Using Recycled Concrete in MDOT's Transportation Infrastructure—Manual of Practice

Final Report

Prepared For:

Michigan Department of Transportation

Prepared By:

Applied Pavement Technology, Inc.
115 W. Main Street, Suite 400
Urbana, IL 61801
(217) 398-3977
www.appliedpavement.com

Michigan Technological University
Civil and Environmental Engineering
Michigan Tech Transportation Institute
1400 Townsend Drive
Houghton, MI 49930
www.mtu.edu

August 2011

applied pavement
TECHNOLOGY

providing engineering solutions to improve pavement performance

Michigan Department
Of Transportation
1959 (10/08)

TECHNICAL REPORT DOCUMENTATION PAGE

1. REPORT NO. Report Number RC-1544	2. GOVERNMENT ACCESSION NO.	3. MDOT PROJECT MANAGER John Staton
4. TITLE AND SUBTITLE Using Recycled Concrete in MDOT's Transportation Infrastructure - Manual of Practice		5. REPORT DATE August 2011
		6. PERFORMING ORGANIZATION CODE
7. AUTHOR(S) Ton Van Dam, Kurt Smith, Carrie Truschke, Stan Vitton		8. PERFORMING ORG. REPORT NO.
9. PERFORMING ORGANIZATION NAME AND ADDRESS Michigan Tech University 1400 Townsend Drive Houghton, MI 49931		10. WORK UNIT NO. (TRAIS)
		11. CONTRACT NO. P0085585
		11a. AUTHORIZATION NO.
12. SPONSORING AGENCY NAME AND ADDRESS Michigan Department of Transportation Office of Research and Best Practices 425 W. Ottawa Street Lansing, MI 48909		13. TYPE OF REPORT & PERIOD COVERED FINAL (February - August 2011)
		14. SPONSORING AGENCY CODE

15. SUPPLEMENTARY NOTES

16. ABSTRACT

Crushed concrete aggregate (CCA) is granular material manufactured by removing, crushing, and processing old concrete for reuse as an aggregate source in new construction. Although the Michigan Department of Transportation (MDOT) has used CCA since the 1980s, issues in the performance of some of the early projects currently limit its use to primarily bound and unbound drainable bases beneath concrete pavements. Some of the performance issues on the early projects developed because of the unique characteristics and properties of CCA materials, such as increased absorption, lower specific gravity, and reduced abrasion resistance.

Although there are potentially some limitations associated with the use of CCA, the effective characterization of these materials during their production and throughout the design and construction process can help lead to their successful use and application. This document is intended to help guide MOOT engineers in using CCA in the State's transportation infrastructure, with particular focus on pavement applications. Information is provided by chapter on the processing and production of CCA, on the physical, mechanical, and chemical characteristics of CCA, and on the use of CCA in base layers, asphalt paving layers, and concrete paving layers; these are presented in conjunction with MDOT's standard specifications for construction and and special provisions to indicate the Department's current usage policies policies and recommendations regarding CCA.

17. KEY WORDS crushed concrete aggregate (CCA), recycled concrete aggre		18. DISTRIBUTION STATEMENT No restrictions. This document is available to the public through the Michigan Department of Transportation.	
19. SECURITY CLASSIFICATION - report Unclassified	20. SECURITY CLASSIFICATION - page Unclassified	21. NO. OF PAGES 44	22. PRICE

SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

SYMBOL	WHEN YOU KNOW	MULTIPLY BY	TO FIND	SYMBOL
		LENGTH		
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		AREA		
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yard	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
		NOTE: volumes greater than 1000 L shall be shown in m^3		
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
		TEMPERATURE (exact degrees)		
°F	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	°C
		ILLUMINATION		
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
		FORCE and PRESSURE or STRESS		
lbf	poundforce	4.45	newtons	N
lbf/in^2	poundforce per square inch	6.89	kilopascals	kPa

APPROXIMATE CONVERSIONS FROM SI UNITS

SYMBOL	WHEN YOU KNOW	MULTIPLY BY	TO FIND	SYMBOL
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
		AREA		
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2
		VOLUME		
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.314	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000 lb)	T
		TEMPERATURE (exact degrees)		
°C	Celsius	1.8C+32	Fahrenheit	°F
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m^2	0.2919	foot-Lamberts	fl
		FORCE and PRESSURE or STRESS		
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2

*SI is the symbol for the International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380.
(Revised March 2003)

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF ACRONYMS

AASHTO	American Association of State Highway and Transportation Officials
ACPA	American Concrete Pavement Association
ADT	Average daily traffic
ASR	Alkali-silica reactivity
ASTM	American Society for Testing and Materials
AWI	Aggregate Wear Index
CADT	Commercial average daily traffic
CRCP	Continuously reinforced concrete pavements
CTE	Coefficient of thermal expansion
CTPB	Cement-treated permeable base
CCA	Crushed concrete aggregate
D-cracking	Durability cracking
FHWA	Federal Highway Administration
HMA	Hot-mix asphalt
JPCP	Jointed plain concrete pavement
JRCP	Jointed reinforced concrete pavement
MDOT	Michigan Department of Transportation
MEPDG	Mechanistic-empirical pavement design guide
MRD	Materials-related distress
MTM	Michigan Test Method
NCHRP	National Cooperative Highway Research Program
PCC	Portland cement concrete
SCM	Supplementary cementitious materials
w/cm	Water-to-cementitious materials ratio
WMA	Warm-mix asphalt

CHAPTER 1. INTRODUCTION

General Overview

The recycling of concrete pavements—crushing of old concrete slabs and reusing the crushed material in some other pavement application—has been used in the U.S. since the 1970s (Hoerner et al. 2001). At that time, common reasons for concrete recycling were noted to be conservation of resources, limited availability of aggregates, minimizing solid waste disposal issues, and reductions in overall construction costs (Yrjanson 1989), all important factors that resonate even stronger in today's climate of sustainable stewardship and environmental awareness.

Data collected from 2009 indicates that concrete pavements are recycled for transportation infrastructure applications in at least 41 states; moreover, about 140 million tons of crushed concrete aggregate (CCA) are produced in the U.S. per year (ACPA 2009). The material has been used in applications ranging from placement in various paving layers (surface, base, subbase) and as fill and embankment material (ACPA 2009).

CCA is granular material manufactured by removing, crushing, and processing portland cement concrete (referred to simply as concrete in this guide) for reuse in similar situations as virgin natural aggregate (FHWA 2007). However, CCA has different properties than natural aggregate, largely because the resultant crushed material is composed of both the original natural aggregate and reclaimed mortar, which significantly affects the properties and behavior of materials produced with CCA unless specific steps are taken to account for it in the design and construction process. Moreover, the composition of CCA can be highly variable, and in addition to aggregates and reclaimed mortar may contain contaminates such as soil and clay balls, joint sealant, and asphalt or other construction waste (ACPA 2009). Further, freshly processed CCA is highly alkaline and may contain chlorides that may limit is use or applicability (Hiller et al. 2011). Nevertheless, when its characteristics are properly considered and accounted for, CCA can be used effectively in a number of transportation infrastructure applications.

Benefits and Limitations

As noted above, perhaps the two primary benefits associated with the use of CCA are resource conservation (reducing the need for natural aggregate) and reducing or eliminating solid waste disposal issues. Although the environmental considerations are usually believed to be of primary interest, there are often significant economic benefits as well, since the use of CCA reduces the need for natural aggregate and for landfill disposal. Furthermore, in the case of pavement reconstruction, the old concrete will still require demolition and removal, so the cost of the CCA is reduced only to the cost of crushing and processing the material. Further, if the material can be processed on site, fuel consumption and related transportation costs are also reduced.

The last several years have seen a focus on sustainability, which has been characterized as a balance between economic, environmental, and societal needs and impacts (Van Dam and Taylor 2009). If properly administered, the use of CCA could potentially play an integral role in fulfilling sustainability needs in each of these three areas, and thus can contribute to the sustainability of pavement construction projects. In fact, the use of recycled materials is directly considered and earns credit in several infrastructure sustainability rating systems that have recently been developed, such as *Greenroads* (Muench et al. 2010) and the *Sustainable Highways Self-Evaluation Tool* (FHWA 2011).

At the same time, CCA have a number of unique characteristics and properties that must be considered during the design and construction process. For example, CCA typically exhibits the following characteristics when compared to natural aggregates (Snyder et al. 1994; Hiller et al. 2011):

- Lower specific gravity, which decreases with increasing amount of reclaimed mortar.
- Higher absorption, which increases with increasing amount of reclaimed mortar.
- Greater angularity.
- Increased abrasion loss, which increases with increasing amount of reclaimed mortar.

In addition, CCA may contain unhydrated cement, which may alter its behavior and complicate stockpiling, especially the fine material. Leaching of calcium hydroxide from the CCA may also be a problem when used as a drainage layer or near a water source, as it will react with atmospheric carbon dioxide forming calcium carbonate, which will clog filter fabrics (Snyder and Bruinsma 1996; ACPA 2009). Finally, the fines produced during the crushing operation (those passing the No. 4 sieve) are coarse and angular, which tend to make CCA concrete mixtures very harsh and difficult to work.

It is important to recognize that not all CCA is appropriate for reuse in all applications. For example, CCA made from concrete exhibiting materials-related distress (MRD) such as alkali silica reactivity (ASR) or D-cracking may preclude its reuse in concrete unless certain mitigation methods are employed (ACPA 2009). Additionally, CCA may have high chloride contents due to extended exposure to deicing chemicals while in service, which may make it unsuitable for use in reinforced concrete. And, the low abrasion resistance may lead to poor performance in an application where intimate aggregate interlock is relied upon for load transfer (for example, in undoweled joints or at transverse cracks of reinforced slabs). Again, these factors don't necessary prevent the use of CCA, but just underscore the importance of adequately characterizing the materials and accounting for their properties as part of the design and construction process.

Potential Uses and Applications

As previously noted, CCA can be broadly used in many of the same applications as natural aggregate, including the following (ACPA 2009):

- Unbound (granular) base and back fill (including both dense-graded and free-draining bases).
- Cement-stabilized base (permeable and dense-graded).
- Asphalt-stabilized base (permeable and dense-graded).
- Concrete mixtures (surface layers, lean concrete base).
- Asphalt pavement mixtures.
- Granular fill.
- Miscellaneous applications, such as soil stabilization, pipe bedding, landscape materials, and railroad ballast.

Recycling can be performed on any existing concrete pavement type: jointed plain concrete pavements (JPCP), jointed reinforced concrete pavements (JRCP), and continuously reinforced concrete pavements (CRCP).

Coarse CCA (defined as that retained on the No. 4 sieve) can be used in most pavement applications, but the use of fine CCA (passing the No. 4 sieve) is more limited, particularly when considered for use in new concrete mixtures. This is because of its high angularity and high absorption, which lead to harsh unworkable mixtures. However, fine CCA can have some self-cementing properties, which adds to the strength and stability of dense-graded bases or subbases such that it may behave like a cement-treated base (ACPA 2009).

Michigan DOT Experience with CCA

The Michigan Department of Transportation has a long history of using CCA, including early use in unbound base courses in the 1970s (Epps and O'Neal 1975), followed by a major program of CCA use in JRCP pavements in the 1980s (McCarthy 1985; McCarthy and MacCreery 1985; Smiley and Parker 1993). Unfortunately, many of these JRCPs did not perform very well, exhibiting a significant amount of deterioration at the mid-panel cracks. Although mid-panel cracks are expected in JRCP designs, the poor aggregate interlock across the cracks (due to the smaller top size aggregate and the poor abrasion resistance of the mortar fraction of the CCA) contributed to their accelerated deterioration (Raja and Snyder 1991). Other studies conducted during this period suggested that other underlying causes (including base uniformity, sympathy cracking from existing joints or transverse cracks in adjoining pavement or shoulders, and shrinkage cracking) may have contributed to the early deterioration of these CCA projects (Hansen 1995).

MDOT's specifications reflect some of the performance concerns observed over the years. In the *2012 MDOT Standard Specifications for Construction*, Section 902.03.B, crushed concrete coarse aggregate is only allowed in concrete used for lower priority applications such as curb and gutter, valley gutter, sidewalks, concrete barriers, driveways, temporary pavement, interchange ramps with commercial average daily traffic (CADT) less than 250, and concrete shoulders (MDOT 2012). The specification also specifically states that crushed concrete course aggregate may not be used in concrete for mainline pavements or ramps with a CADT equal to or in excess of 250, concrete base courses, bridges, box or slab culverts, headwalls, retaining walls, prestressed concrete, or other heavily reinforced concrete.

The specifications are even more restrictive for the use of crushed concrete fine aggregate as described in Section 902.08, simply stating that it should not be used in new concrete mixtures.

In addition, as described in Section 902.05, CCA is not allowed in unbound Class 21AA and 22A dense-graded unbound aggregate base or separation layer when this layer drains into an underdrain, unless at least one of the following conditions exist:

- A vertical layer of at least 12 inches of granular Class I, II, IIA, or IIAA is placed between the CCA dense-graded layer and an underdrain, or
- A geotextile liner or blocking membrane placed between the CCA dense-graded layer and the underdrain will act as a barrier to leachate.

Furthermore, in accordance with Section 902.06, CCA is allowed in open-graded aggregate 4G, as long as building rubble or hot-mix asphalt (HMA) is less than 5.0 percent. CCA is not allowed in open-graded aggregate 34G or 34R. MDOT permits the use of crushed concrete coarse aggregate in asphalt pavement mixtures (Section 902.09.A), but not fine crushed concrete aggregate.

Table 1 provides a summary of allowable use of CCA in fill/embankment, subbase, base, asphalt paving materials, and concrete based on the *2012 MDOT Standard Specifications for Construction* (MDOT 2012).

Table 1. Summary of allowable use of CCA based on 2012 *MDOT Standard Specifications for Construction* (MDOT 2012).

Type of CCA	**Fill/Subbase**[1]	**Dense-Graded Aggregates**[2]	**Open-Graded Aggregates**[3]	**HMA**	**PCC**
Coarse	Yes	Yes	Yes	Yes	Yes[4]
Fine	Yes	Yes	Yes	No	No

[1] *The Engineer will only allow the use of granular material produced from crushed portland cement concrete for swamp backfill, embankment (except the top 3 feet below subgrade) and as trench backfill for non-metallic culvert and sewer pipes without associated underdrains.*

[2] *Ensure dense-graded aggregate produced by crushing portland cement concrete does not contain more than 5.0 percent building rubble or hot mix asphalt by particle count. The Department defines building rubble as building brick, wood, plaster, or other material. The Engineer will allow pieces of steel reinforcement capable of passing through the maximum grading sieve size without aid.*

Do not use Class 21AA, 21A and 22A dense-graded aggregate produced from crushing portland cement concrete to construct an aggregate base or an aggregate separation layer when the dense-graded layer drains into an underdrain, unless at least one of the following conditions apply:

A. A vertical layer of at least 12 inches of granular Class I, II, IIA, or IIAA exists between the dense-graded aggregate layer and an underdrain or,

B. A geotextile liner or blocking membrane, that will be a barrier to leachate, placed between the crushed concrete and the underdrain. Only produce Class 23A dense-graded aggregate from steel furnace slag for use as an unbound aggregate surface course or as an unbound aggregate shoulder.

[3] *Ensure open-graded aggregate 4G produced by crushing portland cement concrete does not contain more than 5.0 percent building rubble or hot mix asphalt by particle count. The Department defines building rubble as building brick, wood, plaster, or other material. The Engineer will allow pieces of steel reinforcement capable of passing through the maximum grading sieve size without aid. Do not use open-graded aggregate 34G or 34R produced from portland cement concrete.*

Also see Special Provision 03SP303(A), Open-Graded Drainage Course, Modified, and Special Provision 03CT303(A 140), Open-Graded Drainage Course, Modified (Portland Cement-Treated Permeable Base Using Crushed Concrete)

[4] *The Contractor may use crushed concrete coarse aggregate in the following concrete mixtures: curb and gutter, valley gutter, sidewalk, concrete barriers, driveways, temporary pavement, interchange ramps with a commercial ADT less than 250, and concrete shoulders. Do not use crushed concrete coarse aggregate in the following: mainline pavements or ramps with a commercial ADT greater than or equal to 250, concrete base course, bridges, box or slab culverts, headwalls, retaining walls, pre-stressed concrete, or other heavily reinforced concrete.*

Purpose and Overview of Guideline Document

Although there are potentially some limitations associated with the use of CCA, the effective characterization of these materials during their production and throughout the design and construction process can help lead to their successful application. This guideline document is intended to help MDOT effectively use CCA in the construction of the State's transportation infrastructure, with particular focus on pavement applications. Information presented herein is based on a recent report completed by Michigan Tech University for MDOT (Hiller et al. 2011) and on current nationwide state-of-the-practice on CCA use, tempered to reflect MDOT's experiences and practices.

The document is divided into seven chapters, including this one. Chapter 2 describes the processing and production of CCA from existing concrete, including initial characterization of the concrete for recycling suitability, breaking and removal, crushing and sizing, and stockpile management. Chapter 3 discusses properties of the CCA itself, including physical, mechanical, and chemical characteristics, as well as typical properties of paving materials incorporating CCA. Chapters 4, 5, and 6 discuss the use of CCA in base layers, asphalt paving layers, and PCC paving layers, respectively. Finally, chapter 7 presents a summary of the report and overall recommendations.

CHAPTER 2. PROCESSING AND PRODUCTION OF CRUSHED CONCRETE AGGREGATE

Introduction

This chapter describes the steps for the production of CCA, including characterization of the source (existing concrete pavement), removal, crushing, sizing, and stockpile management. Before removal, the pavement in question must first be examined and characterized to determine how the derived CCA can best be reused. The pavement is then broken up using appropriate methods, removed from the project site (although some equipment allows this to be done on grade), and then crushed and sized to a usable gradation. If needed, the CCA is processed to remove contaminants. Finally, the CCA is stockpiled for future use, making sure that the stockpiles are properly managed. Each of these key steps is described in the following sections.

Pavement Characterization and Preparation

PCC pavement conditions that suggest it is suitable for removal and reconstruction include the following (Hoerner et al. 2001):

- Little or no remaining structural life, as evidenced by extensive slab cracking throughout the project.
- Extensive slab settlements, heaves, or cracking due to foundation movement (caused by swelling soil or frost heave).
- Extensive joint deterioration (particularly for short-jointed pavements, since full-depth repair would require replacement of a large percentage of the concrete surface).
- Extensive durability problems (D-cracking or reactive aggregate distress over the length of the project).

In some cases, outdated geometric design features (e.g., inadequate lane widths, bridge clearances, or curve superelevations) may also necessitate a need for total reconstruction of the roadway facility.

Once a pavement is identified as being a candidate for removal, collecting detailed information on the existing concrete is desirable to help determine the overall quality of the source to maximize the production of useable CCA in terms of quality and quantity (ACPA 2009). Information about the original mix design should be obtained if available, particularly the type and coarseness of cement, water to cementitious materials ratio (*w/cm*), supplementary cementitious materials (SCMs) such as fly ash or slag cement, and type and shape of aggregate. These factors will help to identify acceptable applications for the CCA, with high-quality materials more suitable for use in concrete, and lower-quality materials relegated to base layers or fill applications (ACPA 2009).

Along those lines, an important determination to make before using a concrete pavement for CCA is whether or not materials-related distress (MRD) is present, such as alkali-silica reactivity or D-cracking. In some applications, and depending on the agency, the presence of MRD in the old concrete may prohibit the use of the CCA in new concrete, or as a minimum it may dictate the need for special mitigation measures (e.g., use of Class F fly ash if ASR was present).

Depending on the shoulder type and condition, it may be removed before recycling, recycled with the mainline concrete if it is also concrete, or left in place for the new pavement. Other factors to note during the pavement evaluation stage include information on the subgrade strength and the presence of subsurface utilities, both of which may be critical in determining the appropriate breaking method to be used for removal.

As shown in table 2, a number of contaminants may be encountered during the recycling process, including HMA overlays and patches, joint sealant, reinforcing steel, dowel and tie bars, and soils and foundation materials (Hoerner et al. 2001). Other contaminants may be present within the concrete itself, such as alkalis and chlorides from deicing salts. Efforts should be made to minimize the potential for introducing contaminants, especially if the CCA is to be considered for use in new concrete (ACPA 2009). The amount of contaminates allowed for various application according to the *2012 MDOT Standard Specifications for Construction* are presented in table 1.

Table 2. Potential contaminants in PCC pavement rubble (adapted from Hoerner et al. 2001).

Contaminant	**How Removed**	**Effect of Contaminant on PCC Mixtures with CCA**
Reinforcing Steel	• On grade • Electromagnet during crushing operations	• No effect (steel effectively removed)
Dowel Bars/Baskets	• On grade • Electromagnet during crushing operations	• No effect (steel effectively removed)
Chemical Admixtures in Original PCC Mix	• Not removed	• Entrained air in original PCC dictates greater air contents in CCA concrete • Other effects not known
Deicing Salts	• Not removed	• May contribute to steel corrosion in new concrete
Oil	• Not removed	• Small quantity believed to have no effect
Joint Sealant	• Removed prior to demolition by some; not removed by others	• Small quantity believed to have no effect
Soil/Base Course Materials	• Careful loading operator • Scalping screen ahead of primary crusher	• May introduce clay balls in mix, reducing PCC strength

Several of the contaminants can be removed prior to the actual concrete breaking operations. For example, some agencies remove joint sealant from CCA prior to the breaking operation through the use of joint plows, whereas others elect to leave the sealants in place during demolition (ACPA 2009).

If present, it is generally recommended that HMA overlays be removed prior to the pavement demolition and recycled separately from the concrete (Hoerner et al. 2001). HMA overlays are most efficiently removed by cold milling.

Concrete Breaking and Removal

The next step in the concrete recycling process is breaking the concrete slabs into pieces small enough to be handled and managed by the crusher. Although sometimes individual slabs can be removed intact and broken later, most PCC pavement is broken into manageable pieces of 18 to 24 inches while on grade (ACPA 2009). The two main types of equipment used for breaking concrete pavement are impact breakers and vibrating beam (or resonant) breakers (see figure 1). Impact breakers generally have higher production rates, but vibrating beam breakers are quieter and generally do not disturb underground utilities and culverts (Hoerner et al. 2001). Production rates of both types of breakers decrease with increasing pavement thickness, concrete strength, and the amount of reinforcement (ACPA 2009). In addition, because a considerable number of MDOT's older concrete pavements are JRCP designs, it is important that the selected breaker produce sufficient impact force to debond the wire mesh reinforcement from the concrete to facilitate handling and crushing (Hiller et al. 2011).

Figure 1. Pavement demolition equipment: a) diesel hammer, b) multi-head pavement breaker, and c) resonant breaker (Hoerner et al. 2001).

Another factor influencing breaker selection is the type of crushing equipment to be used, as some crushing equipment requires smaller pieces of concrete than others. For example, impact crushers typically can handle larger pieces of broken concrete than compression (jaw or cone) crushers, allowing the use of a larger crack pattern and often resulting in higher breaking production rates (ACPA 2009). However, impact crushers generally yield slightly less coarse CCA and correspondingly produce a relatively higher percentage of finer CCA particle sizes than do compression crushers. Maximizing coarse CCA yield may require the use of compression crushers and impact breaking equipment with an appropriate breaking pattern (ACPA 2009).

After breaking, the concrete fragments can be removed easily with standard construction equipment such as front-end loaders, backhoes, and dump trucks. The use of a rhino horn—a 30-inch steel "pick" affixed to a backhoe or crane—can help facilitate loosening of the concrete and pulling the steel free (see figure 2). Some hand work (e.g., workers with torches or hydraulic shears) may still be required to cut the reinforcing steel, but relatively small pieces of embedded steel (including dowel bars and tie bars) will usually not cause problems in the crushing operations and will be removed using electromagnets after crushing (ACPA 2009).

Figure 2. Rhino horn (ACPA 2009).

The pavement rubble is loaded by front-end loaders into dump trucks and hauled to a crushing plant for processing into CCA. Loader operators should work to minimize the amount of underlying material (e.g. base, subbase, or subgrade) that is collected with the PCC, since these contaminants will decrease the quality of the final CCA.

Crushing and Sizing Operations

After removal and transport, the rubble is processed at a crushing plant to produce CCA. A nearby crushing plant may be used, or a "portable" plant may be set up at a location close to the project site. Mobile crushers have seen increasing use, operating on grade. A schematic of the sequence of crushing operations is shown in figure 3.

Crushing

The crushing process is generally a two-staged operation, consisting of a primary crusher (used to break down the large concrete rubble into nominal maximum sizes of about 3 to 4 inches) and a secondary crusher (used to crush the material to the specified CCA sizes). There are three main types of crushers used to produce CCA (ACPA 2009):

- Jaw crushers use a large steel plate to compress concrete fragments against a stationary plate within the crusher housing. Aggregate top size is controlled by varying the amount of jaw closure. Jaw crushers are commonly used as primary crushers because they can handle larger slab fragments than cone crushers.
- Cone crushers use an eccentric rotating cone to trap and crush concrete fragments against the inner crusher housing walls. When the material becomes small enough, it escapes through the bottom of the crusher housing. Most cone crushers can handle slab fragments no larger than 8 inches in diameter. For this reason, they are used most often as the secondary crushing unit in concrete recycling operations.

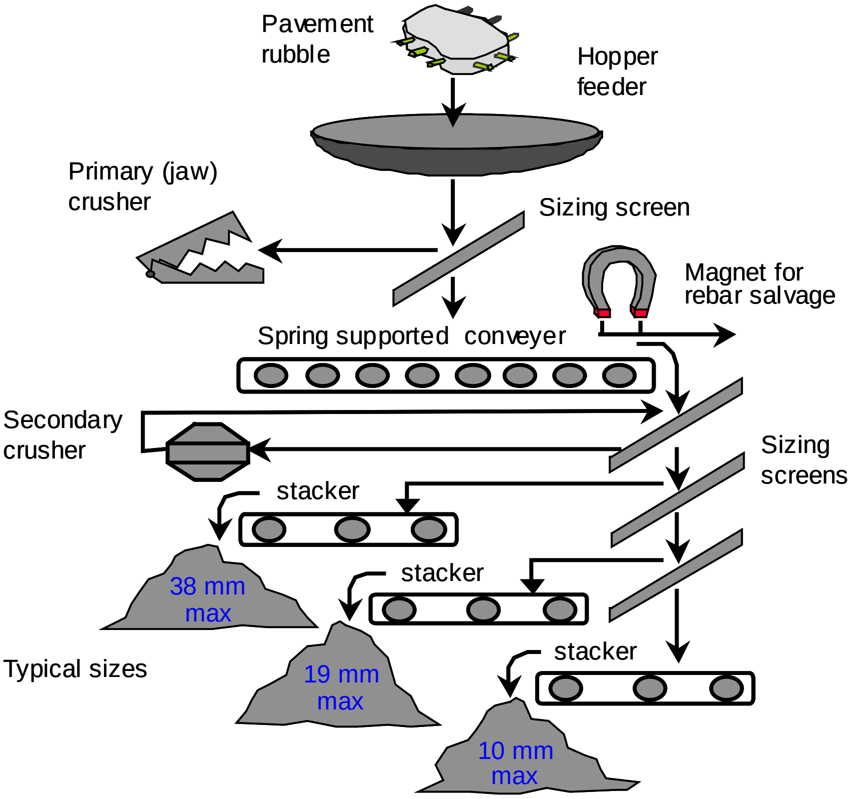

Figure 3. Schematic illustration of crushing operations (Hoerner et al. 2001).

- Impact crushers use heavy steel "blow bars" mounted on a horizontal or vertical rotor to repeatedly impact concrete fragments and hurl them against steel anvils or "break plates" in the crusher housing. The rotor continues to hurl particles that are larger than the desired top size. Impact crushers tend to remove more mortar from the coarse aggregate, resulting in more fine CCA and minus No. 200 fines and lower coarse CCA yield. But the coarse CCA produced in an impact crusher often produces higher quality concrete if used for that application as there is less reclaimed mortar present. Impact crushers must be fabricated to withstand the impact of any steel reinforcement that enters the crusher.

Figure 4 shows schematic illustrations of the different types of crushers. Overall, these crushers are similar to what are used to process natural aggregate, but may undergo some minor modifications to make them suitable for handling recycled concrete (such as adding an electromagnet for removing steel).

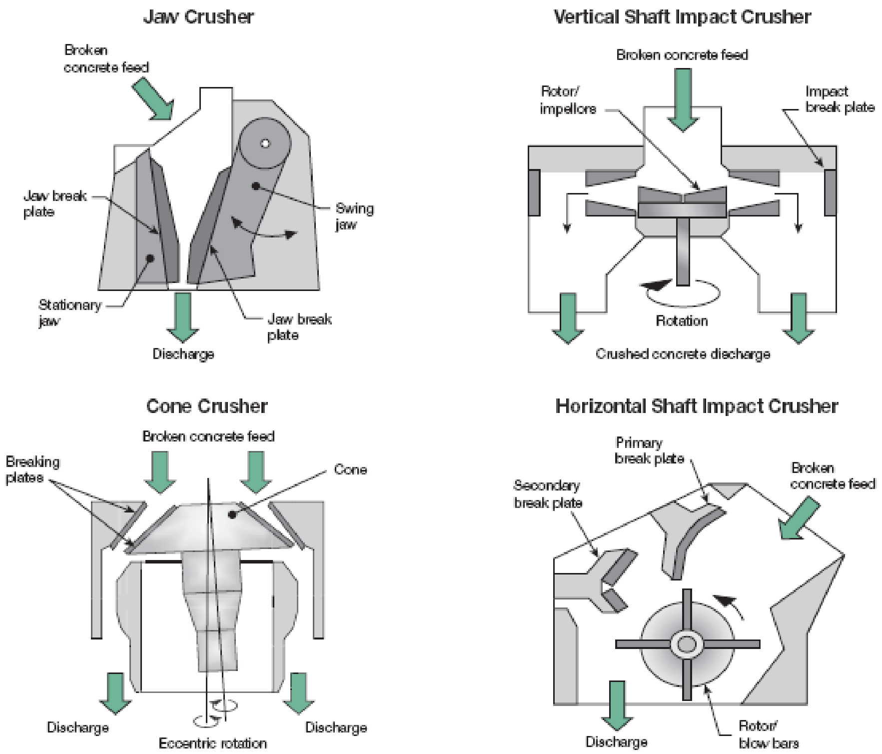

Figure 4. Schematic illustrations of various types of crushing equipment (ACPA 2009).

Smaller construction projects may employ portable mini-concrete crushers that can be towed behind a truck for easy transport and reduced space requirements (Hiller et al. 2011). These crushers significantly reduce the hauling costs associated with off-site crushing operations and can be effectively used to secure desired CCA sizes. Overall, the CCA sizes are selected based on the anticipated use of the CCA, with overall yield largely dependent on the maximum size of the aggregate (since crushing to a smaller size creates more fines that are not usable). However, other factors may also affect the overall yield, including the type, size, quality, and quantity of natural coarse aggregate used in the original concrete; the quality and hardness of the concrete mortar; the breaking and removal operations, and the crushing processes used (ACPA 2009).

Steel Removal

As described previously, much of the steel removal is performed on the project site, but any remaining steel can be removed as part of the crushing operation. The use of an electromagnet placed over the conveyor belt removes virtually all steel, leaving only a small amount of hand work to ensure that no steel enters the sizing screens (Hoerner et al. 2001).

Stockpile Management

After crushing and sizing, the produced CCA is stockpiled using essentially the same techniques and equipment as traditional aggregates. However, there are several factors that may complicate stockpiling CCA materials:

- The exposure of precipitation to mortar and unhydrated cement in the CCA can lead to runoff from stockpiles that can be highly alkaline (Snyder et al. 1994). However, while initially high (generally pH on the order of 9 to 10 but occasionally as high as 11.5), runoff alkalinity usually decreases rapidly within a few weeks as the exposed calcium hydroxide is depleted through neutralization, dissolution, and reaction with carbon dioxide in the air and through neutralization with rainwater (ACPA 2009).
- Some studies have shown the presence of trace amounts of heavy metals and other naturally occurring contaminants in CCA stockpile runoff, although generally not to levels considered hazardous (Sadecki et al. 1996). However, these contaminants can be expected to decrease rapidly with time as well (ACPA 2009).
- CCA typically includes a small percentage of unhydrated cement in the mortar fraction of the aggregate, which can lead to secondary cementing through either direct water exposure or high humidity levels (Hiller et al. 2011). Stockpiles of fine CCA may need to be protected from precipitation to prevent or reduce the potential for this to occur (ACPA 2009).
- Coarse CCA used in new concrete should be washed and maintained in a moist condition prior to batching. Concrete plants should be set up to handle these operations without unacceptable run-off and/or chance of contamination.

Checklist: CCA Processing and Production

Table 3 provides a brief checklist to consider with regards to CCA processing and production.

Table 3. Checklist for CCA processing and production.

Item	✓
Pavement has little remaining life and is a good candidate for reconstruction	
Information on original pavement and mix design reviewed	
Appropriate breaking equipment selected for anticipated CCA use	
Verified that rubble is sized to handle, fit crusher, and separated from embedded steel	
Crusher selected to produce CCA for anticipated use considering gradation	
Stockpile management plan is developed and implemented	

CHAPTER 3. CRUSHED CONCRETE AGGREGATE PROPERTIES AND APPLICATIONS

Introduction

As described in chapter 1, CCA exhibits physical properties and mechanical characteristics that differ from natural aggregates. This does not mean that CCA cannot be effectively used in pavement applications, but does signify that these differences must be directly considered as part of the design and construction process. This chapter describes properties and characteristics of CCA, how these differ from natural materials, and the potential impacts of these differences on the use of CCA. More detailed discussions on using CCA in specific pavement-related applications are presented in chapters 4 through 6.

General Properties and Characteristics of CCA

Table 4 compares some of the typical properties associated with CCA and natural aggregate materials (Snyder et al. 1994). As listed, CCA is very angular as a result of the crushing process. Primary reasons for other differences in the properties lie in the fact that CCA is composed of both the original natural aggregate and a reclaimed mortar fraction, the combination of which results in a higher absorption, a lower specific gravity, and potential for decreased abrasion resistance. As the relative amount of reclaimed mortar increases, so do the differences in properties. For this reason, reclaimed mortar content is discussed in the following section followed by discussions on some of the other properties listed in table 4.

Table 4. Comparison of typical natural aggregate and CCA properties (Snyder et al. 1994).

Property	Natural Aggregate	CCA
Particle Shape and Texture	Well rounded, smooth (gravels) to angular and rough (crushed stone)	Angular with rough surface
Absorption Capacity	0.8 – 3.7 percent	3.7 – 8.7 percent
Specific Gravity	2.4 – 2.9	2.1 – 2.4
L.A. Abrasion Test Mass Loss	15 – 30 percent	20 – 45 percent
Sodium Sulfate Soundness Mass Loss	7 – 21 percent	18 – 59 percent
Magnesium Sulfate Soundness Mass Loss	4 – 7 percent	1 – 9 percent
Chloride Content	0 – 2 lb/yd^3 (0 – 1.2 kg/m^3)	1 – 12 lb/yd^3 (0.6 – 7.1 kg/m^3)

Mortar Content

CCA has a variable reclaimed mortar content that depends on the original concrete mixture proportions and crushing operations (Hiller et al. 2011). The volume of reclaimed mortar in the CCA also depends significantly on the original aggregate type. CCA processed from concrete originally made with rounded, less porous aggregates has less reclaimed mortar as the concrete tends to fracture at the aggregate-mortar interface during the crushing process. In contrast, more reclaimed mortar is often present if the original concrete was made with porous or crushed aggregates. The mechanical properties of the CCA, whether used as an unbound base material or bound by cement or asphalt, are highly influenced by the volume of reclaimed mortar.

Fineness and Composition of Original Cement

The fineness of the cement used in the source concrete can have an effect of the characteristics of the CCA. To meet the demands for higher early strength concrete, modern cements are more finely ground and contain greater amounts of fast setting cement phases (Hiller et al. 2011). Consequently, CCA produced from older concrete pavements (which would typically contain slower setting cement) may have more unhydrated cement present than more recent concrete.

Thus, when crushing older concrete, unhydrated cement grains will likely be exposed in the CCA. The presence of these cement grains can lead to unexpected changes in the physical properties of both the CCA and in the new concrete in which it is used (Hiller et al. 2011). These changes may be positive, such as an increase in strength due to an induced decrease in water-to-cementitious material ratio (*w/cm*), but may also be negative, such as an increase in drying shrinkage that may result in premature cracking in the new concrete. This will be less an issue if the source concrete is fairly modern as most (but not all) of the original cement may be hydrated.

Particle Shape and Texture

The relative proportions of original coarse aggregate and mortar in CCA varies with the original concrete mixture design, the properties of the coarse aggregate particles (i.e., the angularity and surface texture, strength and elasticity), the bond between the natural aggregate particles and the mortar, and the type and extent of crushing used in production (ACPA 2009). Nevertheless, both coarse and fine CCA particles are highly angular and have rough surfaces, although the larger particles tend to contain greater proportions of reclaimed natural aggregate, whereas finer particles (those passing the No. 4 sieve) often are mainly crushed mortar (ACPA 2009). When used in new concrete, recycled fines (which are far more angular than natural sands) greatly increases the harshness of the mix and can make it very difficult to work (Snyder et al. 1994).

Absorption Capacity

Absorption capacity is a measure of the amount of water that an aggregate can absorb. CCA generally have higher absorption capacities than natural materials, primarily due to the porous nature of the cement paste fraction in the reclaimed mortar (Snyder et al. 1994). These higher absorption capacities can lead to a loss of workability. A number of studies have clearly documented that decreasing CCA particle size leads to increased absorption capacity as the volume of reclaimed mortar increases (ACPA 2009). In an attempt to reduce water absorption during concrete mixing, common practice is to saturate coarse CCA before mixing (ACPA 2009). This cannot be done with fine CCA as the unhydrated cement grains will hydrate, causing the stockpiled material to bind together.

Specific Gravity

Specific gravity is a measure of the density of an aggregate relative to the density of water. CCA particles generally have lower specific gravity values than natural materials, attributed to the reclaimed mortar bound to the CCA particles, which is less dense than most natural aggregates due to its porosity and entrained air structure (Snyder et al. 1994). Specific gravity has been observed to decrease as particle size decreases as reclaimed mortar content increases with reduced particle size (ACPA 2009).

Abrasion and Soundness

Several tests are often conducted to assess an aggregate's abrasion resistance, the most common being ASTM C 131, *Standard Test Method for Resistance to Degradation of Small-Size Coarse Aggregate by Abrasion and Impact in the Los Angeles Machine*. Aggregate soundness, or resistance to weathering is also tested using ASTM C 88, *Standard Test Method for Soundness of Aggregates by Use of Sodium Sulfate or Magnesium Sulfate*.

Although the abrasion loss as measured in ASTM C131 is typically higher for CCA than for natural aggregates, most CCA still meets the specified MDOT limit (MTM 102) of 50 percent abrasion loss for dense-grade aggregates (Table 902-2, *2012 MDOT Standard Specifications for Construction*). However, CCA will commonly fail the sodium sulfate test in ASTM C88 yet pass the magnesium sulfate test; because of this discrepancy, it is not clear whether ASTM C88 is applicable to CCA materials and consequently many agencies waive these test requirements for CCA (ACPA 2009).

Chloride Content

High levels of chlorides have been found in CCA produced from pavement sources with long-term exposure to deicing chemicals, which raises concerns about the effects of the chlorides on durability, corrosion of embedded steel, and set times (ACPA 2009). Several studies have indicated that the increased chlorides are found primarily in the fine CCA produced from concrete located near the surface and thus are of little concern when only the coarse CCA is used in new concrete (ACPA 2009).

Freeze-Thaw Durability

Freeze-thaw durability refers to the resistance of the hardened concrete to repeated freeze-thaw cycles while in a saturated state. Freeze-thaw deterioration can occur in the mortar fraction or in the coarse aggregate, leading to cracking and deterioration often starting near joints and cracks (Van Dam et al. 2002).

The freeze-thaw durability of CCA is dependent on a number of factors, including the characteristics of the original aggregate source and the entrained air-system in the reclaimed mortar (Hiller et al. 2011). To ensure freeze-thaw resistance, the CCA should be tested for acceptable freeze-thaw resistance using MTMs 113, 114, and 115.

Pavements that have suffered freeze-thaw distress (such as D-cracking) have been successfully recycled into CCA for use in an unbound granular layer. When used as coarse aggregate in a cement bound layers or new concrete, the CCA is commonly crushed to a 0.75-inch maximum aggregate size (ACPA 2009).

Alkali-Silica Reactivity

Alkali-silica reactivity (ASR) is a result of an undesirable chemical reaction between alkalis in the cement paste and reactive siliceous components of susceptible aggregates. The product of the reaction is a gel that expands significantly in the presence of moisture, destroying the integrity of the weakened aggregate particle and the surrounding cement paste.

The potential for ASR in new concrete containing CCA is affected by the original alkali level of the old concrete, the remaining potential reactivity of the recycled aggregate, and the alkali content of new concrete (Stark 1996). It has been demonstrated that CCA from source concrete that has suffered ASR can be successfully used in unbound granular layers, or as aggregate in cement bound layers or new concrete if the ASR is effectively mitigated. The effectiveness of ASR mitigation should be demonstrated using ASTM C1567, *Standard Test Method for Determining the Potential Alkali-Silica Reactivity of Combinations of Cementitious Materials and Aggregate (Accelerated Mortar-Bar Method).*

Accommodating CCA Materials in Pavement Applications

For every CCA property or characteristic, there are a number of methodologies that can be employed to help mitigate that influence of that property on behavior. Although these will be discussed in more detail in chapters 4 through 6 for specific applications, table 5 summarize some of the potential concerns/issues with the use of CCA and some mitigation strategies.

Table 5. Using CCA as unbound granular material (based on ACPA 2009; Hiller et al. 2011).

CCA Property or Characteristics	**Potential Concerns/Issue**	**Mitigation Measure(s)**
Particle Shape and Texture	Irregular shape and highly angular, which may result in poor workability	Coarse CCA: Generally does not cause significant workability problems in new concrete mixtures. Fine CCA: Limit to 30 percent or less of replacement of natural sand.
Absorption Capacity	More absorptive than natural aggregates, increasingly so as the particle size decreases.	Coarse CCA: Wash aggregate and keep stockpile moist until batching. Using water-reducing admixtures. Fine CCA: Limit amount of fine CCA used.
Specific Gravity	Typically lower than natural aggregates and decreases as particle size decreases.	Addressed through the mixture design process.
Abrasion Resistance	Less abrasion resistant than natural aggregate.	Often meets the abrasion resistance requirements for most concrete mixtures (50 percent mass loss in accordance with MTM 102)
Soundness Resistance	Will often meet magnesium sulfate soundness requirements but fail sodium sulfate soundness.	Inconsistency in results often necessitates waiving soundness resistance testing for CCA.
Chloride Content	Chloride content of CCA is high due to deicer use on source concrete, raising concerns about set time, concrete durability, and corrosion of embedded steel.	Coarse CCA: Generally chloride content is relatively low and not of concern. Fine CCA: May be high requiring limits on amount of fine CCA used. Protect steel using coating, cladding, or non-corrosive material.
Freeze-Thaw Durability	If the source concrete suffered freeze-thaw distress, may be a problem in new application.	Not an issue in unbound applications. If CCA is to be bound with cement, the freeze-thaw resistance must be verified using MTM 115.
Alkali-Silica Reactivity	If the source concrete suffered ASR, may be a problem in new application.	Not an issue in unbound applications. If CCA is to be bound with cement, the ASR resistance must be verified using ASTM C1157.
Leaching	If used as drainage layer, leaching may compromise functionality of system	Don't use unbound material as drainage layer, especially finer fraction.

Checklist: CCA Properties and Applications

Table 6 provides a brief checklist to consider with regards to CCA properties and applications.

Table 6. Checklist for CCA properties and applications.

Item	✓
Mortar fraction of CCA is acceptable for anticipated use	
Volume of unreacted cement is acceptable for anticipated use	
Absorption capacity is acceptable for anticipated use	
Abrasion resistance is acceptable for anticipated use	
Chloride content is acceptable for anticipated use	
Source concrete was free of MRD	
If MRD was present, CCA can be mitigated for anticipated use	

CHAPTER 4. USE OF CRUSHED CONCRETE AGGREGATE IN MDOT BASE LAYERS

Introduction

When held to the same specifications as natural aggregates, CCA can perform very well as a base material and can be used without design adjustments (NCHRP 2000). As described previously, it exhibits highly angular properties, which contribute to a strong, stable base. Untreated CCA bases can even behave like cement-treated bases due to the hydration of unreacted cement exposed during CCA processing.

A major concern regarding the use of CCA in base layer applications is related to leachates. CCA contains calcium hydroxide from the original cement hydration reaction. It is water soluble, and when water flows through a CCA base, some calcium hydroxide will dissolve into the water. Subsequently, it interacts with atmospheric carbon dioxide to form calcium carbonate, precipitating out of solution and leaving deposits where the water flows. This is problematic if the precipitate clogs up elements of a pavement drainage system, such as filter fabrics, drainage pipes, and outlets (ACPA 2009). CCA containing larger amounts of cement paste or exhibiting higher percentages of finer graded particle sizes will produce more precipitate. In these cases, the risks associated with clogging pavement drainage systems can be much greater.

Some environmental concerns exist regarding the use of CCA as base material, primarily because of its alkalinity. However, the alkalinity rapidly decreases with time, and is not considered a major concern although some vegetation may be destroyed where runoff is discharged directly from a CCA base (ACPA 2009).

Unbound bases are not rigid, and therefore are not as sensitive to volume changes as cement- or asphalt-treated bases. For this reason, concerns with CCA expansion due to ASR or freeze-thaw are minimal. When used as a base, the presence of contaminants (e.g., asphalt, wood, steel, and so on) in the CCA is less critical, and therefore limits on amounts of contaminants present in the CCA are generally not as strict as limits for use in HMA or concrete, making production and processing simpler and cheaper. Although most steel must be removed to allow for crushing, some smaller pieces can remain as long as they can pass through the sieve for the maximum size aggregate. This ensures that any steel present will not interfere with proper placement and compaction. Chlorides and other chemicals present in the CCA should not cause problems when it is used in unbound base layers. These factors combine to make recycling concrete for use in base layers simpler and cheaper than recycling it for PCC aggregate. Additionally, almost any PCC pavement is suitable for recycling into CCA for a base layer.

MDOT Requirements for Using CCA in Dense-Graded Base Layers

MDOT requires that dense-graded CCA bases follow the same gradation and quality requirements as natural aggregate bases for classes 21AA, 21A, or 22A. These requirements are summarized in tables 7 and 8. The *2012 MDOT Standard Specifications for Construction* limits foreign matter such as brick, wood, plaster, or similar materials to 5 percent, by particle count (MDOT 2012).

Table 7. MDOT gradation requirements for dense-graded aggregates.

Aggregate Class	**Sieve Analysis (MTM 109) Percent Passing**							
	1½	**1 in**	**¾ in**	**½ in**	**$^3/_8$ in**	**No. 4**	**No. 8**	**No. 200[1]**
21AA	100	85-100		50-75			20-45	4-8
21A		100	90-100		65-85		30-50	4-8
22A		100			60-85		25-60	9-16

[1] Loss by washing (MTM 108)

Table 8. Additional MDOT physical requirements for dense-graded aggregates.

Aggregate Class	**Crushed Material, % min (MTM 110, 117)**	**Loss, % max, Los Angeles Abrasion (MTM 102)**
21AA	95	50
21A	25	50
22A	25	50

During pavement structural design, the engineer should consider that continued hydration of the CCA may lead to base layers that are stiffer and stronger than natural aggregate base layers.

MDOT Requirements for Using CCA in Open-Graded Drainage Course

The *2012 MDOT Standard Specifications for Construction* allow the use of CCA for an open-graded drainage course meeting Class 4G requirements (MDOT 2012). Although no gradation is provided in the 2012 specifications, the commonly used Special Provision 03SP303(A), *Open-Graded Drainage Course, Modified* requires that a Class 4G open-graded aggregate meets the requirements provided in table 9. A unique feature of this specification is the requirement to have a pre-placement and in-place gradation requirement as indicated.

Table 9. MDOT requirements for open-graded aggregates (based on Special Provision 03SP303(A), *Open-Graded Drainage Course, Modified*).

Aggregate Class	**Sieve Analysis (MTM 109) Percent Passing**						
	1½	**1 in**	**¾ in**	**½ in**	**No. 8**	**No. 30**	**No. 200[1]**
4G: Prior to placement	100	85-100		45-65	15-30	6-18	6 max
4G: In-place	100	85-100	60-80	45-70	15-35	8-22	8 max
Additional Physical Requirements							
Crushed Material, % Min (MTM 110,117)				95			
Loss, % max, Los Angeles Abrasion (MTM 102)				45			

[1] Loss by washing (MTM 108)

Specific requirements for the use of CCA as an unbound open-graded base are described in MDOT Special Provision 03SP303(A), *Open-Graded Drainage Course, Modified*, which should be thoroughly reviewed if using CCA in this application. It can be downloaded at: (http://mdotwas1.mdot.state.mi.us/public/dessssp/spss_source/03SP303A.pdf).

Special Provision 03SP303(A) and the *2012 MDOT Standard Specifications for Construction* limit foreign matter such as brick, wood, plaster, or similar materials to 5 percent, by particle count, in a Class 4G CCA (MDOT 2012). This is the only reference specific to CCA contained in the special provision.

Due in part to issues related to excessive leachate flow from unbound CCA open-graded drainage courses, MDOT has examined the use of cement-treated permeable base (CTPB) as specified under Special Provision 03CT303(A140), *Open-Graded Drainage Course, Modified (Portland Cement-Treated Permeable Base Using Crushed Concrete)*. Cement-treatment of open-graded CCA has been used on a limited number of projects and is not currently listed as a "Frequently Used" Special Provision. To date, MDOT pavement performance data show that concrete pavements constructed on stabilized permeable CCA bases are performing very well. The requirements for CCA used in CTPB are provided in table 10.

Table 10. MDOT requirements for open-graded drainage course for CTPB (based on Special Provision 03CT303(A140).

Sieve Analysis (MTM 109)							
Sieve Size	**1½**	**1 in**	**¾ in**	**½ in**	**No. 4**	**No. 8**	**No. 200**[1]
Percent Passing	100	90-100		25-65	0-20	0-8	5 max
Additional Physical Requirements							
Crushed Material, % Min (MTM 110,117)				90[2]			
Loss, % max, Los Angeles Abrasion (MTM 102)				45			

[1] Loss by washing (MTM 108)

[2] The percent crushed material will be determined on that portion of the sample retained on all sieves down to and including the 3/8 inch.

In addition, MDOT Special Provision 03CT303(A140) requires that all CCA used for a CTPB be obtained from the pavement that is being reconstructed, unless otherwise approved by the Engineer. The CTPB mixture is to be proportioned and mixed at a dedicated batch plant or pugmill, and will contain 250 lbs of cement and 100 to 120 lbs of water per cubic yard of material. However, adjustments to the cement and water content may be appropriate, based on field conditions and in place gradation, to ensure that the compressive strengths are maintained within the specified range between 200 and 700 psi at 7 days.

MDOT Requirements for Rubblized Concrete Base Layers

Concrete pavement can be recycled in-place and used as a base by the process of rubblization. Rubblization consists of preparing, shattering, and compacting concrete pavement to provide a base for new pavement. The rubblized concrete provides a base at a lower cost than a natural aggregate base, and often it is less expensive than a CCA aggregate base since the costs of removal, transportation, crushing, and processing are eliminated.

Concrete pavements with significant materials-related distress (such as D-cracking or ASR) are generally good candidates for rubblization. Care should be taken when selecting potential candidate projects for rubblization as poorly supportive subsurface soils may not provide a suitably stable platform for adequately rubblizing the concrete pavement.

Preparation and breaking an existing concrete pavement for the purpose of rubblization is similar to the process for breaking concrete for other CCA applications. The rubblization process is described in the *2012 MDOT Standard Specification for Construction*, Section 304. Two types of breaking equipment can be used: equipment that uses resonant frequency and equipment that uses multiple impact hammers. Resonant frequency breakers should produce breaking force of approximately 2000 lbs at a rate of at least 44 blows per second. Multiple impact hammer equipment should impact in a random sequence, and should break between 3 and 14 feet of width in each pass. Water systems approved by the Engineer must be used to suppress dust. Breaking should debond the PCC from any reinforcing steel and break the PCC into pieces with nominal diameters of 2 to 5 inches. If reinforcement is not present, pieces up to 8 inches in diameter are acceptable. The rubblized concrete should then be compacted using vibratory and pneumatic-tired rollers, with the addition of water if approved by the Engineer, to obtain density. The compacted surface should be uniform and free of asphalt materials and reinforcing steel.

In the new pavement design, the level of support provided by the rubblized concrete is greater than an unbound granular base, but less than support given by an asphalt layer. Rubblized concrete can sometimes provide more support than a stabilized base (ACPA 1998).

Checklist: CCA for Use as Base Material

Table 11 provides a brief checklist to consider with regards to the use of CCA as a base material.

Table 11. Checklist for CCA for use as base material.

Item	✓
CCA to be used as unbound base meets 21AA, 21A, or 22A gradation limits	
CCA to be used as unbound base meets 21AA, 21A, or 22A additional physical requirements	
CCA to be used as unbound open-graded drainage course meets 4G gradation limits before and after placement	
CCA to be used as unbound open-graded drainage course meets 4G additional physical requirements	
CCA to be used as CTPB meets gradation requirements as specified in Special Provision 03CT303(A140)	
CCA to be used as CTPB meets additional physical requirements as specified in Special Provision 03CT303(A140)	
Rubblization meets Section 304 of the *2012 MDOT Standard Specifications for Construction*	

CHAPTER 5. USE OF CRUSHED CONCRETE AGGREGATE IN MDOT ASPHALT PAVING LAYERS

Introduction

Although not common, CCA can be used as an aggregate in asphalt paving layers. As with the application in base courses, CCA can produce a stable mixture because of its high angularity. And, because the asphalt cement forms a film around the aggregate, leaching and other complications from water interacting with the CCA are minimized. However, CCA use in asphalt concrete has not been widely used on MDOT projects.

Coarse CCA is more widely used in asphalt concrete than fine CCA. This is due to the fact that coarse CCA has a smaller portion of mortar present, and therefore behaves more like natural aggregate. Fine CCA (particles passing the No. 4 sieve), however, contains more mortar (which yields a lower specific gravity and higher absorption), the overall result of which is that more asphalt cement must be used to achieve the desired material properties (Mukhopadhyay, Geiger, and Button 2010; ACPA 2009). The cost of using increased asphalt cement quantities may offset the cost benefit of using CCA.

Concerns have also been raised regarding increased stripping potential and the reduced surface friction of asphalt mixtures made with CCA, but there is no consensus on whether or not these are major issues.

CCA Use in Asphalt Mixtures

In general, for CCA to be a sufficient quality for use in asphalt mixtures, it must adhere to the same quality requirements as natural aggregate. Deleterious materials such as soil, ash, or other fine organic materials should be limited, as they will increase asphalt cement demand and decrease overall quality (NCHRP 2000). Soundness, abrasion resistance, and volume stability should also be tested to ensure the CCA is a suitable aggregate for asphalt mixtures. Specific gravity and absorption are generally the properties in which CCA varies the most from natural aggregate, and should be thoroughly evaluated and properly accounted for in the mix design.

Gradation requirements for CCA are the same as for natural aggregate, although fine CCA is not often used in asphalt mixtures as previously mentioned. Particle shape is more important in asphalt mixtures than in concrete, since sufficient fractured faces are needed to obtain a stable, rut-resistant asphalt mixture. Due to the crushing process, CCA is generally very angular and therefore would contribute to good asphalt mixture stability. And CCA should meet the requirements for flat and elongated particles, as excessive amounts of these can lead to a weak aggregate matrix and weak asphalt mixtures. Even if ASR or D-cracking was observed in the source concrete, it is not a concern if the CCA is used as aggregate in an asphalt mixture.

If the CCA passes the same quality tests as are required of natural aggregate, the major remaining issue is the adjustment of asphalt cement quantities to account for the higher absorption. Current research suggests that HMA made with a blend of natural aggregates and CCA, with at most 75 percent coarse CCA, performs similarly to HMA made solely with natural aggregates. Fine CCA is problematic due to its higher absorption, so the best performance will be obtained using only coarse CCA.

A recent study (Mills-Beale and You 2010) conducted for MDOT determined that CCA was acceptable for use on low-volume roads, successfully passing Superpave tests for absorption, uncompacted void content, flat and elongated particles, percent fractured faces, and Los Angeles abrasion. The mechanical properties that were tested include rutting potential, dynamic modulus, moisture susceptibility, and indirect tensile resilient modulus. Under a low-volume traffic scenario, all the HMA mixes tested passed the rutting requirement and the moisture susceptibility testing except for the 75 percent CCA / 25 percent natural aggregate blend. The presence of CCA had a minimal effect on the resilient modulus, and the dynamic modulus increased with reducing CCA amounts.

MDOT Requirements for the Use of CCA in Asphalt Mixtures

According to Section 902.09 of the *2012 MDOT Standard Specifications for Construction*, CCA is permitted as a coarse aggregate in HMA, provided that it meets the same gradation and quality requirements as natural aggregates (MDOT 2012). Fine CCA, however, is not permitted. No other special requirements are listed, but it is again emphasized that MDOT has not widely used CCA in asphalt concrete.

CCA is not permitted for use in paver-placed surface seal (Section 902.10A), micro-surfacing (Section 902.10B), slurry seal (Section 902.10C), or as a mineral filler for HMA mixtures (Section 902.11). The *2012 MDOT Standard Specifications for Construction,* is silent on whether CCA is acceptable as a coarse aggregate for use in chip seals (Section 505), but the Los Angles Abrasion requirement of 35 percent and the minimum aggregate wear index (AWI) requirement of 260 are such for the Class 34CS coarse aggregate that it is unlikely that a CCA coarse aggregate could achieve the required quality.

Construction Considerations When Using CCA as Aggregate in HMA

One major difference between using CCA in asphalt concrete and using it in concrete is in moisture content. Unlike when using CCA as aggregate for concrete, the CCA should be free of moisture to be used as aggregate in asphalt mixture as moisture present in aggregate weakens the bond between asphalt cement and the aggregate and thus must be driven off through the application of heat (Mukhopadhyay, Geiger, and Button 2010). This moisture sensitivity may require different stockpiling procedures or heating the CCA until dry before use.

The use of CCA in warm-mix asphalt (WMA) is not yet well documented, but its use should be no different than it is for HMA with the following exception. Since WMA is produced at a lower temperature than HMA, the CCA may not dry completely during the production process, meaning that additional drying steps may be needed to ensure that the CCA is dry before addition of the asphalt cement (Mukhopadhyay, Geiger, and Button 2010). Nevertheless, at this time, WMA is not addressed in MDOT's specifications.

Checklist: CCA for Use With Asphalt Material

Table 12 provides a brief checklist to consider with regards to CCA for use with asphalt material.

Table 12. Checklist for CCA for use with asphalt material.

Item	✓
CCA meets the gradation requirements for coarse aggregate used in Section 902.09 of the *2012 MDOT Standard Specifications for Construction*	
CCA meets the additional quality requirements for coarse aggregate used in Section 902.09 of the *2012 MDOT Standard Specifications for Construction*	
The CCA stockpile is kept dry to avoid access moisture	

CHAPTER 6. USE OF CRUSHED CONCRETE AGGREGATE IN MDOT CONCRETE PAVEMENT MIXTURES

Introduction

A number of concrete pavement projects (outside of Michigan) have demonstrated that CCA can be used effectively as aggregate in new paving concrete (ACPA 2009). As with all other applications, the same general requirements that are applicable to natural aggregates used in concrete should be applied to CCA. Recognizing that differences exist between the two aggregate types is the key to successful implementation, as these differences can affect the behavior of fresh and hardened concrete. Nevertheless, the differences are manageable if recognized and addressed throughout the mixture design, construction, and pavement design process.

Unique Properties of Concrete Made With CCA

Reclaimed mortar (which either remains bound to the original coarse aggregate or has been freed during the crushing process) is largely responsible for the differences in behavior between concrete made with CCA and that made with natural aggregate. Reclaimed mortar is composed of the original fine aggregate and hydrated cement paste, making it relatively porous. It also contains soluble hydrated cement phases, unhydrated cement grains, and chemical contaminants (most commonly deicing salts), which contribute to leaching and chemical reactivity of the CCA. As the CCA particle size decreases, the relative volume of mortar increases, which is why the influence on concrete behavior becomes more apparent as smaller sized CCA is used. It is for this reason that it is common to use only the coarse CCA particles in new concrete mixtures, although it has been demonstrated that acceptable concrete can be produced using all CCA (ACPA 2009).

The influence of the reclaimed mortar is observed in both fresh and hardened properties on the concrete mixture made with CCA aggregates. The following describes these differences and presents strategies to overcome them in the mix design and proportioning process.

Fresh Concrete Properties

Table 13 provides a summary of the influence of CCA on fresh concrete properties (ACPA 2009). When using only coarse CCA, the major impact is the increased water demand. The angular and rough surface texture of CCA is the major contributor to increasing water demand, although the increased absorption capacity due to the reclaimed mortar also plays a role. According to the FHWA (2007), if using only coarse CCA, 5 percent more water may be needed to maintain the same workability in a similar concrete mixture made with natural aggregate. This will require additional cementitious material to be used to maintain the same *w/cm*. The use of a water-reducing admixture to partially offset the increased water demand should also be considered, as should the use of fly ash (which improves workability due to its spherical shape).

Air content measured on fresh concrete made with CCA is often slightly higher than comparable mixtures made with natural aggregate. This is often attributed to the air that is entrained in the reclaimed mortar. As with any highly absorptive aggregate (including air-cooled slag coarse aggregate), the use of volumetric air content measurement (AASHTO T 196) should be used in lieu of the pressure method (AASHTO T 152).

Table 13. Effects of CCA on fresh concrete properties and behavior (ACPA 2009).

Property	**Range of Expected Changes Compared to Concrete Made with Virgin Aggregate**	
	Coarse CCA Only	**Coarse and Fine CCA**
Workability	Similar to slightly lower	Slightly to significantly lower
Finishability	Similar to more difficult	More difficult
Bleeding	Slightly less	Less
Water Demand	Greater	Much greater
Air Content	Slightly higher	Slightly higher

If both coarse and fine CCA are used, all fresh concrete properties are affected even more significantly. For this reason, MDOT does not allow the use of fine CCA in new concrete.

One other concern with fresh concrete properties is the potential for early setting due to the presence of unhydrated cement in the CCA and the presence of chemical deicers, some of which act as accelerators. Since both these effects are linked predominantly to the reclaimed mortar (which in turn is highest in fine CCA), they are of lesser consequence in concrete mixtures in which only the coarse CCA is used.

Hardened Concrete Properties

As shown in table 14, a number of hardened concrete properties are directly influence by the aggregate source and thus are directly affected by the use of CCA (ACPA 2009). The properties of greatest interest include strength, thermal characteristics, shrinkage, and permeability. Not listed, but of great importance, is the durability of the new concrete with regards to ASR and D-cracking (aggregate freeze-thaw durability). Since MDOT only allows the use of coarse CCA in new concrete, the following discussion will be limited to new concrete containing CCA as a replacement for natural coarse aggregate. Users should be aware that the impacts discussed are more significant if fine CCA is also used.

Table 14. Effects of CCA on hardened concrete properties and behavior (ACPA 2009).

Property	**Range of Expected Changes Compared to Concrete Made with Virgin Aggregate**	
	Coarse CCA Only	**Coarse and Fine CCA**
Compressive strength	0 to 24 percent less	15 to 40 percent less
Tensile strength	0 to 10 percent less	10 to 20 percent less
Strength variation	Slightly greater	Slightly greater
Modulus of elasticity	10 to 33 percent less	25 to 40 percent less
CTE	0 to 30 percent greater	0 to 30 percent greater
Drying shrinkage	20 to 50 percent greater	70 to 100 percent greater
Creep	30 to 60 percent greater	30 to 60 percent greater
Permeability	0 to 500 percent greater	0 to 500 percent greater
Specific Gravity	0 to 10 percent less	5 to 15 percent less

As indicated in table 14, the concrete compressive and tensile strengths, as well as modulus of elasticity, are influenced by the use of coarse CCA. The effects vary from negligible to significant, depending on the quality of the source concrete, the amount of reclaimed mortar, and the *w/cm* of the new concrete. Many studies have been conducted on the strength development of concrete made with coarse CCA. The general conclusion is that although some loss in strength can be anticipated compared to similar mixtures made with natural aggregate, this can be compensated for with small changes in other mixture parameters (e.g., use a lower *w/cm*) and that there is no difficulty in creating concrete that can easily achieve desired design strength (ACPA 2009).

The coefficient of thermal expansion (CTE) of hydrated cement paste is considerably higher than that of natural coarse aggregates (Mindess, Young, and Darwin 2003). As a result, as the reclaimed mortar volume of the CCA increases, so does the CTE of concrete made from the CCA. It has been reported that the CTE of concrete made with CCA is typically 10 percent higher than that made with natural aggregate, although can range to as much as 30 percent higher (Wade et al. 1997). CTE has a direct impact on the generation of curling stresses in pavement slabs and thus this increase in CTE needs to be addressed in the pavement design process. This can be accomplished by using the new Mechanistic-Empirical Pavement Design Guide (MEPDG), which directly accounts for the CTE, thickness, and transverse joint spacing in the design process (AASHTO 2008). However, MDOT's transverse joint spacing ranges from 12 to 16 feet (depending on pavement thickness) so it may not be possible to totally mitigate the higher CTE values unless pavement thickness is significantly increased.

Drying shrinkage is also significantly higher in concrete made with CCA compared to natural aggregates, all other variables held constant. Again, the presence of the reclaimed mortar is responsible, as drying shrinkage occurs in hydrated cement paste, being restrained in concrete by the presence of the natural aggregate. Increased drying shrinkage results in increased potential for slab moisture warping. This may be addressed in the pavement design process by using shorter joint spacing.

Although permeability is not often assessed in paving concrete, it is an important parameter that heavily influences the durability of concrete. As with other hardened concrete properties, the increase in permeability observed in concrete made with CCA compared to that made with natural aggregates is a result of the reclaimed mortar. If the source concrete mortar is of relatively low quality, which would occur if a high *w/cm* was used in original construction, the resulting permeability of the new CCA containing concrete would also be high as these porous zones of reclaimed mortar will provide ready pathways for the ingress of moisture. On the other hand, if the source concrete was made with a low *w/cm*, the influence of the CCA on the new concrete permeability could be negligible. Decreasing the *w/cm* in the new concrete by 0.05 to 0.10 has been found to be sufficient to compensate for the increase in permeability that occurs through the use of CCA (ACPA 2009).

And finally, durable concrete can be produced from CCA even though the source concrete suffered a materials-related distress such as D-cracking or ASR. To determine the suitability of a CCA, it should be tested to the same standards as natural aggregate, using cyclic freeze-thaw testing (MTM 115) and ASR testing (ASTM C1260/C1567) to ensure that strategies are employed that will effectively prevent the recurrence of distress in the new concrete.

Pavement Design Considerations When Using CCA Concrete

Pavement design details that may require adjustment to address some of the unique characteristics of concrete made with CCA include the following (FHWA 2007):

- Increased pavement thickness.
- Decreased joint spacing.

The hardened concrete properties of greatest influence that necessitate these design changes are:

- Reduction in concrete strength (if not addressed through mixture design).
- Increased CTE, resulting in the development of higher curling stresses.
- Increased drying shrinkage.

In addition, MDOT experience has shown that concrete made with CCA should not be used in JRCP designs, as poor aggregate interlock load transfer develops across the crack faces. This poor load transfer is the result of smaller aggregates sizes and the low abrasion resistance of the CCA, which tends to degrade quickly under traffic loading and the low steel reinforcement are unable to withstand the higher than expected stress, leading to rupturing of the steel and deterioration of the crack.

In a similar vein, the low abrasion resistance of CCA also dictates the need for using dowel bars at all transverse joints in JPCP designs. Although dowel bars are used for most highway pavements, thinner concrete pavements where aggregate interlock is relied on for load transfer may not be good candidates for using CCA.

One way to try to compensate for the low abrasion resistance of CCA and to protect the CCA concrete from the harsh conditions at the pavement is to use two-lift concrete paving. In this process, a thicker bottom lift is constructed using a lower-quality aggregate (such as CCA) and a thin surface lift is placed using a high-quality natural aggregate (Hiller et al. 2011). Recently, two-lift concrete pavements have been placed in the U.S. as demonstration projects in Kansas and Missouri, both of which were driven largely by the scarcity of high-quality natural aggregates. Although this is not the case in Michigan, it does demonstrate that the technology is available to construct two-lift paving projects that incorporate a lower-quality material (such as CCA) in the bottom lift.

Construction Considerations When Using CCA Concrete

Producing concrete with CCA is very similar to producing concrete with natural aggregate, with the primary difference resulting from the increased water demand of CCA. This is due to the high adsorption capacity of the CCA associated with the reclaimed mortar, which averages from 3.7 to 8.7 percent (Snyder et al. 1994). This must be addressed during construction by processing the coarse CCA to remove most of the very fine material, which is the most absorptive part of CCA. In addition, washing and then keeping stockpiled CCA coarse aggregate moist prior to batching will help avoid poor workability in fresh concrete and excessive early-age shrinkage once the concrete is placed. Procedures for pre-wetting stockpiles of coarse CCA are similar to those that should be used for any porous, lightweight aggregate, including air-cooled blast furnace slag. However, it is recognized that keeping stockpiles moist is something not easily accommodated at many concrete crushing/batching facilities with limited space, especially if these are temporary facilities established for a given project.

One other construction concern is that CCA may affect the setting time of concrete due to the presence of unreacted cement grains and possibly deicing chemicals, so the set times should be monitored closely to ensure proper timing of joint sawing (ACPA 2009).

MDOT Requirements for the Use of CCA in New Concrete Mixtures

Michigan has a long history of using CCA as aggregate in new concrete. As discussed in the introduction to this guideline, not all of this experience has been good, with some notable early failures on critical sections of pavement. Although much has been learned about the performance of CCA as aggregate in new concrete since then, MDOT's currently approaches this application with justifiable caution.

In Section 902.03B of the *2012 MDOT Standard Specifications for Construction*, only the use of coarse CCA is permitted to be used in new concrete (MDOT 2012). Furthermore, the type of structures in which concrete containing CCA is allowed is limited, including only the following:

- Curb and gutter.
- Valley gutter.
- Sidewalk.
- Concrete barriers.
- Driveways.
- Temporary pavement.
- Interchange ramps with a commercial ADT less than 250.
- Concrete shoulders.

All other uses of concrete containing CCA are prohibited under the MDOT specification.

Checklist: Use of CCA in Concrete Pavement Mixtures

Table 15 provides a brief checklist to consider with regards to the use of CCA in concrete pavement mixtures.

Table 15. Checklist for CCA for use in concrete paving layers.

Item	✓
Workability of CCA concrete is acceptable for application	
CCA concrete set-time is acceptable for application	
Water demand is address by maintaining CCA stockpile in moist condition	
Air content of fresh concrete is verified use volumetric (AASHTO T 196) method	
Strength of CCA concrete meets or exceeds design requirement	
CTE is measured and incorporated in the pavement design process	
Source concrete reclaimed mortar is high-quality, thus permeability is not compromised	
The pavement design considers the unique characteristics of concrete made with CCA	
Application meets requirements of Section 902.03B of the *2012 MDOT Standard Specifications for Construction*	

CHAPTER 7. SUMMARY

CCA aggregates have been used in concrete for many decades, seeing extensive use in Michigan in paving concrete in the 1980s. Due to difficulties that emerged in some of these early projects, the use of CCA as aggregate in new concrete is currently limited in Michigan, with the most recent use being for drainable bases (unbound and bound) beneath new concrete pavements.

Regardless of the application, the CCA should meet similar quality requirements as natural aggregate. The differences that exist between CCA and natural aggregate are largely due to the reclaimed mortar, which is present in increasing volume as the particle size decreases. Reclaimed mortar is responsible for the production of a high pH leachate at early ages in unbound open-graded permeable CCA base layers. Because of this, the drainage outlets of projects incorporating unbound open-graded permeable CCA base layers should be closely monitored to ensure that they are clean and functioning.

Reclaimed mortar is also responsible for the high absorption and water demand of CCA used as aggregate in new concrete. And the threat of frost heave restricts the use by MDOT of unbound fine CCA in layers within 3 feet of the subgrade surface. For this reason, it is common in many applications to use only the coarse CCA material.

Recycling existing deteriorated concrete pavement to create CCA is a cost effective and environmentally sound approach to minimize waste during construction. As seen in table 16, MDOT's standard specifications for construction and special provisions provide a number of alternative uses for CCA, providing MDOT engineers with a valuable tool to improve the sustainability of Michigan's transportation infrastructure.

Table 16. Summary of allowable use of CCA based on 2012 *MDOT Standard Specifications for Construction* (MDOT 2012).

Type of CCA	Fill/Subbase[1]	Dense-Graded Aggregates[2]	Open-Graded Aggregates[3]	HMA	PCC
Coarse	Yes	Yes	Yes	Yes	Yes[4]
Fine	Yes	Yes	Yes	No	No

[1] *The Engineer will only allow the use of granular material produced from crushed portland cement concrete for swamp backfill, embankment (except the top 3 feet below subgrade) and as trench backfill for non-metallic culvert and sewer pipes without associated underdrains.*

[2] *Ensure dense-graded aggregate produced by crushing portland cement concrete does not contain more than 5.0 percent building rubble or hot mix asphalt by particle count. The Department defines building rubble as building brick, wood, plaster, or other material. The Engineer will allow pieces of steel reinforcement capable of passing through the maximum grading sieve size without aid.*

Do not use Class 21AA, 21A and 22A dense-graded aggregate produced from crushing portland cement concrete to construct an aggregate base or an aggregate separation layer when the dense-graded layer drains into an underdrain, unless at least one of the following conditions apply:

A. A vertical layer of at least 12 inches of granular Class I, II, IIA, or IIAA exists between the dense-graded aggregate layer and an underdrain or,

B. A geotextile liner or blocking membrane, that will be a barrier to leachate, placed between the crushed concrete and the underdrain. Only produce Class 23A dense-graded aggregate from steel furnace slag for use as an unbound aggregate surface course or as an unbound aggregate shoulder.

[3] *Ensure open-graded aggregate 4G produced by crushing portland cement concrete does not contain more than 5.0 percent building rubble or hot mix asphalt by particle count. The Department defines building rubble as building brick, wood, plaster, or other material. The Engineer will allow pieces of steel reinforcement capable of passing through the maximum grading sieve size without aid. Do not use open-graded aggregate 34G or 34R produced from portland cement concrete.*

Also see Special Provision 03SP303(A), Open-Graded Drainage Course, Modified, and Special Provision 03CT303(A 140), Open-Graded Drainage Course, Modified (Portland Cement-Treated Permeable Base Using Crushed Concrete)

[4] *The Contractor may use crushed concrete coarse aggregate in the following concrete mixtures: curb and gutter, valley gutter, sidewalk, concrete barriers, driveways, temporary pavement, interchange ramps with a commercial ADT less than 250, and concrete shoulders. Do not use crushed concrete coarse aggregate in the following: mainline pavements or ramps with a commercial ADT greater than or equal to 250, concrete base course, bridges, box or slab culverts, headwalls, retaining walls, pre-stressed concrete, or other heavily reinforced concrete.*

REFERENCES

American Association of State Highway and Transportation Officials (AASHTO). 2008. *Mechanistic-Empirical Pavement Design Guide—A Manual of Practice*. Interim Edition. American Association of State Highway and Transportation Officials, Washington, DC.

American Concrete Pavement Association (ACPA). 1998. *Rubblizing of Concrete Pavements: A Discussion of its Use.* American Concrete Paving Association (ACPA). Skokie, IL. Accessed May 16, 2011 from http://www.acpa.org/Downloads/Rubblization.pdf

American Concrete Pavement Association (ACPA). 2009. *Recycling Concrete Pavements*. Engineering Bulletin 043P. American Concrete Paving Association, Skokie, IL.

Epps, J, and R. O'Neal. 1975. *Engineering Economy and Energy Considerations in Recycling Pavement Materials*. Report No. RR 214-12. Texas State Department of Highways and Public Transportation, Austin, TX.

Federal Highway Administration (FHWA). 2007. *Use of Recycled Concrete Pavement as Aggregate in Hydraulic-Cement Concrete Pavement*. Technical Advisory T5040.37. Federal Highway Administration, Washington, DC.

Federal Highway Administration (FHWA). 2011. *FHWA Sustainable Highways Self-Evaluation Tool*. Available from www.sustainablehighways.org. Federal Highway Administration, Washington, DC. Accessed April 29, 2011.

Hansen, W. 1995. *Uses of Recycled Concrete in Michigan*. Final Report. Michigan Department of Transportation, Lansing, MI.

Hiller, J. E., Y. S. Deshpande, Y. Qin, and C. J. Shorkey. 2011. *Efficient Use of Recycled Concrete in Transportation Infrastructure*. Unpublished Report. Completed for the Michigan Department of Transportation, Michigan Technological University, Houghton, MI.

Hoerner, T. E., K. D. Smith, H. T. Yu, D. G. Peshkin, and M. J. Wade. 2001. *PCC Pavement Evaluation and Rehabilitation*. Reference Manual, NHI Course 131062. National Highway Institute, Arlington, VA.

McCarthy, G. J. 1985. "Recycling of Concrete Freeways by Michigan Department of Transportation." *Transportation Research Record 1040.* Transportation Research Board, Washington DC.

McCarthy, G. J. and W. J. MacCreery. 1985. "Michigan Department of Transportation Recycles Concrete Freeways." *Proceedings, Third International Conference on Concrete Pavement Design and Rehabilitation*. Purdue University, West Lafayette, IN.

Michigan Department of Transportation (MDOT). 2012. *Michigan Department of Transportation, Standard Specification for Construction*. Michigan Department of Transportation, Lansing, MI.

Mills-Beale, J. and Z. You. 2010. "The Mechanical Properties of Asphalt Mixtures with Recycled Concrete Aggregates." *Construction and Building Materials, Volume 24, Issue No. 3.* Elsevier Ltd.

Mindess, S., J. F. Young, and D. Darwin. 2003. *Concrete, 2^{nd} Edition*. Prentice Hall. Pearson Education, Inc. Upper Saddle River, NJ.

Muench, S. T., J. L. Anderson, J. P. Hatfield, J. R. Koester, and M. Söderlund. 2010. *Greenroads Rating System v1.0*. University of Washington, Seattle, WA.

Mukhopadhyay, A. K., B. Geiger, and J. Button. 2010. "Use of Recycled ASR PCC Materials in HMA Airfield Pavement." Final Report AAPTP 06-02. Airfield Asphalt Pavement Technology Program (AAPTP), Auburn University, AL.

National Cooperative Highway Research Program (NCHRP). 2000. *Waste and Recycled Materials in the Transportation Industry*. NCHRP 4-21 Information Database, Version 1.0.8. NCHRP. Washington, DC.

Raja, Z. and M. Snyder. 1991. "Factors Affecting Deterioration of Transverse Cracks in Jointed Reinforced Concrete Pavements." *Transportation Research Record 1307*. Transportation Research Board, Washington DC.

Sadecki, R. W., G. P. Busacker, K. L. Moxness, K. C. Faruq, and L. G. Allen. 1996. *An Investigation of Water Quality in Runoff from Stockpiles of Salvaged Concrete and Bituminous Paving*. Report No. MN/PR – 96/31. Minnesota Department of Transportation. St. Paul, MN.

Smiley, D. L. and D. Parker. 1993. *Ten-Year Performance Review of Michigan Concrete Recycled Pavement*. Michigan Department of Transportation, Lansing, MI.

Snyder, M. B., J. M. Vandenbossche, K. D. Smith, and M. J. Wade. 1994. *Physical and Mechanical Properties of Recycled PCC Aggregate Concrete*. Interim Report, FHWA Contract DTFH61-93-C-00133. Federal Highway Administration, McLean, VA.

Snyder, M. B. and J. E. Bruinsma. 1996. "Review of Studies Concerning Effects of Unbound Crushed Concrete Bases on PCC Pavement Drainage." *Transportation Research Record 1519*. Transportation Research Board, Washington, DC.

Stark, D. 1996. *The Use of Recycled-Concrete Aggregate from Concrete Exhibiting Alkali-Silica Reactivity*. RD114.01T. Portland Cement Association, Skokie, IL.

Van Dam, T. J., L. L. Sutter, K. D. Smith, M. J. Wade, and K. R. Peterson. 2002. *Guidelines for Detection, Analysis, and Treatment of Materials-Related Distress in Concrete Pavements, Volume 1: Final Report*. FHWA-RD-01-163. Federal Highway Administration, McLean, VA.

Van Dam, T. and P. Taylor. 2009. *Building Sustainable Pavements with Concrete*. Briefing Document. Concrete Pavement Technology Center, Ames, IA.

Wade, M. J., G. D. Cuttell, J. M. Vandenbossche, H. T. Yu, K. D. Smith, and M. B. Snyder. 1997. *Performance of Concrete Pavements Containing Recycled Aggregate*. FHWA-RD-96-164. Federal Highway Administration, McLean, VA.

Yrjanson, W. A. 1989. *Recycling of Portland Cement Concrete Pavements*. NCHRP Synthesis of Highway Practice No. 154. Transportation Research Board, Washington, DC.