.H., and Ranaivosoon, A. *Hydraulic and Mechanical Properties of Recycled Materials.* Minnesota Department of Transportation, Research Services Section, St. Paul, 2009.

Guthrie, S.W., Cooley, D., and Eggett, D.L. Effects of Reclaimed Asphalt Pavement on Mechanical Properties of Base Materials. In *Transportation Research Record: Journal of the Transportation Research Board,* No. 2005. Transportation Research Board of the National Academies, Washington, DC, 2007, pp. 44-52.

Hossain, S., Lane, D.S., and Schmidt, B.N. Results of Micro-Deval Test for Coarse Aggregates From Virginia Sources. In *Transportation Research Record: Journal of the Transportation Research Board,* No. 2059. Transportation Research Board of the National Academies Washington, DC, 2008, pp. 1-10.

Hoyos, L.R., Ordonez, C.A., Puppala, A.J., and Hossain, M.S. Engineering Characterization of Cement-Fiber Treated RAP Aggregates. In *GeoCongress 2008: Characterization, Monitoring, and Modeling of GeoSystems.* American Society of Civil Engineers, Reston, VA, 2008, pp. 613-621.

Hoyos, L.R., Puppala, A.J., and Ordonez, C.A. Characterization of Cement-Fiber-Treated Reclaimed Asphalt Pavement Aggregates: Preliminary Investigation. *Journal of Materials in Civil Engineering*, Vol. 23, No. 7, 2011, pp. 977-989.

Idaho Transportation Department. *Standard Specifications for Highway Construction*. Boise, 2012. http://itd.idaho.gov/newsandinfo/docs/2012SpecBook.pdf. Accessed May 7, 2014.

Iowa Department of Transportation. *Production of Certified Aggregate From Reclaimed Roadways*. Ames, 2014. http://www.iowadot.gov/erl/current/IM/content/210.htm. Accessed May 5, 2014.

Kandhal, P.S., and Mallick, R.B. *Pavement Recycling Guidelines for State and Local Governments: Participant's Reference Book, Chapter 4: Economics of Recycling.* FHWA-SA-98-042. National Center for Asphalt Technology, Auburn, AL, 1997. http://www.fhwa.dot.gov/pavement/recycling/98042/. Accessed September 18, 2014.

Kang, D.H., Gupta, S.C., Ranaivoson, A.Z., Roberson, R., and Siekmeier, J. Recycled Materials As Substitutes for Virgin Aggregates in Road Construction: II. Inorganic Contaminant Leaching. *Soil Science Society of America Journal*, Vol. 75, No. 4, 2011, pp. 1276-1284.

Kim, W., Labuz, J. F., and Dai, S. Resilient Modulus of Base Course Containing Recycled Asphalt Pavement. In *Transportation Research Record: Journal of the Transportation Research Board,* No. 2006. Transportation Research Board of the National Academies, Washington, DC, 2007, pp. 27-35.

Koch, S., and Ksaibati, K. *Performance of Recycled Asphalt Pavement in Gravel Roads*. University of Wyoming, Laramie, 2010.

Kwon, J., Boudreau, R.L., Tutumluer, E., and Wayne, M.H. Evaluation and Characterization of Aggregates for Sustainable Use in Pavement Engineering. *Geo-Congress Technical Papers*, *GSP234*. American Society of Civil Engineers, Reston, VA, 2014, pp. 3373-3382.

Li, L., Benson, C.H., Edil, T.B., and Hatipoglu, B. Sustainable Construction Case History: Fly Ash Stabilization of Recycled Asphalt Pavement Material. In *TRB 2007 Annual Meeting CD-ROM.* Transportation Research Board of the National Academies, Washington, DC, 2007.

Li, P., and Liu, J. *Characterization of Asphalt Treated Base Course Material*. Report No. 107049. University of Alaska, Fairbanks, 2010.

Little, D.N., and Nair, S. *Recommended Practice for Stabilization of Subgrade Soils and Base Materials.* NCHRP Web-Only Document 144. Transportation Research Board of the National Academies, Washington, DC, 2009.

Locander, R. *Analysis of Using Reclaimed Asphalt Pavement (RAP) As a Base Course Material.* Colorado Department of Transportation - Research, Denver, 2009.

McGarrah, E.J. *Evaluation of Current Practices of Reclaimed Asphalt Pavement/Virgin Aggregate as Base Course Material*. University of Washington, Seattle, 2007.

Minnesota Department of Transportation. *Materials Lab Supplemental Specifications for Construction*. St. Paul, 2014a. http://www.dot.state.mn.us/pre-letting/spec/2014/2014-Materials-Lab-Supplement.pdf. Accessed May 4, 2014.

Minnesota Department of Transportation. *Quantitative Extraction of Bituminous Mixtures (Centrifuge). Lab Manual.* St. Paul, 2014b. http://www.dot.state.mn.us/materials/manuals/laboratory/1852.pdf. Accessed May 4, 2014.

Mokwa, R.L., and Peebles, C.S. *Evaluation of the Engineering Characteristics of RAP/Aggregate Blends*. Montana State University, Bozeman, 2005.

Nazzal, M. *Non-Nuclear Methods for Compaction Control of Unbound Materials.* NCHRP Synthesis 456. Transportation Research Board of the National Academies, Washington, DC, 2014. http://onlinepubs.trb.org/onlinepubs/nchrp/nchrp_syn_456.pdf. Accessed May 4, 2014.

New York State Department of Transportation. Section 300 – Bases and Subbases. In *Standard Specifications.* Albany, 2008. https://www.dot.ny.gov/main/business-center/engineering/specifications/english-spec-repository/section300.pdf. Accessed May 4, 2014.

North Carolina Department of Transportation. *Standard Specifications for Roads and Structures*. Raleigh, 2012. https://connect.ncdot.gov/resources/specifications/pages/specifications-and-special-provisions.aspx. Accessed May 7, 2014.

Ontario Hot Mix Producers Association. *The ABCs of Recycled Aggregate*. Mississauga, ON, Canada, 2010.

Ontario Ministry of Transportation. *Material Specification for Aggregates – Base, Subbase, Select Subgrade, and Backfill Material.* Ontario Provincial Standard Specification, Downsview, ON, Canada, 2003.

Ooi, P.S.K. *Application of Recycled Materials in Highway Projects*. University of Hawaii at Manoa, Honolulu, 2010.

Osinubi, K., and Edeh, J. *Sawdust Ash Stabilization of Reclaimed Asphalt Pavement*. ISSN 1546-962X. American Society for Testing and Materials, West Conshohocken, PA, 2011.

Reid, R. *Report on the Use of High RAP Asphalt Concrete Mixes for the 2007 Lynchburg District Plant Mix Contracts.* Virginia Department of Transportation, Materials Division, Richmond, 2008.

Road and Transportation Research Association [FGSV]. *Technical Delivery Terms for Aggregates in Road Construction.* TL Gestein-StB 04, Edition 2004, Version 2007. Cologne, Germany, 2012.

Roberts, F.L., Kandhal, P.S., Brown, E.R., Lee, D.Y., and Kennedy, T.W. *Hot Mix Asphalt Materials, Mixture Design, and Construction*. NAPA Education Foundation, Lanham, MD, 1996, pp. 102-114.

Rohde, L., Nunez, W.P., and Ceratti, J.A.P. Electric Arc Furnace Steel Slag Base Material for Low-Volume Roads. In *Transportation Research Record: Journal of the Transportation Research Board,* No. 1819. Transportation Research Board of the National Academies, Washington, DC, 2003, pp. 201-207.

Saeed, A. *Appendixes to NCHRP Report 598*. NCHRP Web-Only Document 119. Transportation Research Board of the National Academies, Washington, DC, 2007. http://onlinepubs.trb.org/onlinepubs/nchrp/nchrp_w119.pdf. Accessed May 4, 2014.

Saeed, A. *Performance-Related Tests of Recycled Aggregates for Use in Unbound Pavement Layers*. NCHRP Report 598. Transportation Research Board of the National Academies, Washington, DC, 2008.

Saeed, A., and Hammons, M.I. Minimum Standards for Using Recycled Materials in Unbound Highway Pavement Layers. In *Airfield and Highway Pavements.* American Society of Civil Engineering, Reston, VA, 2008.

Sayed, S.M., Pulsifer, J.M., and Jackson, N.M. UNRAP: Are We Ready for It? *Journal of Materials in Civil Engineering*, Vol. 23, No. 2, 2011, pp. 188-196.

Schaefer, V., Stevens, L., White, D., and Ceylan, H. *Design Guide for Improved Quality of Roadway Subgrades and Subbases*. Iowa State University, Ames, 2008.

Schwartz, C.W., and Khosravifar, S. *Design and Evaluation of Foamed Asphalt Base Materials*. Maryland State Highway Administration, Baltimore, 2013.

Shedivy, R.F., Meier, A., Edil, T.B., Tinjum, J.M., and Benson, C.H. *Leaching Characteristics of Recycled Asphalt Pavement Used As Unbound Road Base*. University of Wisconsin System Solid Waste Research Program, University of Wisconsin-Madison, 2012.

Siekmeier, J.A., Young, D., and Beberg, D. Comparison of the Dynamic Cone Penetrometer With Other Tests During Subgrade and Granular Base Characterization in Minnesota. In *Nondestructive Testing of Pavements and Backcalculation of Moduli: Third Volume.* American Society of Civil Engineers, Reston, VA, 1999.

Stroup-Gardiner, M., and Wattenberg-Komas, T. *Recycled Materials and Byproducts in Highway Applications*. NCHRP Synthesis 435. Transportation Research Board of the National Academies, Washington, DC, 2013.

Taha, R., Ali, G., Basma, A., and Al-Turk, O. Evaluation of Reclaimed Asphalt Pavement Aggregate in Road Bases and Subbases. In *Transportation Research Record: Journal of the Transportation Research Board,* No. 1652. Transportation Research Board of the National Academies, Washington, DC, 1999, pp. 264-269.

Texas Department of Transportation. *Item 247 Flexible Base*. Austin, 2004a. http://ftp.dot.state.tx.us/pub/txdot-info/cmd/cserve/specs/2004/standard/s247.pdf. Accessed May 4, 2014.

Texas Department of Transportation. *Item 276 Cement Treatment (Plant-Mixed)*. Austin, 2004b. http://ftp.dot.state.tx.us/pub/txdot-info/cmd/cserve/specs/2004/standard/s276.pdf. Accessed May 4, 2014.

Texas Department of Transportation. *Test Procedure for Laboratory Compaction Characteristics and Moisture-Density Relationship of Base Materials*. Austin, 2011. http://ftp.dot.state.tx.us/pub/txdot-info/cst/TMS/100-E_series/pdfs/soi113.pdf. Accessed May 4, 2014.

Thakur, J.K. *Experimental Study on Geocell-Reinforced Recycled Asphalt Pavement (RAP) Bases Under Static and Cyclic Loading*. M.S. Thesis, Tribhuvan University, Kirtipur, Kathmandu, Nepal, 2010.

Thakur, J.K., Han, J., Pokharel, S.K., and Parsons, R.L. Performance of Geocell-Reinforced Recycled Asphalt Pavement (RAP) Bases Over Weak Subgrade Under Cyclic Plate Loading. *Geotextiles and Geomembranes,* Vol. 35, 2012, pp. 14-24.

Thakur, J.K., Han, J., and Parsons, R.L. Creep Behavior of Geocell-Reinforced Recycled Asphalt Pavement Bases. *Journal of Materials in Civil Engineering,* Vol. 25, No. 10, 2013, pp. 1533-1542.

Thøgersen, F., Gregoire, C., Stryk, J., Hornych, P., Descantes, Y., Chazallon, C., Blasi, A., Broere, P., Bizjak, K.F., Hellman, F., and Arm, M. Recycling of Road Materials Into New Unbound Road Layers – Main Practice In Selected European Countries. *Road Materials and Pavement Design,* Vol. 14, No. 2, 2013, pp. 438-444.

Townsend, T.G., and Brantley, A.S. *Leaching Characteristics of Asphalt Road Waste, Final Project Report*. Florida Center for Solid and Hazardous Waste Management, University of Florida, Gainesville, 1998.

Tutumluer, E. *Practices for Unbound Aggregate Pavement Layers*. NCHRP Synthesis 445. Transportation Research Board of the National Academies, Washington, DC, 2013.

U.S. Environmental Protection Agency. Method 1311: Toxicity Characteristic Leaching Procedure. In *Test Methods for Evaluating Solid Waste, Physical/Chemical Methods*, 3rd ed. Office of Solid Waste, U.S. Government Printing Office, Washington, DC, 1992.

U.S. Environmental Protection Agency. Method 1312: Synthetic Precipitation Leaching Procedure. In *Test Methods for Evaluating Solid Waste, Physical/Chemical Methods*, 3rd ed. Office of Solid Waste, U.S. Government Printing Office, Washington, DC, 1994.

U.S. Environmental Protection Agency. *Benchmarks for Storm-Water Sampling*. Business Environmental Resource Center, City of Sacramento, CA, 2005.

Virginia Department of Transportation. *Road and Bridge Specifications*. Richmond, 2007.

Virginia Department of Transportation. *Business Plan for FY14 – FY15*. Richmond, 2013a. http://www.virginiadot.org/about/resources/2013_VDOT_Business_Plan.pdf. Accessed April 6, 2014.

Virginia Department of Transportation. [Construction] Statewide Averages July 2011 through June 2013. 2013b. http://www.virginiadot.org/business/resources/const/StatewideAverage.pdf. Accessed May 1, 2014.

Washington State Department of Transportation. *Standard Specifications for Road, Bridge, and Municipal Construction*. Olympia, 2012. http://www.wsdot.wa.gov/publications/manuals/fulltext/m41-10/ss2012.pdf. Accessed May 4, 2014.

West, R.C. *Reclaimed Asphalt Pavement Management: Best Practices*. National Center for Asphalt Technology, Auburn, AL, 2010.

Wisconsin Department of Transportation. Section 301- General Requirements for Base Aggregates. In *Standard Specifications.* Madison, 2014. http://roadwaystandards.dot.wi.gov/standards/stndspec/ss-03-01.pdf##ss301. Accessed May 4, 2014.

Wu, M. *Evaluation of High Percentage Recycled Asphalt Pavement as Base Course Materials*. M.S. Thesis, Washington State University, Pullman, 2011. http://www.dissertations.wsu.edu/Thesis/Summer2011/m_wu_062911.pdf. Accessed May 4, 2014.