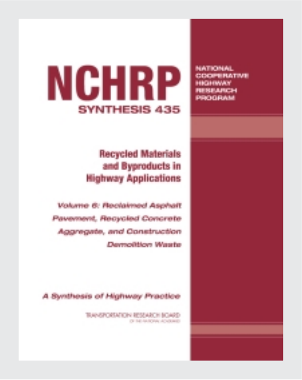

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NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

NCHRP SYNTHESIS 435

Recycled Materials and Byproducts in Highway Applications

Volume 6: Reclaimed Asphalt Pavement, Recycled Concrete Aggregate, and Construction Demolition Waste

A Synthesis of Highway Practice

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NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

Systematic, well-designed research provides the most effective approach to the solution of many problems facing highway administrators and engineers. Often, highway problems are of local interest and can best be studied by highway departments individually or in cooperation with their state universities and others. However, the accelerating growth of highway transportation develops increasingly complex problems of wide interest to highway authorities. These problems are best studied through a coordinated program of cooperative research.

In recognition of these needs, the highway administrators of the American Association of State Highway and Transportation Officials initiated in 1962 an objective national highway research program employing modern scientific techniques. This program is supported on a continuing basis by funds from participating member states of the Association and it receives the full cooperation and support of the Federal Highway Administration, United States Department of Transportation.

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The needs for highway research are many, and the National Cooperative Highway Research Program can make significant contributions to the solution of highway transportation problems of mutual concern to many responsible groups. The program, however, is intended to complement rather than to substitute for or duplicate other highway research programs.

NCHRP SYNTHESIS 435: Volume 6

Project 20-05, Topic 40-01

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FOREWORD

Highway administrators, engineers, and researchers often face problems for which information already exists, either in documented form or as undocumented experience and practice. This information may be fragmented, scattered, and unevaluated. As a consequence, full knowledge of what has been learned about a problem may not be brought to bear on its solution. Costly research findings may go unused, valuable experience may be overlooked, and due consideration may not be given to recommended practices for solving or alleviating the problem.

There is information on nearly every subject of concern to highway administrators and engineers. Much of it derives from research or from the work of practitioners faced with problems in their day-to-day work. To provide a systematic means for assembling and evaluating such useful information and to make it available to the entire highway community, the American Association of State Highway and Transportation Officials—through the mechanism of the National Cooperative Highway Research Program—authorized the Transportation Research Board to undertake a continuing study. This study, NCHRP Project 20-5, “Synthesis of Information Related to Highway Problems,” searches out and synthesizes useful knowledge from all available sources and prepares concise, documented reports on specific topics. Reports from this endeavor constitute an NCHRP report series, *Synthesis of Highway Practice.*

This synthesis series reports on current knowledge and practice, in a compact format, without the detailed directions usually found in handbooks or design manuals. Each report in the series provides a compendium of the best knowledge available on those measures found to be the most successful in resolving specific problems.

PREFACE

By Jon M. Williams
Program Director
Transportation
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Recycled materials and industrial byproducts are being used in transportation applications with increasing frequency. There is a growing body of experience showing that these materials work well in highway applications. This study gathers the experiences of transportation agencies in determining the relevant properties of recycled materials and industrial byproducts and the beneficial use for highway applications. Information for this study was acquired through a literature review, and surveys and interviews with state department of transportation staff. The report will serve as a guide to states revising the provisions of their materials specifications to incorporate the use of recycled materials and industrial byproducts, and should, thereby, assist producers and users in “leveling the playing field” for a wide range of dissimilar materials.

Mary Stroup-Gardiner, Gardiner Technical Services LLC, Chico, California, and Tanya Wattenberg-Komas, Concrete Industry Management Program, California State University, Chico, California, collected and synthesized the information and wrote the report. The members of the topic panel are acknowledged on the preceding page. This synthesis is an immediately useful document that records the practices that were acceptable within the limitations of the knowledge available at the time of its preparation. As progress in research and practice continues, new knowledge will be added to that now at hand.

The report is presented in eight volumes, the first of which is available in hard copy and on the Internet. The next seven volumes are available through the Internet only and can be found at: http://www.trb.org/Publications/NCHRPSyn435.aspx. The eight volumes are:

Volume 1	*Recycled Materials and Byproducts in Highway Applications—Summary Report*
Volume 2	*Coal Combustion Byproducts*
Volume 3	*Non-Coal Combustion Byproducts*
Volume 4	*Mineral and Quarry Byproducts*
Volume 5	*Slag Byproducts*
Volume 6	*Reclaimed Asphalt Pavement, Recycled Concrete Aggregate, and Construction Demolition Waste*
Volume 7	*Scrap Tire Byproducts*
Volume 8	*Manufacturing and Construction Byproducts*

CONTENTS

CHAPTER ONE

INTRODUCTION

This chapter contains information for three types of byproducts:

- Reclaimed asphalt pavement (RAP),
- Recycled concrete aggregate (RCA), and
- Construction and demolition waste (CDW) recycled concrete aggregate.

The RAP information focuses on only the material used after it has been removed from the roadway and recycled through a central plant process. RAP used for in-place recycling is covered in a separate NCHRP synthesis (Steyn 2012). The RCA section includes recycled materials from the production of concrete (i.e., plant production waste) and recycled concrete pavements. CDW RCA is generated when the concrete elements can be successfully separated from other demolition materials (i.e., wood, sheet rock, brick, etc.). The construction demolition waste section summarizes recent information found for RCA from heterogeneous demolition and reconstruction debris. Additional information can be found at the following websites:

- Construction Materials Recycling Association: www.cdrecycling.org
- National Asphalt Pavement Association: www.hotmix.org
- Aggregate and Quarry Association of New Zealand: www.aqa.org.nz
- Recycled Materials Resource Center: www.rmrc.unh.edu/
- Turner–Fairbanks Highway Research Center (TFHRC): http://www.fhwa.dot.gov/research/tfhrc/
- Federal Highway Administration (FHWA) Pavements Recycling: www.fhwa.dot.gov/pavement/recycling/.

CHAPTER TWO

RECLAIMED ASPHALT PAVEMENT

Asphalt concrete is removed during maintenance or rehabilitation activities by grinding (milling) the surface, pulverizing the old pavement along with a portion of the base or subgrade, or ripping up the old pavement. Milled or post-processed old asphalt concrete is referred as reclaimed asphalt pavement, or RAP. RAP can be removed from the job site and stockpiled at a contractor's plant site (central plant recycling) or it can be used on-site with in-place recycling technologies. Central plants can be either hot mix asphalt (HMA) or cold mix asphalt plants.

HOT CENTRAL PLANT RECLAIMED ASPHALT PAVEMENT RECYCLING

Hot mix recycling combines RAP with new aggregates and fresh asphalt in the presence of heat in a central plant and is the most common method used by contractors (Santucci 2007). The amount of RAP used in the new mix varies between agencies and with the layer of the pavement being constructed. The use of RAP by agencies varies between 0% and 30% in the upper layers, and up to 50% in lower layers, shoulders, and stabilized bases (TFHRC 2010). RAP can be added to the HMA at either batch (old technology) or drum mix plants. The location of where the RAP is added to the drum is important because if the RAP is added too close to the flame, emissions (smoking) and overheating damage to the RAP binder will occur.

The drum plant can consist of parallel flow and counterflow configurations (Figure 1). Parallel flow means the air flow and the aggregate move through the drum in the same direction. Counterflow drums move the aggregate and the air flow in opposite directions. Some drum configurations can also include a RAP drier and second mixing chamber.

Parallel flow dryer drums heat the RAP conductively by transferring the heat from the aggregate to the RAP (FHWA 1997). The amount of RAP that can be added is limited by the space in the drum and the time it takes for the materials to move through the drum. The exhaust gases from the drum are at a similar temperature to that of the superheated aggregate and the emissions are increased by the percentage of RAP. The main disadvantage to the parallel flow drum is that the amount of RAP is limited by the air pollution control devices on the plant.

Counterflow drums combine a mixture dryer and a continuous mixing drum into one unit. Double and triple barrel designs have been in use since the 1980s. In a double drum, the inner chamber dries the aggregate and drops it to the outer shell where it combines with the RAP. This configuration results in a reduction of emissions and blue smoke, higher production rates, and lower fuel consumption. The triple drum configuration has a separate drum for heating and drying the RAP, discharging it into the heated aggregate, then dropping the combined aggregate and RAP into the outer drum.

COLD CENTRAL PLANT RECLAIMED ASPHALT PAVEMENT RECYCLING

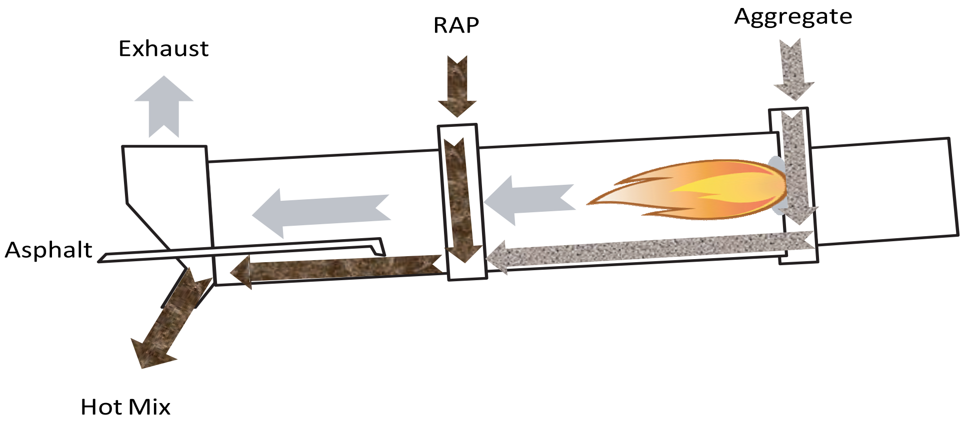
Cold mix recycling combines RAP with new aggregate (if needed) and emulsified asphalt or an emulsified recycling agent (RA) without the use of heat in a central plant. Other additives can be used to help regulate the emulsion rate of set (i.e., how fast the water evaporates from the emulsion), early strength gain, or improved moisture resistance. Cold mix pavement construction and equipment is described by FHWA (1997). The four main steps in the removal and placement process are:

1. Removal of the existing pavement,
2. Crushing and stockpiling of the RAP,
3. Mixing, and
4. Feed rate controls to adjust the amount of RAP.

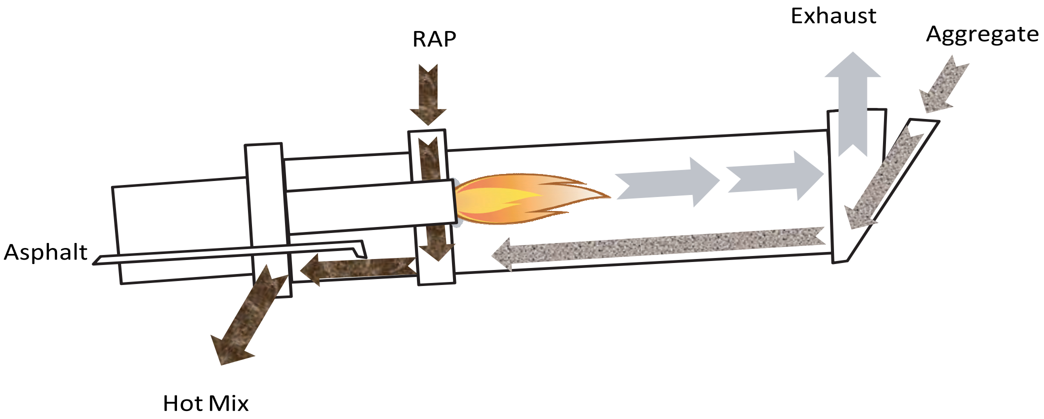
Cold mix plants have the ability to add the emulsion, additional water if needed, and any required modifiers and can produce mix at a faster rate than HMA. Cold mixes consume less energy in the production process (i.e., no heat needed) and produce fewer emissions. Stockpiles need to be available for constant production at the plant site.

During mixing, care is needed so that the material is not overmixed. Excess mixing can result in "scrubbing" the emulsion from the aggregates and/or premature breaking of the emulsion, which results in overly stiff mixes. Undermixing can result in inadequate coating of the aggregates, although further coating is usually obtained during the spreading and rolling operations. The cold mix tends to initially increase in volume because of the water volume in the emulsion, which will evaporate with time (i.e., breaking of the emulsion). An increase in the volume of mix may be required to achieve a similar lift thickness when using typical HMA.

Placement is accomplished with standard paving laydown, spreading, and compaction equipment. Alternatively, a wind-



Parallel Flow Drum Configuration



Counter Flow Drum Configuration

FIGURE 1 Schematic of parallel and counter flow HMA plant configurations (after Santucci 2007).

row can be spread and leveled to the proper cross slope using a motor grader. Overly wet mixes require aeration to reduce the water and volatile content of the mix. This can be accomplished with additional working of the mix back and forth across the roadway to help with evaporation. Cold mix at the proper moisture content can be placed with conventional self-propelled pavers. Sufficient liquid is needed to avoid tearing by the screed and the screed should not be heated.

Compaction can be accomplished with any type, or combination of types, of rollers. Heavy pneumatic-tired rollers (25 short tons or more) are preferred for breakdown, particularly if the lifts are 3 in. or more thick. Vibratory rollers are commonly used at high frequency and low amplitude.

Traffic needs to be limited on the surface of newly placed cold mix. If traffic must be returned to the pavement before placement of the wearing course so that further evaporation (curing) can occur, a fog seal can be used to minimize raveling.

Weather limitations include requirements that the ambient temperatures be 50°F or above, and that construction not continue during rainfall or begin if rain is anticipated. The final wearing course is commonly either an HMA overlay or a double surface treatment (e.g., double chip seal).

PHYSICAL AND CHEMICAL PROPERTIES

RAP gradation will depend on how the recycled material is obtained. Old asphalt pavement can be broken up during rehabilitation processes, transported, crushed and sized, and then stockpiled at the asphalt plant. It can also be obtained through milling the distressed pavement surface prior to maintenance work.

RAP has been historically treated in one of two ways. The first is as “black rock”; that is, the RAP is considered a direct substitution for natural aggregate. In reality, RAP is a composite of aggregate, asphalt, and any additives used in the original construction. The second approach considers all of the asphalt as contributing to the asphalt content of the new mix. Recent research has shown that the truth lies between the two approaches.

This leads to three of the main agency concerns when designing and paying for asphalt concrete. All three of the concerns are related to volumetric measurements and calculations. The concerns are how to:

- Account for the amount of the RAP binder that is contributed to the total asphalt content.
- Determine the rheological properties of the combined fresh and RAP binders.
- Determine the effective specific gravity of the RAP (i.e., effective specific gravity).

When RAP is used as an aggregate in an unbound application, the volume of asphalt in the RAP reduces the specific gravity and the presence of asphalt seals most of the surface area of the particles. These characteristics result in a lower unit weight and a reduced amount of water needed to achieve the desired compaction level. An example of RAP properties compared with a typical aggregate is shown in Table 1.

Asphalt Binders

Asphalt binders used in recycling processes can be typical paving grade asphalts (typically hot recycling) or emulsions (cold recycling) (Clyne et al. 2003):

- Paving grade asphalt
- Emulsions
  - CSS-1, CSS-1h, and CSS-1hP
  - CMS-2S
  - HFMS-2, HFMS-2S
  - HF150, HF-300P.
- Recycling or rejuvenating agents.

Paving Grade Asphalts

Paving grade asphalt can be specified by the standard Superpave performance graded (PG) specification by using the desired properties of the combined asphalt (i.e., combination of new and RAP asphalt). A formal blending program can be conducted to select the fresh binder PG grading, or a less formal “bumping” down one grade to account for the stiffening of the fresh binder because of aged RAP binder can be used.

The binder grade, quantity, and/or any rejuvenating or RA needs to be identified. This is done by the use of blending charts that can be adapted for viscosity or Superpave PG binder tests (Figure 2). The viscosity or G*/sin δ for the RAP binder is plotted on the left y-axis and the properties of the fresh liquid is plotted on the right. A line is drawn horizontally across the graph from left to right until it intersects the diagonal viscosity line. The percentage of fresh liquid needed is read off of the bottom horizontal axis. More comprehensive designs will blend the anticipated percentages of RAP and new binder to determine the full Superpave binder property requirements.

Emulsions

Emulsions are a combination of small asphalt globules suspended in water by the use of surfactants. Typical emulsion grades used in recycling projects, along with specified properties, are shown in Table 2. Regardless of the source of the emulsion specification, there are typically three groups of material property tests needed to determine the properties of emulsions (water, asphalt, additives), distillation of emulsions (removal of water), and the recovered base asphalt (residue). Traditional emulsion specifications use one or more tests to define the asphalt residue properties: absolute and kinematic viscosity, penetration, and ductility testing. The existing specifications rely on older methods of grading asphalts (e.g., penetration grades and viscosity grades); however, there is some desire to develop specifications for the residual asphalt cement on the Superpave performance grading specifications. This is because the states currently use the PG binder specifications for HMA.

Historically, emulsions used in the same environmental conditions may have base asphalts with a wide range of performance-graded asphalt properties that will likely influence the success or failure of recycling projects.

Recycling Agents

RAs are used to restore the aged asphalt to the desired binder properties. ASTM D4552 (Table 3) classifies petroleum product additives specifically for hot mix recycling methods. The RA classifications are viscosity graded with the lower number designation representing the lowest viscosity.

TABLE 1
MATERIAL PROPERTIES REPORTED BY RATHJE et al. (2001)

Material	Specific Gravity (Gs)			Proctor Compaction Information				Tex-113-E Compaction	
	>4.75 mm	<4.75 mm	Composite	Recommended water content (%)	Expected dry unit weight (lb/ft^3)	γ_{min} (lb/ft^3)	γ_{max} (lb/ft^3)	γd (lb/ft^3)	Relative Density (%)
Control	2.62	2.62	2.62	10	119	94.1	110.5	119	141
RAP	2.36	2.28	2.33	3	117	90.1	107.8	117	140

γ_{min} = minimum unit weight.
γ_{max} = maximum unit weight.

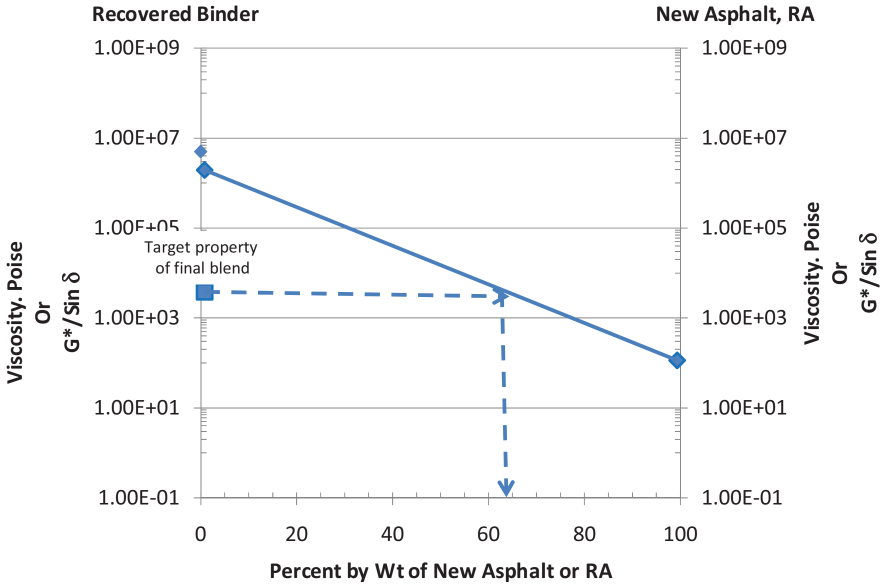


FIGURE 2 Example of typical blending chart for estimating amount of recycling agent (RA) (after FHWA 1997).

TABLE 2
REQUIREMENTS FOR CATIONIC EMULSIFIED ASPHALTS

Type	Medium Setting								Slow Setting			
Grade	HFMS-2		HFMS-2s		HF-150		CMS-2S		CSS-1		CSS-1h	
	Min.	Max.	Min.	Max.	Min.	Max.	Min.	Max.	Min.	Max.	Min.	Max.
Tests on Emulsions												
Viscosity, Saybolt Furol at 25°C (77°F) SFS	100		50		35	150			20	100	20	100
Viscosity, Saybolt Furol at 50°C (122°F) SFS							100	450				
Storage Stability Test, 24-h, %		1		1		1.5		1		1		1
Demulsibility, 35 ml, 0.8% Dioctyl Sodium Sulfonsuccinate, %					40							
Coating Ability and Water Resistance												
Coating, Dry Aggregate	good		good				good					
Coating, After Spraying	fair		fair				fair					
Coating, Wet Aggregate	fair		fair				fair					
Coating, After Spraying	fair		fair				fair					
Particle Charge Test							positive		positive		positive	
Sieve Test, %		0.1		0.1		0.1		0.1		0.1		0.1
Cement Mixing Test, %										2		2
Tests on Distillation												
Oil Distillate, by Volume of Emulsions, %					0.5	4		12				
Residue, %	65		65		62		60		57		57	
Tests on Residue from Distillation Test												
Penetration, 25°C (77°F), 100 g, 5 s	100	200	200		150	250	100	250	100	250	40	90
Ductility, 25°C (77°F), 5 cm/min, cm	40		40				40		40		40	
Solubility in Trichloroethylene, %	97.5		97.5		97.5		97.5		97.5		97.5	
Float Test, 60°C (140°F), s	1200		1200		1200							

After ASTM D2387-05; D977-05; Thompson (2003).
*CQS-1h is used for quick set slurry seal systems.
*CQS-2H emulsions shall meet the requirements outlined in ASTM Practice D3910.

TABLE 3
ASTM D4552 CLASSIFICATIONS FOR RECYCLING AGENTS

Test	ASTM Test Method	RA 1		RA 5		RA 25		RA 75		RA 250		RA 500	
		Min.	Max.	Min.	Max.	Min.	Max.	Min.	Max.	Min.	Max.	Min.	Max.
Viscosity at 140°F, cSt	D2170 or D2171	50	175	176	900	901	4,500	4,501	12,500	12,501	37,500	37,501	60,000
Flash Point, COC, °F	D92	425	—	425	—	425	—	425	—	425	—	425	—
Saturates, wt%	D2007	—	30	—	30	—	30	—	30	—	30	—	30
*Tests on residue from RTFO or TFO oven 325°F (*D2872 or D1754*)*													
Viscosity Ratio	—	—	3	—	3	—	3	—	3	—	3	—	3
Wt Change ± %	—	—	4	—	4	—	3	—	3	—	3	—	3
Specific Gravity	D70 or D1298	Report		Report		Report		Report		Report		Report	

RTFO = rolling thin film oven; TFO = thin film oven.

Products meeting the RA 1 through RA 75 designations are typically used for recycled mixes, with more than 70% RAP in the mixes. When more than 30% of new aggregate is used, the RA 250 and RA 500 grades are more appropriate. The Pacific Coast User-Producer Group defines RAs as a hydrocarbon product with physical characteristics selected to restore aged asphalt binder to the current asphalt binder specifications. By this definition, a softer grade of asphalt can be classified as a RA.

ASTM D5505 provides specifications for emulsifying RAs (Table 4). The base asphalt in these products increases in stiffness (viscosity) with increases in the grade number. The main function of the ER-1 is to rejuvenate aged asphalt and is a petroleum derivative, which is compatible with asphalts. The ER-1 material is viscosity-graded and there are no requirements for viscosity measurements on the residue after rolling thin film oven testing. The ER-2 and ER-3 grades are a combination of rejuvenators and asphalt components. These RAs are typically used when the recycled HMA needs additional asphalt (e.g., when adding new aggregate). They are considered a penetration-graded material since the penetration test is used to set limits on the residue after rolling thin film oven conditioning.

TABLE 4
ASTM D5505 SPECIFICATIONS FOR EMULSIFYING RECYCLING AGENTS

Tests	Test Method	ER-1		ER-2		ER-3	
		Min.	Max.	Min.	Max.	Min.	Max.
Testing on Emulsion							
Viscosity, 50°C, SSF	D224		100	20	450	20	450
Sieve, %	D6933		0.1		0.1		0.1
Storage Stability, 24 h, %	D6930		1.5		1.5		1.5
Residue, by Distillation, %	D6997	65		65		65	
Dilution	—		report[a]				
Specific Gravity	D70		report		report		report
Compactibility[b]	varies		report		report		report
Testing on Residue from Distillation							
Viscosity, 60°C, cSt	D2170	50	200		30		30
Saturates, %	D2007		30				
Solubility in Trichloroethylene	D2042	97.5		97.5		97.5	
On Residue from Distillation after RTFO[C]							
Penetration, 4°C, 50 g, 5 s	D5			75	200	5	75
RTFO, Weight Change, %	D2872		4		4		4

ASTM D5505 (2009).
Notes:

[a] ER-1 shall be certified for dilution with potable water.

[b] This specification allows a variety of emulsions, including high-float and cationic emulsions. The engineer should take the steps necessary to keep incompatible materials from co-mingling in tanks or other vessels. It would be prudent to have the chemical nature (flat test for high-float emulsions, particle charge test for cationic emulsions, or other tests as necessary) certified by the supplier.

[c] RTFO (rolling thin film oven) shall be the standard. When approved by the engineer the Thin Film Oven Test (Test Method D1754) may be substituted for compliance testing.

USE AND PRODUCTION

United States

The National Asphalt Pavement Association (2010) reported that approximately 100 million tons of asphalt concrete pavement are reclaimed every year. Around 75% of this RAP material was used in new pavement construction and another 20% was used in other highway uses such as preservation activities or pavement rehabilitation. An example of the annual agency use of RAP from 2000 through 2005 for New Jersey (Copeland 2010) is shown in Figure 3.

The National Center for Asphalt Technology (Copeland 2010) noted that approximately 500 million tons of HMA were placed each year. About 60 million tons of RAP was recycled back into pavements and about 40 million tons was recycled into other highway applications.

A survey of FHWA division offices (52 divisions, 18 respondents) noted that RAP use was optional and depended on the contractor to propose use and on economic considerations and material availability. The cost was driven by the cost of materials and transportation. Only three respondents mentioned that they tracked the use of RAP. The main difficulty in tracking use was that RAP was not bid as a separate component of the mix. About 45% of the respondents indicated contractors had recently requested to use RAP, with some asking to use more than 25% RAP.

Europe

About 90% of European roadways are made of asphalt materials. The commission of the European Union established a working group on CDW in 1993, which established recycling asphalt pavements as a priority waste stream (EAPA 2005). European regulations governing the use of RAP recommended the separation of RAP using bitumen binders from RAP obtained from pavements that used tar (from coal distillation). Bituminous RAP is considered an inert waste that contains no more than 25 mg/kg polyaromatic hydrocarbons. Tar on the other hand contains significant amounts of benzo(a)pyrene and has less desirable rheological properties.

A wide range of HMA plants and recycling operations was found across Europe (Table 5). A number of the HMA plants used RAP in conjunction with warm mix asphalt (WMA) technologies, which significantly reduced the plant temperature needed to produce workable mixes. The lower temperatures resulted in less heat-related aging of the binder and lower emissions from the hot mix production and construction processes.

COSTS

The increasing cost of asphalt binder and the decreasing availability of natural aggregate sources are pushing the desire of both contractors and agencies to increase the amount of RAP used in the production of asphalt concrete products. Using between 20% and 50% RAP can result in a cost savings of between 14% and 34% per ton (TFHRC 2010).

ENVIRONMENTAL CONSIDERATIONS

Research reported by the Canadian Industry Program for Energy Conservation (CIPEC 2005) in 2005 noted that the road building and heavy construction industry in Canada accounted for more than $5 billion in economic activity in 2003. Recent increases in fuel and raw material costs, restrictions

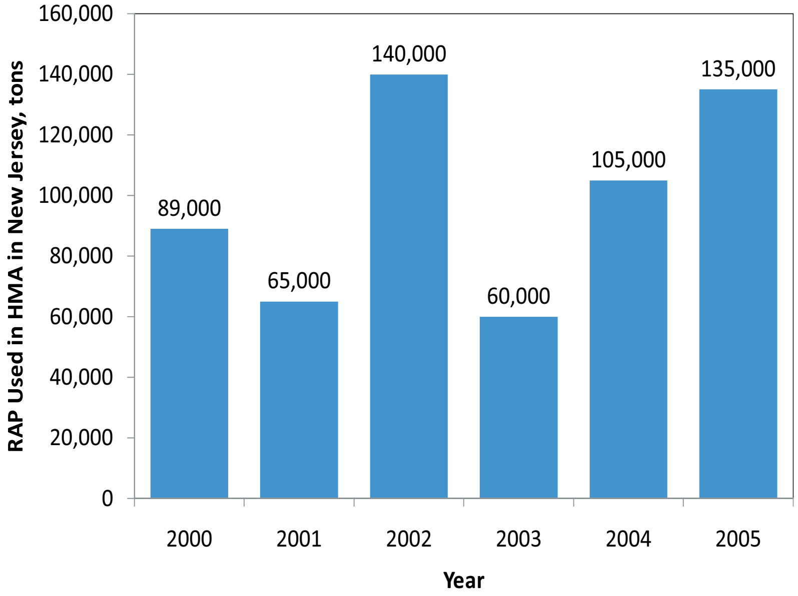


FIGURE 3 Example of annual use of RAP (after Copeland 2010).

TABLE 5
USE OF RAP IN EUROPEAN COUNTRIES FOR 2001

Country	Stationary Plants	Mobile Plants	Number Fit for Warm Recycling	Total HMA	Available RAP	% of the New Production That Contains Reclaimed Material	% Actually Used in Warm Recycling
				x 1.000 tonnes			
Austria	130	0	3	9,500	—	3	—
Belgium	42	0	15	4,500	1.5	25	20–45
Croatia	60	4	4	1,800	20	10	0
Czech Republic	105	2	40	4,300	710	16	10–40
Denmark	48	2	46	2,800	220	31	57
Finland	65	24	23	3,600	200	5–10	40
France	404	100	5	40,500	<5,000	<10	10–45
Germany	740	5	700	63,000	15	60–65	15–80
Hungary	76	4	3	2,900	1,200	—	0.3
Iceland	6	3	1	300	5	0	0
Ireland	50	15	8	3,100	—	—	—
Italy	650	15	150	39,800	13	5	15
Netherlands	56	0	51	600	3,000	60	25–50
Norway	95	12	10	7,700	520	4	6
Poland	300	20	14	4,100	750	0.3	15–30
Romania	40			11,200	80	40	20–40
Slovakia	16	0		2,500	4.6		
Slovenia	300	0	0	1,100	50	15	60
Sweden	129	16	45	1,400	1	19	15
Switzerland	215	2	35	6,700	1.75	—	15
United Kingdom	—	10	—	5,100	5	—	—

After EAPA (2005).
— = not available.

on emissions, and increased emphasis on the sustainable use of materials increased contractor and agency interest in the energy consumption of various roadway materials and construction options. Table 6 presents the calculated energy consumption for traditional HMA construction, binder courses, and high binder course (high-quality lower pavement layers), WMA, RAP HMA, and cold mix asphalt.

The results of the analysis showed that using increased amounts of fresh asphalt binder increased the energy use, in MJ/tonne, by 3% (HMA compared with high modulus HMA). Warm mix technologies decreased energy consumption by 4%, while using only 10% RAP resulted in a 6% reduction. About 13% less energy was necessary to produce and place the lower lifts (i.e., binder course). Increasing the amount of RAP in the HMA increasingly reduced the energy use. Using 50% RAP in HMA applications reduced energy consumption to about the level used to produce cold mix asphalt.

Recent regulations from the EPA require the calculation and reporting of greenhouse gases (GHG) for certain sources starting in 2010 (Marks 2010). The need to report GHG emissions depends on the amount of emissions produced by a source. Facilities not specifically listed by EPA need to report GHG if their total fuel combustion capacity is greater than 30 million Btu per hour and the actual GHG is greater than 25,000 metric tons per year of CO_2 equivalents. However, some states have recently implemented GHG reporting criteria that require reporting emissions from HMA plants at 5,000 tons of CO_2 equivalents.

GHG emissions increase with increases in fuel combustion and burning that is used to dry aggregate, heat asphalt, and in mix production. The main contribution to GHG during the production of HMA is in the drying of aggregate and in mix production. The National Asphalt Pavement Association developed software based on the EPA AP-42 emission factors to estimate the CO_2 equivalents for GHG to help HMA contractors determine if their emissions need to be reported. The calculator uses plant information on consumption of fuel, the type of fuel used, and the tons of mix produced per year, as well as the use of vehicle fuel and electricity to estimate the overall annual emissions.

The limitations of this level of emission reporting are that the reduction of GHG in the acquisition and production of raw materials are not a factor. That is, the environmental impact of using RAP or other recycled byproducts is not con-

TABLE 6
ENERGY USE FOR VARIOUS ROADWAY APPLICATIONS

Product	Energy Use, MJ/tonne						% Reduction in Energy Use
	Binder	Aggregate	Manufacture	Transport	Laydown	Total	
Hot Mix Asphalt Concrete	279	38	275	79	9	680	0
High Modulus Hot Mix Asphalt Concrete	284	38	289	79	9	699	–3
Warm Asphalt Mix	294	38	234	80	9	654	4
Binder Course Hot Mix Asphalt	196	36	275	75	9	591	13
Recycled Hot Mix Asphalt Concrete with 10% RAP	250	35	275	73	9	642	6
Recycled Hot Mix Asphalt Concrete with 20% RAP	157	33	275	64	9	538	21
Recycled Hot Mix Asphalt Concrete with 30% RAP	137	30	275	58	9	510	25
Recycled Hot Mix Asphalt Concrete with 50% RAP	98	25	275	47	9	454	33
Emulsion-Based Cold Mix Asphalt	314	36	14	86	6	457	33

After CIPEC (2005).

sidered. A more inclusive environmental system is needed to capture these benefits.

Miller and Bahia (2009) identified challenges to sustainability analyses of asphalt pavements as defining sustainable asphalt pavements, collection of data, and setting system boundaries. Some of the definitions for sustainable pavements were identified as:

- "A sustainable pavement to be a safe, efficient and environmentally friendly pavement that meets today's transportation needs without jeopardizing the ability to meet such needs in the future" (United Nations Brundtland Commission report).
- "Environmentally friendly roads should minimize ground disturbance; be well-drained and appropriately surfaced to control erosion and loss of material; employ effective erosion control measures; and be regularly maintained while continuing to meet the user's needs."
- "A pavement that minimizes environmental impacts through the reduction of energy consumption, natural resources and associated emissions while meeting all performance conditions and standards" (proposed definition by authors).

Common energy values and conversions can be applied to the analysis; however, most surveys of contractors did not adequately capture information on proprietary methods and techniques. System boundaries needed to be defined so that the environmental and energy information was obtained for each of the relevant system components. This analysis confined the system to five critical processes:

1. Extraction of raw materials
2. Manufacturing or production of paving products
3. Construction or placement of materials
4. Maintenance
5. Removal, recycling, or disposal.

CHAPTER THREE

AGENCY SURVEY

The majority of the states reused HMA baghouse fines in the production of fresh HMA. Most states also used either as-received or fractionated RAP in fresh HMA (Table 7; Figure 4). Fewer states reused fresh HMA leftover mix in fresh HMA. The most common use of unground RAP (i.e., chunks) was in the construction of embankments. A limited number of states used RAP in pavement surfaces in limited amounts that were typically less than 15%, soil stabilization, or drainage materials. Only a few states used RAP in more than one highway application (Table 8).

Agencies were asked to indicate the maximum percent of RAP they allowed in various HMA lifts (Table 9). Four agencies did not allow any RAP in the wearing course. Massachusetts limited the use of RAP to 10% in the wear course and Texas had a 10% limit if the RAP was not fractionated, but would permit up to 20% if the RAP was separated by size. Six states allowed up to 15%, seven states allowed 20%, and two states permitted 25%. Neither Georgia nor Missouri permitted RAP to be used in stone matrix asphalts. Ohio allowed more than 20% RAP if it is used in conjunction with warm mix technology. Alabama increased the limit of 25% RAP in the binder or base courses if warm mix technology was used.

Respondents were also asked to indicate their experience with the performance of RAP mixes (Table 10). Twenty-four agencies specifically noted satisfactory to excellent performance with RAP HMA pavements. Only Missouri mentioned premature pavement failure when the RAP percentages exceeded 20%.

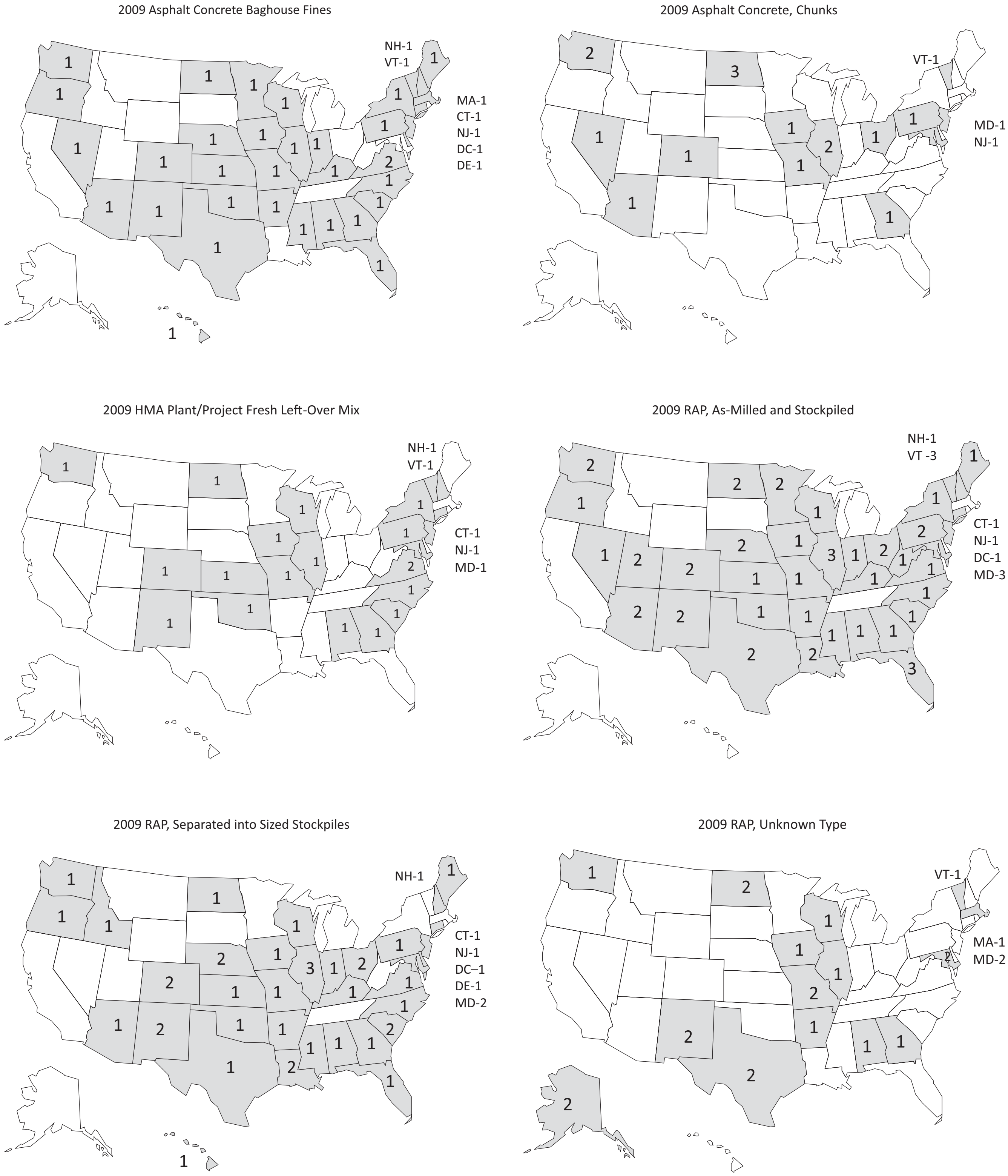
A number of comments were received in response to the question about barriers to increased use (Table 11). The comments can be summarized by the following list of barriers:

- Contractor concerns with meeting specification requirements
- Contractors using more RAP than design requirements
- How to pay for RAP binder in HMA
- Lack of agency experience
- Lack of availability
- Lack of confidence in long-term performance
- Lack of experience with RAP and polymer-modified binders
- Lack of experienced contractors
- Lack of stockpile homogeneity
- Potential presence of coal tar in old pavements
- Tendency of RAP HMA to prematurely crack
- Unknown influence of RAP on binder properties at higher RAP contents.

TABLE 7
NUMBER OF STATES USING RAP BYPRODUCTS IN HIGHWAY APPLICATIONS

Question: Hot Mix Asphalt (HMA) Industry Recycled Materials and Byproducts: Is your state using, or has ever used, these byproducts in highway applications? If you are not sure of the type of reclaimed asphalt pavement (RAP) used in your state, check the RAP, unknown type box at the end of the list.

Type of Byproduct	Asphalt Cements or Emulsions	Crack Sealants	Drainage Materials	Embankments	Flowable Fill	HMA	Pavement Surface Treatments (non-structural)	PCC	Soil Stabilization
Baghouse Fines (HMA plant)	2	0	0	0	0	36	0	0	0
HMA, Unmilled (chunks)	0	0	2	11	0	3	0	0	2
HMA, Plant/Project Fresh Leftover Mix	0	0	0	1	0	18	1	0	1
RAP, as Milled and Stockpiled	0	0	4	9	0	36	3	0	5
RAP, Separated into Sized Stockpiles	0	0	3	2	0	34	3	0	1
RAP, Unknown Type	1	0	1	3	0	13	0	0	3



2009 Asphalt Concrete Baghouse Fines

2009 Asphalt Concrete, Chunks

2009 HMA Plant/Project Fresh Left-Over Mix

2009 RAP, As-Milled and Stockpiled

2009 RAP, Separated into Sized Stockpiles

2009 RAP, Unknown Type

FIGURE 4 Reclaimed asphalt concrete.

TABLE 8
STATES USING RAP BYPRODUCTS IN HIGHWAY APPLICATIONS

Number of Applications	States					
	Baghouse fines (HMA plant)	HMA, unmilled (chunks)	HMA, plant/project fresh left-over mix	RAP, as milled and stockpiled	RAP, separated into sized stockpiles	RAP, unknown type
3	—	ND	—	FL, IL, MD, VT	IL	—
2	VA	IL, WA	VA	AZ, CO, LA, MN, ND, NE, NM, OH, PA, TX, UT, WA	CO, LA, MD, NE, NM, OH, SC, VA	AK, MD, MO, ND, NM, TX
1	AL, AR, AZ, CO, CT, DC, DE, FL, GA, HI, IL, IN, IA, KS, KY, MA, ME, MN, MO, MS, NC, ND, NE, NH, NJ, NM, NV, NY, OK, OR, PA, SC, TX, VT, WA, WI	AZ, CO, GA, IA, MD, MO, NJ, NV, OH, PA, VT	AL, CO, CT, GA, IL, IA, KS, MD, MO, NC, ND, NH, NJ, NM, NY, OK, PA, SC, VT, WA, WI	AL, AR, CT, GA, IN, IA, KS, KY, ME, MO, MS, NC, NH, NJ, NV, NY, OR, OK, SC, VA, WI, WV	AL, AZ, CT, DC, DE, FL, GA, HI, ID, IN, IA, KS, KY, ME, MO, MS, NC, ND, NH, NJ, OR, OK, PA, TX, VA, WA, WI	AL, AR, GA, IL, IA, MA, VT, WA, WI

TABLE 9
AMOUNT OF RAP CURRENTLY ALLOWED BY STATES IN EACH LIFT

State	Lift		
	Wear	Binder	Base
DE	NS	NS	NS
IA	NS	Limited to 30% max. binder contribution from RAP; 10% RAP max. for unknown RAP source	NS
IL	Varies	Varies	Varies
LA	NS	NS	NS
MO	NS; not allowed in SMA	NS	NS
ND	NS	NS	NS
PA	NS	NS	NS
SC	Varies	Varies	Varies
WV	Skid resistance requirements limit use in wear course	Varies	Varies
KY	% unlimited unless RAP contains PG76-22 when max. is 20%	% unlimited unless RAP contains PG76-22 when max. is 20%	% unlimited unless RAP contains PG76-22 when max. is 20%
DC	0	NS	NS
ID	0	Varies	Varies
KS	0	NS	NS
OK	0	15	
MA	10	40% with drum mix plant; 20% with modified batch plant	40% with drum mix plant; 20% with modified batch plant
CT	15	15	15
FL	15	No restriction	No restriction
IN	15	25	25
ME	15	25	25
NJ	15	25	25
NM	15	35	35
AL	20	25%; 35% with warm mix technology	25%; 35% with warm mix technology
AZ	20	25	25
CO	20	25	25
HA	20	30	30
MD	20% with no change in fresh binder grade	25% with no change in fresh binder grade	25% with no change in fresh binder grade
NY	20	20	30
OH	20; more if warm mix technology used	20; more if warm mix technology used	50
OR	20	30	30
TX	20% fractionated RAP 10% unfractionated	30% fractionated RAP 20% unfractionated	40 fractionated RAP 30% unfractionated

TABLE 9
(*continued*)

State	Lift		
	Wear	Binder	Base
WS	20	20	20
MS	25	30	30
UT	25	20	20
MN	30	40	40
GA	40; no RAP in SMA or OGFC/PEM	40	40
NC	50% max; 15% to 25% typical	50% max; 15% to 25% typical	50% max; 15% to 25% typical
VT	50% upon mix design approval	50% upon mix design approval	50% upon mix design approval

NS = RAP is used but amount not indicated in response; SMA = stone mix asphalt; OGFC/PEM = open-graded friction course/porous European mix.

TABLE 10
STATE RESPONSES FOR PERFORMANCE EXPERIENCE

State	Comments
AK	No data
AL	We have had good performance with RAP materials.
AR	ACHM with RAP have performed well in Arkansas.
AZ	The Department is currently working with industry to write specifications to allow the use of Recycled Asphalt Pavement (RAP) in hot mix asphalt. Three projects using RAP were constructed in 2008. All are performing satisfactorily. Milled AC has been blended with aggregate base material at 50%/50% meeting virgin aggregate base specs.
CO	The performance has been good.
DC	Good
DE	Performed well
FL	FDOT has recycled asphalt since the late 1970s and has excellent results.
GA	Similar to HMA
ID	Still new to this
IN	Good performance to date. Have allowed RAP in category 3, 4, and 5 surface mixtures for first time in 2009.
IA	Used in many projects. Some cracking issues with high RAP%
KS	Using less than 15%; RAP is a great way to reuse both aggregate and binder.
KY	The performance of asphalt pavements containing RAP in Kentucky has been as good as or better than the performance of asphalt pavements containing virgin materials exclusively. Additionally, the moisture-susceptibility resistance of HMA as measured by the tensile strength ratio is typically improved with higher RAP contents.
MA	Experience has been good. Currently looking at modifying our specs to allow 15% RAP in surface mixes.
MD	Performance has been comparable to non-rap mixes.
ME	Satisfactory performance in most situations
MO	Past experience with amounts greater than 20% resulted in failures. Using current guidelines, the mixtures have been performing well.
MS	HMA mixtures with RAP perform very well.
NC NC	When properly managed no performance issues exist Good performance. Most contractors routinely use RAP in all mixes.
ND	OK to this point
NE	We have used mixes with RAP for years and they have proven to be successful.
NH	We use it commonly and we do have an approximately 30-year old RAP project that we are currently doing a study on to evaluate the properties of the asphalt in the roadway section since we have good documentation of its original characteristics.
NJ	We have not documented any difference in performance between HMA made with RAP versus virgin HMA.
NM	So far we don’t have any problems, but we started using RAP for the last 5 to 7 years. So we don't have historical data for experience.
NY	We find HMA with RAP to be comparable to virgin mixes.
OH	RAP has generally worked well. Ohio continues to increase proportions allowed, depending on initial control of the RAP's quality. Generally use higher percentages the lower we get in the pavement. Have controls to assure a certain minimum virgin AC so that amount of rap can be limited based on the amount of AC within the RAP.
OR	Most all of our mixes incorporate RAP into the mix design. We have seen no performance issues.
PA	Generally, performance with RAP has been good. Some very limited issues with cracking of HMA mixtures containing RAP possibly due to mix asphalt content or stiffness of assumed blended asphalt binder.
SC	The recycled materials (RAP and shingles) show additional rutting resistance in laboratory tests; however, the fatigue of high RAP pavements causes premature stiffness and cracking in older pavements.
VA	Great experience using HMA recycled materials checked above.
VT	Generally very good, but process control problems are routinely overlooked. Unwritten QC procedures are implemented in the field during milling operations that improve quality, but to an unknown and nonstandard level.
WI	Same performance as HMA not utilizing recycle
WS	RAP has performed the same as virgin materials.
WV	Variable

TABLE 11
STATE RESPONSES TO BARRIERS TO INCREASED USE OF RAP

State	Comments
AK	Lack of confidence in the long-term performance. How to pay the contractor for it?
AR	Availability is an issue in Arkansas.
CO	Using RAP with highly polymerized mixes is a barrier due to the perceived stiffening of the mix.
DC	Do not use in surface course due to high skid resistance on city streets and intersections.
DE	Handling of RAP
FL	High stiffness of the RAP binder. Different aggregate sources in the same pile (granite and limestone). Perpetual piles are difficult to characterize. Trying to prevent the contractor from using more RAP than the design calls for.
GA	Variability issues can theoretically be overcome by fractionation. Binder hardening is still a concern for higher RAP contents.
ID	Not enough experienced contractors
IA	Binder grade bumping often limits use.
KS	Too much stiffens the mix, leaving it more susceptible to premature transverse cracking.
KY	Very few contractors in Kentucky fractionate their RAP. In turn, the inconsistency of some RAP utilized in higher percentages results in erratic HMA volumetric properties. Also, higher percentages of RAP normally require a softer virgin asphalt binder. Some softer virgin binder grades (e.g., PG 58-28) are difficult to obtain in this region. In some instances, inadequately heated RAP has presented mixture coating concerns.
MA	Overall QC/QA process with plants and knowing that the RAP is consistent. These plant unknowns keep us from allowing higher RAP.
MD	Allowable percentages have been increased in the last year as to allowance in polymer and high polish mixes.
ME	Using RAP in surface courses has been a concern but [we] have not experienced measurable difference in performance.
MO	RAP is not available for all projects.
MS	The availability of RAP by some HMA producers is the largest barrier.
NC	Better processing and handling of RAP is required as the percentage incorporated into HMA increases.
NC	Concerns about proper binder grade when RAP is used in high percentages
ND	Variability in RAP environmental issues; binder in the RAP is old and stiffer, which is more prone to thermal cracking.
NE	In the past the incentive to incorporate RAP was minimal; however, we now offer a payment incentive to use RAP and are having great success with that.
NH	We are looking to do some high RAP projects with greater than 25% RAP.
NJ	Producer's concerns about QC and meeting specifications when using higher percentages of RAP
NM	For 15% RAP we don't change the grade of asphalt. For >15% to 25%, we drop down a grade and for >25% (up to 35%) RAP we require Blending Charts.
NV	Performance compared to virgin aggregate mixes is the main barrier.
NY	Variability of RAP must be controlled, has an impact on volumetrics. Long-term performance not yet verified.
OH	The limits like all byproducts are controlling and identifying the differences in the recycled materials. Performance is the chief and only issue. Not knowing what is in the RAP, quality of the RAP AC; assuming that the old and new AC really intermix within the asphalt concrete process; controlling material variance both AC quality, quantity and size.
PA	Lack of comprehensive mix design procedure that analyzes high RAP content mixtures for their performance. Lack of mandated RAP materials management; only best practices are recommended that HMA producers do not necessarily have to follow.
SC	Stockpiled material QC, aging of asphalt due to high viscosity RAP, fluctuations in RAP viscosity and gradation, dust/asphalt ratio.
UT	Uncertainty of what additional RAP will do to the mix.
VA	The more recycled asphalt that is used the stiffer the product will be and the harder the HMA will be to apply. If you follow the guidelines it works extremely well.
VT	RAP characterization strategies don't exist. Categorical definition and standards would be essential to furthering the use of RAP. In a rural state we need to exclude RAP encountered in deep reclaim projects that may be coal tar-based or aged beyond recognition as an asphaltic binder. Additionally, superheating virgin aggregates is approaching a level where significant thermal cracking is introduced to the virgin stone in the mix. Defining recommended moisture/preheat level for RAP would narrow the control issues.
WI	Effect on PG—binder grade of HMA mixture
WA	None. We use all RAP that is produced.
WV	Stock pile control—Ensuring that the material in the stock piles is known and consistent.

QC = quality control; QA = quality assurance; AC = asphalt concrete.

CHAPTER FOUR

LITERATURE REVIEW

APPLICATIONS: BOUND—HOT MIX ASPHALT

Recent research by (McDaniel et al. 2000) suggested that the fresh binder grade not change from the one commonly used for geographical area of construction project if the percentage of RAP is 15% or less. At over 25% RAP, extracted-recovered-tested RAP binder properties, along with fresh binder properties, are to be used in blending charts to determine the appropriate grade of fresh binder. The results for RAP content of between 15% and 25% varied with regard to the grade of fresh asphalt needed to achieve the desired properties. “Bumping” the PG grade by one grade was considered a reasonable approach for this range of RAP content; that is, if a PG 64-22 is normally used in a non-RAP mix, the binder grade needs to be adjusted to the next grade softer, which would be a PG 58-28 (PG binder change in increments of six).

Quality control (QC) concerns focused on the amount of RAP added to the mix, variability of asphalt content and aggregate properties, moisture content amount and variability, long-term performance, and the need for softening or rejuvenating agents. Most RAP HMA mix research indicated that the stiffer RAP binder improves the stiffness of the mix, thus improving the mixes resistance to rutting. The research also indicated this stiffening effect may result in increased tendencies for thermal cracking and reduced resistance to fatigue cracking as a result of the loss of flexibility of the mix. Rejuvenators (e.g., softer grade of virgin asphalt, proprietary products, lubricating oil, and extender oils) could be used to soften the aged properties of the RAP binder.

Stephens et al. (2001) investigated the amount of blending of RAP binder with fresh binder and a simple test method to determine the appropriate PG grade. Binder properties were determined for fractionated RAP to determine if they were dependent on the size of RAP particles and the heating time used for the RAP. The degree of RAP binder blending with the fresh binder was considered to be a function of the temperature of the RAP at the time of mixing.

The indirect tensile strength was selected for evaluating the appropriate binder grade of the fresh binder. Testing was conducted at the high and low PG temperature range for mixes with 0%, 15%, and 25% RAP.

The results showed no size-dependent properties. The RAP mixed with no preheating were about 30% stiffer than the control mix. A further increase in stiffness was seen with one minute of heating time; however, further increases in the heating times did not show other significant increases in stiffness. Results showed that indirect tension testing can be used to estimate the effective PG grading of the blended binder in the RAP HMA.

FHWA (2000) presented a summary of a review of Specific Pavement Study (SPS) 5 sections. Each SPS5 site consisted of one control and eight test sections with different combinations of thin (51 mm) and thick (127 mm) overlays, virgin and recycled mixtures used for the overlays, and milled and nonmilled surfaces before overlay placement. Six different pavement distresses or performance indicators were used to evaluate the influence of the various combinations on the different distresses. At the time of the review, most of the sections were less than 4 years at the time of review. At this early age, the RAP HMA overlays showed a greater extent of longitudinal cracking in the wheel path than the control, but a lower extent of longitudinal cracking in the nonwheel path areas.

Lee et al. (2002) evaluated the low temperature performance-based binder properties. The study included two sources of RAP, two PG binder grades (PG 58-28 and PG 64-22), and various RAP binder percentages (0%, 10%, 20%, 30%, 40%, 50%, 75%, and 100%). Conventional viscosity testing (absolute viscosity) showed, as expected, increasing viscosity with increasing RAP binder percentages.

Results for the Superpave dynamic shear testing showed similar trends in the complex shear modulus (G*) (Table 12). The phase angle decreased with increasing RAP content indicating that the binder behavior was increasingly less viscous and more elastic in response to the decreasing temperatures. This translated into decreasing ductility and increased brittle behavior with increasing RAP binder content. Similar trends were seen for G* and the phase angle of short-term oven-aged and long-term oven-aged, pressure aging, vessel-treated binders. The bending beam rheometer (BBR) testing to evaluate low temperature properties showed that the low temperature PG grade increased (i.e., became warmer) with increasing RAP content after about 30% RAP binder. The results were strongly dependent on the source of the fresh asphalt binder. Results for the performance-based mix testing showed that the fracture toughness at low temperatures was decreased (i.e., samples were weaker) with increasing RAP percentage and decreased with decreasing test temperature.

TABLE 12
UNAGED DYNAMIC SHEAR MODULUS AND PHASE ANGLE FOR VARIOUS BLENDS OF FRESH ASPHALT AND RAP BINDER

Percent RAP Binder, %		PG 58-28		PG 64-22	
	Temperature, °C	G*	δ	G*	δ
0	52	2.73	85.1	5.54	81.8
	58	1.20	86.5	2.53	84.1
	64	0.61	87.8	1.15	85.9
	70	0.31	88.7	0.59	87.3
	76	0.17	89.0	0.31	88.3
10	52	3.85	83.7	6.77	80.5
	58	1.64	85.7	3.11	82.7
	64	0.81	87.0	1.47	84.7
	70	0.41	88.2	0.74	86.5
	76	0.20	88.8	0.39	88.0
20	52	5.94	81.9	9.49	78.9
	58	2.68	84.0	3.94	81.3
	64	1.22	85.9	1.89	83.5
	70	0.61	87.3	0.96	85.1
	76	0.32	88.2	0.49	86.2
30	52	6.43	81.7	11.70	77.2
	58	2.80	83.0	5.14	79.5
	64	1.40	85.1	2.57	82.1
	70	0.67	86.9	1.21	83.6
	76	0.36	87.9	0.60	84.3
40	52	9.48	78.7	16.65	75.7
	58	4.12	81.3	7.32	78.6
	64	2.02	83.6	3.15	81.3
	70	0.99	85.4	1.53	83.7
	76	0.50	87.2	0.79	85.6
50	52	13.97	76.8	20.01	74.2
	58	5.79	79.7	8.59	77.4
	64	2.70	82.4	3.95	80.0
	70	1.33	84.4	1.91	83.0
	76	0.66	86.2	0.95	85.2
75	52	31.47	71.7	38.92	39.8
	58	14.03	74.9	17.97	73.6
	64	6.23	78.1	7.84	76.8
	70	2.90	80.9	3.58	80.0
	76	1.42	83.8	1.78	82.8
100	52	65.03	66.9	65.03	66.9
	58	29.56	70.7	29.56	70.7
	64	13.03	74.6	13.03	74.6
	70	6.30	78.1	6.30	78.1
	76	2.92	80.9	2.92	80.9

After Lee et al. (2002).

Thompson (2003) reported that in 1977 the Oregon Department of Transportation (DOT) started using the ignition oven for determining asphalt contents and gradation of RAP. The first approach for determining RAP asphalt content evaluated using volumetric relationships derived from measuring the effective specific gravity. This approach did not provide acceptable results and a second method that accounted for differences in the specific gravity of the RAP and fresh asphalt specific gravity was evaluated. It also provided unacceptable results. The main conclusion from the research was that future research was needed that could lead to a more complete volumetric equation solution.

Li et al. (2004) evaluated the impact of RAP on mix and binder properties. This study used three RAP percentages (0%, 20%, and 40%), two different fresh asphalts (PG 58-28 and PG 58-34), and two different sources of RAP (recycled asphalt and millings). Millings were obtained for one project. The RAP materials were recycled from a number of sources and crushed at the HMA plant.

Mixture properties were evaluated using dynamic modulus at five temperatures (−20°C, −10°C, 4°C, 20°C, and 40°C) and five frequencies (25, 10, 1, 0.1, and 0.01 Hz). The complex modulus master curves showed that the modulus increased with increasing RAP content and the magnitude of the change was dependent on the RAP source. At lower temperatures, the complex modulus did not always increase with the addition of RAP or millings. Finer gradations showed lower stiffness than a coarser gradation. The inclusion of RAP increased the variability of the test results and the variability increased with decreasing temperature.

Indirect tension creep and strength tests were conducted at two temperatures (–18°C and –24°C). As expected, creep stiffness increased with increasing RAP content. The extracted and recovered binder from the samples used for dynamic modulus testing was used to determine changes in the binder properties. The binder from mixes prepared with the millings produced mixes that were somewhat stiffer than those prepared using the RAP source. The differences were less obvious at colder temperatures. The dynamic shear rheometer testing showed a high amount of variability (35% to 50% coefficient of variation). The bending beam rheometer (BBR) testing had a lower variability (5% to 20% coefficient of variation). The PG grading increased the high temperature value with increasing RAP or milling content; with only a limited influence on the cold temperature value. A change in the cold temperature PG value only increased with 40% of RAP or millings.

Zofka et al. (2004) developed a modified blending chart method for determining the optimum percent of RAP for a mix with given fresh and RAP binder properties. The goal was to develop a simple mix test to obtain binder properties required for charts to select the appropriate percentage of RAP. The materials used in the study consisted of two RAP types, three RAP percentages, and two binders.

Tests selected for evaluation were the scratch test, the indentation tester, and the BBR. The scratch test used a rock strength device originally intended for measuring the strength-related parameters of sedimentary rocks by scratching. The indentation test consisted of pressing a hard indenter of specified geometer into the test material to obtain strength properties, fracture parameters, strength degradation, and deformation behavior. This test is commonly used to evaluate properties in metallurgy, ceramics, mining, and biomedicine. Both of these methods were eliminated because they failed to adequately differentiate between mixes.

The third method investigated the BBR using beams of dense HMA mixes. Preliminary testing showed that the standard 100 g load was not sufficient to provide measurable beam deflections. Modified software was obtained from the manufacturer that allowed the increase in the resolution of the deflection measurements. The load time used for BBR testing was 240 s followed by 240 s of unload time. Five steps were needed to prepare the mix beams for testing. The first step was to prepare gyratory compacted mix samples per standard compaction procedures. Second, the top 10 mm of the sample was cut to provide a smooth surface. Third, six 12-mm-thick slices of the sample were trimmed from the sample. Fourth, each slice was cut into seven 6- to 8-mm-thick bars. Last, the end of each bar was trimmed so that the final length of the rectangular beam was 101 mm long.

The results were obtained over a range of test temperatures. Measurements of the stiffness of the mixes without and with various percentages of RAP were used to construct blending charts to select the amount of RAP that can be used to obtain the desired mix stiffness.

Buttlar et al. (2004) evaluated various approaches for QC to determine the actual RAP content in HMA during production. The goal of this research was to identify and/or develop a method. Researchers initially conducted a survey of Illinois contractors to identify the current practices used for stockpiling, handling, and monitoring the rate of RAP proportions. The survey responses indicated that 89% of the contractors were capable of continual monitoring and recording of the amount of RAP used in the HMA. The cost of upgrading older plants varied widely, depending on the type of existing equipment and the desired complexity of the upgrades. Almost all contractors maintained at least one homogenous stockpile at the plant, which was constructed with RAP from pavements with the same gradation and surface from jobs built under state specifications. The contractors indicated that the RAP may be crushed, screened, or both crushed and screened before use. Based on the survey results, the researchers recommended that the DOT use contractors plant records and sampling of the RAP stockpiles for QC programs.

Several experimental test methods were evaluated for use in a QC testing program. The four methods were the ignition oven, partial solvent extraction, solvent extraction-recovery-testing of binder, and gradation-void analysis of compacted samples. Ignition oven chamber temperature profiles showed initial peaks as a result of the heat produced by the lighter fractions of the mix being burnt off first; however, current equipment limitations of oven heat generation did not allow for repeatable measurements. Future equipment improvements may provide sufficient control, but the current technology was not appropriate for QC of RAP HMA. The partial extraction assumed that an adequate portion of the RAP aggregates had a hardened inner coating of aged asphalt that was not easily removed, whereas the fresh binder was softer and more easily removed. Testing variables that were considered included the duration of solvent, rate of solvent flow through the mix, and the aggressiveness (e.g., solvent polarity and percent dilution) of the solvent. The extraction-recovery-testing procedure was the most commonly used but it was not considered a QC method because of the time required for all of the processing and testing.

Results led the researchers to conclude that the partial extraction method showed the most promise for a rapid QC method using a two-step extraction method. The first soak was 120 min in methylene chloride, followed by a second soak for 1 min in 85% methylene chloride.

Daniel and Lachance (2005) noted that the New Hampshire DOT allows for the use of 30% RAP from a known source, but only 15% RAP from an unknown source, in HMA. The objective of the research was to define how the use of RAP altered the volumetric properties as well as the dynamic modulus, and creep characteristics of the mixes. The processed RAP was obtained from rehabilitation of the entire pavement and can include HMA, portland cement, and some organic materials. The millings were obtained from resurfacing an old HMA pavement.

The RAP binder in the processed and milled materials were 3.6% and 4.9%, respectively, and the recovered binders graded as a PG 94-14 and a PG 82-22, respectively. The materials used in the study included two sources of RAP (processed and millings), four RAP percentages (0%, 15%, 25%, and 40%), and one HMA gradation (1 mm Superpave).

Results showed that the RAP HMA volumetrics for the control and 15% processed RAP mixes were similar, whereas the voids in mineral aggregate (VMA) and voids filled with asphalt (VFA) were higher than these two for the 25% and 40% RAP. The millings increased the VMA with increasing RAP content, and the VFA for RAP HMA was consistently higher than for the control. The effect of the heating time of the RAP on the mix properties was investigated using heating times of 2, 3.5, and 8 h before mixing. The 2-h heating time is the one typically used by the New Hampshire DOT. The air voids decreased by 0.5% when the RAP was heated for 3.5 h compared with the standard 2 h. At 8 h of heating, the VMA increased by about 3%. Researchers concluded that the shorter heating time was not allowing sufficient time for the RAP particles to be broken up during mixing. At the longer heating time, the RAP likely aged further and the RAP particles hardened sufficiently so that they were not easily broken up.

To evaluate the impact of RAP on HMA volumetrics, the laboratory heating times should reflect those used at the plant. Performance testing showed that the mix properties were influenced by changes in volumetrics and gradations. The dynamic modulus and creep compliance for the 25% and 40% RAP mixes were similar to those obtained for the control mix. The creep flow time increased with higher percentages of processed RAP. The 25% RAP was an anomaly in all of the testing, with values decreasing compared with the control.

Variability increased with increasing RAP content although the tensile strength testing variability was not as strongly influenced by RAP content as the dynamic modulus or creep compliance.

Shen et al. (2007) evaluated the effects of rejuvenators on RAP HMA properties. The materials used were two types of aggregates (granite and gneiss), two sources of RAP (one from each aggregate source), and two fractions of RAP for each source of RAP. The final binder target specification properties were set as a PG 64-22. The control mix used a fresh PG 64-22 and a PG 52-28 was used for the RAP HMA mixes without rejuvenator. One type of rejuvenator was used and the required percentage was determined using the blending chart process (Figure 5). The Superpave binder properties were obtained for three percentages of rejuvenator, graphed, and then used to determine the percentage of rejuvenator needed to achieve the required combined binder properties. The percentage of RAP was estimated using the equation:

$$\%\text{RAP} = \left(T_{\text{Blend}} - T_{\text{Virgin}}\right) / \left(T_{\text{RAP}} - T_{\text{Virgin}}\right)$$

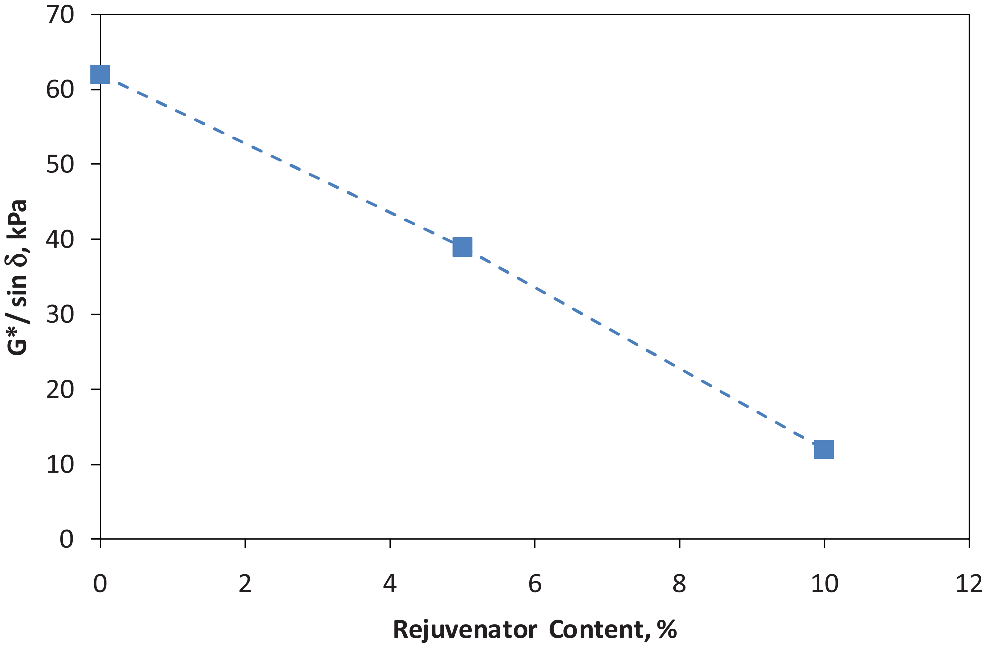


FIGURE 5 Example of how blending chart is used to select the appropriate amount of rejuvenator (after Shen et al. 2007).

Where:

$\%RAP$ = the percent RAP in the mixture in decimal form,
T_{Virgin} = critical temperature of virgin binder (PG 58-22 in this study),
T_{Blend} = critical temperature of blended binder (PG 64-22 in this study),
T_{RAP} = critical temperature of extracted RAP binder.

Blending charts for each of the Superpave binder properties were used to provide estimates of the required rejuvenator percentages needed for the RAP HMA. When the softer PG binder was used as the softening agent, only 30% and 38% for the two RAP sources could be used in the mix. When the rejuvenator was used as the softening agent, 40% and 48% RAP could be used. The amount of RAP that could be used in the mix and still obtain similar mix binder properties increased significantly when the rejuvenator was used.

Mix design parameters were developed for the various RAP HMA mixes (Table 13). Testing showed Superpave mixes containing RAP and a rejuvenator produced indirect tensile strengths and rutting performance similar to or better than mixes using only the softer binder. The percent of RAP used in the mix could be increased when using a rejuvenator and still obtain similar mechanical properties to those for mixes using only a softer binder grade.

Bartoszek (2008) described an example using the Advera warm mix technology with RAP HMA. The project was constructed for the city of Milwaukee public works in early November 2007. The project placed a 19 mm E-1 Superpave base layer and a 12 mm surface layer, both using a PG 64-22 and 25% RAP. In addition, the RAP was fractionated for better control on the RAP gradation. The mix was produced at a temperature of 50°F lower than typical, resulting in fewer emissions and less heat hardening of the binder. Comments noted improved workability of the RAP HMA even with the cool paving temperatures, which were in the 40s.

Construction variations were needed to obtain the desired aggregate drying at the lower plant temperatures. Infrared temperature profile information was wired into the plant control so that real-time measurements of the mix temperature

TABLE 13
RESULTS FOR 9.5 MM SUPERPAVE MIXES USING EITHER FRESH ASPHALT OR REJUVENATOR AS SOFTENING AGENT

Information		Aggregate Source C						Aggregate Source L					
Sieve	Spec. Limit	CV0	CV15	CR15	CV38	CR38	CR48	LV0	LV15	LR15	LV30	LR30	LR40
12.5 mm	98–100	100	100	100	100	100	98	100	100	100	100	100	100
9.5 mm	90–100	91	90	90	90	90	88	95	94.2	94.2	94	94	95
4.75 mm	54–70	61	58	58	59	59	58	53	62.7	62.7	57	57	61
2.36 mm	32–48	42	41	41	40	40	39	32	42	42	35	35	40
0.6 mm	14–26	21	21	21	21	21	21	18	24.7	24.7	21	21	25
0.15 mm	13–5	8.4	7.8	7.8	8.1	8.1	8.7	5.7	8.3	8.3	9.3	9.3	10.6
0.075 mm	9–3	4.95	4.4	4.4	4.62	4.62	5.11	5.02	4.5	4.5	5.5	5.5	5.9
Aggregate Blend, % Passing													
Stone789		50	49.2	49.15	31.4	31.4	25	69	52.9	52.85	59.3	59.3	50
Regular screenings		18	10	10	5	5	4	25	12	12	10	10	4
Manufactured screenings		31	25	25	25	25	20	5	19	19	0	0	5
Lime		1	0.85	0.85	0.6	0.6	1	1	0.85	0.85	0.7	0.7	1
−4.75 mm RAP		0	9	9	0	0	0	0	9	9	18	18	24
+4.75 mm RAP		0	0	6	6	0	0	0	6	6	12	12	16
+ 2.36 mm RAP		0	0	0	38	38	48	69	52.9	52.85	59.3	59.3	50
Test Results													
% VMA	15.5–17.5	16.2	15.8	15.6	15.5	15.6	15.5	16.6	15.8	15.9	15.5	15.6	15.7
% VFA	70–80	72.5	76.1	75.0	71.9	72.0	74.5	76.2	76.1	74.5	71.9	70.0	72.0
% Max. density at N_{des}	96	95.5	95.9	96.0	95.8	96.0	96.0	94.9	95.9	96.0	95.8	96.0	96.0
% Max. density at N_{ini}	<89	88.0	88.4	88.0	88.5	88.3	88.2	87.0	88.4	89.0	88.5	88.3	87.8
% Max. density at N_{max}	<98	96.5	97.1	96.5	96.9	97.2	97.3	96.1	97.1	97.0	96.9	97.4	97.0
Dust-to-asphalt ratio	0.6–1.2	0.95	0.83	0.89	0.94	0.92	1.05	0.91	0.83	0.90	0.94	1.13	1.18
Optimum binder content %		5.02	5.30	4.93	5.05	5.01	4.87	5.50	5.40	88.50	4.90	4.80	4.85

After Shen et al. (2007).
C = aggregate source C; L = aggregate source L; V = virgin binder; R = rejuvenator; 0, 15, 38, 48 = % RAP.

during construction could be obtained. The mat temperature took about 1.5 h to cool from 245°C to 120°C even at the cool ambient temperature. Required in-place densities were obtained with standard compaction equipment.

Maupin et al. (2008) noted that the Virginia DOT (VDOT) usually allowed a maximum of 20% RAP in HMA. This study considered allowing up to 30% RAP in HMA without a change in the fresh binder grade. This decision was made to provide a lower cost for the HMA mix. Several projects were constructed with 30% RAP, which resulted in six contractors placing a total of 129,277 tons of mix. Considerations in developing bids for high RAP content mixes assumed that allowing RAP as an additional mix design option would not increase HMA costs; however, requiring RAP use could end up increasing costs, depending on RAP availability. The agency estimate of cost showed a potential reduction in the unit price of HMA of $7.55 per ton if the “allowed” wording was used, but only $2.98 per ton if the “required” wording was used. The agency analysis also indicated that an increased number of bidders on the projects would result in a further savings.

Once the bids were received, an analysis of the bid data showed that there was not a statistically significant reduction in the cost of HMA with the higher 30% RAP content when compared with the previously used maximum of 20% RAP. Only three projects were bid at the 30% RAP content.

Seven other high RAP content projects were constructed as a result of value engineering. These projects suggested that at least in some cases a cost savings could be realized. The cost savings by the contractors needed to be at least $18,977 per project to make it worthwhile for value engineering. If the cost savings was smaller than this, the use of a higher RAP content was not economically attractive to the contractor.

Al-Qadi et al. (2009) noted that the Illinois DOT currently assumes that 100% of the RAP binder combines with fresh binder in RAP HMA mixes. This study evaluated the correctness of this assumption by using a combination of binder and mix tests. The initial testing showed that the dynamic modulus measurements of the mix were not sufficiently sensitive to identify the amount of partial blending of the RAP and fresh binder. The fracture energy evaluated at low temperatures showed that RAP reduced the fracture energy, which indicated that mixes with RAP will show thermal cracking at warmer temperatures compared with the control mixes. However, variations in the test results made it difficult to see subtle changes in mix properties.

Results from the binder testing using various percentages of recovered RAP and fresh binder showed that significant PG binder property changes were not seen at a level of 20% RAP binder; however, at 40% RAP, the PG grade of the fresh binder needed to be reduced by one temperature grade.

Xiao et al. (2009) evaluated the use of recycled tire crumb rubber in RAP HMA mixes. Materials used in the study included one level of crumb rubber content (10%), three sizes of crumb rubber (Nos. 40, 30, and 14), two types of grinding (ambient and cryogenic), two RAP fractions (+4.75 mm and −4.75 mm), 25% RAP, 9.5 mm Superpave HMA mix, and one PG 64-22 fresh binder. Testing focused on measurements of volumetrics for Superpave mix designs, and indirect tensile strength and toughness, resilient modulus, loaded wheel rutting, and beam fatigue.

Results showed that the volumetrics were not significantly dependent on the crumb rubber size; however, the type of grinding showed some differences. Cryogenic ground crumb rubber resulted in a slight increase in VMA, VFA, and optimum binder content (Table 14). The combination of RAP and crumb rubber increased the resilient modulus. Ambient ground crumb rubber slightly increased the resilient modulus compared with cryogenic ground rubber. The rutting resistance was substantially improved regardless of the type or size of crumb rubber. The conclusion was that the combination of crumb rubber and RAP helped compensate for the loss of fatigue life typically seen in RAP HMA without the crumb rubber.

Zeyher (2009) reported on a 2.8-mile-long pilot project on I-44 in Franklin County, Missouri, near Six Flags over Mid-America. The roadway was three lanes of an old portland

TABLE 14
PROPERTIES OF HMA WITH AND WITHOUT RAP AND CRUMB RUBBER

Properties		10% Crumb Rubber with Various Sizes							
		Control	No Rubber	40 Mesh		30 Mesh		14 Mesh	
				Ambient	Cryogenic	Ambient	Cryogenic	Ambient	Cryogenic
Bulk Specific Gravity		2.345	2.364	2.339	2.362	2.352	2.332	2.348	2.347
Voids in Mineral Aggregate, %		16.6	14.7	15.6	16	15.7	15.8	15.6	17.1
Voids Filled with Asphalt, %		73.9	74.4	73.7	75.3	73.1	41.1	75.8	76.5
Opt. Binder Content, %		5.4	4.7	5.08	5.35	5.08	5.18	5.23	5.8
Tensile Strength Ratio, %		81	88	107	99	93	113	96	96
Toughness, %	Dry, N/mm	3.3	3.1	3.1	3	3	2.9	3.1	3
	Wet, N/mm	2.8	2.8	3	2.9	3	2.8	3	3.1

After Xiao et al. (2009).

cement concrete (PCC) pavement with an HMA overlay, with approximately 12,000 average daily traffic (ADT) and about 6.3% truck traffic. An Evotherm warm mix overlay material with 20% RAP was placed at a temperature of 250°F and the control HMA at 340°F. Both were produced with a PG 70-22 binder. Roller patterns were the same and densities were achieved in both sections. Compaction used five passes of a 12-ton vibratory breakdown roller, five passes with an intermediate vibratory roller, and finish rolling with five passes in the static mode. Performance of the sections will be monitored in the coming years.

Copeland (2010) reported on the state of the art for agency considerations when using RAP in asphalt concrete applications. Agencies noted that material costs were approximately 70% of the asphalt production categories. About 15% of the cost to the agencies was for trucking, 10% for plant production, and 5% for laydown. With the recent high asphalt cement costs and diminishing sources of high-quality natural aggregates, both contractors and agencies have increased motivation for using higher percentages of RAP in mixes.

As of 2008, most states allowed up to 10% RAP in either intermediate or surface layers. No state used 30% or higher RAP in the surface course and fewer than 5% allowed more than 30% in the intermediate layers. The report listed the factors preventing higher allowable percentages from being used as:

- Specification limits;
- Lack of RAP processing, which contributes to the RAP variability;
- Lack of RAP availability; and
- Past experiences.

Barriers for the agencies included:

- Quality concerns,
- Consistency of RAP,
- Selection of binder grade and blending,
- Mix design procedures,
- Volumetric requirements,
- Durability and cracking performance, and
- Use with polymers.

Barriers listed by the contractors included:

- State specifications,
- Control of RAP,
- Dust and moisture content, and
- Increased QC testing.

Good stockpiling practices helped with some of these limitations and barriers. Good stockpiling practices included creating arc-shaped, uniformly layered stockpiles for milled or unprocessed RAP. Conical or small, low-sloped piles are preferred for processed RAP. All of the stockpiles are to be placed so that there is sufficient drainage, because RAP does not drain as well as natural aggregates. High moisture content slowed down production because of the additional drying time needed. If the RAP was not sufficiently dry, there could be durability problems with the pavement. Ideally, separate stockpiles would be developed for each source of RAP to minimize material variability.

Processing the RAP into two or more sizes (fractionation) helped reduce variability in the final mix gradations and asphalt contents. A two-size fractionation separated the RAP into coarse and fine byproducts. Three-size fractionation produced oversize, coarse, and fine RAP stockpiles. Crushing before separation could be an additional help in reducing material variations.

Copeland (2010) also reported on the use of high RAP content. Information was collected from the FHWA Expert Task Group for RAP use. North Carolina DOT conducted a survey of agencies in 2007 to collect information about the use of high RAP mixes. Figure 6 shows the findings from this survey. The more than 30 agencies reported using up to 19% in the intermediate and surface layers. A number of additional agencies indicated the potential for increasing the amount of RAP up to 29%. No agencies were using more than 29% in the surface mixes.

Information was summarized for stockpiling processing, mix designs, performance, cost, and barriers. When stockpiles contained large chunks of old pavement, the material was crushed to a useful top size particle size. Crushing helped improve consistency when multiple sources of RAP were combined into one stockpile and contractors tended to crush the RAP so that the top size particle was small enough to be used in any specified gradation. However, crushing to smaller top sizes also increased the dust content, which then limited the amount of RAP that could be used. Recommendations were to crush and size the RAP before introduction into the plant. Operations that combined crushing, screening, and feeding into the plant in one operation were not recommended because of limitations on the ability to determine RAP properties prior to production. Once crushed and sized, normal good stockpiling practices can be used and RAP stockpiles be periodically skimmed to break lumps.

Stockpiles that were managed by sizes were thought to provide a more consistent (less variable) RAP byproduct. Size separation, referred to as fractionation, and was defined as the act of processing and separating RAP into at least two sizes, typically a coarse fraction that is retained on the 12.5 or 9.5 mm (½ or ⅜ in.) sieve and a fine fraction passing these sizes. A 2008 survey by the Ohio DOT, which collected responses from 29 states, noted that three states had specifications for fractionating RAP, and three states were in the process of drafting specifications for fractionation. These states allowed a higher percentage of RAP when the RAP was fractionated. By 2009 and the North Carolina DOT

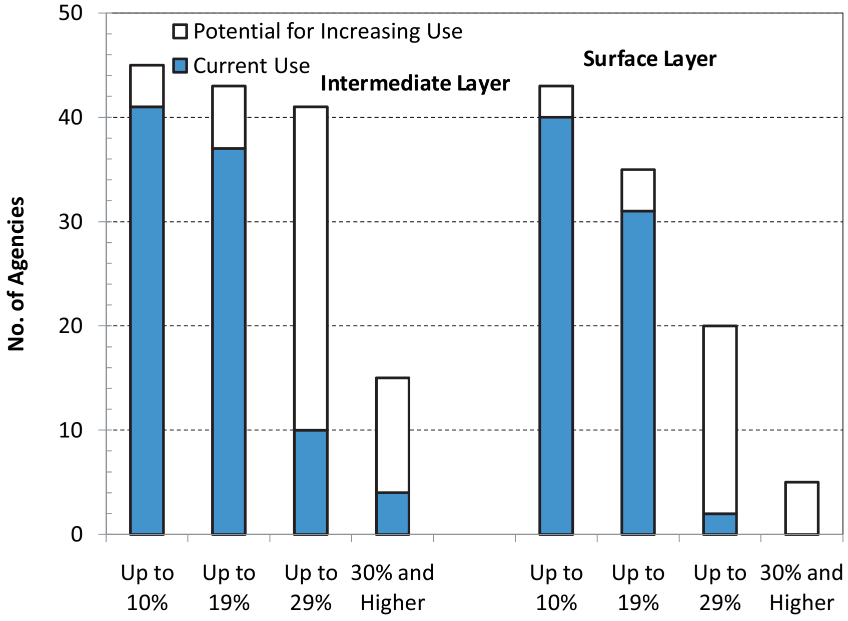


FIGURE 6 Use of high RAP mixes from 2007 NCDOT survey (after Copeland 2010).

survey, 10 agencies were requiring fractionation. Ten states allowed a 5% increase in RAP when it was fractionated. Research by National Center for Asphalt Technology for the contractors indicated no significant reduction in variability noticeable as a result of fractionating the RAP.

Materials characterizations needed for mix design information was collected from the 2008 Ohio DOT survey that showed that the ignition oven was the most commonly used method for determining the asphalt content of the RAP. About 30% of the respondents indicated they used both solvent extraction and the ignition oven. The Superpave PG binder and volumetric mix design methods were the most commonly used methods for design purposes. Six of 25 respondents indicated they also used either Marshall or Hveem mix designs. Most agencies used a limit of 20% RAP before going to a softer grade of virgin binder for RAP mixes. Although a number of agencies have used WMA, as of 2009 few states had used a combination of WMA and RAP. Volumetric considerations for mix designs addressed calculations for binder content, binder properties, and aggregate properties. When RAP binder needed to be recovered for testing, the AASHTO T319 was recommended because it had the least tendency to further age the RAP binder. RAP aggregate requirements for the mix were generally required to meet the virgin aggregate requirements.

The results from previous research on the performance of high RAP content mixes was included in the report. Table 15 summarizes the reported information.

The 2007 survey found that 18 of 23 FHWA respondents did not pay for asphalt cement separately from the mix. Other variations of payment were based on paying for the residual RAP binder at the same rate as for virgin asphalt, binder as a separate line item accounted for at the mix design phase, or indexed based on virgin asphalt.

TABLE 15
SUMMARY OF PERFORMANCE OF HIGH RAP MIXES

Project Info.	No. of Projects or Test Sections	Age, Years	Percent RAP	Performance Conclusions
NCAT	Not noted	1 to 3	10% to 40%	Similar to conventional HMA
Louisiana		6 to 9	20% to 50%	Similar to conventional HMA
LTPP (NCAT)	18 Projects	6 to 17	30% (most projects)	Similar to conventional HMA
LTPP (FHWA)	18 Projects	Not noted	30% (most projects)	Similar to conventional HMA
Texas	5 Sections	16	35%	Higher cracking, less rutting, similar ride quality
California	47 Sections 3 climate zones	Not noted	15%	Similar to conventional HMA
Florida	Not noted	Not noted	30% to 50%	11 years of life for conventional HMA 10 to 13 years of life for RAP mixes

After Copeland (2010).

UNBOUND APPLICATIONS: BACKFILL

A mechanically stabilized embankment (MSE) wall is a vertical or nearly vertical earth retaining structure consisting of three major components: a facing panel, earth reinforcement, and a reinforced backfill. The retaining ability of the structure is obtained by the interaction between the soil and earth reinforcement. MSE design and performance focus on providing internal and external stability of the wall. External stability depends on the geometry of the entire wall system. Potential failure mechanisms focus on resistance sliding, overturning potential, bearing capacity, and deep-seated stability. Internal stability focuses on the interaction between the reinforcing elements and the backfill. Critical material properties for MSE walls include hydraulic conductivity, shear strength parameters, interface friction, compaction characteristics, compressibility of compacted materials, time-dependent effects (i.e., creep), and corrosivity.

Rathje et al. (2001) evaluated the use of RAP and RCA for use in MSE applications and concentrated on the impact of the recycled materials on the durability of geosynthetic and metallic reinforcements. Polymeric reinforcement needed to be designed to resist most forms of degradation and provide adequate performance. RAP from mixes with a tendency to show continued loss of asphalt in the presence of water (i.e., stripping, contact between the backfill and reinforcement) should be avoided.

Metallic reinforcement was influenced by a range of backfill properties including resistivity, pH, differential environment, water hardness, soluble salts, redox potential, texture, moisture content, dissolved oxygen, and organic content. Although RAP may contain some deicing chemical salts, the content was limited as compared with RCA chemistry and was not considered a problem for long-term durability. The pH was typically around 8, which was considered satisfactory for MSE walls, and the resistivity values ranged between 2,640 and 4,830 ohms-c.

It is important that the shear strength properties of the RAP provide stability and adequate interaction with the reinforcement. Backfill needs to be well compacted so that the optimum shear strength, and internal friction, and minimum long-term deformation are obtained. Backfill material needs to be free draining so that water pressure does not build up behind the wall. For free-draining backfill material, effective stress shear strength parameters are used in the design. If the backfill held water, then undrained shear strength parameters need to be used. Backfill material that could breakdown during construction or compaction to generate addition fine materials could lower hydraulic conductivity and change the shear strength parameters.

Creep deformation could inhibit the development of forces in the reinforcement. Poorly compacted materials settle, which could result in potentially critical deformations. Texas DOT and FHWA specification requirements for backfill are shown in Table 16.

The internal friction angle needed to be considered for calculating the pullout capacity of the reinforcement. High angularity and a well-graded aggregate provided the best internal friction angle. Moisture content could also influence the pullout capacity. Texas DOT backfill requirements are also shown in Table 16.

Additional research by Rathje et al. (2002) continued to explore the backfill properties of RAP used as an MSE backfill. The laboratory testing included triaxial testing to determine the cohesion and angle of internal friction, and corrosive potential. Short-term testing soaked each of the materials in water, and then the water was decanted and

TABLE 16
EXAMPLE OF SPECIFICATION REQUIREMENTS FOR MSE BACKFILL

Requirement		TxDOT (Type A)	TxDOT (Type B)*	FHWA
Gradation	Maximum size	3 in.	6 in.	4 in.
	Percent passing sieve 3 in.	—	75–100	—
	Percent passing sieve No. 40	0–60	—	0–60
	Percent passing sieve No. 200	0–15	0–15	0–15
Plasticity Index (PI)		—	—	<6
Compaction	Dry density	95% (Tex-114-E)	Not specified	95% (AASHTO T-99)
	Moisture content	±2% of W_{opt}		within 2% dry of W_{opt}
pH		5.5–10		5–10
Resistivity (ohm-cm)		>3000		>3000

After Rathje et al. (2001).
*Type B backfill that does not meet the sieve No. 200 requirement may be used if:
- Less than 25% passes sieve No. 200
- PI ≤ 6
- At 95% dry density (Tex-114-E) and W_{opt}, $\varphi \geq 34°$ (Tex-117-E).

TABLE 17
SUMMARY OF DRAINED STRENGTH PROPERTIES

Measurements	Control	RCA	RAP
Effective Confining Pressure Range (psi)	12–40	12–37	12–45
Effective Stress Friction Angle, φ′	55°	54°	39°
Effective Cohesion, c′ (psi)	0	0	8

After Rathje et al. (2002).

used as an electrolyte in a corrosion cell. Preliminary results (64 days) did not show statistically different corrosive potentials.

The triaxial testing showed that the RAP generated a small cohesive value as a result of the asphalt particles adhering together, but the lowest angle of internal friction (Table 17). Field density measurements were made using a nuclear gauge and the rubber balloon volumetric methods (Table 18). The nuclear readings showed higher densities than the volumetric methods.

The nuclear gauge also showed higher readings for moisture content than measurements obtained with oven drying (Table 18). The differences were not linear; therefore, it may be necessary to use the oven drying method for moisture content determination. The conclusion was that correlation curves were needed for each project.

Carley (2002) evaluated the use of RAP and RCA as backfill for MSE walls. Recycled materials were compared with traditional crushed limestone. Results showed that the RAP provided adequate strength and hydraulic conductivity for use in MSE walls. The RCA also provided adequate strength but had a relatively low hydraulic conductivity. QC testing needed additional sampling and testing of the recycled stockpiles to account for the increased material variability.

SUMMARY OF RECLAIMED ASPHALT PAVEMENT INFORMATION

List of Candidate Byproducts

The majority of the RAP was recycled back into fresh HMA concrete paving materials because of the savings over the cost of virgin asphalt cement. The two methods of using RAP in central plant processes were the production of hot and cold asphalt mixes.

Test Procedures

AASHTO and ASTM test methods used for evaluating RAP and application properties are shown in Tables 19 and Table 20, respectively.

Material Preparation and Byproduct Quality Control

Material preparation can include separation of RAP sizes (fractionation) to make it easier to control the final mix gradation. RAP stockpiles were commonly tested to determine the asphalt content, aggregate gradation, and other aggregate properties as required by specifications.

Materials Handling Issues

Good stockpiling practices included protection to minimize moisture content, and additional crushing and screening to provide more consistent and uniform properties. The moisture content is to be kept as low and consistent as possible. Crushing and screening can be completed prior to use in the central plant so that the stockpile properties can be obtained. Occasional skimming of the stockpile may be needed to break up lumps of RAP.

Transformation of Marginal Materials

The use of rejuvenators had the potential for allowing for a higher RAP content in an HMA mix while still achieving the desired combined binder properties needed for good

TABLE 18
RESULTS FOR FIELD DENSITY TESTING OF BACKFILL MATERIALS

Statistics	Ratio of Nuclear Density to Balloon Density			Ratio of Nuclear Moisture to Oven Drying Measurement		
	Control	RCA	RAP	Control	RCA	RAP
Average	1.19	1.19	1.08	0.99	1.19	3.07
Standard Deviation	0.06	0.13	0.05	0.12	0.10	0.69
Min. to Max. Values	1.11 to 1.28	1.06 to 1.48	1.01 to 1.14	0.84 to 1.19	1.03 to 1.33	2.36 to 4.51

Rathje et al. (2002).

TABLE 19
AASHTO TEST METHODS

AASHTO M320	Standard specification for performance-graded asphalt binder
AASHTO PP19	Standard practice for volumetric analysis of compacted hot mix asphalt
AASHTO R30	Standard practice for mixture conditioning of hot mix asphalt
AASHTO T164	Quantifiable extraction of bitumen from bituminous paving mixtures
AASHTO T166	Bulk specific gravity of compacted hot mix asphalt mixtures using saturated surface dry specimens
AASHTO T170	Standard method of test for recovery of asphalt binder from solution by Abson method
AASHTO T180	Standard method of test for moisture density relations of soils using a 4.54 kg (10 lb) rammer and a 457 mm (18 in.) drop
AASHTO T209	Theoretical maximum specific gravity and density of hot mix asphalt paving mixtures
AASHTO T240	Test method for effect of heat and air on a moving film of asphalt (rolling thin film oven test)
AASHTO T283	Standard method of test for resistance of compacted for mix asphalt (HMA) of moisture induced damage
AASHTO T312	Standard method of test for preparing and determining the density of hot mix asphalt (HMA) specimens by means of the Superpave gyratory compactor
AASHTO T313	Standard method of test for determining the flexural creep stiffness of asphalt binder using the bending beam rheometer (BBR)
AASHTO T315	Test method for determining rheological properties of asphalt binder using a dynamic shear rheometer
AASHTO T319	Quantitative extraction and recovery of asphalt binder from asphalt mixtures
AASHTO T321	Standard method of test for determining the fatigue life of compacted hot mix asphalt (HMA) subjected to repeated flexural bending
AASHTO T322	Determining the creep compliance and strength of hot mix asphalt (HMA)
AASHTO T99	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
AASHTO TP2	Method for the quantitative extraction and recovery of asphalt binder from hot mix asphalt (HMA)
AASHTO TP31	Standard test method for determining the resilient modulus of bituminous mixtures by indirect tension
AASHTO TP62	Standard method of test for determining dynamic modulus of hot mix asphalt (HMA)
AASHTO TP7	Standard test method for determining the permanent deformation and fatigue cracking characteristics of hot mix asphalt (HMA) using the simple shear test (SST) device
AASHTO TP9-96	Standard test method for determining the creep compliance and strength of hot mix asphalt (HMA) using the indirect tensile test device

long-term performance. The use of crumb rubber and RAP in HMA had some potential for mitigating increased brittle behavior of the mix.

Design Adaptations

In general, HMA projects used standard highway application project designs. Standard laboratory mix designs were also used for HMA concrete.

Cold mix tended to increase in volume more than conventional HMA; therefore, additional material may be needed to achieve the desired layer thickness. There were a range of different methods that had been developed for use in designing cold mix products.

Construction Issues

One agency recommended that mix variability could be reduced by recommending ranges of moisture and preheat levels for RAP. Care needed to be taken during the mixing of cold RAP mixes so that over-mixing was avoided. Cold mixes with the proper moisture contents could be placed with conventional paving equipment and operations. Mix property variability tended to increase with increased RAP content; therefore, an increased number of samples were needed for process control and assurance. The use of WMA technologies improved the workability of RAP HMA.

If RAP was used as backfill in an MSE, it needed to be well compacted so that deformation was minimized and adequate contact with the reinforcement was obtained. The lower angle of internal friction needed to be considered in calculating the pullout capacity of the reinforcement. Density measurements of RAP backfill could be accomplished with standard nuclear gauges as long as the readings had been correlated with a standard laboratory compaction measurement as the nuclear gauge readings tended to report higher than actual densities. Correlation curves were needed for each project.

Failures, Causes, and Lessons Learned

The major problem noted when using RAP in central plant recycling was that too much RAP without the proper adjustment to the selection of the fresh binder grade could result in accelerated fatigue and thermal cracking.

TABLE 20
ASTM TEST METHODS

ASTM D1193	Standard Specification for Reagent Water
ASTM D4253	Standard Test Method for Maximum Index Density and Unit Weight of Soils Using a Vibratory Table
ASTM D7313	Standard Test Method for Determining Fracture Energy of Asphalt-Aggregate Mixtures Using the Disk-Shaped Compact Tension Geometry
ASTM C1012	Standard Test Method for Length Change of Hydraulic Cement Mortars Exposed to a Sulfate Solution
ASTM C127	Standard Test Method for Specific Gravity and Absorption of Coarse Aggregate
ASTM C1293	Standard Test Method for Determination of Length Change of Concrete Due to Alkali Silica Reaction
ASTM C33	Standard Test Method for Direct Shear Test of Soils Under Consolidated Drained Conditions
ASTM C452	Standard Test Method for Potential Expansion of Portland Cement Mortars Exposed to Sulfate
ASTM D1557	Standard Test Methods for Laboratory Compaction Characteristics of Soils Using Modified Effort
ASTM D1566	Standard Test Methods for Density and Unit Weight of Soil in Place by the Sand Cone Method
ASTM D1856	Standard Test Method for Recovery of Asphalt from Solution by Abson Method
ASTM D1883	Standard Test Method for CBR of Laboratory Compacted Soils
ASTM D2167	Standard Test Methods for Density and Unit Weight of Soil in Place by the Rubber Balloon Method
ASTM D2172	Standard Test Method for Quantitative Extraction of Bitumen from Bituminous Paving Mixtures
ASTM D2434	Standard Test Method for Permeability of Granular Soils (Constant Head)
ASTM D2435	Standard Test Method for One-Dimensional Consolidation Properties of Soils
ASTM D2922	Standard Test Methods for Density of Soil and Soil Aggregate in Place by Nuclear Methods (Shallow Depth)
ASTM D2950	Standard Test Methods for Density of Bituminous Concrete in Place by Nuclear Methods
ASTM D3080	Standard Test Method for Direct Shear Test of Soils Under Consolidated Drained Conditions
ASTM D4125	Standard Test Method for Determining Bitumen Content in Bituminous Paving Mixtures by Use of Ignition Oven
ASTM D422	Standard Test Method for Particle Size Analysis of Soils
ASTM D4254	Standard Test Methods for Minimum Index Density and Unit Weights of Soils and Calculation of Relative Density
ASTM D4972	Standard Test Method for Ph of Soils
ASTM D5030	Standard Test Method for Density of Soil and Rock in Place by the Water Replacement Method in a Test Pit
ASTM D5311	Standard Test Method for Load Controlled Cyclic Triaxial Strength of Soil
ASTM D5333	Standard Test Method for Measurement of Collapse Potential of Soils
ASTM D5520	Standard Test Method for Laboratory Determination of Creep Properties of Frozen Soils Samples by Uniaxial Compression
ASTM D698	Standard Test Methods for Laboratory Compaction Characteristics of Soils Using Standard Effort
ASTM D854	Standard Test Method for Specific Gravity of Soil Solids by Water Pycnometer
ASTM D979	Standard Practice for Sampling Bituminous Paving Mixtures
ASTM G51	Standard Test Method for Measuring Ph of Soil for Use in Corrosion Testing
ASTM G57	Standard Test Method for Field Measurement of Soil Resistivity Using the Wenner Four Electrode Method

Barriers

The barriers to increased usage (i.e., percent of RAP in mix) were:

- Lack of long-term performance data for high RAP content mixes
- Lack of confidence in long-term performance of high RAP mixes
- Lack of agency experience
- Lack of confirmed cost savings
- Contractor concerns with meeting specification requirements at higher RAP contents
- Contractors using more RAP than design requirements
- How to pay for RAP binder in HMA
- Lack of availability
- Lack of experience with RAP and polymer-modified binders
- Lack of experienced contractors
- Lack of stockpile homogeneity
- Potential presence of coal tar in old pavements
- Unknown influence of RAP on binder properties at higher RAP contents.

Costs

Fuel costs were a major component in producing and placing asphalt concrete mixes. Warm mix technologies decreased energy consumption by 4%. Using only 10% RAP resulted in a 6% reduction. About 13% less energy was needed to produce and place the lower lifts (i.e., binder course). Increasing the amount of RAP in the HMA increasingly reduced the energy use. Using 50% RAP in HMA applications reduced energy consumption by about as much as cold mix asphalt pavements.

Increasing the allowable RAP content from 20% to 30% resulted in a statistically significant cost savings and at least three bids were needed to notice cost savings in the bids. More benefits were seen when higher RAP contents were considered as value engineering. A minimum threshold of cost savings to the contractor was needed before increased RAP content was considered economically attractive.

It was difficult to assess the cost savings when agencies did not pay for asphalt cement separately from the mix as a bid item. Other variations of payment for RAP binder and RAP aggregate were based on paying for the residual RAP binder at the same rate as for virgin asphalt, paying binder as a separate line item, accounting for binder changes at the mix design phase, or indexing based on virgin asphalt.

Gaps

The following gaps were identified:

- Recent emphasis on reducing greenhouse gas emissions will require more advanced environmental assessments of the benefits of using RAP in highway applications.
- A more inclusive environmental system is needed to capture emissions benefits.
- There is a need for repeatable performance testing and specification limits for those performance tests.
- Test methods are needed for QC practices for determining the actual amount of RAP in the mix, the combined binder properties in the final mixes.
- Performance data for high RAP content mixes is needed.
- Standardized methodology for selecting fresh asphalt or rejuvenator grade and quantities is needed.
- QC tests and procedures to address the variability in RAP asphalt content, moisture content, combined aggregate properties, and mix volumetrics are needed.
- Use of RAP in stone matrix asphalts and open graded friction courses is not allowed by at least two states. RAP in these mix gradations could be explored.

CHAPTER FIVE

RECYCLED CONCRETE AGGREGATES

FHWA (2004) limited the definition of RCA to PCC byproduct obtained from the removal of old PCC pavements, bridge structures/decks, sidewalks, curbs, and gutters and that have the steel removed from the old concrete. The specific definition is:

> Recycled concrete aggregate is a granular material manufactured by removing, crushing, and processing hydraulic-cement concrete pavement for reuse with a hydraulic cementing medium to produce fresh paving concrete. The aggregate retained on the 4.75 mm sieve is called coarse aggregate and the material passing the 4.75 mm sieve is called fine aggregate.

One of the main advantages to using these sources for RCA is that state projects historically use high-quality aggregates with consistent properties defined in state specifications. High-quality and durable old concrete may be useful in new structural PCC applications, while lower quality old concrete may be more useful in subbase or fill applications (ACPA 2008). Commercial construction debris might be useful as RCA; however, state agencies prefer to reuse material recovered from either state projects or known sources of supply. Construction debris RCA can have contaminates such as bricks, wood, steel, ceramics, and glass (discussed as a separate category in this chapter).

The Construction Material Recycling Association (2009) indicated RCA can be used to:

- Provide high-quality material in some highway applications
- Provide aggregate acceptable by ASTM and AASHTO standards
- Produce concrete and asphalt products
- Provide improved base and subbase materials
- Reduce haul and material costs
- Reduce landfill waste streams
- Minimize environmental impacts.

An example of reduced landfill disposal, provided by FHWA (2004), noted that one lane-mile of 10-in. thick PCC pavement requires about 2,000 yd^3 of PCC, which uses approximately 3,000 tons of coarse and fine aggregate. The same lane-mile of pavement can produce about 4,000 tons of RCA at the end of the pavement life for using as RCA. This also saves energy by reducing the need for mining or extraction of aggregate and haul distances. All of these factors result in reduced energy and fuel consumption that can be seen as reductions in greenhouse gases. Recycling old PCC as aggregate also results in the removal of CO_2 from the air when the fresh RCA reacts with the calcium hydroxide. The rates of carbonation increase with increasing humidity, temperature, and RCA surface area.

PROCESSING

One of the keys to recovering old PCC for use as RCA is in the initial processing that involved:

- Removal of as many potential contaminates before demolition of PCC as possible
- Demolition of PCC structure
- Crushing and sizing RCA
- Secondary removal of contaminates
- Removal of dust and fines
- Washing (optional but desirable)
- Stockpiling under consistent moisture conditions.

The ACPA (2008) provided guidance for recycling pavement PCC into RCA. The recycling started with the removal of potential contaminates such as HMA shoulders, patches, or crack sealants. No more than 10% contaminants were recommended by ACPA, although agencies and other countries have various limitations. For example, Minnesota allowed no more than 3% asphalt binder by weight of aggregate, whereas in California there was no limit on RAP in RCA. In Australia, as much as 20% HMA byproducts were allowed when lower quality RCA was produced. Removal of motor oils and other surface contaminants needed to be considered. These surface contaminates were reported as limited to the upper few millimeters of the pavement surface.

Pre-crushing preparation needed to consider the maximum feed size needed for crusher and how much steel, wood, dirt, and other contaminates need to be removed before crushing (CMRA 2009). Primary jaw crushers typically produced 4 to 8 inch minus crushed materials that could be used as fill. Impact crushers used a spinning rotor with bars or hammers that threw the concrete into solid objects (plate or plates) and produced 2 in. minus recycled materials that could be further reduced in size in primary, secondary, or tertiary crushers. Cone crushers are compression crushers and reduced 6 in. minus feed stalk to 1.5 in. minus recycling material and were typically used as secondary crushers.

Crushing, sizing, and removal of contaminates of the old concrete was accomplished with portable, mobile, or stationary recycling plants (CMRA 2009). Mobile plants were track-mounted and moved from site to site. Portable plants consist of a crusher and a feeder (loader or backhoe) selected to produce the required RCA specification properties. Portable crushers were usually mounted on rubber tired chassis, towed to the site, and moved around with loaders or tugs. Mobile crushers had their own track-mounted drive system. Stationary crushers were permanently fixed to the ground and the material was trucked to the site. Old PCC with 30 in. minus initial feedstock was reduced to 1.5 in. minus RCA.

The old slab needed to be sufficiently broken so that the concrete was debonded from the reinforcing and dowel bars and the old concrete could be lifted out of the pavement and the steel mesh, rebar, and dowel bars removed. Any metals left in the concrete were removed with magnets placed over the feeder belt into the secondary crusher. Air blowing through the crushed concrete helped remove any lightweight contaminates and dust. Crusher dust was considered a contaminate when present in sufficient quantities. Closed system aggregate processing plants are preferred because of better QC of RCA properties.

Crushing concrete reveals unexposed surfaces that contain some calcium hydroxide and partially unreacted cement grain that react with air to create calcium carbonate precipitate. High levels of sodium chloride have been found in RCA produced from pavements subjected to deicing salts over years of service and may cause corrosion concerns if used in new PCC with steel. The alkalinity decreased rapidly when diluted with low pH water and exposure of the dissolved calcium hydroxide with CO_2. The runoff could also be highly alkaline owing to the leaching of calcium hydroxide from freshly crushed concrete. Precipitate could clog drain pipes and filter fabrics, but washing the crushed concrete helped minimize some of these problems.

The moisture content in the RCA stockpiles needed to be controlled for uniformity of the RCA byproduct. The ACPA recommended that contractors use a stockpile sprinkling system to keep coarse RCA stockpiles uniformly moist when the RCA is used in PCC applications.

An alternative to removal and post-processing was on-site and in-place recycling, which can be accomplished when the RCA is to be used as subbase materials. For pavements, in-place systems typically have primary and secondary crushers adapted for this specific purpose, which were mounted on crawler tracks and capable of separating fine and coarse RCA.

PHYSICAL AND CHEMICAL PROPERTIES

RCA is typically highly angular with higher water absorption capacity, lower specific gravity, lower strength, and lower abrasion resistance than conventional construction aggregates ACPA (2008) (Table 21). All of these properties showed higher variability than conventional materials. Two of the most commonly produced gradations of RCA were 38 to 76 mm with 100% passing the upper sieve size, although gradations could be tailored to fit specification requirements.

In 2004 in Spain, Gutierrez and Sanchez de Juan evaluated the physical and chemical properties of recycled debris that contained a significant amount of brick in the processed stockpile. The results were compared with Spain's standards (Table 22). Fines content, water absorption, toughness (LA abrasion), percent of lightweight particles, and clay lumps may have trouble meeting specification limits.

Tam and Tam (1998) conducted research in Hong Kong to evaluate the suitability and variability of 11 individual RCA sources as a construction material (Table 23). Specific gravities were similar for the two sizes of RCA (2.215 average) with similar standard deviations (around 0.15) and coefficients of variation (around 5%). The water absorption capacity average was 6.6% and 6.32% for the 10 and 20 mm fractions, respectively, with a coefficient of variation (CV) of around 26%.

Shape was evaluated for both size RCA fractions using the flakiness index. The index was used to evaluate the thin and flat particles that could reduce the strength and workability of the hybrid PCC. An upper limit used in Hong Kong was 40% by mass. The average flakiness of the RCA sources was 15% and 12% for the 10 and 20 mm fraction, respectively, with CVs of 28% and 55%. The variation was high but the average values are well under the upper limit. The shape of the RCA should generally be acceptable for PCC applications.

TABLE 21
COMPARISON OF NEW AGGREGATE AND RCA PROPERTIES

Property	New Aggregate	RCA
Shape and Texture	Well-rounded, smooth (gravel) to angular and rough (crushed rock)	Angular with rough surface
Water Absorption Capacity, %	0.8 to 3.7	3.7 to 8.7
Specific Gravity	2.4 to 2.9	2.1 o 2.4
LA Abrasion, % loss	15 to 30	20 to 45
Sodium Sulfate Soundness, % loss	7 to 21	18 to 59
Magnesium Sulfate Soundness, % loss	4 to 7	1 to 9
Chloride Content, lb/yd^3	0 to 2	1 to 12

After Snyder (1994) and ACPA (2008).

TABLE 22
RANGE OF RCA PROPERTIES

Property	Test Method	Range	Spanish Specification	Pass/Fail
Fineness Modulus, %	UNE 7133:58	6.7 to 7.2	—	—
Fines Content, %	UNE 7133:58	0.28 to 1.14	≤1	May fail
Shape Index	UNE-EN 933-4:00	8.8 to 22.5	>0.2	--
Density, kg/cm^3	UNE 83134:98	2.09 to 2.40	≥2	Pass
Water Saturated Surface Dry Density, kg/cm^3	UNE 83134:98	2.30 to 2.45	—	—
Water Absorption, %	UNE 83134:98	4.91 to 9.74	≤5	May fail
Los Angeles Abrasion , %	UNE-EN 1097-2:99	35.1 to 41.7	≤40	May fail
Cl– Solubles in Water, %	UNE-EN 1744-1:99	0.0006 to 0.005	≤0.05	Pass
Cl– Total, %	UNE 80-217:91	0.0008 to 0.005	≤0.05	Pass
Acid Sulfate Content as SO_3, %	UNE-EN 1744-1:99	0.10 to 0.42	≤0.8	Pass
Total Sulfur Content as SO_3, %	[0,15-0,58]	≤1	—	—
Lightweight Particles, %	UNE-EN 1744-1	0.06 to 5.85	≤1	May fail
Clay Lumps, %	UNE 7133:58	0.04 to 0.62	≤0.25	May fail
Impurities, %	UNE-EN 933-7	0.4 to 11.5	—	—

After Gutierrez and Sanchez de Juan (2004).
— = not available.

Two methods were used to evaluate the strength of the RCA fractions. The first was the value of ten percent fines value (TFV), which was used to reflect the strength performance of the aggregate. For heavy-duty PCC concrete elements, TFV measurements of at least 150 kN were needed. For nonstructural elements and subbase, TFV measurements of at least 50 kN were required. The average value for the RCA was 100 kN with a CV of 23%, which indicated that these materials would not generally be acceptable for structural elements. The second method was measurements of aggregate impact value (AIV). AIV measurements for nonstructural or subbase applications were no more than 25% for structural elements, 30% for lower quality applications, and 35% for subbases. The average RCA value was 31%, with a fair CV of 14%, which would be acceptable for subbase applications.

The chloride content of RCA could be high in Hong Kong as a result to exposure to or use in marine environments (i.e., salt content). Requirements in Hong Kong for the chloride content allowed no more than 0.015% for prestressed concrete and no more than 1% for other applications. The average RCA chloride content was 0.02, but the CV for both the 10 and 20 mm fractions are both over 145%, which indicated it was the upper limit that would likely be exceeded.

Sulfate content also needed to be controlled so that potential problems with expansive reactions were minimized. The maximum allowable limit of 1% for any PCC application could be met by any of the RCA sources in this study.

The average RCA properties could be considered as examples of co-mingled sources of old structural concrete. If individual stockpiles were prepared for each source of RCA, it was possible that a specific source of RCA may meet the structural requirements. The authors summarized the usefulness of each source of RCA for use in a range of typical highway applications based on the requirements in their region of the world (Table 24). Most, but not all, of the sources were acceptable for nonstructural, base course, and embankment applications. Source 6 met the requirements for all of the applications, whereas sources 2 and 9 met none of the requirements. Separating sources of RCA improved the usefulness of the RCA material and limited the RCA material variability.

ENGINEERING PROPERTIES

RCA used in new concrete influenced the fresh and hardened properties (ACPA 2008) and the degree of influence depended on the amount of mortar in the RCA. A high percentage of coarse and fine RCA could produce substantial changes in properties. Admixtures and pozzolans could be used to mitigate detrimental effects on fresh and hardened properties. The use of RCA in PCC commonly resulted in a higher demand for water and changes in PCC volumetrics owing to the difference in water absorption capacity and lower specific gravities. Both angularity and water demand decreased the workability of the fresh PCC. Water demand was mitigated by pre-wetting or washing the RCA before use.

The hardened properties of RCA PCC typically had higher permeability, increased drying shrinkage, lower compressive and tensile strengths, lower modulus, higher creep potential, and higher coefficient of thermal expansion (Table 25). The reduction in compressive and tensile strengths depended on the percent and size of the RCA. The variability in the production of RCA PCC was higher than for conventional PCC. When developing the volumetric mix design for this hybrid product, using a value of 700 psi for the standard deviation was considered as a fair representation of the variability.

TABLE 23

SUMMARY OF RCA MATERIAL PROPERTIES FROM DIFFERENT HONG KONG SOURCES

Sample	Particle Size Distribution		Particle Density		Porosity and Absorption		Particle Shape		Strength and Toughness		Chemical Composition		Sulfate Content, %
	Sieve Analysis		Particle Density on an Oven-Dried Basis, mg/m^3		Water Absorption, %		Flakiness Index, %		TFV, kN	AIV, %	Chloride Content, %		
	10 mm	20 mm	10 mm	20 mm	10 mm	20 mm	10 mm	20 mm			10 mm	20 mm	
Control	Pass	Pass	2.59	2.62	0.77	0.57	28.27	22.52	189.38	21	0.0012	0.0016	0.003
1	Pass	Pass	2.16	2.2	5.83	6.89	11.13	9.68	93.89	33	0.0078	0.0089	0.031
2	Pass	Pass	2.22	2.14	6.36	6.4	10.44	10.08	61.36	36	0.0108	0.0091	0.017
3	Pass	Pass	2.2	2.18	7.5	7.35	15.17	8.61	107.42	31	0.0013	0.0019	0.005
4	Pass	Pass	2.2	2.2	6.93	7.25	15.42	7.91	112.82	23	0.0019	0.0019	0.005
5	Pass	Pass	2.15	2.19	7.31	6.82	17.82	12.96	92.09	32	0.0054	0.0061	0.006
6	Pass	Pass	2.25	2.27	5.2	5.77	11.96	9.93	155.53	25	0.0008	0.0025	0.006
7	Pass	Pass	2.11	2.13	8.74	7.3	12.86	5.7	110.18	30	0.0976	0.0902	0.013
8	Pass	Pass	2.1	2.12	8.58	7.99	15.12	9.78	83.48	34	0.0013	0.0014	0.005
9	Pass	Pass	2.21	2.24	6.94	6.11	13.78	12.17	92.87	36	0.0459	0.0352	0.024
10	Pass	Pass	2.2	2.23	6.85	5.95	16.47	9.92	89.91	28	0.0494	0.043	0.018
11	Pass	Pass	2.46	2.53	2.63	1.65	25.97	29.52	102.97	33	0.0021	0.007	0.008
Average for RCA			2.21	2.22	6.62	6.32	15.10	11.48	100.23	31.00	0.02	0.02	0.01
Std. Deviation for RCA			0.10	0.11	1.69	1.69	4.26	6.29	23.31	4.22	0.03	0.03	0.01
Coefficient of Variation			4.36%	5.07%	25.47%	26.75%	28.22%	54.78%	23.26%	13.61%	152.88%	146.21%	71.24%

After Tam and Tam (1998).

The statistics were calculated using the reported data; the statistics were not included in the original reference.

TABLE 24
SUMMARY OF ACCEPTABLE USES FOR INDIVIDUAL SOURCES OF RCA BASED ON HONG KONG REQUIREMENT

Sample	Structural Element	Minor Structural Element	Non-Structural Element	Pre-Stressed Concrete Element	Road Surface	Base Course	Embankment and Fill	Insulation Barrier
1			√			√	√	
2								
3		√	√		√	√	√	√
4		√	√	√	√	√	√	√
5			√			√	√	
6	√	√	√	√	√	√	√	√
7			√					
8			√			√	√	
9								
10			√			√	√	
11			√			√	√	
Control	√	√	√	√	√	√	√	√

After Tam and Tam (1998).
The specific locations or designations of the sources were not reported in the document.

Shrinkage in RCA PCC could be from 20% to 50% higher with RCA coarse and natural sand fine aggregate. Using both coarse and fine RCA could increase the shrinkage by 70% to 100%. Permeability of RCA PCC could be up to five times that of conventional PCC, but was mitigated by reducing the water to cement ratio by 0.05 to 0.1 or substituting fly ash or slag cement for part of the cement. Potential alkali–silica reactivity (ASR) was a potential problem because of original alkali levels that may remain reactive in the RCA. Potential ASR could be mitigated with the use of Class F fly ash and/or slag cement or other admixtures. The coefficient of thermal expansion of RCA mixes was about 10% higher than for conventional PCC.

When RCA PCC was used in pavements, higher shrinkage occasionally resulted in higher PCC pavement moisture warping stresses that needed to be addressed in the design using shorter panel lengths to compensate for the higher stresses. The increased thermal expansion (and contraction) of RCA PCC led to a loss of aggregate interlock for load transfer, which also led to shorter slab lengths and/or the use of load transfer devices (e.g., dowel bars).

ENVIRONMENTALLY RELATED PROPERTIES

Molin et al. (2004) evaluated heavy metal contaminates for two sources of building RCA (bridge, parking structure). Heavy metal contaminates from vehicles and environments were typically found only in the outer 5 mm layer of a structure. The level of each heavy metal found in the RCA varied based on the structure sampled (Table 26).

Portuguese researchers Evangelista and de Brito (2008) used EcoConcrete software to qualify and quantify the overall environmental impact of RCA PCC. The EcoConcrete program was developed by the concrete industry in Europe and is a proprietary Excel-based program. The inputs for environmental considerations included material quantities, distance from origin to production site, and production processes. Outputs were obtained for material, energy, emissions to air,

TABLE 25
TYPICAL INFLUENCE OF RCA ON PCC PROPERTIES

Property	Expected Changes in Properties	
	Coarse RCA Only	Coarse and Fine RCA
Specific Gravity	0 to 10% lower	5 to 15% lower
Compressive Strength	0 to 24% lower	15 to 40% lower
Tensile Strength	0 to 10% lower	10 to 20% lower
Strength Variability	Slightly greater	Slightly greater
Modulus of Elasticity	10 to 33% lower	25 to 40% lower
Creep	30 to 60% higher	30 to 60% higher
Drying Shrinkage	20 to 50% higher	70 to 100% higher
Permeability	0 to 500% higher	0 to 500% higher
Coefficient of Thermal Expansion	0 to 30% higher	0 to 30% higher
Corrosion Rate	May be faster	May be faster
Freeze-Thaw Durability	Dependent on air void system	Dependent on air void system
Carbonization	65% greater	65% greater
Sulfate Resistance	Dependent on mixture	Dependent on mixture

After ACPA (2008); FHWA (2008); ACI (2001); Hansen and Lauritzen (2004).

TABLE 26
PRESENCE OF HEAVY METAL CONTAMINATES FROM USE AND TRAFFIC

Heavy Metal	Bridge		Multi-story Car Parking		Multi-story Car Parking	
	On surface 0 to 5 mm	In structure	On surface 0 to 5 mm	In structure	On surface 0 to 5 mm	In structure
Cd	—	—	—	—	0.174	0.0051
Co	24.7	6	—	—	—	—
Pb	41.3	6.4	376	11	22.5	9.23
Zn	1,049	31	—	—	—	—
Number of Samples	3	3	4	4	1	1

After Molin et al. (2004).
— = not available.

water, soil, and waste. All information was collected in a life-cycle inventory (LCI) that was then used to determine the environmental impact of the application product in terms of ozone layer depletion, smog, or greenhouse gas effect and provides a cradle-to-grave evaluation. The life-cycle assessment was divided into four parts per EPA (2008):

- Resources consumed: materials and energy spent in extraction and transport activities.
- Production: raw material transformation, processing, and transportation to destination.
- Use, reuse, and maintenance: activities and consumptions resulting from the use and quality maintenance of the hybrid product.
- Recycling and waste treatment: activities associated with the application demolition, impact of resulting byproduct, or waste at end of life.

Each of three evaluation protocols was used for the analysis:

- Centre for Environmental Studies (CML) version 1992
- Environmental Design of Industrial Production (EDIP)
- Eco-Indicator 99.

The CML was the methodology developed at the Institute for Environmental Sciences of the Leiden University in Holland. This program evaluates the negative impact on eight different categories: abiotic depletion, acidification, global warming, ecotoxicity, eutrophication, human toxicity, production of photo-oxidant agent, and destruction of the ozone layer.

The EDIP was developed in partnership with various Danish entities and was similar to CML and evaluated the impact on global warming, destruction of the ozone layer, acidification, nutrients enrichment, ecotoxicity, human toxicity, photochemical ozone formation, waste gross production, toxic waste production, nuclear waste production, sludge slag, and ash production. The main difference between the CLM and EDIP methods was in the compiled LCI and the quantifications of impacts of different activities.

The Eco-Indicator 99 method evaluated the environmental damage in natural resources, public health, and the ecosystem, and was developed by experts in Switzerland. In this methodology, damage to ecosystems and health had the same weight in the analysis. The damage to natural resources was assigned one-half of the weight of the other two.

The EcoConcrete software was still under development at the time the analyses were conducted so there are currently some limitations including:

- Limited database for analysis.
- Only contained environmental costs already inventoried from birth to gateway (beginning of transport to destination).
- Allowed only limited adjustments to substitution of recycled materials for natural resources.
- RCA was currently accounted for at the end of life (i.e., salvage value).

The analysis evaluated environmental impact when substituting fine recycled aggregates for natural aggregates (Table 27). The differences in the outputs between the CML and EDIP methods categories are identified in this table and highlight the differences in focus between the two methods. Although both methods used different environmental parameters for assessment, they both indicated a reduction of about 6.5% in environmental impact when using 30% RCA replacement for natural fine aggregate and about 20% when using 50%.

The Eco-Indicator 99 used a rating number as the output (Table 28) and the diffusion coefficient for estimating the life of the PCC with and without RCA. The expected life of the RCA-modified PCC had a decreasing life expectancy with increasing RCA content. Higher numbers indicate better environmental performance. All three methods used different parameters but appeared to arrive at similar conclusions with regard to percent change in environmental impacts. The loss in service life currently drove the results of the analysis. The authors believed the initial versions of software used in this analysis may overbalance the importance of the life expectancy of the application.

Estevez et al. (2008) evaluated the impact of RCA on the LCI of the concrete recycling phase as obtained from mobile recycling plants in Catalonia, Spain. The control for

TABLE 27
CHANGES IN ENVIRONMENTAL PARAMETERS (RCA MIXES COMPARED WITH CONTROL) FOR CML AND EDIP METHODOLOGIES

CML Impact Parameter	RCA		EDIP Impact Parameter	RCA	
	30% Fine RCA	50% Fine RCA		30% Fine RCA	50% Fine RCA
Abiotic depletion	–6.4	–19.1	Acidification	–7.3	–21.8
Acidification	–6.9	–21.0	Acute aquatic toxicity	–4.7	–15.1
Aquatic toxicity (fresh water)	–6.9	–20.6	Acute ground ecotoxicity	–7.5	–22.3
Aquatic toxicity sediments (fresh water)	–7.2	–21.7	Aerial human toxicity	–7.5	–22.3
Destruction of the ozone layer	–7.6	–23.0	Aquatic human toxicity	–6.9	–21.5
Eutrophication	–6.7	–20.3	Chronic aquatic toxicity	–4.7	–15.1
Global warming	–6.8	–20.4	Chronic ground ecotoxicity	–7.2	–23.2
Ground ecotoxicity	–6.7	–20.1	Destruction of the ozone layer	–6.4	–19.1
Human toxicity	–6.8	–20.7	Global warming	–6.9	–21.0
Production of photo-oxidant agents	–6.6	–19.7	Ground human toxicity	–7.6	–22.5
			Nuclear waste	–3.3	–10.6
			Nutrients enrichment	–7.4	–22.2
			Overall waste	–8.3	–27.1
			Production of photo-oxidant agents	–6.9	–20.7
			Sludge slag and ashes	–7.0	–22.7
			Toxic waste	–5.2	–16.8
Average Decrease in Environmental Impact	–6.9	–20.7	Average Decrease in Environmental Impact	–6.6	–20.3

After Evangelista and de Brito (2008).

the analysis was the impact of the extraction processes of natural sand and gravel operations. The analysis looked at the CO_2, NO_x, SO_2, SO_x, and dust as the main emissions with a major influence on greenhouse gases, acidification, and eutrophication. Recent policies such as the European Directive on Integrated Pollution Prevention and Control of 1996 were driving the life-cycle assessments (LCA) in a number of European industry sectors.

The LCA evaluated the contributions of all processes involved in the manufacture of a product based on a minimum list of selected environmental effects for all parts of the process, from extraction of resources to the processing of the final waste. The inventory analysis was the process of assembling the amount of natural resources and energy used by the system and the amount of waste discharged to the environment from the system. Systems consisted of a collection of individual processes needed to produce the final product. The summaries of the material and energy used for each of the processes were used in the analysis. The itemization of this information formed the LCI needed for the assessment.

TABLE 28
ESTIMATED CHANGE IN SERVICE LIFE OF THE CONCRETE WITH AND WITHOUT RCA

Method	Control	30% Fine RCA	50% Fine RCA
EI99	8.316	8.128	7.75
EI99/ANO	0.166	0.182	0.207
Δ (%)	—	9.33	24.59

After Evangelista and de Brito (20080.

Results, using the values presented in Table 29, showed that processing the natural materials resulted in a heavier environmental load than recycling the concrete portion of CDW. CO_2 emissions showed the most difference. The major individual process in the systems with the most environmental impact was transport. Therefore, transport distances had a significant influence on the LCA rankings. System boundary differences made direct comparisons between the production of natural aggregates and processing demolition-recovered concrete difficult. Boundary conditions were selected for environmental and construction practices in Spain. The results were location-specific. Specific information needed in the calculations is limited in its availability.

USES AND PRODUCTION

According to the USGS (ACPA 2008), the United States generated 100 million tons of RCA per year in 2000. The primary application was as subbase and base, although it has also been used in concrete and HMA paving layers, as high value rip rap, and as general fill and embankment materials.

Oregon DOT (2005) recovered 2,400 tons of concrete aggregate from two bridges, which was crushed into 1 in. particles and used as gravel. The two bridges produced the recovery of 250 tons of steel during the recycling process.

The Recycled Aggregate Producers (2008) reported the number of tons of RCA from fixed and mobile crushing operations in the United States (Table 30).

TABLE 29
EMISSIONS TO AIR FROM EXTRACTION PROCESSES OF PRIMARY AND SECONDARY AGGREGATES

Emissions to Air, g/ton	Inventory of Concrete Recycling, g/ton		Inventories of SimaPró 4.0			
			Gravel I, g/ton		Sand I, g/ton	
	Transport	Crushing	Transport	Electricity	Transport	Electricity
CO_2	1,704	1,261	4,920	2,820	4,920	1,950
NOx	26.36	19.50	94.20	5.36	94.20	5.49
SO_2	1.62	1.20	12.00	0.42	12.00	11.20
Dust	0.17	0.126	0.49	0.037	0.49	0.873

After Estevez et al. (2008).

COST

USGS (2000) estimated that the capital investment for recycling equipment was between $4.40 and $8.80 (1998 dollars). The processing costs for an aggregate recycler were estimated from $2.76 to $6.61 per metric ton of annual capacity. Costs decreased with economy of scale. The RCA byproducts were valued at between $1 and $18 per metric ton, and varied from region to region. The article noted that the recycler costs can be offset by charging a tipping fee and need to compete with natural aggregate producer prices.

The cost of producing RCA from old PCC pavement was limited to the costs of crushing the demolished concrete, screening, backhauling, and QC (ACPA 2008). The costs of demolition, removal, and hauling were required regardless of end use or disposal, and were usually accounted for in the demolition of the structure. RCA byproducts varied in price from $1 to more than $16 per ton and resulted in savings of as much as $4 per ton of square yard of PCC paving. Some estimates of savings from recycling PCC have been as high as $5 million on a single project.

FHWA (2004) reported expected cost savings when using RCA from PCC pavements for in-place recycling resulting from the reduced cost of hauling, particularly when recycling was less expensive than landfill disposal for the contractor. Overall project savings were more likely to be seen as bid price reductions when the contractor was the owner of the recycled material. The contractor benefits were from reduced new aggregate costs and the resale of scrap metal. Critical distance for a cost-effective recycling facility was approximately 50 miles from the construction site. Additional project cost reductions for the agencies were the result

TABLE 30
TONS PER YEAR OF RECYCLED AGGREGATES

Tons per Year	No. of Plants		States or Regions Served
	Fixed	Mobile	
2.75 million	1	9	Ohio, W. Va., Pa., the Southeast
2.5 million	1	5	California and Arizona
2.2 million	20	0	Arizona, California, Illinois, New Mexico, Virginia
2.1 million (est.)	1	8	Southeastern U.S.
1.9 million	3	3	Georgia
1.825 million	2	8	Western U.S.
1.73 million (est.)	0	6	Southern California
1.45 million	0	4	Minnesota and the Dakotas
1.43 million (est.)	3	0	Texas
1.275 million	3	3	Texas and Louisiana
1.09 million (est.)	9	0	Texas
1.07 million (est.)	3	2	Nevada, Arizona, Utah, California
825,000	4	1	California
816,000	0	4	California
800,000	2	0	Massachusetts, New Hampshire, Rhode Island
660,000	1	1	California
600,000	0	4	S. Carolina, N. Carolina, Ga., Va., Fla., Ala., Miss.
588,000 (est.)	1	5	Iowa, Minnesota, Nebraska, Missouri, S. Dakota
577,000	4	2	New Jersey
500,000 (co. est.)	0	3	New Jersey, New York, Delaware, Pennsylvania
Total	58	68	

After Recycled Aggregate Producer (2008).

of minimizing the need to alter placement of existing appurtenances. The Michigan DOT (MDOT) noted a savings of $144,000 on a $3 million job for the agency. State and contractor shared the savings equally. They also provided an environmental incentive of a 10% price break when using recycled materials.

Vetter (2008) summarized economic lessons learned from a concrete recycling pilot demonstration project for the Sandia National Laboratory LEED (Leadership in Energy and Environmental Design) project. The initial crushing events at the landfill site showed that the RCA variability needed to be improved. A decision was made to establish permanent recycling areas for individual materials to be recycled. A resulting search was conducted for a location, and development of planning activities [National Environmental Policy Act, storm water pollution prevention plans (SWPPPs), and maintenance] and operations (generator contract, requirements, crushing contract, signage, promotion, awareness and outreach). The stockpiles of raw feed stock were collected as individual recycled materials and once sufficient material had been collected, crushing was completed and the crushed materials stockpiled for use. The crushing was done to meet specific base courses specifications so that the material in the stockpiles was ready for use. The recycling facility worked with facilities and project managers to obtain commitments to use recycled materials. Initial seed money for the first crushing was funded by recycling revenues and the aggregate users paid for material by the dollars per ton of crushing costs.

The cost was $9.40 per ton for crushing, whereas the local vendor cost for crushed concrete base course material was $15.45 per ton. The estimated cost savings of $6 per ton included transportation and delivery costs. The cost savings were achieved by cost sharing with the soil borrows site maintenance activities for stockpile management. The SWPPP maintenance replaced the track off pads at the entrance of the recycling and soil borrow site and diverted about 6,000 tons of concrete from the landfill. The RCA was constantly promoted to the contractor for delivery to a recycling facility and the importance of controlling contamination. The facility also promoted project partnerships and options for new applications.

CHAPTER SIX

AGENCY SURVEY

The most commonly used highway applications were embankment and drainage material followed by use in PCC applications (Table 31). Most states used RCA washed or unwashed (Table 32). Six states allowed recycling of end of day waste and water. Only one state indicated use of the fresh PCC added to a new batch. The states using recycled concrete in highway applications are shown in Figure 7.

TABLE 31
NUMBER OF STATES USING RCA BYPRODUCTS IN HIGHWAY APPLICATIONS

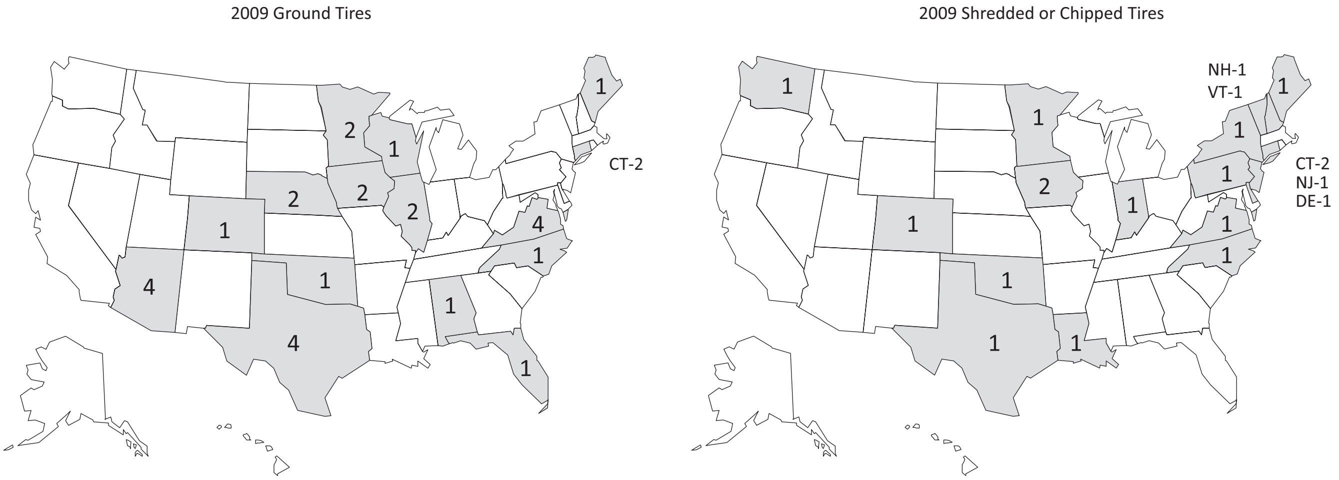
Question: Concrete Industry Recycled Materials and Byproducts: Is your state using, or has ever used, these byproducts in highway applications? If you are not sure of the type of recycled concrete materials (RCM) used in your state, check the RCM, unknown type at the end of the list.
* Concrete plant, end of day waste, and water: any material not used at either the plant or in the trucks by the end of the day's production, including any water used to clean the equipment
* Reclaimed (hardened) concrete materials (RCM): produced by the demolition of concrete roads and structures
* Reclaimed concrete material, crushed and washed: RCM processed for size and fines content
* Returned fresh mix added to new batches: mixing older fresh mix with new batch of concrete

	Asphalt Cements or Emulsions	Crack Sealants	Drainage Materials	Embankments	Flowable Fill	HMA	Pavement Surface Treatments (non-structural)	PCC	Soil Stability
Concrete, Plant, End of Day Waste, and Water	0	0	1	2	0	0	0	3	0
Returned Fresh Mix Added to New Batch	0	0	0	0	0	0	0	1	0
Reclaimed Concrete Materials, Crushed and Washed	0	0	8	12	1	2	1	9	0
Reclaimed, Hardened Concrete Material	0	0	7	18	0	0	1	6	2
RCM, Unknown Type	1	1	2	4	1	1	2	1	1

TABLE 32
STATES USING RCA BYPRODUCTS IN HIGHWAY APPLICATIONS

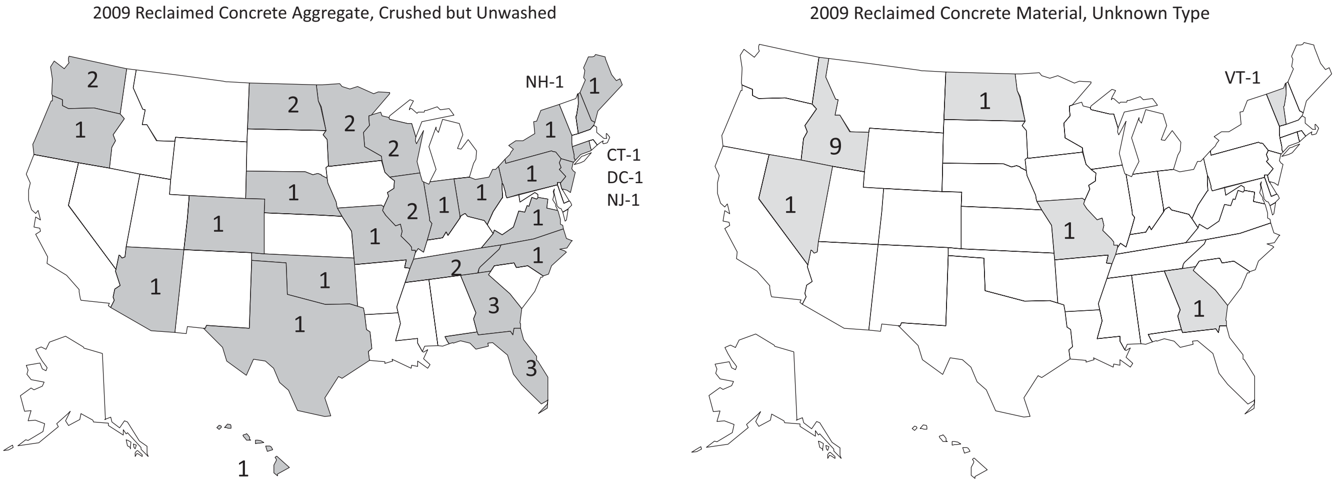
Number of Applications	States				
	Concrete, Plant, End of Day Waste, and Water	Returned Fresh Mix Added to New Batch	Reclaimed Concrete Materials, Crushed and Washed	Reclaimed, Hardened Concrete Material	RCM, Unknown Type
9	—	—	—	—	ID
4	—	—	IL	—	—
3	—	—	CO, ND	FL, GA	—
2	IL	—	LA, MD, NC, VA, VT, WA	IL, KY, MN, ND, WA, WI	—
1	MO, NC, NE, VA,TX	NC	AL, DE, FL, MN, MS, NJ, OR, OK, SC, WI	AZ, CO, CT, DC, HI, IN, ME, MO, NC, NE, NH, NJ, NY, OH, OK, PA, TX, VA	GA, MO, ND, NV, VT

— = not applicable.



2009 Ground Tires

2009 Shredded or Chipped Tires



2009 Reclaimed Concrete Aggregate, Crushed but Unwashed

2009 Reclaimed Concrete Material, Unknown Type

FIGURE 7 States using recycled PCC byproducts in highway applications.

CHAPTER SEVEN

LITERATURE REVIEW

FRESH PORTLAND CEMENT CONCRETE RECYCLING

FHWA (2004) reported that the quantity of PCC mix not used was commonly between 5 and 30 cubic yards per day, and reusing the fresh PCC had the potential for a significant savings for the batch plant. California was reclaiming aggregates by washing the fresh PCC and then reusing the aggregate. The paste needed to be dosed with a rate of set retarders and dosed with activators upon remixing to restart the hydration process. This reduced the added water content by up to 40%. The current practice was to disregard the cement content of the reused paste and was adopted from the European market.

RETURNED HARDENED CONCRETE RECYCLING

Blankenagel and Guthrie (2006) noted that RCA only became available for use as base material in Utah around 2000. The authors estimated that the RCA base was about 25% less expensive than natural aggregates for construction applications. The literature review noted the use of Benkelman beam deflections to determine the structural capacity of RCA base.

The subsequent laboratory evaluation used two sources of RCA (demolition and haul back/over load). The haul back RCA had a significantly higher moisture-density curve than the demolition RCA (Table 33). The haul back/over load RCA also had a higher California bearing ratio (CBR), initial modulus, final unconfined compressive strength, dielectric value, solution salinity, and solution pH with a lower LA abrasion loss.

Obla et al. (2007) noted that between 2% and 10% of the estimated 455 million cubic yards of ready-mixed concrete was returned to the plant (2006 estimate). Options for the returned concrete included:

- Added to fresh concrete if the quantity is sufficiently small.
- Processed through a reclaimer system to reuse or dispose of the individual components.
- Used for site paving and production of other products such as concrete blocks for resale or disposal.

When the concrete was returned to the plant, hydration stabilization admixtures were sometimes used to help with this reuse. This approach to recycling was only good for small quantities and commonly restricted by PCC specification requirements. A hydration stabilizer was also needed for this option. A reclaimer system, applicable for larger quantities, required significant capital investment and is limited by available area at the plant, demand for products, and available markets. Returned PCC that was discharged on the ground at the plant could be used later for crushed concrete aggregate (CCR). The CCR designation was used to distinguish this byproduct from RCA produced with old recycled concrete byproducts with potential contaminates and reinforcing. This approach could be useful for about 60% of the returned PCC.

A study evaluated properties of CCR using three types of PCC product (1,000 psi, 3,000 psi, and 5,000 psi 28-day-strength design mixes). These mixes were non-air entrained, but did have small doses of Type A water reducer. Color was added to each concrete mix so that the byproduct could be sorted. The returned PCC was discharged to ground and tested for slump, air content, temperature density, and compressive strength at various times. Two curing conditions for testing used two curing methods that were the standard lab curing procedure and curing under field conditions near location of discharge.

BOUND APPLICATIONS—PORTLAND CEMENT CONCRETE

Waste and Resources Action Programme (WRAP 2002) reported on research conducted by the German Committee of Reinforced Concrete. This study found that shrinkage and creep were the most influenced properties by RCA in the PCC applications. An effort to increase the workability with prewetting the RCA prior to mixing was found to be unsuccessful and required superplasticizer to maintain workability. The compressive and tensile strengths in this study were not significantly affected by the RCA, but the modulus decreased with increasing RCA content. No difference was found in the freeze-thaw resistance. The composition and use of RCA in reinforced PCC was presented for use as a German standard and guideline in Table 34.

Gutierrez and Sanchez de Juan (2004) conducting research in Spain evaluated the properties of structural concrete used to produce RCA. The materials were obtained from two structures. A double impact crusher was used to prepare RCA. The specific gravity of coarser fractions was higher than for fine RCA (Table 35). The water absorption coefficient of

TABLE 33
RECYCLED CONCRETE MATERIAL CHARACTERIZATION OF RECYCLED MATERIALS USED IN PROJECT

Properties of Recycled Materials		Demolition	Haul-back
Plasticity Index		NP	NP
USCS		GP	SP
AASHTO Classification		A-1-a	A-1-a
Specific Gravity		2.59	2.66
Water Absorption, %		5.3	6.5
CBR, average of 3		21.7	55.0
Freeze-Thaw	Modulus, 7-day, MPa	108	153
	Residual stiffness, MPa	70	30
	Overall stiffness loss, %	35	80
	Cycles before meeting residual stiffness	2	9
Unconfined Compressive Strength	7 day, kPa	1,260	1,816
	Final unconfined compressive strength, kPa	610	1,300
	Final gravimetric moisture content, %	11.9	10.4
	Strength loss compared with 7-day control, %	52	28
Tube Suction Test, Dielectric Value		6	15
LA Abrasion, %		31	17
Solution Salinity, μS/cm		1,000	6,100
Solution pH		11.64	12.87

After Blankenagel and Guthrie (2007).
NP = non-plastic; GP = poorly graded gravel with sand; SP = poorly graded sand with silt and gravel.

variation was 25% and 5.1% for LA abrasion. The shape was considered acceptable for 13 of the 15 RCA sample sources tested. These researchers recommended that only blends of RCA with new aggregates be used so that standard aggregate specifications for the blended stockpile can be met.

German researchers Weimann and Muller (2004) evaluated the use of RCA fines post-processed with a wet treatment and a jig for density separation. The crusher fines were obtained from two structural concrete demolition projects (structure and pavement) and were processed by crushing and dry sieving the concrete. The 4 mm and below fines from each project were treated in a continuous pilot plant that included a stirring unit to remove the binder matrix from the aggregates using one of four speeds for the stirring process (100, 300, 600, or 1,000 rpm). A hydrocyclone was used to remove particles below 0.01 mm and a jig was used to separate the material by density (light and heavy fractions). The flow rate ranged from 0.3 to 1.5 tons per hour and was dependent on the material composition. Pulsating water was

TABLE 34
GERMAN STANDARD AND GUIDELINE RECOMMENDATIONS

	Composition, %									Maximum Amount of Coarse RCA, % of Total Aggregate		
Type of Concrete	Concrete, Natural Aggregate	Brick	Calcareous Sandstone	Other Mineral Constituents	Asphalt	Contaminates	Amount of Soluble Chlorides, 5% of mass	Particle Density, lb/ft^3	Water Absorption, % by mass	Reinforced Concrete		Fill or Subbase Material
	Min.	Mixed	Mixed	Max.	Max.	Max.	Max.	Min.	Max.	Interior Element	Exterior Element	
Type 1: Concrete Aggregate	90	≤10	≤10	2	1	0.2	0.4	125	10	50	40	100
Type 2: Building Aggregate	70	≤30	≤30	3	1	0.5	0.4	125	15	50	—	100
Type 3: Masonry Aggregate	20	≥80	≤5	5	1	0.5	0.4	112	20	40	—	100
Type 4: Mixed Aggregate	80	≥80	≥80	20	20	1	0.15	1500	NR	—	—	100

After WRAP (2002).
— = not available; NR = not relevant.

TABLE 35
RANGE OF RCA PROPERTIES

Property	Test Method	Range	Spanish Specification (EHE)	Pass/Fail
Fineness Modulus, %	UNE 7133:58	6.7 to 7.2	—	
Fines Content, %	UNE 7133:58	0.28 to 1.14	≤1	May fail
Shape Index	UNE-EN 933-4:00	8.8 to 22.5	>0.2	
Density, kg/dm^3	UNE 83134:98	2.09 to 2.40	≥2	Pass
Water Saturated Surface Dry Density, kg/dm^3	UNE 83134:98	2.30 to 2.45	—	
Water Absorption, %	UNE 83134:98	4.91 to 9.74	≤5	May fail
Los Angeles Abrasion, %	UNE-EN 1097-2:99	35.1 to 41.7	≤40	May fail
Cl- Solubles in Water, %	UNE-EN 1744-1:99	0.0006 to 0.005	≤0.05	Pass
Cl- total, %	UNE 80-217:91	0.0008 to 0.005	≤0.05	Pass
Acid Sulfate Content as SO_3, %	UNE-EN 1744-1:99	0.10 to 0.42	≤0.8	Pass
Total Sulfur Content as SO_3, %	[0,15-0,58]	≤1	—	
Lightweight Particles, %	UNE-EN 1744-1	0.06 to 5.85	≤1	May fail
Clay Lumps, %	UNE 7133:58	0.04 to 0.62	≤0.25	May fail
Impurities, %	UNE-EN 933-7	0.4 to 11.5	—	
Rc of Tested Cores, N/mm^2	UNE 83.304:84	10.2 to 53.3	—	

After Gutierrez and Sanchez de Juan (2004).
— = not applicable.

used to float the particles that stratified by density within the material flow and the top, middle, and bottom levels of flow were discharged separately.

Testing of the discharged water included chemical (acid soluble, acid insolubles, sulfates, and chlorides) and physical (size distribution and microscopy). Mortar testing assessed the workability and water absorption (mix design), as well as compressive strength, flexural strengths, and Young's modulus.

The results showed acid soluble materials, representative of the adherent cement matrix, were removed from the aggregate grains with these processing procedures (Table 36). A reduction in acid soluble in the heavy fraction and a higher percent in the finest fraction show the lowest cement content in the heavy fraction and the highest cement content in the finest fraction. The difference in the paste content accounts for the changes in the water absorption percentages (more paste results in more absorption). Acid leaching tests showed that cement, quartz, and other rock components are involved in this process as can be seen in the acid insolubles in the fine fraction. Similar results were obtained for stirring levels of 100 and 1,000 RPMs. The lower stirring revolutions will use less energy; therefore, the lower RPMs were recommended.

TABLE 36
RESULTS FOR VARIOUS LEVELS OF DISCHARGE DURING HYDROCYCLONE SEPARATION OF PARTICLE SIZE

Testing		Natural Sand	Combined Heat-Power Plant				Pavement				Trend of Property with Density
			Input Material	Heavy	Light	Finest	Input Material	Heavy	Light	Finest	
Loss by Washing, <0.01 mm, %		0.55	5.41	0.39	2.49	100.00	3.46	0.44	1.45	100.00	Increased
Acid	Insolubles, %	99.70	77.65	83.55	72.91	56.38	82.81	87.34	78.51	65.46	May decrease
	Solubles, %	ND	22.35	16.56	27.09	43.61	17.19	12.66	21.49	34.54	Increased
Water Absorption, %		ND	9.24	6.28	11.01	ND	5.46	3.28	6.18	ND	Increased
Apparent Density, g/cm		2.49	1.88	1.96	1.74	ND	1.92	1.87	1.79	ND	May decrease
Consistency, cm		39.00	50.83	46.90	44.88	ND	45.00	49.25	42.20	ND	Decreased
Compressive Strength, MPa		40.20	17.37	19.45	16.00	ND	15.98	15.93	15.73	ND	May decrease
Flexural strength, MPa		5.80	3.38	3.84	3.07	ND	2.98	2.98	2.90	ND	May decrease
Dynamic Modulus of Elasticity, MPa		27,300	12,312	15,030	9,526	ND	13,423	13,880	1,154	ND	Decreased

After Weimann and Muller (2004).
ND = no data.

The results were dependent on the pilot plant settings and the source of the RCA fines. Concrete samples made with 50% of the wet-treated RCA had little influence on compressive strength. Concrete made with unprocessed RCA significantly lowered compressive strength. The wet processing did not completely remove the paste in the RCA and the loss of strength was contributed to the remaining paste, which resulted in higher water absorption and reduced density, and undesirable RCA particle shapes. Overall, wet treatment of the RCA fines reduced water demand, particularly for the larger sizes.

Molin et al. (2004), Swedish researchers, evaluated the influence of two different methods of crushing techniques (jaw crusher and rotation crusher) on the cyclic load triaxial properties of RCA mixes. Two gaps between crushing surfaces were used (0 to 100 mm and 0 to 45 mm). Concretes designed for three levels of compressive strengths were crushed and samples were prepared for triaxial testing. The levels of compressive strengths were a very low (1,000 psi), normal (4,350 psi), and high (10,588 psi) strength concrete.

Results showed that the original concrete strength influenced resilient modulus and creep (i.e., accumulated permanent strain). RCA from the high-strength PCC-produced strength concrete had similar values to the control but failed earlier than the control PCC mixes. The RCA from the normal strength concrete produced mixes with higher moduli up to total stresses of 175 psi with moduli that were less sensitive to changes in total stress.

The accumulated permanent deformation showed slightly lower total deformation for the medium strength RCA compared with the control. The high original strength RCA mixes showed more deformation over time than the control, while the low original strength RCA showed significant deformation followed by an early failure in the samples.

The influence of the type of crusher on RCA properties was evaluated using both resilient modulus and deformation with time measurements. The resilient modulus with the 0 to 100 mm sizes of RCA had higher moduli than the 0 to 45 mm sizes, regardless of the type of crusher. The jaw crusher 0 to 100 mm RCA size had higher moduli than the same sized RCA prepared with the rotational crusher. The 0 to 45 mm opening rotational crusher RCA size had moduli values similar to the control mix. Both of these mixes had the lowest moduli values.

Total deformation was significantly less for either size of the jaw crushed RCA. Deformation with the 0 to 45 mm opening on the rotational crusher materials was similar at longer times for the control (granite) and slightly better for the larger size rotation crusher material.

FHWA (2004) summarized case studies in five states (Texas, Virginia, Michigan, Minnesota, and California). Texas used more than 60% of the RCA produced in Texas and had been using this byproduct for more than 10 years. In Texas, the RCA was not considered a waste product as long as the stockpile was being worked on in a yearly basis. Barriers that needed to be overcome during the construction of the projects included:

- Reduced workability of the PCC
- Increased creep and shrinkage
- Initial unfavorable perceptions of RCA
- Grading and compaction difficulties.

Reduced workability of RCA PCC was addressed by contractors improving the process control with more attention to the RCA stockpile moisture content and increased frequency of QC testing for moisture in stockpiles. Owing to potential problems with creep and shrinkage, the RCA PCC was used where the risk associated with dimensional change was minimal and had high potential for good performance. Education and training helped significantly in overcoming initial perceptions of RCA as a substandard material. Grading and compacting of RCA base materials tended to segregate the base material because of excessive working. The recommendations to overcome this problem were to use minimal shaping of the RCA base and compact the RCA material in a saturated state to aid in the distribution of fines throughout the material. Overall, the RCA bases had excellent performance and higher load bearing capacity as a result of a tighter interlock and re-cementing actions.

Virginia DOT (VDOT) regulations provided a neutral playing field for new aggregates and RCA, with the RCA byproducts most commonly used in commercial applications. An income tax credit for the purchase of recycling equipment that was operated on the company's site encouraged recycling (mobile crushers not included). VDOT provided compaction recommendations for RCA base and subbase, which included compaction at a saturated state with steel wheel rollers. Established agreements on solid waste management between waste management and VDOT also encouraged the recycling of PCC. The one construction concern noted by VDOT occurred during the construction of RCA bases; minor amounts of steel were found to be occasionally harmful to the pneumatic roller tires.

MDOT used recycled materials when they enhanced or provided similar performance as when virgin materials were used. Since 1983, MDOT has placed 26 projects with 650 lane-miles of RCA PCC. The standard specification for construction allowed for the use of coarse RCA in PCC for curb, gutter, valley gutter, sidewalk, concrete barriers, driveways, temporary pavement, interchange ramps, and shoulders Benefits found included a reduction of D-cracking problems when using smaller RCA aggregates. RCA PCC was more advantageous in urban rather than rural areas because of the availability of RCA.

MDOT's metro region approved a set of guidelines for management of the use of RCA in the Detroit area. First, the

RCA needed to come from MDOT projects rather than from commercial demolition to ensure consistent source and properties of RCA. Second, separate stockpiles needed to be kept for each RCA feed stock and crushed materials. Third, there were requirements for certification of recycling aggregate producers and approval of stockpiles when the source of RCA was from highways and the producer has adequate process control. RCA producers could get the byproduct preapproved so that contractors could use the lower cost materials in bids.

The Minnesota DOT (MnDOT) developed specifications that allowed the use of RCA as a coarse aggregate in PCC, for surface and base course, or as granular materials. MnDOT used RCA in PCC pavements for more than 20 projects from the 1970s through the 1990s; however, concerns with the ability of RCA PCC to meet their current requirement of a 60-year pavement design life has restricted its use. RCA originally used in structural concrete in pavements resulted in a moratorium in the 1990s because of accelerated distresses. The distresses were eventually attributed to design issues rather than the RCA-related load transfer, which was thought to be the result of the smaller sized RCA gradations not providing adequate aggregate interlock.

Li (2005) evaluated ASR reactions between alkali hydroxide in the concrete pore solution and reactive siliceous aggregate that generated an expansive reaction. This research evaluated RCA with evidence of ASR (expansive) distresses and the use of washing RCA and various admixtures to minimize ASR reactions in RCA PCC applications. The effect of washing the RCA as well the use of pozzolans (fly ash, silica fume, ground granulated blast furnace slag, and lithium salts) was evaluated for their ability to reduce calcium hydroxide and alkali. The calcium depletion during pozzolanic reaction could be sufficient to offset ASR reactivity. The use of powdered glass was also investigated as a means of mitigating ASR because glass contains amorphous silica and has a high reactivity for use as a supplementary cementitious material. Initial research established that the chemical properties of various sources of powdered glass (post-consumer glass, window glass, and E-glass). All glass powders had more than 50% silica by weight.

Testing included an evaluation of the RCA specific gravities and water absorption capacities. ASTM methods (C1260/1567, C1293) were considered for evaluating ASR potential. Two modifications to soaking conditions for ASTM C1260/1567 were used to obtain normality of hydroxyl ions between lithium to alkali in solution and lithium to alkali in mortar bars. The first method added lithium hydroxide to the solution. The second added lithium nitrate to maintain normality. Thermal gravimetric analysis (TGA) and the extraction of pore solution used a method developed at the University of Cape Town in South Africa to quantify the alkalinity of the pore water solution. The extraction of pore solution was accomplished using compressive pressure of the sample to force water out of sample which was then collected and analyzed.

Results showed the RCA properties, as expected, had higher water absorption compared with natural aggregates. Both absorption and specific gravity varied with RCA particle size. These properties were considered a function of the paste content of the RCA. Washing the RCA removed only about 10% of the alkali found in the soaking test. ASR reactivity in RCA with a history of expansion problems was successfully modified with fly ash (25%), silica fume (12%), or slag (55%) to meet expansion testing criteria. Similar results were obtained with RCA and PCC mixes made with a new aggregate with known ASR reactivity. These pozzolans also reduced the alkali concentration and pH of the pore solution. The lithium solution modification significantly reduced any expansion of the mortar bars and did not compare well with ASTM C1293 results. The conclusion was that balancing the normality of the solution overestimated the ability of the lithium to mitigate expansive reactions. Both methods for achieving normality produced similar results and resulted in requiring higher doses of lithium for RCA than for conventional aggregate to achieve the same level of expansive reduction. The author explained that this was likely as a result of the older paste absorbing more lithium than potassium or sodium.

FHWA (2008) described options for dealing with old PCC pavement as:

- Removal from the site and disposal in a landfill, or usage in other environmentally favorable ways such as rip rap.
- Cracking and seating or rubblizing the old pavement and constructing a new pavement on top of it.
- Processing the removed pavement into an aggregate product for use in granular or stabilized base, subbase, or shoulder materials.
- Processing the removed concrete pavement into a RCA suitable for use as bedding, backfill, granular embankment, or in asphalt or hydraulic-cement concrete with lower performance expectations.
- Processing the removed concrete pavement into a high-quality RCA product suitable for use in high performance hydraulic cement concrete or asphalt.

Material-related distresses could be dealt with if the material problems were noted before recycling and additives were used with the RCA in new PCC products. Quality RCA needed to have:

- Limited or no harmful components such as chlorides and reactive materials
- More than 90% cement paste and aggregate
- Less than 1% asphalt
- Absorption less than 10%
- Properties that met requirements for natural aggregates
- Mix designs adjusted for RCA material properties
  - Evaluation of freeze-thaw damage
  - Evaluation of shrinkage and thermal expansion characteristics

- LA abrasion values for small size coarse aggregate less than 5%
- Evaluation of alkali from deicers.

Pavement design issues needed to consider differences in strength (lower for RCA PCC), increased shrinkage, changes in thermal characteristics, and the impact of the RCA source on properties. Mix designs for RCA PCC should use water to cementitious material ratios of 0.45 or lower and consider the potential need to increase cement content to achieve desired properties. RCA PCC mixes could require more water (up to 15% more) and use no more than 30% fine RCA. These mixes should not use fine RCA in freeze-thaw susceptible areas.

Standard production and construction processes could be used to mix and place the RCA PCC. These mixes needed to be closely monitored for water content and air entrainment to achieve good fresh and hardened concrete properties.

Research in Spain by Gomez-Soberon (2004) evaluated structural concrete properties prepared with RCA. Mixes used RCA at 0%, 10%, 15%, 30%, 60%, and 100%. Test conditions used 50% relative humidity at 20°C and creep test results were collected for more than 270 days. The first creep measurement was taken at 28 days. Results showed that the axial creep increases with time and with increasing RCA content.

Kuennen (2007) summarized 12-year performance re-evaluations of nine RCA PCC pavements constructed by five state DOTs (Connecticut, Kansas, Minnesota, Wisconsin, and Wyoming) in 1994. Initially, one of the nine sections exhibited significantly more cracking than the control section. The 1994 evaluation recorded 88% cracking for the RCA PCC compared with 22% for the control section. By 2006, the cracking had increased to 92% versus 24% for the RCA PCC and control sections, respectively. Initial cracking was attributed to a large difference in the total mortar content between the two sections. The Wyoming RCA PCC was produced from old concrete with ASR problems. This section showed evidence of surface cracking, suggesting that there were recurrent problems with ASR in the RCA PCC. Other RCA PCC performed similarly to the control for the remaining sections. Recommendations were that jointed RCA PCC include dowels as load transfer through aggregate interlock did not appear to be sufficient. The thermal coefficient of expansion was different for RCA PCC and the slab lengths needed to be designed accordingly.

In France, Hadjieva-Zaharieva and Buyle-Bodin (2003) evaluated the carbonation of hardened cement paste and chloride attack in RCA PCC mixes. Carbonation progresses slowly from the surface inward and can lead to shrinkage and a decrease of alkalinity. High porosity and permeability increases this carbonation.

Results showed that the rate of carbonation was about five times that of conventional PCC. This characteristic means that structural designs would require greater cover depths for protecting reinforcing steel in structures. The depth of carbonation measured on molded sample surfaces was about twice as high as that on a sawn surface. The rate of carbonation was significantly decreased in wet curing conditions. Longer curing in a wet environment reduced the depth of carbonation by two times. Water absorption was well correlated (linearly) with carbonation depth. Surface permeability was also well correlated with depth of carbonation; however, the relationship was nonlinear.

Conventional diffusion relationships relate rate of penetration to the square root of time. However, the actual penetration rate for fine RCA PCC was higher than would be predicted using the standard diffusion equations. The authors suggested using measurements of surface permeability, water sorptivity, and compressive strength as measurements that are sensitive to the impact of RCA fines on concrete durability.

Italian researchers Corinaldesi and Moriconi (2008) assessed the durability of RCA PCC by measurements of carbonation and chloride penetration depth as well as freeze-thaw resistance. Mix variables and estimates of hardened PCC concrete indicated mixes with RCA, fly ash, and a low water to cementitious material ratio could produce mixes with improved concrete properties compared with conventional PCC with a 0.6 water to cementitious material ratio (Table 37).

ACPA (2008) provided recommendations for the design, construction, and QC of RCA PCC pavements. The aggregate mix design requirements for fresh RCA PCC should meet the same requirements as for conventional aggregates. The ASR potential needed to minimize the use of pozzolans, limiting the amount of RCA fines, reducing the permeability, and reducing the exposure to moisture or the use of other admixtures for reducing ASR. D-cracking should be minimized by limiting the top size RCA to 19 mm or less and by reducing exposure to moisture. Air content should be determined using the Roll-o-Meter method (AASHTO T-196/T196; ASTM C173/173M). Pavement design considerations when using RCA are summarized in Table 38.

Guidelines for the construction of RCA PCC pavements started with the preparation of the foundation and subbase. Localized weak areas needed to be repaired to ensure proper and uniform compaction of materials on top of the subbase. Fresh RCA PCC testing should be similar to conventional testing with the exception of specifically using a Roll-O-Meter for air content determination. No changes were needed to conventional paving operations or ride quality requirements. If a two-course construction process was used, wet-on-wet placement should be used with the top lift being a high-quality PCC wearing surface. This was a commonly used method in Europe. Guidelines were included in appendices of this reference for removing and crushing exist-

TABLE 37
EXAMPLE OF RCA PCC MIX DESIGNS AND PROPERTIES

Mixture	NAT-0.6	REC-0.3	REC-WRA-0.3	REC-FA-0.6
Water to Cement Ratio, w/c	0.6	0.3	0.3	0.6
Water to Cementitious Material Ratio, w/cm	0.6	0.3	0.3	0.3
Mixture proportions, kg/m^3				
Water	230	230	165	230
Cement	380	760	550	380
Fly Ash		—	—	380
Natural Sand	314	—	—	—
Crushed Aggregate	1,338	—	—	—
Fine Recycled Fraction	—	—	372	—
Coarse Recycled Fraction	—	1,169	1,060	1,057
Superplasticizer	—	—	5.5	6.8
Properties				
Compressive Strength, 28-day, MPa	27	32	30	28
Carbonation Depth, 7 days, mm	3.3	0.8	1.5	2.2
Chloride Penetration, 7 days, mm	12.5	8	7.3	6
Diffusion Coefficient at 20°C, cm^2/s x 10^{-6}	1.9	0.87	0.72	0.46
Weight Change at 200 Cycles, %	99.6	99.63	100.3	100.2

After Corinaldesi and Moriconi (2008).
Some property values were estimated from graphs provided in the reference.
— = no data.

ing concrete pavement, using RCA in unstabilized (granular) subbases, and using RCA in concrete paving mixtures. Recommended AASHTO and ASTM standards for use with RCA in highway applications were also included in the appendices.

PCA (2010) reported on the placement of one RCA PCC and a control section in gate lanes at O'Hare Airport in 2009. The RCA was produced on-site using PCC recycled at the airport and the ready mix supplier treated the RCA PCC like a lightweight PCC. Comments from the contractor indicated the RCA PCC had similar workability and finishing characteristics as the conventional PCC control materials. Sensors were placed in the concrete to measure the internal relative humidity, temperature, and lift-off of the slab from the cement-treated permeable base. Surface appearance and joint width were also monitored. After 5 months the measured properties of the two lanes were not statistically different.

TABLE 38
SUMMARY OF RCA CONCRETE PAVEMENT STRUCTURAL DESIGN CONSIDERATIONS

Design Element	Recommendation
Pavement Type	JPCP panel length ≤ 15
	JRCP and CRCP interlock needs to be improved with larger top size aggregate or blend of new/RCA coarse aggregate
Slab Thickness	Same as conventional PCC if adequate strength achieved
	Two-course construction: overall slab thickness may need to be increased depending on materials and mix proportions
Joint Spacing	Select to minimize mid-panel cracking
Load Transfer	Same as conventional PCC
Joint Sealant Reservoir Design	Select for shrinkage and thermal movement
Subbase Type	Select for structural requirement
	Consider free-draining subbase for RCA produced from D-cracked and ASR-damaged concrete
Reinforcement	May require higher amounts of longitudinal steel in JRCP and CRCP
Shoulder Type	Same as for conventional PCC

After ACPA (2008).
CRCP = continuously reinforced concrete pavement; JRCP = jointed reinforced concrete pavement.

UNBOUND APPLICATIONS

FHWA (2004) identified four main uses for unbound RCA:

1. Base and subbase
2. Rip rap
3. Erosion control
4. Specialty uses such as establishment of oyster beds (artificial reef).

The performance advantages to using RCA were increased structural strength in the base that increased the structural support, 100% use of the RCA in base applications, stable platforms for building, and the potential to minimize D-cracking and ASR in the old concrete. One potential disadvantage was that reflective cracking increased as a result of an overly stiff base.

The documented information found in the literature focused on the use of RCA as structural fill, base, and subbase applications.

ReTAP (1998) investigated the use of nuclear density gauges to evaluate the moisture and density of RCA structural fill for QC purposes. It was considered desirable to adapt the same equipment for RCA base testing as is currently used for density testing conventional structural fill material. The nuclear moisture-density gauge measures the total hydrogen content, which in the case of natural materials is solely a function of the moisture content. However, the RCA contributes to the hydrogen counts as well as the water in the material. This resulted in the recording of higher moisture contents and lower densities than were actually present.

The research evaluated two modifications to the conventional nuclear density testing procedures. The first method used compaction specifications bases on determining the wet density (modified Proctor curve). Moisture density curves were developed for two RCA gradations samples (minus 32 mm and minus 19 mm). The second approach set the compaction specification using moisture content correlation curves based on the development of field nuclear moisture and laboratory moisture contents relationships.

Results for the first method (modified Proctor) showed that field nuclear moisture contents varied between 9% and 20%, and the laboratory moisture between 4% and 11%. At low moisture contents, the nuclear gauge recorded densities about twice that of the laboratory density. The difference in results increased with moisture content. That is, the relationship between laboratory and field moisture was nonlinear.

The correlation equation approach showed that the nuclear gauge consistently measured the moisture content as twice that of the laboratory moisture (linear relationship). The authors recommended this approach because it was simple to use and the QC program could be implemented using confirmation samples for every 250 to 500 cubic yards of material placed (6 in lift evaluated).

Kuo and Chini (2001) summarized the findings for RCA research that showed that RCA could be used effectively when QC techniques were implemented. The research recommended the following guidelines and specifications for Florida. The first step in a recycling QC program was to use a recycling facility to provide RCA, which has been prepared to meet material properties for gradation; limestone bearing ratio, which is Florida's version of CBR; LA abrasion; sodium sulfate soundness; sand equivalent; heavy metals; optimum moisture content and maximum dry weight; permeability; impurities; and application mechanical properties such as resilient modulus. Fractured concrete sources needed to have separate storage for individual buildings and/or facilities and the reinforcing steel must have been removed. Impact mills needed to be used to crush rubble and air classifiers used to remove lightweight debris such as wood and plastic. The RCA needed to be washed before use and additional testing used to estimate tufa precipitation. The RCA had to possess comparable compressive and shear strengths similar to natural aggregates and meet graduation requirements. No harmful impurities such as lead or asbestos were allowed or RCA content that reacted with either cement or reinforcement. The output quality needed to guarantee by systematic and rigorous monitoring intensive sampling and testing of material characteristics.

The AASHTO (2002) Standard Specification for Designation M 319-02 (Reclaimed concrete aggregate for unbound soil-aggregate base course) had physical property requirements for Atterberg limits, sand equivalent, LA abrasion, and deleterious substances. The liquid limit is not to be greater than 30 and the plasticity index not greater than 4. The sand equivalent needed to be a minimum of 25% for the 0.425 fraction. The LA abrasion loss needed to be 50% at the most. The deleterious substances needed to be limited to not more than 5% bituminous concrete materials, not more than 5% brick by mass, free of solid waste or hazardous materials, and substantially free of wood, metal, plaster, and gypsum board. If more than 5% bituminous material was included, a validation of support value is required using AASHTO T193 (CBR), AASHTO T292 (resilient modulus), or validation by field testing.

Compaction was controlled by comparing the in-place density with maximum dry Proctor density when the RCA is from a consistent source. When the source of RCA was not consistent, alternative procedures were used to continually adjust the moisture content to determine maximum density.

Tufa-like deposits may clog drainage features, so the use of RCA required validation by field experience (3 years of experience with RCA and the same geotextile) or comparative permeability testing by ASTM D5101.

FHWA (2004) reported that MnDOT used almost 100% of the RCA produced in the state as base material as it performed better than standard base materials. Minnesota did not apply quality requirements for new aggregates for the RCA, which comes from known sources. The DOT currently crushes the old concrete on-site, which results in a reduction in the number of haul trucks and fuel consumption. The main recommendation for post-processing was washing RCA to eliminate excess fines.

RCA could be used as a filter/separation layer under a permeable aggregate base drainage layer in accordance with the applicable drainage specifications. A blend of RCA with new aggregate could be used near drainage systems when at least 95% of the RCA was retained on the 4.75 mm sieve. When RCA was used with edge drains, the fines (minus 4.75 mm size) needed to be minimized in drained, unstabilized pavement foundation layers and drainage system designs needed to accommodate increased fines. The use of RCA fines should be restricted to areas below drainage systems that use drainage pipes with or without fabric with high initial permeability. Alkaline effluent from the RCA layer was not a significant issue when RCA was kept a sufficient distance from the drainage outlets. A blend of open-graded RCA with new aggregate could be used for improved stability and density.

The regulations for the use of RCA included a permanent rule relating to the beneficial use of solid waste, which will be instrumental in establishing a database of information on other non-RCA recycled source materials. The lack of data and base line on effluent leachate and particulate quality was considered a barrier because of the new National Pollutant Discharge Elimination System (NPDES) and Total Maximum Daily Load (TMDL) rules.

MDOT instituted changes in the design of a permeable base that could be met with RCA by increasing the density of the base and modifying the design of the fabric drainage system to address clogging of systems.

The California DOT removed most old highway PCC from the roadway and post-processed for use as an RCA base. There were no constraints on contaminates. The city of San Francisco was exploring nonstructural concrete options using RCA. RCA was exempt from solid waste regulations as long as it remained on the construction site. State legislation required state agencies to divert at least 25% of solid waste away from landfills.

Blankenagel and Guthrie (2006) noted that RCA for base material only became available for use as base material in Utah around 2000. A field test site that used demolition RCA to construct a parking area near the east side of Utah Lake was constructed in 2004. The RCA was placed on a geotextile and capped with HMA. Testing for layer thickness was accomplished using a dynamic cone penetrometer and to estimate the CBR values using the rate of penetration, and ground penetrating radar was used to evaluate the uniformity of the layers (Table 39). The stiffness was evaluated by three methods (Clegg impact value, soil stiffness gauge, and portable falling weight deflectometer). The results were variable over the length of the test section. The author estimated that the RCA base was about 25% less expensive than natural aggregates for construction applications.

Landsaver (2006) described the use of reclaimed concrete aggregate as a designation for structural fills. This document recommended crushed concrete base defined by criteria for structural integrity, which included gradations to meet AASHTO M43 with at most 5% fines. The reclaimed concrete aggregate needed to meet ASTM D2488 for angular and subangular classification. Deleterious materials were limited to a maximum of 20% reclaimed pavement materials and a maximum of 0.15% building materials. The material hardness needed to be evaluated as indicated by a maximum loss of 40% in the LA abrasion test (AASHTO T96). The freeze-thaw resistance was limited to a maximum loss of 12% after five cycles in magnesium sulfate solution. An example of RCA use in a drainage system design is shown in Figure 8.

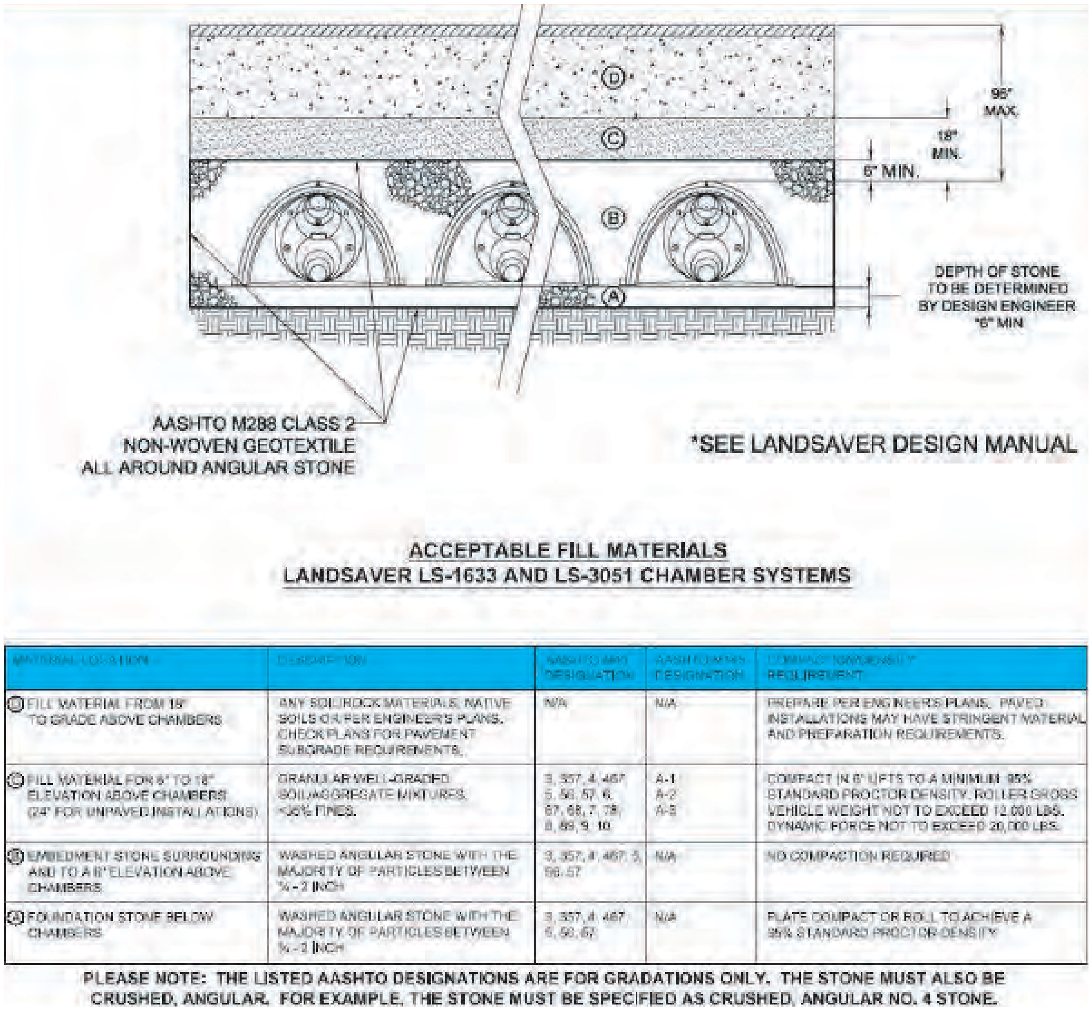
ACPA (2008) provided recommendations for the design, construction, and QC of RCA base and subbase in pavement applications. Pavement design needed to consider the stiffer RCA layer properties compared with unstabilized base materials, which was a function of the additional hydration associated with the RCA materials. The stiffening effect was enhanced when using dense gradations with high RCA fines contents.

Properties that influenced the performance of RCA base materials for pavements included aggregate toughness, frost

TABLE 39
IN SITU PROPERTIES FOR RCA BASE FOR 11 TEST LOCATIONS, ONCE A MONTH FOR THREE SUMMER MONTHS

Properties of Recycled Materials		Demolition
CBR from DCP		12 to 65
Stiffness	Clegg impact	10.15 to 21.45
	Soil stiffness, MN/m	7.65 to 24.95 (June 2004)
		6.13 to 11.5 (May 2005)
	Portable falling weight deflectometer, kN/m^2	23 to 298

After Blankenagle (2005).
DCP = dynamic cone penetrometer



ACCEPTABLE FILL MATERIALS
LANDSAVER LS-1633 AND LS-3051 CHAMBER SYSTEMS

MATERIAL LOCATION	DESCRIPTION	AASHTO M43 DESIGNATION	AASHTO M145 DESIGNATION	COMPACTION/DENSITY REQUIREMENT
Ⓓ FILL MATERIAL FROM 18" TO GRADE ABOVE CHAMBERS	ANY SOIL/ROCK MATERIALS, NATIVE SOILS OR PER ENGINEER'S PLANS. CHECK PLANS FOR PAVEMENT SUBGRADE REQUIREMENTS.	N/A	N/A	PREPARE PER ENGINEER'S PLANS. PAVED INSTALLATIONS MAY HAVE STRINGENT MATERIAL AND PREPARATION REQUIREMENTS.
Ⓒ FILL MATERIAL FOR 6" TO 18" ELEVATION ABOVE CHAMBERS (24" FOR UNPAVED INSTALLATIONS)	GRANULAR WELL-GRADED SOIL/AGGREGATE MIXTURES, <35% FINES.	3, 357, 4, 467, 5, 56, 57, 6, 67, 68, 7, 78, 8, 89, 9, 10	A-1 A-2 A-3	COMPACT IN 6" LIFTS TO A MINIMUM 95% STANDARD PROCTOR DENSITY. ROLLER GROSS VEHICLE WEIGHT NOT TO EXCEED 12,000 LBS. DYNAMIC FORCE NOT TO EXCEED 20,000 LBS.
Ⓑ EMBEDMENT STONE SURROUNDING AND TO A 6" ELEVATION ABOVE CHAMBERS	WASHED ANGULAR STONE WITH THE MAJORITY OF PARTICLES BETWEEN ¾ - 2 INCH	3, 357, 4, 467, 5, 56, 57	N/A	NO COMPACTION REQUIRED
Ⓐ FOUNDATION STONE BELOW CHAMBERS	WASHED ANGULAR STONE WITH THE MAJORITY OF PARTICLES BETWEEN ¾ - 2 INCH	3, 357, 4, 467, 5, 56, 57	N/A	PLATE COMPACT OR ROLL TO ACHIEVE A 95% STANDARD PROCTOR DENSITY

PLEASE NOTE: THE LISTED AASHTO DESIGNATIONS ARE FOR GRADATIONS ONLY. THE STONE MUST ALSO BE CRUSHED, ANGULAR. FOR EXAMPLE, THE STONE MUST BE SPECIFIED AS CRUSHED, ANGULAR NO. 4 STONE.

FIGURE 8 Example of use of RCA in drainage system design (after Landsaver 2006).

susceptibility, shear strength, and stiffness. Recommendations for QC/QA testing included micro-Deval (AASHTO T327), tube suction, static triaxial (AASHTO T234), repeated load testing, and resilient modulus. Research cited by the ACPA guidelines and reported by Saeed and Hammons (2008) defined recommendations for QC/QA differences in PCC when using RCA for a range of traffic, moisture, and climate conditions (Table 40). Unbound RCA bases should limit the fines content to prevent clogging drainage features and be used below the drainage systems. Stabilizing the RCA could bind excess fines.

AQA (2007), the Aggregate and Quarry Association of New Zealand, prepared guidelines for light to medium trafficked roadways (Class A); base courses (Class B); fill (Class C); urban, rural development, and embankments (Class D); and fill for drainage lines and drainage structures (Class E). According to this reference, sources of RCA should include crushed concrete, bricks, masonry roof tile (concrete or terracotta), ceramic tile, or rock. The material quality was assessed by determining the product of the percent passing the 0.425 sieve times the plasticity index (i.e., PI × $\%P_{0.425\ \text{mm}}$) to ensure that both properties were not at the upper limits for the same material.

QC provides suggested frequencies for testing for RCA byproduct control (Table 41). Production planning included defining reference specimens, production control tests, and control charting of test data. QC charts were constructed for each type of material and each durability and strength test property.

It is important that quality assurance plans have at a minimum:

- Product identification and traceability
- Process control
- Inspection and testing
- Inspection and test status
- Control of nonconforming product
- Corrective and preventive action
- Handling and storage of product
- Control of quality records.

An article, Close the Loop (2010), noted that RCA is used as an alternative to Class 2, 3, and 4 crushed rock in stabilized road base in Canada (VicRoad). The Class 2 was used

TABLE 40
RECOMMENDED RCA SUBBASE QUALITY TESTS AND VALUES FOR VARIOUS APPLICATIONS

Tests		Traffic, ESALs per Year									
		<1 M	<1 M	100,000 to 1 M		<1 M	<1 M	100,000 to 1 M	100,000	100,000 to 1M	100,000
		Moisture									
		High	Low	High	Low	High	Low	Low	High	High	Low
		Climate									
		Freeze	Freeze	Freeze	Freeze	Non-Freeze	Non-Freeze	Freeze	Non-Freeze	Non-Freeze	Non-Freeze
		Test Limits for Various Traffic, Moisture, and Climate Conditions									
Micro Deval, % loss		<5	<5	<5	<15	<15	<15	<15	<30	<30	<45
Tube Suction Test (dielectric constant)		≤ 7	≤ 7	≤ 7	≤10	≤10	≤10	≤10	≤15	≤15	≤20
Static Triaxial Test, maximum deviator stress, psi	OMC 5 psi stress	>100	>100	>100	≥60	≥60	≥60	≥60	≥25	≥25	Not required
	Sat. 15 psi stress	>100	>100	>100	≥135	≥135	≥135	≥135	≥60	≥60	Not required
Repeated Load Test, failure deviator stress, psi	OMC, 15 psi stress	≥180	≥180	≥180	≥160	≥160	≥160	≥160	≥90	≥90	Not required
	Sat. 15 psi stress	≥180	≥180	≥180	≥160	≥160	≥160	≥160	≥60	≥60	Not required
Resilient Modulus, ksi		≥60	≥60	≥60	≥40	≥40	≥40	≥40	≥25	≥25	Not required

After APCA (2008); Saeed and Hammons (2008).
OMC = optimum moisture content; ESAL = equivalent single axle load.

directly below the pavement surface and has the highest quality material requirements. The material quality requirements decreased with increasing class number. The cost of the recycled concrete in Victoria, Canada, needed to be competitive with natural aggregate. The cost was quoted on a weight basis. Recycled concrete had a lower unit weight (low density); the cost per ton would be lower than for conventional aggregate. The quality of the byproduct was accomplished with written verification supplied by the manufacturer. The article also noted that mobile technology increased options for recycling.

ECCO (1997) reported that contractors and subcontractors used in-place concrete recycling to prepare an RCA base on a 4.8 mile highway reconstruction project on I-80 near Des Moines, Iowa. A primary crusher was adapted for in-place recycling by placing it on crawler tracks. A secondary crusher was towed behind the primary crusher and was also placed on crawler tracks. The equipment design was patent pending at the time the article was published (i.e., Paradigm system).

In 1995, the contractor elected to use this in-place recycling process on about 20 miles of work on I-30 just outside of Little Rock, Arkansas. The DOT let the contractor select the recycling method. Production rates depended on the amount of steel and the material properties. A rate of 2,000 ft per day for one lane width for the eastbound lane was achieved. The contractor expanded crushing equipment to span the full width of the roadway for the westbound lanes,

TABLE 41
DRAFT OF NEW ZEALAND GUIDELINES FOR RCA MATERIALS
FOR VARIOUS HIGHWAY APPLICATIONS

Test	Suggested Number of Tests per Cubic Meter				
	Class A	Class B	Class C	Class D	Class E
Grading	3	2	2	2	2
Index Properties	3	2	2	2	2
Strength Properties	1	1	1	1	1
Particle Shape	3	2	1	1	1
Foreign Material	1	1	1	1	1

After AQA (2010).

which improved the production rate. The RCA used for new subbase and the steel was recycled as scrap.

There were seven main steps for the in-place recycling process. First, the joint seal material was removed. Second, ditches were cut for drain. A guillotine breaker was used to crack PCC and expose steel and the broken PCC was pulled up with a track hoe equipped with a rhino horn. Labors used bolt cutters to cut wire mesh and dowels. A bucket-equipped track hoe fed broken concrete into the primary impact crusher with a three deck screen in tow along with an 8,000 gallon water truck for dust control. Conventional equipment was used to shape and compact the subgrade.

The original reconstruction design required 4 in. of aggregate base, 4 in. of asphalt permeable base, and a 12-in.-thick concrete pavement. However, issues during the first half of the project that needed to be overcome were poor soil conditions; expansive and wet soils resulted in stability problems. These site conditions were the main causes of failure of the original pavements, which was faulting at the joints. The DOT and contractor partnered to redesign the last half of the section using a stabilization fabric placed on the original subbase before placing original design in the eastbound lane. The westbound lane removed 4 in. of the poor soil subgrade, placed fabric, then 8 in. of RCA, followed by 4 in. of permeable asphalt base and 12 in. of PCC pavement. The benefits achieved using in-place recycling included 25,000 to 30,000 gallons of truck fuel, 95,000 tons of crushed stone base, and reduced bid prices (not specified).

SITE LOCATION

Robinson and Kapo (2004) used regional aggregate production operations (Virginia, Maryland, and the District of Columbia) to develop spatial association models for the recycled aggregate industry based on the regional transportation network and population density. Both urban and developing areas provided a high demand for aggregate products that resulted in RCA recycling facilities being located in counties with population densities in excess of 200 people per square mile. None are located in areas with fewer than 50 people per square mile. This was attributed to the lack of a CDW source in the lower population areas and a lower aggregate production demand.

Geographical Information System (GIS) analysis was used to develop a spatial prediction model using two parameters: county population density and transportation proximity. One drawback was the size of scale for which county and census data were available. This made small local differences in parameters difficult to see in the analysis. GIS modeling was used to quickly identify optimum locations for recycling operation placement. The approach simplified the information needed for the analysis and prior knowledge of cost inputs were not needed before the model could be developed. The GIS approach did not have to assume that sources of supply or sites of consumption were fixed in space and time. The data-drive weight of evidence (WofE) method measured and optimized spatial associations between potential RCA production sites locations and map patterns. The hypothesis was that an area is suitable for the occurrence of a type of site, defined by a response variable with respect to a set of predictor variables.

In this study, the response variable was the set of point locations for current RAP and RCA recycling sites (referred to as training sites for the program). Predictor variables (referred to as evidence themes) were the map layers showing transportation network patterns, population density distribution, and natural aggregate site locations and production information. Weighted pairs were calculated relative to the training sites, one for the presence of evidence criteria (w+) and one for the absence of criteria (w–). The difference between the weights was used as an indication of the strength of the association between sites and themes. A difference of zero indicated random distribution. An ArcSDM extension for ArcView was used for the weighted logistic regression and WofE evaluations.

Sources of data were 65 sites of operations that produced RCA. The sites had been active from 1997 through 2001. RAP was produced at 37 of the sites, while 28 sites (12 in Maryland and 16 in Virginia) produced RCA. Site locations were spatially overlaid on both population and transportation network GIS maps. Aggregate production (an evidence theme) was designated as "excess" when the aggregate produced at a location exceeded their demand by more than 133% for product. A rating of "deficient" was assigned when the aggregate demand exceeded the production quantity by more than 33%. "Sufficient" was used to represent an approximate balance between supply and demand. Spatial data of population was provided at two different scales: county and census. The census track scale used areas of a few tens of square kilometers to indicate proximity to construction markets and local settings of recycling facilities. The county scale provided an indicator of the regional construction market place.

Table 42 summarizes the results from the analysis. None of the recycling facility sites were located in the lowest population category. The slight decline in the sites located in the highest census population area (>722 people per kilometer) may indicate increased difficulty in obtaining permits or space for recycling in the highest density areas. The results suggested there may be an optimum population that balances need with restrictions. Sites were also located within short distances of interstates. More than 60% of the sites were located within 4.8 miles of an interstate entrance. The market competition could have been more of an influence on facility locations than the demand for recycled RCA.

A number of agencies provided comments with regard to barriers to wider use of recycled PCC byproducts (Table 43). Two states noted concerns with RCA meeting specification requirements when used in unbound application. Design concerns focused on leachate properties, high fines content, and wider ranges of RCA material properties. General considerations included primarily a lack of locally available RCA byproducts followed by QC and perception topics.

TABLE 42
LOCATION OF RECYCLING FACILITIES WITH RESPECT TO AREA DENSITY, PROXIMITY TO INTERSTATE, NATURAL AGGREGATE PRODUCTION SITES, AND AVAILABILITY OF AGGREGATE SUPPLIES

Evidence	Criteria	Number of Sites	Area, %
Population Density (county)	0–77 people/ km^2	0	77.9
	77–386 people/km^2	7	13.6
	>386 people/ km^2	21	8.5
Population Density (census tract)	0–39 people/ km^2	0	73.2
	39–722 people/ km^2	16	23.6
	>722 people/ km^2	12	3.2
Proximity to Interstate Highway	Outside 4.8 km	8	85.9
	Within 4.8 km	20	14.1
Proximity to Natural Aggregate Production Sites	Outside 8 km	17	85.2
	Within 8 km	11	14.8
Aggregate Production Status	Excess aggregate supply	4	43.5
	Sufficient aggregate supply	11	16.9
	Deficient aggregate supply	13	39.6

After Robinson and Kapo (2004).

TABLE 43
BARRIERS NOTED BY STATE AGENCIES WHICH WILL RESTRICT THE USE OF RECYCLED PCC BYPRODUCTS

State	Barriers
Use as Aggregate	
GA	Contractors are still somewhat reluctant to go to the effort to process the material such that it meets our GAB specification.
WI	Aggregate gradation issues
Design Barriers	
DC	Drainage problem in wet areas
FL	Typically the alkalis are a problem and other unknowns such as admixtures (chloride accelerators) may be in the recycled materials so we restrict their use in structural concrete. Roadway GAB use is hindered by producers not meeting gradation specification bands.
KY	Specifically, Kentucky has experienced environmental and leachate concerns with the usage of reclaimed hardened concrete.
NC	How to handle high fines generated when crushing for use in fresh concrete
NE	They do not drain as well as some other foundation materials, but we design for that.
PA	Materials management of reclaimed hardened concrete materials from mixed sources where some sources may not have used air entrained concrete which may break down under freeze/thaw conditions. Concerns over formation of tufa and affects on drainage of this material.
UT	UDOT specs typically are based on performance. Mix designs and uses allow the use of most materials as long as it meets the spec.
VA	These products do not lend themselves to normal statistical quality control measures; i.e., crushed concrete has increased liquid limit when compared to conventional.
General Barriers	
IL	Illinois used recycled concrete back into a PCC pavement in the late 90s. We are currently evaluating that pavement because it will be overlaid with HMA next summer. There were some issues with the pavement but most were due to poor construction rather than the RCC.
LA	Tracking of source of "raw" material prior to crushing
MD	We are ready to accept more. The use of recycled RCA material will be reviewed and evaluated with environmental, engineering, and quality assurance teams.
MO	Always thought of waste product in the past
MS	Availability of crushed concrete
NC	Limited supply of concrete to be crushed for use as aggregates
NV	Limited availability
OH	ODOT is just currently adopting a specification to use RCM as aggregate in portland concrete. We will be limiting fines as the control of the mixes is a real problem.
TX	Supply is somewhat limited for use as a coarse aggregate.
WA	We are not reconstructing much PCC, so there is not much product to reuse.

SUMMARY OF RECYCLED CONCRETE AGGREGATE INFORMATION

List of Candidate Byproducts

The main term used to identify recycled PCC used in highway applications is RCA. The definition of the term by FHWA limited the source of recycled PCC to that obtained from highway projects only. However, recycling facilities and some researchers used the same term to mean RCA obtained from any concrete material (e.g., residential and commercial building demolition). Communications between users and sources of RCA need to focus on definition specifics. It is important that agencies make sure that when they allow the use of RCA, they actually receive the desired byproduct.

In addition, suppliers of fresh PCC have used recycled PCC in three ways:

- Fresh concrete reused in other loads of fresh concrete.
- End of day hardened PCC, fractured (washed or unwashed for fines control).
- Washed fresh concrete to recover the original components (primarily aggregates).

These recycled materials, while potentially useful in highway applications, will have different physical and chemical properties than those of old recycled concretes.

In one case, cracked and seated as well as rubblized PCC concrete pavements were considered RCA PCC byproducts. The use and classification of RCA sources need to be consistently and uniformly defined to avoid confusion in specifications.

Test Procedures

A wide range of specifications and test procedures have been used to evaluate recycled byproducts and the hybrid application products (Tables 44–46).

Material Preparation and Byproduct Quality Control

Preparation procedures are needed for each of the individual RCA byproducts. RCA from old highway projects and from construction demolition waste have five main steps in common:

1. Removal of as many potential contaminates before demolition of PCC as possible
2. Demolition of structure
3. Crushing and sizing RCA
4. Secondary removal of contaminates
5. Removal of dust and fines (air blowing or washing).

Although the steps are the same, the work needed to produce quality RCA is significantly more involved for CDW byproducts than for PCC highway structures. The increased physical and chemical property variability will require increased QC testing during construction.

Materials Handling Concerns

Different sources of RCA must be kept separate if at all possible if high quality and RCA with consistent properties are to be obtained. RCA, regardless of source, tends to significantly increase the water demand during mixing. The best way to control the variability within and between stockpiles of RCA is to maintain constant moisture content. Sprinkling systems are recommended along with increased testing for stockpile moisture contents.

It is important that stockpiles of RCA be constructed so that nearby water sources are not affected by alkaline content.

Transformation of Marginal Materials

Washing of the RCA can be used to improve the fines content of the RCA byproducts. The use of fly ash with the RCA will improve the ASR resistivity and decrease the volume changes in RCA PCC.

Design Adaptations

The water to cement, or cementitious materials, ratio may need to be adjusted to maximize workability. Alternatively, water reducers or superplasticizer can be used to maintain strength requirements while achieving a workable mix. The PCC mix

TABLE 44
AASHTO SPECIFICATIONS FOR USING RCA IN HIGHWAY APPLICATIONS

AASHTO	Title
M6	Standard Specification for Fine Aggregate for Hydraulic Cement Concrete
M43	Standard Specification for Sizes of Aggregate for Road and Bridge Construction
M80	Standard Specification for Coarse Aggregate for Hydraulic Cement Concrete
M92	Standard Specification for Wire-Cloth Sieves for Testing Purposes
M146	Standard Specification for Terms Relating to Subgrade, Soil-Aggregate, and Fill Materials
M147	Standard Specification for Materials for Aggregate and Soil-Aggregate Subbase, Base, and Surface Courses
M319	Standard Specification for Reclaimed Concrete Aggregate for Unbound Soil-Aggregate Base Course
MP16	Standard Specification for Reclaimed Concrete Aggregate for Use as Coarse Aggregate in Hydraulic Cement

After ACPA (2008).

TABLE 45
AASHTO TEST METHODS FOR EVALUATING RCA AND RCA PCC APPLICATIONS

AASHTO	Title
T2	Standard Method of Testing for Sampling of Aggregates
T11	Standard Method of Test for Materials Finer Than 75 um (No. 200) Sieve in Mineral Aggregates by Washing
T19	Standard Method of Test for Bulk Density (“Unit Weight”) and Voids in Aggregate
T27	Standard Method of Test for Sieve Analysis of Fine and Coarse Aggregates
T85	Standard Method of Test for Specific Gravity and Absorption of Coarse Aggregate
T87	Standard Method of Test for Dry Preparation of Disturbed Soil and Soil-Aggregate Samples for Test
T88	Standard Method of Test for Particle Size Analysis of Soils
T89	Standard Method of Test for Determining the Liquid Limit of Soils
T90	Standard Method of Test for Determining the Plastic Limit and Plasticity Index of Soils
T96	Standard Method of Test for Resistance to Degradation of Small-Size Coarse Aggregate by Abrasion and Impact in the Los Angeles Machine
T99	Standard Method of Test for Moisture-Density Relationships of Soils Using a 2.5 kg (5.5 lb) Rammer and a 305 mm (12 in.) Drop
T103	Standard Method of Test for Soundness of Aggregates by Freezing and Thawing
T104	Standard Method of Test for Soundness of Aggregate by Use of Sodium Sulfate or Magnesium Sulfate
T112	Standard Method of Test for Clay Lumps and Friable Particles in Aggregate
T113	Standard Method of Test for Lightweight Pieces in Aggregate
T161	Standard Method of Test for Resistance of Concrete to Rapid Freezing and Thawing
T176	Standard Method of Test for Plastic Fines in Graded Aggregates and Soils by Use of the Sand Equivalent Test
T180	Standard Method of Test for Moisture-Density Relations of Soils Using a 4.54 kb (10 lb) Rammer and a 457 mm (18 in.) Drop
T193	Standard Method of Test for the California Bearing Ratio
T196	Standard Method of Test for Air Content of Freshly Mixed Concrete by the Volumetric Method
T234	Standard Method of Test for Strength Parameter of Soils by Triaxial Compression
T260	Standard Method of Test for Sampling and Testing for Chloride Ion in Concrete and Concrete Raw Materials
T277	Standard Method of Test for Electrical Indication of Concrete’s Ability to Resist Chloride Ion Penetration
T299	Standard Method of Testing for Rapid Identification of Alkali-Silica Reaction Product in Concrete
T303	Standard Method of Test for Accelerated Detection of Potentially Deleterious Expansion of Mortar Bars Due to Alkali-Silica Reaction
T307	Standard Method of Test for Determining the Resilient Modulus of Soils and Aggregate Materials
T327	Standard Method of Test for Resistance of Coarse Aggregate to Degradation by Abrasion in the Micro Deval Apparatus

After ACPA (2008).

design testing needs to include evaluations of freeze-thaw and ASR resistivity as well as volume changes as a result of drying and thermal contractions and expansions.

Structural designs need to consider that there will be lower specific gravities, compressive and tensile strengths, and resilient moduli values. RCA PCC will also likely have higher water demands, creep, drying shrinkage, permeability, coefficients of thermal contraction/expansion, corrosion rate, and carbonization. Sulfate resistance will be dependent on the mixture components.

When RCA is used in drainage systems it needs to be used below the drainage lines to prevent contamination of the water supply. Filter fabrics need to be chosen so that they are not clogged by the fines and carbonation byproducts.

Construction Issues

If the water demand-related workability issues are adequately addressed during the mix design, then construction processes should not be different when using RCA PCC compared with conventional PCC. Additional testing will be needed for process control programs.

Failures, Causes, and Lessons Learned

Good stockpile management and processing improved the uniformity of the byproducts. Byproducts that were sorted by source and original material characteristics (e.g., original compressive strength requirements) improved the usability of the recycled byproducts. The quality and uniformity of the construction material was improved by the organization and staging of the removal/demolition of the original structure components.

Mix designs were adjusted to compensate for the influence of byproduct characteristics on binder content and workability. ASR and sulfate resistance was addressed with either pozzolans or chemical admixtures. High shrinkage characteristics were considered carefully in the mix design phase so that early cracking failures were avoided. Changes in the selection and use of virgin materials and/or the use of additives were made to improve the workability and performance of the final product.

TABLE 46
ASTM TEST METHODS FOR EVALUATING RCA AND RCA PCC APPLICATIONS

ASTM	Title
ASTM C33	Standard Specification for Concrete Aggregates
ASTM C88	Standard Test Method for Soundness of Aggregates by Use of Sodium Sulfate or Magnesium Sulfate
ASTM C125	Standard Terminology Relating to Concrete and Concrete Aggregates
ASTM C131	Standard Test Method for Resistance to Degradation of Small Size Coarse Aggregate by Abrasion and Impact in the Los Angeles Machine
ASTM C173	Standard Test Method for Air Content of Freshly Mixed Concrete by the Volumetric Method
ASTM C227	Standard Test Method for Potential Alkali Reactivity of Cement Aggregate Combinations (Mortar Bar Method)
ASTM C289	Standard Test Method for Potential Alkali Silica Reactivity of Aggregates (Chemical Method)
ASTM C395	Standard Guide for Petrographic Examination of Aggregates for Concrete
ASTM C342	Standard Test Method for Potential Volume Change of Cement Aggregate Combinations (withdrawn 2001)
ASTM C441	Standard Test Method for Effectiveness of Pozzolans or Ground Blast Furnace Slag in Prevent Excessive Expansion of Concrete Due to the Alkali Silica Reaction
ASTM C586	Standard Test Method for Potential Alkali Reactivity of Carbonate Rocks for Concrete Aggregates (Rock Cylinder Method)
ASTM C618	Standard Specification for Coal Fly Ash and Raw or Calcined Natural Pozzolan for Use in Concrete
ASTM C666	Standard Test Method for Resistance of Concrete to Rapid Freezing and Thawing
ASTM C856	Standard Practice for Petrographic Examination of Hardened Concrete
ASTM C1202	Standard Test Method for Electrical Indication of Concretes Ability to Resist Chloride Ion Penetration
ASTM C1293	Standard Test Method for Determination of Length Change of Concrete Due to Alkali Silica Reaction
ASTM C1567	Standard Test Method for Determining the Potential Alkali Silica Reactivity of Combinations of Cementitious Materials and Aggregate (Accelerated Mortar Bar Method)
ASTM D2940	Standard Specification for Graded Aggregate Material for Bases or Subbases for Highways or Airports
ASTM D5101	Standard Test Method for Measuring the Soil-Geotextile System of Clogging Potential by the Gradient Ratio
ASTM D6928	Standard Test Method for Resistance of Coarse Aggregate to Degradation by Abrasion In the Micro Deval Apparatus

After ACPA (2008).

Barriers

Barriers noted in the agency surveys and the literature review included:

- Increased byproduct and hybrid product variability in material and chemical properties,
- Needed considerations in application designs for fines contents and lower quality materials and products,
- Lack of locally availability of RCA byproducts,
- Needing to compete economically with new aggregate sources, and
- Increased need for QC/QA testing.

Costs

The costs of recycling PCC byproducts varied by source of PCC byproduct, region of country, and the quality needed for a given highway application. RCA used in unbound or non-structural concrete had less restrictive physical and chemical requirements. The cost of using RCA needed to be less than the tipping fees charged for landfilling PCC waste. The cost of RCA also needed to compete with the cost of purchasing new aggregates.

In some cases, the contractor achieved cost savings when using RCA because of the reduced number of haul trucks and reduced fuel consumption. Agencies limited project costs because of declining needs to alter existing highway features such as curbs, gutters, and overhead clearances.

Gaps

The following gaps were noted from the agency surveys and literature reviews:

- Lack of consistent terminology
- Lack of information on material variability
- Best practices guidelines for various RCA byproduct sources
- Design guidelines for various highway applications using RCA byproducts
- Cost and environmental savings data.

CHAPTER EIGHT

CONSTRUCTION AND DEMOLITION WASTE

The FHWA definition of RCA narrowly limits the sources of old PCC to reclaimed highway pavements and some states expand the definition to include reclaimed bridge PCC. Florida Administrative Code 62-701.200 (25) defines construction and demolition debris as ". . . discarded materials generally considered to be not water soluble and non-hazardous in nature including but not limited to steel, glass, brick, concrete, asphalt material, pip, gypsum wallboards, and lumber, from the construction or destruction of structures. . . ." Until recently, little work has been done in the United States on the use of CDW byproducts in highway applications.

Most of the information on this byproduct was found in the international publications and research.

The main barriers to the use of CDW in highway applications were identified by Lauritzen (2004 a,b). An integrated resource management plan is needed to overcome the most common barriers and should be comprised of the following components:

- Selective demolition
- Recycling, reuse, recovery
- Handling of hazardous waste and nonrecyclable materials
- Transportation
- Substituting (savings) of natural resources.

Demolition, processing, and recycling processes are to be designed and evaluated as a single process to produce a quality byproduct for construction use. Sorting of recyclable materials at the construction site, or recycling facility, was needed. Optimal sorting of materials starts with the development of the demolition process and technologies (selective demolition) and correct handling of the recyclable materials. This took more time and planning than traditional demolition. Until recently, demolition has been considered a low tech process, with rapid removal and disposal being the main focus. Quality standards for recycled materials were needed as was education and technology transfer. This required effective cooperation between all stakeholders and decision makers to avoid conflicts of interest (e.g., between recycling companies and raw material suppliers). Implementation of the management followed typical project management routines that described:

- National policies (legal and fiscal instruments)
- Concepts (high versus low recycling)
- Feasibility studies (specific proposals for recycling)
- Computer optimization (e.g., waste resource streams and economic models)
- Master planning
- Design
- Supervision
- Quality and environmental management.

Final reports were needed that describe the development and findings of the specific work packages and general project information.

PROCESSING CONSTRUCTION AND DEMOLITION WASTE

CDE Ireland Ltd. (2009) described the development of a single site organization of a collection of existing equipment and technologies for the preparation, crushing, sizing, sorting, and stockpiling for a CDW recycling facility in Ireland. The first stage of processing included an integrated hopper and conveyor located at the beginning of the operation that feeds CDW into the first of several screens.

The second stage was a rinsing screen that removes the minus 5 mm material and transfers this material to a sand plant with a full water treatment phase, thickener, and overhead filter press. The plus 5 mm material was routed to a log washer that could handle the very dirty or clay bound materials seen in traditional quarry operations. The traditional design of the log washer had been modified to remove organic materials such as wood, plastic, and polystyrene in CDW waste. The organic material was floated off the rear of the equipment to a trash screen. The additional minus 5 mm fraction was transferred back to the sand plant, while the remaining plus 5 mm was discharged to another dewatering screen. The sand plant produced both coarse and fine sand. The dewatering component produced material with a moisture content of about 12%. The thickener portion of the water treatment added a small amount of flocculent, transferred to a holding tank where a thick sludge formed and settled to the bottom; water was sent to a recirculating system. Sludge was mechanically moved to the center of the tank and kept from setting. Sensors are used to stop and start the sludge pump as required. The pumped sludge was sent to a buffer tank for further treatment with the filter press.

The third stage removes the nonferrous material from the plus 5 mm material before it reaches the final sizing screen by sending it to a skip. Remaining aggregate-sized materials were sent to another screen deck to size particles into +40 mm, +20 mm, +20 mm, and 5 to 10 mm fractions.

Mitsubishi (2007) noted that Shin Caterpillar Mitsubishi (SCM) is marketing the SOCIO Series for recycling CDW. The equipment included crushers, wood crushers and wood hip blowers, soil stabilizer systems, and shredders, all self-propelled. However, no information was easily found that described the implementation of the equipment.

PHYSICAL AND CHEMICAL PROPERTIES

The physical and chemical properties are a function of the processing of the CDW. Any information reported on these properties is presented for each of the publications documented later in this chapter.

Environmentally Related Properties

Townsend and Kibert (1998) noted that CDW debris was generally less regulated in terms of disposal and monitoring of environmental impacts and further research was needed in these areas. Ground-water contamination could be classified as one of two types: organic compounds and heavy metals, and nontoxic chemicals. Organic compounds were thought to be the result of small amounts of hazardous chemicals either applied to the construction materials or by the improper disposal of residues and bulk chemicals in the CDW waste stream. Nontoxic chemicals that could impact water quality included chloride, sodium, sulfate, and ammonia. In most cases, the contamination did not exceed primary drinking water standards but could exceed secondary standards for taste, odor, and aesthetics. The number of large CDW recycling facilities has increased in southern Florida; however, a primary concern was a stable market for recovered materials. There were some markets for recycled concrete and wood, but gypsum drywall and asphalt shingles lacked markets as of the late 1990s. The presence of trace metals, arsenic in particular, have limited the reuse of ground and screened CDW material.

Swedish researchers Roth and Eklund (2004) used four different levels for the life-cycle analysis. Levels for the analysis included the materials level, local environmental level where the materials will be used, narrow life-cycle level, and the industrial system level where the production processes of the byproduct or used building material is used (Figure 9). Each level progressively expanded from the

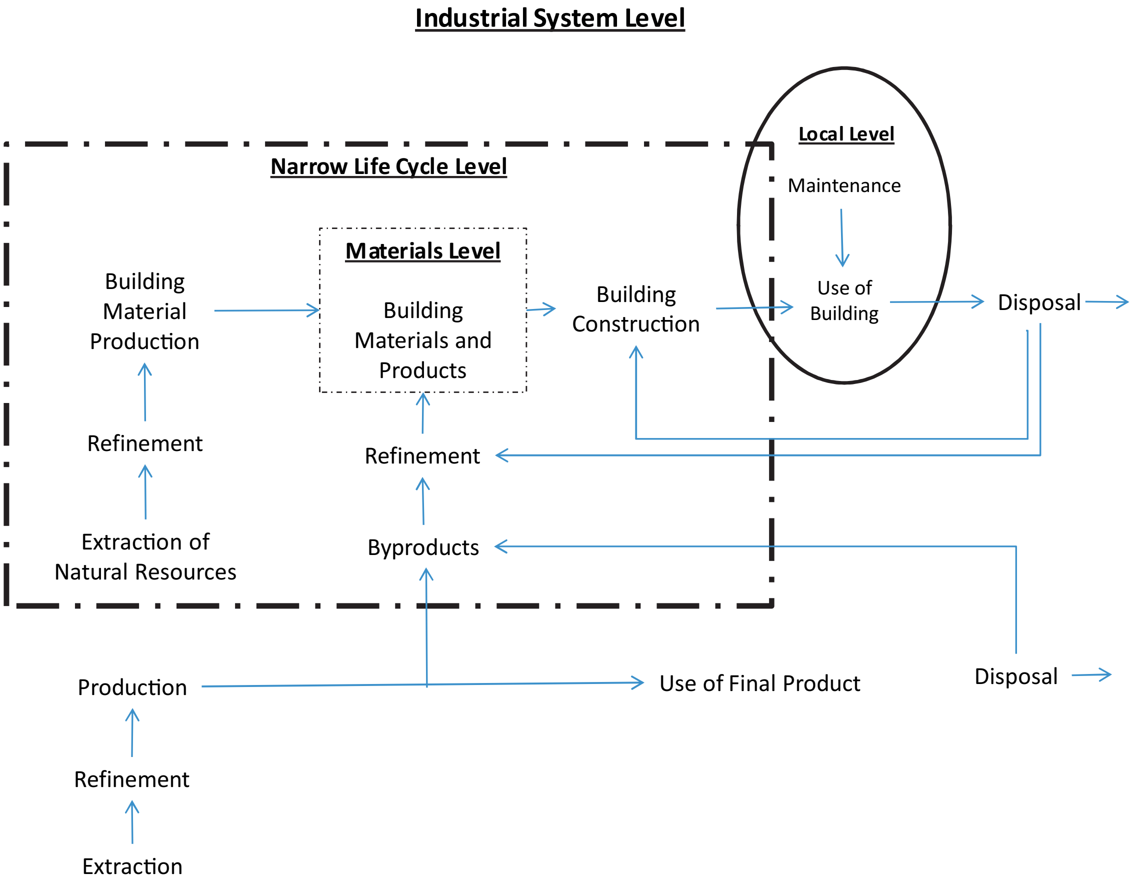


FIGURE 9 Schematic for selecting system components for environmental assessments (after Roth and Ekland 2004).

most narrowly defined system to a cross-sectional dimensional assessment. At the *material level* the focus is the chemical content and leaching possibility of the material. This level provided a means of comparing byproduct usage with that of conventional raw materials used in a specific application.

The *local environment level* evaluated the building sector and included the indoor environment. Field studies included the evaluation of existing environmental conditions and the incremental impact the application would have on the local air and water quality. The base information for a spatially defined area was collected to form a substance flow analysis. Key environmental indicator elements were needed at this point in the data collection. This was used to model the material stocks and flows of a substance. This could also include environmental impact assessment.

The *narrow life-cycle level* approach was the same as for the local level, but the boundaries of the spatial area were expanded to encompass additional processes and factors such as transportation construction techniques, consumption, and disposal. Studies at this level provided information on a case-by-case basis. Because of the increase in the boundary, environmental assessments included location-specific contributors to environmental parameters. At this point it became difficult to determine the impact from one process on the larger system.

At the *industrial system level* the boundaries were further expanded so that the ability to evaluate the impact of a change to one system within these wider limits would likely not be seen in the analysis. The function of this level was primarily to identify and assess the impacts of the most prevalent source(s) of contaminates. Summary of levels and various aspects are shown in Table 47.

Recycling Construction and Demolition Waste Program Development

Inform (2010) provided a general background for several strategies for reducing waste and preventing pollution during building construction, renovation, and demolition. C&D Waste Prevention Basics provided simple definitions for words and terms commonly used to describe CWD materials, recycling, and applications.

The *Construction Materials and Hazardous Waste* strategy considered that hazardous compounds were present in CWD debris owing to the use of pressure-treated woods, lead-based paints (pre-1997), thermostats, light switches, and other electrical heating, ventilation, and air conditioning components. These waste products were considered the source of trace amounts of mercury. Other materials that could be included in the CWD debris included plastic plumbing and floor coverings containing polyvinyl chloride.

The *Waste Prevention Strategies for Local Government Officials* dealt with CDW considerations at the planner and policymaker levels. At this level, regulations could restrict the sale of thermostats containing mercury, barometers and electrical switches in furnaces, sump pumps, and other building materials. New Hampshire and some local governments have already passed prohibitions on the "nonessential" use of mercury. Agencies could provide incentives for mercury recovery, promote waste reduction and pollution prevention in government projects, and encourage creative renovation projects. Incentives for contractors to reduce waste, such as the waste fees used in San Jose, California, as part of the building permit process, were also useful. Strategies at this level included the maintenance of databases of local construction materials recyclers and contractors.

TABLE 47
COMPONENTS ADDRESSED WITHIN EACH BOUNDARY LEVEL

Components	Material Level	Local Environment Level	Narrow Life-Cycle Level	Industrial System Level
Environmental Aspects Addressed	Total chemical content and leaching behavior	Materials in use and their spatial context	Key environmental aspects during a part of the life cycle	Overall environmental aspects
Addressing Environmental Pollution?	Yes	Yes	Partly	Partly
Addressing the Use of Natural Resources?	No	Partly	Yes	Yes
Example of Methods/Tools	Chemical analysis	EIA, SFA	LCA, EIA	SEA, LCA
Results of an Environmental Assessment	Contingent upon values, dependent on substances studied	Contingent upon values, dependent on substances studied	Contingent upon values, dependent on selected parameters, system boundaries, and allocation principles	Contingent upon values, dependent on system boundaries

After Roth and Eklund (2004).
EIA = environmental impact assessment; SFA = substance flow analysis; LCA = life-cycle analysis (i.e., assessment); SEA = strategic environmental assessment.

Environmental regulators could implement strategies to develop specifications and contracts to cover the identification, removal, and proper management of CWD components. These regulations should consider the waste reduction/building materials pollution prevention elements SWPPPs. Purchasing agents and construction departments could require waste prevention and resource management in all bid documents, or require bidders to submit a CDW debris management plan.

Developing, Designing and Managing Buildings with Waste Prevention in Mind strategies focused on estate developers and facility managers who could specify materials that provide the best life-cycle cost and maximize use of existing built-infrastructure usage. Developers can be encouraged to reuse rather than demolish and rebuild, as well as plan for deconstruction. At this level, strategies facilitated linking the debris generator with users of the recycled byproducts.

Architects and designers could design with future changes in mind by considering innovations that consider multiple uses for the same space and uses of standard-sized building supplies to minimize waste during construction.

Construction materials specifiers could choose environmentally preferable construction materials, select prefabricated materials, use salvaged materials, and contract with suppliers with recycling plans.

Prevention of Waste and Pollution during Construction, Renovation, and Demolition strategies took charge of knowing the location of all toxic chemicals present in a building scheduled for demolition or deconstruction. Requirements could be implemented for heating, ventilation, and air conditioning and other contractors to participate in industry-sponsored mercury recovery programs. They could also encourage the conservation and reuse building materials such as bricks, aggregates, and masonry materials. This type of strategy could help plan for efficient purchase and delivery of materials, educate workers about the proper handling of hazardous substances, and work with suppliers to minimize shipping waste.

The *Model Green Building Policy* approach helped pass green building policies to promote environmentally responsible and fiscally prudent decisions for the life of the building and specifications using recycled materials by application. For example, a Texas DOT (2004) specification allowed for the use of recycled aggregates in subbase and base layers as course aggregates for flexible base, lime treatment (road and plant mixed), cement-treated (road and plant mixed), or asphalt-treated (plant mixed), excavation and backfill. Texas DOT also allowed the use of nonstructural concrete in concrete pavements, full-depth repair of concrete pavements, driveways and turnouts, sidewalks, concrete medians and directional islands, chain link fences, foundations for traffic control devices, and small roadside sign supports.

USAGE AND PRODUCTION

Nitivanttananon and Borongan (2008) provided estimates of CDW generation in Asian countries (Table 48). Of all of these countries, China generated the greatest quantity of CDW. Formal demolition permits were required in China, Hong Kong, India, Japan, South Korea, Malaysia, Philippines, Singapore, Taiwan, and Vietnam. Informal permits were used by Indonesia and Thailand and no information was available for Bhutan, Nepal, and Sri Lanka.

Rao et al. (2007) reported that 2.7 billion tonnes of aggregate were produced in the United States, but only 10% to 15% used in pavements. Road construction and maintenance work used 20% to 30%, and structural concrete uses about 60% to 70%. The market share of aggregates used in these applications are split between aggregate producers (50%), contractors (36%), and recycling centers (14%).

In Japan, there has been more than 25 years of research into using RCA in construction applications; however, there has been only limited implementation using CDW sources because of the difficulty in meeting ready mix specifications (JIS A-5308). In 1991, the Recycling Law was established, which requires relevant ministries to nominate materials they must control, recycle, and encourage reuse. The former Ministry of Construction nominated demolished concrete, soil, asphalt concrete, and wood as construction byproducts. In 1992, the Ministry issued “Recycle 21” that specified the targets for recycling. In 1994, tentative quality specifications for reusing materials from demolished concrete for construction works were issued. The initiatives resulted in an improvement for recycling concrete from 48% in 1990 to about 96% in 2000. The recycled concrete was used mostly as a subbase material in road construction.

In Europe, an estimated 450 million tons of CDW was produced per year, which makes it the largest single waste stream next to farm waste. In the late 1990s, about 28% of the CDW was recycled by European Union (EU) countries. The recycled amounts varied by country and inadequate

TABLE 48
CDW GENERATION IN ASIA

Asian Country	Quantity
Peoples Republic of China (2005)	200
Hong Kong (2004)	20.5
India (2001)	14.7
Japan (2000)	85
South Korea (2000)	28.75
Malaysia (1994)	1.55
Taiwan (2004)	16.32
Singapore (2003)	0.423
Viet Nam (2004)	1.35

After Nitivanttananon and Borongan (2008).

records have made it difficult to obtain historical numbers. Most EU countries have set a goal of recycling from 50% to 90% of CDW.

In Bulgaria, modernization and construction of infrastructure facilities that started in the 1990s produce large quantities of CDW. As of 2000, only 0.5% of the 22% of the total expenditure on environmental protection and rehabilitation was for CDW waste management.

Hong Kong and Taiwan generate approximately 14 million tons of CDW annually, which is reused as inert materials in land reclamation projects. However, this reuse has become increasingly objectionable to the public. In 2002, a pilot CDW materials recycling facility was established. This facility can process 2,400 tonnes per day for use in government projects and relevant research and development work. The facility accepted only crushed rocks and concrete to assist with establishing QC of the recycled products. Products were rock fill as well as coarse and fine RCA. By 2003, more than 10 projects had been constructed using these products in reinforced pile caps, ground slabs, beams and parameter walls, eternal building and retaining walls, and mass concrete. These projects used 22,700 cubic meters of RCA concrete. In 1999, Taiwan initiated a comprehensive plan for management after the major earthquake in Central Taiwan, which caused significant structural damage. The damage resulted in a large quantity of CDWs as the buildings were repaired or replaced.

The management plan needed immediate implementation coupled with a QC/QA program. This resulted in the establishment of pilot sorting plants that recycle about 80% of the CDW materials, 30% of which is used in road base applications.

Perez et al. (2010) noted that Spain produces about 13 million tons of CDW materials, of which less than 5% of the volume is reused or recycled. Other countries in the European Union recycled or reused an average of 28% of the total generated CDW. In 2001, the Spanish National Construction and Demolition Waste Plan 2001–2006 was passed, which has a goal of reusing or recycling 60% of the CDW by 2006. The original goal was not achieved, which resulted in the Spanish National Construction and Demolition Waste Plan 2008–2015 revising the goal to 55% by 2015.

CHAPTER NINE

LITERATURE REVIEW

APPLICATIONS

Schimmoller et al. (2005) identified the main drivers of recycling programs as a lack of virgin material, public opposition to aggregate mining, high transportation costs, opposition to landfilling, and high population densities. The best model for recycling was identified as the one used in the Netherlands. The key components of its program were to:

- Develop a formal policy for sustainable development in highway construction that actively promotes the use of recycled materials.
- Promote using recycled materials within a market system.
- Agency-industry cooperation by risk and profit sharing.
- Unambiguous technical and environmental standards.
- Government assistance in starting companies specializing in marketing lightly contaminated soils.

The economics of recycling focused on the beneficial use of engineering and environmental life-cycle costs, tax incentives and disincentives, restrictive landfill taxes, and policies. High-quality recycled byproducts were needed to compete favorably with conventional materials. Alternatively, byproducts were more likely to be used in countries where the demand exceeds the availability of raw materials. Warranties that reduced government or owner environmental liability were widely used and provided flexibility for increased recycling and innovative public sector research.

Engineering issues addressed successfully in the European countries used performance-based testing requirements rather than approved product lists. However, there were still concerns that performance-based tests typically used for conventional materials may not work for estimating the performance of recycled materials. Engineering property measurements would include the use of cyclic load triaxial testing, gyratory compaction procedures, accelerated testing facilities, and price to performance ratio to determine the best market-oriented application. Technical and environmental QC/QA programs for recycled materials commonly certified the material processor or supplier.

Environmental considerations were addressed by national environmental research laboratories to develop test methods and approaches for evaluating environmental performance and set standards. A consistent agreement to move from laboratory work to performance modeling based on field validation was also needed. Government maintenance of environmental databases (e.g., leaching test results) was also provided. Public education was needed to overcome perceived, rather than real, environmental risks. Several environmental tests were used to evaluate the total amount of a compound that will be emitted over the life of the application, rather than the concentration in the material at the outset of its reuse.

Bound—Mortar

Brazilian researchers, Miranda and Selmo (2006), conducted research that evaluated mortar characteristics applied to partition walls. The mortar mix design used a cement content equal to 10% of the total material by dry mass of mortars. The total material finer than the 0.075 mm sieve was varied in the study to investigate mixes with 18%, 25%, and 32% by dry mass of mortar. The control mix was cement (10%), lime, and natural sand mortar with 24% total minus 0.075 mm (Table 49).

The results showed that the flexural strength, compressive strength, and modulus of elasticity increased with increasing percent of fines, regardless of CDW composition (Table 50). However, the drying shrinkage volume change also increased with increasing fines contents.

Bound—Portland Cement Concrete

Basham (2004) noted that CDW debris is a significant contributor to U.S. Army installations' solid waste landfill disposal, with concrete making up the majority of the CDW debris. The Department of Defense estimated that a building with a total of 50 million square feet of floor space was in need of demolition. The author noted a previous study from 1997 that showed that 46% of the recycled concrete used in the United States is from demolition, 32% from road work, and 22% for other uses. Previously developed information on use of recycled aggregate as of 1997 was subbase (68%), HMA (9%), fill (7%), concrete pavement aggregate (6%), rip rap (3%), and other uses (7%).

Basham (2004) also noted that the concrete from demolition will likely contain contaminates, such as plaster and gypsum, that may create problems with expansive sulfate reactions, particularly in the presence of water. Chemical reactions between CDW and portland cement components

TABLE 49
MIX-PROPORTION OF THE STUDIED MORTARS IN DRY WEIGHT, WATER/CEMENT (W/C), AND EFFECTIVE W/C RATIOS FOR THE CONSISTENCY INDEX OF 285 ± 15 MM

Mortars		Cement	Hydrated Lime	CDW Recycled Aggregate	CDW Composition in the Recycled Aggregate (unit wt)				Total w/c Ratio, Mortar	Effective w/c Ratio, Concrete Block
Total material <75 lm	Identification code				Ceramic unit	Mortar	Concrete block	Natural fine sand		
18%	18%-T2	1	—	T2	0.6	0.48	—	7.92	2.5	2.39
	18%-T4	1	—	T4	—	1.33	—	7.67	2.5	2.45
	18%-T6	1	—	T6	—	0.61	0.75	7.64	2.4	2.34
25%	25%-T2	1	—	T2	1.68	1.37	—	5.95	2.3	2.06
	25%-T4	1	—	T4	—	3.74	—	5.26	2.3	2.24
	25%-T6	1	—	T6	—	1.72	2.1	5.18	2.1	2.02
32%	32%-T2	1	—	T2	2.76	2.26	—	4	2.3	1.94
	32%-T4	1	—	T4	—	6.2	—	2.8	2.3	2.22
	32%-T6	1	—	T6	—	3.45	2.83	2.7	2	1.89
24%	M	1	1	—	—	—	—	8	2.5	2.46

After Miranda and Selmo (2006).
— = not applicable.

could show expansive reactions from ASR. When concrete pavements were recycled, concretes from marine environments might have high chloride concentrations that could cause damage to any steel reinforcement when the recycled concrete was used in new mixes. Chloride content could also pose problems with metal culverts when used as embankments or fill. Ideally, testing of RA would be the same as for traditional aggregates.

Typical crushers in the United States were jaw crushers (61% of recyclers) or cone crushers (43%). The jaw crushers can handle larger-sized materials than cone crushers. Steel was removed following the initial crushing. The author recommended the stockpiling of processed recycled aggregate for future use and that stockpiles should be separated based on the feedstock source. Transportation was a major part of the environmental burden for construction activities and also a costly part of the recycling process. On-site processing for larger projects tended to be more cost-effective. Estimates of annual operating costs are show in Table 51.

Barriers to increased use of recycled aggregate in high-grade concrete included the lack of standards, experience, and general knowledge. A survey of base installations indicated that common concerns of the base administration were sizing and contamination. The identification of the reuse application

TABLE 50
MORTAR PROPERTIES AFTER 28 DAYS OF CURING

Mixes	Average Values			
	Flexural strength (MPa)	Compressive strength (MPa)	Modulus of elasticity (GPa)	Total drying shrinkage (%)
18%-T2	0.87	2.43	2.8	–0.09
25%-T2	0.94	2.94	3.4	–0.105
32%-T2	1.29	4.71	5.1	–0.133
18%-T4	0.92	2.46	2.8	–0.073
25%-T4	0.85	2.56	2.8	–0.141
32%-T4	0.97	3.20	3.1	–0.148
18%-T6	0.89	2.57	3.4	–0.09
25%-T6	1.04	3.29	3.9	–0.118
32%-T6	1.32	4.33	4.9	–0.175
Control	0.74	1.55	3.2	–0.083

After Miranda and Selmo (2006).

TABLE 51
ANNUAL COST COMPARISON FOR DIVERSION AND DISPOSAL OF 240 TONS/YEAR OF CDW

Operational Costs	Diversion	Disposal
Crusher Costs (labor and rental)	$1,000	$0
Waste Disposal	$0	$240
Hauling	$0	$1,200
Total Operational Costs	$0	$1,440
Total Recovered Income	$2,900	$0
Net Annual Cost/Benefit	$1,900	–$1,400

After Basham (2004).

facilitated the use of recycled aggregate by allowing the recycled material to be processed on site to meet the requirements for a specific application. Federal agencies were required to purchase environmentally preferable products and services under Executive Order 13101, Greening the Government through Waste Prevention, Recycling and Federal Acquisition. At the time of the writing of this report, 44 states allowed the use of RA for use in backfill (15 states), concrete (8 states), and asphalt (7 states). Only 27 states have formal specifications of which the most common approach was to use in applications with lower quality material requirements. The biggest challenge facing recyclers was government regulations related to plant permitting, exclusion of recycled materials from the project specifications, specifications that disallow fair competition of recycled with virgin aggregates, and disposal regulations for all free dumping of waste concrete. FHWA was working to reduce these barriers and promote reuse in the new transportation bill.

A case example was developed of the construction of the new Tennessee National Football League Stadium in Nashville. This stadium was built on land with an existing building that needed to be demolished before the start of the stadium construction. The project had to be completed in phases owing to the continuing land acquisition and tenant relocation activities. The initial plan was to process the concrete for use as temporary roads on the construction site. A delay in the initial construction resulted in the need to stockpile and store the recycled materials (more than 40,000 tons). Initial use of the recycled aggregate showed that the material could not hold up to the heavy construction equipment loads. It was used instead as structural fill where one of the benefits of using the recycled materials was to help dry fill dirt as a result of the wet weather encountered during the construction.

During Phase II construction, the recycled aggregate was used as structural fill around the basement walls because suitable soil was not available as a result of the wet winter weather. The specifications were prepared ahead of the crushing for Phase II applications (about 24,000 tons). The important lesson learned was to plan the purpose for the recycled aggregate early in the project so that a specification can be developed and the material tested before construction. It was also found that some concrete building components were not suitable for recycling, such as concrete beams, because these building elements have large amounts of steel and are difficult to crush.

Another example was provided for a project in Fort Campbell, Kentucky. The demolition of barracks projects on the base was estimated to generate CDW over the next 20 years at a cost of $20 million for landfilling the waste. Concrete crushing operations were set up on base to process the CDW debris, which reduced the required landfill use by 80%. The estimated additional annual benefits from recycling included revenue of about $50,000 per year from recycled steel and a cost avoidance savings of $500,000 per year.

Rao et al. (2007) reported that concrete with recycled aggregate typically followed traditional mix design methods, which accounted for required changes to mitigate the loss of workability (low slump) resulting from the high absorption of the recycled aggregate. In 1994, RILEM issued recommendations for proportioning concrete using recycled aggregate:

- Use of a higher standard deviation to account for the increased recycled aggregate material variability.
- Assumption of the free water to cement ratio as the same as would be used for a conventional concrete.
- Requirements for water in the recycled aggregate mix to be approximately 5% more than for conventional concrete.
- The sand to recycled aggregate/natural aggregate ratio the same as for conventional concrete sand to coarse aggregate ratio.
- Trial mix designs to establish the correct proportioning and admixtures.

Fresh concrete properties tended to show workability lower for recycled aggregate mixes. Suggestions to overcome this problem included moisture conditioning of the recycled concrete stockpile or saturation of the coarse recycled aggregate. Both methods were reported to provide more consistent results. The air content was somewhat higher when 100% replacement of virgin aggregate with recycled aggregate was used. The unit weight (density) was slightly lower than conventional concrete.

Hardened properties showed that compressive strength decreased with the use of recycled aggregate and was a function of the type of concrete being designed (e.g., high, medium, and low strength concrete), replacement ratio, water to cement ratio, and moisture condition of the recycled concrete. Increasing the water to cement ratio for the recycled concrete mix improved the compressive strength. At ratios greater than 0.55, 100% of the aggregate could be replaced and still achieve comparable compressive strengths as the conventional aggregate mixes. At a 0.4 ratio, only 75% of the conventional mix strength was achieved. The ratio of flexural to compressive strength was reported as being between 16% and 23%, and between 9% to 13% for tensile strength. An additive such as silica fume improved the strengths. The modulus of elasticity had reported values that ranged between 50% and 70% of conventional concrete, but this range was based on limited information.

Creep and shrinkage showed that high absorption values increase shrinkage by 80% to 167%. Limited research suggested that after one year creep was about 20% more for recycled aggregate mixes than for conventional concrete. Carbonation showed that after 6 months of curing the recycled aggregates mixes had depths of carbonation 1.3 to 2.5 times greater for recycled aggregate mixes. The increased permeability of the RA mixes was suggested as one cause for the increase in depth of carbonation.

Freeze-thaw resistance showed mixed results, with some indication that recycled aggregate produced from originally air-entrained PCC was more resistant to damage. Variations in air content were attributed to producing differences in pore structure of the RCA materials. Both durability and bond strength changes were inconclusive as of the date of this report.

Barriers to increased use were identified as the:

- Cost of disposal having direct bearing on recycling operations,
- Lack of appropriately located recycling facilities,
- Lack of awareness,
- Absence of appropriate technology,
- Lack of government support,
- Lack of standards,
- Low cost dumping fees, and
- Small amounts of CDW generated at wide spread locations.

Potential approaches to overcoming these barriers included using portable equipment that could be set up in close proximity to sources of byproducts; however, commercially available methods to crush CDW were required before QC/QA methods could be developed. Recycling possibilities not widely known and dissemination of information was needed. There was also a need to create a market for recycled products and encourage recycling in projects. Appropriate policies supported by proper regulatory framework were required along with help in compiling data, documentation, and control of CDW materials. Most of the formal standards for RCA have been developed internationally; few were available for U.S. use.

Bound—Hot Mix Asphalt

In Spain, Perez et al. (2010) evaluated HMA mixes with 0%, 20%, 40%, and 60% recycled aggregates from CDW on the indirect tensile strength ratio (TSR) for compacted samples. Two types of virgin aggregates (schist and calcite) and one asphalt cement were included in the experimental design. The schist was composed of quartz (35%), albite (30%), mica (20%), and chlorite (15%). The calcite dolomite was composed of calcite (40%), dolomite (40%), and quartz (20%). The recycled aggregates were selected at the source, but crushed at the CDW facility. Pollutants were removed and the remaining material sieved, washed, and classified according to standard HMA aggregate specification. The filler was a portland cement with a surface area of 3,350 cm^2/g and a specific gravity of 3.12. The asphalt cement was a Penetration Grade 69 with a softening point of 48.5°C, a Pfeiffer's penetration index of –0.8, and a density of 1.03 g/cm^3.

The results were analyzed using various analyses of variance methods. Mix design data indicated that the optimum asphalt content increased with increasing recycled aggregate percentages for both mixes with either aggregate type (Table 52). The VMA, VFA, flow, and stability also increased with the increasing percentage of recycled aggregate; however, the unit weight decreased with increased recycled aggregate. All of the mixes met the minimum specification requirements. The TSR percentages decreased with the increasing percentage of recycled aggregates (Table 53). Analysis of variance analyses showed significant differences between the control mix and mixes with recycled aggregate; the 60% recycled aggregate TSR were significantly lower than either the 20% or 40% recycled aggregate. The type of aggregate used with the recycled aggregate also had a significant effect on the TSR values.

Bound—Specifications

The Washington State DOT (WSDOT 2010) specifications permitted the use of recycled materials in pavement mixtures, guardrail posts and blocks, and compost. Contractors could reuse or purchase recycled materials using the Standard Specification for Road, Bridge, and Municipal Construction or apply for conditional use through the WSDOT New Products Committee. The contractor was responsible for the disposal of CDW per sections 2-02 and 2-03.3(7) solid waste regulations enforced at the local level.

Unbound Applications

Swedish researchers, Schouenborg et al. (2004) evaluated the suitability of standard aggregate tests for evaluating the properties of alternative aggregates. Sieve analysis testing that typically uses a mechanical shaker may not be suitable for alternative aggregates that were more easily abraded. Water absorption needs to consider that alternative aggregates may absorb water over a longer time frame than conventional aggregates. Because water absorption could have a profound influence on the durability and long-term dimensional properties, it needed careful attention during material property evaluations. Three methods of evaluating aggregate toughness were considered (LA abrasion, aggregate impact, and Schlagversuch). The aggregate impact and Schlagversuch

TABLE 52
INFLUENCE OF RA ON HMA VOLUMETRICS

Mixture	Marshall Test Parameters				
	Compacted bulk specific gravity	Optimum asphalt content, %	Voids in mineral aggregate, %	Air voids, %	Voids filled with asphalt, %
Schist					
S-0	2.66	4.5	14.5	5	66.8
S-20	2.63	5.0	15.5	5	69.6
S-40	2.59	5.5	17.0	5	69.1
S-60	2.57	5.5	17.0	5.5	67.0
Calcite Dolomite					
C-0	2.75	4.0	14.0	5	71.0
C-20	2.70	4.3	15.0	5	65.5
C-40	2.63	4.5	16.5	7	62.1
C-60	2.56	4.8	16.0	6	63.3
Specification	—	Min. 3.5	14.0	5–9	—

After Perez et al. (2010).
— = not available.

placed the material in a cylinder and allowed a weight to fall on the sample a prescribed number of times before evaluating the change in gradation.

The authors hypothesized that sieving highly porous heterogeneous materials may generate misleading gradation results owing to degradation of the particles from mechanical agitation. Because most aggregate test methods are based on sample preparation involving recombining sieved fractions of particles, the subsequent test results may be compromised. The dynamic breakdown (toughness) of heterogeneous particles in actual applications would be difficult to assess with

TABLE 53
INFLUENCE OF RECYCLED AGGREGATE ON THE MOISTURE SENSITIVITY OF HMA

Recycled Aggregate %	Specimen	Tensile Strengths, MPa, and Average Tensile Strength Ratio, % by Aggregate Type			
		Schist		Calcite Dolomite	
		Wet	Dry	Wet	Dry
0	Replication #1	0.99	1.19	0.79	0.78
	Replication #2	0.97	0.91	0.72	0.9
	Replication #3	0.91	1.18	0.85	0.79
	Average	0.96	1.09	0.79	0.82
	TSR, %	88%		96%	
20	Replication #1	0.89	1.04	0.93	1.27
	Replication #2	0.81	1.32	1.02	1.05
	Replication #3	0.84	1.30	0.84	0.93
	Average	0.85	1.22	0.93	1.08
	TSR, %	70%		86%	
40	Replication #1	0.78	1.25	0.65	1.16
	Replication #2	0.87	1.33	0.84	1.23
	Replication #3	0.92	1.40	0.79	1.3
	Average	0.86	1.33	0.76	1.23
	TSR, %	65%		62%	
60	Replication #1	0.86	1.25	0.80	1.46
	Replication #2	0.77	1.45	0.76	1.65
	Replication #3	0.86	1.48	0.85	1.55
	Average	0.83	1.39	0.80	1.55
	TSR, %	60%		52%	

After Perez et al. (2010).

TABLE 54
INFLUENCE OF SIEVE ANALYSIS SHAKING TIME ON CDW PARTICLE SIZE

Sieving Method and Time	Percent Weight Passing 8 mm Sieve, %					
	Concrete		Bricks		Slag	Natural gravel granitic
	25.5 MPa	41 MPa	51 MPa	80 MPa		
Manual	2.9	3.2	2.7	1.4	4.5	0.0
Mech. 2 min	4.3	5.2	2.4	1.4	3.3	0.0
Mech. 5 min	6.2	7.4	3.7	2.0	4.3	0.1
Mech. 10 min	7.9	9.5	5.3	2.5	5.1	0.2

After Schouenborg et al. (2004).

particle-only test methods. Functional particle properties needed to be evaluated by simulating forces acting on the materials by testing in an actual layer configuration. Conditioning and testing times when water absorption was a factor that needed to be altered.

Results showed that alternative aggregates are more sensitive to variations in sieving method and time than for conventional aggregates (Table 54). Although no data were included in the report, the authors noted that the resistance to abrasion of alternative aggregates was best described by testing the as-received gradation rather than sieving and recombining.

Water absorption was evaluated using three methods of soaking the aggregates: longtime soak, pycnometer for 5 h at 50 mbar pressure, and boiling for 24 h (Table 55). The data showed both the boiling water and pycnometer method provided consistent data over a 24-h period. It took the long time soaking samples more than 90 days to reach a stable absorption percentage. In some cases, more than a year of soaking was needed to stabilize the absorption. The standard absorption method was found to significantly underestimate the water demand of the alternative aggregates.

An investigation in India, by Kumar and Reddy (2008), evaluated the shear strength parameters, maximum dry density, and CBR values of embankment and base materials using jute textile reinforcement in demolition materials. The recycled aggregate consisting of 46% brick, 17% cement mortar, 12% lime mortar, 13% combination of brick and mortar, and the remaining 12% crushed concrete pieces. The CDW material was dried and sieved through the 19 mm sieve. Other materials used in the mixes included natural aggregates (locally available), locally available subgrade soil, and a jute geotextile in woven sheet form in rolls (44% lignin, 47% cellulose). Key properties of the individual soil and CDW debris materials are shown in Table 56.

Testing included aggregate tests obtaining measurements of crushing value, impact value, abrasion resistance, soundness, particle shape, specific gravity, and water absorption. CBR testing was used to evaluate the bearing capacity of samples prepared with no geotextile, and the jute geotextile placed at from one-third, one-half, and two-thirds of the sample height (from surface). The geotextile had a diameter of slightly less than the sample diameter. CBR samples were subjected to a 4 day soak. The plate load test was conducted per IS: 9214-1979 to determine the subgrade reaction, *K*. Direct shear testing was also completed.

Results showed that the CDW had a higher optimum moisture content but a lower maximum density than the soil. Both materials were nonplastic (Atterberg limits). The natural aggregate used in blends had low impact and crushing values; therefore, blends that increased the amount of natural aggregate resulted in a corresponding decrease in the blend values (Table 57). Both materials had similar flakiness and elongation values; therefore, this value remained relatively constant, regardless of the blend percentages. The CBR values decreased with increasing recycled CDW content (Table 58). Laboratory samples were used to evaluate the impact of the geotextile layer on the direct shear values of the materials. The cohesive values and angles of internal friction for the CDW

TABLE 55
DIFFERENCES IN MOISTURE CONTENT FOR VARIOUS METHODS OF CONDITIONING

Conditioning		Oven Dry	Boiling Water Results, mass (grams) and moisture (%)					
			1 hr, g	%	8 hr, g	%	24 hr, g	%
Porous Basalt	Oven dried	1957.8	2031.2	3.8	2037.1	4.1	2050.4	4.7
	Not oven dried	1913.3	1996.1	4.3	2005.2	4.8	2018.5	5.5
Crushed Concrete	Oven dried	1721.2	1843.3	7.1	1847.9	7.4	1849.9	7.5
	Not oven dried	1739.0	1865.4	7.3	1871.5	7.6	1872.3	7.7

TABLE 56
PROPERTIES OF RECYCLED AND NATURAL AGGREGATES

Recycled Aggregate	Recycled Aggregate:Natural Aggregate				NA	IRC Requirement (max.) Subbase
	90:10	80:20	70:30	60:40		
Aggregate Impact Value, %	43.15	41.72	36.7	32.62	17.87	50
Crushing Value, %	33.92	30.82	28.78	24.92	19.08	40
Flaky and Elongation Indices, %	22.92	23.2	22.9	22.47	21.49	30
LA Abrasion, %	45.62	43.25	41.24	35.54	24.13	40
Specific Gravity	2.32	—	—	—	2.73	2.67–2.9

After Kumar and Reddy (2008).
NA = natural aggregate.

debris with and without the geotextile were 0 and 31.5°, and 0.24 and 38°, respectively. The presence of the geotextiles provided a small influence on the cohesiveness of the mix, and increased the angle of internal friction. The subgrade reaction, *K,* was determined to be 4.631 kg/cm^3.

BARRIERS

Nitivanttananon and Borongan (2008) reported that partnerships to increase recycling have been formed in several Asian countries related to CDW waste management. Singapore had a collaborative effort between government agencies including the Defense Science and Technology Agency and the Housing and Development Board. Glasgow had a joint effort between the Kyoto University and the Sustainability Center in Glasgow. Malaysia used a collection of waste management professionals including engineering, law, science, and management disciplines. Barriers to the Asian recycling efforts were identified as:

- Lack of data on CDW waste management
- Lack of understanding of environmental impact
- Lack of necessary expertise
- Lack of policies
- Responsibilities divided between different agencies and local administrations
- Weak coordination of education and training programs
- Lack of public awareness
- Need for stakeholder joint participation
- Inadequate resources and technologies.

TABLE 57
MATERIAL PROPERTIES OF SOILS WITH RA

Material Proportions		CBR 2.5, %	CBR 5.0, %	CBR Value, %
Recycled aggregate, %	Natural aggregate, %			
100	0	10.2	9.9	10.2
90	10	14.6	13.8	14.6
80	20	18.8	17.6	18.8
70	30	25.3	24.1	25.3
60	40	34.5	32.5	34.5
0	100	83.2	82.2	83.2

After Kumar and Reddy (2008).

SUMMARY OF CONSTRUCTION AND DEMOLITION WASTE INFORMATION

List of Candidate Byproducts

The primary byproducts from CDW were recycled aggregates and roofing shingles. The recycled aggregates were referred to in a number of instances as RCA that did not sufficiently distinguish this byproduct from the formal FHWA definition of RCA. Terms need to be standardized. Recycled roofing shingles is covered in Volume 8.

Test Procedures

Traditional test methods were commonly used for evaluating recycled aggregates and the hybrid application products (see Table 57). However, standard tests such as the sieve analysis showed significant dependence of results on the duration of the mechanical shaking. Determination of specific gravities and water absorption capacities were occasionally difficult to determine owing to the different drying characteristics of the recycled materials. Only a limited number of commonly used standards in the United States were found in the literature, as most of the information was found in the international publications.

Material Preparation and Byproduct Quality Control

The main concern with materials preparation was in the demolition process. A sequential demolition sequence was needed so that homogenous stockpiles could be prepared for the major structural components. Sequential dismantling increased the time for demolition and was not commonly practiced by contractors.

TABLE 58
STANDARDS USED FOR EVALUATING RECYCLED AGGREGATES FROM CDW

Standard	Title
ASTM D2940	Standard Test Method for Graded Aggregate Material for Bases and Subbases for Highways or Airports
AASHTO M147	Aggregate and Soil-Aggregate Subbase, Base, and Surface Courses
AASHTO M80	Coarse Aggregate for Portland Cement Concrete
AASHTO M6	Fine Aggregate for Portland Cement Concrete
AASHTO M319	Standard Specification for Reclaimed Concrete Aggregate for Unbound Soil-Aggregate Base Course

Materials Handling Issues

CDW was more likely to contain a wider range of contaminates than RCA from highway pavements and structures. Care needed to be taken to avoid ground-water contamination from organic compounds and heavy metals and nontoxic chemicals. Contaminates came from building thermostats, light fixtures, wire, pressure-treated woods, lead-based paints, and ventilation and air conditioning components.

Transformation of Marginal Materials

The most commonly cited method for producing quality recycled aggregates from CDW was the selective deconstruction of structures, with an emphasis being on developing homogenous byproducts.

Design Adaptations

Recycled aggregates produced from CDW materials showed more variability and contaminates than RCA produced from recycled highway projects. Difficulty in meeting ready mix specifications could be a concern. Additional mix design and performance-based testing was needed to account for the recycled aggregate variability.

Recommendations for proportioning PCC using recycled aggregate were to:

- Use a higher standard deviation to account for the increased recycled aggregate material variability. A value of 700 psi appeared to be reasonable.
- Assume the free water to cement ratio was the same when using a recycled aggregate/sand combination as would be used for a conventional concrete.
- The required water for the recycled aggregate mix should be approximately 5% more than for conventional concrete.
- The sand-to-aggregate ratio should be the same for the recycled aggregate/sand-to-recycled aggregate and the natural aggregate ratio should be the same as for conventional concrete.
- Trial mix designs are required to establish the correct proportioning and needed admixtures.

High absorption capacity resulted in an increased demand for water in PCC and asphalt cement in HMA applications.

Construction Issues

Once the CDW was used to produce recycled aggregate, the construction issues were similar, although more variable, to those for RCA from highway structures.

Failures, Causes, and Lessons Learned

Initial use of the recycled aggregate showed that the material would not hold up to the heavy construction equipment loads. It was used instead as structural fill where one of the benefits of using the recycled materials was to help dry fill dirt resulting from wet weather encountered during the construction. An important lesson learned was to plan the purpose for the recycled aggregate early in the project so a specification can be developed and the material tested before construction. It was also found that some concrete building components such as concrete beams were not suitable for recycling because these building elements have large amounts of steel and are difficult to crush.

Barriers

A number of barriers limited the increased use of RAP, RCA, and CDW byproducts in highway applications:

- Lack of a stable market for recycled materials
- Lack of appropriately located recycling facilities
- Lack of awareness of byproduct potential
- Absence of appropriate technology for processing some byproducts (e.g., CDW)
- Lack of government support
- Lack of standards
- Low cost dumping fees
- Small amounts of byproducts generated at widespread locations
- Lack of data on waste management byproducts
- Lack of understanding of environmental impact
- Lack of necessary expertise

- Lack of policies
- Responsibilities divided between different agencies and local administrations
- Weak coordination of education and training programs
- Lack of public awareness
- Need for stakeholder joint participation
- Inadequate resources and technologies.

Costs

The economics of recycling focused on the beneficial use of engineering and environmental life-cycle costs, tax incentives and disincentives, and restrictive landfill taxes and policies. High-quality recycled byproducts needed to compete favorably with conventional materials. In one case, annual benefits from recycling included revenue of about $50,000 per year from recycled steel, and a cost avoidance savings of $500,000 per year.

Gaps

- Formal policy for sustainable development in highway construction that actively promotes the use of recycled materials.
- Promotion for using recycled materials within a market system.
- Agency–industry cooperation by risk and profit sharing.
- Unambiguous technical and environmental standards.
- Government assistance in starting companies specializing in marketing lightly contaminated soils.

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Abbreviations used without definitions in TRB publications:

A4A	Airlines for America
AAAE	American Association of Airport Executives
AASHO	American Association of State Highway Officials
AASHTO	American Association of State Highway and Transportation Officials
ACI–NA	Airports Council International–North America
ACRP	Airport Cooperative Research Program
ADA	Americans with Disabilities Act
APTA	American Public Transportation Association
ASCE	American Society of Civil Engineers
ASME	American Society of Mechanical Engineers
ASTM	American Society for Testing and Materials
ATA	American Trucking Associations
CTAA	Community Transportation Association of America
CTBSSP	Commercial Truck and Bus Safety Synthesis Program
DHS	Department of Homeland Security
DOE	Department of Energy
EPA	Environmental Protection Agency
FAA	Federal Aviation Administration
FHWA	Federal Highway Administration
FMCSA	Federal Motor Carrier Safety Administration
FRA	Federal Railroad Administration
FTA	Federal Transit Administration
HMCRP	Hazardous Materials Cooperative Research Program
IEEE	Institute of Electrical and Electronics Engineers
ISTEA	Intermodal Surface Transportation Efficiency Act of 1991
ITE	Institute of Transportation Engineers
MAP-21	Moving Ahead for Progress in the 21st Century Act (2012)
NASA	National Aeronautics and Space Administration
NASAO	National Association of State Aviation Officials
NCFRP	National Cooperative Freight Research Program
NCHRP	National Cooperative Highway Research Program
NHTSA	National Highway Traffic Safety Administration
NTSB	National Transportation Safety Board
PHMSA	Pipeline and Hazardous Materials Safety Administration
RITA	Research and Innovative Technology Administration
SAE	Society of Automotive Engineers
SAFETEA-LU	Safe, Accountable, Flexible, Efficient Transportation Equity Act: A Legacy for Users (2005)
TCRP	Transit Cooperative Research Program
TEA-21	Transportation Equity Act for the 21st Century (1998)
TRB	Transportation Research Board
TSA	Transportation Security Administration
U.S.DOT	United States Department of Transportation