

AUGUST 2018

Recycling Concrete Pavement Materials:

A PRACTITIONER'S REFERENCE GUIDE



National Concrete Pavement
Technology Center



IOWA STATE UNIVERSITY
Institute for Transportation

About the National CP Tech Center

The mission of the National Concrete Pavement Technology (CP Tech) Center at Iowa State University is to unite key transportation stakeholders around the central goal of advancing concrete pavement technology through research, tech transfer, and technology implementation.

Notice

This document is disseminated under the sponsorship of the U.S. Department of Transportation in the interest of information exchange under DTFH61-12-H-00010 Technology Transfer of Concrete Pavement Technologies. The U.S. Government assumes no liability for the use of the information.

The U.S. Government does not endorse products or manufacturers. Trademarks or manufacturers' names appear in this material only because they are considered essential to the objective of the material. They are included for informational purposes only and are not intended to reflect a preference, approval, or endorsement of any one product or entity.

Quality Assurance Statement

The Federal Highway Administration (FHWA) provides high-quality information to serve Government, industry, and the public in a manner that promotes public understanding. Standards and policies are used to ensure and maximize the quality, objectivity, utility, and integrity of its information. FHWA periodically reviews quality issues and adjusts its programs and processes to ensure continuous quality improvement.

Iowa State University Non-Discrimination Statement

Iowa State University does not discriminate on the basis of race, color, age, religion, national origin, pregnancy, sexual orientation, gender identity, genetic information, sex, marital status, disability, or status as a U.S. veteran. Inquiries regarding non-discrimination policies may be directed to Office of Equal Opportunity, 3410 Beardshear Hall, 515 Morrill Road, Ames, Iowa 50011, Tel. 515-294-7612, Hotline: 515-294-1222, email eooffice@iastate.edu.

Front Cover Image Credits

Top: Gary Fick, Trinity Construction Management Services, Inc.

Center: Iowa Department of Transportation

Bottom: Federal Highway Administration

Technical Report Documentation Page

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.	
4. Title and Subtitle Recycling Concrete Pavement Materials: A Practitioner's Reference Guide		5. Report Date August 2018	
		6. Performing Organization Code	
7. Author(s) Mark B. Snyder, Tara L. Cavalline, Gary Fick, Peter Taylor, and Jerod Gross		8. Performing Organization Report No.	
9. Performing Organization Name and Address National Concrete Pavement Technology Center Iowa State University 2711 South Loop Drive, Suite 4700 Ames, IA 50010-8664		10. Work Unit No. (TRAIS)	
		11. Contract or Grant No. Part of DTFH61-12-H-00010	
12. Sponsoring Organization Name and Address Office of Pavement Technology Federal Highway Administration 1200 New Jersey Ave., S.E. Washington, DC 20590		13. Type of Report and Period Covered Guide	
		14. Sponsoring Agency Code	
15. Supplementary Notes Visit http://www.cptechcenter.org/ for color pdfs of this and other reports from the National Concrete Pavement Technology Center.			
16. Abstract <p>Recycling concrete pavements has been a common practice for many years, dating back to at least the 1940s with the reconstruction of US Route 66 in Illinois when the existing pavement was recycled back into the new project. It is with renewed interest that public agencies are now more closely examining the opportunities for recycling concrete pavements.</p> <p>One reason for considering recycling is the diminishing quantity of good natural materials. However, many states still have specification or policy restrictions that do not allow concrete pavements to be recycled and utilized to the extent that is possible. In addition, the contracting industry may overlook opportunities to use recycled concrete aggregates (RCAs) on projects due to a lack of familiarity with the technical requirements or an uncertainty of how RCAs will perform for a specific application.</p> <p>This practitioner's reference guide for recycling concrete pavement materials was developed as part of a Federal Highway Administration (FHWA) cooperative agreement to support more sustainable concrete pavement technical solutions.</p>			
17. Key Words concrete pavement recycling—recycled concrete aggregate—sustainable concrete pavements—transportation infrastructure sustainability		18. Distribution Statement No restrictions.	
19. Security Classification (of this report) Unclassified.	20. Security Classification (of this page) Unclassified.	21. No. of Pages 88	22. Price NA

Recycling Concrete Pavement Materials: A Practitioner's Reference Guide

August 2018

Principal Investigator

Peter Taylor, Director
National Concrete Pavement Technology Center, Iowa State University

Project Manager

Tom Cackler

Authors

Mark B. Snyder, Tara L. Cavalline, Gary Fick, Peter Taylor, and Jerod Gross

Managing Editor

Sue Stokke

Graphic Designer and Digital Communication Specialist

Alicia Hoermann

Copyeditors

Brandy Haenlein, Mary Adams, and Sue Stokke

Sponsored by

Federal Highway Administration

A guide from
National Concrete Pavement Technology Center
Iowa State University
2711 South Loop Drive, Suite 4700
Ames, IA 50010-8664
Phone: 515-294-5798 / Fax: 515-294-0467
www.cptechcenter.org

Contents

Acknowledgments	ix
Reference information for this guide	x

Chapter 1

Introduction to Concrete Pavement Recycling ...	1
Definition of Concrete Pavement Recycling	2
Brief Historical Perspective	2
Benefits of Recycling Concrete Pavements	2
Economics of Concrete Pavement Recycling.....	2
Environmental Impacts of Concrete	3
Pavement Recycling.....	3
Effects of Using RCA on Pavement Performance.....	3
Applications for RCA	4
Performance of Pavements Constructed using RCA ..	4
Scope of the Manual	5
Summary	5
References	5

Chapter 2

Economics and Sustainability	7
Introduction	8
Benefits Associated with Concrete Recycling	8
Economics of Concrete Recycling.....	8
Sustainability Benefits of Concrete Recycling.....	10
Assessment Tools and Techniques	12
Economic Analysis.....	13
Environmental Assessment.....	13
Rating Systems.....	14
Summary	15
References	16

Chapter 3

Project Selection and Scoping	19
Introduction	20
Characterization of the Source Concrete and Use Selection	21
Material Characteristics.....	21
Identification of Candidate Uses.....	21
Agency Specifications.....	21
Use Selection.....	22

Production Options for RCA	22
Mobile On-Site Processing for Base and Fill Uses.....	23
Stationary On-Site Processing for PCC, Base, and Fill Applications.....	23
Off-Site Processing Options.....	24
General Considerations for RCA Processing.....	24
Economic Considerations	24
Cost of Virgin Aggregate.....	24
Management of Residual Material.....	25
Other Factors	25
Project Staging.....	25
Weighing Factors and Making Decisions	26
Summary	27
References	27

Chapter 4

Using RCA in Pavement Base Products	29
Introduction	30
Unbound Aggregate Base Applications	30
Performance Considerations	31
Structural Matters.....	31
Drainage Issues.....	32
Qualification Testing	33
General.....	33
Gradation.....	34
Other Physical Requirements.....	34
Application-Based Requirements.....	35
Base Design and Construction Considerations	36
Concrete Pavement Design Considerations	36
Environmental Considerations	37
Example Projects	37
Edens Expressway, Chicago, Illinois—1978 (ACPA 2009).....	37
Holloman Air Force Base, New Mexico—Sulfate Attack Problems (Saeed et al. 2006).....	38
Other Projects.....	38
Bound (Stabilized) Base Applications	38
Lean Concrete Base (LCB) and Cement-Stabilized Base (CSB).....	38
Asphalt Concrete and Asphalt-Stabilized Base.....	38
Performance Concerns.....	38

Example Projects.....	39
Hartsfield-Jackson Atlanta International Airport (ATL).....	39
Michigan DOT Experience (Van Dam et al. 2011)..	40
Summary.....	40
References.....	41
Chapter 5	
Using RCA in Unbound Aggregate Shoulders...43	
Introduction	44
Qualification Requirements.....	45
General.....	45
Gradation.....	45
RCA Shoulder Design Considerations.....	46
Placement and Compaction Equipment.....	46
Moisture and Density Control.....	46
Assessing Potential Economic Benefits.....	47
Environmental Considerations.....	47
Summary	48
References.....	48
Chapter 6	
Using RCA in Concrete Paving Mixtures.....49	
Introduction.....	50
Constructability (Fresh Properties).....	50
Workability.....	50
Finishing Characteristics.....	50
Bleeding.....	51
Air Void System.....	51
Setting Time.....	51
Pavement Design Considerations (Hardened Properties).....	51
Mechanical Properties.....	51
Potential Durability.....	52
Developing Concrete Mix Designs Using RCA.....	53
Qualification Testing.....	53
Proportioning.....	53
Construction.....	53
Examples/Case Studies.....	53
D-Cracking Aggregate.....	53
Alkali Reactive Aggregate.....	54

Continuously Reinforced Concrete Pavement (CRCP)..	54
Summary.....	55
References.....	56
Chapter 7	
Mitigating Environmental Concerns.....57	
Introduction.....	58
Legislative and Regulatory Considerations.....	58
Water Quality	58
Waste.....	58
Air Quality.....	59
State Regulations and Specifications.....	59
Environmental Concerns Requiring Consideration..	59
Contamination from the Source Concrete	59
Water Quality.....	60
Air Quality.....	61
Noise and Other Local Impacts.....	61
Waste Generation–Concrete Residuals.....	61
Planning Considerations and Design Techniques that Protect Water Quality.....	62
Qualification of Source Concrete.....	62
Mitigating Water Quality Concerns for RCA Leachate ..	63
Preventing Drainage Issues from Sediments and Solid Precipitate.....	64
Guidance and Training.....	65
Construction Strategies and Controls to Mitigate Environmental Concerns	65
Project Site Controls to Mitigate	67
Environmental Impacts	67
Mitigating Impacts from RCA Production and Handling.....	68
Minimizing Waste Generation and Promoting Beneficial Reuse of Fines.....	70
Air Quality–Respirable Crystalline Silica.....	71
Summary.....	71
References.....	72
National Standard and Specification References.....	77
AASHTO.....	77
ACI	77
ASTM	78

Figures

Chapter 1

Figure 1.1. Typical off-site concrete pavement recycling operation.....	2
Figure 1.2. Typical on-site mobile concrete pavement recycling operation.....	2
Figure 1.3. Historic US Route 66 sign in Illinois.....	2
Figure 1.4. End uses for crushed cement concrete.....	4

Chapter 2

Figure 2.1. Mobile aggregate processing plant	9
Figure 2.2. On-site crushing operations at the Beltline Highway project	10
Figure 2.3. Conventional virgin aggregate quarrying operation.....	11
Figure 2.4. Pile of waste concrete in Grand Teton National Park, prior to crushing into RCA.....	11
Figure 2.5. Generalized life cycle of a system for LCA ...	13

Chapter 3

Figure 3.1. Project selection and scoping considerations flowchart.....	20
Figure 3.2. Mobile on-site crushing equipment	23
Figure 3.3. Crushing and sizing of source concrete at an on-site stationary plant	23
Figure 3.4. On-site crushing operation	25

Chapter 4

Figure 4.1. 2012 responses to survey of RCA use for unbound bases	30
Figure 4.2. RCA stockpile for aggregate base in Minnesota.....	31
Figure 4.3. US 59 recycling project showing use of RCA fines as a stabilizing layer on top of existing aggregate base (and RCA aggregate in new concrete pavement surface).....	31
Figure 4.4. Typical drainage system for use of free-draining RCA base.....	33
Figure 4.5. Concrete recycling operation set up inside of Edens Expressway cloverleaf interchange.....	37
Figure 4.6. Airfield pavement layout at Hartsfield-Jackson Atlanta Airport showing features with RCA base	39
Figure 4.7. ATL slabs stacked for future concrete recycling	40

Chapter 5

Figure 5.1. RCA aggregate shoulder (50% blend with natural aggregate) on US 34 east of Fairfield, Iowa	44
Figure 5.2. Specified RCA gradation ranges for four states using 1.5 in. top-size material (2017).....	46

Chapter 6

Figure 6.1. TH 59 in southwestern Minnesota, 2006...54
Figure 6.2. I-80 SE in Wyoming, 2016.....54
Figure 6.3. Illinois I-57 ride quality summary.....55

Chapter 7

Figure 7.1. Scale indicating typical pH range of RCA leachate/runoff and some common liquids.....	60
Figure 7.2. Recommended actions for qualification of source concrete to protect water quality.....	63
Figure 7.3. Well-implemented on-site material crushing program in urban area.....	67
Figure 7.4. Demolished material stockpiled beneath bridge prior to crushing with silt fence and vegetative buffer used.....	67
Figure 7.5. Spray nozzle for dust control on aggregate conveyor	67
Figure 7.6. Jobsite dust suppression (misting) equipment.....	67
Figure 7.7. Concrete stockpiles set inside of roadway depression with stormwater inlets taken offline.....	68
Figure 7.8. High-performance perimeter control using concrete blocks wrapped in geotextile fabric.....	68
Figure 7.9. Perimeter control at waterway near demolition and concrete crushing operations with RCA filter berm on inside of geotextile-wrapped Jersey barrier.....	68
Figure 7.10. RCA stockpile tarped with plastic and bounded by perimeter berm of wrapped RCA.....	69
Figure 7.11. Localized mitigation of high-pH leachate from drain near receiving waters using pH log and bioswale.....	69
Figure 7.12. Flocc log tied to wooden stake in outflow path.....	70

Tables

Chapter 2

Table 2.1. Typical considerations for sustainability assessment tools.....	12
--	----

Chapter 3

Table 3.1. Checklist of considerations for use of RCA in different applications.....	26
--	----

Chapter 4

Table 4.1. AASHTO M 147-17 grading requirements for soil-aggregate materials.....	34
---	----

Table 4.2. Test criteria for various unbound base applications	35
--	----

Table 4.3. MDOT requirements for RCA use in cement-treated permeable base.....	40
--	----

Chapter 5

Table 5.1. Reported RCA grading requirements for shoulder surface applications.....	45
---	----

Chapter 6

Table 6.1. Effects of RCA on fresh concrete properties..	50
--	----

Chapter 7

Table 7.1. Planning considerations and design techniques that protect water quality.....	62
--	----

Table 7.2. Construction controls to protect the environment.....	66
--	----

Acknowledgments

The authors would like to thank the American Concrete Pavement Association (ACPA) for sponsoring the two-part recycled concrete aggregate (RCA) benchmarking survey that was conducted in 2016, and the many state highway agencies and contracting firms that took the time to respond. Your survey responses helped guide the work for this part of the Federal Highway Administration (FHWA) cooperative agreement to support increased use of sustainable concrete pavement technologies.

The National Concrete Pavement Technology (CP Tech) Center thanks the FHWA for the partnership and support in developing these technology transfer materials to help address technical barriers and enable the broader use of RCA in future projects. The Center and authors of this guide are grateful to the knowledgeable and experienced professionals, public and private, who served on the technical advisory committee for this project:

Wayne Adaska, Portland Cement Association (PCA)
Gina Ahlstrom, FHWA
John Becker, ACPA – Pennsylvania Chapter
Ross Bentsen, Illinois State Toll Highway Authority (Illinois Tollway)
Brent Burwell, ACPA – Oklahoma/Arkansas (OK/AR) Chapter
Greg Dean, ACPA – Southeast Chapter/Carolinas Concrete Paving Association
Gary Fick, Trinity Construction Management Services, Inc.
Steve Gillen, Illinois Tollway
Dale Harrington, HCE Services
Brian Hunter, North Carolina DOT (NCDOT)
Cecil Jones, Diversified Engineering for American Association of State Highway and Transportation Officials (AASHTO) Subcommittee on Materials
Rich Jucha, ACPA – Pennsylvania Chapter
Steve Koser, Pennsylvania DOT (PennDOT)
Steve Kosmatka, PCA
Todd LaTorella, ACPA – Missouri/Kansas (MO/KS) Chapter
Bryan Lee, Utah DOT (UDOT)
Will Lindquist, Kansas DOT (KDOT)
Colin Lobo, National Ready Mixed Concrete Association (NRMCA)
Maria Masten, Minnesota DOT (MnDOT)
Mitzi McIntyre, CTS Cement Manufacturing Corp.

Rod Montney, Kansas DOT (KDOT)
Andy Naranjo, Texas DOT (TxDOT)
Mehdi Parvini, California DOT (Caltrans)
Jim Powell, ACPA – Northwest Chapter
Jan Prusinski, Cement Council of Texas
Charles Rea, California Construction and Industrial Materials Association
Randy Riley, ACPA – Illinois Chapter
Greg Schieber, KDOT
Kenny Seward, Oklahoma DOT (ODOT)
Charles Stuart, Southwest Concrete Pavement Association
Tom Tietz, California Nevada Cement Association (CNCA)
Jeff Uhlmeier, Washington State DOT (WSDOT)
Leif Wathne, National ACPA
Tom Yu, FHWA

While the authors generated the overall content, it was the committee's careful reviews of drafts and thoughtful suggestions that make this guide a useful resource. The authors would also like to thank the following individuals for their input and contributions:

Jeralee L. Anderson, Greenroads International
Amit Armstrong, Western Federal Lands Highway Division
Anne Beeldens, AB Roads
Terrence Beaudry, MnDOT
Eleanor Bloom, University of Wisconsin-Madison
Rolf Breitenbücher, Ruhr-Universität Bochum
Howe Crockett, Western Federal Lands Highway Division
Anthony Freeman, City of Bellingham, Washington
Matthew Ginder-Vogel, University of Wisconsin-Madison
Brian Hunter, NCDOT
Steve Klocke, Snyder & Associates, Inc.
Phillip Lamoureux, FHWA
Mark Lindemann, Nebraska DOT (NDOT)
Robin Maycock, Louis Berger
Craig A. Mueller, City of Bellingham, Washington
Luc Rens, EUPAVE
Hermann Sommer, Austrian Cement Research Institute
Dwayne Stenlund, MnDOT
Steven Theisen, Wisconsin DOT (WisDOT)
Bryan Wagner, Illinois Tollway

Parts of this guide are reprinted from previously published National CP Tech Center publications that were also developed during the course of this project:

Cavalline, T. L. 2018. *Concrete Pavement Recycling Series: Protecting Water Quality through Planning and Design Considerations*. Technical Brief. National Concrete Pavement Technology Center, Iowa State University, Ames, IA.

Cavalline, T. L. 2018. *Concrete Pavement Recycling Series: Protecting the Environment during Construction*. Technical Brief. National Concrete Pavement Technology Center, Iowa State University, Ames, IA.

Cavalline, T. L. 2017. *CP Road Map: Concrete Pavement Recycling—Project Selection and Scoping*. National Concrete Pavement Technology Center, Iowa State University, Ames, IA.

Cavalline, T. L. 2016. *Concrete Pavement Recycling Series: Quantifying the Sustainability Benefits of Concrete Pavement Recycling*. Technical Brief. National Concrete Pavement Technology Center, Iowa State University, Ames, IA.

Snyder, M. B. 2018. *Concrete Pavement Recycling Series: Using Recycled Concrete Aggregate (RCA) in Unbound Aggregate Shoulders*. Technical Brief. National Concrete Pavement Technology Center, Iowa State University, Ames, IA.

Snyder, M. B. 2018. *CP Road Map: Using Recycled Concrete Aggregate in Pavement Base Products*. National Concrete Pavement Technology Center, Iowa State University, Ames, IA.

Snyder, M. B. 2016. *Concrete Pavement Recycling Series: Introduction to Concrete Pavement Recycling*. Technical Brief. National Concrete Pavement Technology Center, Iowa State University, Ames, IA.

Snyder, M. B. 2016. *CP Road Map: Concrete Pavement Recycling and the Use of Recycled Concrete Aggregate in Concrete Paving Mixtures*. National Concrete Pavement Technology Center, Iowa State University, Ames, IA.

Reference information for this guide

Snyder, M. B., T. L. Cavalline, G. Fick, P. Taylor, S. Klokke, and J. Gross. 2018. *Recycling Concrete Pavement Materials: A Practitioner's Reference Guide*. National Concrete Pavement Technology Center, Iowa State University, Ames, IA.

Chapter 1

Introduction to Concrete Pavement Recycling

Definition of Concrete Pavement Recycling	2
Brief Historical Perspective	2
Benefits of Recycling Concrete Pavements	2
Applications for RCA	4
Performance of Pavements Constructed using RCA	4
Scope of the Manual	5
Summary	5
References	5

Definition of Concrete Pavement Recycling

Concrete recycling is the breaking, removal, crushing, and processing of hardened concrete to produce recycled concrete aggregate (RCA), a granular material that is generally suitable for use as a substitute for virgin aggregate in various (generally construction-related) applications (see Figures 1.1 and 1.2).



Copyright ©2012–2018 RJ Smith, photography by John Cappello

Figure 1.1. Typical off-site concrete pavement recycling operation



Copyright ©2018 Manatt's, all rights reserved, used with permission

Figure 1.2. Typical on-site mobile concrete pavement recycling operation

Concrete pavements are 100% recyclable and are generally excellent sources for producing RCA, because they are typically comprised of materials that have previously met agency specifications for quality (ACPA 2009). In addition, pavement recycling streams are generally free of potentially harmful contaminants that may be present in building demolition streams (e.g., bricks, gypsum, asbestos, etc.).

Brief Historical Perspective



Figure 1.3. Historic US Route 66 sign in Illinois

One of the first uses of RCA in pavement construction was on US Route 66 in Illinois in the 1940s (which is now an historic route, see Figure 1.3), when concrete from a portion of the existing two-lane concrete road was crushed and stockpiled for use as aggregate in the second two lanes of the highway when it was expanded to four lanes after World War II (Epps et al. 1980).

Concrete recycling became more common in the years that followed, and the practice has been adopted extensively in the US since the 1970s (Darter et al. 1998).

The recycling of paving materials (including concrete pavement) into new paving applications is supported

by the Federal Highway Administration (FHWA 2002), which states that “reusing the material used to build the original highway system makes sound economic, environmental, and engineering sense.” Recycling concrete pavement into paving applications is now practiced in at least 43 states. In 2000, government estimates of RCA production in the US was 100 million tons/year (USGS 2000) and, more recently, an industry estimate placed RCA production from all sources at 140 million tons/year (CDRA 2014).

Benefits of Recycling Concrete Pavements

There are many good reasons to recycle concrete pavement. They can be broadly categorized as economic, environmental, and performance-related, and all have potential impacts on pavement sustainability.

Economics of Concrete Pavement Recycling

Economics have historically been the primary driving force for concrete pavement recycling. In recent years, environmental concerns, reduced availability of quality aggregates, and the desire for a more sustainable highway infrastructure have also become important drivers. The cost of aggregates for use in fill, foundation, and surface layers may account for 20 to 30% of the cost of paving materials and supplies (Halm 1980) and 10 to 15% of total construction costs (excluding engineering and

right-of-way acquisition). These costs have increased in recent years as the demand for quality aggregates has continued to increase in the face of limited and diminishing resources. Concrete pavement recycling offers the potential for reduced project costs.

The costs of RCA to the contractor/buyer are typically comparable to the costs of virgin material. For example, the U.S. Geological Survey (USGS) reported that the average cost of RCA in 2005 was \$6.95/ton (ranging from \$3.41 to \$8.35 or more in the continental US), while the cost of virgin aggregate at about the same time averaged \$6.51/ton (ranging from \$3.54 to \$10.82) (Kuennen 2007). The complete initial monetary cost of using RCA includes the costs of demolishing the pavement, removing and hauling (for off-site processing) the slab fragments, crushing the demolished concrete, screening the RCA, conducting associated quality control costs, and backhauling the product to the job site (for off-site processing only). The complete cost of using virgin aggregate instead of RCA (for comparison purposes) must include the costs of purchasing and transporting the new material to the job site, as well as the costs of demolishing the old pavement, removing and hauling the slab fragments, and any tipping or disposal fees for the old concrete. Costs that are common to both can be excluded from the comparison. Tipping fees in the US averaged \$34.29/ton (ranging regionally from \$24.06 to \$70.53/ton) in 2004, with much lower tipping fees at recycling facilities than at landfills (Kuennen 2007).

In summary, the overall economic benefits of concrete pavement recycling vary with many factors, such as the availability and cost of virgin aggregates; costs of transport, processing, and quality control; and hauling and tipping fees for the disposal of old pavement. In addition, the use of RCA can result in faster construction and lower impacts on local traffic, particularly when on-site recycling is performed; therefore, the economic, environmental, and social impacts of these benefits must also be considered.

The cost savings from concrete pavement recycling has been reported to be as high as \$5 million on a single project (CDRA 2008). The Illinois Tollway reported savings of more than \$45 million in materials and hauling costs from recycling 3.4 million tons of concrete into base materials on tollway projects between 2008 and 2016 (Gillen and Vavrik 2016).

A more detailed discussion of the economics of concrete recycling is presented in Chapter 2.

Environmental Impacts of Concrete Pavement Recycling

Concrete pavement recycling is an environmentally sustainable choice that conserves aggregate and other resources, reduces unnecessary consumption of limited landfill space, saves energy, reduces greenhouse gas (GHG) emissions, and captures carbon dioxide (CO₂) from the atmosphere. Concrete recycling can reduce or eliminate the need for mining or extracting new virgin aggregates and can reduce haul distances and fuel consumption associated with both aggregate supply and concrete slab disposal.

The U.S. Environmental Protection Agency (EPA) has identified the “management and recycling of industrial products and materials” as one of the four national priorities of the Resource Conservation Challenge, an organized national effort to reduce GHG emissions and to conserve natural resources (EPA 2010).

An in-depth discussion of the sustainability aspects of concrete pavement recycling is presented in Chapter 2.

Effects of Using RCA on Pavement Performance

Concrete recycling may offer the opportunity to improve the performance of the reconstructed pavement while addressing roadway deficiencies (e.g., geometric issues, deficient foundation materials) during reconstruction. For example, when RCA is used in pavement foundation layers, the angular, rough-textured nature of the particles can provide an exceptionally stable construction platform. In addition, secondary cementing mechanisms (discussed in Chapter 4) often provide a degree of erosion resistance unmatched in unbound material, while increasing foundation support to a degree that, in some cases, permits a reduction in the thickness of the pavement surface layer.

The inclusion of coarse and fine RCA in concrete mixtures may impact several physical and mechanical properties of the concrete (e.g., strength, elasticity, coefficient of thermal expansion, shrinkage). The degree of impact can range from negligible to significant and depends on the amount of reclaimed mortar in the RCA, properties of the aggregate in the RCA, amount of RCA used in the mixture, and other factors. These properties, in turn, may impact pavement performance. However, mix design modifications (e.g., reduced water-to-cementitious materials [w/cm] ratio, use of chemical and/or mineral admixtures) can offset negative impacts and result in pavement performance that is comparable or superior to that of conventional aggregate concrete pavements (ACPA 2009). Research also indicates that,

in concrete mixtures, the replacement of up to 25% of the natural fine aggregate with recycled concrete fine aggregate can result in a slight increase in concrete strength, probably due to improvements in the resulting total aggregate gradation (Fergus 1981).

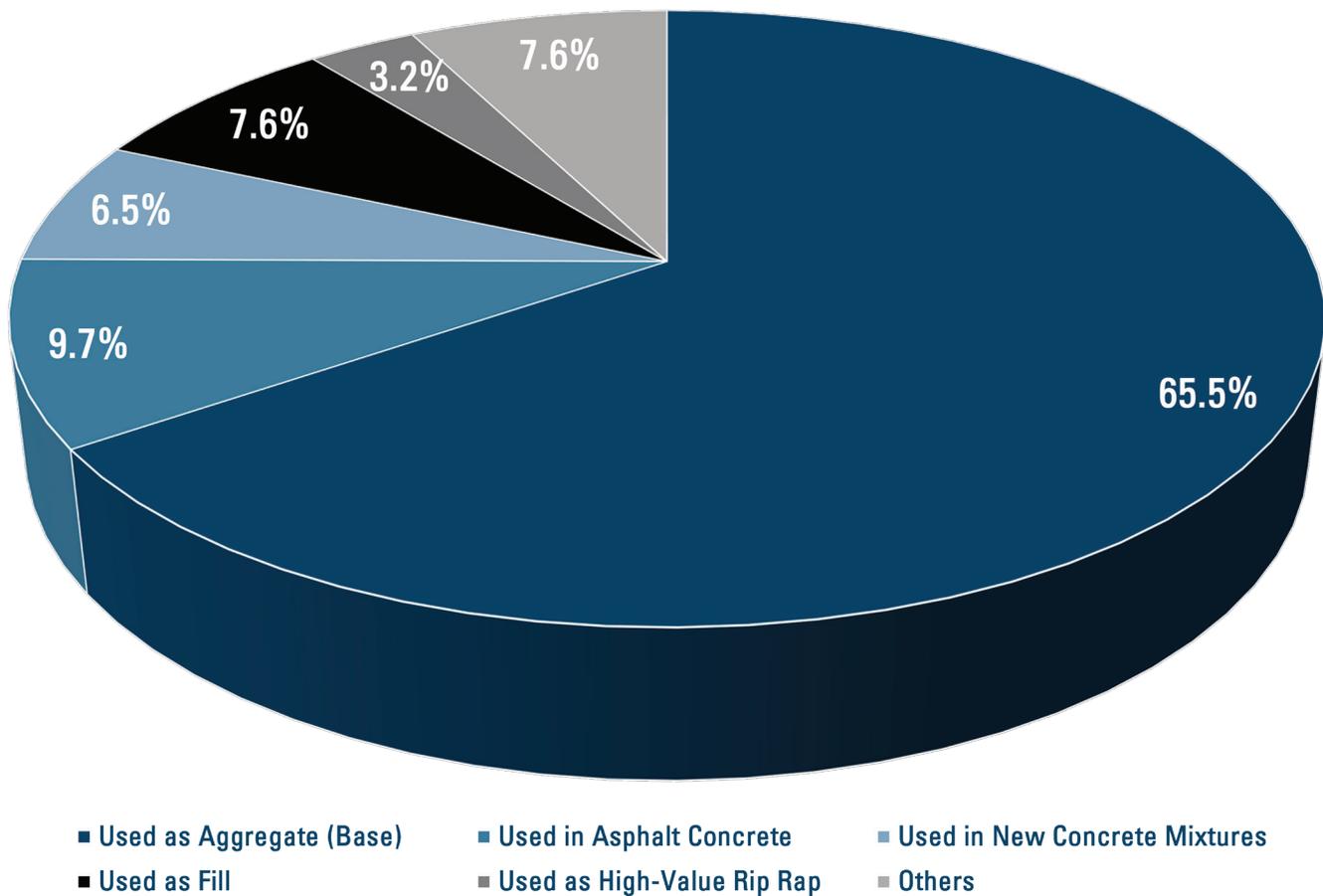
The impacts of RCA use in foundation and pavement surface layers on pavement performance are presented in greater detail in Chapters 4 and 5, respectively, of this manual.

Applications for RCA

The primary application of RCA has been its use in pavement subbase materials, but it has also been used in concrete and asphalt paving layers, as general fill and embankment material, as “rip-rap” for erosion control, and in many other applications. Figure 1.4 presents a summary of the use of RCA in paving applications.

Performance of Pavements Constructed using RCA

Since the 1970s, RCA has been used in the construction of hundreds of highway projects in the US and around the world. These projects have included the use of RCA in pavement fill, foundation, subbase, and surface layers (both asphalt and concrete). They have included relatively low-volume roads as well as some of the most heavily traveled pavements in the world (e.g., Edens Expressway in Chicago, Illinois, and Interstate 10 near Houston, Texas). They have also included the use of RCA produced by recycling pavements that failed due to alkali-silica reactivity (ASR) damage and durability (“D”) cracking in new concrete paving mixtures (e.g., I-80 near Pine Bluff, Wyoming, and US 59 near Worthington, Minnesota, as described in Chapter 5).



After Van Dam et al. 2015 (from USGS 2000 after T. A. Deal 1997)

Figure 1.4. End uses for crushed cement concrete

Most of these projects have performed very well, meeting or exceeding expectations. Lessons learned from project failures provided valuable information for the design and construction of subsequent pavements built using RCA and/or led to improved guidance in RCA concrete mixture proportioning. These improvements have resulted in the ability to produce RCA concrete mixtures with properties that are similar to (and, in some cases, superior to) those of conventional concrete mixtures, as well as in guidance for designing and constructing reliable pavement systems. Therefore, no significant reduction in performance should be expected for a well-designed RCA pavement that has been properly constructed. The keys to success are to produce RCA that is suitable for the intended application, understand the physical and mechanical properties of the product, and make any engineering adjustments (e.g., mixture proportioning, aggregate grading, structural design) that are necessary to ensure both ease of construction and long-term performance.

Case studies and examples of the design, construction, and performance of several projects that incorporated RCA in different ways are presented in Chapters 3 through 7. Guidance for mitigating environmental concerns associated with concrete recycling, along with guidance for management of residual materials from the recycling process is presented in Chapter 7.

Scope of the Manual

This manual has been developed to serve as a comprehensive resource for practitioners (agency staff, consultants, and contractors) for determining whether concrete recycling is an appropriate option for a given project, what applications of the RCA product are most appropriate, and how to specify and inspect the recycling process and subsequent pavement construction. It covers the following topics:

- Chapter 2: Economics and sustainability aspects of concrete recycling
- Chapter 3: Considerations for project selection and scoping
- Chapter 4: Using RCA in pavement base products (both stabilized and unbound)
- Chapter 5: Use of RCA in unbound aggregate shoulders
- Chapter 6: Use of RCA in concrete paving mixtures
- Chapter 7: Mitigating environmental concerns

Chapters 3, 4, 5, 6 and 7 provide instructive case studies and examples.

Summary

Incorporating RCA products into highway applications can provide many benefits to the owner/agency. The key to realizing these benefits is to remember that RCA is an engineered material and that there are many effective ways to incorporate RCA into a project. The best value to the owner/agency will often result from developing project specifications that allow flexibility on the part of the contractor in the choice of RCA applications on the project. This manual is intended to be a resource for owners/agencies, the design community, and contractors in the decision-making, design, and construction processes.

References

- ACPA. 2009. *Recycling Concrete Pavements*. Engineering Bulletin EB043P, American Concrete Pavement Association, Skokie, IL.
- CDRA. 2018. *Good Economic Sense*. Construction & Demolition Recycling Association, Chicago, IL. <https://cdrecycling.org/materials/concrete/>.
- CDRA. 2008. *Case Histories*. Construction & Demolition Recycling Association. Chicago, IL. <https://cdrecycling.org/materials/concrete/case-histories/>. Last accessed March 2018.
- Darter, M. I., S. H. Carpenter, et al. 1998. *Techniques for Pavement Rehabilitation: A Training Course – Participant’s Manual, 3rd Revision*. FHWA-HI-99-006. National Highway Institute, Federal Highway Administration, Washington, DC.
- EPA. 2010. *Resource Conservation Challenge Programs – Brief Summaries and Links to Further Information on Programs in Region 6*. Environmental Protection Agency, U.S. EPA Region 6, Dallas, TX.
- Epps, J. A., D. N. Little, R. J. Holmgren, and R. L. Terrell. 1980. *NCHRP Report 224: Guidelines for Recycling Pavement Materials*. National Cooperative Highway Research Program, Washington, DC.
- Fergus, J.S. 1981. Laboratory Investigation and Mix Proportions for Utilizing Recycled Portland Cement Concrete as Aggregate. *Proceedings of the National Seminar on PCC Pavement Recycling and Rehabilitation*. Federal Highway Administration, Washington, DC. pp. 144–160.

FHWA. 2002. *Formal Policy on the Use of Recycled Materials*. Federal Highway Administration, Washington, DC. www.fhwa.dot.gov/legsregs/directives/policy/recmatmemo.htm. Last accessed July 2017.

Gillen, S. and W. Vavrik. 2016. Implementing Sustainability within a Transportation Agency – Illinois Tollway’s Experience. Paper presented at the 95th Annual Meeting of the Transportation Research Board, January 10–14, Washington, DC.

Halm, H. J. 1980. Concrete Recycling. *Transportation Research News*, Transportation Research Board, Vol. 89, pp. 6–10.

Kuennen, T. 2007. The Economics of Recycling. *Rock Products*, Vol. 110, No. 10.

USGS. 2000. *Recycled Aggregates—Profitable Resource Conservation*. Fact Sheet FS-181-99. U.S. Geological Survey, Washington, DC.

Van Dam, T., J. T. Harvey, S. T. Muench, K. D. Smith, M. B. Snyder, I. L. Al-Qadi, H. Ozer, J. Meijer, P. V. Ram, J. R. Roesler, and A. Kendall. 2015. *Towards Sustainable Pavement Systems: A Reference Document*. FHWA-HIF-15-002. Federal Highway Administration, Washington, DC.

Chapter 2

Economics and Sustainability

Introduction	8
Benefits Associated with Concrete Recycling	8
Assessment Tools and Techniques	12
Summary	15
References	16

Introduction

Production of virgin aggregate in the US was estimated at 2 billion tons per year in 2004, at which time it was projected to increase to 2.5 billion tons in 2020 (FHWA 2004). Concern about the economic viability and adverse environmental impacts of quarried aggregates, as well as the feasibility of continuing to dispose of aging infrastructure in landfills, has raised the attractiveness of recycled concrete aggregate (RCA) as an economical and sustainable alternative to conventional aggregates. Recent federal legislation, including the Moving Ahead for Progress in the 21st Century Act (MAP-21) and Transportation Equity Act for the 21st Century (TEA-21), has emphasized that agencies need to use resources wisely to maximize cost savings and improve the sustainability of highway infrastructure. The FHWA Recycled Materials Policy acknowledges that recycling offers engineering, environmental, and economic benefits, and “calls upon us [the FHWA], and the state transportation departments, to explicitly consider recycling as early as possible in the development of every project” (Wright 2002, Wright 2015).

Recycling concrete pavements can save money, and the recycling of existing concrete pavements is generally considered to be one of the most sustainable end-of-life options for this infrastructure component (Van Dam et al. 2015). Much of the existing concrete infrastructure is already comprised of the best available materials, so long-lasting new infrastructure can be constructed using RCA if the RCA is treated as an engineered material.

The environmental and societal benefits of concrete recycling are well-documented (Behera et al. 2014) but are often not included in analyses of project alternatives. Decisions are often made based on initial cost, which can sometimes eliminate options that include recycling. Quantification of economic and sustainability benefits will generally help to support the choice of recycling.

The intent of this chapter is to present information on economics and sustainability that can be used by stakeholders to justify and promote concrete recycling. In this chapter, overviews of economic and sustainability benefits of concrete recycling are presented and supported with case study examples. Tools for quantifying these benefits are then described and a brief summary of considerations specific to concrete recycling is provided. This chapter also directs users to additional resources to support the use of these tools, as appropriate.

Benefits Associated with Concrete Recycling

For environmental, economic, and societal reasons, the use of recycled concrete in rehabilitation and new construction is an important step in the development of more sustainable infrastructure. As agencies promote recycling, policies and specifications are being modified to allow the use of RCA in an increasing number of applications. In many cases, stakeholders can save money by recycling concrete pavements. The decision to include recycling in a project often relies on the ability of agencies and other project stakeholders to demonstrate the economic and sustainability benefits of recycling. Summaries of such benefits are provided in the following sections, along with brief details from case study projects showcasing these benefits.

Economics of Concrete Recycling

In the selection of project alternatives, decisions are often made based upon initial cost. Therefore, for recycling to be the first-choice option, cost savings for the owner and other project stakeholders should be identified during the early stages of project conception, design, and bidding. Project-specific conditions, such as scope, site logistics, local industry and market factors, and hauling and tipping fees, will control the costs of both virgin aggregates and RCA. However, if contractors are provided project options and flexibility, recycling opportunities can be incorporated into the bidding process at a cost savings.

Recycling can save money in several ways, including the following:

- Recapturing the value of prior investments in concrete paving materials
- Time and fuel savings associated with haul time reductions
- Better processing and quality control (producing RCA on site that meets specifications)
- Improved contractor and production efficiency
- Reduction of economic impact to surrounding communities due to reduced trucking to/from jobsite

As stated in Chapter 1, the cost of RCA varies with production methods and efficiencies, hauling, quality assurance/quality control (QA/QC) considerations, and other factors. Virgin aggregate costs also vary with project location and local market conditions. When comparing the cost of using RCA to the cost of using

virgin aggregate, the cost of using RCA should include pavement removal, hauling, and processing, and the cost of using the virgin aggregate should include the material costs to the project site and the costs associated with removal and disposal of the existing pavement if not recycled. The decision to utilize on-site recycling operations where feasible, using mobile or portable recycling plants (as shown in Figure 2.1), can be a key driver for cost savings due to reductions in hauling time and fuel savings.



CDRA, used with permission

Figure 2.1. Mobile aggregate processing plant

Cost savings related to decreased virgin material use and reduced hauling are amplified due to the higher yield of recycled aggregates, since RCA yields more volume by weight (up to 15%) than natural aggregates (CDRA 2008).

Recently, some agencies have found that RCA produced with on-site materials can be supplemented with other RCA from construction and demolition (C&D) waste, further reducing cost (Bloom et al. 2016a, Gillen and Vavrik 2016). The quality of the off-site RCA, however, should be confirmed using methods discussed in Chapters 4 and 5 of this manual.

In time, economic conditions in some areas may result in recycling increasingly becoming the lowest cost option. The reduced availability of good quality aggregates, paired with increased aggregate demand, will result in an increase in raw material prices (Behera et al. 2014). Landfill space is dwindling, with fewer landfills accepting concrete construction and demolition waste each year. As landfill space dwindles, tipping fees will increase, further increasing the cost of options that do not include recycling.

Broad-based economic incentives for recycling exist as well. Industry survey results compiled by the Construction & Demolition Recycling Association (CDRA) revealed that the C&D recycling industry could be responsible for the direct support of over 19,000 jobs in the United States in 2012, with facility

owners investing over \$4.5 billion in the development and construction of C&D recycling infrastructure (Townsend et al. 2014). With recycling cost savings freeing up agency dollars to support other projects and needs, the economic impact of increased recycling likely supports economic growth in other sectors as well.

In Chapter 1, the cost savings of the Illinois Tollway was briefly mentioned. In addition to the \$45 million savings in materials and hauling costs on the Congestion Relief and Move Illinois Programs (2008–2016), more than \$29.5 million in savings were incurred through elimination of excavation, reduced purchase and transport of natural aggregate, and reduced pavement thickness over stiffer base (Gillen and Vavrik 2016). Several other notable examples of cost savings incurred with concrete recycling have also been documented. For example, TH 59 near Worthington, Minnesota, was a 16-mile, two-lane, D-cracked Portland cement concrete pavement (PCCP), which was reconstructed in 1980. The reconstruction of this pavement included use of both the coarse and fine fractions of RCA, with the coarse fraction used in the new 8-inch PCCP and the fine aggregate used in a 1-inch lift on top of the subbase. The Minnesota Department of Transportation (MnDOT) estimated that use of the RCA in this project resulted in approximately 27% total cost savings, with 150,000 gallons of fuel saved due to reduced hauling (Yrjanson 1989).

Almost \$5 million in purchase and hauling costs were saved in an I-5 improvement project (Route 22 Freeway to Route 9 Freeway) in Anaheim, California, by using both recycled concrete and asphalt aggregates. This six-year project included widening the roadway from three to six lanes in both directions, with RCA used in the base material. A portable crusher was used to perform on-site recycling, maximizing hauling efficiency and lowering costs (CDRA 2008).

A recent example of cost savings realized by concrete recycling is the Beltline Highway project in Madison, Wisconsin. In this project, a 1.5-mile segment of roadway was reconstructed using several recycled materials, including RCA. The existing concrete pavement was crushed and graded on site in a closed area of the work zone (see Figure 2.2) and utilized in base course and embankments.



Steven Theisen, WisDOT

Figure 2.2.
On-site crushing operations at the Beltline Highway project

Additional RCA was obtained from off-site sources, further lowering costs. Use of RCA on this project provided a cost savings of approximately \$130,000 at initial construction and a total savings of “about \$250,000 from the use of all recycled material over the project’s lifetime” (Bloom et al. 2016a, Bloom et al. 2016b).

Sustainability Benefits of Concrete Recycling

Sustainability is often defined as “development that meets the needs of the present without compromising the ability of future generations to meet their own needs” (WCED 1987). The quality of sustainability is defined by impacts in three major areas: economic, environmental, and societal, which are often referred to as the “triple bottom line.”

The economic benefits of concrete pavement recycling are relatively easy to estimate but may not be sufficient to justify the process. As described in the previous section, recycling can often result in cost savings. However, in some cases, economic benefits are not as readily evident, or cost analysis can result in equivalent costs. Without the opportunity to provide cost savings, it may be necessary to consider other benefits (e.g., environmental and societal) in determining the most sustainable option for a given project and justifying the choice to use RCA.

The FHWA has recently expended considerable effort to advance the application of sustainability principles to pavements through the Sustainable Pavements Program (FHWA 2015), which maintains a website that provides a clearinghouse of pavement sustainability-related information, including references, technical briefs, publications, and recorded webinars.

As supplies and sources of high-quality virgin aggregates are depleted, the use of RCA is becoming an increasingly desirable strategy for conserving resources and lowering the environmental impact of construction. End-of-life options for concrete pavements include recycling, reuse, or landfilling. In an ideal world, older infrastructure is recycled into new, well-performing infrastructure, which is, in turn, utilized to produce recycled materials for new construction at the end of its service life. This concept of a “closed-loop” or “zero-waste” for pavement systems is an important way of thinking that could be transformative in improving the overall sustainability of pavements (Van Dam et al. 2015).

The sustainability benefits associated with concrete recycling include (but are not limited to) the following:

- Lower reliance on virgin quarried aggregates, reducing impact of acquisition, processing, and transport (see Figure 2.3)
- Reduced energy consumption
- Reduced use of landfill space and extension of the life of existing disposal sites
- Reduced greenhouse gas emissions compared with mining, crushing, and transporting virgin aggregate
- Lower impact to surrounding communities (noise, emissions, travel time delays) due to reduced hauling

Additionally, the use of RCA in some unbound base applications has been shown to provide improved performance due to more effective aggregate interlock and secondary cementing of RCA particles (Van Dam et al. 2011, Hiller et al. 2011). The performance and durability of concrete pavements constructed using RCA concrete mixtures can also be improved over that of the source concrete pavement through adjustments to mixture proportioning and particle sizing, thereby providing the sustainability benefits associated with longer service life and reduced maintenance, repair, and rehabilitation.

Several recent projects have documented the reduced environmental impact and other sustainability benefits associated with RCA. For example, the use of recycled materials in the Beltline Highway project in Madison, Wisconsin (shown in Figure 2.2), resulted in quantified life-time environmental impact reductions in all life-cycle assessment (LCA) criteria for the as-built



M. Garard 2006, <https://en.wikipedia.org/w/index.php?curid=7096182>

Figure 2.3. Conventional virgin aggregate quarrying operation

project, including energy use (13% reduction), water consumption (12% reduction), carbon dioxide (CO₂) emissions (13% reduction), and hazardous waste (9% reduction) (Bloom et al. 2016a). Another example, the North Park Road project in Grand Teton National Park, Wyoming, utilized RCA produced from a large pile of concrete that had been accumulating on park maintenance grounds for several years (see Figure 2.4).



Phillip Lamoureux, FHWA Western Federal Lands

Figure 2.4. Pile of waste concrete in Grand Teton National Park, prior to crushing into RCA

The RCA produced—approximately 3,500 tons—was utilized as a pavement subbase in frost-susceptible areas (Crockett 2016), providing needed material for construction and removing an eyesore from a treasured national park.

Pavement systems also impact the societal component of sustainability. Potential positive societal impacts associated with concrete recycling include the preservation of natural resources, reduced landfill use, and reductions in traffic, noise, and emissions from processing and transport (Van Dam et al. 2015). There are no direct measures, however, of the societal impact of projects. The ability to identify and quantify sustainability benefits in each of the three sustainability areas (economic, environmental, and societal) is key to their use to justify project options that include recycling. These tools are described in subsequent sections of this chapter.

Assessment Tools and Techniques

Recent focus on more sustainable practices and changes in legislation has resulted in increased interest in metrics other than initial cost to evaluate and select projects. Quantification of the environmental and societal benefits of concrete recycling can assist stakeholders in making the decision to use recycled concrete. Assessment tools that incorporate considerations associated with concrete recycling are available to support decision-making, and the increased use of these tools will result in a more sustainable highway system. These assessment

tools can be broadly categorized as economic analysis, environmental assessment, and rating systems.

Critical to the successful use of these tools is the gathering of data and identification of appropriate assumptions to support the analyses. The exact information required to perform each analysis will vary with the tool utilized, the end goal of the analysis, project characteristics, alternatives to be compared, and other considerations. However, a partial list of typical information required to support these tools is provided in Table 2.1.

Table 2.1. Typical considerations for sustainability assessment tools

	Economic Analysis	Environmental Assessment	Rating Systems
General Considerations	<p>Agency costs</p> <ul style="list-style-type: none"> Pavement costs Non-pavement costs such as safety, engineering, inspection, and testing <p>User costs</p> <ul style="list-style-type: none"> Vehicle operating costs Travel delay costs Crash costs <p>“Equivalent” designs</p> <p>Rehabilitation options and schedules</p> <ul style="list-style-type: none"> Time to first activity Activity life Cost of activities <p>Analysis period</p> <p>Discount rate (inflation and cost of money/ opportunity cost)</p> <p>End of analysis (residual) value</p> <ul style="list-style-type: none"> Remaining service life Salvage value Value as recycled materials Demolition costs and landfill tipping fees 	<p>Functional unit</p> <p>System boundaries</p> <p>Inputs of raw materials, feedstock and energy</p> <p>Outputs of waste and pollution</p> <p>Impacts of transport</p> <p>Evaluate over the following phases:</p> <ul style="list-style-type: none"> Raw material acquisition Material processing Manufacturing Construction Use End-of-life 	<p>Most consider pavement as a contributing subsystem to a larger system or project such as:</p> <ul style="list-style-type: none"> Infrastructure projects Roadway projects Site development projects Agency sustainability efforts <p>Factors considered often include:</p> <ul style="list-style-type: none"> Ecological impact Community impact Connectivity Aesthetics <p>Rating systems differ by:</p> <ul style="list-style-type: none"> Grouping of performance criteria Delineation and computation of metrics Thresholds for obtaining points and ratings status Certification methodology (self-certification or third party certification)
Specific considerations for recycling activities can include:	<p>Economic costs of alternatives to recycling</p> <ul style="list-style-type: none"> Purchase and hauling costs for virgin material Landfill tipping fees for disposal of existing material <p>Economic costs of recycling</p> <ul style="list-style-type: none"> Hauling costs Crushing/grading equipment (on-site or off-site) Contractor efficiency Production efficiency 	<p>Fuel consumption</p> <p>Emissions</p> <p>Non-renewable resource use</p> <p>Freshwater use</p> <p>Hazardous and non-hazardous waste generation</p> <p>Local impacts such as noise and dust</p>	<p>Amount of materials reused (mass or volume percentage)</p> <p>Method of recycling utilized</p> <p>Use of recycled materials in new mixtures</p> <p>Emissions reductions</p> <p>Noise reductions</p> <p>Planning initiatives</p> <p>End-of-life considerations</p>

After Cavalline 2016, National CP Tech Center

Economic Analysis

Economic analysis decision support tools can be used to effectively evaluate the costs of different alternatives over the project lifetime. The most common approach to economic analysis—the life-cycle cost analysis (LCCA)—is “...a process for evaluating the total economic worth of a usable project segment by analyzing initial costs and discounted future costs, such as maintenance, user costs, reconstruction, rehabilitation, restoring, and resurfacing costs over the life of the project segment” (U.S. DOT 1998). The FHWA encourages the use of LCCA to support decisions, and a widely accepted LCCA tool called RealCost is available as free software (RealCost 2011). Potential sources of cost savings associated with the use of recycled concrete include the following:

- Lower initial costs for recycled aggregates
- Lower hauling costs (shorter haul distances)
- Increased efficiency for the contractor’s execution of a project, resulting in lower bid costs
- Reduced landfill tipping fees

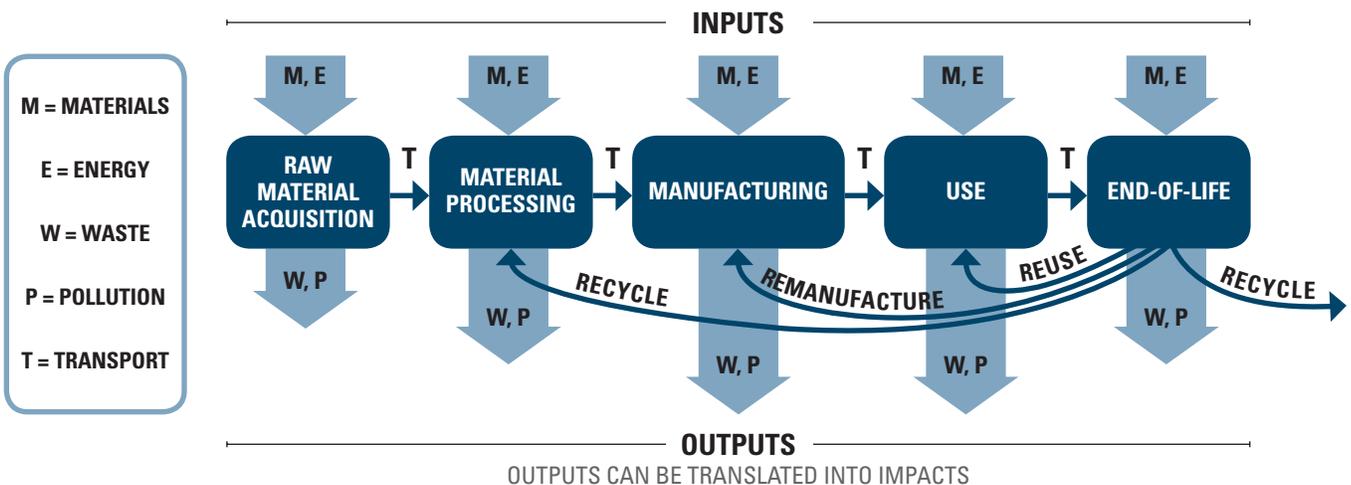
Concrete recycling can also be considered as part of the “salvage value” used as the end-of-life value for a project in an economic analysis, although care must be taken not to double count the benefits of recycling as both a salvage value at the end of one life cycle and a reduction in initial costs at the beginning of the next. All of these potential economic benefits can lead to the selection

of pavement project options that incorporate recycled concrete materials through the use of economic analysis.

LCCA tools can provide direct consideration of only those factors that can be accurately quantified monetarily; thus, LCCA is not generally used to quantify or assess the potential environmental or societal benefits associated with the use of recycled concrete. This limitation to LCCA has resulted in an increased emphasis on use of other assessment tools (described in subsequent sections), in addition to LCCA.

Environmental Assessment

A commonly used environmental assessment tool is the LCA. Developed in the 1960s and recently standardized by the International Standardization Organization (ISO) under ISO 14040 and ISO 14044, an LCA is utilized to quantify the impact of a product or process on the environment in terms of mass or energy use, along with waste and emissions produced during the life cycle. The use of LCA in pavement projects provides a quantitative approach for comparing the environmental impacts of competing alternatives and can assist in making decisions that lower the environmental impact of a pavement over its life cycle. In addition to quantifying environmental impacts, an LCA can also be used to some extent to evaluate or quantify the societal and economic impacts of the product or process. A generalized life cycle of a production process, as used for LCA, is shown in Figure 2.5.



After Kendall 2012, used with permission

Figure 2.5. Generalized life cycle of a system for LCA

The LCA process generally consists of four phases: goal and scope definition, inventory analysis (life-cycle inventory or LCI), impact assessment (life-cycle impact assessment or LCIA), and interpretation. In recent years, calls have been made for development of an LCA framework for pavements and for nonproprietary LCI inputs and environmental product declarations (EPD) to support LCA for pavements. To promote the implementation of LCA, the FHWA has recently supported development of a Pavement Life-Cycle Assessment Framework, which provides guidance tailored to the pavement community on the LCA approach, methodology, and system boundaries (Harvey et al. 2016). The recent release of this framework presents a unique opportunity for agencies to measure and assess sustainability in an organized manner, facilitating more direct comparisons that can be used in decision making. Using this pavement-specific LCA framework, environmental impacts over the life cycle can be quantified, adverse environmental impacts can be identified and avoided, and progress towards a more sustainable infrastructure can be monitored (Harvey et al. 2016).

Currently, LCAs are typically performed using software programs supporting an LCA model. These programs include the following:

- Athena (Athena 2013)
- SimaPro (Pré 2011)
- TRACI (EPA 2012)

Other programs developed specifically for LCA of pavements and roadways are available, such as the following:

- Pavement Life-Cycle Assessment Tool (PaLATE) (Horvath 2007)
- Building Environmentally and Economically Sustainable Transportation-Infrastructure Highways (BE2ST-in-Highways) (Lee et al. 2013)
- Illinois Tollway LCA (in development) (Harrell et al. 2016)

Often these models provide data and options for common materials to support an LCA, although it is important to verify that the tool is maintained and that the associated databases are current. Also, some tools utilize a hybrid LCA approach, considering only portions of a more robust LCA. An example of this is the PaLATE tool, which considers energy use, air emissions, and leachate, and may require an update of data to be appropriately utilized (Van Dam et al. 2015).

Key to consideration of recycled concrete in an LCA is its definition as a waste or a product. Treatment of a waste flow as a material with value (or as a material that can become valuable after additional processing) requires consideration in a manner that accounts for economic and environmental impacts and avoids double counting in the analysis.

As indicated previously, impact categories in LCA are typically defined as energy or resource usage, emissions, toxicity, water, and waste. The use of concrete recycling can be incorporated in several LCA impact categories, as described in Table 2.1 previously. With the release of FHWA's pavement-specific LCA framework, it is anticipated that a greater number of agencies and stakeholders will begin utilizing LCA and contributing new data to support this type of analysis.

Rating Systems

Rating systems promote innovation in design and construction and provide an avenue for communicating sustainability achievements. During recent years, several rating systems have emerged to facilitate the rating of pavement projects based on LCCA, LCA, and other environmental and sustainability metrics. These systems each provide a way to evaluate and differentiate between projects, and many ultimately include criteria and programs for recognizing stakeholders (e.g., by providing award or certification levels).

In addition to identifying, evaluating, and ranking the environmental impacts of projects, many of these systems address other metrics, such as community (social) and economic benefits. Of the tools discussed in this chapter, rating systems provide the only direct indicators of societal impacts (however, it is noted that LCCA and LCA can provide indirect indicators of social benefits).

Although these rating systems differ in the grouping of performance criteria, delineation and computation of metrics, and thresholds for obtaining points and ratings status, the approach of each tends to be similar.

The four most commonly utilized rating systems for pavement projects are listed and briefly described next:

- **INVEST (Infrastructure Voluntary Evaluation Sustainability Tool):** Supported by the FHWA, INVEST is available on the web for use as a self-evaluation and self-certification tool for transportation services and projects. Modules included in the tool include those for system planning on both regional and state levels, project development, and operations and maintenance, with most opportunities for

considering the benefits of concrete recycling falling under the project development modules. Additional information on each INVEST module and scoring criteria can be found on the INVEST website (INVEST 2016).

- **Greenroads:** The Greenroads rating system was developed as a third-party rating system for roadway projects and is owned by the Greenroads Foundation, which is based at the University of Washington. Similar to most rating systems discussed here, Greenroads provides tools for multiple levels of use, including planning, design, construction, operations, and maintenance. Information on Greenroads is available on the Greenroads website (Greenroads 2016) and in other publications (Muench et al. 2011).
- **Envision:** Envision was developed by the Institute for Sustainable Infrastructure to fill the need for a “holistic” rating system capable of rating the sustainability of a broad range of infrastructure projects, such as pavements, water treatment systems, pipelines, dams, and airports. An overview of this rating system, along with details regarding the system framework and means for projects to achieve recognition, is provided on the Institute for Sustainable Infrastructure website (Envision 2016).
- **GreenLITES (Green Leadership in Transportation and Environmental Sustainability):** Developed by the New York State DOT (NYSDOT), GreenLITES provides a self-certification tool for project design and operations. Tailored to the ongoing initiatives and organizational structure of NYSDOT, the GreenLITES rating system offers two certifications (Project Design Certification and Operations Certification). Details concerning GreenLITES can be found on the NYSDOT website (NYSDOT n.d.).

From the standpoint of concrete recycling, credits and points can often be earned via performance criteria related to the items presented in Table 2.1. More detailed information on the specific modules and credits for which concrete recycling can be considered for each of the four rating systems described previously is provided in Cavalline (2016).

Summary

Recycling concrete provides economic, environmental, and societal benefits and, as stated in FHWA’s Recycled Materials Policy, “recycling of aggregates and other highway construction materials makes sound economic, environmental, and engineering sense” (Wright 2015).

The economic benefits of recycling result in cost savings to the owner, allowing funds to be utilized for other infrastructure projects. The sustainability benefits associated with recycling are important components of responsible stewardship of our nation’s resources, environment, and infrastructure. As state highway agencies increasingly view RCA as an economical, sustainable pavement material that offers the potential for satisfactory performance, opportunities exist to further increase the volume of concrete repurposed in new infrastructure in the coming decades.

The sustainability benefits of recycling concrete pavements can be quantified using LCCA, LCA, and other rating systems, each of which can help to promote concrete pavement recycling as an attractive option. The approach, assumptions, and analysis techniques used by each tool are different but when the tools are used singularly or in concert, various aspects of sustainability can be quantified. The goals of the stakeholders should be carefully considered prior to selecting one or more of the above approaches. Overall, as outlined in Van Dam et al. (2015):

- LCCA is an economic analysis technique that can be used to quantify the economic components of sustainability.
- LCA is most suitable for analyzing and quantifying the environmental impacts of a specific project or strategy over a life cycle.
- Rating systems rely heavily on providing incentives (points and recognition) for addressing a broad set of sustainability best practices, including societal impacts, which are not directly addressed by the other two tools. Rating systems are typically used for incentivizing new construction strategies and often do not adequately reflect the significant impacts of the use phase of the life cycle on pavement sustainability.

Each of these types of tools provides one or more means of considering the potential benefits of recycling-related activities and materials choices in the analyses and evaluations, providing guidance and potentially rewarding or recognizing good recycling practices. These tools have been successfully used by a number of agencies to justify and support concrete recycling activities; see Cavalline (2016) for additional information on the case studies presented in this chapter. More extensive utilization of these tools could incentivize stakeholders to utilize concrete recycling more frequently in pavement construction and move towards more sustainable highway infrastructure.

References

- Athena. 2013. *Impact Estimator for Highways: User Guide*. Athena Sustainable Materials Institute, Ottawa, Ontario, Canada.
- Behera, M., S. K. Bhattacharyya, A. K. Minocha, R. Deoliya, and S. Maiti. 2014. Recycled Aggregate from C&D Waste & Its Use in Concrete – A Breakthrough Towards Sustainability in the Construction Sector: A Review. *Construction and Building Materials*, Vol. 68, pp. 501–516.
- Bloom, E. F., G. J. Horstmeier, A. P. Ahlman, T. B. Edil, and G. Whited. 2016a. Assessing the Life-Cycle Benefits of Recycled Material in Road Construction. Paper presented at Geo-Chicago 2016: Sustainability, Energy, and the Geoenvironment, August 14–18, Chicago, IL.
- Bloom, E., G. J. Horstmeier, A. P. Ahlman, and T. B. Edil. 2016b. Urban Highway Life-Cycle Assessment and Data Collection Methodology. Paper presented at 4th International Conference on Sustainable Construction Materials and Technologies (SCMT4), August 7–11, Las Vegas, NV.
- Cavalline, T. L. 2016. *Concrete Pavement Recycling Series: Quantifying the Sustainability Benefits of Concrete Pavement Recycling*. Technical Brief. National Concrete Pavement Technology Center, Iowa State University, Ames, IA.
- CDRA. 2008. *Case Histories*. Construction & Demolition Recycling Association. Chicago, IL. <https://cdrecycling.org/materials/concrete/case-histories/>. Last accessed February 2018.
- Crockett, H. 2016. Western Federal Lands Highway Division. Personal communication with T. L. Cavalline, June 2016.
- Envision. 2016. *Institute for Sustainable Infrastructure*. www.sustainableinfrastructure.org. Last accessed November 2016.
- EPA. 2012. *Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts (TRACI) User's Manual*, Document ID: S-10637-OPP-1-0. Environmental Protection Agency, Washington, DC.
- FHWA. 2004. *Transportation Applications of Recycled Concrete Aggregate: FHWA State of the Practice National Review*. Federal Highway Administration, Washington, DC. www.fhwa.dot.gov/pavement/recycling/applications.pdf.
- FHWA. 2015. *Sustainable Pavements Program*. Federal Highway Administration, Washington, DC. www.fhwa.dot.gov/pavement/sustainability/. Last accessed November 2016.
- Gillen, S. and W. Vavrik. 2016. Implementing Sustainability within a Transportation Agency – Illinois Tollway's Experience. Paper presented at the 95th Annual Meeting of the Transportation Research Board, January 10–14, Washington, DC.
- Greenroads. 2016. www.greenroads.org. Last accessed November 2016.
- Harrell, M., T. Wilson, and S. Gillen. 2016. Sustainable Infrastructure: Quantifying the Impact of Pavement Construction. Paper presented at the ASCE International Conference on Transportation and Development, June 26–29, Houston, Texas.
- Harvey, J. T., J. Meijer, H. Ozer, I. L. Al-Qadi, A. Saboori, and A. Kendall. 2016. *Pavement Lifecycle Analysis Framework*, Report No. FHWA HIF-16-014. Federal Highway Administration, Washington, DC.
- Hiller, J. E., Y. S. Deshpande, Y. Qin, and C. J. Shorkey. 2011. *Efficient Use of Recycled Concrete in Transportation Infrastructure*, Report Number RC-1544. Michigan Department of Transportation, Lansing, MI.
- Horvath, A. 2018. PaLATE: Pavement Life-cycle Assessment Tool for Environmental and Economic Effects. Consortium on Green Design and Manufacturing, University of California, Berkeley, CA. <http://faculty.ce.berkeley.edu/horvath/palate.html>.
- INVEST. 2016. *Invest Version 1.2*. Federal Highway Administration, Washington, DC. www.sustainablehighways.org. Last accessed November 2016.

- Kendall, A. 2012. Life Cycle Assessment for Pavement: Introduction. Presentation in Minutes, FHWA Sustainable Pavement Technical Working Group Meeting, April 25–26, Davis, CA.
- Lee, J. C., T. B. Edil, C. H. Benson, and J. M. Tinjum. 2013. Building Environmentally and Economically Sustainable Transportation Infrastructure: Green Highway Rating System. *Journal of Construction Engineering and Management*, Vol. 139, No. 12, pp. 1–10.
- Muench, S. T., J. L. Anderson, J. P. Hatfield, J. R. Koester, and M. Söderlund, et al. 2011. *Greenroads Manual v1.5*. (J. L. Anderson, C. D. Weiland, and S. T. Muench, Eds.). University of Washington: Seattle, WA.
- NYSDOT. no date. GreenLITES. New York State Department of Transportation. <https://www.dot.ny.gov/programs/greenlites>.
- Pré (Pré Consultants). 2011. *SimaPro 6*, Amersfoort, Netherlands. www.pre-sustainability.com/.
- RealCost. 2011. *Life-Cycle Cost Analysis Software*, Federal Highway Administration, Washington, DC. www.fhwa.dot.gov/infrastructure/asstmgmt/lccasoft.cfm. Last accessed November 2016.
- Townsend, T., C. Wilson, and B. Beck. 2014. *The Benefits of Construction and Demolition Materials Recycling in the United States*. Construction & Demolition Recycling Association, Chicago, IL. <https://www.usagypsum.com/wp-content/uploads/2016/05/CDRA-White-paper-executive-summary.pdf>.
- U.S. DOT. 1998. Transportation Equity Act for the 21st Century (TEA-21) (PL 105-178). U.S. Department of Transportation, Washington, DC. www.fhwa.dot.gov/tea21/.
- Van Dam, T., K. Smith, C. Truschke, and S. Vitton. 2011. *Using Recycled Concrete in MDOT's Transportation Infrastructure – Manual of Practice*, Report Number RC-1544. Michigan Department of Transportation, Lansing, MI.
- Van Dam, T., J. T. Harvey, S. T. Muench, K. D. Smith, M. B. Snyder, I. L. Al-Qadi, H. Ozer, J. Meijer, P. V. Ram, J. R. Roesler, and A. Kendall. 2015. *Towards Sustainable Pavement Systems: A Reference Document*. FHWA-HIF-15-002. Federal Highway Administration, Washington, DC.
- WCED. 1987. *Report of the World Commission on Environment and Development: Our Common Future*. Oxford University Press, Oxford, England, UK.
- Wright, F. G. 2002. *Formal Policy on the Use of Recycled Materials*. Federal Highway Administration, Washington, DC. www.fhwa.dot.gov/legregs/directives/policy/recmatmemo.htm.
- Wright, F. G. 2015. *FHWA Recycled Materials Policy, Administrator's Message*. Federal Highway Administration, Washington, DC. www.fhwa.dot.gov/legregs/directives/policy/recmatpolicy.htm.
- Yrjanon, W.A. 1989. *NCHRP Synthesis of Highway Practice 154: Recycling of Portland Cement Concrete Pavements*. National Cooperative Highway Research Program, Washington, DC.

Chapter 3

Project Selection and Scoping

Introduction	20
Characterization of the Source Concrete and Use Selection	21
Production Options for RCA	22
Economic Considerations	24
Other Factors	25
Weighing Factors and Making Decisions	26
Summary	27
References	27

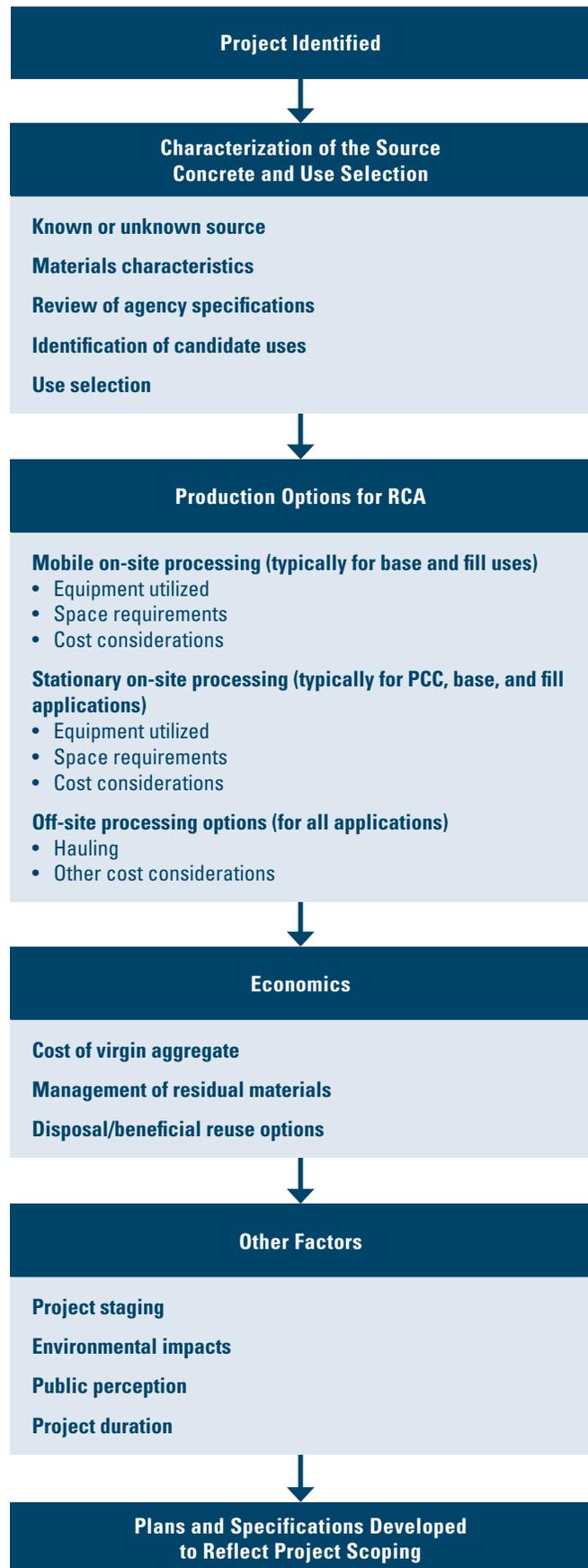
Introduction

Most concrete pavement projects can and should be considered to be candidates for recycling. In fact, FHWA policy states that “recycled materials should get first consideration in materials selection” (Wright 2015). However, characteristics that make a project a “good” candidate for recycling are driven by specification requirements, production options, availability of space for recycling, environmental permitting restrictions, the cost of virgin materials, and other considerations (Fick 2017). There must also be a favorable balance between the potential benefits of recycling (i.e., sustainability considerations and initial economic benefits) and the impact of using recycled products on pavement performance and service life (i.e, life-cycle costs).

In this chapter, project selection and scoping considerations for concrete recycling are presented, along with ways stakeholders can ensure recycling opportunities are identified and incorporated in a manner that maximizes economic and environmental benefits. Specifically, this chapter includes guidance on the following:

- Determining whether concrete recycling is an option for a particular project
- Identifying which type of recycled material could be produced and where this recycled material could be utilized
- Pavement crushing and specification expectations that drive project scoping
- Economic considerations
- Other factors impacting and guiding the identification of candidate projects and uses

All projects are unique, and there are many appropriate and proven approaches to project selection and scoping for concrete recycling. A flowchart that shows one generalized approach to project selection and scoping is presented in Figure 3.1. The considerations presented are subsequently discussed in this chapter in a similar order to that shown in the flowchart.



After Cavalline 2017, National CP Tech Center

Figure 3.1.
Project selection and scoping considerations flowchart

Characterization of the Source Concrete and Use Selection

Material Characteristics

Prior to deciding to recycle concrete from existing infrastructure, a level of knowledge of the characteristics and quality of source material should be obtained.

Most concrete on a project can be recycled if properly matched to the quality of material needed for a specific application. Typically, concrete sourced from agency infrastructure is of known (and often good) quality, having met previous quality assurance/quality control (QA/QC) requirements. For concrete of unknown quality or sourced from non-agency projects, testing is recommended to determine important material characteristics, such as compressive strength, abrasion resistance, and susceptibility to materials-related distress (such as alkali-aggregate reactivity or AAR and D-cracking).

Concrete pavements with alkali-silica reactivity (ASR) and D-cracked pavements have been successfully recycled into new concrete pavements (Wade et al. 1997), but mitigating provisions (such as the use of fly ash or slag cement and reduced w/cm ratio) are typically incorporated into the new concrete mixture. This illustrates that the successful use of RCA in any concrete mixture may require deviation from typical agency prescriptive mixture proportioning requirements.

In almost every paving application, the source concrete should be “clean” (i.e., free of significant amounts of undesirable material that could impact the quality of the end-product). Materials often present in pavement concrete, including sealants and bituminous patch material, are typically not an issue because they are of negligible total volume (Darter et al. 1998). Therefore, the presence of these materials should not impact project selection or scoping. If RCA is to be used for new PCCP applications, additional QA/QC measures are typically implemented, as is discussed later in this manual.

The agency should review the specifications for typical aggregate products in the context of potential use of RCA and align the material requirements with the potential application and source of the RCA.

Identification of Candidate Uses

Once the material characteristics of the source concrete from a project have been confirmed, candidate uses for the RCA can be identified. These uses in highway applications generally include the following:

- Concrete pavement (single- and two-lift)
- Asphalt pavement
- Base material (unbound and stabilized)
- Fill or embankment material (along the pavement or elsewhere on project)
- Filter material around drainage structures
- Drainage layer

The contractor should be given as much flexibility as possible in selecting the specific applications for which RCA can be used on a project. From a sustainability perspective, concrete should be recycled into the highest-grade use practical, which contributes to a zero-waste highway construction stream (Van Dam et al. 2015). However, recycling in any use is still preferable to disposal. In cases of source material of marginal or varying quality, use as fill and/or unbound base material may be better applications than use as aggregate for new concrete mixtures.

Agency Specifications

To promote concrete recycling, agency specifications should be modified to reduce or remove barriers to RCA use and to maximize the usable portion of RCA produced. Agencies should review their specifications to ensure that the RCA produced, or some significant fraction thereof, can meet the appropriate agency requirements. FHWA policy states that “restrictions that prohibit the use of recycled materials without technical basis should be removed from specifications” (Wright 2015). Existing specifications may include language that implicitly (or explicitly) restricts the use of recycled materials through unnecessary restrictions on aggregate mechanical properties, gradation, or durability. Guidance to help agencies revise restrictive or limiting specification provisions is provided throughout this manual, and a few specification provisions that often present barriers to concrete recycling are briefly discussed in this chapter.

Aggregate gradation requirements commonly impact concrete recycling project selection and scoping. For instance, many agencies specify that a minimum of 5% passes the No. 200 sieve for unbound base applications, but experience shows that typical on-grade crushing operations can produce material with 1 to 2% passing the No. 200 sieve (Fick 2017). Widening the gradation requirements, particularly for fine particle sizes, can support successful implementation of concrete recycling for many unbound base applications.

Durability provisions, especially abrasion resistance requirements, have also been a barrier to the increased utilization of RCA. The abrasion loss of RCA (measured using ASTM C131 for small-size coarse aggregate and ASTM C535 for large-size coarse aggregate) is often higher than that of virgin aggregate, and typical specification limits of 30 to 40% may preclude the use of RCA, which typically exhibits loss values of up to 45% (Snyder et al. 1994). Raising this limit slightly or using other specification modifications have been shown to successfully encourage the use of RCA. For example, the Oklahoma DOT (ODOT) increased the allowable LA abrasion test loss for unbound aggregate bases from 40% to 50% in their 2009 specifications (ODOT 2009). Iowa DOT specifications for RCA granular subbase require only gradation testing if RCA is from known agency sources. However, abrasion resistance and freeze-thaw testing are required for RCA from unknown sources, lower quality sources, or RCA blended with virgin aggregate (Iowa DOT 2014).

Alternatively, some state agencies have successfully modified existing specifications to apply to both natural and recycled aggregates. For example, the Colorado DOT (CDOT) allows RCA to be treated equally to natural aggregates (i.e., subjected to the same specified gradation and quality requirements) and to be used on all projects. The choice to use RCA, as well as selection of application, is driven by the contractor's economic and engineering decisions. Contractors are responsible for developing workable mixture designs that meet specifications, regardless of aggregate type used. Successful experience with this approach on one project (I-225) has resulted in CDOT stating that they treat RCA as "just another rock" (Prieve and Niculae 2016).

Use Selection

Once source material characteristics are known, one or more uses for RCA can be targeted by an agency or other stakeholders. In addition to ensuring that the RCA can meet the specifications, use selection may ultimately be determined by factors discussed subsequently in this chapter. As stated previously, sustainability principles encourage material reuse at the highest grade possible (Van Dam et al. 2015). However, site conditions, contractor experience, economic considerations, and agency preferences each play a role in use selection. Many laboratory and field studies, as well as successful in-service performance, have supported the development of a wealth of technical guidance for use of RCA in bound and pavement applications, as well as lower-grade uses such as fill

material. Guidance to support use selection are provided in Chapters 4, 5, and 6 of this manual.

Production Options for RCA

RCA can be produced in several ways, and feasible alternatives vary with site location, project characteristics, and market factors. One key difference in production options is whether they are performed on-site or off-site. On-site processing can be performed using conventional stationary crushing and grading facilities set up at one or more locations on or near the project site or using mobile on-grade processing equipment. In addition, urban areas often have permanent aggregate processing and recycling facilities that could be used, and this option may be enticing when on-site space is limited. The decision to use a mobile crusher or a stationary plant requires consideration of technical, financial, and environmental aspects of a project, including hauling costs, transport distances, plant production capacities, and economy of scale (Zhao et al. 2010).

The economic and environmental benefits of selecting RCA over virgin aggregates are highly linked to transportation costs. On-site processing of RCA provides the advantages of reduced hauling distances, resulting in reduced emissions and the potential for reduced construction duration (Braga 2015, Van Dam et al. 2015). The location of the source concrete and the use(s) of recycled material must also be considered. In both on-site and off-site production, hauling should be minimized. Environmental regulations associated with dust and runoff (discussed in Chapter 7) and safety regulations may also play a role in scoping and selecting production options.

Production of RCA requires equipment for breaking, excavating, removing steel and other undesirable materials, crushing, screening, and hauling. Equipment must be provided to prepare the existing concrete pavement for recycling, including cutting tooth plows or high-pressure water jets to remove joint sealants, excavators for removal of asphalt patches (if necessary), and milling machines to remove overlays (if necessary). Pavement breakers and drop hammers are often used to break the existing pavement into pieces of manageable size for excavation using slab crab buckets on backhoes, end loaders, and other suitable equipment. One consideration in choosing pavement breaking equipment is the resulting size of the broken pavement, since smaller pieces of broken concrete may result in either lower recovery rates or contamination of the recovered material with material from lower pavement layers. Reinforcing

steel can typically be salvaged and recycled once it is removed (Snyder and Cavalline 2016).

Mobile On-Site Processing for Base and Fill Uses

On-site processing for unbound RCA base is often performed using on-grade (or near-grade) crushing. In the on-grade process, crushing, screening, and grading are all done sequentially as the equipment passes over the existing pavement. After pavement breaking, a hydraulic hammer may be used to break oversized rubble pieces. An excavator feeds the mobile crushing equipment (as shown in Figure 3.2), which includes crusher(s), magnet belts to remove metals from crushed pieces, and sizing screens.



Iowa DOT

Figure 3.2. Mobile on-site crushing equipment

Many mobile crushing units have conveyors that return oversized material to the crusher. The finished RCA is transferred to conveyors, which windrow the material alongside the roadway. Very few hauling trucks are required, since the excavator feeds the crusher. This method does, however, require space on one side of the

roadway for the windrows of RCA. Crusher fines can also be windrowed separately for subsequent removal and hauling to disposal or reuse sites.

Stationary On-Site Processing for PCC, Base, and Fill Applications

On-site stationary processing of RCA requires space and equipment to support crushing, screening, and stockpiling at a central location. Site selection should minimize the impact on private property, as well as impacts to local communities (discussed in Chapter 7). Production and operational considerations also include pre- and post-processing of the material, since the quality of the RCA can be affected, as well as production rates and waste generation (Silva et al. 2017). Therefore, the land required to support a stationary on-site recycling operation will depend on several factors, including required production capacity, number of crushers and screens, size of equipment, stockpile area required, roadway area to support truck traffic, and other considerations. However, on-site RCA production facilities have been reported on sites as small as 1/2 acre (DETR 2000). Ramp interchange areas (e.g., inside the loops of a cloverleaf or the areas between ramps and the mainline pavement) are often ideal and tend to be easier to permit from an environmental standpoint (Fick 2017). For larger projects, on-site production is sometimes relocated during various project stages to help optimize hauling efficiency and support construction staging. A typical on-site stationary plant crushing and sizing yard is shown in Figure 3.3.



Gary Fick, Trinity Construction Management Services, Inc.

Figure 3.3. Crushing and sizing of source concrete at an on-site stationary plant

Off-Site Processing Options

Recycling at stationary plants tends to be more economical in urban markets, where transportation costs can be kept low (USGS 2000). These recycling facilities often accept construction and demolition (C&D) debris (including materials other than concrete) from multiple sites and typically charge tipping and/or processing fees. Although these fees must be considered, they may be offset by the potentially greater production capacity of some stationary plants, since larger recycling plants tend to have lower RCA production costs and higher operational efficiencies (Zhao et al. 2010). Another advantage of stationary recycling plants is the additional capacity that many have over mobile plants, resulting in production of stockpiles of different qualities of materials for use in different applications (Silva et al. 2017).

Since stationary plants are often involved in processing and handling C&D waste from a variety of sources, contamination may be an issue, particularly if RCA is to be used for PCC mixtures. However, stationary plant technologies and practices have progressed to the point where the quantity of contaminants introduced to the RCA can be minimized and high-quality RCA can be produced for a variety of applications (Silva et al. 2017).

General Considerations for RCA Processing

For both on-site and off-site RCA processing, production rates, availability of material during different stages of a project, hauling distance, and equipment need to be considered. Crushing and screening equipment for RCA is generally identical to the equipment used for producing virgin aggregate at a quarry. However, the types and sizes of the crushers used are important: the crushing mechanism (e.g., jaw, cone, or impact) will affect the gradation of RCA produced and the quantity of fines generated, and the crusher size will affect production rates. Impact crushers tend to crush both mortar and aggregate, resulting in the production of more fines (O'Mahony 1990). If fines production is to be limited, use of a jaw crusher may be warranted. In addition, impact crushers tend to require a smaller feed size (12 in. or less) (Fick 2017). Depending on the selected end use and specification requirements, a combination of primary and secondary crushers may be required to achieve the desired final product.

Conveyers and screens need to be sized for the appropriate production rates and material to be produced to meet specifications. If the RCA must be fractionated to meet project specifications, additional screening equipment and space for separate stockpiles

may also be required. RCA for new PCC mixtures will likely need to be held to higher QA/QC standards than RCA for base or fill applications.

Aggregate washing equipment may need to be accommodated at the RCA processing site to remove crusher dust from the RCA that will be used in concrete mixtures (to reduce water demand and prevent weak aggregate-paste bond). Washing may also be beneficial for reducing high-pH runoff and drain system deposits when RCA is used in drainable base layers and drainage backfill applications. More on these topics is discussed in Chapters 4 and 6 of this Guide.

Economic Considerations

Cost of Virgin Aggregate

Although concrete recycling promotes a more sustainable highway infrastructure, the decision to recycle and use RCA is largely driven by the relative cost of using virgin aggregates (Fick 2017). There are construction commonalities between RCA and virgin aggregate, including many construction processes. However, when considering costs, there are certain features associated with RCA and virgin aggregate that need to be compared. When comparing costs, the cost of recycled aggregate production and hauling must be weighed against the purchase and hauling costs for virgin aggregates (and disposal of unrecycled concrete). Market prices for both virgin aggregates and RCA produced by off-site recyclers vary over time, by geographic location, and quality and gradation. It is often very difficult to forecast economics during the design phase, as it is too early in the project life cycle to accurately predict market prices. Therefore, this cost comparison is easier to do during the construction phase. One factor to include in this cost comparison is that RCA typically has a lower specific gravity than virgin aggregate, so the required batch weights of RCA will be lower than for virgin aggregate for any required volume of material (Van Dam et al. 2015).

FHWA policy states that after an initial review of engineering and environmental suitability “an assessment of economic benefits should follow in the selection process” (Wright 2015). As discussed in other chapters, RCA typically provides comparable performance to virgin aggregates (ACPA 2010). Therefore, the LCCA for pavements containing RCA should produce similar results to those produced for the same pavements containing virgin aggregates, if the initial costs of the aggregates are similar. If the RCA is less expensive than available natural aggregates, a lower life-cycle cost will

result if the lower initial costs are not offset by reduced pavement performance. In some studies, use of RCA has been predicted to *improve* pavement performance, resulting in economic savings over the lifetime. For example, an LCCA of a project in Wisconsin indicated that using recycled materials in base and subbase layers could potentially save 21% over the life cycle while extending service life (Lee et al. 2010).

Management of Residual Material

Specifications typically dictate the size fractions of RCA that can be used and, conversely, the fractions that may be unusable for any given application (i.e., residual materials). Specifications for material sizes larger than the No. 4 sieve are generally easy to meet, while requirements for the size fractions passing sieves smaller than No. 4 are more difficult to meet (Fick 2017). This may result in a portion of finer RCA becoming waste. The quantity of fine material allowed in RCA is dependent on the application (e.g., drainable base specifications typically allow fewer fines than the specifications for dense-graded granular base, and specifications for coarse RCA used in concrete typically allow fewer fines than RCA used in bases). Residual material from RCA production may include solids and/or liquids (slurries).

Implementing measures to reduce the quantities of residual materials produced will reduce associated costs. Ultimately, residual materials can be either disposed of or reused in various applications at the project site. Disposal of RCA solids or slurries is generally not desirable. Beneficial reuse options include use as fill material, unbound base (if gradation requirements allow) and other applications, such as a less-costly alternative for subgrade stabilization (Lindeman and Varilek 2016)

and in new concrete paving mixtures (Naranjo 2016). Cost savings associated with these beneficial reuse applications should be considered. Strategies to reduce the production, handling, and transport of residual materials are presented in subsequent chapters.

Stakeholder flexibility in design and construction choices will help to optimize the production and use of RCA and minimization of residuals. For example, the staging plan used for the I-225 reconstruction project in Colorado allowed space for crushing and stockpiling operations (shown in Figure 3.4), which were moved several times during construction. RCA was utilized in the temporary detour pavement, which was, in turn, also crushed and reused (Prieve and Niculae 2016).

Other Factors

Project Staging

Project staging plays a key role in the availability of source concrete material for RCA, timing of its availability, stockpile and storage needs (Figure 3.4), and what applications (and areas within a project site) are potential candidates for use of the RCA.

For example, contractors may need to supplement RCA with virgin material to have adequate material to accomplish the project scope when widening is performed. During the initial stages of a project, such as when widening existing roadway shoulders to allow traffic to be diverted, RCA produced from on-site material may not be available for use. In such cases, virgin aggregate or RCA from other sources will be needed until RCA is available from demolition of the existing pavement.



J-2 Contracting Co.

Figure 3.4. On-site crushing operation

Another issue associated with project staging is that, if all concrete pavement on a site is recycled to produce RCA, surplus RCA, or salvaged base materials sometimes remain and must be accommodated. Fick (2017) describes a roadway widening project where project staging requirements resulted in leftover salvaged granular base after RCA was used as base material. Identifying alternative uses for RCA, such as in portions of new PCC pavement, aided in optimizing the use of RCA and reducing the amount of surplus material at the end of the project.

Other factors affecting project selection and scoping are those associated with environmental or societal impacts. Environmental requirements in sensitive areas

may restrict recycling operations. Public perception increasingly favors concrete recycling, since reuse of existing infrastructure is generally seen as a prudent decision. Project duration may also provide limitations to (or potentially support) the decision to recycle.

Weighing Factors and Making Decisions

All existing concrete pavement projects are potential candidates for concrete recycling. However, consideration of the factors listed previously, and potentially others, will drive project selection and scoping. A checklist of considerations for different RCA uses is summarized in Table 3.1.

Table 3.1. Checklist of considerations for use of RCA in different applications

RCA Use	Materials Considerations	Production Considerations	Other Considerations
New RCA concrete and stabilized base materials	<ul style="list-style-type: none"> ✓ Source concrete is suitable for RCA production ✓ RCA can meet agency specifications for concrete or stabilized base aggregates ✓ New RCA concrete and/or stabilized base materials can meet agency specifications 	<ul style="list-style-type: none"> ✓ Processing options (on-site vs. off-site) ✓ Hauling ✓ Crusher types ✓ Required production rates ✓ QA/QC may be more stringent than for unbound uses ✓ Residuals production, management, and disposal/beneficial reuse 	<ul style="list-style-type: none"> ✓ Staging allows for availability of RCA in appropriate quantities at appropriate time ✓ Cost of virgin aggregate ✓ Environmental considerations and permitting ✓ Public perception
Unbound bases and drainage layers	<ul style="list-style-type: none"> ✓ Source concrete is suitable for RCA production ✓ RCA can meet agency specifications 	<ul style="list-style-type: none"> ✓ Processing options (on-site vs. off-site) ✓ Hauling ✓ For on-site production, stationary or on-grade ✓ Crusher types ✓ Required production rates ✓ Residuals production, management, and disposal/beneficial reuse 	<ul style="list-style-type: none"> ✓ Staging allows for availability of RCA in appropriate quantities at appropriate time ✓ Cost of virgin aggregate ✓ Environmental considerations and permitting ✓ Public perception
Filter material around drainage structures	<ul style="list-style-type: none"> ✓ RCA can meet agency specifications 	<ul style="list-style-type: none"> ✓ Processing options (on-site vs. off-site) ✓ Hauling ✓ Crusher types 	<ul style="list-style-type: none"> ✓ Staging allows for availability of RCA in appropriate quantities at appropriate time ✓ Temporary stockpile/storage area ✓ Cost of virgin aggregate ✓ Environmental considerations and permitting ✓ Public perception
Fill (beneficial reuse of fines) not in pavement structure	<ul style="list-style-type: none"> ✓ Meets agency specifications 	<ul style="list-style-type: none"> ✓ Solids/slurry management techniques ✓ Temporary stockpile/storage area ✓ Hauling 	<ul style="list-style-type: none"> ✓ Proximity to receiving waters ✓ Other environmental considerations and permitting ✓ Public perception

After Cavalline 2017, National CP Tech Center

In order to weigh factors, agency preferences and allowable uses should be clearly articulated through specifications, special provisions, preconstruction conferences, and other means. With available options clearly evident from the initial project planning and development, the decision to recycle, as well as decisions on how and where to use the recycled material, can be made in a manner that maximizes benefits to involved parties.

Summary

“Recycling is most effective when it is driven by the client and considered from the start of the project.” (Silva et al. 2017)

Existing concrete pavement structures are agency assets that can be used beneficially to support a more sustainable highway infrastructure. Agencies should provide guidance for allowable and desirable uses of RCA, as well as specifications that reflect agency objectives (cost, sustainability, quality, etc.). The decision to mandate or specify RCA for certain uses should be weighed against the approach of allowing the contractor (market) to determine the most efficient use(s) of RCA.

To maximize the benefits of recycling, project scoping and selection should engage all key project stakeholders. The owner-agency will gain the best value from recycling when specifications, RCA material requirements, and the contractual framework allow flexibility in choosing the most appropriate RCA applications on the project. Practical guidance, presented here and in other publications, and accumulated experience should provide agencies with the confidence that RCA can be successfully utilized in a number of applications. Publicizing the resulting benefits from recycling will also aid in promoting recycling in future projects (DETR 2000).

References

ACPA. 2010. *ACPA Concrete Pavement Technology Series: Performance of Concrete Pavements with RCA*. TS043.6P. American Concrete Pavement Association, Skokie, IL.

Braga, A. M. 2015. *Compared environmental impact of the life cycle of concrete with natural and recycled coarse aggregates*. Instituto Superior Técnico, University of Lisbon, Portugal.

Cavalline, T. L. 2017. *CP Road Map: Concrete Pavement Recycling—Project Selection and Scoping*. National Concrete Pavement Technology Center, Iowa State University, Ames, IA.

Darter, M. I., S. H. Carpenter, et al. 1998. *Techniques for Pavement Rehabilitation: A Training Course – Participant’s Manual, 3rd Revision*. FHWA-HI-99-006. National Highway Institute, Federal Highway Administration. Washington, DC.

DETR. 2000. *Controlling the Environmental Effects of Recycled and Secondary Aggregates Production: Good Practice Guidance*, Department of the Environment, Transport, and the Regions. Crown Publishing, London, England.

Fick, G. 2017. *Construction Considerations in Concrete Recycling*, Webinar. National Concrete Pavement Technology Center, Institute for Transportation, Iowa State University, Ames, IA. www.cptechcenter.org/webinars/.

Iowa DOT. 2014. *Production of Certified Aggregate from Reclaimed Roadways*, IM 210. Iowa Department of Transportation, Ames, IA.

Lee, J. C., T. B. Edil, J. M. Tinjum, and C. H. Benson. 2010. Quantitative Assessment of Environmental and Economic Benefits of Recycled Materials in Highway Construction. *Transportation Research Record: Journal of the Transportation Research Board*, No. 2158, pp. 138–142.

Lindemann, M. and B. Varilek. 2016. *Use of Recycled Crushed Concrete (RCC) Fines for Potential Soil Stabilization*. In-house Research. Nebraska Department of Transportation, Lincoln, NE.

Naranjo, A. 2016. Case History of 100% RCA Paving Mixture, Houston I-10. 11th International Conference on Concrete Pavements, August 28–September 1, San Antonio, TX.

ODOT. 2009. Section 703: Bases and Miscellaneous Aggregates. *Standard Specifications Book*, Oklahoma Department of Transportation, Oklahoma City, OK.

O’Mahony, M. M. 1990. *Recycling Materials in Civil Engineering*. New College, University of Oxford, Oxford, England.

- Prieve, E. and V. Niculae. 2016. RCA Experience of Pavements in Colorado. 11th International Conference on Concrete Pavements, August 28–September 1, San Antonio, TX.
- Silva, R. V., J. de Brito, and R. K. Dhir. 2017. Availability and Processing of Recycled Aggregate within the Construction and Demolition Supply Chain: A Review. *Journal of Cleaner Production*, Vol. 143, pp. 598–614.
- Snyder, M. B., J. M. Vandenbossche, K. D. Smith, and M. Wade. 1994. *Synthesis on Recycled Concrete Aggregate*. Interim Report – Task A, DTFH61-93-C00133. Federal Highway Administration, Washington, DC.
- Snyder, M. B. and T. L. Cavalline. 2016. *Introduction to Concrete Pavement Recycling*, Webinar. National Concrete Pavement Technology Center, Institute for Transportation, Iowa State University, Ames, IA. www.cptechcenter.org/webinars/
- USGS. 2000. *Recycled Aggregates—Profitable Resource Conservation*. Fact Sheet FS-181-99. U. S. Geological Survey, Washington, DC.
- Van Dam, T., J. T. Harvey, S. T. Muench, K. D. Smith, M. B. Snyder, I. L. Al-Qadi, H. Ozer, J. Meijer, P. V. Ram, J. R. Roesler, and A. Kendall. 2015. *Towards Sustainable Pavement Systems: A Reference Document*. FHWA-HIF-15-002. Federal Highway Administration, Washington, DC.
- Wade, M. J., G. D. Cuttell, J. M. Vandenbossche, H. T. Yu, K. D. Smith, and M. B. Snyder. 1997. *Performance of Concrete Pavements Containing Recycled Concrete Aggregate*. Interim Report No. FHWA-RD-96-164. Federal Highway Administration Turner-Fairbank Highway Research Center, McLean, VA.
- Wright, F. G. 2015. *FHWA Recycled Materials Policy, Administrator’s Message*. Federal Highway Administration, Washington, DC. www.fhwa.dot.gov/legregs/directives/policy/recmatpolicy.htm.
- Zhao, W., R. B. Leefink, and V. S. Rotter. 2010. Evaluation of the Economic Feasibility for the Recycling of Construction and Demolition Waste in China – The Case of Chongqing. *Resources, Conservation and Recycling*, Vol. 54, No. 6, pp. 377–389.

Chapter 4

Using RCA in Pavement Base Products

Introduction	30
Unbound Aggregate Base Applications	30
Performance Considerations	31
Qualification Testing	33
Base Design and Construction Considerations	36
Concrete Pavement Design Considerations	36
Environmental Considerations	37
Example Projects	37
Bound (Stabilized) Base Applications	38
Summary	40
References	41

Of the six responding states that did not then allow the use of RCA as an aggregate base, two were considering allowing its use and a third indicated that it would if requested, while two others had stopped using RCA bases because of potential environmental (pH and runoff) problems, durability concerns, or clogged rodent screens at drain outlets.

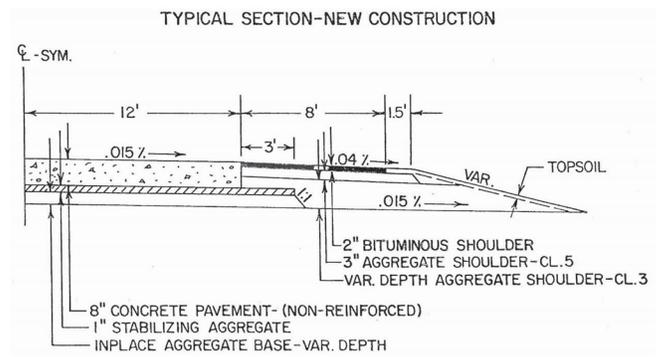
An important benefit to using RCA as unstabilized base material is that the presence of typical contaminants to the base material (e.g., asphalt concrete, joint sealant materials) has relatively little impact on the quality or performance of the base. For example, Minnesota allows up to 3% asphalt cement by weight of aggregate (see Figure 4.2), and California has no limit on the relative proportions of reclaimed asphalt pavement (RAP) and RCA in their base materials. This provides contractors with flexibility in production and construction.



FHWA 2004

Figure 4.2. RCA stockpile for aggregate base in Minnesota

Through process control and blending, contractors can produce RCA material suitable for a range of base applications. For example, RCA can be produced to provide excellent free-draining base material that is both permeable and highly stable when crushing and screening processes yield relatively angular, rough-textured particles that are graded to applicable specification requirements. Similarly, the use of RCA to provide dense-graded base material is economical because a higher proportion of the crushed concrete can be reused and is highly effective because the angular, rough-textured particles provide excellent primary stability, while the secondary hydration of RCA fines often results in further strengthening of the base layer. Additional uses of RCA fines alone (when the coarse fraction is used for free-draining base or concrete aggregate applications) include stabilization of fine-grained soils and a “cap” layer for existing dense-graded materials, as was done on the US 59 project near Worthington, Minnesota, in 1981 (see Figure 4.3).



MnDOT (from Nelson 1981)

Figure 4.3. US 59 recycling project showing use of RCA fines as a stabilizing layer on top of existing aggregate base (and RCA aggregate in new concrete pavement surface)

Performance Considerations

Structural Matters

RCA has been widely and successfully used in unbound base layer and fill applications. Available literature appears to contain no reports of pavement performance problems related to structural deficiencies in any properly designed and constructed RCA foundation layer. Some agencies believe that RCA outperforms natural aggregate in unbound base applications (FHWA 2004). The potential for improved performance of unbound RCA materials relative to natural aggregate can be attributed to the angular, rough-textured nature of crushed concrete, as well as the potential for re-cementation of the particles (particularly the fines), both of which contribute to the stability of properly constructed RCA base layers.

However, there are anecdotal reports of possible frost and/or moisture heave in some more densely graded RCA base materials in Michigan and Minnesota. These problems seem to disappear with more open gradations (permeability greater than ~300 ft/day) achieved by removing 15 to 25% of the recycled fines or limiting the percent passing through the No. 200 sieve to 0 to 6%.

A Texas study of the use of RCA fines in various applications (Lim et al. 2003) found that RCA fines often contain a large amount of material passing the No. 200 sieve and that this material often contained soil and clays from the demolition and removal process. As a result, water demand to reach optimum moisture content was increased and excessive capillary rise was observed under continued soaking conditions, thus “indicating possible moisture susceptibility of the mixture.” Strength testing, however, indicated that the material was not as susceptible to moisture, as would be suggested by its absorption properties. These researchers concluded that

the test results supported the use of crushed concrete (including fines) in unbound base applications.

In addition, sulfate attack of the RCA base was noted in one instance (see the Example Projects section later in this chapter), which illustrates the need to be mindful of potential chemical concrete attack mechanisms even when the concrete has been crushed for use as aggregate.

Drainage Issues

RCA has been used with great success in most pavement base applications, especially in dense-graded, undrained foundation layers and fill applications. The use of RCA in unbound applications that are exposed to drainable water (e.g., free-draining base layers, drain pipe backfill material, and dense-graded base layers that carry water to pavement drainage systems) have been associated with the deposit of crushed concrete dust and leachate (calcium carbonate precipitate or “calcareous tufa”) in drainage pipes and on filter fabric. These products can clog the fabrics and form deposits in drainage pipes, thereby inhibiting the function of the drainage system and possibly causing water to be retained in the pavement structure for longer periods. Accumulations of precipitate and residue in drainage pipes can be significant and can reduce discharge capacity, but rarely (if ever) completely prevent drainage flow. The accumulation of these materials typically takes place early in the pavement life and the rate of accumulation dissipates as the dust and soluble calcium hydroxide are removed from the RCA particle surfaces.

The mechanism of precipitate formation is discussed by Bruinsma et al. (1997), who describe the dissolution of calcium hydroxide (a by-product of cement hydration) into water from freshly exposed crushed concrete surfaces and the subsequent precipitation of calcium carbonate as the dissolved calcium ions react with atmospheric carbon dioxide. The availability of calcium hydroxide increases with increasing crushed concrete surface area (i.e., with increasing fine RCA content) and decreases over time as the available calcium hydroxide is depleted. Additional possible mechanisms include evaporation and temperature changes that result in supersaturation of the calcium hydroxide-infused solution, resulting in precipitate formation.

The hydroxide ions that remain in solution can result in the efflux of high-pH (alkaline) water from pavement drains and runoff from RCA stockpiles. The environmental impact of this phenomenon and its mitigation are discussed in Chapter 7 of this guide.

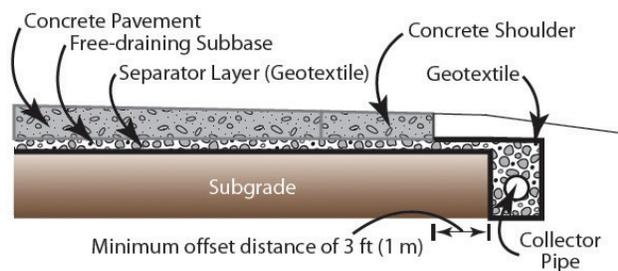
Bruinsma (1995) and Tamirisa (1993) also determined that as much as 50% of the material deposited in drainage structures and on associated filter fabrics may be dust and insoluble residue produced by crushing operations. Washing RCA prior to use reduces the presence of this material (Bruinsma 1995).

All recycled concrete aggregates that are exposed to water have the potential to produce precipitate, regardless of the product gradation. The amount of precipitate that will be produced is directly related to the amount of freshly exposed cement paste surface (i.e., increased quantities of cement paste fines), the amount of water flowing over the aggregate surfaces, and the amount of time that the water is exposed to atmospheric conditions.

Snyder (1995) and Snyder and Bruinsma (1996) summarized several lab and field studies to characterize and identify solutions to the potential problems of accumulated precipitate and dust/insoluble residue from crushing. The following techniques have been suggested and can often be used in various combinations to prevent problems with pavement drainage systems when using unbound RCA base materials in drainable layers:

- **Washing**—Wash the RCA (or use other dust removal techniques, such as air-blowing) prior to placement in the base to minimize the contribution of “crusher dust” to drainage system problems. While effective for controlling crusher dust, washing is not believed to significantly reduce the potential for precipitate formation.
- **Avoid using fine RCA**—Selectively grade the RCA to eliminate the inclusion of fine RCA particles (i.e., material passing the No. 4 sieve, which has the greatest surface area per unit weight of material) to significantly reduce inclusion of crusher dust and potential for precipitate formation. Use unbound fine RCA in layers that do not supply water to the pavement drainage system.

- **Blend with virgin aggregate**—Use virgin aggregate to partially replace the RCA (particularly for small particle sizes) to reduce inclusion of crusher dust and the potential for precipitate formation.
- **Use high-permittivity filter fabrics**—Use filter fabrics with initial permittivity values that are at least double the minimum required so that adequate flow will be maintained even if some clogging takes place (Snyder 1995).
- **Use effective drainage design features**—Design the drainage system to allow residual crusher dust to settle in a granular filter layer at the bottom of the trench rather than allowing direct entry to the pipe. This can be accomplished by placing the pipe (with slots oriented to the bottom) on the filter layer rather than directly at the bottom of the trench. Also, wrap the drain pipe trench (leaving the top of the trench unwrapped (see Figure 4.4) rather than wrapping the pipe.



©ACPA 2008a, used with permission

Figure 4.4. Typical drainage system for use of free-draining RCA base

- **Use daylighted base designs**—Consider using daylighted base designs that provide broad paths for drainage (rather than concentrating all residue in outlet structures), as described in the American Concrete Paving Association’s (ACPA’s) EB204P (ACPA 2007).
- **Stabilize the base**—Stabilize the base layer with cement or asphalt. This is effective in practically eliminating dust and leachate concerns.

Qualification Testing

General

Many highway agencies require only gradation control when recycling pavements from their own networks (i.e., known sources), requiring more extensive testing only for the processing of materials from other sources. When additional testing is required, RCA materials are generally required to meet the same quality requirements as conventional aggregate base materials, with the exception of sulfate soundness testing, which typically produces RCA mass loss values that are higher than specified limits but are not indicative of the potential durability of the RCA. Alternative soundness tests are described later in this chapter.

RCA materials may be subject to some qualification tests not generally applied to natural aggregates (e.g., limits on certain potentially deleterious substances, such as asphalt concrete, brick, plaster, gypsum board, and hazardous materials). Most of these substances are found in RCA obtained from building demolition and are not common in RCA from pavement sources. Limitations on pavement-related material inclusions, such as asphalt concrete and soils, are discussed later in this chapter.

A detailed specification concerning the use of RCA “for Unbound Soil-Aggregate Base Course” can be found in AASHTO M 319-02 (2015). This document considers the possible recycling of concrete from any source, including building and demolition debris, pavements, etc. Further guidelines specific to the use of crushed concrete from existing pavements are available in Appendix B of the ACPA publication “Recycling Concrete Pavements” (ACPA 2009). The following sections discuss some of the key qualification testing issues from these documents and others related to the use of RCA in unbound base applications.

Table 4.1. AASHTO M 147-17 grading requirements for soil-aggregate materials

Sieve Designation		Mass Percentage Passing					
Standard, mm	Alternate	Grading A	Grading B	Grading C	Grading D	Grading E	Grading F
50.0	2 in.	100	100	—	—	—	—
25.0	1 in.	—	75–95	100	100	100	100
9.5	3/8 in.	30–65	40–75	50–85	60–100	—	—
4.75	No. 4	25–55	30–60	35–65	50–85	55–100	70–100
2.00	No. 10	15–40	20–45	25–50	40–70	40–100	55–100
0.425	No. 40	8–20	15–30	15–30	25–45	20–50	30–70
0.075	No. 200	2–8	5–20	5–15	5–20	6–20	8–25

Source: Table 1 in *Standard Specifications for Transportation Materials and Methods of Sampling and Testing*, AASHTO 2017; original © 2017 AASHTO; used with permission.

Gradation

The gradation of unbound base materials is critical for providing stability (to both the pavement structure and the paving equipment) and the desired degree of drainability. To achieve a balanced achievement of these requirements, unbound RCA base materials are typically required to meet the same grading requirements that are applied to conventional unbound base materials (e.g., AASHTO M 147, ASTM D2940/D2940M, or local requirements). Table 4.1 presents typical grading bands for unbound aggregate base and base materials.

In addition, good dense-graded unbound base materials should have a plasticity index (PI) of 6.0 or less, with no more than 12 to 15% passing through the No. 200 sieve (ACPA 2008b, ASTM 2015).

The aggregate top size should not exceed 1/3 the layer thickness, and base layers thicker than 6 in. are not economical or recommended in most cases. Regardless of the size(s) produced, the grading bands should be adjusted to provide suitable gradations for the intended application (e.g., free-draining vs. dense-graded) and to minimize production of materials that cannot be used.

Guidance on specific gradations to achieve unstabilized base materials that provide good stability with varying degrees of permeability (free drainage capacity) can be found in ACPA’s EB204P (ACPA 2007).

Other Physical Requirements

Los Angeles abrasion test (AASHTO T 96) requirements for RCA are typically the same as for natural aggregate materials (i.e., loss of not more than 50%). RCA usually

meets this requirement without difficulty but generally exhibits higher losses than most conventional aggregate types. This can be a concern in construction, where compaction efforts result in an effective change in gradation, as is discussed later in this chapter.

Soundness testing of RCA is sometimes required but cannot be performed with conventional sodium or magnesium sulfate soundness tests (AASHTO T 104) because RCA is susceptible to sulfate attack, which produces unusual mass loss values that are not representative of the actual durability of the RCA. Therefore, soundness testing of RCA is often waived (particularly for unbound base applications). For similar reasons, unbound RCA bases should not be used in areas with high-sulfate soils.

AASHTO M 319 describes alternative soundness testing approaches, including AASHTO T 103 (a freeze-thaw procedure conducted in water with 25 cycles of freezing and thawing and a maximum allowable loss of 20%). Other listed alternates are the NYSDOT Test Method NY 703-08 and Ontario Ministry of Transportation Test Method LS-614, both of which involve freeze-thaw cycles in a sodium chloride brine solution with a maximum allowable mass loss of 20%.

Limits on deleterious materials are often provided because while RCA is primarily comprised of crushed concrete material and natural aggregate particles, it is not uncommon to find the inclusion of some natural soils, asphalt concrete (from shoulder, base, or repair materials), and other potentially deleterious materials.

These should be limited as follows:

- Bituminous concrete materials are limited to 5% or less, by mass, of the RCA in AASHTO M 319, with a note that validation testing should be performed to justify the use of higher percentages. Appendix X4 of that specification describes the use of the California Bearing Ratio Test (AASHTO T 193) and Resilient Modulus Test (AASHTO T 307) for validation. It also describes validation by field application (construction of a test strip or historical data to show that higher percentages of asphalt concrete will not adversely affect the performance of the granular base). As a result, many agencies allow significantly more than 5% asphalt material in their unbound RCA base materials.
- AASHTO M 319 limits the inclusion of plastic soils such that the liquid limit (AASHTO T 89) of materials passing the No. 40 sieve is 30 or less and the plasticity index (AASHTO T 90) of the same material is less than 4. Alternatively, the sand equivalent test (AASHTO T 176) value of the same material must be a minimum of 25%.
- RCA should be free of all materials that can be considered solid waste or hazardous materials, as defined locally.
- RCA should also be “substantially free” (i.e., each less than 0.1% by mass) of other potentially deleterious materials, such as wood, gypsum, metals, plaster, etc. These limits can be adjusted if it is determined that the adjustments will not negatively impact the performance of the base course.

Application-Based Requirements

The final report for NCHRP Project 4-31 (Saeed 2008) identifies several properties of recycled aggregate base materials that influence the performance of the overlying pavement. These properties include aggregate toughness, frost susceptibility, shear strength, and stiffness. The following tests are recommended for evaluating these properties: Micro-Deval (AASHTO T 327), Tube Suction*, Static Triaxial (ASTM D2850-15) and Repeated Load Tests*, and Resilient Modulus* (with * indicating test procedure described in Saeed et al. 2006). Saeed and Hammons (2008) provided a matrix (Table 4.2) that summarizes recommendations or critical test values for each of these tests to ensure good RCA base performance in specific traffic, moisture, and temperature conditions.

These tests and criteria are not required for any particular RCA base application but do offer guidance that may be useful in assuring the potential for good performance for the intended application with any specific RCA material.

Table 4.2. Test criteria for various unbound base applications

Tests and Test Parameters	Traffic	High		Med.		High		Low		Med.	Low	
	Moisture	High	Low	High	Low	High	Low		High		Low	
	Climate	Freeze				Nonfreeze		Freeze		Nonfreeze		
Micro-Deval Test (percent loss)		< 5 percent				< 15 percent				< 30 percent		< 45 percent
Tube Suction Test (dielectric constant)		≤ 7				≤ 10				≤ 15		≤ 20
Static Triaxial Test (Max. Deviator Stress)	OMC, $\sigma_c = 5$ psi (35 kPa)	> 100 psi (0.7 MPa)				> 60 psi (0.4 MPa)				> 25 psi (170 kPa)		Not required
	Sat., $\sigma_c = 15$ psi (103 kPa)	≥ 180 psi (1.2 MPa)				≥ 135 psi (0.9 MPa)				≥ 60 psi (410 kPa)		Not required
Repeated Load Test (Failure Deviator Stress)	OMC, $\sigma_c = 15$ psi (103 kPa)	≥ 180 psi (1.2 MPa)				≥ 160 psi (1.1 MPa)				≥ 90 psi (620 kPa)		Not required
	Sat., $\sigma_c = 15$ psi (103 kPa)	≥ 180 psi (1.2 MPa)				≥ 160 psi (1.1 MPa)				≥ 60 psi (410 kPa)		Not required
Stiffness Test (Resilient Modulus)		≥ 60 ksi (0.4 MPa)				≥ 40 ksi (275 kPa)				≥ 25 ksi (170 MPa)		Not required

Low traffic: < 100,000 ESALs/year; Medium traffic: 100,000 to 1,000,000 ESALs/year; High traffic: 1,000,000 ESALs/year

Source: ACPA 2009 after Saeed and Hammons 2008 with © 2008 ASCE

Base Design and Construction Considerations

Design of unbound RCA base layers should be performed using the same tools used for conventional unbound aggregate base layers and should result in layers of similar thickness. Thicknesses commonly range from a minimum of 4 in. (a typical minimum value for constructability and stability of the construction platform) to a maximum of 6 in. (because additional base thickness provides no significant added structural benefit for concrete pavements). Thicker base layers may be used for other reasons, such as added frost protection for local soils. Blending with virgin aggregate may be necessary when the designed base thickness exceeds the amount of properly graded material that can be produced from the original pavement.

In many cases, more RCA base material is produced from the original pavement than is required for the new base layer (e.g., when a 12 in. concrete pavement is recycled to produce material for a 4 in. base layer). The use of RCA base across the full pavement cross-section (including the shoulders) is often recommended to minimize hauling or waste of the RCA base material.

RCA bases can be placed using standard equipment and techniques. Avoid excessive handling and movement of the RCA during placement and compaction because these activities can produce additional fine material through abrasion, particle fracture, and other mechanisms.

RCA (and blends of RCA and natural aggregate) should be placed close to the optimum moisture content to ensure that compaction efforts are efficient. Optimum moisture content for RCA is typically significantly higher than for natural aggregate because of the higher absorption capacity of typical RCA. Placement at sub-optimal moisture contents will require additional compaction effort, which may result in unnecessary degradation of the RCA and the creation of fines that change the drainage and stability characteristics of the material. Additional fines from RCA degradation also increase the potential for precipitate formation.

Compaction density control is typically accomplished by performing a standard proctor test (AASHTO T 99 or ASTM D698) and requiring a minimum in-place density of no less than 95% of standard proctor. If the RCA is to be free-draining (i.e., a target permeability of 150 to 350 ft/day), it may be difficult to achieve the desired density without crushing the base material during compaction. In such cases, it may be preferable to relax the compaction requirement slightly and/or

adopt a procedural standard of compaction (i.e., require a specified number of compaction passes to achieve adequate density, based on agency experience). Appendix X1 of AASHTO M 319 provides a detailed description of an alternative field control method that involves the use of variable acceptance criteria for compaction that is based on testing performed on each designated lot and subplot on the project.

No matter the compaction control method selected, construction specifications must be appropriately written and enforced to ensure compaction is achieved to such an extent that no significant densification of the compacted base material occurs due to service traffic loadings.

There have been concerns with the impact and efficacy of on-site concrete pavement recycling in urban areas because of the generation of noise and dust in breaking and crushing operations. Excessive noise must be abated in accordance with local ordinances and requirements, often through limitations on the times when noisy operations can be conducted, which can impact production schedules. Dust abatement procedures (e.g., dust collection hoods and/or water sprays at the crushing and screening stations) are less problematic but do add cost to the process.

Concrete Pavement Design Considerations

Significant stiffening of unstabilized RCA base materials is possible over time due to the continued hydration of cementitious materials (especially for dense-graded RCA base materials containing fine RCA particles). This stiffening over time can cause unstabilized bases to behave more like stabilized bases, which results in excellent strength and erosion resistance, but also in somewhat higher curling and warping stresses in overlying jointed concrete slabs. It may also produce levels of slab restraint in jointed and continuously reinforced concrete pavements (CRCP) that are higher than those developed with typical unbound aggregate base materials and are comparable to those developed with cement-treated base materials. The Design Principles chapter of ACPA's EP204 (ACPA 2007) provides a more detailed discussion of the potential impacts on increased base stiffness on concrete pavement behavior, design, and performance.

Concrete pavement design thickness requirements might be reduced by the increased levels of foundation support provided by a re-cemented RCA base. Conversely, added thickness (or shorter panel lengths) might be needed to address increased curl/warp stresses. Similarly, it is possible that stiffening of the RCA base could

result in a need for additional quantities of reinforcing steel in jointed and continuously reinforced concrete pavements. Sophisticated design software, such as AASHTO PavementME, can directly consider these effects on pavement design and predicted performance if appropriate design inputs are provided.

There is little evidence in the literature to indicate that any agency has yet significantly modified their pavement thickness, panel size, or panel reinforcing designs to address long-term base stiffening due to secondary cementing. In addition, there is no evidence in the literature to suggest that concrete pavements built on unbound RCA foundations have performed poorly due to a failure to adjust panel length, thickness, or reinforcing design. Thus, the practical perspective appears to be that there are no particular concrete pavement design implications associated with the use of RCA in unbound base layers for concrete pavements.

Environmental Considerations

Water percolating through RCA foundation layers can result in effluent that is initially highly alkaline, often with pH values of 11 or 12. This is an effect that generally diminishes with time in service as the calcium hydroxide near the exposed RCA surfaces is dissolved and removed from the system. Furthermore, this high pH effluent is generally not considered to be an environmental hazard, because it is effectively diluted at a very short distance from the drain outlet with much greater quantities of surface runoff (Sadecki et al. 1996, Reiner 2008). It is not uncommon, however, to see very small regions of vegetation kill in the immediate area of the drain outlet.

Consideration of the sensitivity of local soils, surface waters, and groundwater to the presence of alkaline effluent may necessitate setting limits on the proximity of RCA placement to sensitive areas. This same effluent may also cause or accelerate corrosion of exposed metals in culverts and other appurtenant structures, so those types of exposure should be avoided.

The gradation and washing recommendations provided previously to prevent precipitate formation are generally effective in reducing initial pH levels in RCA base drainage effluent (Snyder and Bruinsma 1996). Chapter 7 of this manual provides additional information and guidance on mitigating environmental impacts, such as elevated pH effluent. Additional information on ways to mitigate environmental concerns associated with concrete recycling is presented in Chapter 7.

Example Projects

Edens Expressway, Chicago, Illinois–1978 (ACPA 2009)

The 1978 reconstruction of the Edens Expressway (I-94 through the northern suburbs of Chicago) presented many “firsts” (Dierkes 1981, Krueger 1981):

- First major urban freeway in the US to be completely reconstructed
- Largest highway project on which concrete recycling had been used
- Largest single highway contract ever awarded in the US at that time, with a total project cost of \$113.5 million (in 1978 dollars)
- First major US project to include recycling of an existing mesh-reinforced concrete pavement

In 1978, the Illinois DOT (IDOT) permitted the use of RCA in base layers and fill applications. While there were adequate supplies of acceptable virgin base aggregate approximately 18 miles from the project site, the haul from the source to the job site would have required a three hour round trip during daytime traffic conditions, so the recycling option was exercised (NHI 1998).

The crushing plant was set up in an interchange cloverleaf area (see Figure 4.5).



NHI 1998

Figure 4.5. Concrete recycling operation set up inside of Edens Expressway cloverleaf interchange

The area was heavily populated, so noise was a serious concern. Crushing operations were suspended from midnight until 6 am every day, and some modifications to typical operational procedures were instituted (e.g., truck drivers were not allowed to bang their tailgates to help discharge materials from the truck beds).

About 350,000 tons of the old pavement were crushed at this site, with about 85% of the RCA produced being used in fill areas, while the remaining 15% was used as a 3-in. unbound aggregate base. An asphalt-treated base and 10-in. CRCP was placed over the RCA base. It was estimated that recycling the old concrete pavement saved 200,000 gallons of fuel that would otherwise have been consumed in disposing of demolished concrete and hauling virgin aggregate (NHI 1998).

This pavement provided excellent service for nearly 40 years under extremely heavy traffic (up to 170,000 vehicles per day in 2007) and demonstrated the feasibility (and economy) of completely recycling and reconstructing a high-volume urban concrete expressway.

Holloman Air Force Base, New Mexico—Sulfate Attack Problems (Saeed et al. 2006)

The Holloman Air Force Base is located in a high desert plateau area of New Mexico where the soils are typically loose silty sands and sandy silts, the water table is often high, and the sulfate content of the local soils is also very high. Because of these difficult site conditions, all construction at Holloman is placed on at least 2 ft of non-expansive fill and Type V sulfate-resistant cement is used in all concrete that is near or in contact with the ground.

The “German Air Force” apron was built in 1995 using 2 ft to 5 ft of RCA fill and an RCA base that was produced from concrete being removed from a different airport apron that was undergoing repairs. The source concrete had minor distresses and construction defects but showed no signs of durability problems. Tests conducted on this material indicated that it was sulfate resistant, and no sulfate attack had been observed before it was removed.

Heaving began soon after construction, appearing first in localized areas and then spreading and becoming progressively worse and more widespread with time. It was reported that heaving was occurring in a wide range of structures that were placed on the RCA fill, including rigid and flexible pavements, sidewalks, and foundation slabs.

Sulfate attack (on supposedly sulfate-resistant concrete) was determined to be the source of the heaving. The most likely reason for this phenomenon is that the fill and base course material were more permeable than intact Portland cement concrete, so sulfate-bearing water had easy access to the limited alumina available in the Type V cement.

Other Projects

Additional examples of the successful use of RCA in unbound aggregate base layers in Wisconsin and Illinois Tollway applications were described briefly in Chapter 2 of this manual.

Bound (Stabilized) Base Applications

Lean Concrete Base (LCB) and Cement-Stabilized Base (CSB)

LCB and CSB layers can be constructed using RCA. Coating or embedding the RCA in fresh cement paste or mortar prevents the migration of crusher fines and the dissolution and transport of significant amounts of calcium hydroxide, which can otherwise form calcium carbonate precipitate in drain pipes.

The physical and mechanical properties of RCA (particularly the absorption characteristics) must be considered in the design and production of LCB and CSB materials, similar to their consideration in concrete production using RCA. Chapter 5 of this manual provides detailed information and guidance on the design and production of concrete mixtures using RCA; the concepts presented there are generally applicable to the production of cement-stabilized RCA base materials as well.

Asphalt Concrete and Asphalt-Stabilized Base

RCA has been used successfully in new asphalt concrete and asphalt-stabilized base applications at replacement rates of up to 75%. Typical RCA particle angularity and rough texture provide excellent potential for stability and surface friction, and the use of asphalt to encapsulate RCA particles effectively eliminates the potential for logging of drainage structures in base applications.

Unfortunately, the more absorptive nature of typical RCA particles significantly increases asphalt demand, which may increase costs. However, it is worth noting that USGS (2000) determined that about 10% of all RCA being produced at that time was being used in asphalt concrete mixtures.

Performance Concerns

RCA intended for use in bound base layers requires none of the special treatment or handling described previously to prevent drainage problems because encapsulation of the aggregate particles with asphalt or cement paste or mortar stabilizes any remaining crusher dust and prevents the dissolution of calcium hydroxide. There

are no known pavement performance concerns that are related specifically to the use of RCA in bound base layers for either asphalt or concrete pavements.

Examples of the use of RCA in bound base applications are presented next.

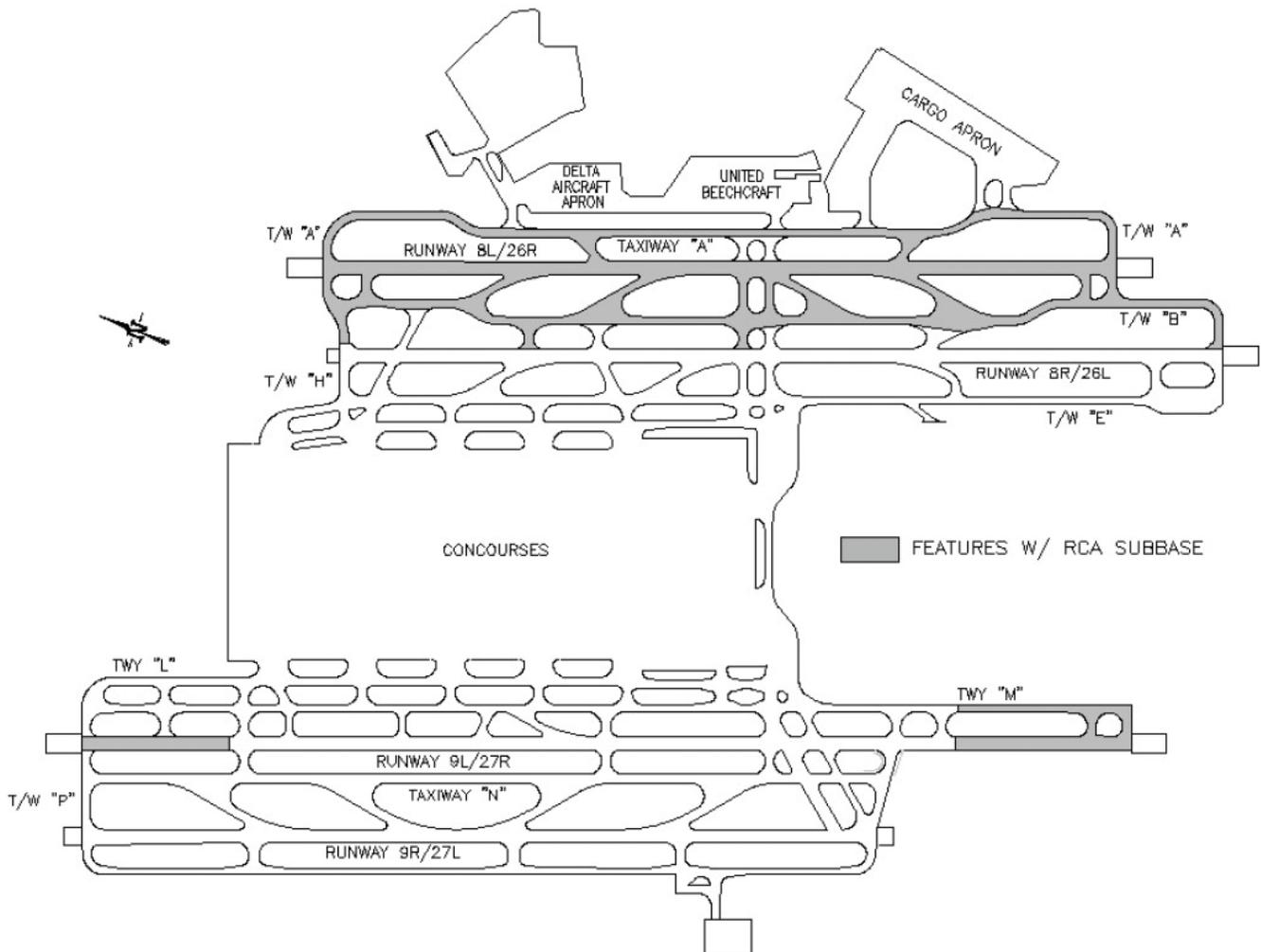
Example Projects

Hartsfield-Jackson Atlanta International Airport (ATL)

The typical section for all pavements at the airport is 16 in. of PCC over a 6-in. cement-treated base, over a 6-in. cement-stabilized subgrade and compacted natural subgrade. RCA is allowed at the contractor's option for use in both fill and base material at the airport. The primary reason for its use is the savings of landfill costs in disposing of existing concrete. When used as fill, the RCA complies with the Georgia DOT (GDOT) specifications for graded aggregate bases.

RCA at ATL must exceed GDOT virgin aggregate standard specifications for Sections 800 (Coarse Aggregate) and 815 (Graded Aggregate). This results in a 1.5-in. top size material with 4% to 11% passing the No. 200 sieve, LA abrasion maximum mass loss of 51 to 65%, and a sand equivalent test result of at least 28.

Figure 4.6 shows locations at the ATL where RCA has been used as a cement-treated pavement base. In addition, it has also been used successfully under flexible (asphalt) pavement at the Southeast Navigation, Lighting, and Visual Aid Road (not shown).



Saeed et al. 2006

Figure 4.6. Airfield pavement layout at Hartsfield-Jackson Atlanta Airport showing features with RCA base

RCA at the ATL has been produced on site using pavement slabs from construction in the 1980s, some of which had alkali-silica reactivity. As of 2006, some of those slabs were still stacked and stored for future production of RCA (see Figure 4.7).



Saeed et al. 2006

Figure 4.7. ATL slabs stacked for future concrete recycling

Construction of RCA bases at ATL has been accomplished using conventional equipment. There was concern that the RCA would degrade during compaction, but no evidence of degradation was observed. It is reported that the RCA fill and bases have performed adequately (Saeed et al. 2006).

Michigan DOT Experience (Van Dam et al. 2011)

The Michigan DOT (MDOT) has constructed a few projects under Special Provision 03CT303(A140): “Open-Graded Drainage Course, Modified (Portland Cement-Treated Permeable Base Using Crushed Concrete).” This was done, at least in part, due to issues related to excessive flow of precipitate from unbound open-graded RCA drainage courses.

The special provision requires that all RCA used for the cement-treated permeable base (CTPB) be obtained from the pavement that is being reconstructed (unless otherwise approved). Physical requirements for the RCA are presented in Table 4.3.

The CTPB mixture is proportioned with 250 lbs of cement and 100 to 120 lbs of water per cubic yard, with adjustments allowed to achieve compressive strengths between 200 and 700 psi at 7 days. As of the date of this manual, the pavements constructed on an RCA CTPB were “performing very well.”

Summary

RCA is commonly used with great success in pavement base and fill applications. Reasons for the wide acceptance in these applications include the following: the stable nature of the typically angular, rough-textured particles; added stability often provided by secondary cementation; relative insensitivity of the material to the presence of minor amounts of asphalt, metals, and other typical materials found in the pavement environment; economics associated with reduced hauling costs and tipping fees for disposal; environmental benefits of resource conservation and reductions in processing and hauling energy; and excellent performance potential.

RCA generally meets all of the same quality and physical requirements used for natural base aggregate. An exception is that sulfate soundness testing is not indicative of RCA durability so other durability tests must be used.

Structural concerns due to frost heave, moisture swelling, or sulfate attack have presented in a very few cases. These rare instances can be avoided through selected RCA gradation to minimize exposure to and retention of moisture.

The flow of water over and through RCA can result in highly alkaline effluent—at least initially—and the depositing of crusher dust and calcareous tufa in drainage systems. Several approaches to mitigating these issues are presented in this chapter.

Table 4.3. MDOT requirements for RCA use in cement-treated permeable base

Sieve Analysis (MTM 109)							
Sieve Size	1½ in.	1 in.	¾ in.	½ in.	No. 4	No. 8	No. 200*
Percent Passing	100	90–100	—	25–65	0–20	0–8	5 max.
Additional Physical Requirements							
Crushed Material, % Min (MTM 110,117)					90**		
Loss, % max, Los Angeles Abrasion (MTM 102)					45		

* Loss by washing (MTM 108)

** The percent crushed material will be determined on that portion of the sample retained on all sieves down to and including the ¾ inch.

Source: Michigan DOT via Applied Pavement Technology, Inc.

References

- AASHTO. 2017. *Standard Specifications for Transportation Materials and Methods of Sampling and Testing*, M 147-17. American Association of State Highway and Transportation Officials, Washington, DC.
- AASHTO. 2015. *Standard Specification for Reclaimed Concrete Aggregate for Unbound Soil-Aggregate Base Course*, M 319-02. American Association of State Highway and Transportation Officials, Washington, DC.
- ACPA. 2009. *Recycling Concrete Pavements*. Engineering Bulletin EB043P, American Concrete Pavement Association, Skokie, IL.
- ACPA. 2008a. *ACPA Concrete Pavement Technology Series: Drainage in Concrete Pavement Structures*. TS204.9P. American Concrete Pavement Association, Skokie, IL. 1204075.sites.myregisteredsite.com/downloads/TS/EB204P/TS204.4P.pdf.
- ACPA. 2008b. *Concrete Pavement Field Reference: Pre-Paving*. Engineering Bulletin EB237P. American Concrete Pavement Association, Skokie, IL.
- ACPA. 2007. *Subgrades and Subbases for Concrete Pavements*. Engineering Bulletin EB204P. American Concrete Pavement Association, Rosemont, IL.
- ASTM. 2015. *Standard Specification for Graded Aggregate Material for Bases or Subbases for Highways or Airports*, D2940/D2940M-15. ASTM International, West Conshohocken, PA.
- Bruinsma, J. E. 1995. Formation and Mitigation of Calcium Carbonate Precipitate and Insoluble Residue from Recycled Concrete Aggregate Bases. MS thesis. University of Minnesota Department of Civil Engineering, Minneapolis, MN.
- Bruinsma, J. E., K. R. Peterson, and M. B. Snyder. 1997. Chemical Approach to the Formation of Calcite Precipitate from Recycled Concrete Aggregate Base Layers. *Transportation Research Record: Journal of the Transportation Research Board*, No. 1577, pp 10–17.
- CDRA. 2012. *Recycled Concrete Aggregate – A Sustainable Choice for Unbound Base*, White paper. Construction & Demolition Recycling Association, Chicago, IL.
- Darter, M. I., S. H. Carpenter, et al. 1998. *Techniques for Pavement Rehabilitation: A Training Course – Participant’s Manual, 3rd Revision*. FHWA-HI-99-006. National Highway Institute, Federal Highway Administration, Washington, DC.
- Dierkes, J. H., Jr. 1981. Urban Recycling of Portland Cement Concrete Pavement—Edens Expressway, Chicago, Illinois. *Proceedings of the National Seminar on PCC Pavement Recycling and Rehabilitation*, St. Louis, MO, pp. 172–175.
- FHWA. 2004. *Transportation Applications of Recycled Concrete Aggregate: FHWA State of the Practice National Review*. Federal Highway Administration, Washington, DC. www.fhwa.dot.gov/pavement/recycling/applications.pdf.
- Krueger, O. 1981. Edens Expressway Pavement Recycling—Urban Pavement Breakup, Removal, and Processing. *Proceedings of the National Seminar on PCC Pavement Recycling and Rehabilitation*, St. Louis, MO, pp. 165–169.
- Lim, S., D. Kestner, D. G. Zollinger, and D. W. Fowler. 2003. *Characterization of Crushed Concrete Materials for Paving and Non-paving Applications*. Texas Transportation Institute, Texas A&M University, College Station, TX.
- Nelson, L. A. 1981. Rural Recycling. *Proceedings of the National Seminar on PCC Pavement Recycling and Rehabilitation*, St. Louis, MO, pp. 176–185.
- Reiner, M. 2008. *Evaluation of Potential pH Environmental Hazards and Mitigation Measures when Utilizing Recycled Concrete Aggregate in the Field*. Symbiotic Engineering Green Paper Number Six. Symbiotic Engineering, Boulder, CO.
- Sadecki, R. W., G. P. Busacker, K. L. Moxness, K. C. Faruq, and G. Allen. 1996. *An Investigation of Water Quality in Runoff from Stockpiles of Salvaged Concrete and Bituminous Paving*, Report No. MN/PR-96/31. Minnesota Department of Transportation, St. Paul, MN.
- Saeed, A., M. I. Hammons, D. Rufino Feldman, and T. Poole. 2006. *Evaluation, Design and Construction Techniques for Airfield Concrete Pavement Used as Recycled Material for Base*. Innovative Pavement Research Foundation, Skokie, IL.
- Saeed, A. 2008. *NCHRP Report 598: Performance-Related Tests of Recycled Aggregates for Use in Unbound Pavement Layers*. National Cooperative Highway Research Program, Washington, DC.

- Saeed, A. and M. I. Hammons. 2008. Minimum Standards for Using Recycled Materials in Unbound Highway Pavement Layers. *Airfield and Highway Pavements: Efficient Pavements Supporting Transportation's Future*. American Society of Civil Engineers, Reston, VA, pp. 452–463.
- Snyder, M. B. 1995. *Use of Crushed Concrete Products in Minnesota Pavement Foundations*, Minnesota Department of Transportation, St. Paul, MN.
- Snyder, M. B. and Bruinsma, J. E. 1996. A Review of Studies Concerning the Effects of Unbound Crushed Concrete Bases on PCC Pavement Drainage. *Transportation Research Record: Journal of the Transportation Research Board*, No. 1519, pp. 51–58.
- Tamirisa, R. 1993. Study of Highway Base/Subbase Aggregates That Cause Depositions of Calcareous Tufa in Drains. MS thesis. Department of Civil Engineering, University of Toledo, Toledo, OH.
- USGS. 2000. *Recycled Aggregates—Profitable Resource Conservation*. Fact Sheet FS-181-99. U. S. Geological Survey, Washington, DC.
- Van Dam, T., K. Smith, C. Truschke, and S. Vitton. 2011. *Using Recycled Concrete in MDOT's Transportation Infrastructure – Manual of Practice*. Applied Pavement Technology, Inc., Urbana, IL and Michigan Tech Transportation Institute, Michigan Technological University, Houghton, MI.

Chapter 5

Using RCA in Unbound Aggregate Shoulders

Introduction	44
Qualification Requirements	45
RCA Shoulder Design Considerations	46
Assessing Potential Economic Benefits	47
Environmental Considerations	47
Summary	48
References	48



Iowa DOT

Figure 5.1. RCA aggregate shoulder (50% blend with natural aggregate) on US 34 east of Fairfield, Iowa

Introduction

RCA can be (and has been) successfully used in unbound aggregate shoulder surface applications (see Figure 5.1).

For example, nine of thirteen states responding to a survey conducted by the National Concrete Pavement Technology (CP Tech) Center (2017) stated that RCA was allowed for use as shoulder surfacing by their agency (although one of those agencies—the South Dakota DOT—noted that they were unsure whether RCA had ever actually been used for shoulder surfacing in their state). Furthermore, the FHWA (2004) reported that the Michigan DOT (MDOT) also allows the use of dense-graded RCA in shoulder surfacing applications.

Many of the material qualification requirements and construction considerations that apply to the use of RCA in unbound base applications (see Chapter 4) also apply to the use of RCA in unbound aggregate shoulder surfaces.

When used in unbound shoulder surface applications, RCA may be blended with natural aggregate or used as a sole material source, depending on the relative quantities of required material and available RCA product, as well as other project-specific or agency requirements. For example, the Iowa DOT requires that RCA be blended

with natural aggregate for shoulder surface applications and allows 30% maximum RCA for new shoulders and 50% maximum RCA when adding to existing shoulders (Iowa DOT 2015). Before these limits were implemented in Iowa, shoulders made from 100% RCA were initially very unstable for heavy trucks and took several years to become stable when wet. No other agency responding to the previously referenced CP Tech Center survey (CP Tech Center 2017) indicated a requirement for blending with natural aggregate, although they may allow it.

While it is allowed in many states, the use of RCA in unbound shoulder surfaces is not common and very little published information on the topic is available. This is most likely because roadways with recyclable concrete mainline pavements typically have asphalt- or concrete-surfaced shoulders and little or no need for aggregate shoulder surfacing. In addition, it is far more common and more broadly accepted to use RCA in unbound base applications beneath travel lanes and shoulders.

This chapter describes qualification requirements, design techniques, and construction considerations for unbound RCA shouldering materials.

Qualification Requirements

General

Many highway agencies require only gradation control when recycling concrete pavements from their own networks (i.e., known sources) and require more extensive testing only for the processing of materials from other sources. When additional testing is required, RCA materials are generally required to meet the same quality requirements as conventional aggregate materials. An exception is typically made for sulfate soundness testing because RCA is often susceptible to sulfate attack when tested using sodium or magnesium sulfate materials, which may make the results of tests like AASHTO T 104 unreliable. Alternative soundness tests for RCA are described in Chapter 4.

Guidelines specific to the use of crushed concrete from existing pavements in unbound bases are available in Appendix B of the American Concrete Pavement Association’s (ACPA’s) “Recycling Concrete Pavements” (ACPA 2009). This guidance is also generally applicable to the use of RCA in unbound shoulder surfaces. The relevant general guidance can be summarized as:

- “RCA material ... should be free of all materials that are considered to be solid waste or hazardous materials, as defined by the state or local highway agency.”
- “If RCA or combinations of RCA and other approved virgin aggregate materials are to be used ... proposed percentages of combined materials should be established as part of the request [for approval]. Revised density acceptance criteria are recommended when percentages or sources of material change because RCA specific gravity and absorption characteristics are different from those of natural aggregate and may vary significantly between sources.”

- “If RCA is blended with other approved aggregates, blending should be accomplished using a method that ensures uniform blending and prevents segregation.”
- “The quality control (QC) plan for the RCA should detail the production procedures, test methods, and frequency of testing to ensure consistent production of RCA meeting the requirements of the intended application. The QC will also describe methods to be used to ensure that RCA materials are not contaminated with unacceptable amounts of deleterious materials.”

RCA materials may be subject to some qualification tests not generally applied to natural aggregates (e.g., limits on certain potentially deleterious substances, such as asphalt concrete, brick, plaster, gypsum board, and hazardous materials). Most of these substances are found in RCA obtained from building demolition and are not common in RCA from pavement sources. Limitations on pavement-related material inclusions, such as asphalt concrete and soils, are also discussed in Chapter 4.

Gradation

The gradation of unbound aggregate shoulder surface materials is critical to the stability of the material under service. Good dense-graded unbound base materials are typically required to have a plasticity index (PI) of 6.0 or less, with no more than 12 to 15% passing the No. 200 sieve (ACPA 2008, ASTM 2015). Similar requirements are probably appropriate for state DOT shoulder surfacing materials; some relaxation of these requirements may be possible for lower volume roads (i.e., some county and other rural roads).

Table 5.1 summarizes aggregate grading requirements for RCA shouldering material, as reported by respondents to the National CP Tech Center survey (2017).

Table 5.1. Reported RCA grading requirements for shoulder surface applications

State	Percent Passing (by mass)															
	1.5 in.	1.25 in.	1 in.	3/4 in.	5/8 in.	1/2 in.	3/8 in.	#4	#8	#10	#16	#30	#40	#60	#100	#200
GA	97–100			60–95						25–45				10–30		2–11
IL	100		90–100			60–80		30–56			10–40					4–12
NC	100					55–95		35–74								
TN	100		85–100	60–95			50–80	45–65			20–40				5–18	
WA		99–100			80–100			35–45					3–18			0–7.5
IA			100	95–100		70–90		30–55	15–40							6–16
OH			100	60–90			35–75	30–60				9–33				0–15
MN				100			65–95	40–85		25–70			10–45			5–15
SD				100				50–78	37–67				13–35			4–15

Source: National CP Tech Center 2017



Figure 5.2. Specified RCA gradation ranges for four states using 1.5 in. top-size material (2017)

Figure 5.2 presents a plot of the gradations for the four states that use 1.5 in. top-size material and shows that the specified ranges are fairly well-graded and plot near the 0.45 power curve. Similar plots can be produced for the other top-size gradations.

RCA Shoulder Design Considerations

Design of unbound RCA shoulders should be performed using the same tools used for conventional unbound aggregate shoulders and should result in shoulders with similar (if not identical) thickness.

Placement and Compaction Equipment

RCA shoulders can be placed using standard equipment and techniques. However, excessive handling and movement of the RCA during placement and compaction should be avoided because these activities can produce additional fine material through abrasion, particle fracture, and other mechanisms, thereby resulting in a changed particle size distribution that could result in reduced shoulder stability.

There are two schools of thought on the type of compaction equipment that should be used for constructing RCA base/subbase layers. One line of thinking recommends the use of rubber-tired compactors because steel wheel compaction equipment may produce more RCA particle breakage and degradation that could

result in reduced material stability. This is generally the more broadly accepted approach. However, some agencies recommend using steel-wheeled compaction equipment when the RCA may contain embedded steel fragments that could damage rubber-tired rollers. Similar thinking may apply to the construction of unbound RCA shoulders, although the RCA processing should remove any steel that would be hazardous to either compaction equipment or vehicles that might use the shoulder in service conditions.

Moisture and Density Control

RCA (and blends of RCA and natural aggregate) should be placed close to the optimum moisture content to ensure that compaction efforts are efficient. Optimum moisture content for RCA is typically significantly higher than for natural aggregate because of the higher absorption capacity of typical RCA. Placement at sub-optimal moisture contents may cause segregation and will require additional compaction effort, which may result in unnecessary degradation of the RCA and the creation of fines that change the drainage and stability characteristics of the material.

As with RCA base applications, compaction density control is typically accomplished by performing a standard proctor test (AASHTO T 99 or ASTM D698) and requiring a minimum in-place density of no less

than 95% of standard proctor. In some cases, it may be difficult to achieve the desired density without crushing the base material during compaction. In such cases, it may be preferable to relax the compaction requirement slightly and/or adopt a procedural standard of compaction (i.e., require a specified number of compaction passes to achieve adequate density, based on agency experience). Appendix X1 of AASHTO M 319 provides a detailed description of an alternative field control method that involves the use of variable acceptance criteria for compaction based on tests performed on each designated lot and subplot on the project.

No matter the compaction control method selected, construction specifications must be appropriately written and enforced to ensure compaction is achieved to such an extent that the compacted shoulders are sufficiently stable under traffic loading immediately after construction (without requiring secondary hydration of cementitious particles).

Assessing Potential Economic Benefits

The economic benefits of using RCA in aggregate shoulder surfacing depend mainly on the difference in cost between using virgin material and using recycled concrete aggregate. These costs typically include the following:

Virgin material:

- Material costs
- Hauling virgin material
- Place and compact virgin material
- Haul out demolished concrete (to disposal)
- Concrete disposal

Recycled concrete:

- Haul demolished concrete (to crusher and back to the project site, unless recycled in-place)
- Material and haul costs for virgin blending material (optional)
- Crush and screen RCA
- Place and compact RCA

Note that the cost of breaking and removing the existing concrete pavement is required for both operations and can, therefore, be included in or eliminated from both calculations without affecting the difference in costs. The differences in these costs are highly project-specific and generally (but not always) favor concrete recycling. Use of on-site or mobile crushing equipment for RCA may provide cost savings.

An additional economic benefit to recycling into aggregate shoulder surfacing or unbound aggregate base rather than into higher-type applications (e.g., aggregate for asphalt or concrete mixtures) is the reduced need to eliminate typical contaminants (e.g., asphalt concrete, joint sealant materials, reinforcing steel fragments, etc.) and crusher dust from the recycling stream prior to use of the RCA. This provides contractors with flexibility in production and construction and generally results in lower unit material costs. Furthermore, shoulder surface aggregates are generally somewhat densely graded (for stability under traffic loads), so a greater proportion of the crushed concrete can be reused, resulting in a higher reclamation efficiency than for most other RCA applications.

Environmental Considerations

Water passing over and percolating through RCA materials can produce runoff and effluent that is initially highly alkaline, often with pH values of 11 or 12. This is an effect that generally diminishes with service time as the calcium hydroxide near the exposed RCA surfaces is dissolved and removed from the system. Furthermore, this high pH effluent is generally not considered to be an environmental concern because it is effectively diluted at a very short distance from the source with much greater quantities of surface runoff (especially for unbound RCA shoulders, which typically are not drained and do not have drainage outlets or other point sources), as described in Chapter 4.

Consideration of the sensitivity of local soils, surface waters, and groundwater to the presence of alkaline effluent may necessitate setting limits on the proximity of RCA placement to sensitive areas. Chapter 7 of this manual provides additional information and guidance on mitigating environmental impacts like elevated pH effluent.

Another potential negative impact of concrete recycling is the noise and dust produced by the concrete breaking, hauling, and crushing operations, particularly for off-site crushing, although these impacts can be managed through the use of mobile crushing units or proper crushing site selection, dust and noise suppression systems, operation hour restrictions, etc.

These potential negative impacts are generally completely offset by reductions in impacts that would result from the use of natural aggregates, such as consumption of natural aggregate resources, energy consumed and emissions produced in aggregate production and hauling, consumption of landfill space for demolished concrete, etc.

Summary

RCA is allowed for use in aggregate shoulder surface applications in at least 10 states. It has been used successfully in many instances, although at least one state requires blending with 50 to 70% natural aggregate to ensure adequate stability immediately after construction.

Many highway agencies require only gradation control for RCA base/subbase and shouldering materials when the source concrete is from their own network. Other source materials may be required to meet the same quality requirements as conventional aggregate materials. RCA grading requirements typically call for a maximum particle size of 3/4 to 1.5 in. and a relatively dense gradation with some material (but no more than 12 to 15%) passing the No. 200 sieve to aid in achieving compaction and density.

Standard equipment and techniques can be used to construct RCA shoulders, although steps should be taken to minimize handling and movement of the RCA and to achieve density with a minimum number of compaction passes, thus minimizing the potential for producing additional fines through abrasion and other mechanisms. A key step is to place and compact the RCA at optimum moisture content, which is typically higher than for natural aggregate materials.

The potential economic benefits of using RCA in shoulder surfaces are often large, but vary among projects, mainly with the cost and proximity of suitable natural aggregate sources. The potential for negative environmental impacts with RCA shoulder surfaces is relatively small and is associated with diffuse high pH surface runoff and noise/dust from production operations. These negative impacts are generally offset by reductions in impacts that would result from the use of natural aggregates.

References

- ACPA. 2008. *Concrete Pavement Field Reference: Pre-Paving*. Engineering Bulletin EB237P. American Concrete Pavement Association, Skokie, IL.
- ACPA. 2009. *Recycling Concrete Pavements*. Engineering Bulletin EB043P. American Concrete Pavement Association, Skokie, IL.
- ASTM. 2015. *Standard Specification for Graded Aggregate Material for Bases or Subbases for Highways or Airports*. D2940/D2940M-15. ASTM International, West Conshohocken, PA.
- FHWA. 2004. *Transportation Applications of Recycled Concrete Aggregate – FHWA State of the Practice National Review*. Federal Highway Administration, Washington, DC. <https://www.fhwa.dot.gov/pavement/recycling/applications.pdf>.
- Iowa DOT. 2015. Section 4120 - Granular Surfacing and Granular Shoulder Aggregate. *Standard Specifications with GS-15005 Revisions*. Iowa Department of Transportation, Ames, IA.
- National CP Tech Center. 2017. *Survey of NCC Member Agencies Concerning Use of RCA in Shoulder Surfacing Applications*. National Concrete Pavement Technology Center, Iowa State University, Ames, IA.

Chapter 6

Using RCA in Concrete Paving Mixtures

Introduction	50
Constructability (Fresh Properties)	50
Pavement Design Considerations (Hardened Properties)	51
Developing Concrete Mix Designs Using RCA	53
Examples/Case Studies	53
Summary	55
References	56

Introduction

More than 100 projects have been constructed in the United States using recycled crushed concrete as a part of the aggregate system (Snyder et al. 1994, Reza and Wilde 2017). Most have performed satisfactorily while others have indicated some limitations and presented opportunities to identify some of the changes required when using RCA in concrete paving mixtures (FHWA 2007). A thorough review by MnDOT indicated that durable concrete mixtures can be prepared using RCA if the properties of the RCA are properly evaluated and considered in mixture proportioning (Reza and Wilde 2017).

The fundamental principles behind preparing a long-lasting mixture are no different for RCA than for conventional concrete. The additional factors that need to be considered in preparing a mixture for use in a pavement that contains RCA are discussed in this chapter. Some agencies may treat RCA like regular aggregate, but consideration should be given to the changes in properties while addressing questions about the source concrete and why it was taken out of service. It is critical that, while striving to improve sustainability by using RCA, the engineering performance of the final pavement should not be compromised (FHWA 2007).

Note that the trends discussed here are broad and the quality of the source material must be assessed for each project.

Constructability (Fresh Properties)

RCA may affect the constructability of a mixture. These changes are summarized in Table 6.1 and discussed in the following sections. The effects are different when considering using RCA as coarse or fine aggregate, as noted in Table 6.1.

Table 6.1. Effects of RCA on fresh concrete properties

Property	Coarse RCA Only	Coarse and Fine RCA
	Greater	Much greater
Finishability	Slightly more difficult	More difficult
Bleeding	Slightly less	Less
Air void system	Similar	Increased*
Setting time	May be accelerated	May be accelerated

*Reported air content will include the air in the source concrete paste

Sources: After FHWA 2007, ACI 2001

Workability

In general, the absorption of RCA is higher than virgin aggregate because the mortar fraction in RCA is more porous than rock. This difference is greater in fine aggregate than in coarse aggregate because fine RCA typically has a higher percentage of mortar and paste. As a result, workability and rate of slump loss of the concrete mixture will be affected. One approach to controlling these system properties may be to ensure that RCA aggregate is sprinkled with water and saturated before it is batched, similar to lightweight aggregate. Coarse aggregate should be free of high sorption dust (FHWA 2007).

RCA, by definition, is a crushed material. Therefore, particle shapes are angular and rough-textured rather than rounded and smooth. As with conventional crushed aggregate, flaky and highly angular particles will reduce workability. Particle shape is influenced by the crushing equipment used and how it is operated (FHWA 2007, ACPA 2009).

The combination of these factors (angularity, surface texture, and absorption) will tend to reduce workability unless mixture proportions are adjusted by increasing paste content and adjusting coarse and fine aggregate percentages. The American Concrete Pavement Association has recommended limiting the amount of fine RCA to about 30% of the total fine material to avoid workability problems (ACPA 2009).

Retempering to address increased slump loss caused by water absorbed into the aggregate should be avoided to ensure the specified w/cm ratio is not exceeded.

Finishing Characteristics

Inclusion of large amounts of fine RCA will increase the harshness of a mixture, making it more difficult to finish (ACPA 2009). This is less of an issue for machine-finished pavements than for hand-finished slabs on grade.

Bleeding

Bleeding and the rate of bleeding are affected by the gradation of the fine material and, to a limited extent, the density of the aggregate. As such, coarse RCA is unlikely to have a marked influence on bleeding, while increasing amounts of fine RCA may decrease bleeding and the rate of bleeding (ACPA 2009).

Air Void System

Clean RCA should have little influence on the formation of entrained air in a fresh mixture. However, air contents measured using the pressure method may be high, possibly because the test is also detecting the air bubbles in the source paste system (Snyder et al. 1994). This effect can be accommodated by determining an aggregate correction factor in accordance with ASTM C231 (Cuttell et al. 1997) or by using the volumetric method ASTM C173. (ACPA 2009).

The densities (unit weights) of mixtures containing RCA are reportedly slightly lower than those of conventional mixtures, likely because of the increased air content (Hansen and Narud 1983).

Organic contaminants may influence the formation of the air void system, especially its variability, and this potential issue should be assessed using trial batches.

Setting Time

Setting time may not be the same as with virgin aggregate mixtures and may need to be evaluated. Research conducted by the National Ready Mixed Concrete Association (NRMCA) indicated the setting times of mixtures made using crushed returned concrete mixtures to be about 45 minutes to 1 hour shorter than that of a control mixture (Obla et al. 2007). This is likely due to a chemical effect of the hydrated cement and calcium hydroxide in the RCA causing some acceleration in setting, especially with more fines.

Pavement Design Considerations (Hardened Properties)

Pavement structural design is based on a number of parameters controlled by the performance of the hardened concrete. RCA will affect these parameters and should be accounted for at the design stage. The general trends discussed next are dependent on the source material and should be evaluated for each case.

On the other hand, structural design methods assume that the mixture will be able to resist the environment for the intended life of the system. Consideration should also therefore be given to the potential durability of the system.

Mechanical Properties

The effects of RCA on mechanical properties are discussed next. These effects are likely not critical but are part of the inputs for structural design models.

Strength: RCA in a mixture may decrease the compressive and flexural strengths when all other mix parameters are held constant, but, in general, sufficient strength can be achieved with appropriate mixture proportioning and control of the w/cm ratio (Reza and Wilde 2017).

Factors that will affect strength include the following (ACPA 2009, ACI 2001):

- Coarse RCA has less of an effect than fine RCA, likely because it typically comprises more natural aggregate and less adhered hardened paste (Snyder 1994).
- The stronger the source concrete mixture, the smaller the reduction in strength.
- The greater the amount of RCA as a percentage of total aggregate, the greater the effect on concrete strength.
- The increased water demand for target slump can reduce concrete strength if the cementitious content is not increased proportionately (i.e., increase the paste content while holding the w/cm ratio constant rather than just increasing the water content).
- RCA may act as a form of internal curing if it is wet when batched, thus potentially enhancing hydration of the new paste system.

Variability in strength may be increased with the use of RCA because of inherent variability in the source RCA (ACI 2001).

Increased strengths of some pavements were reported by Cuttell et al. (1997) and were attributed to a low w/cm ratio in the new mixture and the amount of fine RCA being limited to 25%.

Flexural strength is slightly higher as a function of compressive strength in RCA mixtures (Abou-Zeid and McCabe 2002). This is considered to be due to the roughness and angularity of the recycled concrete aggregate and a possible chemical reaction between the RCA concrete and the surrounding cement paste.

Modulus of elasticity is influenced by the amount of source mortar in the mixture, with increasing amounts of RCA reducing the modulus (ACPA 2009). This is because hardened mortar typically has a lower modulus than virgin aggregate. Modulus typically tracks with strength, meaning that as strength increases, the modulus of elasticity will increase.

Coefficient of thermal expansion (CTE) is also dependent on the properties of the source concrete mixture, especially the nature of the original coarse aggregate. Typically, it will increase with increasing RCA amounts (Cuttell 1997, ACPA 2009).

Drying shrinkage of RCA concrete, like conventional concrete, is governed by the amount and properties of the total (source and new) cement paste. Increasing paste content will increase movements in the concrete with changing moisture contents. Fine RCA normally has a higher proportion of source paste and may, therefore, be expected to have an increase in moisture-related volume changes (Cuttell et al. 1997, ACPA 2009, FHWA 2007, Reza and Wilde 2017).

Potential Durability

The ability of a pavement to resist environmental exposure is a critical pavement life factor. Like the mechanical properties, the effects of including RCA on potential durability are varied and strongly dependent on the quality of the source concrete.

Permeability is a measure of the system to resist penetration of fluids (that might otherwise lead to degradation of the system). It is primarily controlled by the w/cm ratio of the paste and the use of supplementary cementitious materials, both in the source and new mixtures (ACPA 2009, ACI 2001). In general, permeability of RCA concrete is higher than that of conventional concrete because it contains higher total quantities of paste (new and source), which is more permeable than virgin aggregate.

Freeze-thaw resistance of any mixture is governed by the air void system of the paste, both recycled and new. Therefore, if the source concrete contained a poor air void system, deterioration due to freezing and thawing cycles may originate in the RCA. Reducing the

permeability of the concrete may reduce the potential for achieving critical saturation and resulting damage due to freezing and thawing. If the source concrete had an adequate air void system, then the RCA should not influence the freeze-thaw performance of the new mixture, provided the new paste has an adequate air void system (Gokce et al. 2004). The air void system of the source concrete can be assessed using a hardened air void analysis before crushing, if necessary.

Alkali aggregate reaction is a slow expansive reaction between certain aggregates and alkali hydroxides in the paste that leads to cracking in the concrete. A number of factors have to be considered when planning to use AAR-prone concrete as RCA. Some tend to increase expansion while others will decrease it:

- If concrete affected by AAR is taken out of service when the reaction is close to completion (i.e., one of the reactants has been fully consumed), then future expansion may be limited, assuming that the missing reactant (e.g., alkali hydroxide) is not replenished in the new mixture. There is no good way to assess this, except to consider the age and degree of damage of the existing system. The AASHTO R 80 protocol can assess the risk of ASR for a given set of materials (AASHTO 2017).
- RCA contains significant amounts of mortar, thus diluting the amount of reactive virgin aggregate in the system (ACPA 2009).
- Crushing the RCA may expose new unreacted faces of the aggregate, potentially accelerating the reaction. Fine RCA will pose a higher risk than coarse RCA.

There are several examples of AAR-damaged concrete being used as RCA in pavements without distress, as discussed in the Examples/Case Studies section of this chapter.

It is recommended that appropriate measures be taken to control future expansion such as inclusion of appropriate amounts of low-calcium fly ash or slag cement (ACPA 2009).

D-Cracking is a form of aggregate distress in which water is readily absorbed into aggregate particles with critically sized pore structures, and subsequently freezes and expands before it can be expelled from the pores, causing cracking in cold weather. A pavement containing D-cracking aggregate in Minnesota was recycled into the new concrete in 1980. In 2015, there was still no sign of recurrent D-cracking (Zeller 2016).

Mitigating actions to address alkali-aggregate reaction (AAR) and D-cracking include ensuring effective drainage of the pavement (to prevent aggregate saturation) and use of supplementary cementitious materials (SCMs) and a low w/cm ratio to reduce system permeability (ACPA 2009). Crushing the RCA and reducing the maximum size of the source concrete aggregate particles, as well as the dilution effect, may both help to slow damage growth. The RCA should be assessed for its reactivity in accordance with AASHTO R 80 if the source concrete contained reactive aggregate (AASHTO 2017).

Developing Concrete Mix Designs Using RCA

Two aspects of preparing RCA concrete mixtures are discussed in this section: the prequalification of the RCA material and process of mixture proportioning.

Qualification Testing

It has been recommended that RCA used to construct new concrete pavements should meet the same quality requirements as virgin aggregate (FHWA 2007), but it may be more effective to properly characterize and control the variability of the physical and mechanical properties of the RCA and consider them in the mixture design. Other recommendations include the following:

- Magnesium and sodium sulfate soundness tests may be waived because they may be unreliable in predicting RCA durability (ACPA 2009)
- Attention must be paid to sources known to be subject to ASR and D-cracking (ACPA 2009) by testing the materials in accordance with AASHTO R 80 (AASHTO 2017)
- Contaminants should be limited to (ACPA 2009):
 - Asphalt: 1% by volume (although significantly higher asphalt content has been included in the lower lift of some two-lift concrete pavement systems)
 - Gypsum: 0.5% by weight
 - Glass: 0
 - Chlorides: 0.06 lb/yd³
- RCA washing, air blowing, or other mitigation techniques should be considered to remove dust from crushing and handling operations that might otherwise increase water demand or reduce paste-aggregate bond, resulting in reduced concrete strength

Proportioning

The fundamental principles of mixture proportioning for RCA concrete are the same as conventional concrete. Some changes may have to be made to accommodate differences in the properties of the RCA (FHWA 2007, ACPA 2009):

- W/cm ratio may need to be decreased to achieve the desired hardened properties.
- Fine RCA should be limited to less than 30% by mass of fine aggregate.
- Gradation of the combined aggregate system should be assessed using tools such as the tarantula curve, Shilstone workability plot, or power 45 curve.
- Paste content may have to be increased to maintain workability, particularly if fine RCA is used.
- The mixture should be designed correctly for yield with consideration of the lower specific gravity (SG) of RCA.

Fathifazl et al. (2009) reported a RCA concrete proportioning method known as the equivalent mortar volume (EMV) method. This method is based on fixing the total amount of mortar in a RCA concrete mixture (including the residual mortar content on the RCA) to be equal to an equivalent conventional mixture. These mixtures tend to be harsh and rocky, especially when the RCA contains higher amounts of residual mortar.

Construction

Better monitoring of stockpile moisture content and batch quantity adjustments will be required to ensure that the final required w/cm ratio is achieved.

Examples/Case Studies

As noted previously, well over 100 paving projects have been constructed using RCA in the concrete mixture. In general, pavements for which data are available are in fair or better condition up to 20 years after recycling.

The following summaries describe three examples of pavements that have been constructed using RCA concrete.

D-Cracking Aggregate

TH 59 (a US “trunk” highway) in southwestern Minnesota was originally placed in 1955 and contained a D-cracking aggregate (Zeller 2016). Strength of the source concrete was about 5,500 psi. The pavement was recycled in 1980 with all of the 3/4 in. coarse aggregate

comprised of RCA. The design w/cm ratio of the new mixture was 0.44. The pavement was inspected in 1995 and appeared to be satisfactory, although cores failed a freeze-thaw test in the laboratory. It was noted that the pavement system was well drained and therefore the concrete was unlikely to be saturated, which may explain the satisfactory field performance. Some repair work was required at that time to retrofit dowels, reseal transverse joints, and grind. A review in 2006 indicated that the pavement was still in satisfactory condition (Gress et al. 2009) (see Figure 6.1).



Mark B. Snyder

Figure 6.1. TH 59 in southwestern Minnesota, 2006

The conclusion drawn is that D-cracked source concrete used to make RCA appears to be acceptable for recycling if the new system is well drained.

Alkali Reactive Aggregate

Interstate 80 in southeast Wyoming was originally placed between 1965 and 1978 containing alkali-reactive aggregate (Rothwell 2016). Due to the cracking induced by the ASR, portions of the pavement were recycled into new concrete pavement surfacing between 1987 and 1990. Before paving, laboratory testing indicated that the RCA would have limited potential for future reactivity. The new mixture contained 20% Class F fly ash, with 65% of the coarse aggregate comprising RCA and 25% of the fine aggregate comprising RCA.

A petrographic examination of cores extracted in 1991 indicated no evidence of new ASR gel forming. Other analyses in 1995 and 1997 indicated trace amounts of gel, but this could not be connected to any damage in the system. Some cracking has recently been observed in the new pavement, but the cause has not been identified.

The agency is satisfied that the exercise was successful in that the RCA pavement provided 30 years of service (see Figure 6.2).



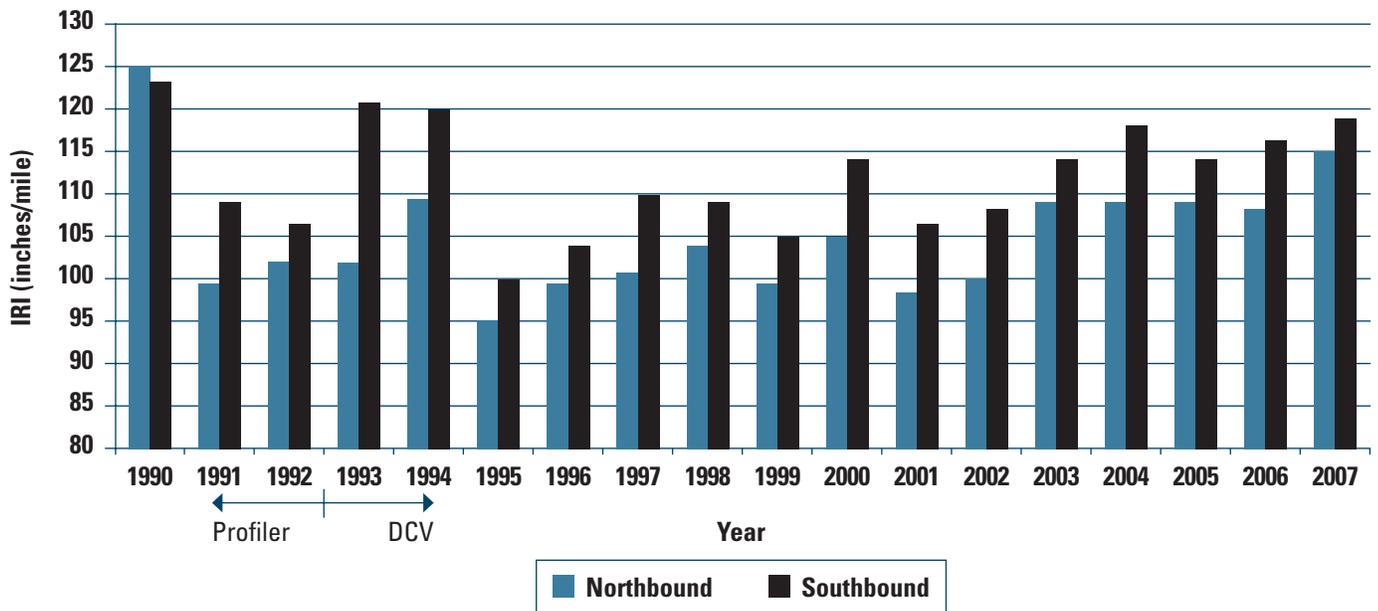
Rothwell 2016, Wyoming DOT

Figure 6.2. I-80 SE in Wyoming, 2016

Continuously Reinforced Concrete Pavement (CRCP)

Interstate 57 in Illinois was recycled in 1986 after approximately 20 years because of extensive faulting and cracking (Roesler et al. 2011). The aggregate in the source concrete system was considered sound. The new mixture contained 20% fly ash at a w/cm ratio of 0.37 to 0.40. All of the coarse aggregate was RCA, while 35% of the fine aggregate was RCA. The system was designed to last 20 years, and distress and video surveys were conducted regularly. After 20 years, it was concluded that the use of RCA had not reduced the service life of the RCA CRCP compared to that of a conventional CRC pavement. Figure 6.3 shows a ride quality summary for the pavement based on the average international roughness index (IRI).

I-57 Average International Roughness Index



Profiler=Illinois Road profiler, modeled after the South Dakota profiler
 DCV=Data collection vehicle equipped with video inspection equipment
 Recreated from Roesler and Huntley 2009, Illinois Center for Transportation

Figure 6.3. Illinois I-57 ride quality summary

Summary

Practice has shown that RCA can be used satisfactorily as aggregate in new concrete mixtures. The variability of RCA materials makes it difficult to rigidly define recommendations for use, but, in general the following guidelines apply:

- The aggregate must be evaluated for its quality and uniformity
- All of the coarse aggregate can be replaced with RCA, and fine aggregate should be limited to a maximum of about 30% replacement
- Desired hardened properties can be achieved, but some proportions may need to be adjusted to accommodate effects of the RCA
- Trial mixtures must be prepared to confirm that the mixture will perform as intended

References

- AASHTO. 2017. *Practice for Determining the Reactivity of Concrete Aggregates and Selecting Appropriate Measures for Preventing Deleterious Expansion in New Concrete Construction*, R 80-17. American Association of State Highway and Transportation Officials, Washington, DC.
- Abou-Zeid, M. N. and S. L. McCabe. 2002. Feasibility of waste concrete as recycled aggregates in construction. *Proceedings of the International Conference on Waste Management and the Environment*, Cadiz, Spain, pp. 537–546.
- ACI. 2001. *Removal and Reuse of Hardened Concrete*. ACI 555R-01 (currently under revision). American Concrete Institute, Farmington Hills, MI.
- ACPA. 2009. *Recycling Concrete Pavements*. Engineering Bulletin EB043P, American Concrete Pavement Association, Skokie, IL.
- Cuttell, G. D., M. B. Snyder, J. M. Vandenbossche, and M. Wade. 1997. Performance of Rigid Pavements Containing Recycled Concrete Aggregates. *Transportation Research Record: Journal of the Transportation Research Board*, No. 1574, pp. 89–98.
- Hansen, T. C. and H. Narud. 1983. Strength of Recycled Concrete Made from Crushed Concrete Coarse Aggregate. *Concrete International*, Vol. 5, No. 1, pp. 79–83.
- FHWA. 2007. *Use of Recycled Concrete Pavement as Aggregate in Hydraulic-Cement Concrete Pavement*, Technical Advisory T 5040.37. Information and data retrieved August 2017 from the Federal Highway Administration website: www.fhwa.dot.gov/pavement/t504037.cfm.
- Fathifazl, G., A. Abbas, A. G. Razaqpur, O. B. Isgor, B. Fournier, and S. Foo. 2009. New Mixture Proportioning Method for Concrete Made with Coarse Recycled Concrete Aggregate. *Journal of Materials in Civil Engineering*, Vol. 21, No.10, pp. 601–611.
- Gress, D., M. Snyder, and J. Sturtevant. 2009. Performance of Rigid Pavements Containing Recycled Concrete Aggregate. Update for 2006. *Transportation Research Record: Journal of the Transportation Research Board*, No. 2113, pp. 99–107.
- Gokce, A., S. Nagataki, T. Saeki, and M. Hisada. 2004. Freezing and Thawing Resistance of Air-Entrained Concrete Incorporating Recycled Coarse Aggregate: The Role of Air Content in Demolished Concrete. *Cement and Concrete Research*, Vol. 34, No. 5, pp. 799–806.
- Obla, K., K. Haejin, and L. Colin. 2007. *Crushed Returned Concrete as Aggregates for New Concrete*. RMC Research & Education Foundation, Silver Spring, MD.
- Reza, F. and W. J. Wilde. 2017. *Evaluation of Recycled Aggregates Test Section Performance*. Minnesota Department of Transportation, St. Paul, MN.
- Roesler, J. and J. G. Huntley. 2009. *Performance of I-57 Recycled Concrete Pavements*. Illinois Center for Transportation, University of Illinois at Urbana-Champaign, Urbana, IL.
- Roesler, J., J. G. Huntley, and A. N. Amirkhanian. 2011. Performance of Continuously Reinforced Concrete Pavement Containing Recycled Concrete Aggregates. *Transportation Research Record: Journal of the Transportation Research Board*, No. 2253, pp. 32–39.
- Rothwell, R. 2016. Performance History of Recycling ASR-Susceptible Concrete into I-80 in Wyoming, Workshop 3: Recycled Concrete Aggregate. 11th International Conference on Concrete Pavements, August 28–September 1, San Antonio, TX.
- Snyder, M. B., J. M. Vandenbossche, K. D. Smith, and M. J. Wade. 1994. *Physical and Mechanical Properties of Recycled PCC Aggregate Concrete*. Interim Report – Task A. DTFH61-93-C00133. Federal Highway Administration, Washington, DC.
- Zeller, M. 2016. Performance History of Recycling D-Cracking Susceptible Concrete into TH 59 in Minnesota, Workshop 3: Recycled Concrete Aggregate. 11th International Conference on Concrete Pavements, August 28–September 1, San Antonio, TX.

Chapter 7

Mitigating Environmental Concerns

Introduction	58
Legislative and Regulatory Considerations	58
Environmental Concerns Requiring Consideration	59
Planning Considerations and Design Techniques that Protect Water Quality	62
Construction Strategies and Controls to Mitigate Environmental Concerns	65
Summary	71
References	72

Introduction

Use of recycled materials is inherently a sustainable practice. Concrete pavement recycling offers the potential for many highly positive environmental benefits, including the reduced use of virgin aggregate and landfill facilities, reduced fuel consumption and associated emissions in mining, processing and hauling natural aggregate, and more. There is no more preferred end-of-life goal for highway materials than suitable recycling or reuse at the highest grade. Similar to almost all types of other construction activities, some impacts to the environment (including water quality, air quality, waste generation, noise, and other local impacts) are possible during concrete recycling activities. However, it is very important to note that these environmental concerns generally do not differ significantly from those associated with production and use of virgin aggregate or many other materials typically used in highway construction. Each of these concerns has been consistently shown to be mitigated through planning and design considerations, use of conventional best management practices (BMPs), and through readily implementable construction controls.

This chapter provides the following:

- A summary of legislative and regulatory considerations
- An overview of potential environmental concerns associated with recycled concrete aggregate (RCA) production and use
- Strategies for mitigating environmental concerns during project *planning and design*
- Strategies for mitigating environmental concerns during *construction*

Legislative and Regulatory Considerations

Water Quality

In the United States, federal legislation protecting water quality includes the Clean Water Act (CWA) and Federal Water Pollution Control Act and Amendments (EPA 2017a). These laws require state, territorial, or tribal regulatory agencies to develop lists of waterways that are impaired or otherwise do not meet their beneficial use requirements, and establish total maximum daily loads (TMDLs) and waste load allocations (WLAs) for such waters. The National Pollutant Discharge Elimination System (NPDES) permit program (EPA 2017b) is administered by delegated states or by the U.S. Environmental Protection Agency (EPA). NPDES

permits control point source pollution, such as from pipes/drainage ditches, and are required for construction sites with greater than 1 acre of disturbance. NPDES regulations require operators of municipal separate storm sewer systems (MS4s) to obtain an NPDES permit and to develop a stormwater management plan (OSU et al. 2006). The National Environmental Policy Act (NEPA) (EPA 2017c) also provides judicially enforceable obligations requiring federal agencies to identify environmental impacts of planned activities, a framework under which environmental impacts are evaluated, and serves as a starting point for application/enforcement of other environmental regulations (Austin 2010).

Best Management Practices to address potential impacts of RCA during construction can be incorporated into a Stormwater Pollution Prevention Plan.

Most state departments of transportation (DOTs) implement their own NPDES permit programs, although the EPA is responsible for control of the permitting process in several states. A wide variation exists in permitting approaches and, although a discussion of specific agency approaches is beyond the scope of this manual, a summary is presented in NCHRP Report 565 (Austin 2010). Minimum approaches to permitting include provisions for construction runoff control, post-construction controls, pollution prevention, good housekeeping, TMDL compliance, monitoring requirements, and development of a Stormwater Pollution Prevention Plan (SWPPP). SWPPPs are often referred to by other names, including an Erosion and Sediment Control Plan, Construction Site Best Management Practices Plan, and other terms (EPA 2017b). BMPs to address potential impacts of RCA during construction can be incorporated into a SWPPP.

Waste

Federal legislation that guides handling of construction waste includes provisions of the Resource Conservation and Recovery Act (RCRA) (EPA 2017d). The EPA regulates disposal of hazardous solid waste, and states are encouraged to develop solid waste management plans. Due to the expense of developing and enforcing these plans, some states use federal solid waste programs as their state programs (OSU et al. 2006). RCRA provisions are relevant for some highway construction and maintenance activities, and classification of recycled concrete and treatment under RCRA is important to

further use of RCA in beneficial applications in new infrastructure. Although regulatory policies differ by state, a review of state agencies has indicated that RCA is typically defined as an inert material and, therefore, is *not* subject to hazardous waste regulations (Cackler 2018).

Air Quality

Pollutants affecting air quality in the US are regulated under the Clean Air Act and Amendments (EPA 2017e). Air quality standards for six “criteria pollutants” (carbon monoxide, lead, ground-level ozone, nitrogen dioxide, particulate matter, and sulfur dioxide) are established by the EPA, and states are required to develop and adopt enforceable plans to maintain air quality meeting federal standards. The FHWA provides guidance to state highway agencies on meeting air quality goals and transportation project conformity on its website (FHWA 2017).

From a health standpoint, many construction operations (including those involving RCA) produce dust and airborne particulates. A new Occupational Safety and Health Administration (OSHA) Crystalline Silica Rule was announced in March 2016. This new “final rule” amends silica exposure regulations that had been in effect since 1971. Two standards comprise the rule: Construction Standard and General Industry and Maritime Standard. Concrete pavement construction activities, including those associated with concrete recycling, are covered under the Construction Standard, which is available on OSHA’s website (OSHA 2016a).

State Regulations and Specifications

To enforce these water quality, air quality, and solid waste legislative requirements, agencies implement regulations using a variety of approaches. Agency regulations, specifications, and compliance strategies change periodically. Therefore, a detailed discussion of how each state complies with these laws, and how these state regulations and compliance strategies impact concrete recycling activities, is beyond the scope of this manual. Instead, examples of useful specification provisions that support concrete recycling efforts and aid in compliance with environmental legislation/regulations are presented throughout this chapter.

It is important to note that some regulations or specifications can cause delays, expense, risk (perceived or real), and a decreased potential for recycling. Reducing regulatory burden can increase use of RCA, and the FHWA Recycled Materials Policy Administrator’s message (Wright 2015) states the

following: “Restrictions that prohibit the use of recycled materials without technical basis should be removed from specifications.” Ultimately, reducing the regulatory burden on project stakeholders could increase use of RCA and recycling of concrete in other applications. Up-front guidance and a “clear path” through regulation minimizes risk for the contractor and may provide cost savings for the owner. Legislation and compliance agreements related to the definition of wastes and practices, along with guidance for allowable (and encouraged) recycling activities, are provisions that can reduce the regulatory burden. With the increased prevalence of contractors working in multiple states, uniform consideration of environmental impacts and treatment of RCA in specifications could streamline these processes (CDRA 2012).

Environmental Concerns Requiring Consideration

Recycled materials often contain minor amounts of contaminants and/or pollutant materials, and construction and use of these materials in systems that are exposed to air and water may present some environmental risks (Schwab et al. 2014). However, the **potential negative environmental impacts of concrete recycling have consistently been shown to be readily mitigated through planning and design considerations, use of conventional BMPs, and through readily implementable construction controls.** A summary of the potential environmental impacts of concrete recycling is presented in this section. Mitigation strategies that can be incorporated into project planning, design, and construction to address these concerns are then presented in the sections that follow.

Contamination from the Source Concrete

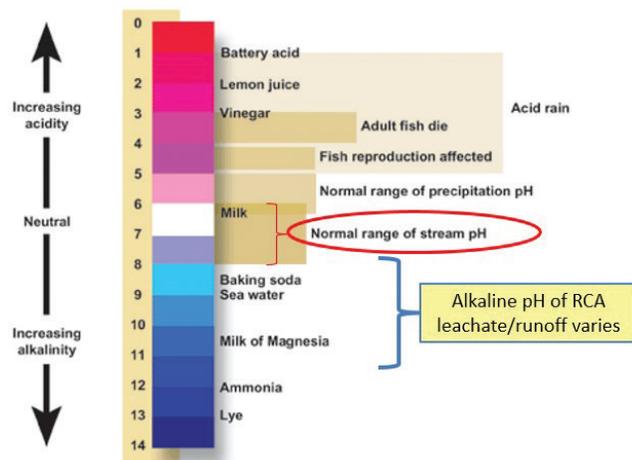
Concrete from building and demolition debris can include contaminants that could be problematic (e.g., asbestos). However, by using concrete from known sources, such as existing agency infrastructure, contaminants can likely be reduced. Chemicals, metals, sealants, and other materials present in highway concrete used for recycling could also become pollutants. However, these contaminants are not generally present in appreciable amounts (NHI 1998), and environmental impacts associated with contaminated source concrete from bound or unbound applications have not been reported.

Water Quality

As reported by Steffes (1999) and Sadecki et al. (1996), RCA stockpile runoff and drainage (leachate) from in situ RCA can or may:

- Be highly alkaline (i.e., high pH due to dissolved calcium hydroxide)
- Contain chemical contaminants
- Potentially cause formation of deposits of suspended solids or precipitates in drainage systems or other downstream features

High-pH runoff results primarily from dissolution of exposed calcium hydroxide, a byproduct of the hydration of cement. The typical range of alkaline pH from RCA runoff or leachate is shown in Figure 7.1, along with the normal range of stream pH.



© Her Majesty the Queen in Right of Canada, as represented by the Minister of the Environment, 2013, used with permission; Annotations added to illustration from Environment Canada 2013

Figure 7.1. Scale indicating typical pH range of RCA leachate/runoff and some common liquids

High-pH runoff can cause concern and may result in the imposition of unreasonable protection requirements. In other cases, it may be considered beneficial for neutralizing acidic condition, as in agricultural applications.

Compared to the total volume of surface water runoff from a project site, the volume of runoff from areas containing RCA (e.g., in stockpiles or drained pavement layers) is typically low. However, high-pH runoff from RCA materials can negatively impact receiving natural waters, vegetation, and zinc-coated and aluminum pipe (through corrosion), until diluted with rainfall and other surface waters. These concerns are typically

restricted to small areas surrounding the drainage outlet, since adequate dilution typically takes place within several feet of the point of discharge (ACPA 2008a), although there may be concern when discharged into streams or waterways.

Strategies for mitigating these localized impacts should be considered during both the design and construction phases. Placing drains away from receiving waters, along with use of conventional stormwater BMPs, such as bioswales (discussed later in this chapter), have been shown to mitigate issues with high pH. In addition to dilution with rain and other surface waters, high-pH runoff is also often neutralized by infiltration and exposure to soils and rock.

The potential for deposit formation, which can clog pavement drainage systems, is the result of materials that are dissolved or suspended in the leachate. These deposits are often referred to as calcareous tufa (calcium carbonate precipitate, formed by the reaction of dissolved calcium hydroxide with atmospheric carbon dioxide) and insoluble residue (crusher dust). Several proven strategies to mitigate these concerns are discussed later in this chapter.

Deicing salts leaching from RCA, in theory, could adversely change soil characteristics, negatively impact water quality, and damage roadside vegetation (Fay et al. 2013), although this phenomenon was not identified in the literature.

RCA leachate and runoff also typically include small amounts of pollutant materials, including “heavy” metals like vanadium, chromium, and lead (Sadecki et al. 1996, Chen et al. 2012, Edil et al. 2012). **Although these pollutants can occasionally be present in quantities higher than permissible limits for drinking water, dilution of the runoff/leachate and capture or uptake into environmental systems (i.e., bioswales) have been consistently shown to mitigate their impact on receiving waters, particularly when separation is adequate and/or BMPs are used.**

Although drinking water standards are often referenced in research studies related to RCA leachate and runoff, these pollutant limits do not directly apply to runoff and leachate, which do not need to comply with these standards. Other appropriate criteria (such as those for stormwater quality or permitted discharge to receiving waters) should be utilized in evaluation of RCA leachate/runoff.

Use of RCA in bound applications (such as new RCA concrete or in cement-stabilized bases) significantly decreases the potential for water quality issues associated with leaching, and water quality issues associated with the use of RCA in bound applications have not been reported. Use of fly ash in concrete tends to increase binding of some ionic constituents, further eliminating concerns with potential contaminants in leachate from these applications (Sani et al. 2005).

Air Quality

Air quality concerns associated with concrete recycling activities include fugitive dust and emissions from equipment used in production and hauling, similar to air quality concerns associated with most other types of construction activities. In addition to impacting the environment, air pollutants from any construction activity could be a nuisance to the local community.

Use of virgin aggregates is also associated with air quality impacts from similar production equipment. Air quality impacts from hauling will be dependent on equipment used and hauling distances from off-site quarrying operations to the project site.

From a broader perspective, use of RCA can result in greenhouse gas *reductions* due to sequestration of carbon via carbonation, since crushing particles and exposing freshly fractured particle faces to air will expedite the carbonation process that occurs naturally in concrete (Santero et al. 2013). Some researchers have indicated that “more than one third and nearly one half of the calcination emission is reabsorbed by carbonation uptake after the concrete is crushed and exposed for four months and one year, respectively,” and further benefits can be realized through longer-term exposure, in which “about two-thirds is reabsorbed if the crushed concrete is exposed for 30 years” (Dodoo et al. 2009).

On the jobsite, dust is of increased concern due to enhancement of OSHA regulations in recent years. Air quality impacts of concrete recycling are heavily driven by haul distances, dust suppression efforts, and methods used for source concrete removal and the production of RCA. Emissions due to hauling and transport are often reduced by performing recycling operations on site (or nearby). The highest contribution of dust is from vehicular sources and wind effects (DETR 2000) and efforts focused on mitigating these factors (addressed subsequently in this chapter) are effective in reducing the overall impacts of recycling operations.

Noise and Other Local Impacts

Like other construction operations and stationary industry activities, concrete recycling operations can be viewed as unfriendly to local communities due to lighting, noise, vibration, dust, and traffic impacts (DETR 2000). The selection of on-site vs. off-site recycling will heavily influence local impacts, which may be most pronounced when operations occur in urban settings.

Noise and vibrations are most commonly caused by engines powering crushing and screening equipment, with additional contributions from material in chutes and hoppers and hauling vehicles (Silva et al. 2017). The nature of concrete recycling operations, however, is such that noise and vibration cannot entirely be eliminated (O’Mahony 1990). A number of planning considerations and construction controls have been proven to successfully mitigate noise and other impacts to local communities and are presented later in this chapter.

Waste Generation—Concrete Residuals

Production of RCA can also result in the generation of solid waste and wastewater (slurries) that need to be managed and ultimately disposed of or used beneficially. Solid waste associated with concrete recycling can include crusher fines (generated during concrete processing to produce RCA) and other unused materials from the source concrete, such as sealants, reinforcing steel, and repair materials. Wastewater may be created from equipment washing operations and stockpile runoff. The quantity and nature of residuals produced varies by concrete source, techniques utilized for crushing and beneficiation, and wash-off frequency and methods.

To improve sustainability of the overall highway system, options for beneficial reuse of concrete residuals are becoming increasingly common and should be promoted. Several beneficial reuse strategies for residuals from concrete recycling are discussed next.

Planning Considerations and Design Techniques that Protect Water Quality

If considered during project planning and design, use-phase water quality concerns can be mitigated or prevented entirely. In fact, **most projects utilizing RCA have been in service for years with no reported water quality or drainage issues** (Cackler 2018). Table 7.1 provides a summary of the potential water quality concerns for concrete recycling projects, the associated RCA uses, and mitigation strategies considered during project planning and design that have been successfully utilized to address these concerns.

A discussion of each of these concerns and mitigation strategies follows. Also, it should be noted that placing the RCA in fill, undrained bases, and other protected layers (including cement- and asphalt-treated base layers) is inherently a form of mitigation.

Qualification of Source Concrete

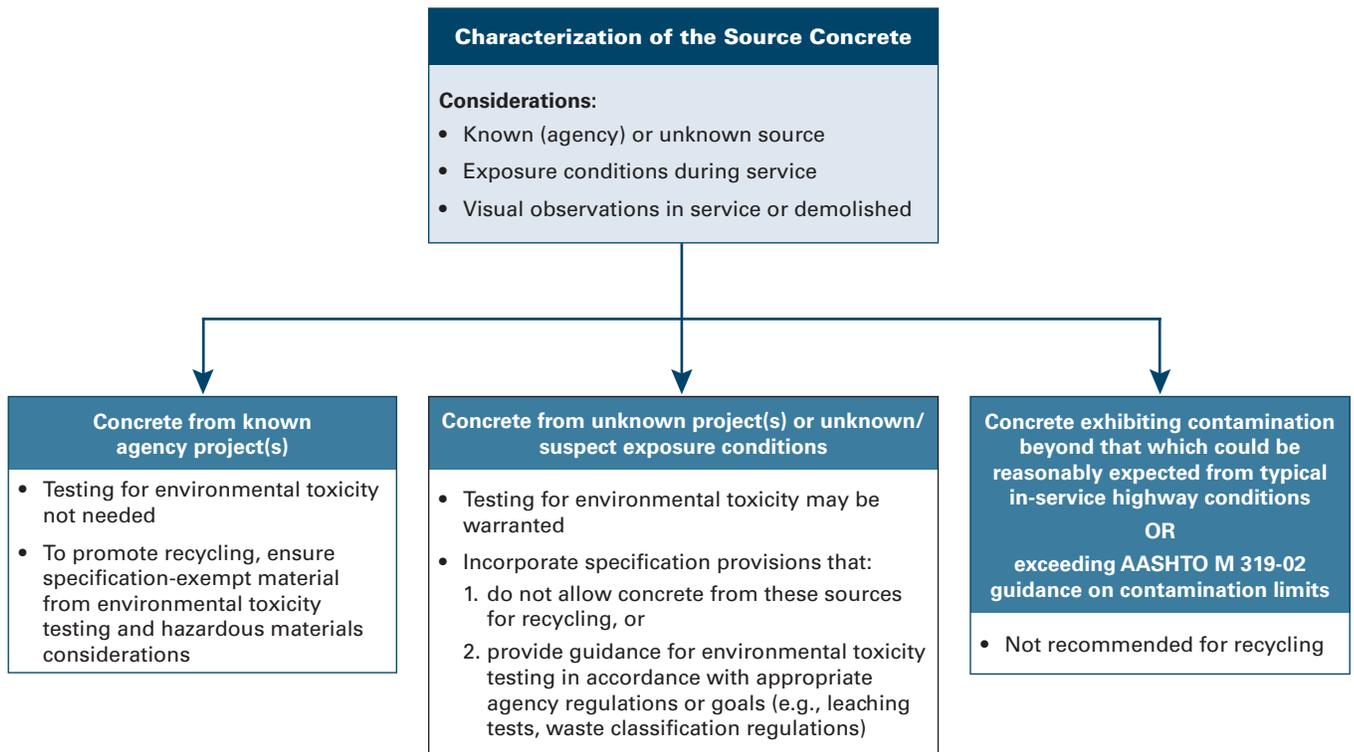
Recycled materials often contain minor amounts of contaminants and/or pollutant materials (Schwab et al. 2014). Concrete from building and demolition debris can include contaminants that could be problematic (e.g., asbestos). However, by using concrete from known sources, such as existing agency infrastructure, the likelihood of contaminants is highly reduced. Chemicals, metals, sealants, and other materials present in highway concrete used for recycling could also become pollutants. However, these contaminants are not generally present in appreciable amounts (NHI 1998) and, over the decades of service of many projects using RCA, **environmental impacts associated with contaminated source concrete from bound or unbound applications have not been reported.**

A flowchart showing recommended actions for concrete sourced from different projects is shown in Figure 7.2.

Table 7.1. Planning considerations and design techniques that protect water quality

RCA Use	Consideration	Mitigation Strategies
Unbound bases	Contamination/pollutants from the source concrete	<ul style="list-style-type: none"> Use of concrete from known agency sources Prequalification of source material
	High-pH leachate	<ul style="list-style-type: none"> Place drainage outlets away from receiving waters Use hardy vegetation and bioswales near drain outlets Consider temporary use of pH adjustment products, such as pH (“shock”) logs, at potentially problematic locations (after construction)
	Pollutants in leachate	<ul style="list-style-type: none"> Construct drains away from receiving waters Utilize bioswales or mechanical sediment traps
	Sediments and solid precipitate	<ul style="list-style-type: none"> Use daylighted bases Prequalify geotextile fabric per AASHTO M 319-02 Wrap trench (rather than pipe) in geotextile fabric Consider eliminating rodent screens Consider blending RCA with natural aggregate Utilize mechanical sediment trap at outlet structure Utilize chemical coagulant products, such as “floc” logs, at local problematic locations (after construction)
Fill (beneficial reuse of fines)	High-pH leachate	<ul style="list-style-type: none"> Construct away from receiving waters Utilize hardy vegetation and bioswales in surrounding area
	Pollutants in leachate	<ul style="list-style-type: none"> Construct away from receiving waters
New RCA concrete mixtures	Contamination/pollutants from the source concrete	<ul style="list-style-type: none"> None required

After Cavalline 2018a, National CP Tech Center



After Cavalline 2018a, National CP Tech Center

Figure 7.2. Recommended actions for qualification of source concrete to protect water quality

If concrete for recycling is sourced from an agency project (or projects), testing for environmental toxicity is not recommended, and incorporating specification provisions stating this policy may encourage concrete recycling. An example of such a consideration is the Washington State DOT (WSDOT) specifications, which exempt recycled materials obtained from WSDOT roadways from toxicity testing and certification for toxicity characteristics (WSDOT 2017).

For concrete sourced from unknown projects, or projects with unknown or suspect exposure conditions, some common tests to evaluate the suitability for use as RCA may be warranted. For known projects, review of service history and/or visual observations of the material may provide evidence of whether contamination is an issue. Some states have specified tests such as total lead content testing or the Toxicity Characteristic Leaching Procedure (TCLP) if concrete is to be sourced from non-agency or unknown sources. Test results could be compared to requirements for dangerous wastes and, if not classified as such, should be considered for recycling. Concrete exhibiting contamination during a visual inspection or suspected to be exposed to harmful substances during its service life, should not be considered for recycling. AASHTO M 319-02, Standard Specification for Reclaimed Concrete Aggregate for Unbound Soil-Aggregate Base Course, also provides limits

on contaminants in the RCA, provisions for stockpile management to prevent contamination, and guidance for assessment of RCA, including lot/sublot descriptions and sizes to facilitate testing and acceptance (AASHTO 2010).

Mitigating Water Quality Concerns for RCA Leachate

It is important to note that most projects that include RCA have provided long-term service without water quality issues. However, water quality issues have been very infrequently reported at isolated locations at some concrete recycling projects. RCA characteristics vary by site, as do pavement drainage characteristics and local conditions adjacent to drain outlets. Many research studies have been performed in the US and Europe to gain a better understanding of water quality issues associated with RCA. Studies have consistently shown that the leaching characteristics (concentrations, release mechanisms, and timing) of many elements, including heavy metals and other ions of interest for water quality, depend on pH, temperature, and the ability of the contaminant to bind with components of the RCA (Engelson et al. 2010, Mulugeta et al. 2011, Chen et al. 2012, Edil et al. 2012). However, the characteristics of RCA leachate measured in laboratory tests have often been different than the characteristics of RCA leachate obtained from field sites (Qin and Yang 2015). The pH of RCA leachate measured in the laboratory using

traditional column leaching tests is typically fairly high (often in the range of pH 10 to 13). Although often initially high, RCA leachate levels from field sites tend to return to a relatively neutral pH level in the long term (often in the range of pH 6 to 8 within a few months or years of service) and are acceptable for discharge (Sadecki et al. 1996, Edil et al. 2012, Engelsen et al. 2012). Infiltration and exposure to soils, vegetation, and rock aid in pH neutralization and binding of ionic components.

The characteristics of leachate from unbound RCA vary over time, based on RCA composition, gradation, exposure to moisture, and other factors.

The lower pH values typically measured in field-obtained leachate have been attributed to changes in the RCA over time due to carbonation. In addition to carbonation, additional hydration of cement in the RCA could also occur. Changes in the RCA are dependent on many factors, including composition, gradation, exposure to moisture, and compaction (Engelsen et al. 2012, Edil et al. 2012, Chen et al. 2013, Qin and Yang 2015, Galvin et al. 2014, Abbaspour et al. 2016). In field sites, the pH of leachate from unbound RCA bases may initially be high (in the range of pH 10 to 12), but tends to become lower during the later years of service (Engelsen et al. 2012). Placement of a dense PCC or ACC pavement layer above unbound RCA will slow carbonation, altering the rate of change of leachate pH, and subsequently the release of pH-dependent constituents (Engelsen et al. 2010, Qin and Yang 2015). Ongoing research is being performed to gain a better understanding of the leaching characteristics of in-service unbound RCA bases and to provide guidance for BMPs near stockpiles and in unbound applications (Townsend et al. 2016, Ginder-Vogel 2017).

Strategies presented in Table 7.1 have been shown to successfully mitigate water quality concerns for almost all in-service projects with an unbound RCA base. Ensuring that subsurface drain outlet locations are adequately separated from receiving waters during project planning and design should prevent issues. For example, the Illinois State Toll Highway Authority has included a provision in their *Drainage Design Manual* (Illinois Tollway 2016) stating that: “Subsurface drain outlets shall not be located within 200 ft upstream of the eventual watercourse. This allows the necessary spacing for the construction of any biological treatment feature downstream from the outlet to treat fine material that

may wash out from the RCA.” Furthermore, specification provisions indicate that “if the outlet must be constructed closer than 200 feet from a watercourse, the designer shall allow space for a mechanical sedimentation trap to be constructed to remove the RCA fines.”

Use of hardy vegetation near subsurface drainage outlets is also suggested. Bioswales have been successfully utilized as biological treatment features to neutralize alkaline runoff and capture sediments at outlets close to receiving waters. If high-pH or sediment-laden leachate is present after construction at isolated locations, commercial products such as pH (or “shock”) logs and chemical coagulant (or “floc”) logs have been utilized as a temporary measure until acceptable leachate characteristics are achieved (Wagner 2017). Some soils have been shown to successfully reduce the pH of alkaline runoff and leachate, and ongoing research in this area is focused on the development of practical solutions to runoff and leachate from RCA (Townsend et al. 2016, Ginder-Vogel 2017).

Preventing Drainage Issues from Sediments and Solid Precipitate

In unbound applications, all RCA is capable of producing calcium carbonate-based precipitate and insoluble residue (crusher dust). Calcium salts and calcium hydroxide from RCA are soluble, and calcium-based mineral deposits (often referred to as tufa) form when these minerals come out of solution. Formation of this deposit is affected by the minerals present, temperature, and the presence of CO₂ (Bruinsma and Snyder 1995).

Runoff from all RCA can produce sediments and solid precipitates. However, the potential for tufa formation appears to be related to the amount of freshly exposed cement paste and increases with surface area (smaller particles) and higher paste content.

Washing RCA may reduce the potential for accumulation of dust and other fines but does not greatly reduce the potential for tufa formation (Bruinsma and Snyder 1995). When RCA is used in drained layers, these deposits can affect the permeability of geotextile fabrics, drainable bases, drainage pipes, or other drainage features downstream of the RCA base (AASHTO 2010); this is not usually a problem when RCA is used in undrained layers or layers below the drains.

Drainage outlets with rodent screens can be more readily affected than drainage outlets without rodent screens (Ceylan et al. 2014).

In general, precipitate formation and sediment deposit does not occur at all sites, and systems with some tufa formation are functioning adequately at many sites. For example, a MnDOT field study showed that precipitate and insoluble residue were not observed in most drainage systems in amounts that would significantly reduce the flow capacity (Snyder and Bruinsma 1996).

The researchers also found that, although precipitate can reduce the permeability of drainage filter fabrics, pipe drains that are unwrapped and placed in drain trenches backfilled with permeable granular materials functioned better than those with wrapped pipes in similar trenches.

In more recent field observations to support research conducted for the Iowa DOT, Ceylan et al. (2014) found less tufa formation from RCA base in drainage systems where plastic (PVC) outlet pipe is used without rodent guards, and when blends of RCA and virgin materials are utilized. **The researchers concluded that “tufa from RCA materials does not need to be mitigated or removed through any alternative solutions such as RCA material quality control, outlet design, and maintenance, etc.”** (Ceylan et al. 2014).

Considerations to mitigate drainage structure clogging can be incorporated into edge drain design (as discussed in Chapter 4), or a daylighted subbase could be considered. Fabrics with higher permittivity that can withstand significant amounts of precipitate deposits and still facilitate adequate flow can be utilized (Snyder and Bruinsma 1996).

A resource for design and specification considerations to mitigate potential negative environmental impacts of RCA in unbound bases is AASHTO M 319-02. Specifically, Section X2 “Tufa-Like Deposits” of this specification provides guidance on validating geotextile or fine-grained drainage layers by field experience and comparative permeability testing to mitigate impacts of deposit formation.

Additional provisions to prevent the formation of deposits and sediments include those aimed at minimizing fines and blending RCA with virgin materials, although Bruinsma and Snyder (1995) suggested that selective grading with natural aggregates may reduce, but not prevent, tufa formation.

Guidance and Training

Guidance on mitigating water quality issues is provided by the U.S. Environmental Protection Agency (EPA) in *Developing Your Stormwater Pollution Prevention Plan*

(EPA 2007). This publication provides information and tools to assist with stormwater pollution prevention plan (SWPPP) development and implementation, including site assessment and planning, selection of BMPs, inspection, maintenance, recordkeeping, and final stabilization.

BMP details for water and air pollution protection related to the production and use of RCA can be provided in project drawings or special provisions, and agency guidance documents for implementing and maintaining BMPs are helpful tools for ensuring stakeholders understand permissible (and unacceptable) activities associated with recycling.

Personnel training is also an important component of programs for preventing adverse environmental impacts. Agencies can integrate information on concrete recycling and mitigation of environmental concerns into existing training courses and seminars for stormwater and erosion control.

On a project basis, strategies for mitigating environmental impacts associated with RCA (along with plans for monitoring and oversight) should be discussed at pre-construction and construction progress meetings.

Construction Strategies and Controls to Mitigate Environmental Concerns

Strategies to mitigate environmental impacts during construction for concrete recycling projects are very similar to those regularly used in highway projects without concrete recycling and are not different from those used for production of other aggregates.

Proactive preconstruction decisions regarding the location(s) and site layout of recycling operations, along with implementation of conventional process controls and operational practices at the construction site, can be used to reduce negative impacts to air quality, water quality, and the local community. The sustainability and economic benefits of the project can be further improved during the construction phase by enabling (and promoting) beneficial reuse of waste materials produced during concrete recycling.

Table 7.2 presents environmental concerns associated with concrete recycling that should be considered during the construction phase and also summarizes mitigation strategies that can be implemented in different construction focus areas.

Table 7.2. Construction controls to protect the environment

Consideration	Mitigation Strategies			
	Location	Site Layout and Controls	Process Controls	Operations
Air quality (emissions and dust)	<ul style="list-style-type: none"> Consider prevailing wind conditions in site selection Use natural topography, roadway features, buildings, or vegetation as wind screen 	<ul style="list-style-type: none"> Minimize haul distances Reduce vehicle movements Maintain haul roads (surfacing, chemical stabilization of surfaces, application of water) Provide wind screens for processing operations and stockpiles 	<ul style="list-style-type: none"> Application of water (mistifiers, spray rigs/ nozzles for prewetting and crushing operations) Maintain vehicles and plant equipment <ul style="list-style-type: none"> Maximize fuel efficiency, utilize emissions checks Avoid leaving plant equipment and/or vehicles operating unnecessarily 	<ul style="list-style-type: none"> Work during periods of low wind velocities if mitigation techniques are not effective Reduce vehicle speeds Shrouds or tarps on haul trucks Vehicle wheel and chassis washes Limit stockpile height and minimize disturbance Cover stockpiles or provide a wind barrier Comply with OSHA's crystalline silica rule (OSHA 2016, 2017)
Water quality	<ul style="list-style-type: none"> Select processing and stockpile locations away from receiving waters 	<ul style="list-style-type: none"> Construct runoff collection trenches around stockpiles and processing equipment Use enhanced or redundant BMPs around perimeter of stockpiles and processing equipment (EPA 2017) 	<ul style="list-style-type: none"> Utilize conventional stormwater BMPs, such as berms, straw bales, and grass/filter channels around stockpiles and processing equipment (EPA 2017) Trap runoff and sediment, preventing discharge of wash water to open stormwater inlets or receiving waters 	<ul style="list-style-type: none"> Cover stockpiles and maintain perimeter BMPs Monitor and maintain BMPs around stockpiles and processing equipment Mitigate pH and solids content of runoff as needed using localized treatment such as mechanical catchments and floc/ pH logs
Waste generation	<ul style="list-style-type: none"> Identify appropriate locations for washing equipment Identify appropriate on-site locations for beneficial reuse of waste material (if allowed) 	<ul style="list-style-type: none"> Capture wash water using approved methods 	<ul style="list-style-type: none"> Use evaporative techniques in appropriate areas to reduce wash water volume 	<ul style="list-style-type: none"> Optimize crushing operations to minimize fines Promote beneficial reuses of waste in pavement or fill applications
Community impacts	<ul style="list-style-type: none"> Use on-site or nearby recycling (to reduce impact of haul and transport vehicles) Locate away from sensitive areas, businesses, or homes 	<ul style="list-style-type: none"> Encourage two-way transport to reduce trips Provide noise attenuation barriers 	<ul style="list-style-type: none"> Use chutes/conveyors to reduce noise 	<ul style="list-style-type: none"> Minimize drop height of material For off-site recycling using public roadways, reduce trips during peak hours

After Cavalline 2018b, National CP Tech Center

Further discussion of strategies to minimize the job-site footprint, mitigate impacts associated with RCA production and handling, implement waste product

reduction and management, and comply with water and air quality regulations follows.

Project Site Controls to Mitigate Environmental Impacts

The decision to perform crushing and grading operations on site vs. off site is a key factor in determining the types of environmental impacts that should be addressed during the construction phase. On-site (or near-site) recycling generally reduces the impacts associated with RCA transport, such as noise, dust, emissions, and traffic issues.

When selecting sites for recycling operations (particularly in urban settings), stakeholders should avoid “sensitive receptors,” which include populations, facilities, certain ecosystems, and any nearby entities that could be adversely impacted by the presence of a material crushing and grading facility and associated hauling equipment (DETR 2000).

Provisions to control dust and emissions can be incorporated into site location, layout, process controls, and operations, similar to air quality measures that can be incorporated into other construction activities. For example, dust control strategies should account for prevailing wind conditions and utilize the natural topography or vegetation. Existing features, such as elevated roadways or roadway depressions, can be used to shelter operations from wind and rain, and can provide some runoff control (see Figures 7.3 and 7.4).

Local community impacts can be mitigated by encouraging two-way transport (to reduce haul vehicle trips) and reducing noise through use of chutes, conveyors, and attenuation barriers. For off-site recycling, hauling during off-peak hours may reduce traffic issues on local roadways.

Emission reductions can be achieved by minimizing haul distances and vehicle movements, as well as by encouraging proper maintenance of plant equipment and vehicles. Simple changes in site geometry and vehicle movement controls can have significant impacts. For example, one study found that reducing vehicle speeds from 30 to 20 mph reduced dust by 22% (BCPH 2017). Reducing idle time, maximizing fuel efficiency, and utilizing emissions checks provide additional ways to minimize the impacts of greenhouse gases and other emissions associated with job-site activities.

Site controls, such as applying water to ground surfaces and equipment (Figure 7.5) and misting the surrounding air (Figure 7.6) can be very effective in mitigating job-site dust.



Dwayne Stenlund/MnDOT

Figure 7.3. Well-implemented on-site material crushing program in urban area



Dwayne Stenlund/MnDOT

Figure 7.4. Demolished material stockpiled beneath bridge prior to crushing with silt fence and vegetative buffer used



Dwayne Stenlund/MnDOT

Figure 7.5. Spray nozzle for dust control on aggregate conveyor



Dwayne Stenlund/MnDOT

Figure 7.6. Jobsite dust suppression (misting) equipment

The use of water spray bars near crushing operations has been shown to significantly reduce dust problems. One research study showed that the use of spray bars resulted in a nearly 50% reduction of dust emissions measured at a distance of 33 ft (10 m) from the crusher (DETR 2000).

Other situations that cannot be directly controlled by site personnel (e.g., dust blowing due to windy weather) can be addressed with operational controls, such as suspending demolition when wind speeds exceed certain thresholds (MnDOT 2017). Provisions to mitigate dust should be included in a dust control plan.

Mitigating Impacts from RCA Production and Handling

On-site RCA production and handling should be managed in a manner that protects nearby receiving waters, reduces dust, and complies with applicable agency regulations. **Strategies for mitigating these impacts for concrete recycling projects differ very little from those utilized for natural aggregate processing/handling and for conventional construction projects.**

One of the earliest studies of RCA impacts on water quality was performed for MDOT in the early 1990s to evaluate runoff from stockpiles of coarse RCA, fine RCA, and recycled asphalt pavement. To mitigate impacts of alkaline runoff, sediments, and other water pollutants on receiving streams, the researchers recommended using conventional stormwater BMPs around stockpiles, including the use of berms, straw bales, grass/filter channels, and selecting stockpile sites away from surface waters (Sadeki et al. 1996). Many agencies have adopted these traditional stormwater BMP measures around RCA stockpiles and other concrete recycling operations and have reported success in compliance with regulations (Stenlund 2017, Wagner 2017).

In addition to the stormwater BMPs listed previously, constructed erosion control methods—including silt fences and seeding/slope control—and other physical and natural methods should be used to control and treat runoff. Strategic placement of operations and stockpiles to take advantage of existing site features can aid in the effectiveness of these BMPs.

Drainage from recycled aggregate processing operations and stockpile areas can be directed to a maintained sediment trap or a bioswale for capture of sediments and treatment of runoff if warranted. Nearby stormwater inlets, taken off line, have been successfully utilized as traps for runoff and sediment. An example of this

approach is shown in Figure 7.7, where stockpiles of concrete are set inside a roadway depression where stormwater inlets are taken off line.



Dwayne Stenlund/MnDOT

Figure 7.7. Concrete stockpiles set inside of roadway depression with stormwater inlets taken offline

When working close to receiving waterways, enhanced perimeter controls to prevent unacceptable discharge can include concrete blocks (Figure 7.8) or Jersey barriers (Figure 7.9) wrapped in geotextile fabric.



Dwayne Stenlund/MnDOT

Figure 7.8. High-performance perimeter control using concrete blocks wrapped in geotextile fabric



Dwayne Stenlund/MnDOT

Figure 7.9. Perimeter control at waterway near demolition and concrete crushing operations with RCA filter berm on inside of geotextile-wrapped Jersey barrier

Crushed concrete can act as a filter berm, and some state agencies allow use of the RCA as part of the BMP along with geotextile-wrapped barriers (as shown in Figure 7.9) (Stenlund 2017).

For RCA, many states require the same general handling and stockpiling practices utilized for conventional aggregates. As with conventional or natural aggregate, different gradations of RCA should be stored in separate stockpiles, as should RCA products from different concrete sources. Practices to keep materials “clean” (such as removal or non-inclusion of visibly contaminated material prior to the crushing operation) and to reduce segregation (limiting stockpile heights and implementing appropriate stockpiling and loading techniques) should be required. Measures must also be taken to prevent contamination or mixing of additional fines or subgrade material.

Best practices for stockpile management to mitigate air quality impacts include controlling stockpile height and minimizing the production of fines to prevent dust. For example, Washington State Department of Transportation (WSDOT) specifications limit stockpile height to 24 ft and require stockpile construction in layers less than 4 ft thick for stockpiles that will contain more than 200 cy of material (WSDOT 2017). Stockpile areas should be misted with water for dust control when materials are being added to or taken from the stockpiles (shown in Figure 7.5).

RCA stockpiles are also susceptible to the re-cementing of particles, a phenomenon more prominent in stockpiles of fine aggregate due to increased surface area and particle contact area (ACPA 2006). For this reason, as well as to reduce dust and impacts of runoff on the water quality of nearby receiving waters, consideration should be given to tarping or covering RCA stockpiles (see Figure 7.10).



Dwayne Stenlund/MnDOT

Figure 7.10. RCA stockpile tarping with plastic and bounded by perimeter berm of wrapped RCA

Other provisions, such as placing stockpiles beneath elevated roadways (shown in Figure 7.4), can also be effective. Agencies often require redundant perimeter controls, such as an enhanced silt fence with vegetative buffer (also shown in Figure 7.4) or other types of BMPs in sensitive areas. The redundant perimeter control for the tarped stockpile in Figure 7.10 consists of RCA wrapped in a geotextile fabric “burrito” (which acts as a sediment filter and perimeter berm for stockpile runoff) in combination with a bioswale, which provides natural capture and treatment mechanisms for the runoff. Trenches around RCA stockpiles are also effective in controlling runoff (Sadecki et al. 1996).

Some soils may be more effective at neutralizing leachate pH than others, with clayey soils having some ability to neutralize alkaline runoff (Townsend et al. 2016). Research supporting development of soil-based BMPs for RCA leachate and runoff is currently ongoing (Ginder-Vogel 2017). Treatment of RCA stockpile runoff (or early-age leachate from drains for unbound RCA bases) may be required in some situations (but very infrequently).

Suspended and dissolved solids from both stockpile runoff and RCA leachate at pavement subdrains can be reduced using bioswales (as shown in Figure 7.10), mechanical catchments (see Figure 7.11), and chemical methods such as floc logs (polyacrylamide products that flocculate/chelate suspended and dissolved solids) (see Figure 7.12).



Huff & Huff, Inc. 2013 for the Illinois Tollway on I-94 eastbound milepost 10.3 (facing northwest)

Figure 7.11. Localized mitigation of high-pH leachate from drain near receiving waters using pH log and bioswale



Copyright © 2016 Hydrograss, used with permission from GeoEnvironmental, Inc.

Figure 7.12. Floc Bloc tied to wooden stake in outflow path

Methods of treating runoff to adjust pH include CO₂ bubblers, chemical addition, and products such as pH logs or shock logs.

Water quality monitoring and testing should be performed in accordance with the agency's NPDES permit, the project's Stormwater Pollution Prevention Plan (SWPPP) (EPA 2007), and in compliance with applicable federal, state, and local regulations. Special provisions utilized with RCA should provide guidance on the water quality characteristics that should be monitored, required test methods, and frequency of testing. All structural BMP features should be inspected and maintained regularly, and runoff pH management and removal of accumulated materials should be performed as needed or required.

Minimizing Waste Generation and Promoting Beneficial Reuse of Fines

The type(s) of crushers(s) utilized will affect the final product gradation and the production of fines—a solid waste product that must be disposed of or beneficially reused (Embacher 2001). To reduce production of fines, jaw crushers are often used for primary crushing operations because they can handle larger slab fragments and produce fewer fines than cone and impact crushers (Snyder and Cavalline 2016, Yrjanson 1989, O'Mahony 1990).

Projects should be approached in a manner that gives the contractor recycling options that can be incorporated into the bidding process.

Many disposal and reuse options exist for waste materials associated with the production and use of

RCA, including disposal at a landfill, on-site burial, beneficial reuses such as RCA in new concrete (Naranjo 2016, Rowden 2016), soil stabilization (Lindemann and Varilek 2016), and as pipe bedding (Prieve and Niculae 2016). To promote concrete recycling, agencies should consider approaching projects in a manner that gives the contractor options for the use of RCA so that beneficial reuses of recycling waste products can be considered during the bidding process.

Specified concrete aggregate gradations in some states are wide enough to allow the use of all RCA material produced, including the fines, in concrete paving mixtures. For example, the Texas DOT (TxDOT) used 100% RCA (including RCA fines) in the reconstruction of 5.8 miles of IH 10 (Naranjo 2016). The section has been in service since 1998, with good performance reported to date. Based on experience with this project, TxDOT specifications were developed for using RCA in new concrete mixtures; these specs currently limit RCA fine aggregate to 20% of the fine aggregate blend to reduce mixture harshness (Naranjo 2016). Similarly, the Illinois DOT (IDOT) specifications for an I-57 project using RCA were modified to allow for fines produced during crushing to be utilized in new concrete (Rowden 2016). In another approach, the Colorado DOT (CDOT) recycled 100% of original concrete in an I-25 project, with RCA coarse aggregate blended with virgin aggregate and used in new concrete pavement, and crusher fines used as pipe bedding (Prieve and Niculae 2016).

Concrete fines have also been successfully used for soil stabilization in Nebraska. The Nebraska Department of Roads (NDOT) tested virgin and lime-stabilized soils with and without additional RCA fines. Soil test results led NDOT to conclude that, at an additional rate of 3% RCA fines by dry weight of soil, the amount of time required for modification was unchanged and the fines were either an inert stabilizer or a short-term modifier. NDOT also concluded that the use of RCA fines may provide a less costly alternative for subgrade stabilization and that there may be further cost savings due to elimination of landfill tipping fees (Lindemann and Varilek 2016).

Slurries and wash water can result from washing equipment, vehicles, and tools used for concrete recycling, as well as from other on-site activities. NPDES construction permits often require concrete wash-off management to prevent discharge of liquids and solids to soils/waters (unless in defined designated areas) using BMPs. Designated areas for wash-off, discharge,

and disposal need to be maintained and recorded on the SWPPP, with such activities restricted from sensitive areas. Best wash water practices utilized by the Minnesota Department of Transportation (MnDOT 2009), for example, include the following:

- Perform wash operations and wash water disposal at designated areas of open subgrade or along shoulder
- Wash at designated areas on a closed surface; then subsequent disposal
- Work area isolation, with subsequent capture and disposal
- Sump manhole isolation trap and vacuum removal

Wastewater and slurries can also be captured in lined ponds, fractionation tanks (or frac tanks), and closed stormwater inlets. Some agencies allow ponding in approved areas, where evaporation can be utilized to help reduce the volume of the waste material. Solids can then be subsequently disposed of or beneficially reused. In all situations, stakeholders should comply with applicable regulations.

Air Quality–Respirable Crystalline Silica

The Occupational Safety and Health Administration’s (OSHA’s) new crystalline silica rule, aimed at protecting workers from harm from respirable crystalline silica, was effective September 23, 2017 for construction and was scheduled to become effective, in general, on June 23, 2018. OSHA’s Construction Standard (with Table 1) provides guidance for engineering and work practice control methods and required respiratory protection and minimum assigned protection factors for a variety of equipment and tasks (OSHA 2017).

Best practices for dust protection for concrete recycling activities include use of spray bars and other water suppression systems at the points of dust generation, protecting operators with ventilated enclosures when possible, and restricting access to work areas to limit exposure of non-essential personnel. Required respiratory protection differs by duration of operating shift, as well as utilization venue (i.e., indoors vs. outdoors).

Hand-held equipment and equipment operated without protective enclosures for operators tend to have more stringent respiratory protection requirements than larger equipment and machinery. Heavy equipment utilized for crushing and demolition activities does not require respiratory equipment, per OSHA’s Table 1. However, operators of smaller equipment often utilized in concrete pavement recycling, such as jackhammers

and hand-held powered chipping tools, are required to use respiratory protection for some exposure conditions and shift durations. Additionally, a Written Exposure Control Plan must be established and implemented by all construction employers covered by OSHA. Project personnel should be sure to consult applicable OSHA regulations for guidance in preparing this plan and otherwise ensuring compliance with the rule (OSHA 2016 and 2017). The American Concrete Paving Association (ACPA) also published a Technical Bulletin, *Understanding OSHA’s Crystalline Silica Rule*, to provide guidance for stakeholders in the concrete pavement industry (ACPA 2016).

Summary

Concrete recycling is a sustainable practice providing many environmental and economic benefits. However, similar to other construction activities, concrete recycling activities should be approached in a manner that prevents or mitigates potential adverse environmental impacts. **Environmental concerns associated with concrete recycling generally do not differ significantly from those associated with production and use of virgin aggregates, and potential negative environmental impacts of concrete recycling have consistently been shown to be readily mitigated through planning and design considerations, use of conventional BMPs, and through readily implementable construction controls.**

Existing BMPs and readily implementable design and construction controls have been shown to be effective in preventing adverse environmental impacts of use of RCA.

Many agencies have not incorporated environmental considerations for concrete recycling into specifications or other regulations, but several agencies have had success requiring that concrete to produce RCA be sourced from the agency’s own infrastructure to reduce the potential for environmental impact (Cackler 2018). Many beneficial reuse and disposal options exist for waste materials associated with concrete recycling. Beneficial uses (e.g., backfill, bound and unbound bases, concrete aggregate, soil stabilization, pipe bedding, etc.) have been proven in field studies and in long-serving pavement projects, and should be enticing to owners for improving overall sustainability efforts.

Concrete recycling has been successfully performed on many highway projects without adversely affecting the environment or local communities. Appropriate design and construction controls to mitigate environmental impact are simply steps in treating RCA as an engineered material, ensuring a more sustainable highway infrastructure system.

References

- Abbaspour, A., B. Tanyu, and B. Cetin. 2016. Impact of Aging on Leaching Characteristics of Recycled Concrete Aggregate. *Environmental Science and Pollution Research*, Vol. 23, No. 20, pp. 20835–20852.
- AASHTO. 2010. *Standard Specification for Reclaimed Concrete Aggregate for Unbound Soil-Aggregate Base Course*, AASHTO M 319-02. American Association of State Highway and Transportation Officials, Washington, DC.
- ACPA. 2016. *Understanding OSHA's Crystalline Silica Rule*. Technical Bulletin. Information and data available on the American Concrete Pavement Association website: http://wikipave.org/index.php?title=Crystalline_Silica_Rule.
- ACPA. 2008a. *ACPA Concrete Pavement Technology Series: Recycled Concrete in Subbases: A Sustainable Choice*. TS204.9P. American Concrete Pavement Association, Skokie, IL. 1204075.sites.myregisteredsite.com/downloads/TS/EB204P/TS204.9P.pdf.
- ACPA. 2008b. *ACPA Concrete Pavement Technology Series: Drainage in Concrete Pavement Structures*. TS204.4P. American Concrete Pavement Association, Skokie, IL. 1204075.sites.myregisteredsite.com/downloads/TS/EB204P/TS204.4P.pdf.
- Austin, L. 2010. *Cost and Benefit of Transportation Specific MS4 and Construction Permitting*. National Cooperative Highway Research Program Project 25-25(56) Final Report. Prepared for American Association of State Highway and Transportation Officials Standing Committee on Environment. Geosyntec Consultants, Oakland, CA.
- BCPH. 2017. *Take Control of Your Dust: Fugitive Dust Best Management Practices*. Boulder, CO. Information and data retrieved February 2017 from the Boulder County Public Health website: www.bouldercounty.org/doc/publichealth/dustbestmgmtpract.pdf.
- Bruinsma, J. E. and M. B. Snyder. 1995. *Measurement and Mitigation of Precipitate from Crushed Concrete Base Materials*. Michigan Concrete Paving Association, Okemos, MI.
- Cackler, T. 2018. *Technology Transfer of Concrete Pavement Technologies: Recycled Concrete Aggregate Usage in the US*. National Concrete Pavement Technology Center, Iowa State University, Ames, IA.
- Cavalline, T. L. 2018a. *Concrete Pavement Recycling Series: Protecting Water Quality through Planning and Design Considerations*. Technical Brief. National Concrete Pavement Technology Center, Iowa State University, Ames, IA.
- Cavalline, T. L. 2018b. *Concrete Pavement Recycling Series: Protecting the Environment during Construction*. Technical Brief. National Concrete Pavement Technology Center, Iowa State University, Ames, IA.
- Ceylan, H., S. Kim, and K. Gopalakrishnan. 2014. Use of Crushed/Recycled Concrete as Drainable Base/Subbase and Possible Future Plugging of Pavement Systems. ASCE Iowa Geotechnical Engineering Conference, April 10, Ames, IA.
- Chen, J., S. Bradshaw, C. H. Benson, J. M. Tinjum, and T. B. Edil. 2012. pH-dependent Leaching of Trace Elements from Recycled Concrete Aggregate. *Proceedings of GeoCongress 2012*, Oakland, CA, pp. 3729–3738.

-
- Chen, J., J. M. Tinjum, and T. B. Edil. 2013. Leaching of Alkaline Substances and Heavy Metals from Recycled Concrete Aggregate Used as Unbound Base Course. *Transportation Research Record: Journal of the Transportation Research Board*, No. 2349, pp. 81–90.
- Darter, M. I., S. H. Carpenter, et al. 1998. *Techniques for Pavement Rehabilitation: A Training Course – Participant’s Manual, 3rd Revision*. FHWA-HI-99-006. National Highway Institute, Federal Highway Administration. Washington, DC.
- DETR. 2000. *Controlling the Environmental Effects of Recycled and Secondary Aggregates Production: Good Practice Guidance*. Department of the Environment, Transport, and the Regions, Crown Publishing, London, England.
- Dodoo, A., L. Gustavsson, and R. Sathre. 2009. Carbon Implications of End-of-Life Management of Building Materials. *Resources, Conservation and Recycling*, Vol. 53, No. 5, pp. 276–286.
- Edil, T. B., J. M. Tinjum, and C. H. Benson. 2012. *Recycled Unbound Materials*. Minnesota Department of Transportation, St. Paul, MN.
- Engelsen, C. J., H. A. van der Sloot, G. Wibetoe, H. Justnes, W. Lund, and E. Stoltenberg-Hansson. 2010. Leaching Characterization and Geochemical Modelling of Minor and Trace Elements Released from Recycled Concrete Aggregates. *Cement and Concrete Research*, Vol. 40, No. 12, pp. 1639–1649.
- Engelsen, C. J., G. Wibetoe, H. A. van der Sloot, W. Lund, and G. Petkovic. 2012. Field Site Leaching from Recycled Concrete Aggregates Applied as Sub-Base Material in Road Construction. *Science of the Total Environment*, Vol. 427–428, pp. 86–97.
- Environment Canada. 2013. Acid Rain. Environment and Climate Change Canada, (as archived). <http://www.ec.gc.ca/eau-water/default.asp?lang=En&n=FDF30C16-1>.
- EPA. 2017a. *Summary of the Clean Water Act*. Washington, DC. Information and data retrieved March 2017 from the U.S. Environmental Protection Agency website: <https://www.epa.gov/laws-regulations/summary-clean-water-act>.
- EPA. 2017b. *National Pollutant Discharge Elimination System (NPDES) - National Menu of Best Management Practices (BMPs) for Stormwater*. Washington, DC. Information and data retrieved February 2017 from the U.S. Environmental Protection Agency website. <https://www.epa.gov/npdes> or <https://www.epa.gov/npdes/national-menu-best-management-practices-bmps-stormwater#edu>.
- EPA. 2017c. *National Environmental Policy Act*. Washington, DC. Information and data retrieved March 2017 from the U.S. Environmental Protection Agency website: <https://www.epa.gov/nepa>.
- EPA. 2017d. *Summary of the Resource Conservation and Recovery Act*. Washington, DC. Information and data retrieved March 2017 from the U.S. Environmental Protection Agency website: <https://www.epa.gov/laws-regulations/summary-resource-conservation-and-recovery-act>.
- EPA. 2017e. *Summary of the Clean Air Act*. Washington, DC. Information and data retrieved March 2017 from the U.S. Environmental Protection Agency website: www.epa.gov/laws-regulations/summary-clean-air-act.

- EPA. 2007. *Developing Your Stormwater Pollution Prevention Plan: A Guide for Construction Sites*. U.S. Environmental Protection Agency, Washington, DC. https://www3.epa.gov/npdes/pubs/sw_swppp_guide.pdf.
- EPA. 1992. *Method 1311 Toxicity Characteristic Leaching Procedure*. Washington, DC. Information and data retrieved from the U.S. Environmental Protection Agency website: www.epa.gov/sites/production/files/2015-12/documents/1311.pdf.
- Fay, L., X. Shi, and J. Huang. 2013. *NCHRP Synthesis 449: Strategies to Mitigate the Impacts of Chloride Roadway Deicers on the Natural Environment*. National Cooperative Highway Research Program, Washington, DC.
- Fick, G. 2017. *Construction Considerations in Concrete Pavement Recycling*, Webinar. National Concrete Pavement Technology Center, Institute for Transportation, Iowa State University, Ames, IA.
- FHWA. 2017. *Air Quality*. Washington, DC. Information and data retrieved March 2017 from the Federal Highway Administration website: www.fhwa.dot.gov/environment/air_quality/.
- Galvin, A. P., J. Ayuso, I. Garcia, J. R. Jimenez, and F. Gutierrez. 2014. The Effect of Compaction on the Leaching and Pollutant Emission Time of Recycled Aggregates from Construction and Demolition Waste. *Journal of Cleaner Production*, Vol. 83, pp. 294–304.
- Ginder-Vogel, M. 2017. Personal communication. University of Wisconsin-Madison, Madison, WI.
- Huber, W. C., E. W. Strecker, J. P. Heaney, and N. Weinstein. 2006. *NCHRP Report 565. Evaluation of Best Management Practices and Low Impact Development for Highway Runoff Control*. National Cooperative Highway Research Program, Washington, DC.
- Illinois Tollway. 2017. *Drainage Design Manual*. Illinois State Toll Highway Authority. www.illinoistollway.com/documents/20184/238191/Drainage+Design+Manual_04202017.pdf/498191e4-6457-43a5-b4b3-5c601d4c2478?version=1.1.
- Lindemann, M. and B. Varilek. 2016. *Use of Recycled Crushed Concrete (RCC) Fines for Potential Soil Stabilization*, In-house research. Nebraska Department of Transportation, Lincoln, NE.
- Line, D. E. 2016. *Pilot Study on Direct Discharge of Concrete Grinding Residuals to Roadside Shoulders: Part 2*. Technical Assistance Report 2017-2 and 3. North Carolina Department of Transportation, Raleigh, NC.
- MnDOT. 2009. *Best Management Practice (BMP) for Concrete Washoff of Vehicles, Equipment, Pavement and Walls*, Vol. 3. St. Paul, MN. Information and data retrieved March 2017 from Minnesota Department of Transportation website: www.dot.state.mn.us/environment/pdf/concrete-washoff.pdf.
- MnDOT. 2017. *Fugitive Dust BMPs Template*. St. Paul, MN. Information and data retrieved February 2017 from Minnesota Department of Transportation website: www.dot.state.mn.us/environment/erosion/index.html.
- Mulugeta, M., C. J. Engelsen, G. Wibetoe, and W. Lund. 2011. Charge-based Fractionation of Oxyanion-forming Metals and Metalloids Leached from Recycled Concrete Aggregates of Different Degrees of Carbonation: A Comparison of Laboratory and Field Leaching Tests. *Waste Management*, Vol. 31, No. 2, pp. 253–258.
- Naranjo, A. 2016. Case History of 100% RCA Paving Mixture, Houston I-10. 11th International Conference on Concrete Pavements, August 28–September 1, San Antonio, TX.
- O'Mahony, M. M. 1990. *Recycling Materials in Civil Engineering*. New College, University of Oxford, Oxford, England.
- OSHA. 2016. *OSHA Fact Sheet: Workers' Exposure to Respirable Crystalline Silica Final Rule Overview*. Occupational Safety and Health Administration, U.S. Department of Labor, Washington, DC. <https://www.osha.gov/Publications/OSHA3683.pdf>.

- OSHA. 2017. *Silica: Construction: Complying with the Construction Standard and Respirable Crystalline Silica Standard for Construction*. Occupational Safety and Health Administration, U.S. Department of Labor, Washington, DC. <https://www.osha.gov/dsg/topics/silicacrystalline/construction.html#tableOneTasks> and <https://www.osha.gov/Publications/OSHA3681.pdf>.
- Qin, Y. and H. Yang. 2015. Carbonation Dominates the Acid Intake of Recycled Concrete Aggregate Subjected to Intermittent Leaching. *Construction and Building Materials*, Vol. 89, pp. 110–114.
- Prieve, E. and V. Niculae. 2016. RCA Experience of Pavements in Colorado. 11th International Conference on Concrete Pavements, August 28–September 1, San Antonio, TX.
- Rowden, L. 2016. Performance History of I-57 in Illinois. 11th International Conference on Concrete Pavements, August 28–September 1, San Antonio, TX.
- Sadecki, R. W., G. P. Busacker, K. L. Moxness, K. C. Faruq, and L. G. Allen. 1996. *An Investigation of Water Quality in Runoff from Stockpiles of Salvaged Concrete and Bituminous Paving*. Minnesota Department of Transportation, St. Paul, MN.
- Sani, D., G. Moriconi, G. Fava, and V. Corinaldesi. 2005. Leaching and Mechanical Behaviour of Concrete Manufactured with Recycled Aggregates. *Waste Management*, Vol. 25, No. 2, pp. 177–182.
- Santero, N., A. Loijos, and J. Ochsendorf. 2013. Greenhouse Gas Emissions Reduction Opportunities for Concrete Pavements. *Journal of Industrial Ecology*, Vol. 17, No. 6, pp. 859–868.
- Schwab, O., P. Bayer, R. Juraske, F. Verones, and S. Hellweg. 2014. Beyond the Material Grave: Life Cycle Impact Assessment of Leaching from Secondary Materials in Road and Earth Constructions. *Waste Management*, Vol. 34, No. 10, pp. 1884–1896.
- Silva, R. V., J. de Brito, and R. K. Dhir. 2017. Availability and Processing of Recycled Aggregate within the Construction and Demolition Supply Chain: A Review. *Journal of Cleaner Production*, Vol. 143, pp. 598–614.
- Snyder, M. B. and J. E. Bruinsma. 1996. Review of Studies Concerning Effects of Unbound Crushed Concrete Bases on PCC Pavement Drainage. *Transportation Research Record: Journal of the Transportation Research Board*. No. 1519, pp. 51–58.
- Snyder, M. B. and T. L. Cavalline. 2016. *Introduction to Recycling of Concrete Pavements*. National Concrete Pavement Technology Center, Iowa State University, Ames, IA. Webinar and PDF available at: www.cptechcenter.org/webinars/.
- Steffes, R. 1999. *Laboratory Study of the Leachate from Crushed Portland Cement Base Material*. Iowa Department of Transportation, Ames, IA.
- Stenlund, D. 2017. Personal Communication. Minnesota Department of Transportation, St. Paul, MN.
- Townsend, T. G., P. Chadik, N. Gupta, M. Kluge, T. Vinson, and J. Schert. 2016. *Concrete Debris Assessment for Road Construction Activities*. Florida Department of Transportation, Tallahassee, FL.
- Wagner, B. 2017. Personal communication, Illinois State Toll Highway Authority, Downers Grove, IL.
- WSDOT. 2017. Chapter 3: Aggregate Production and Acceptance. *WSDOT Construction Manual*. Washington State Department of Transportation, Olympia, WA.
- Yrjanson, W.A. 1989. *NCHRP Synthesis of Highway Practice 154: Recycling of Portland Cement Concrete Pavements*. National Cooperative Highway Research Program, Washington, DC.

National Standard and Specification References

These standards and specifications are listed in alphanumeric order by standard/specification designation (after each title) for each organization.

AASHTO

AASHTO. 2017. *Standard Specifications for Transportation Materials and Methods of Sampling and Testing*, M 147-17. American Association of State Highway and Transportation Officials, Washington, DC.

AASHTO. 2015. *Standard Specification for Reclaimed Concrete Aggregate for Unbound Soil-Aggregate Base Course*. M 319-02. American Association of State Highway and Transportation Officials, Washington, DC.

AASHTO. 2017. *Standard Practice for Determining the Reactivity of Concrete Aggregates and Selecting Appropriate Measures for Preventing Deleterious Expansion in New Concrete Construction*. R 80-17. American Association of State Highway and Transportation Officials, Washington, DC.

AASHTO. 2013. *Standard Method of Test for Determining the Liquid Limit of Soils*. T 89. American Association of State Highway and Transportation Officials, Washington, DC.

AASHTO. 2016. *Standard Method of Test for Determining the Plastic Limit and Plasticity Index of Soils*. T 90. American Association of State Highway and Transportation Officials, Washington, DC.

AASHTO. 2002. *Standard Method of Test for Resistance to Degradation of Small-Size Coarse Aggregate by Abrasion and Impact in the Los Angeles Machine*. T 96. American Association of State Highway and Transportation Officials, Washington, DC.

AASHTO. 2017. *Standard Method of Test for Moisture-Density Relations of Soils Using a 2.5-kg (5.5-lb) Rammer and a 305-mm (12-in.) Drop*. T 99. American Association of State Highway and Transportation Officials, Washington, DC.

AASHTO. 2008. *Standard Method of Test for Soundness of Aggregates by Freezing and Thawing*. T 103. American Association of State Highway and Transportation Officials, Washington, DC.

AASHTO. 1999. *Standard Method of Test for Soundness of Aggregate by Use of Sodium Sulfate or Magnesium Sulfate*. T 104. American Association of State Highway and Transportation Officials, Washington, DC.

AASHTO. 2017. *Standard Method of Test for Plastic Fines in Graded Aggregates and Soils by Use of the Sand Equivalent Test*. T 176. American Association of State Highway and Transportation Officials, Washington, DC.

AASHTO. 2013. *Standard Method of Test for the California Bearing Ratio*. T 193. American Association of State Highway and Transportation Officials, Washington, DC.

AASHTO. 1999. *Standard Method of Test for Determining the Resilient Modulus of Soils and Aggregate Materials*. T 307. American Association of State Highway and Transportation Officials, Washington, DC.

AASHTO. 2012. *Standard Method of Test for Resistance of Coarse Aggregate to Degradation by Abrasion in the Micro-Deval Apparatus*. T 327. American Association of State Highway and Transportation Officials, Washington, DC.

ACI

ACI. 2001. *Removal and Reuse of Hardened Concrete*. ACI 555R-01 (currently under revision). American Concrete Institute, Farmington Hills, MI.

ASTM

ASTM. 2014. *Standard Test Method for Resistance to Degradation of Small-Size Coarse Aggregate by Abrasion and Impact in the Los Angeles Machine*. C131/C131M-14. ASTM International, West Conshohocken, PA.

ASTM. 2016. *Standard Test Method for Air Content of Freshly Mixed Concrete by the Volumetric Method*. C173/C173M-16. ASTM International, West Conshohocken, PA.

ASTM. 2014. *Standard Test Method for Air Content of Freshly Mixed Concrete by the Pressure Method*. C231/C231M-14. ASTM International, West Conshohocken, PA.

ASTM. 2016. *Standard Test Method for Resistance to Degradation of Large-Size Coarse Aggregate by Abrasion and Impact in the Los Angeles Machine*. C535-16. ASTM International, West Conshohocken, PA.

ASTM. 2012. *Standard Test Methods for Laboratory Compaction Characteristics of Soil Using Standard Effort (12,400 ft-lbf/ft³ (600 kN-m/m³))*. D698-12e2. ASTM International, West Conshohocken, PA.

ASTM. 2015. *Standard Specification for Graded Aggregate Material for Bases or Subbases for Highways or Airports*. D2940/D2940M-15. ASTM International, West Conshohocken, PA.

ASTM. 2015. *Standard Test Method for Unconsolidated-Undrained Triaxial Compression Test on Cohesive Soils*. D2850-15. ASTM International, West Conshohocken, PA.

National Concrete Pavement
Technology Center

