SPECIFICATIONS AND RECOMMENDATIONS FOR RECYCLED MATERIALS USED AS UNBOUND BASE COURSE

by

Principal Investigator: Tuncer B. Edil

December 2011

Recycled Materials Resource Center
University of Wisconsin-Madison
Madison, WI 53706 USA

This report provides recommendations and specifications for recycled asphalt pavement and recycled concrete aggregate that can be used as unbound base course. It is based on research conducted at the University of Wisconsin-Madison and elsewhere and the discussions with the industry representatives and other professionals.

INTRODUCTION

The production of demolition and construction waste has been increasing at a gradual rate in recent years. The use of these materials as recycled unbound base course in new roadway construction has become more common in the last twenty years. Recycled roadway materials are typically generated and reused at the same construction site, providing increased savings in both money and time. It has been speculated that in some municipalities recycled materials costs less to use than conventional crushed-stone base material by as much as 30%.

The most widely used recycled materials are recycled asphalt pavement (RAP) and recycled concrete aggregate (RCA). RAP is produced by removing and reprocessing existing asphalt pavement and RCA is the product of the demolition of concrete structures such as buildings, roads and runways. The production of RAP and RCA results in an aggregate that can be well graded and of high quality. The aggregates in RAP are coated with asphalt cement that reduces the water absorption qualities of the material. In contrast, the aggregates in RCA are coated with a cementitious paste that increases the water absorption qualities of the material.

There is some ambiguity regarding the nomenclature involved in the production of RAP. The following classification is recommended to remove ambiguity in nomenclature: RAP refers to the removal and reuse of the hot mix asphalt (HMA) layer of an existing roadway; full depth reclamation (FDR) refers to the removal and reuse of the HMA and the entire base course layer; and recycled pavement material (RPM) refers to the removal and reuse of either the HMA and part of the base course layer or the HMA, the entire base course layer and part of the underlying subgrade implying a mixture of pavement layer materials. Unless specified, these three distinct recycled asphalt materials can be collectively referred to as RAP.

RAP is typically produced through milling operations, which involves the grinding and collection of the existing HMA, and FDR and RPM are typically excavated using full-size reclaimers or portable asphalt recycling machines. RAP can be stockpiled, but is most frequently reused immediately after processing at the site. Typical aggregate gradations of RAP are achieved through pulverization of the material, which is typically performed with a rubber tired grinder.

The production of RCA involves crushing the concrete material to a gradation comparable to that of typical roadway base aggregate. Fresh RCA typically contains a high amount of debris and reinforcing steel, and the RCA must be processed to remove this debris prior to placement. The remaining concrete material after debris removal is further crushed and screened to a predetermined gradation. RCA can be derived from concrete pavements or buildings (building derived concrete).

SPECIFICATIONS

There are no approved national specifications for RAP or RCA. To remedy this situation, specifications have been introduced in ASTM Subcommittee D18.14 Geotechnics of Sustainable Construction. This committee was established with the encouragement of RMRC in 2007. There are specifications that have been introduced and are going through the ASTM process. A standard specification entitled "**Standard Specification for Grading Requirements and Density Determination of Recycled Asphalt Pavement Materials as Unbound Base and Subbase for Highways and Airports,"** was approved at the subcommittee level and was balloted in the Main Committee D18 for Soil and Rock. It received some comments and negative votes and being revised and prepared for re-balloting. This standard is in Appendix A. This specification covers the use of unbound recycled asphalt pavement material for construction of base and subbase for pavement applications. When properly processed and compacted on a prepared grade to appropriate density standards, this material is expected to provide adequate stability and load support for use as highway or airport bases or subbases. There is also a guideline that is also prepared in ASTM D18.14 Subcommittee entitled "Standard Guide for Recycled Aggregates As Unbound Roadbase", which covers both RAP and RCA and aimed at crushers. This guide is reviewed in the subcommittee and is being held for the outcome of on-going research relevant to some aspects of this guide such as allowable deleterious materials content.

COMPOSITION OF RAP AND RCA

As part of a research project (RMRC Project No. 46), 7 samples of RAP, 2 samples of RPM, and 6 samples of RCA were collected from from a wide geographical area, covering eight different states: California, Colorado, Michigan, Minnesota, New Jersey, Ohio, Texas and Wisconsin. A summary of the grain characteristics and classifications for the seventeen materials is shown in Table 1.

Table 1. Index properties for Recycled Materials and Class 5 aggregate

Material	States	D_{10} (mm)	D_{30} (mm)	D_{50} (mm)	D_{60} (mm)	C_u	C_c	G_s	Absorption (%)	Asphalt Content /Mortar Content (%)	Impurities (%)	Gravel (%)	Sand (%)	Fines (%)	USCS	AASHTO
Class 5 Aggregate	MN	0.1	0.4	1.0	1.7	21	1.4	2.57	_	_	0.25	22.9	67.6	9.5	GW-GM	A-1-b
Blend	MN	0.2	0.6	1.5	2.8	13	0.5	_	_	_	0.36	32.7	63.8	3.4	SP	A-1-b
RCA	MN	0.1	0.4	1.0	1.7	21	1.4	2.39	5.0	55	0.87	31.8	64.9	3.3	SW	A-1-a
	MI	0.4	4.1	9.7	12.3	35	3.9	2.37	5.4	_	0.35	68.5	28.3	3.2	GP	A-1-a
	CO	0.1	0.6	2.8	4.9	66	1.1	2.28	5.8	47	0.26	40.9	46.3	12.8	SC	A-1-b
	CA	0.3	1.7	4.8	6.8	22	1.4	2.32	5.0	37	0.26	50.6	47.1	2.3	GW	A-1-a
	TX	0.4	6.5	13.3	16.3	38	6.0	2.27	5.5	45	0.86	76.3	21.6	2.1	GW	A-1-a
	OH	0.2	1.2	3.4	5.3	34	1.7	2.24	6.5	65	0.16	43.2	49.5	7.3	SW-SM	A-1-a
	NJ	0.2	0.5	2.0	5.1	28	0.3	2.31	5.4	_	1.67	41.2	54.6	4.3	SP	A-1-b
RAP	MN	0.3	0.7	1.6	2.3	7	0.7	2.41	1.8	7.1	0.06	26.3	71.2	2.5	SP	A-1-a
	CO	0.4	0.9	2.2	3.3	9	0.7	2.23	3.0	5.9	0.09	31.7	67.7	0.7	SP	A-1-a
	CA	0.3	1.3	3.0	4.2	13	1.2	2.56	2.0	5.7	0.33	36.8	61.4	1.8	SW	A-1-a
	TX	0.7	2.5	5.4	7.9	11	1.1	2.34	1.3	4.7	0.05	41.0	44.9	1.0	SW	A-1-a
	OH	0.5	1.6	2.9	3.8	7	1.3	2.43	0.6	6.2	0.06	32.1	66.2	1.7	SW	A-1-a
	NJ	1.0	2.8	4.9	5.9	6	1.3	2.37	2.1	5.2	0.48	50.9	48.4	0.7	GW	A-1-a
	WI	0.6	1.4	2.7	3.6	6	0.9	2.37	1.5	6.2	0.08	30.9	68.5	0.5	SP	A-1-b
RPM	NJ	0.5	2.1	5.8	8.7	18	1.0	2.35	2.6	4.3	0.04	55.7	43.6	0.6	GW	A-1-b
	MI	0.4	1.7	4.6	6.5	17	1.1	2.39	1.7	5.3	0.13	49.3	50.4	0.4	SW	A-1-b

Note: Asphalt Content determined for RAP/RPM and Mortar Content determined for available RCA

D_{10} = effective size, D_{30} = particle size for 30% finer, D_{50} = median particle size, D_{60} = particle size for 60% finer, C_u = coefficient of uniformity, C_c = coefficient of curvature, G_s= Specific Gravity, AC= Asphalt Content, Abs=Absorption, Note: Particle size analysis conducted following ASTM D 422, G_s determined by ASTM D 854, Absorption of coarse aggregate were determined by ASTM C127-07, USCS classification determined by ASTM D 2487, AASHTO classification determined by ASTM D 3282, asphalt content determined by ASTM D 6307

These materials all are classified as non-plastic per the Unified Soil Classificati System (USCS). The samples of RCA ranged from a poorly graded sand (SP) to a we graded gravel (GW) classification via USCS and A-1-a or b for AASHTO. T he vario RAPs and RPMs classify as SP, SW, or GW, whereas their AASHTO classifications a A-1-a or b. All materials are coarse-grained granular materials with fines contents mos less than 7%. Absorption varied 5-6.5% for RCA samples and 0.6-2.6% for RAP/RF samples. Asphalt content varied 4-7 % for RAP/RPM and mortar content varied 37- % for RCA samples.

Impurities and Fines Content

The amount of deleterious materials present in RCA and RAP/RPM varied amongst t samples. Generally, asphalt aggregate, aggregate with plastic fibers, and wood chi were the most predominant type of impurities for RCA. The impurity content was le than 1% for RCAs obtained from different states (CO, OH, TX, MN, CA, MI, WI, and N Geotextiles and pavement markings were the predominant type of impurities RAP/RPM. The average impurity amount was generally lower than RCA and also le than 1% for all RAP/RPM samples from different states (CO, OH, TX, MN, CA, MI, V except for the sample from NJ which was 1.7%.

The production of RCA and RAP/RPM involves the removal and reprocessing existing asphalt pavement from roadway structures. During the removable process asphalt pavement, some additional materials mix into the recycled materials, such wood chips or pavement markings. Even though the majority of the recycled materials recycled and used in the same year, some of them were stockpiled in order to use lat The stockpiling conditions of the recycled materials also could create addition impurities. It seems the crushing and processing of RCA and RAP has improved recent years limiting the impurities to very small percentages to be of concern. Buildi derived concrete aggregate can contain stone, brick, asphalt pieces, porcelain a decorative concrete. It may also have a higher soil fraction.

Fines content of the RCA samples varied 2-13% but was mostly less than 4 The fines content was lower for RAP/RPM samples than RCA samples (i.e., <2.5%).

Compaction Characteristics

Maximum dry unit weight (MDU) varied within a narrow range of about 1 kN/m^3 and optimum moisture contents within 3 % for both RAP/RPM and RCA samples. The average MDU was about 19-20 kN/m^3 for both RAP/RPM and RCA samples. However, the average OMC was higher for RCA (about 10%) than RAP/RPM (about 7%) samples due to higher absorptive capacity of RCA samples. OMC can be estimated empirically as a function of uniformity coefficient and percent absorption and MDU as a function of optimum moisture content for both RCA and RAP/RPM samples as given in RMRC Project No. 46 report.

Resilient Modulus and Plastic Strains

Resilient modulus is the primary design property of pavement materials. Various studies as well as the tests conducted on these samples indicate that the resilient modulus of both RCA and RAP/RPM are equal or higher than that of natural aggregate. Typically, a representative modulus is computed for base course termed Summary Resilient Modulus (SRM) as suggested in NCHRP 1-28a, corresponding to a bulk stress of 208 kPa. For the RAP/RPM samples, SRM ranged from 627 to 989 MPa. RCA samples had slightly lower SRM (ranging from 549 to 715 MPa) in comparison to RAP/RPM, while Class 5 natural aggregate has the lowest SRM (525 MPa). The resilient modulus of both RCA and RAP/RPM can be estimated empirically in terms of compositional characteristics such as grain size, asphalt content, absorption, percent fines as given in Project No. 46 report.

Various studies indicate that the plastic strains of RAP is greater (nearly 10 times) than that experienced by natural aggregate and RCA. This may be of concern for potential conribution to rutting. This concern will be addressed in the design section.

Scaling

Resilient modulus is a non-linear function of stress conditions (i.e., bulk and octahedral stresses). The current models of resilient modulus takes this dependency on the state of stress in the base course but does not consider the effect of strain amplitude on resilient modulus. In other words, a thicker base couse of the same granular material under the same wheel load would deform less even if the difference in stress level is taken into account because the thicker layer would have lower strains and consequently higher modulus. How this is taken into account is described in the next section on design.

DESIGN

Determining the appropriate thickness of the pavement layers based on engineering properties is a critical task in the design of pavements, and can be particularly challenging when alternative materials such as recycled aggregates e.g., RAP, RPM, RCA or reclaimed road surface gravel (RSG) are used. A methodology to incorporate granular recycled aggregates as base course (alone and stabilized with binders such as fly ash, cement, cement kiln dust) in pavement design is developed. Mechanical behavior of these materials was characterized through a large-scale model experiment (LSME) as well as laboratory bench-scale resilient modulus (BSRM) tests in accordance with NCHRP 1-28a at the University of Wisconsin-Madison (RMRC Projects 46, 48, 53, and 61). In some cases, field modulus data were obtained via falling weight deflectometer (FWD) tests. Data from the BSRM test were compared to those from the LSME and FWD to account for the effects of the test conditions and scale on resilient modulus. Resilient moduli and plastic deformations obtained from the LSME were then used to develop a methodology for designing pavements with these materials. Two design methods using the AASHTO 1993 and AASHTO 2008 (Mechanistic Empirical Pavement Design Guide (MEPDG) were considered.

As mentioned earlier, modulus of a granular pavement layer depends not only the stress level but also the strain level thus layer thickness. An example of the SMR as a function of layer thickness is shown in Fig. 1. When considered for the typical range of base course thicknesses (i.e., 0.1 to 0.4 m), for the unstabilized base materials, the SRM is consistently higher for thicker base course layers due to the lower shear strain amplitude in thicker layers for the same surface load whereas it is essentially constant for the cementitiously stabilized materials.

Two design approaches are provided for flexible pavements using unstabilized and stabilized recycled aggregates in the base: (1) design using AASHTO-1993 design guide and (2) lifetime expectancy-based design using the Mechanistic Empirical

Pavement Design Guide (MEPDG). To simulate field conditions, SRM from the LSME were used to develop the method.

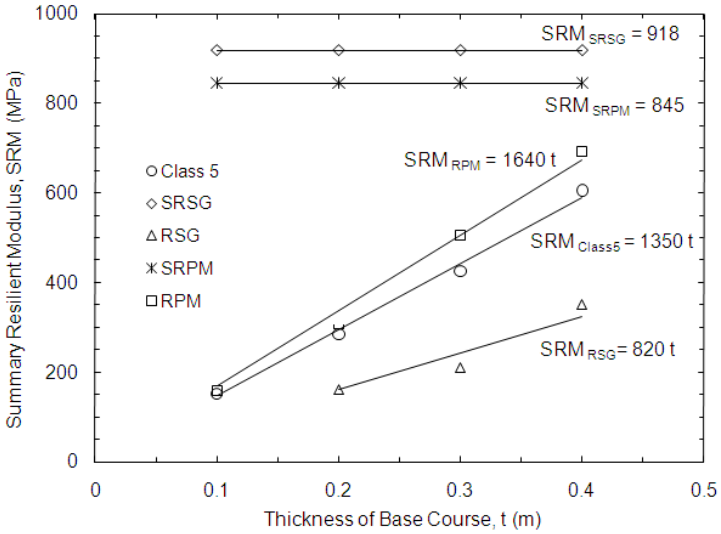


Figure 1. Summary resilient modulus (SRM) of Class 5 base, RPM, RSG, stabilized RPM and RSG (SRPM, and SRSG) as a function of base course thickness

Design Using AASHTO 1993

AASHTO-1993 *Guide for Design of Pavement Structures* uses the structural number (SN) to describe the structural capacity and contribution of each pavement layer. Two main factors control the SN of the base course according to the AASHTO 1993: layer thickness and layer coefficient, the latter reflecting the stiffness of the layer (function of the SRM). The SN of the entire pavement is defined as the summation of the SN of the pavement layers (AASHTO 1993)

$$SN = [SN_1 + SN_2\,m_2 + SN_3\,m_3]/25 = [b_1\,t_1 + b_2\,t_2\,m_2 + b_3\,t_3\,m_3]/25 \qquad \text{(Eq. 1)}$$

where m_i is the drainage modification factor, b_i is the layer coefficient, and t_i is the thickness (mm) of the layer i (i=1 asphalt, i=2 base course, i=3 subbase). The layer coefficient (b_2) of a granular base course is empirically related to resilient modulus by

$$b_2 = 0.249 \log SRM - 0.44 \qquad \text{(Eq. 2)}$$

where SRM is the summary resilient modulus of the granular base material (in MPa). Base course material stabilized with binders is also assumed to follow Eq. 2.

Layer coefficients (b_2) for the recycled materials are calculated using Eq. 2 by employing the SRM corrected for scale effects as described in the reports for RMRC Projects 46, and 53) from the LSME or FWD. The layer coefficients, thus calculated, are within the typical range of layer coefficients presented in AASHTO-1993 for base course layers. For the materials without cementitious stabilization, the layer coefficient varies with thickness because the lower strain amplitude in thicker layers results in higher SRM. For example, the layer coefficient of 0.3-m-thick RPM is 0.20, whereas the layer coefficient for a 0.2-m-thick RPM is 0.17 because of the higher strains in a thinner layer of RPM. In contrast, the layer coefficient for the materials stabilized with a does not vary with base course thickness because the SRM of stabilized materials is not stress or strain dependent in the typical base course layer. The layer coefficient for the stabilized materials is also higher than the layer coefficients for unstabilized materials, indicating that base courses constructed with stabilized materials have higher structural capacity.

Design Using MEPDG

A design approach is proposed using the Mechanistic Empirical Pavement Design Guide (MEPDG) so that plastic deformation of base course could be accounted for explicitly in the design (plastic deformation is not implicit in the AASHTO-1993 method). MEPDG uses mechanistic-empirical models to predict damage accumulation over the predicted service life of a pavement data on traffic, climate, materials, and the pavement structure as input.

Strain corrected SRM for the planned thickness of the base course and base course thickness are the input data for the MEPDG along with traffic information, surface layer thickness and properties, subgrade modulus and assumed thickness, environmental information for the location of the project, and rutting calibration factor. Plastic deformation that can be obtained from the LSME should be used in the MEPDG to predict the rut depth and international roughness index (IRI) of a pavement. The rutting calibration factor (B_{s1}) is determined by inversion of the LSME data (plastic deformations from the LSME are matched with predictions from the MEPDG). B_{s1} can be set at 1.71 for RSG, 1.41 for RPM or RAP, 1.0 for natural aggregate and RCA base course of 0.1 m thickness, and 0.1 for cementitiously stabilized base materials. The rut depth and international roughness index (IRI) are then determined in pavement structures consisting of various base course materials. Example input materials to MEPDG are shown in Table 2.

Table 2. Example Input parameters for the MEPDG program

<table>
<tr><td rowspan="5">Traffic</td><td>Initial Two-way</td><td colspan="3">4000 AADTT</td></tr>
<tr><td>Number of Lanes</td><td colspan="3">2</td></tr>
<tr><td>Operation Speed</td><td colspan="3">110 km/h</td></tr>
<tr><td>Dual Tire Spacing</td><td colspan="3">0.3 m</td></tr>
<tr><td>Tire Pressure</td><td colspan="3">800 kPa</td></tr>
<tr><td>Environment</td><td colspan="4">I-94 Minnesota -USA</td></tr>
<tr><td rowspan="3">Asphalt Binder Superpave Binder Grading</td><td>Thickness</td><td colspan="3">0.1 m</td></tr>
<tr><td>A</td><td colspan="3">10.98</td></tr>
<tr><td>VTS</td><td colspan="3">-3.6</td></tr>
<tr><td rowspan="2">Base Course A-1-a</td><td>Thickness</td><td colspan="3">0.3 m</td></tr>
<tr><td>Modulus</td><td colspan="3">From LSME, presented in Fig. 8</td></tr>
<tr><td rowspan="2">Subgrade</td><td>Thickness</td><td colspan="3">0.5 m</td></tr>
<tr><td>Modulus</td><td colspan="3">70 MPa</td></tr>
<tr><td colspan="5">Rutting for Granular Materials</td></tr>
<tr><td>Rutting Calibration Factor</td><td>RSG</td><td>RPM</td><td>Class 5</td><td>SRPM/ SRSG</td></tr>
<tr><td>B_{s1}</td><td>1.7</td><td>1.4</td><td>1.0</td><td>0.1</td></tr>
</table>

Service lives of pavement structures constructed with recycled unstabilized and stabilized aggregates as base course can be determined based on two criteria: a limiting rut depth such as 12.7 mm and a limiting IRI of 2.7 m/km. The service life of a pavement constructed with RSG is shorter than for Class 5 aggregate due to the lower resilient modulus and more rapid rutting of RSG. The service life of a pavement constructed with RPM is similar to the service life for a pavement with Class 5 aggregate base, even though RPM has higher rutting potential compared to Class 5 aggregate (i.e., rutting calibration factor = 1.4 vs. 1.0). RPM has higher resilient modulus (500 MPa for RPM vs. 400 MPa for Class 5 aggregate for 0.3-m thickness), which results in different stress distribution and consequently different contributions to rutting from the base course layer. Consequently, rutting is comparable for RPM and Class 5 aggregate. Cementitious stabilization of recycled aggregates increases the service life appreciably. Using 0.3-m-thick stabilized RPM or RSG base instead of 0.3-m-thick Class 5 or RPM base increases the service life of the pavement structure from 17 to 21 years. A more detailed discussion of the design procedures can be found in Appendix B.

Durability

Freeze/thaw cycling influences the stiffness properties of unbound recycled pavement and recycled concrete aggregates used for base course as it does all other materials. Resilient modulus can be used to investigate the effect of freeze-thaw (F-T) cycles on unbound road base/subbase layers consisting of RAP and RCA as well as natural aggregate for comparison. The seismic modulus (SM) method is nondestructive and thus can be conducted many times on the same specimen exposed to multiple freeze-thaw cycles. For tracking the effect of freeze-thaw cycles on a recurring basis and determining the long-term effects. This method is effective for RCA and natural aggregate, however, the SM testing method does not work well for RAP.

The stiffness of RAP as well as other materials decreases over the first 5 F-T cycles, with smaller decrease recorded thereafter (Report for RMRC Project 46). This decrease in stiffness of RAP subjected to F-T cycles may be attributed to particle degradation and progressive asphalt-binder weakening. For RCA, the exposure to F-T cycles lead first to a decrease in stiffness (about 10%), followed by an increase (e.g., 30%), which may be attributed to progressive generation of fines and hydration of cement paste. The seismic modulus method confirmed the trends of changing stiffness of RCA during F-T cycling. There are quantitative differences in F-T response, which is reflective of material grading and source. The stiffness of RAP can decrease up to 50% depending on the RAP, a change larger than in natural aggregate and RCA (less than 10%) although building derived concrete aggregate with more than 5% brick content may have enhanced freeze-thaw and wet-dry issues. However, the stiffness of the recycled materials can be still greater than natural aggregate, even after F-T induced decrease. Cementitiously stabilized RAP/RPM experiences small decreases in stiffness (i.e., about 10%).

DISSEMINATION OF INFORMATION

To disseminate the available information about properties, design and construction relating to RAP and RCA, a webinar was organized through the American Society of Civil Engineers. Dr. Jeffrey Melton of RMRC prepared and presented the webinar. The slides used are attached in Appendix C.

LIST OF RELATED RMRC PROJECT REPORTS USED

1. No. 46 Engineering Properties of Recycled Materials for Unbound Applications
2. No. 48 Using High Carbon Coal Fly Ashes to Stabilize Recycled Pavement Materials
3. No. 53 Reconstruction of Railroads and Highways with In-Situ Reclaimed Materials
4. No. 61 Large-Scale Model Experiments of Recycled Base Course Materials Stabilized with Cement Kiln Dust

APPENDIX A

1. **Standard Specification for Grading Requirements and Density Determination of Recycled Asphalt Pavement Materials as Unbound Base and Subbase for Highways and Airports**
   (in ASTM balloting process)

2. **Standard Guide for Recycled Aggregates As Unbound Roadbase**
   (in draft form)

Standard Specification for
Grading Requirements and Density Determination of Recycled Asphalt Pavement Materials as Unbound Base and Subbase for Highways and Airports[1]

This standard is issued under the fixed designation X XXXX; the number immediately following the designation indicates the year of original adoption or, in the case of revision, the year of last revision. A number in parentheses indicates the year of last reapproval. A superscript epsilon (ε) indicates an editorial change since the last revision or reapproval.

1. Scope

1.1 This specification covers the use of unbound recycled asphalt pavement material for construction of base and subbase for pavement applications. When properly processed and compacted on a prepared grade to appropriate density standards, this material is expected to provide adequate stability and load support for use as highway or airport bases or subbases.

1.2 *This standard practice does not purport to address all the safety concerns, if any, associated with its use. It is the responsibility of the user of this standard to establish appropriate safety and health practices and determine the applicability of regulatory limitations prior to use.*

2. Referenced Documents

ASTM Standards:
C 117 Test Method for Materials Finer than 75-µm (No. 200) Sieve in Mineral Aggregates by Washing
C136 Test Method for Sieve Analysis of Fine and Coarse Aggregates
C702 Practice for Reducing Field Samples of Aggregates to Testing Size
D8 Terminology Relating to Materials for Roads and pavements
D75 Practice for Sampling Aggregates
D698 Test Methods for Laboratory Compaction Characteristics of Soil Using Standard Effort (12 400 ft-lbf/ft3 (600 kN-m/m3))
D1556 Standard Test Method for Density and Unit Weight of Soil in Place by Sand-Cone Method
D1557 Standard Test Methods for Laboratory Compaction Characteristics of Soil Using Modified Effort (56,000 ft-lbf/ft3(2,700 kN-m/m3))
D2167 Standard Test Method for Density and Unit Weight of Soil in Place by the Rubber Balloon Method
D6938 Test Methods for In-Place Density and Water Content of Soil and Soil-Aggregate by Nuclear Methods (Shallow Depth).

3. Terminology

3.1 Definitions are in accordance with Terminology D8

3.2 Definitions of terms specific to this standard

3.2.1 Recycling – The process of taking a discarded or abandoned material, breaking down the material, and using it as a raw material in a new product.

3.2.2 Reuse – The process of utilizing a discarded or abandoned material in a new use with little change to the original product.

---

[1] This Practice/Guide is under the jurisdiction of ASTM Committee *D18* and is the direct responsibility of Subcommittee *D18.14*.

Current edition approved XXX. XX, XXXX. Published XX XXXX.

3.2.3 Recycled asphalt pavement (RAP) - Asphalt is exclusively generated from roads, and Recycled Asphalt Pavement is the most common end product made from it.

4. **Significance and Use**

4.1 The test method described is useful as a specification for constructing a pavement base and subbase with recycled asphalt pavements.
4.2 The test method is used for quality control and acceptance testing of compacted soil and soil-aggregate mixtures as used in construction and also for research and development.
4.3 This standard only addresses gradation and compaction. Specifications published by state or local agencies should be referred to for other material properties, such as stiffness and durability.

5. **Gradation Requirements**

5.1 The gradation of RAP shall meet the criteria in Table 1. A representative sample of a mass at least the size required in Method C136.

Table 1. Gradation Requirements for RAP as Base/Subbase Material.

Sieve Opening Size	Percent Passing (by mass)
37.5 mm (1½ in)	100%
25 mm (1 in)	90-100%
9.5 mm (3/8 in)	50-90%
No. 200 sieve (75-µm)	10% max.

Note -1 RAP shall be free from Chemical of Concern (COC), i.e., any chemical that has the potential to adversely affect human health, the environment, or waters in the state, when applied to the land, due to its concentration, distribution, and mode of toxicity. COCs are identified after considering the originating sources and processes that generated the RAP.

5.2 RAP may contain inert materials such as wood, metal, plaster, rubbery material, glass, and geotextile as long as these materials are not classified as solid waste and their total mass does not to exceed 0.5% of the dry mass of RAP as determined by manual separation following the gradation testing following Method C136. Solid waste (as defined by state regulatory agency) shall not be permitted in RAP.
5.3 RAP may be used alone or in mixtures with other aggregate materials (virgin and/or recycled) in the production of unbound base course materials. Mixtures shall also meet the gradation requirements in Table 1.
5.4 Base acceptance decisions on average results obtained on samples from at least three units or batches picked at random from each lot. A lot shall be defined as being not more than 3000 Mg [3300 ton] or a full day's production for delivery to a given project, whichever is smaller.

6. **Sampling and Testing for Gradation**

6.1 Sample each unit, or batch, in accordance with Practice D75. A batch shall be defined as the amount of material required that fills one normal-sized haul truck. Thoroughly mix the sample and reduce it to an amount suitable for testing using the applicable procedures described in Practice C 702. The sample for test shall be approximately the quantity desired when dry and shall be the end result of the reduction. Reduction to an exact predetermined quantity shall not be permitted.
6.2 Particle Size Analysis (Dry Sieving) – Determine the particle size distribution using Method C136, except the drying temperature shall not exceed 60°C (140°F)

6.3 Perform gradation testing in conformance with Method C136 on each separate specimen. Average values of all sieve size determinations for a given lot shall comply with the requirements above. Noncompliance shall necessitate the entire lot be resampled or rejected.

6.4 For testing other than gradation, the sample frequency and lot size shall be designated by the specifying agency. It is recommended to make at least three determinations to represent a lot. Base acceptance or rejection on the average of all determinations for a lot.

7. Density Determination and Measurement

7.1 Sample the material in accordance with Practice D75.

7.2 Maximum Dry Density

7.2.1 Laboratory Method: Maximum dry density and optimum moisture content shall be determined in accordance with ASTM D 1557 or D 698 as specified by the agency.

7.2.2 Field Measurement of Density: Density shall be determined in the field in accordance with ASTM D 1556, D 2167, or D 6938. When ASTM D 6938 is used, corrections shall be made to account for the effects of moisture and asphalt.

Note: The asphalt binder in recycled asphalt may affect the water content reported by a nuclear density gauge. Some agencies use a correction factor to compensate for the effect of asphalt.

8. Keywords

8.1 Recycled asphalt pavement; base course; subbase; density; gradation

Standard Guide for Recycled Aggregates As Unbound Roadbase[1]

This standard is issued under the fixed designation X XXXX; the number immediately following the designation indicates the year of original adoption or, in the case of revision, the year of last revision. A number in parentheses indicates the year of last reapproval. A superscript epsilon (ε) indicates an editorial change since the last revision or reapproval.

1. Scope

1.1 *Guidelines for the use of recycled aggregates as a roadbase.*

1.2 *Include in this section the system of units to be used. Refer to the above ASTM Standards Units toolbar button for a dropdown menu of ASTM's Form and Style Manual statements.*

1.3 *This standard does not purport to address all of the safety concerns, if any, associated with its use. It is the responsibility of the user of this standard to establish appropriate safety and health practices and determine the applicability of regulatory limitations prior to use.*

2. Referenced Documents

2.1 *ASTM Standards*:

ASTM C 136 Sieve Analysis of Fine and Course Aggregates

D 2844-07 Standard Test Method for Resistance R-Value and Expansion Pressure of Compacted Soils

D2419-09 Standard Test Method for Sand Equivalent Value of Soils and Fine Aggregate

D3744-03 Standard Test Method for Aggregate Durability Index

3. Terminology

---

[1] This Practice/Guide is under the jurisdiction of ASTM Committee *D18* and is the direct responsibility of Subcommittee *D18.14*.

Current edition approved XXX. XX, XXXX. Published XX XXXX.

3.1 *Definitions:*

Recycled aggregates are defined as aggregate-based materials that have been generated from construction and demolition projects. These can include concrete, asphalt, and in certain instances for certain end uses, asphalt shingles.

Concrete is a construction material composed of cement (commonly Portland cement) as well as other cementitious materials such as fly ash and slag cement, aggregate (generally a coarse aggregate such as gravel, limestone, or granite, plus a fine aggregate such as sand), water, and chemical admixtures. Recycled Concrete Aggregate (RCA) is generated from several sources, but in general the material comes from four main categories: road and bridge, building-related, airport, and waste new concrete. These four sectors are also the best potential users for the recycled concrete products.

Asphalt concrete, normally known simply as asphalt, consists of asphalt binder and mineral aggregate mixed together then laid down in layers and compacted. It may also contain recycled materials ranging from recycled ground tires, recycled asphalt pavement, and recycled asphalt shingles. It is a composite material commonly used for construction of pavement, highways and parking lots. Recycled asphalt is exclusively generated from roads, and Recycled Asphalt Pavement (RAP) is the most common end product made from it.

For purposes of this guide “asphalt/concrete recycling operator” (or “Operator”) shall be defined as the company, or companies that receive disposed asphalt and concrete material and transform it into a finished recycled aggregate product. “Asphalt/concrete recycling facility” (or ”Facility”) shall be defined as the physical plant where asphalt and concrete are received, processed, tested, and stockpiled.

4. Summary of Practice

For purposes of this ASTM specification the Operator is assumed to:

4.1 Secure a supply of disposed asphalt and concrete, stockpile it, process/crush the disposed material, test and stockpile the recycled aggregate product.

4.2 Be compliant with local and state jurisdictions, solid waste management rules, laws, and regulations.

4.3 Be compliant with Air Quality and other local, state and federal rules, laws and regulations.

4.4 Have the necessary plans in place for protecting worker health, safety and the environment.

4.5 Meet recycled aggregate material quality standards specified herein prescribed to help ensure optimum performance when used in the construction of roads, highways and foundations.

4.6 Meet stockpiling, sampling and testing requirements specified herein.

5. Material Quality Specifications

The material quality specifications are designed to ensure the Operator and its Facilities produce a recycled aggregate that meets appropriate, generic quality specifications. Therefore, the limits contained in this ASTM guide may be considered “minimum” quality standards. Agencies may wish to make their individual recycled aggregate specifications more stringent.

The Operator and Facility must meet the following sourcing, inspection, sampling, testing and stockpiling standards to ensure that the product is free of organic and/or deleterious materials.

5.1 Only clean disposed asphalt and concrete are admissible for producing recycle aggregate materials.

5.2 Concrete material reinforced with rebar and/or wire mesh must be clean and trimmed flush to the concrete.

5.3 Each incoming load of asphalt and/or concrete must be inspected at the Operators facility prior to unloading materials for disposal and recycling.

5.4 Materials shall be free from clay brick, clay roofing tiles, dirt, trash, wood, roots, vegetation, hazardous or deleterious materials.

5.5 Aggregate may include material processed from reclaimed asphalt concrete, portland cement concrete, lean concrete base, cement treated base, natural earthen aggregates or other rock materials. All rock products shall be clean, hard, sound, durable, uniform in quality and free of any detrimental quantity of soft, friable, thin, elongated or laminated pieces, disintegrated material or other deleterious materials.

5.6 The final recycled aggregate product shall conform to the sieve analysis given in Table 1 when tested in accordance with test method ASTM C 136 ”Sieve Analysis of Fine and Course Aggregates” and shall be of such nature that it can be compacted readily under watering and rolling to form a firm stable base. However, the user may follow a local state Department of Transportation standard for aggregate size distributions.

5.7 The final recycled aggregate product shall conform to the aggregate quality tests results given in Table 2.

6. Significance and Use

6.1

Table 1. AGGREGATE GRADING REQUIREMENTS

Sieve Sizes	Percent Passing	
	1 ½" Maximum	¾" Maximum
2"	100	
1 ½"	90 - 100	
1"		100
¾"	50 – 85	90 - 100
#4	25 - 45	35 - 60
#30	10 – 25	10 - 30
#200	2 – 9	2 – 9

Table 2. AGGREGATE QUALITY TESTS

Test	Test Method	Contract Compliance
Resistance (R-value)	D 2844-07	78 minimum
Sand Equivalent	D2419-09	25 minimum
Durability Index**	D3744-03	35 minimum

**The aggregate shall not be treated with lime, cement or other chemical material before Durability Index test is performed. Untreated reclaimed asphalt concrete and portland cement concrete will not be considered to be treated with lime, cement or other chemical material for purposes of performing Durability Index test.

7. Hazards

7.1

8. Procedure

8.1 Material shall be processed by the proper equipment to create a product that meets the above specifications

8.2 Spreading

Recycled aggregate shall be delivered to the roadbed as uniform mixtures. The mixture shall be deposited and spread to the required compacted thickness within tolerances specified. At the time recycled aggregate is spread it shall have a moisture content sufficient to obtain the required compaction. The moisture shall be uniformly distributed throughout the material. Where the required thickness is .50 foot or less the recycled aggregate may be spread and compacted in one layer. Where the required thickness is more than .50 foot the recycled aggregate shall be spread in two or more layers of approximately equal thickness, and the maximum compacted thickness of any one layer shall not exceed .50 foot. Segregation of recycled aggregate shall be avoided and each layer shall be free from pockets of coarse or fine material.

Compacting

The relative compaction of each layer of compacted recycled aggregate material shall not be less than 95 percent (95%).

9. Precision and Bias

9.1

10. Report

10.1

11. Keywords

11.1 Recycling, recycled aggregate, roadbase, sustainability

ANNEX

(Mandatory Information)

A1.

California Standard Specification for Public Works Construction 2006 edition section 200-2.4.
State of California Department of Transportation Standard Specifications May 2006 edition Section 26.
February 2007 amendments to State of California Department of Transportation Standard Specifications May 2006 Standard Specifications edition.

APPENDIX B

Practical Approach for Designing Flexible Pavements Using Recycled Roadway Materials as Base Course

Practical Approach for Designing Flexible Pavements Using Recycled Roadway Materials as Base Course

Ali Ebrahimi[1] -- Brian R. Kootstra[2] -- Tuncer B. Edil[3] -- Craig H. Benson[4]

[1] *Senior Staff Engineer*
Geosyntec Consultant
Formerly Graduate Student
University of Wisconsin- Madison
2243 Engineering Hall, 1415 Engineering Drive
Madison, WI 53706-1691
ebrahimi@wisc.edu

[2] *Project Engineer*
US Army Corps of Engineers
Formerly Graduate Student
Recycled Materials Resource Center
University of Wisconsin- Madison
brian.r.kootstra@us.army.mil

[3] *Professor and Research Director*
Recycled Materials Resource Center
Geological Engineering
University of Wisconsin-Madison
2226 Engineering Hall, 1415 Engineering Drive
Madison, WI 53706-1691
tbedil@wisc.edu

[4] *Wisconsin Distinguished Professor and*
Director of Sustainability Research and Education
Office of Sustainability
University of Wisconsin-Madison
Madison, WI 53706-1691
chbenson@wisc.edu

ABSTRACT

Resilient modulus and plastic deformation of two recycled base course materials, recycled pavement material (RPM) and road surface gravel (RSG), were investigated using a large-scale model experiment (LSME) and laboratory bench-scale resilient modulus (BSRM) tests. The RPM and RSG were tested alone and with 10% by weight Class C fly ash. A natural limestone aggregate (Class 5) was also tested as a reference material. The LSME is a prototype-scale pavement test apparatus where cyclic loading is applied and deformations are measured. The LSME replicates field conditions and accounts for scale effects as well as mixing and curing conditions. The LSME tests indicate that the summary resilient modulus (SRM) increases with increasing thickness of the unbound recycled materials and that RPM and RSG exhibit significantly higher rate of plastic deformation (i.e., 3-4 times) than Class 5 aggregate. Use of self-cementing fly ash to stabilize RPM and RSG results in a 2-5 times increase in SRM and reduces plastic deformations to negligible levels. Data obtained from the LSME were used to develop an equivalency-based design procedure for the recycled materials with and without fly ash. Stabilization of the recycled materials by fly ash reduced the required thickness of a pavement base course up to 30% when designed in accordance with the AASHTO-1993 design guide. The SRM and plastic deformation from LSME tests were used in the Mechanistic Empirical Pavement Design Guide (MEPDG) to predict the lifetime expectancy of a pavement with a base course consisting of recycled materials alone and with fly ash stabilization. Stabilization with fly ash may increase the service life by as much as 4 year.

1. Introduction

Recycling existing pavement materials during rehabilitation and reconstruction of roads provides a more sustainable alternative to conventional methods such as full removal and replacement of the pavement materials. Existing deteriorated asphalt surface can be pulverized and mixed with the underlying materials to form a new recycled base layer known as recycled pavement material (RPM). The depth of pulverization typically ranges from 100 to 300 mm and includes some or all of the existing base course and even part of the underlying subgrade *(1)*. Similarly, when upgrading unpaved gravel roads to a roadway with a paved surface, the existing road surface gravel (RSG) can be recycled to form a base or subbase.

In-situ recycling of roadway materials is cost effective and environmentally friendly, resulting in reduced energy consumption, greenhouse gas emissions, and waste material disposal *(2, 3)*. However, the asphalt binder in RPM and fines in RSG may adversely affect the strength, stiffness, and plastic deformation of recycled materials used as base course *(4-8)*. One method to enhance the performance of these recycled roadway materials is chemical stabilization with binders like cement, asphalt emulsion, lime, cement kiln dust, or fly ash.

The behavior of pavement materials stabilized with fly ash has been receiving increasing attention in recent years *(7, 9-13).* Fly ash is a byproduct of coal combustion at electric power plants, and often has self-cementing properties. Adding Class C or self-cementing high-carbon fly ash to RPM and RSG increases the California bearing ratio (CBR) and resilient modulus *(2, 14-18)*. Field studies have also shown significant and persistent increases in the modulus of fly ash stabilized layers over several years of service *(2, 10-11, 14)*.

Determining the appropriate thickness of the pavement layers based on engineering properties is a critical task in the design of pavements, and can be particularly challenging when alternative materials are used. The objective of this study was to develop a methodology to incorporate RPM and RSG as base course (alone and with fly ash stabilization) in pavement design. Mechanical behavior of the materials was characterized through a large-scale model experiment (LSME) as well as laboratory bench-scale resilient modulus (BSRM) tests in accordance with NCHRP 1-28a. Data from the BSRM test were compared to those from the LSME to account for the effects of the test conditions and scale on resilient modulus. Resilient moduli and plastic deformations obtained from the LSME were used to develop a methodology for designing pavements with these materials. Two design methods using the AASHTO 1993 and AASHTO 2008 (Mechanistic Empirical Pavement Design Guide (MEPDG) were considered.

2. Materials

Recycled RPM and RSG used alone and with fly ash stabilization were evaluated as alternatives to conventional crushed aggregate base. Limestone aggregate, meeting the Minnesota Department of Transportation's (MnDOT) gradation specification for Class 5 base course, was selected as a reference base course aggregate (referred to herein as Class 5 aggregate). The RPM was an equal mixture of pulverized hot mix asphalt and limestone base course from a roadway reconstruction project in Madison, WI. Asphalt coated aggregates in the RPM were mostly limestone and dolomite (based on X-ray diffraction) and were coated with 0.1 to 3-mm of asphalt binder (Fig. 1). The RPM had an asphalt content of 4.7% (ASTM D6307). Actual RSG was not available. Thus, a synthetic RSG was created by combining Class 5 base with clay fines to meet the gradation and plasticity requirements for surface course materials as described in AASHTO M 147. Particle size distributions of the Class 5, RPM, and RSG are given in Fig. 2.

Fly ash was obtained from Unit 2 of Columbia Power Station (Alliant Energy) in Portage, WI. Columbia fly ash has self-cementing properties and classifies as Class C according to ASTM C 618 (Table 1). RPM and RSG alone and with 10% by weight fly ash (called 'SRPM' and 'SRSG', respectively) were tested as stabilized recycled base course materials. Index properties, classification, and compaction characteristics of these base materials are in Table 2.

TABLE 1. *Chemical composition of Columbia fly ash and typical Class C fly ash*

Parameter	Columbia fly ash	Typical Class C ASTM C618
SiO_2 , %	31.1	40
Al_2O_3 , %	18.3	17
Fe_2O_3 , %	6.1	6
$SiO_2 + Al_2O_3 + Fe_2O_3$, %	55.5	63
CaO , %	23.3	24
MgO , %	3.7	2
SO_3 , %	-	3
CaO/SiO_2	0.8	0.6
$CaO/(SiO_2+Al_2O_3)$	0.4	0.4
Loss on Ignition, LOI, %	0.7	6

Table 2. *Index properties of base course materials used in study.*

Material	w_{opt} (%)	$\gamma_{d\,max}$ (kN/m^3)	LL (%)	PL (%)	Fines Content (%)	AASHTO (USCS)	Poisson Ratio (ν)
Class 5	5.0	20.9	NP	NP	4	A-1-a (SP)	0.35*
RPM	7.5	21.2	NP	NP	11	A-1-a (GW-GM)	0.35*
RSG	7.5	22.6	21	14	12	A-2-4 (SC-SM)	0.32*
SRPM	8.5	20.4	-	-	-	-	0.2
SRSG	6.6	22	-	-	-	-	0.2

NOTE.- Particle size analysis by ASTM D422, $\gamma_{d\,max}$ and w_{opt} by ASTM D698, AASHTO classification by ASTM D3282, asphalt content by ASTM D6307, and Atterberg limits by ASTM D 4318. *Data from Schuettpelz et al. *(19)*

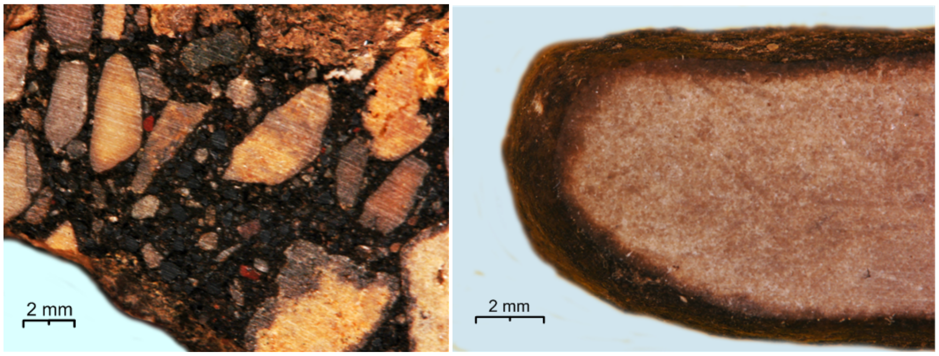


Figure 1. *Cross section of RPM particles coated with asphalt binder.*

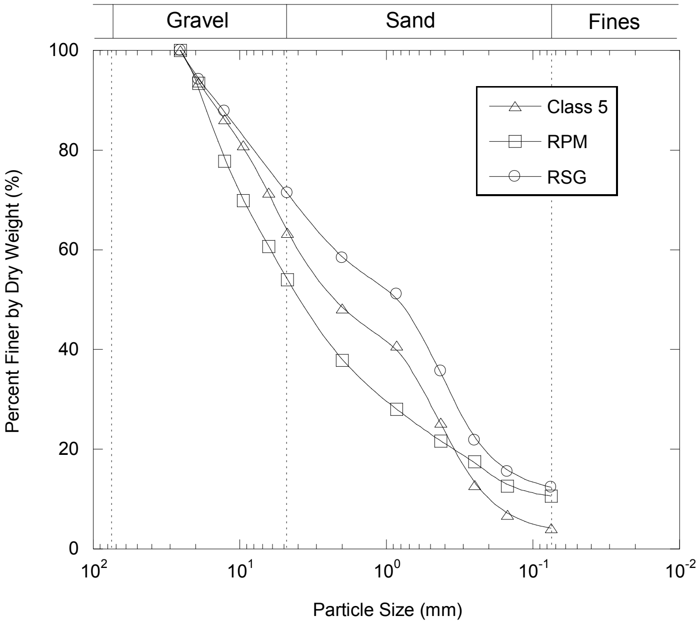


Figure 2. *Particle size distributions of Class 5 base, RPM, and RSG*

3. Methods

3.1 Large-Scale Model Experiment

Elastic and plastic deformations of the alternative recycled base course materials were measured in the large-scale model experiment (LSME) (Fig. 3). The LSME applies cyclic loading simulating truck traffic to a prototype pavement structure. The loads and deformations are used to determine the resilient modulus and plastic strain of the base course materials under conditions similar to the field. The LSME accounts for scale effects and strain amplitude due to varying layer thickness and accumulated plastic deformation *(20)*.

The LSME consists of a pavement profile in a 3 x 3 x 3 m test pit (Fig. 3). The pavement profile consists of 2.5-m of uniform sand simulating a deep subgrade and a base course layer. The RPM, RSG, and Class 5 aggregate were tested in two base course thicknesses (0.2 and 0.3 m) to account for the effect of strain amplitude on the resilient modulus and plastic deformations. Each material was compacted to 100% of standard Proctor maximum dry unit weight at optimum moisture content (Table 1) in 0.1-m lifts using a plate vibratory compactor. A nuclear density gauge was used to check the as-compacted dry unit weight. Fly ash stabilized materials were tested only with 0.3-m depth corresponding to typical field conditions *(14)*. For fly ash stabilization, air-dried base material was mixed with 10% by weight of Class-C fly ash and then water was added to bring the mixture to optimum moisture content. The stabilized layers were placed in 0.15-m lifts and compacted to standard Proctor maximum dry unit weight within 1 h of adding water.

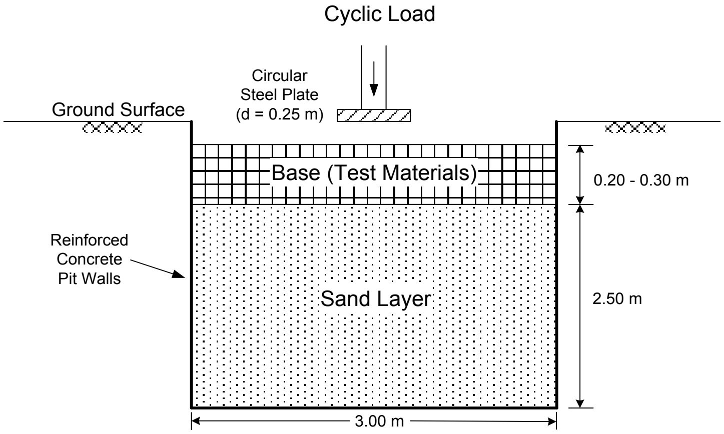


Figure 3. *Schematic of large-scale model experiment (LSME) used for prototype pavement testing*

A loading frame (100-kN actuator with 165-mm stroke) and a steel loading plate (125-mm radius and 25-mm thickness) were used to apply cyclic loading to the surface of the pavement. The stress applied to the surface of the base course was obtained by conducting nonlinear finite-element simulations of a pavement profile similar to the one in the LSME, but with a 0.1-m-thick HMA layer. The program MICHPAVE *(21)* was used to simulate stress dependency of the base course modulus. The simulated pavement was subjected to traffic wheel loads corresponding to 4-axle trucks (70 kN per axle and 35 kN per wheel set) with a tire pressure of 700 kPa.

The MICHPAVE analysis showed that the stress at the surface of the base course decreased to 144 kPa and was relatively uniform within the 125-mm radius of the loading plate. Thus, a load of 7 kN was applied to the plate so that the average stress for the plate was 144 kPa. This load was applied as a haversine pulse shape with a loading period of 0.1 s followed by a rest period of 0.9 s (NCHRP 1-28a).

Deflections at the surface of the base course layer and subgrade were measured using six linear variable differential transducers (LVDTs) with 5-mm stroke. Four of the LVDTs measured the deflection at the surface of the base course, and two of them at the surface of the subgrade. Total, elastic, and plastic deflections at top of the loading plate and the subgrade were determined, and the difference designated as the deformation in the base course. The recoverable portion of the deflection during a loading pulse was designated as the elastic deflection. The difference between the total deflection and elastic deflection was designated as the plastic deflection. More details on the testing conditions can be found in Benson et al. *(22)*.

MICHPAVE was used to backcalculate the resilient modulus of each base course material using the elastic deflection data for the base course recorded in the LSME. Resilient modulus of the base layer (M_r) was assumed to follow the nonlinear elastic power function model

$$M_r = k_1 (\frac{\sigma_b}{p_r})^{k_2} \quad \text{(Eq. 1)}$$

where σ_b is the bulk stress, p_r is a reference stress (1 kPa in this study), and k_1 and k_2 are empirical parameters. The parameter k_2 is dimensionless and represents the stress dependency of modulus. Typically k_2 falls in the range of 0.45 to 0.62 for granular base course materials *(23)*. The parameter k_2 of each base course material was assumed to be constant in the LSME and set at the value obtained for the same material from the BSRM test. The parameter k_1 was varied until the deflection predicted by MICHPAVE matched the measured elastic deflection in the LSME. The underlying sand layer was assumed to be linear elastic with a modulus of 70 MPa. This inversion yields the resilient modulus as a function of bulk stress, σ_b, as well as the distribution of stress and strain within the pavement system. A summary resilient modulus (SRM) was computed, as suggested in NCHRP 1-28a, corresponding to a bulk stress of 208 kPa.

The average plastic strain (ε_p) in the base layer was defined as:

$$\varepsilon_p = \frac{d_p}{t} \times 100 \quad \text{(Eq. 2)}$$

where d_p is the plastic deflection and t is the thickness of the base layer.

3.2 Bench-Scale Resilient Modulus Tests

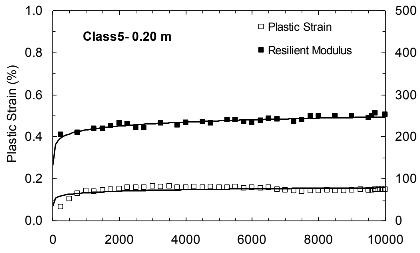
BSRM tests were conducted on compacted specimens of the base course materials in accordance with NCHRP 1-28a (Procedure Ia). Specimens were compacted in six lifts of equal mass and thickness in a split mold (152-mm diameter, 305-mm height). All materials were compacted to 100% of standard Proctor maximum dry unit weight at optimum water content (Table 1). Eq. 1 was fit to the resilient moduli obtained from the BSRM test and a summary resilient modulus (SRM) was calculated corresponding to σ_b of 208 kPa.

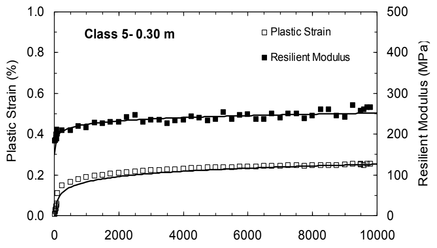
4. Results and Discussion

4.1 *Resilient Modulus and Plastic Deformation from LSME*

Plastic strain (ε_p) and summary resilient modulus (SRM) of the RPM, RSG, and Class 5 base as a function of number of load cycles (N) in the LSME are shown in Fig. 4 for two base thicknesses (0.20 and 0.30 m). In all cases, the SRM and plastic strain increase monotonically with number of loading cycles.

The Class 5 base reaches a steady-state condition (negligible rate of plastic strain $d\varepsilon_p/d\ln N = 0.01$, or “plastic shakedown”) in 2000 cycles. Werkmeister et al. *(24)* showed similar behavior for conventional base course materials and natural aggregates. In contrast, RSG exhibits a high initial rate of permanent deformation for both layer thicknesses, which diminishes to a lower and near constant rate of deformation after 2000 cycles. This behavior is attributed to the plastic fines (12%) in RSG (also noted by Yang et al. *(25)*) and suggests that RSG exhibits creep shakedown behavior. The RPM exhibits a similar behavior as the RSG. However, for RPM, the initial rate of plastic strain is lower, although the transition to a constant rate of plastic strain also occurs after 2000 cycles. The rate of plastic strain accumulation of RPM ($d\varepsilon_p/d\ln N = 0.07$) is lower than that of RSG ($d\varepsilon_p/d\ln N = 0.12$) when the rate of plastic strain becomes constant. Similar findings have been reported by Mohammad et al. *(26)* for base courses constructed with recycled asphalt pavement (RAP) subjected to cyclic loading. The longer transition to a constant rate of plastic deformation for RPM is attributed to the viscous characteristic of the asphalt coatings on the aggregates in RPM (Fig. 1).





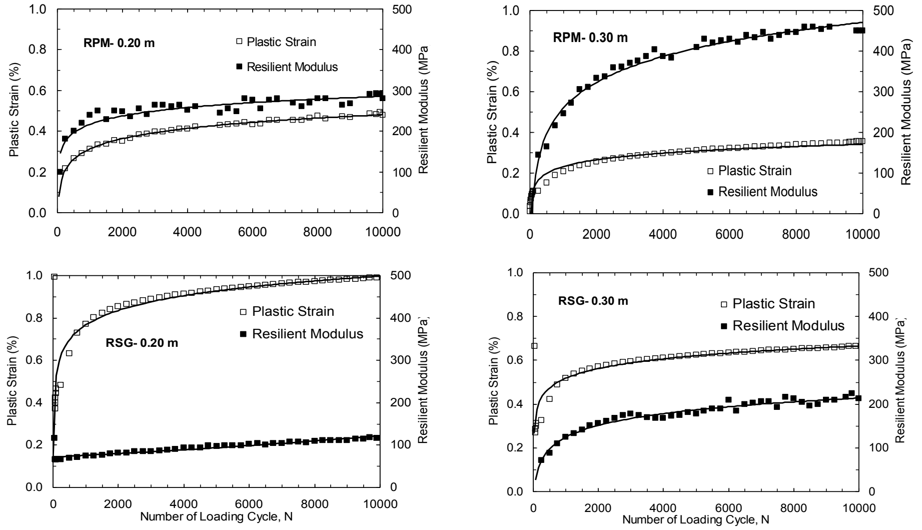


Figure 4. *Plastic strain and resilient modulus vs. number of load cycles for (a) Class 5, (b) RPM, and (c) RSG with thickness of 0.2 (left) and 0.3 m (right)*

Plastic strain and resilient modulus of RPM and RSG stabilized with 10% fly ash (i.e., SRPM and SRSG) are shown in Fig. 5 as a function of number of loading cycles. Four LSME test sequences of 10,000 cycles each were conducted on each material, with 7 d of curing between tests. The resilient modulus increases with increasing curing time for SRPM and SRSG. The SRPM exhibits a small and near constant rate of plastic strain after approximately 4000 cycles, and the SRSG exhibits a constant and very small plastic strain (< 0.1%). Mohammad et al. *(26)* also report small plastic strains for recycled foamed asphalt and blended calcium sulfate (BCS) stabilized with fly ash and slag.

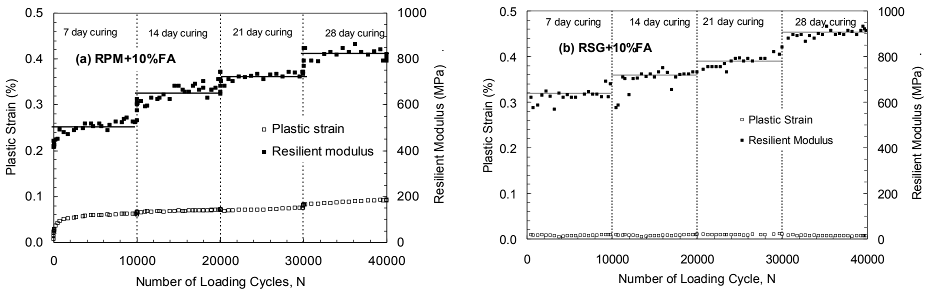


Figure 5. *Permanent deformation and resilient modulus versus the number of load cycles for (a) RPM and (b) RSG stabilized with fly ash (0.3 m thicknesses)*

Lower plastic strains generally are associated with materials having higher resilient modulus *(8)*. However, in this study, the largest plastic strains are associated with the RPM and RSG, even though these materials have similar or higher resilient modulus than the Class 5 base (see subsequent discussion). The higher plastic strain is attributed to viscous creep of the asphalt in the RPM and the fines in the RSG. In contrast, the SRPM and SRSG have the lowest plastic strains and the highest resilient moduli. Binding by the self-cementing fly ash reduces plastic creep in the RPM and RSG appreciably, which is also evident when Figs. 4 and 5 are compared.

The cumulative permanent deformation of unstabilized RPM and RSG under traffic loading likely will be higher than conventional natural aggregate. Thus, excessive rutting may be encountered in flexible pavements that employ RPM or

RSG in lieu of conventional base course materials. In contrast, RPM or RSG stabilized with cementitious fly ash should result in less rutting than conventional base aggregate *(8)*.

4.2 Resilient Modulus from BSRM Test

Table 3 shows resilient modulus and fitting parameters in Eq. 1 for RPM, RSG, and Class 5. The stress dependency of base course materials is reflected in k_2 parameter in Eq. 1. Class 5 base has $k_{2=}$ 0.53, which is in the typical range for the granular materials *(23)*. RPM has lower k_2 (= 0.34) indicating lower dependency on bulk stress. RSG has k_2 =0.44, intermediate between RPM and Class 5 base, reflecting the effect of fines content compared to Class 5 aggregate (i.e., less sensitive to the bulk stress than Class 5), as described by Huang (23). For the materials stabilized with fly ash, the resilient modulus is independent of bulk stress ($k_2 \approx 0$) due to the cementation of particles. Chemical bonds between particles prevail over the interparticle friction, which precludes stress dependency of the resilient modulus. Therefore, the stress and strain levels do not affect the resilient modulus and plastic deformation of SRPM and SRSG in the pavement, (fatigue cracking would be an exception).

Table 3. *Summary resilient modulus (SRM) and power model fitting parameters from Eq. 1 for base course materials.*

Material	Test method	Thickness (mm)	Fly Ash Content (%)	Curing Time (day)	Measured Parameters		
					k_1	k_2	M_r (MPa)
Class 5 base	Lab*	-	0	-	13.6	0.53	236
	LSME	200		-	19.7	0.53	284
		300		-	29.5	0.53	426
RPM	Lab*	-	0	-	49.2	0.34	309
	LSME	200		-	50	0.34	307
		300		-	82	0.34	505
SRPM	Lab*	-	10	7	1753	0	1753
		-		28	2702	0	2702
	LSME	300		7	483	0	483
		300		28	845	0	845
RSG	Lab	-	0	-	21.6	0.44	226
	LSME	200		-	11	0.44	115
		300		-	20.6	0.44	216
SRSG	Lab	-	10	28	5150	0	5150
	LSME	300		7	673	0	673
		300		28	918	0	918

Note: Summary Resilient Modulus (M_r) is calculated at a bulk stress of 208 kPa.
* Reported by Camargo *(17)*.

4.3 *Comparison between SRM from LSME and BSRM Tests*

SRM of base course materials from the LSME and BSRM tests are shown in Fig. 6. SRM of the Class 5 base, RPM, and RSG from the LSME are up to 1.5 times larger than those from the BSRM test. This difference in the resilient moduli of the unstabilized materials is attributed to the interplay of the strain amplitude in the two test methods. Tanyu et al. *(20)* indicate that the resilient moduli of granular materials from the LSME are higher than those from BSRM tests because of the lower strains in the thicker layers at prototype scale.

To illustrate this effect, strain dependency of the modulus of the unstabilized materials was characterized using the backbone curve developed by Hardin and Drnevich *(27)*. Resilient moduli from the LSME and BSRM tests were normalized with respect to the low strain Young's modulus from seismic tests (E_s), as shown in Fig. 7 (More details in Benson et al. *(22)*). The seismic tests were conducted using micro-electromechanical systems (MEMS) buried at various depths in the compacted base course materials in the LSME. They were used to measure the travel time of seismic waves transmitted from the surface by a hammer impact. The shear strain for the low strain Young's modulus (E_s) was < 10^{-5}.

The E_s was calculated as described by Schuttpelz et al. *(19)*:

$$E_s = V_P^2 \rho \frac{(1+\nu)(1-2\nu)}{(1-\nu)} \qquad \text{(Eq. 3)}$$

where V_P = P-wave velocity calculated from seismic testing, ρ = mass density, and ν = Poisson's ratio (see Table 2). As shown in Fig. 7, the same stress level in the

LSME and BSRM test (confining stress = 45 kPa) resulted in different strain levels due to the scale effect.

SRM from the BSRM test on the SRPM and SRSG consistently was 3 to 5 times higher than the SRM from the LSME, i.e., opposite the behavior for granular materials. This difference is attributed to the mixing and curing conditions associated with fly ash stabilized materials, as reported in several investigations *(2, 10, 16)*. More thorough mixing and controlled curing occurs when preparing small specimens for a BSRM test compared to the LSME or the field. For example, the temperature varied from 25^o to 30 ^{o}C and the humidity was between 70 to 80% during the LSME test, whereas the BSRM specimens were cured at 25 ^{o}C and 100% humidity. Thus, the BSRM specimens probably cured more uniformly than the fly ash stabilized materials in the LSME.

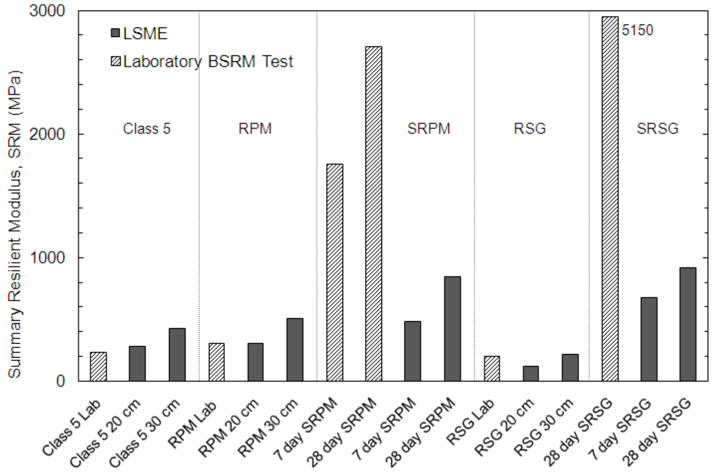


Figure 6. *Summary resilient modulus (SRM) from the LSME and laboratory BSRM test*

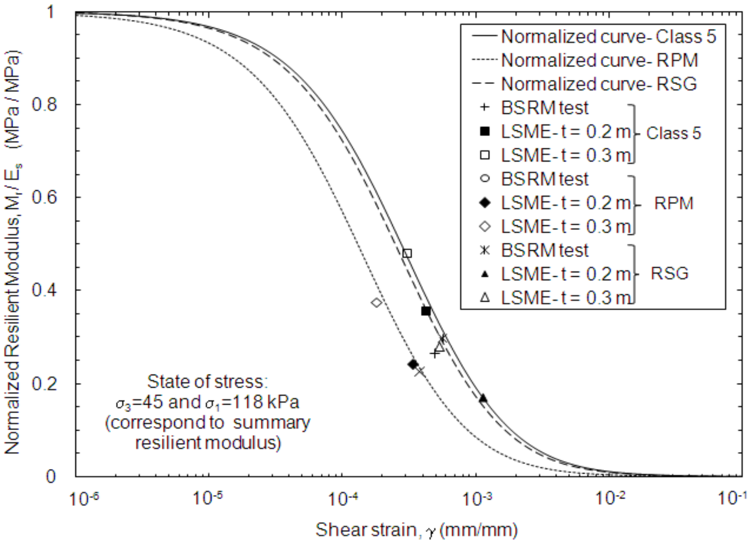


Figure 7. *Strain dependency of the resilient modulus of recycled materials from the BSRM test and LSME*

The relationship between SRM and layer thickness of base course from the LSME is shown in Fig. 8. Resilient moduli corresponding to typical base course thicknesses other than the 0.20-m and 0.30-m thicknesses tested in the LSME were predicted using the backbone curve calibrated with the LSME (More details is presented in Benson et al. *(22)*). For the unstabilized base materials, the SRM is consistently higher for thicker base course layers due to the lower shear strain amplitude in thicker layers for the same surface load.

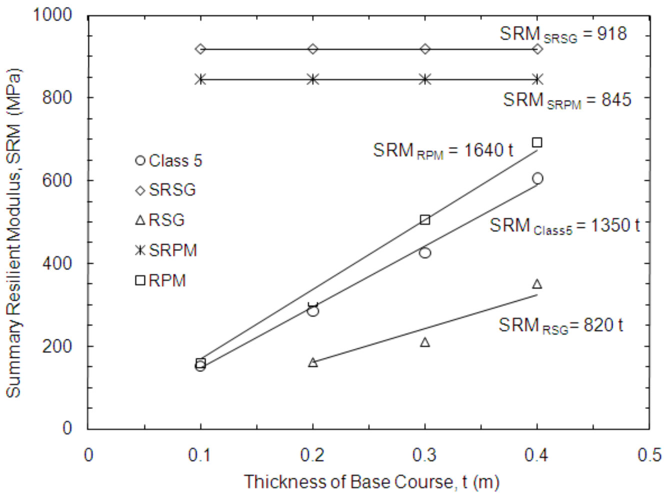


Figure 8. *Summary resilient modulus (SRM) of Class 5 base, RPM, RSG, SRPM, and SRSG as a function of base course thickness*

5. Design Approaches for Recycled Materials as Base Course

Two design approaches were developed for flexible pavements using unstabilized and stabilized RPM and RSG in the base: (1) an equivalency-based design using AASHTO-1993 design guide *(28)* and (2) lifetime expectancy-based design using the Mechanistic Empirical Pavement Design Guide (MEPDG *(29)*). To simulate field conditions, SRM from the LSME were used to develop the method.

5.1 *Equivalency-Based Design Using AASHTO 1993*

Equivalency-based design was developed based on the premise of generating a pavement structure constructed with recycled base course materials that have equivalent structural capacity as the pavement constructed with conventional base course materials. AASHTO-1993 *(28) Guide for Design of Pavement Structures* uses the structural number (SN) to describe the structural capacity and contribution of each pavement layer. Two main factors control the SN of the base course according to the AASHTO 1993: layer thickness and layer coefficient, the latter reflecting the stiffness of the layer (function of the SRM). The SN of the entire pavement is defined as the summation of the SN of the pavement layers (AASHTO 1993)

$$SN = [SN_1 + SN_2\, m_2 + SN_3\, m_3]/25 = [b_1\, t_1 + b_2\, t_2\, m_2 + b_3\, t_3\, m_3]/25 \qquad \text{(Eq. 3)}$$

where m_i is the drainage modification factor (assumed equal to 1 in this study), b_i is the layer coefficient, and t_i is the thickness (mm) of the layer i (i=1 asphalt, i=2 base course, i=3 subbase). The layer coefficient (b_2) of a granular base course is empirically related to resilient modulus *(28)* by

$$b_2 = 0.249 \log SRM - 0.44 \qquad \text{(Eq. 4)}$$

where SRM is the summary resilient modulus of the granular base material (in MPa). Base course material stabilized with fly ash was also assumed to follow Eq. 4.

Layer coefficients (b_2) for the recycled materials used in this study were calculated using Eq. 4 by employing the SRM from the LSME (Fig. 8), and are shown in Fig. 9. The layer coefficients are within the typical range of layer coefficients presented in AASHTO-1993 *(28)* for base course layers. For the materials without fly ash, the layer coefficient varies with thickness because the lower strain amplitude in thicker layers results in higher SRM (Fig. 7). For example, the layer coefficient of 0.3-m-thick RPM is 0.20, whereas the layer coefficient for a 0.2-m-thick RPM is 0.17 because of the higher strains in a thinner layer of RPM. In contrast, the layer coefficient for the materials stabilized with fly ash (SRPM and SRSG) does not vary with base course thickness because the SRM of stabilized materials is not stress or strain dependent. The layer coefficient for the stabilized materials is also higher than the layer coefficients for unstabilized materials, indicating that base courses constructed with stabilized materials have higher structural capacity.

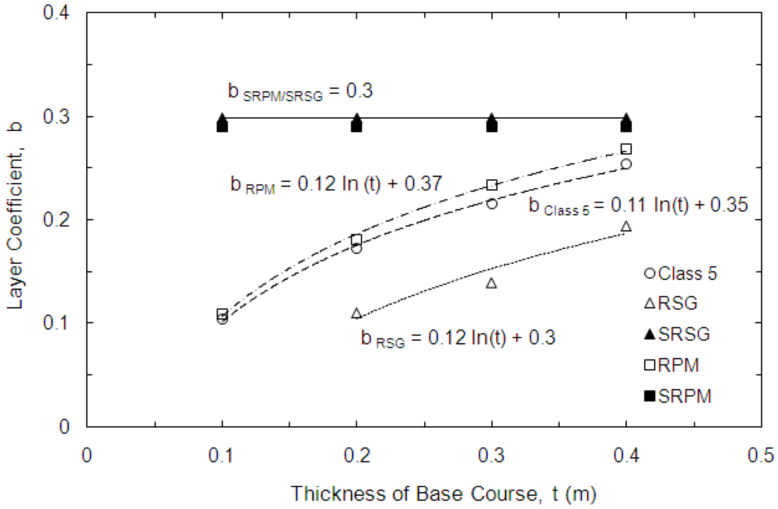


Figure 9. *Layer coefficients for Class5 base, RPM, RSG, SRPM, and SRSG as a function of base course thickness*

The layer coefficients presented in Fig. 9 can be applied directly to the design of flexible pavements in accordance with AASHTO 1993. However, an equivalency design approach was developed as a design tool to relate the required thickness of recycled materials relative to the thickness of conventional base course aggregate. Designers have experience with common thicknesses of natural aggregate base in many applications. Thus, this approach gives them a simple tool for selecting a base course comprised of recycled materials.

The equivalency-based design equates the SN of a pavement having an alternative recycled base course to that of a pavement constructed with quality aggregate base. MnDOT's Class 5 base *(30)* was used as the standard base material. The structural number of base course consisting of recycled material (SN_r) was set equal to the structural number of conventional base course material (SN_c). These SN are computed as

$$SN_r = b_1\, t_1 + b_r\, t_r \qquad \text{(Eq. 5)}$$

$$SN_c = b_1\, t_1 + b_c\, t_c \qquad \text{(Eq. 6)}$$

where the subscripts r and c denote the conventional and the alternative recycled base course materials (Fig. 10).

If the HMA thickness and properties are assumed to be the same for the two pavement configurations, the relationship between thicknesses and layer coefficients for the conventional and recycled base materials is

$$\frac{t_c}{t_r} = \frac{b_r}{b_c} \qquad \text{(Eq. 7)}$$

Substituting Eq. 4 into Eq. 7 yields

$$\frac{t_r}{t_c} = \frac{0.249 \log \mathrm{SRM}_c - 0.44}{0.249 \log \mathrm{SRM}_r - 0.44} \qquad \text{(Eq. 8)}$$

where SRM is in MPa.

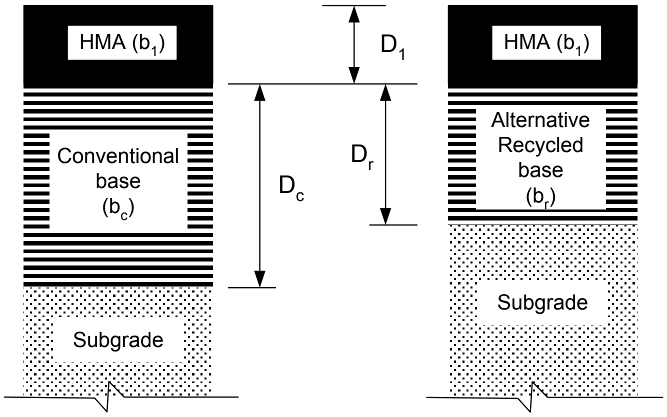


Figure 10. *Schematic pavement profiles for equivalency based design between conventional and alternative recycled base course materials*

The relationship between SRM and thickness in Fig. 8 was used in Eq. 8 to create a design graph for recycled materials as a base course (Fig. 11). RPM has nearly an equivalent thickness to Class 5 base in a pavement structure because both materials have similar moduli. A thicker layer of RSG is required to obtain a base equivalent to the Class 5 base because RSG has lower SRM than Class 5 aggregate. Similarly, fly ash stabilization improves the structural capacity of the RPM and RSG and results in a thinner equivalent base course layer (e.g., a 0.22-m-thick SRPM or SRSG layer is equivalent to a 0.3-m-thick Class 5 base).

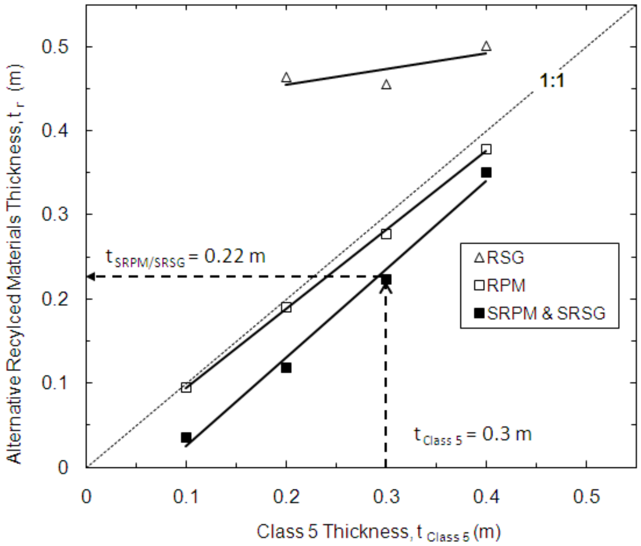


Figure 11. *Alternative recycled material thickness as a function of Class 5 thickness*

5.2 *Equivalency-Based Design Using MEPDG*

An equivalency-based design approach was developed using the Mechanistic Empirical Pavement Design Guide (MEPDG *(29)*) so that plastic deformation of base course could be accounted for explicitly in the design (plastic deformation is not implicit in the AASHTO-1993 method). MEPDG uses mechanistic-empirical models to predict damage accumulation over the predicted service life of a pavement data on traffic, climate, materials, and the pavement structure as input. The data input to MEPDG are shown in Table. 3.

SRM and plastic deformation obtained from the LSME were used in MEPDG to predict the rut depth and international roughness index (IRI) of a pavement. The calibration factor (B_{s1}) in Table 3 was determined by inversion of the LSME data (plastic deformations from the LSME were matched with predictions from MEPDG). The rut depth and international roughness index (IRI) were then determined in pavement structures consisting of various base course materials (i.e., Class 5, RPM, RSG, and SRPM/SRSG). Material properties and geometry of HMA and subgrade layers were assumed to be the same for all cases. The subgrade modulus was assumed to be 70 MPa and the average annual daily truck traffic (AADTT) was assumed to be 4000.

Table 4. *Input parameters for MEPDG program*

<table>
<tr><td rowspan="5">Traffic</td><td>Initial Two-way</td><td colspan="3">4000 AADTT</td></tr>
<tr><td>Number of Lanes</td><td colspan="3">2</td></tr>
<tr><td>Operation Speed</td><td colspan="3">110 km/h</td></tr>
<tr><td>Dual Tire Spacing</td><td colspan="3">0.3 m</td></tr>
<tr><td>Tire Pressure</td><td colspan="3">800 kPa</td></tr>
<tr><td>Environment</td><td colspan="4">I-94 Minnesota -USA</td></tr>
<tr><td rowspan="3">Asphalt Binder Superpave Binder Grading</td><td>Thickness</td><td colspan="3">0.1 m</td></tr>
<tr><td>A</td><td colspan="3">10.98</td></tr>
<tr><td>VTS</td><td colspan="3">-3.6</td></tr>
<tr><td rowspan="2">Base Course A-1-a</td><td>Thickness</td><td colspan="3">0.3 m</td></tr>
<tr><td>Modulus</td><td colspan="3">From LSME, presented in Fig. 8</td></tr>
<tr><td rowspan="2">Subgrade</td><td>Thickness</td><td colspan="3">0.5 m</td></tr>
<tr><td>Modulus</td><td colspan="3">70 MPa</td></tr>
<tr><td colspan="5">Rutting for Granular Materials</td></tr>
<tr><td>Rutting Calibration Factor</td><td>RSG</td><td>RPM</td><td>Class 5</td><td>SRPM/ SRSG</td></tr>
<tr><td>B_{s1}</td><td>1.7</td><td>1.4</td><td>1.0</td><td>0.1</td></tr>
</table>

Service lives of pavement structures constructed with RSG, RPM, Class 5 aggregate, and SRPM/SRSG as base course were determined based on two criteria: a limiting rut depth of 12.7 mm (*23*) and a limiting IRI of 2.7 m/km (*29*). Service lives based on limiting rutting depth are shown in Fig. 12a and based on IRI in Fig. 12b for pavements with different base course materials and thicknesses. The rutting calibration factors and SRM for base course thicknesses other than 0.2 and 0.3 m were extrapolated from the LSME data.

The service life of a pavement constructed with RSG is shorter than for Class 5 aggregate due to the lower resilient modulus (Fig. 6) and more rapid rutting (Fig. 12) of RSG. The service life of a pavement constructed with RPM is similar to the service life for a pavement with Class 5 aggregate base, even though RPM has higher rutting potential compared to Class 5 aggregate (i.e., rutting calibration factor = 1.4 vs. 1.0 in Table 4). RPM has higher resilient modulus (500 MPa for RPM vs. 400 MPa for Class 5 aggregate for 0.3-m thickness, Fig. 8), which results in different stress distribution and consequently different contributions to rutting from the base course layer. Consequently, rutting is comparable for RPM and Class 5 aggregate.

Fly ash stabilization of RPM or RSG increases the service life appreciably. Using 0.3-m-thick SRPM or SRSG base instead of 0.3-m-thick Class 5 or RPM base increases the service life of the pavement structure from 17 to 21 years.

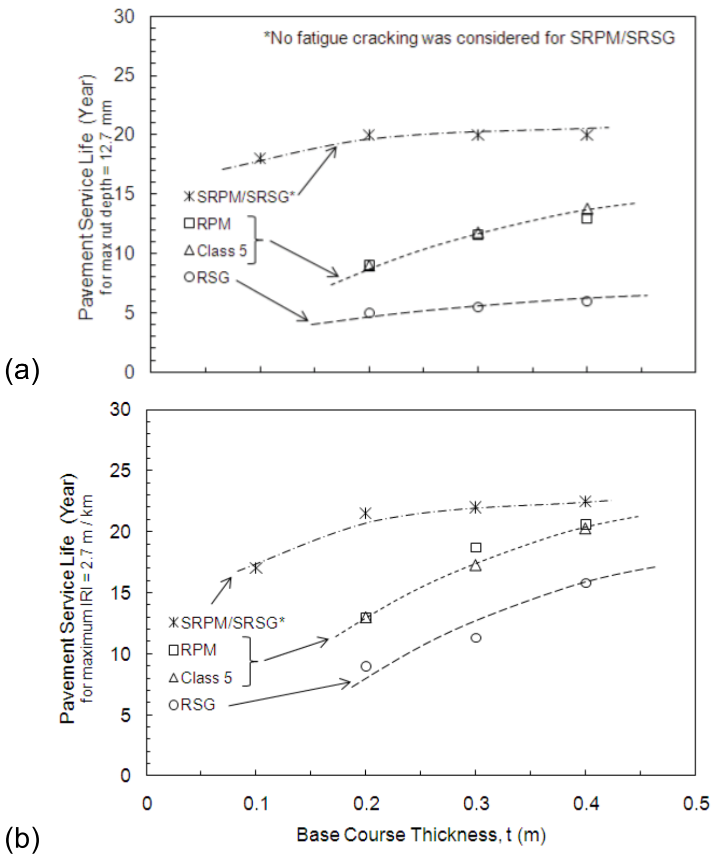


Figure 12. *Life time expectancy of pavement structure with conventional and recycled base course materials for limiting rut depth (a) and IRI (b) from MEPDG.*

6. Conclusions

Large-scale model experiments (LSME) and standard bench-scale resilient modulus (BSRM) tests were conducted on recycled pavement material (RPM), reclaimed road surface gravel (RSG), and conventional Class 5 base from Minnesota. The RPM and RSG were tested alone and with fly ash stabilization. Based on the findings of this study, the following conclusions are made:

1. RSG has the lowest summary resilient modulus (SRM), RPM the highest, and the Class 5 gravel falls in between. Stabilization of RPM or RSG with self-cementing fly ash (10% by weight) increased the SRM significantly.
2. SRM of unstabilized base course materials backcalculated from LSME tests was higher than SRM from BSRM tests and varies with layer thickness. These differences in SRM are due to differences in strain amplitudes in the LSME and BSRM tests.
3. SRM backcalculated from the LSME for RPM and RSG stabilized with fly ash is smaller than SRM from BSRM tests and is independent of layer thickness. This difference is attributed to the more thorough mixing and curing procedure used to prepare specimens for BSRM tests compared to the LSME. Similar differences also occur in the field.

4. LSME tests indicated that RPM and RSG have higher potential for accumulating plastic deformation during the service life of a pavement compared to natural aggregate RPM and RSG stabilized with fly ash (SRPM and SRSG) exhibit negligible plastic deformation.
5. Resilient modulus and plastic strain obtained from the LSME are considered to be more representative of field conditions than those from BSRM tests and are recommended for developing design methodologies for use of recycled base materials, such as the methods described in this paper.
6. Layer coefficients of unstabilized granular base materials increase with thickness of the base course layer. The layer coefficients for RSG and RPM are in the range of 0.10-0.20 and 0.10-0.25, depending on layer thickness (0.1 to 0.4 m). SRPM and SRSG have a layer coefficient of 0.30, which is independent of layer thickness.
7. Pavements constructed with RPM base have a similar service life as those with Class 5 aggregate base. Pavements constructed with RSG base have shorter service life due to the lower resilient modulus and more rapid rutting of RSG.
8. Stabilization of recycled materials used as base course can reduce the required thickness of the base course up to 30% or increase the service life of pavements by more than 20%.

ACKNOWLEDGMENT

The Minnesota Local Roads Research Board (LRRB) and the Recycled Materials Resource Center (RMRC) provided financial support for this study. Xiaodong Wang of the University of Wisconsin-Madison assisted with the LSME tests.

Bibliography

1. Epps, J. A. *Cold-Recycled Bituminous Concrete Using Bituminous Materials*. NCHRP Synthesis of Highway Practice 160, NCHRP, Washington DC, 1990.

2. Wen, H. and Edil, T. B. (2009). Sustainable Reconstruction of Highways with In-situ Reclamation of Materials Stabilized for Heavier Loads, *Proc.* 2nd Int. Conf. on Bearing Capacity of Roadway, Railways and Airfields, Urbana-Champaign, IL, on CD-ROM.

3. Lee, J. C., Edil, T. B., Tinjum, J. M. and Benson, C. H. A Quantitative Assessment for Environmental and Economic Benefits of Using Recycled Materials in Highway Construction, *Transportation Research Record*, No. 2158, Transportation Research Board, National Research Council, Washington DC, 2010, 138-142.

4. Taha, R. Evaluation of Cement Kiln Dust-Stabilized Reclaimed Asphalt Pavement Aggregate Systems in Road Bases. *J. of Trans. Res. Rec.*, No. 1819, Transportation Research Board, Washington, DC, 2003, 11-17.

5. Cooley, D. Effects of Reclaimed Asphalt Pavement on Mechanical Properties of Base Materials. *MS Thesis*, Brigham Young University, Provo, UT, 2005.

6. Kim, W., Labuz, J., Dai, S. Resilient Modulus of Base Course Containing Recycled Asphalt Pavement, *J. of Trans. Res. Board,* No. 1981, Transportation Research Board, Washington, DC, 2007, 27-35.

7. Mohammad, L. N., Herath, A., Rasoulian, M. and Zhongjie, Z. (2006). Laboratory Evaluation of Untreated and Treated Pavement Base Materials: Repeated Load Permanent Deformation Test, *J. of the Trans. Res. Board*, No. 1967, Transportation Research Board, Washington, DC, 78–88.

8. Kootstra, B. R., Ebrahimi, A., Edil, T. B., and Benson, C. H. Plastic Deformation of Recycled Base Materials, *Proc. GeoFlorida 2010*, Advances in Analysis, Modeling and Design, ASCE Geo Institute, GSP 199, West Palm Beach, FL, 2682-2691

9. Edil, T. B., Benson, C., Bin-Shafique, M., Tanyu, B., Kim, W. and Senol, A. Field Evaluation of Construction Alternatives for Roadways over Soft Subgrade, *J. of Trans. Res. Board,* No. 1786, Transportation Research Board, Washington, DC, 2002, 36-48.

10. Bin-Shafique, S., Edil, T. B., Benson, C. H. and Senol, A. Incorporating a Fly-Ash Stabilized Layer into Pavement Design. *Geotechnical Engineering-ICE*, 157 (GE4), 2004, 239-249.

11. Li, L., Benson, C. H., Edil, T. B. and Hatipoglu, B. Sustainable Construction Case History: Fly Ash Stabilization of Recycled Asphalt Pavement Material, *Geotechnical and Geological Engineering,* 2008, Vol. 26, No. 2, pp. 177-188 (also TRB Paper 07-0914).

12. Edil, T. B., Acosta, H. A. and Benson, C. H. Stabilizing Soft Fine-Grained Soils with Fly Ash. *J. of Mat. in Civil Eng.*, 18(2), 2006, 283-294.

13. Senol, A., Edil, T. B., Bin-Shafique, M. S., Acosta, H. A., Benson, C. H. Soft Subgrades' Stabilization by Using Various Fly Ashes, *Resources Conservation and Recycling,* 46(4), 2006, 365-376.

14. Wen, H., Tharaniyil, M., Ramme, B. and Krebs, U. Field Performance Evaluation of Class C Fly Ash in Full-depth Reclamation: Case History Study, *J. of Trans. Res. Board,* No. 1869, Transportation Research Board, Washington, DC, 2004, 41-46.

15. Wen, H., Warner, J., Edil, T. B. and Wang, G. Laboratory Comparison of Crushed Aggregate and Recycled Pavement Material With and Without High Carbon Fly Ash, *Geotechnical and Geological Engineering*, 28(4), 2010, 405-411.

16. Hatipoglu, B., Edil, T. B., and Benson, C. H. Evaluation of Base Prepared from Road Surface Gravel Stabilized with Fly Ash, *ASCE Geo. Special Publication,* 177, 2008, 288-295.

17. Camargo, F. F., Edil, T. B., Benson, C. H. Strength and Stiffness of Recycled Base Materials Blended with Fly Ash, *Proc.* 88th Annual Meeting, CD-ROM, 09-1971, National Research Council, Washington DC, 2009.

18. Crovetti, J. Construction and Performance of Fly Ash-Stabilized Cold In-place Recycled Asphalt Pavement in Wisconsin, *J. of Tran. Res. Board,* No. 1730, Transportation Research Board, Washington, DC, 2000, 161-166.

19. Schuettpelz, C. C., Fratta, D., and Edil, T. B. Mechanistic corrections for determining the resilient modulus of base course materials based on elastic wave measurements. *Journal of Geotechnical and Geoenvironmental Engineering*. Vol. 136, No. 8, 2010, 1086-1094

20. Tanyu, B. F., Benson, C. H., Edil, T. B., and Kim, W. Equivalency of Crushed Rock and Three Industrial By-products Used for Working Platforms During Pavement Construction, *J. of Trans. Res. Rec.,* No.1874, Trans. Research Board, Washington, DC, 2004, 59-69.

21. Harichandran, R. S., Baladi, G. Y., Yeh, M. Development of a Computer Program for Design of Pavement Systems Consisting of Bound and Unbound Materials, Dept. of Civil and Envir. Eng., Michigan State University, Lansing, Michigan, 1989.

22. Benson, C. H., Edil, T. B., Ebrahimi, A., Kootstra, R. B., Li, L., and Bloom, P. *Use of Fly Ash for Reconstruction of Bituminous Roads: Large Scale Model Experiments,* Minnesota Department of Transportation, St Paul, MN, 2009. (http://www.recycledmaterials.org/Research/current/project_47/project_47_final_report.pdf)

23. Huang, Y. *Pavement analysis and design*, Prentice-Hall, Inc., Englewood Cliffs, New Jersey, 2003.

24. Werkmeister, S., Dawson, A. R., and Wellner, F. Permanent Deformation Behavior of Granular Materials and the Shakedown Concept, *J. of the Trans. Res. Board*, No. 1757, Transportation Research Board,, Washington, DC, 2001, 75–81.

25. Yang S. R., Huang. W. H., and Liao. C. C. Correlation Between Resilient Modulus and Plastic Deformation for Cohesive Subgrade Soil Under Repeated Loading, *J. of the Trans. Res. Board*, No. 2053, Transportation Research Board, Washington, DC, 2008, 72-79.

26. Mohammad, L. N., Herath, A., Rasoulian, M. and Zhongjie, Z. Laboratory Evaluation of Untreated and Treated Pavement Base Materials: Repeated Load Permanent Deformation Test, *J. of the Trans. Res. Board*, No. 1967, Transportation Research Board, Washington, DC, 2006, 78–88.

27. Hardin, B. O., and Drnevich, V. P. Shear Modulus and Damping in Soils: Design Equations and Curves. *J. Soil Mech. and Found. Div.*,98, SM7, 1972, 667–692.

28. *AASHTO Guide for Design of Pavement Structures*, American Association of State Highway and Transportation Officials, Washington DC, 1993.

29. NCHRP 1-37A. *Mechanistic-empirical design method for the structural design of new and rehabilitated pavement structures*. Final Report for NCHRP 1-37A, National Cooperative Highway Research Program, Washington, DC, 2004.

30. MnDOT. *Standard Specifications for Construction*, MNDOT, St. Paul, MN, 2005.

APPENDIX C

Recycled Base Aggregates in Pavement Applications Webinar Slides

by

Jeffrey Melton

Recycled Base Aggregates in Pavement Applications

Jeffrey S. Melton, Ph.D.
Outreach Director, Recycled Materials Resource Center
jeffrey.melton@unh.edu

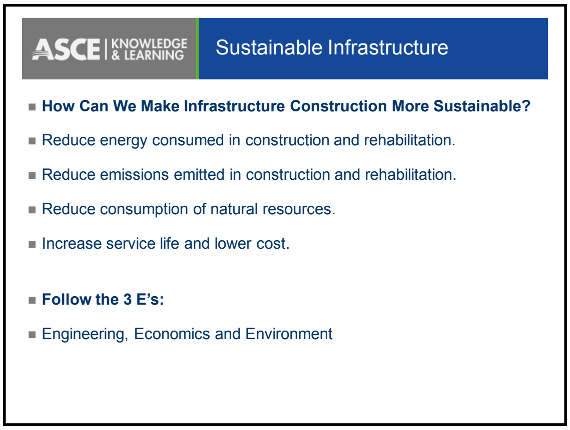
ASCE | KNOWLEDGE & LEARNING

The Big Picture

ASCE | KNOWLEDGE & LEARNING

Sustainability

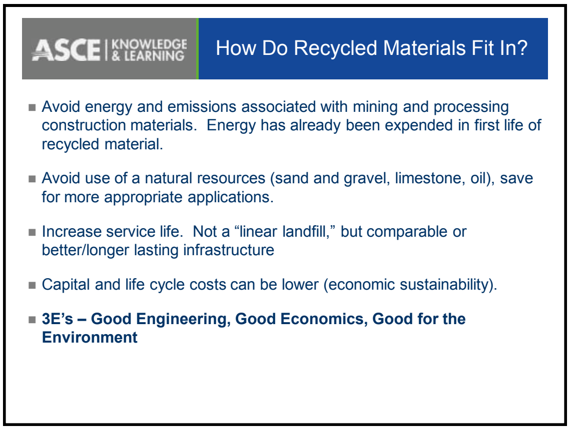
- Nexus of major issues caused by rapidly growing global economy:
  - Global warming
  - Energy constraints
  - Resource availability (metals, cement, oil etc.)
- World population is 6 billion (B) → 12 B projected by 2100. US at 0.5B by 2050.
- US and EU (combined population = 0.75 B) consume most of world resources. China catching up fast.
- Remaining 5.25 B want everything we have. Not enough to go around if we do business as usual.
- **NOT SUSTAINABLE!**



Sustainable Infrastructure

- **How Can We Make Infrastructure Construction More Sustainable?**
- Reduce energy consumed in construction and rehabilitation.
- Reduce emissions emitted in construction and rehabilitation.
- Reduce consumption of natural resources.
- Increase service life and lower cost.

- **Follow the 3 E's:**
- Engineering, Economics and Environment



How Do Recycled Materials Fit In?

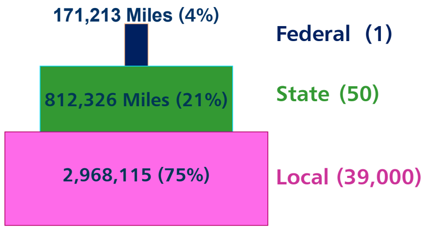
- Avoid energy and emissions associated with mining and processing construction materials. Energy has already been expended in first life of recycled material.
- Avoid use of a natural resources (sand and gravel, limestone, oil), save for more appropriate applications.
- Increase service life. Not a "linear landfill," but comparable or better/longer lasting infrastructure
- Capital and life cycle costs can be lower (economic sustainability).
- **3E's – Good Engineering, Good Economics, Good for the Environment**

Objections and Response

- **Objections**
- Global warming and sustainability are pure hooey….
- We tried using material x once in 1983 (197x, 199x) and it didn't work…
- We have plenty of sand and gravel, we don't need to recycle….
- We tried to use material x once and the public got mad….
- It costs too much to use recycled materials….

- **Response**
- Recycled Materials **CAN** provide high quality, more environmentally friendly roads that save money. **It has been done. It's good business!**

The US Highway Pyramid



171,213 Miles (4%)

Federal (1)

812,326 Miles (21%)

State (50)

2,968,115 (75%)

Local (39,000)

Roads and Streets Jurisdictional Control

Approximate Annual Highway Materials Use

- 350 million tons of material are used for highway construction each year

Aggregates	320 million TPY
Asphalt	20 million TPY
Portland cement	10 million TPY

- 353 - 859 million tons of recyclable materials are generated each year
- Can we substitute recycled aggregate materials for the natural aggregates in a cost-effective, environmentally sound method that also produces roads that are as good or better than current roads?
- Maybe not for all natural aggregates, but we can replace a large portion.

Most Common Recycled Aggregates

Recycled Concrete Aggregate (RCA)

- RCA is mostly obtained from concrete pavements.
- Stiff and angular material composed of natural aggregates with adhered mortar.
- Generally free of other materials.
- Fines from the mortar fraction can cause “self-cementation” or “re-cementation” when water is added. Individual particles adhere, forming a stiffer layer.

Recycled Asphalt Pavement (RAP)

- Crushed or milled asphalt pavement. Natural aggregate with coating of aged asphalt binder.
- Generally clean, with little deleterious materials.
- Asphalt binder is viscoelasto-plastic material. Can improve stiffness and strength, but may be susceptible to rutting.
- Use as unbound material generally **NOT** the highest value application. Check the 3E’s.

Recycled Pavement Material (RPM)

- Generated by grinding up the bound layers and some of unbound base.
- Can be a mixture of RAP and RCA (left), or RAP and base aggregate or RAP, RCA and aggregate.
- Properties depend on the constituents to some degree, may behave more like RAP or more like regular mineral aggregate depending on the proportions.

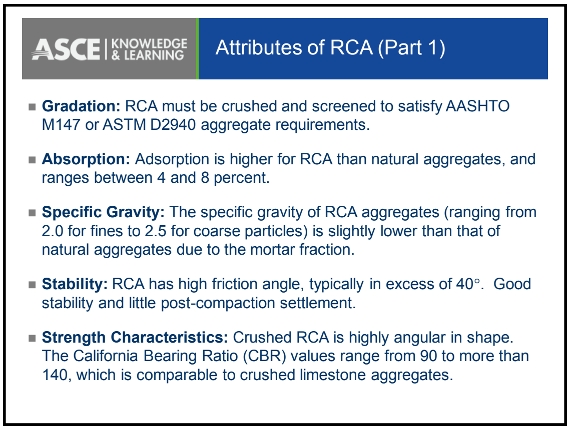
Building Derived Concrete (BDC)

- Crushed concrete primarily derived from the demolition of industrial buildings and related infrastructure.
- Can contain stone, brick, asphalt pieces, porcelain and decorative concrete. May also have a higher soil fraction.
- Gradation depends on processing, but typically has a higher fines content.
- Currently not accepted by most transportation agencies.

Recycled Road Surface Gravel (RSG)

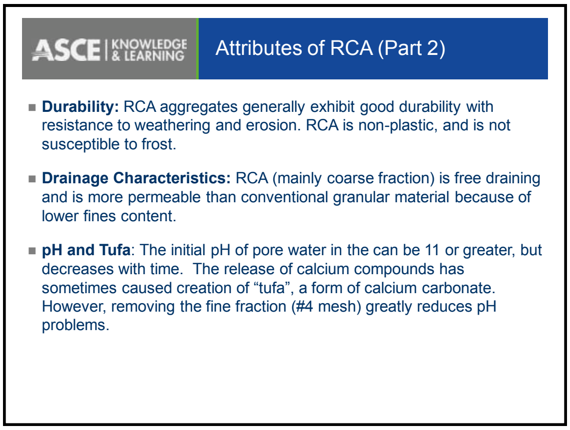
- Natural mineral aggregate used to surface unpaved roads.
- Actually a blend of gravel (or aggregate), sand and fines that will compact for form a hard crust.
- Mostly used for low volume roads without heavy loads.
- Can be stabilized into a base layer for hot mix asphalt if the road needs to be upgraded.

Attributes of Recycled Aggregates



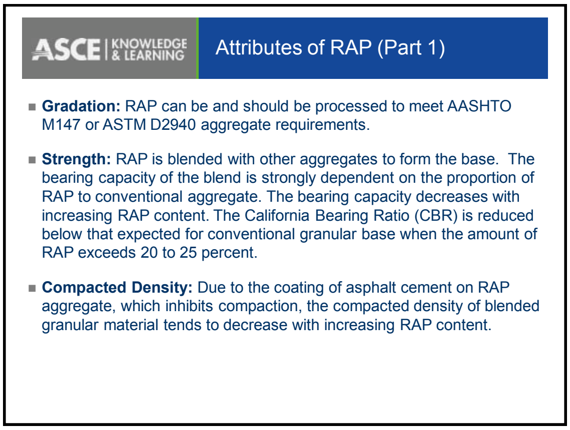
Attributes of RCA (Part 1)

- **Gradation:** RCA must be crushed and screened to satisfy AASHTO M147 or ASTM D2940 aggregate requirements.
- **Absorption:** Adsorption is higher for RCA than natural aggregates, and ranges between 4 and 8 percent.
- **Specific Gravity:** The specific gravity of RCA aggregates (ranging from 2.0 for fines to 2.5 for coarse particles) is slightly lower than that of natural aggregates due to the mortar fraction.
- **Stability:** RCA has high friction angle, typically in excess of 40°. Good stability and little post-compaction settlement.
- **Strength Characteristics:** Crushed RCA is highly angular in shape. The California Bearing Ratio (CBR) values range from 90 to more than 140, which is comparable to crushed limestone aggregates.



Attributes of RCA (Part 2)

- **Durability:** RCA aggregates generally exhibit good durability with resistance to weathering and erosion. RCA is non-plastic, and is not susceptible to frost.
- **Drainage Characteristics:** RCA (mainly coarse fraction) is free draining and is more permeable than conventional granular material because of lower fines content.
- **pH and Tufa**: The initial pH of pore water in the can be 11 or greater, but decreases with time. The release of calcium compounds has sometimes caused creation of “tufa”, a form of calcium carbonate. However, removing the fine fraction (#4 mesh) greatly reduces pH problems.



Attributes of RAP (Part 1)

- **Gradation:** RAP can be and should be processed to meet AASHTO M147 or ASTM D2940 aggregate requirements.
- **Strength:** RAP is blended with other aggregates to form the base. The bearing capacity of the blend is strongly dependent on the proportion of RAP to conventional aggregate. The bearing capacity decreases with increasing RAP content. The California Bearing Ratio (CBR) is reduced below that expected for conventional granular base when the amount of RAP exceeds 20 to 25 percent.
- **Compacted Density:** Due to the coating of asphalt cement on RAP aggregate, which inhibits compaction, the compacted density of blended granular material tends to decrease with increasing RAP content.

Attributes of RAP (Part 2)

- **Moisture Content:** The optimum moisture content for RAP blended aggregates is reported to be higher than for conventional granular material, particularly for RAP from pulverizing operations, due to higher fines content and the absorptive capacity of these fines.
- **Permeability:** The permeability of blended granular material containing RAP is similar to conventional granular base course material.
- **Durability:** Since the quality of virgin aggregates used in asphalt concrete usually exceeds the requirements for granular aggregates, there are generally no durability concerns regarding the use of RAP in granular base, especially if the RAP is less than 20 to 25 percent of the base.

Attributes of RPM (Part 1)

- **Gradation:** RPM can be pulverized in-place or using traditional methods. It can be difficult to specify a in-place gradation because the original aggregate, depth of cut and pulverizing methods all affect gradation. Often maximum limit on size, for example 97% passing 50 mm (2 in) mesh. If done ex situ, then can follow AASHTO M147 or ASTM D2940 aggregate requirements.
- **Strength:** The bearing strength depends on the proportion of RAP to other aggregates, and the fraction of fine material. There seems to be a trend of lower CBR for material pulverized in place, due to the fines, compared to materials that are mixed pulverized and screened off-site. RPM is often stabilized with a binder to improve the strength.
- **Compacted Density:** The compacted density will generally be lower due to the inclusion of RAP and possibly RCA.

Attributes of RPM (Part 2)

- **Moisture Content:** Like RAP mixtures, the optimum moisture content for RPM is generally higher than for conventional granular material, particularly for in place material tends to have more fines.
- **Permeability:** The permeability of compacted RPM depends on the constituents and the addition of stabilizers. However, the permeability through the compacted layer is generally decreased, which reduces moisture issues.
- **Durability:** Again, the durability depends on the original aggregate, and the proportions of the RAP and other aggregates, and stabilizers. A durable base can be made from compacted RPM, though stabilizers are often added to improve durability.

Attributes of BDC (Part 1)

- **Gradation:** BDC must be crushed and screened to satisfy AASHTO M147 or ASTM D2940 aggregate requirements.
- **Absorption:** Adsorption is higher for BDC than natural aggregates. Depends on proportions of concrete, rock, RAP, etc.
- **Specific Gravity:** The specific gravity of BDC aggregates (ranging from 2.0 for fines to 2.5 for coarse particles) is slightly lower than that of natural aggregates due to the mortar fraction and RAP.
- **Stability:** Generally has a medium to high friction angle due to the crushed aggregate.
- **Strength Characteristics:** The CBR values are similar to RCA (>90), but decrease with the addition of RAP. Also, brick tends to lower CBR, especially wet CBR.

Attributes of BDC (Part 2)

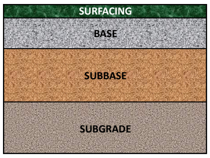
- **Durability:** BDC aggregates generally exhibit good durability with resistance to weathering and erosion. Presence of clay-based aggregates may increase moisture sensitivity and weathering.
- **Drainage Characteristics:** BDC is generally free draining because the fines are usually screened off.
- **pH and Tufa**: Like RCA, the initial pH of pore water in the can elevated, but decreases with time. Since BDC contains a much higher fractions of non-concrete material, pH issues are not as significant.

Attributes of RSG

- **Gradation:** RSG generally has a finer gradation than other road aggregates, with more than 50% passing the 6.3 mm (0.25") mesh. This material would not be recycled for use as unbound base, but would be stabilized. Coarser aggregates may be added to improve the base performance.
- **Strength Characteristics:** CBR values are lower than for coarse aggregates, on the order of 50, depending on the fines content. In order to create a strong base, coarser material can be added to RSG, and binders are mixed in to increase the strength and stiffness.
- **Durability:** Somewhat limited data, but durability is expected to be good based on experience with stabilized subbase and base layers.

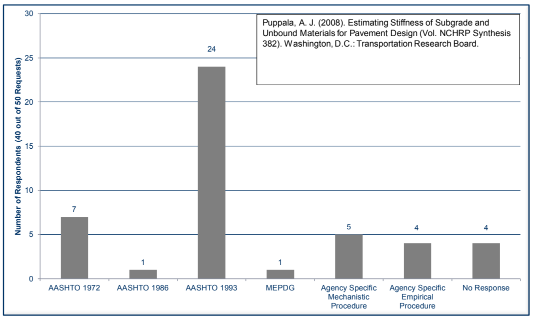
Design Considerations

Flexible Pavement Design



- For this webinar, considering only flexible pavement design.
- There are empirical and mechanistic-empirical pavement design.
- Will focus on mechanistic-empirical design for unbound applications.
- Will consider stabilization at the end.

Pavement Design Methods in Use



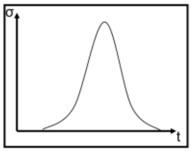
Puppala, A. J. (2008). Estimating Stiffness of Subgrade and Unbound Materials for Pavement Design (Vol. NCHRP Synthesis 382). Washington, D.C.: Transportation Research Board.

Early Pavement Design

http://www.fhwa.dot.gov/pavement/recycling/98042/01.cfm

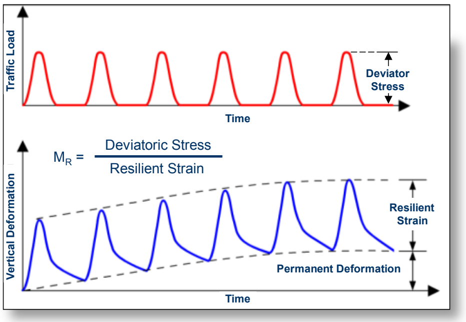
- Early pavement design was based on soil strength. The California Bearing Ratio (CBR) test and other tests were used to characterize the bearing capacity of pavement layers.
- However, flexible pavement layers very rarely fail due to soil strength failure.
- Pavement layers are more likely to fail due to rutting and cracking from fatigue.

Stiffness and Plastic Strain



- Stiffness a measure of how much deformation for a given load.
- For high stiffness, there is less deformation, but for low stiffness there is more deformation, possibly permanent.
- For the unbound layers, rutting is the primary failure mode.
- Can think of rutting as the accumulation of permanent deformation due to vehicle loading.
- Want to measure ability of road materials to recover from deformation.

Resilient Modulus M_R



$$M_R = \frac{\text{Deviatoric Stress}}{\text{Resilient Strain}}$$

ASCE | KNOWLEDGE & LEARNING

Resilient Modulus Test Pictures

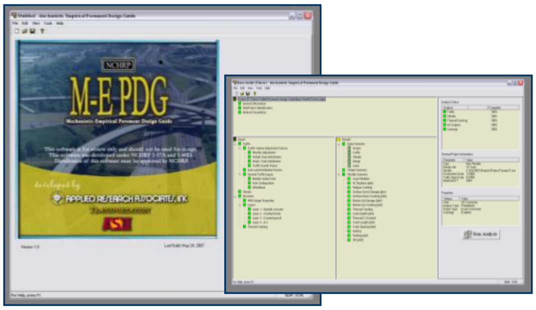
ASCE | KNOWLEDGE & LEARNING

CBR Test

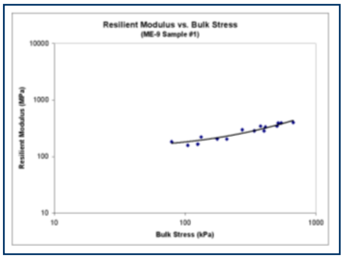
- Resilient modulus test is not fast test, and there is a learning curve.
- A number of agencies are currently using the CBR test to measure the bearing capacity of material.
- CBR is faster and cheaper to run. Not a very high learning curve.
- There are relationships relating CBR to the resilient modulus.
- $M_R = 2555 * CBR^{0.64} [psi] = 17.6161 * CBR^{0.64} [MPa]$

ASCE | KNOWLEDGE & LEARNING

MEPDG - Newest Design Guide

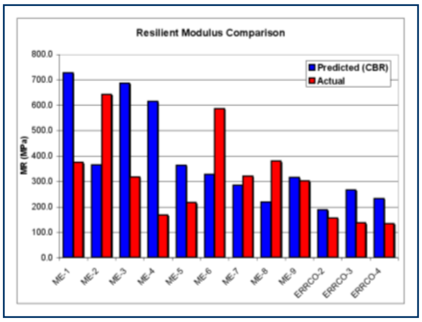


Resilient Modulus Results



$$M_R = K_1 \, Pa \left(\frac{\theta}{P_a} \right)^{K_2} \left(\frac{\sigma_d}{P_a} \right)^{K_3}$$

Predicting M_R from CBR



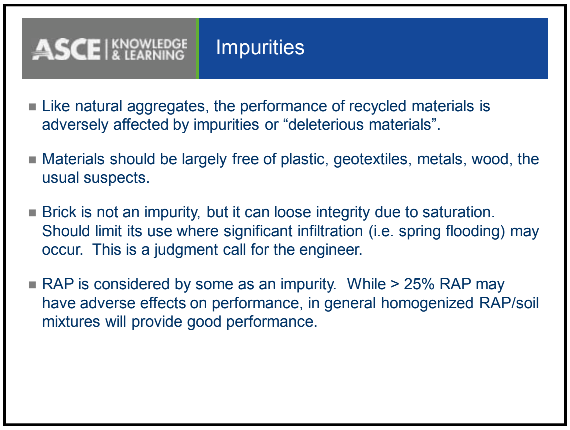
Correlation doesn't work for coarse materials.

SRM M_R Values From RMRC

- **RCA/RAP/RPM Project**
- RPM → 215 MPa
- RAP → 200 MPa
- RCA → 178 MPa
- Class 5 Aggregate → 152 MPa

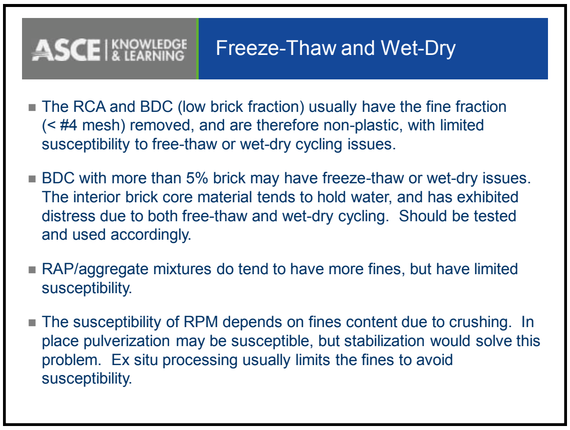
- **BDC Project**
- BDC → 223 MPa
- Crushed Gravel → 174 MPa
- Sand → 181 MPa

Summary Resilient Modulus evaluated at a bulk stress of 208 kPa. In both studies the recycled materials performed better than natural aggregates.



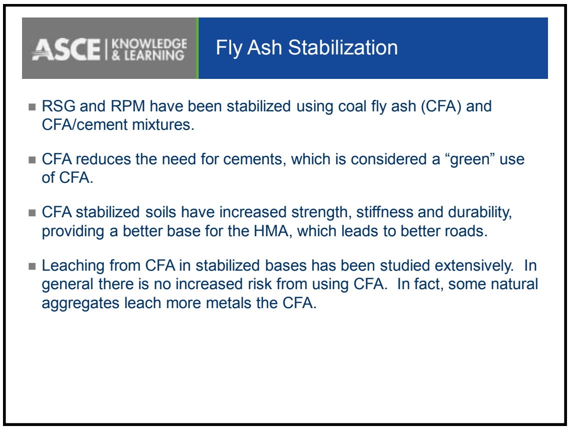
Impurities

- Like natural aggregates, the performance of recycled materials is adversely affected by impurities or “deleterious materials”.
- Materials should be largely free of plastic, geotextiles, metals, wood, the usual suspects.
- Brick is not an impurity, but it can loose integrity due to saturation. Should limit its use where significant infiltration (i.e. spring flooding) may occur. This is a judgment call for the engineer.
- RAP is considered by some as an impurity. While > 25% RAP may have adverse effects on performance, in general homogenized RAP/soil mixtures will provide good performance.



Freeze-Thaw and Wet-Dry

- The RCA and BDC (low brick fraction) usually have the fine fraction (< #4 mesh) removed, and are therefore non-plastic, with limited susceptibility to free-thaw or wet-dry cycling issues.
- BDC with more than 5% brick may have freeze-thaw or wet-dry issues. The interior brick core material tends to hold water, and has exhibited distress due to both free-thaw and wet-dry cycling. Should be tested and used accordingly.
- RAP/aggregate mixtures do tend to have more fines, but have limited susceptibility.
- The susceptibility of RPM depends on fines content due to crushing. In place pulverization may be susceptible, but stabilization would solve this problem. Ex situ processing usually limits the fines to avoid susceptibility.



Fly Ash Stabilization

- RSG and RPM have been stabilized using coal fly ash (CFA) and CFA/cement mixtures.
- CFA reduces the need for cements, which is considered a “green” use of CFA.
- CFA stabilized soils have increased strength, stiffness and durability, providing a better base for the HMA, which leads to better roads.
- Leaching from CFA in stabilized bases has been studied extensively. In general there is no increased risk from using CFA. In fact, some natural aggregates leach more metals the CFA.

Resources

- Recycled Materials Resource Center www.recycledmaterials.org
- User Guidelines for Byproduct and Secondary Use Materials in Pavement Construction www.recycledmaterials.org/tools/uguidelines/index.asp
- AASHTO M 319-02 (2006) Reclaimed Concrete Aggregate for Unbound Soil-Aggregate Base Course
- FHWA Report: Transportation Applications Of Recycled Concrete Aggregate www.recycledmaterials.org/Research/tools/RCAREPORT.pdf
- Fly Ash Facts for Highway Engineers http://www.fhwa.dot.gov/pavement/recycling/fafacts.pdf