DEPARTMENT OF
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Evaluation of Recycled Aggregates Test Section Performance

Farhad Reza, Principal Investigator
Center for Transportation Research and Implementation
Minnesota State University, Mankato

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The need to consider sustainability in design dictates that materials should be recycled and reused whenever possible. The Minnesota Department of Transportation (MnDOT) is quite progressive in allowing the use of recycled aggregates in new construction. While the use of recycled concrete aggregate (RCA) in the base course of new pavements is quite common in Minnesota and many other states, it is rarely used in the concrete pavement itself. In fact, Minnesota was one of the few states to build multiple trial projects and has one of the largest number of concrete pavements constructed using the RCA in the concrete itself. The performance of those pavements, most of which are still in service, has never been formally evaluated against similar conventional concrete pavements. This prompted the current research study. Additional objectives were to assess the current state of practice across the nation, conduct experimental investigations using RCA in concrete, assess the sustainability and in particular the economics of using RCA in concrete, and finally to provide some recommendations for guidelines on using RCA in concrete. It has been shown by the authors and other researchers that it is possible to create strong and durable concrete mixtures using RCA as coarse aggregate in volume replacement levels of natural coarse aggregate up to 100%.

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FINAL REPORT

Prepared by

Dr. Farhad Reza, P.E.
Dr. W. James Wilde, P.E.
Center for Transportation Research and Implementation
Minnesota State University, Mankato

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Members of the Technical Advisory Panel:

Bernard Izevbekhai, concrete research operations engineer, MnDOT Office of Materials and Road Research, technical liaison

Maria Masten, concrete engineer, MnDOT Office of Materials and Road Research

Shelly Pedersen, assistant pavement management engineer, MnDOT Office of Materials and Road Research

Tim Andersen, pavement design engineer, MnDOT Office of Materials and Road Research

Matt Zeller, executive director, Concrete Paving Association of Minnesota

Daniel Warzala, administrative liaison, MnDOT Research Services

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EXECUTIVE SUMMARY

The need to consider sustainability in design dictates that materials should be recycled and reused whenever possible. The Minnesota Department of Transportation (MnDOT) is quite progressive in allowing the use of recycled aggregates in new construction. While the use of recycled concrete aggregate (RCA) in the base course of new pavements is quite common in Minnesota and many other states, it is rarely used in the concrete pavement itself. In fact, Minnesota was one of the few states to build multiple trial projects and has one of the largest number of concrete pavements constructed using the RCA in the concrete itself. The performance of those pavements, most of which are still in service, has never been formally evaluated against similar conventional concrete pavements. This prompted the current research study. Additional objectives were to assess the current state of practice across the nation, conduct experimental investigations using RCA in concrete, assess the sustainability and in particular the economics of using RCA in concrete, and finally to provide some recommendations for guidelines on using RCA in concrete.

In Chapter 1 of this report, the state-of-practice across the nation is evaluated by means of recently conducted surveys of the state highway agencies as well as a general literature review. The surveys show that the use of RCA in new construction in the US seems to have begun in the late 1970s. Its use as an aggregate in the base course is widespread and has flourished since that time. On the other hand, its use in new concrete is not common. While about 11 states report using it, most have built only a limited number of projects with it, and some may only have it available in the specifications but do not have any experience with it. The highest number of trial projects built in the 1980s were by Michigan, Wisconsin, Iowa, and Minnesota. Michigan placed a moratorium on the use of RCA in new concrete pavements following the development of mid-slab transverse cracking. Very few additional projects have been constructed since that time; however, there seems to be some recent revived interest in this area as evidenced by several recently conducted surveys of the state-of-practice and recent state funded research projects.

A vast amount of technical literature exists on the mechanical properties of concrete made with RCA. Most of these indicators would seem to be unfavorable for concrete made with RCA compared to conventional concrete and thus might predict a worse performance in the field. This assumption has not been substantially validated in the field. Most evaluations of RCA pavement performance have been based on field evaluations and petrographic analyses of a limited number of sections. The relatively large number of pavements made with RCA that exist in the MnDOT network provided a good opportunity to study the long-term behavior and quantify the differences, if any, with conventional concrete pavements. Thus, Chapter 2 reviews historical pavement performance data and determines if there is any statistically significant difference in the performance between RCA pavements and non-RCA pavements.

Historical pavement performance data were evaluated for roughly 212 miles of RCA pavements. This was compared to a randomly sampled conventional concrete pavement database of the same size with similar time periods of construction and range of traffic levels. One of the main variables of interest was the time taken to reach the terminal RQI of 2.5, which necessitates a major concrete pavement rehabilitation. For the cases where a pavement had not yet reached this condition or had been rehabilitated before getting to this point, it was necessary to forecast the time taken to reach this condition. This was achieved using triple exponential smoothing and autoregressive integrated moving average modeling. The mean time to reach CPR condition for RCA pavements was found to be 27 years while that for non-RCA sections was 32 years. This difference was found to be statistically significant. In terms of intermediate minor repairs, the two types of pavements behaved fairly similarly. On average, for RCA pavements the first repair tended to occur after 16 years and the second repair was at about 21years. On average, for non-RCA pavements the first repair was at about 18 years and the second repair was at about 23 years. Markov models were also developed for both the RCA and non-RCA sections. These models can be useful for pavement management processes as they give an idea of the most likely condition state that a pavement will be in during future years given its current condition state.

MnDOT's current policies include designing all pavements for 35 years of traffic with the expectation of actual longer service lives. A trial project was completed in 2000 with a 60-year design life. Chapter 3 describes an experimental program conducted to evaluate the properties of concrete made with RCA. It was of interest to see whether RCA concrete could be made to similar high-performance specifications that MnDOT used in its 60-year design life trial project with the help of modern day admixtures. A total of twelve concrete mixes were tested. Coarse aggregate replacement with RCA was studied at 0%, 50%, and 100% levels. The effect of recycled fines at 50% and 100% replacement was evaluated. The use of recycled aggregates, both coarse and fine, after presoaking for 24 hours was also evaluated based on this suggested practice reported in some of the earlier literature.

A significant reduction in compressive strength was noted in all of the mixes with respect to the control at relatively low water-cementitious material ratios of 0.37. Mixes containing only coarse RCA may still have satisfactory performance with respect to strength and shrinkage; however, it does not seem reasonable to use the same structural design of the RCA pavement as with the non-RCA and expect the same performance. The use of RCA fines had a major negative influence on the strength, shrinkage, and workability and therefore is not recommended. The practice of presoaking the recycled aggregates made it difficult, especially in the case of fines, to control the water requirements for the concrete mix due to the high absorption. Microwave tests were conducted to evaluate the suitability of this test to determine the water-cementitious material ratio for the concrete mix. A total of nine cores were taken from various roads with actual or expected time to reach major CPR ranging from 5 years to 42 years. No visible distresses were observed, alkali-silica reaction disruptions were minimal, and carbonation depths were only about 5 mm. There does appear to be a correlation with RCA percentage of the total aggregate, design water-cement ratio, and observed air content.

Chapter 4 presents the economics analysis of using RCA with the aid of lifecycle cost analysis (LCCA). The analysis period was taken as 50 years and the real discount rate was 1.5%. Eight alternatives were investigated. In every scenario, any remaining RCA crushed from the old pavement that was not used in the new concrete was applied to the base. The eight alternatives were:

1. Conventional concrete pavement with no RCA in the concrete with an expected life until first major CPR of 59 years
2. Pavement with 50% coarse RCA in the concrete with similar structural design as (1), but with an expected life to first major CPR reduced to 50 years

3. Pavement with 50% coarse RCA in the concrete with a 12% thicker design than (1) and similar life expectancy of 59 years to first major CPR
4. Pavement with 50% coarse RCA in the concrete with a lower w/cm ratio (0.36) and similar structural design as (1) with a similar life expectancy of 59 years to first major CPR
5. Pavement with 100% coarse RCA with similar structural design as (1) but with reduced joint spacing of 12 ft and reduced life to first major CPR of 46 years
6. Pavement with 100% coarse RCA in the concrete with a 24% increase in thickness from (1) and reduced joint spacing of 12 ft and similar life expectancy of 59 years to first major CPR
7. Pavement with 100% coarse RCA in the concrete with a lower w/cm ratio (0.35) and similar structural design as (1) with a similar life expectancy of 59 years to first major CPR
8. Two-lift construction that has 50% RCA in the lower lift and exposed aggregate concrete in the top lift with a similar life expectancy to first major CPR as (1), i.e. 59 years

The results of the LCCA shows that it can be very economical to use RCA in new concrete pavement construction. The practice of utilizing crushed RCA in the base course is already quite common in Minnesota; however, because the natural aggregate for concrete may be more expensive than that for base courses, it may make good economic sense to substitute RCA for natural aggregate in concrete. Long-life pavements tend to be more economical then shorter-life pavements (with lower initial costs) in the long run. Concrete pavements with concrete containing RCA that were made with lower w/cm and higher cement content proved to be more economical than concrete pavements with increased thickness. In most cases, the amount of RCA available from crushing an existing concrete pavement locally is expected to be less than what is needed to construct both the new concrete pavement as well as the base course. At current rates, the cost of purchasing recycled concrete base is significantly less than that of natural aggregates; therefore, if the contractor purchases extra RCA to make the entire base up to 70% recycled, then the project becomes even more economical. Economics is just one of the triple bottom line principles of sustainability, with the others being environment and social aspects. One comprehensive tool for assessing sustainability is the Federal Highway Administration INVEST tool. The utilization of a large amount of RCA material either in the base or the new concrete can qualify a project for several points in the INVEST program, thus indicating the sustainable impact of using RCA.

Chapter 5 presents a review of guidelines or specifications of various agencies as well as recommendations in the literature regarding the use of RCA in concrete. A set of recommendations are given that MnDOT may wish to consider in developing any future specifications regarding the use of RCA in the construction of new concrete pavements. The authors feel that the emphasis in the specifications should be on mixture proportioning and producing a concrete with satisfactory strength and durability properties rather than specifying multiple tests on the RCA itself. It has been shown by the authors and other researchers that it is possible to create strong and durable concrete mixtures using RCA as coarse aggregate in volume replacement levels of natural coarse aggregate up to 100%.

CHAPTER 1: SUMMARY OF STATE DOT SURVEYS AND LITERATURE REVIEW

The objective of the initial stage of the project had originally been to perform a survey of other states' experience with recycled concrete aggregates. However; as the literature search progressed, it was discovered that similar surveys had recently been performed in 2011 and 2012 by Caltrans. It was then decided to write a synthesis report covering these and other older surveys instead of performing a new survey. This chapter is broadly divided into two main sections: a summary of available surveys of other states experience with RCA in Portland Cement Concrete (PCC) pavements, and a literature review focusing only on the specific topic of RCA use in PCC.

1.1 SURVEYS OF STATES' EXPERIENCES

1.1.1 1994 Survey by Mark Snyder

One of the pioneering studies was conducted by Mark Snyder and others under an FHWA sponsored study. Portions of this study have been presented at both the TRB annual conference (Gress et al 2008) and the Minnesota Concrete Conference (Snyder 2008), and portions have also been published in the Master's Thesis of Jeffrey Sturvenant at University of New Hampshire (Sturvenant 2007), and a study conducted for Washington DOT (Anderson et al. 2009).

In the survey, eleven states were identified which built trial projects of PCC pavement using RCA. A total of 98 projects were listed. These are presented in Table 1. The state with the most number of trials was Michigan with 30, followed by Wisconsin 17, Iowa 16, and Minnesota 14. In general, most of the states observed good performance in pavements with RCA except for Michigan which in fact issued a moratorium on the use of RCA in pavements in 1991.

Table 1. Projects Built Using RCA Obtained from 1994 Survey by Mark Snyder and others

State	Highway/ Location	Year Recycled	Remarks	Qualitative Performance
Colorado	I-70/I-76 Denver	1982	JRCP	
Conn.	I-84, Waterbury	1979-1980	JRCP into JRCP, with a control section	Same as control
Illinois	I-57, Effingham	1986-1987	JRCP into a CRCP	Good
Iowa	U.S. 75, Lyon County	1976	JRCP into JRCP, two courses placed monolithically	
	IA-167, Lyon County	1976		
	Co. Rd. A-34, Lyon Co.	1976		

	IA-27, Lyon County	1976		
	I-680, Pottawattamie County	1977		
	Rt. 2, Taylor & Page County	1978-1979	JPCP	
	E-18, Green County	1985-1993	Ten sections of JPCP varying in length from 0.5 to 6.2 miles.	Good
	E-18, Greene County	1987	JPCP	Good
	E-26, Greene County	1987	JPCP	Good
	E-18, Greene County	1987	JPCP	Good
	E-33, Greene County	1988	JPCP	Good
	P-14, Greene County	1988	JPCP	Good
	E-19, Greene County	1988	JPCP	Good
	P-46, Greene County	1988	JPCP	Good
	P-46, Greene County	1989	JPCP	Good
	E-35, Greene County	1993	JPCP	Good
Kansas	I-235, Wichita	1985	D-cracked JRCP into JPCP	Good
	K-7, Johnson County	1985	D-cracked JRCP into JPCP	
	I-70 W. of Junction City	1990	D-cracked JRCP into JPCP	
Michigan	Arterial, Kent County	1981		
	Garfield Road, Macomb Co.	1982	JRCP into JPCP	
	I-94, Battle Creek	1983	JRCP into JRCP, first of 10 projects on I-94	
	I-94, Hartford	1984		Fair
	I-75, Flat Rock	1984	JRCP into JRCP	
	I-75, Luna Pier	1985		Poor
	I-94, Albion	1985	JRCP into JRCP, 30% recycled fines	
	I-94, Battle Creek	1986	JRCP into JRCP	
	I-94, Kalamazoo	1985	JRCP into JRCP, 100% natural sand	Poor

	I-94, Paw Paw EB	1986	JRCP into JRCP	Good
	I-94, Paw Paw WB	1986	JRCP into JRCP	Poor
	Lodge Freeway, Detroit	1987	JRCP into JRCP	Good
	I-96, Clarksville	1987		
	I-96, Portland	1987		
	I-96, Portland	1987		
	I-96, Portland	1987		
	I-75, Monroe County	1988	5 additional projects on I-75 since 1985	
	I-94, Paw Paw EB	1988	JRCP into JRCP	Poor
	I-94, Paw Paw WB	1988	JRCP into JRCP	
	I-75, Luna Pier	1988		
	I-96, East County	1988	5 additional projects on I-96 since 1986	
	I-94, Marshall	1988		
	I-84, Ypsilanti	1988		
	I-96, Grand Rapids	1988		
	I-75, Luna Pier	1989		
	I-75, Monroe	1989		
	I-75, Newport	1990		
	I-94, Battle Ground	1990		
	I-94, Battle Ground	1994		
	I-96, Howell	1992		
Minnesota	U.S. 59, Worthington	1980	JPCP into JPCP, 1st use of D- cracked aggregate, WB is control section	Fair
	T.H. 14, Steele County	1983	JRCP with D-cracking	
	T.H. 15, Martin County	1982-1983		
	T.H. 15, Nicollet County	1984		
	U.S. 52 Goodhue Co.	1984	JRCP	Fair
	I-90, Beaver Creek	1984	JRCP D-cracked pavement recycled	Fair
	U.S. 52, Olmstead Co.	1985	JRCP	

	I-94, Ottertail Co.	1985	JRCP	
	I-94, T.H. 79 to T.H. 59	1986	JRCP	
	I-60, Watonwan Co.	1987		
	I-94, Fergus Falls	1987-1988	D-cracked pavement recycled	
	I-94, T.H. 79 to T.H. 114	1988		
	I-94, Brandon	1988	JRCP	Good
	T.H. 60, Mountain Lake	1988	N. of I-90	
North Dakota	I-94, Cleveland	1983	JPCP into JPCP, pavement showed signs of D-cracking	
	I-29, Hillsboro	1984	CRCP into JPCP	Fair
	I-94, Eckelson	1984	JPCP into JPCP, pavement showed signs of D-cracking	
Oklahoma	I-40, Oklahoma City	1983	JPCP into JPCP, D-cracked, nondoweled	
	I-35, Edmond	1988	CRCP with epoxy-coated steel	
Wisconsin	I-94, Menomonie	1983	JRCP into JPCP	Poor
	I-90 & I-94, Madison	1984	Addition of two lanes and shoulders	
	I-90, Janesville	1984	JRCP into CRCP	
	I-90, Rock County	1985	JRCP into CRCP	
	I-90/94, Monroe County	1985	JRCP & CRCP into CRCP	
	I-90 Rock County	1986	JRCP into CRCP	Very Good
	I-90 Rock County	1986	JRCP into CRCP	
	I-90/94, Monroe County	1986	JRCP & CRCP into CRCP	
	I-90, Rock County	1987	JRCP into CRCP & JRCP	
	I-94, Jackson County	1987	JRCP into CRCP	
	I-94, Jackson County	1988	JRCP into CRCP	
	I-90, Rock & Dane Co.	1989	JRCP into JPCP	
	I-90, Dane County	1990	JRCP into JPCP	

	I-90/94, Sauk & Juneau Co.	1990	JRCP into JPCP	
	I-90/94, Sauk & Juneau Co.	1990-1992	JRCP into JPCP	
	STH 29, Chippewa Co.	1993	JRCP into JPCP	
	I-95, Dune County	1993	JRCP into JPCP	
Wyoming	I-80, Pine Bluffs	1985	1st use of ASR reactive aggregate	Good
	I-80, Green River	1985		Good
	I-25, Evanston Vic.	1986	JPCP into JPCP	Good
	I-80, Rock Springs Vic.	1986	JPCP into JPCP	Good
	I-80, Rock Springs Vic.	1987	JPCP into JPCP	Goods
	I-80, Cheyenne Vic.	1987	JPCP into JPCP	Good
	I-80, MP Pine Bluffs Vic.	1987	JPCP into JPCP	Good
	I-80, MP Cheyenne Vic.	1988	JPCP into JPCP	Good
	I-80, Burns Vic.	1989	JPCP into JPCP	Good
	I-80, Cheyenne	1994	JPCP into JPCP with doweled joints	

Some additional performance information obtained from the primary users of RCA is noted below.

1.1.1.1 Iowa

- Some projects experienced excessive midslab transverse cracking on JPCP with 8 inch slabs and 20 foot joint spacing.

1.1.1.2 Michigan

- A number of failures were noted on their JRCP built with RCA due to midslab transverse cracking. Failure is attributed to a number of factors that included the small size of the aggregate (19 mm) which did not resist the cracking, high amounts of mortar, which detracted from the abrasion resistance, insufficient slab thickness, and incompatible joint spacing (41 feet).
- The roads built with RCA did not perform as well as roads built with virgin aggregates.
- The roads built on open-graded bases cracked and faulted sooner than expected and resulted in more maintenance and shorted life.

1.1.1.3 Minnesota

- Performance of the pavements was very good.
- Fly ash was used to reduce the D-cracking potential and improve the workability allowing the use of less water, thereby rendering the mix less permeable.

1.1.1.4 Wisconsin

- A variety of processes were used, JRCP into CRCP, JRCP into JPCP, JRCP into JRCP, CRCP into CRCP.
- Performance was generally good and many of the sections have been in service for 20-25 years.
- A good candidate for recycling is an existing pavement that has performed well; problems usually occur where the original concrete or aggregate was of marginal quality.

1.1.1.5 Wyoming

- All projects recycled JPCP into JPCP.
- ASR aggregates were successfully used.
- Later projects used dowel joints.

1.1.2 2004 FHWA Survey

In 2004, the FHWA conducted a survey to determine the extent and types of transportation related applications of RCA (FHWA 2004). The results are displayed in color coded maps of the fifty states. It was found that forty-one states recycle concrete as aggregate, thirty-eight states use RCA as aggregate base, and only eleven use RCA in PCC. The eleven states identified are: Colorado, Idaho, Illinois, Michigan, Minnesota, North Dakota, South Carolina, Texas, Virginia, West Virginia, and Wyoming. Cross-checking with the list from the 1994 survey by Mark Snyder, we find that five states drop off: Connecticut, Iowa, Kansas, Oklahoma, and Wisconsin. In addition, five new states appear: Idaho, South Carolina, Texas, Virginia, and West Virginia (see also Table 4).

RCA is generally thought of as old PCC pavement, bridge structures/decks, sidewalks, curbs and gutters that are being removed from service, steel removed, and can be crushed to a desired gradation. Commercial construction debris can be used for RCA, provided the material is cleaned of unwanted material like bricks, wood, steel, ceramics, and glass. Most state transportation agencies tend to want to re-use material recovered from either state projects or known source of supply.

Five states were selected for a more in-depth review based on their relatively high consumption of RCA, and large supply of RCA: Texas, Virginia, Michigan, Minnesota, and California. Some of the relevant findings are summarized below.

1.1.2.1 Texas

- The use of RCA created problems with mix workability due to the high absorption of aggregate and the difficulty in maintaining a consistent and uniform saturated surface dry (SSD) condition

of RCA aggregate. The contractors overcame this hurdle by improving their process control program. Their process control program heightened their awareness of the need to water stockpiles and to conduct frequent testing of aggregate for moisture content.
- An increase in creep and shrinkage was noted.
- There was an initial perception that RCA was a substandard waste material, but that perception has been changed with education and test section findings.
- Initially, there were issues with lower compressive strength and workability. Research linked this to the use of RCA fines, and a limit of 20% RCA fines was established.
- Excessive working of the RCA base will segregate the base materials. Minimum shaping of the RCA base material should occur. Compaction of the RCA base should be in a saturated state to aid in the migration of fines throughout the mix. Overall the performance of RCA as a base material has been excellent, the material has a higher load bearing capacity due to the re-cementing action.

1.1.2.2 Michigan

- Allows the use of RCA as coarse aggregate in PCC for curb and gutter, valley gutter, sidewalk, concrete barriers, driveways, temporary pavement, interchange ramps and shoulders. RCA is also allowed to be used as coarse aggregate in hot mix asphalt and as dense-graded aggregate for base course, surface course, shoulders, approaches and patching.
- RCA was widely used in the pavement surface structure during the 1980s. A moratorium has been in place on the use of RCA in concrete pavement in Michigan since the early 1990s. This moratorium stems from failures of concrete pavements built using RCA, as well as blast furnace slag. Research accomplished by Mark Snyder, places most of the distress issues on some of the design features. The only aspect assigned to the RCA is a minor loss of aggregate interlock. This is most likely due to the smaller aggregate size obtained when producing the recycled aggregate. The requirement for aggregate interlock to provide load transfer has been displaced by the use of dowel bars.
- D-Cracking performance problems in RCA pavements can be reduced when the old pavement is crushed to a smaller aggregate size.
- Recommendations for the reduction of cracking when using RCA in highways that enhance its performance and minimizes the reliance on aggregate interlock:
    - Increased foundation stiffness
    - Reduction of slab tension
    - Additional steel reinforcement
    - Use of a deformed wire mesh
    - Use of hinge joints

1.1.2.3 Minnesota

- Currently uses almost 100% of the concrete removed from its pavements as dense graded aggregate base.
- From the late 1970s through the 1990s, RCA was used as coarse aggregate for PCC pavements on more than 20 projects. Today, MnDOT uses a 60-year pavement design life on its high-

volume freeways and a 35-year design life on all other highways with associated warranties. These factors have contractors shying away from its use in the concrete pavement since the belief is aggregate washing would be required to produce useable aggregates. This increase in cost is the main issue to using in PCC as course aggregate.
- Observations suggest that RCA when used in the base and sub-base material performs better than virgin aggregate.
- Substitution of RCA for virgin aggregate can provide savings in the final cost of the project. It is a common practice in Minnesota to crush the material on site. This lowers the transportation costs and has less effect on traffic.
- Washing of RCA is required if used in PCC pavements in order to eliminate excess fines.
- Quality requirements for new aggregate do not specifically apply to RCA when the pavement comes from a known source.
- In presence of drainage layers and/or perforated drainage pipes a blend of RCA with new aggregate may be used as subgrade when at least 95% of the RCA is retained on the 4.75 mm sieve.
- RCA may be used up to 100% in construction of the filter/separation layer under a permeable aggregate base drainage layer in accordance with the applicable drainage specifications.

1.1.3 2006/2009 Limited Survey by Washington DOT

In 2006, Washington DOT conducted a follow-up survey with a limited number of states, mainly those previously identified as having used RCA in PCC, and then again in 2009 only with those states deemed to be most active in their trials of RCA. The results are summarized below.

1.1.3.1 Colorado

- RCA was used in the past in base courses and mixes and it worked well, but there is no documentation.

1.1.3.2 Idaho

- RCA was used on one project on I-84 near Mountain Home in 1990-91.
- No RCA fine aggregate was used.
- Mix was harsh and required more water.
- Have not used it since, but would consider if contractor proposed.

1.1.3.3 Illinois

- Recommendations are based on report by Roesler and Huntley (2009), Performance of I-57 Recycled Concrete Pavements, January 2009, Illinois Center for Transportation Report ICT-09-032.
- A twenty year performance evaluation of only one project, a CRCP built with RCA showed it was performing equivalent to other CRCP pavements of the same age built with virgin aggregates.

- Further use of RCA is recommended as long as material passes freeze-thaw requirements, accommodations are made for greater drying shrinkage and slightly lower tensile strength, and the concrete is checked for ASR.
- Suggest moist curing to prevent premature cracking and possibly using RCA in the bottom layer of a two-lift paving operation.

1.1.3.4 Iowa

- Most of the RCA projects in Iowa were built by counties, only a few by the DOT
- RCA is currently being used in bases.

1.1.3.5 Michigan

- Michigan currently only allows RCA to be used in curb and gutter, valley gutter, sidewalks, concrete barriers, driveways, temporary pavement, interchange ramps with commercial ADT below 250, and concrete shoulders.
- All other uses are prohibited.
- In addition, the aggregate must pass the freeze-thaw test which takes about three months to complete.

1.1.3.6 Minnesota

- Currently using RCA for base layers due to an abundance of good virgin aggregate.
- MnROAD, however, is building two of its new test cells with Applied Research Associates, Inc. (ARA) using SHRP R21 composite pavement funding with 100% RCA from old MnROAD concrete test cells.

1.1.3.7 South Carolina

- One project built on I-97 in 2003-04.
- No RCA fine aggregate used.
- Mix met or exceeded strength, air and slump requirements.
- RCA coarse aggregate use was encouraged by performance of this project.

1.1.3.8 Texas

- Used on IH-10 in Houston in 1995 – CRCP.
- Used both coarse and fine aggregate, no virgin aggregates.
- Approximately 30% old mortar was attached to recycled aggregate.
- Compressive and tensile strengths lower than concrete made with virgin aggregate.
- Density was lower, water absorption was higher.
- Moisture control was difficult, so they resorted to watering the stockpiles.
- Pavement is performing well with no spalling, wide cracks or punchouts.
- Currently limit the RCA fine aggregate amount to a maximum of 20%.

- Performance of Continuously Reinforced Concrete Pavement Containing Recycled Concrete Aggregate; Moon Won, January 2001, Texas Dept. of Transportation, Report 1753-1.

1.1.3.9 Virginia

- Did not use RCA in concrete pavement but rather in cement stabilized subbase.
- Pavement recycled was JRCP (61.5 foot joint spacing) wire mesh, dowels, joint sealing materials, and asphalt patches. Contractor did not go for the option of RCA in pavement.

1.1.3.10 Wisconsin

- Currently Wisconsin contractors are electing to use the recycled concrete aggregate less frequently in the pavement, but rather incorporating it into either the base or shoulder material.

1.1.3.11 Wyoming

- RCA used on 8-11 projects as of 2006.
- All projects were undoweled JPCP.
- RCA coarse aggregate was limited to 60% with the remainder being virgin aggregate.
- RCA fine aggregate was limited to 15%.
- Cement content requirement increased by 1/2 sack.
- Some issues with ASR were handled without problems.
- Mostly JPCP into JPCP between 1985 and 1994.
- Four projects added to the list since Snyder completed his survey in 1994. One project had issues with aggregate polishing, but they were with the virgin aggregate added to the mix, not the RCA.

An additional eight projects of RCA in PCC pavements were identified in this survey which are given in Table 2.

Table 2. Additional RCA Projects Identified by 2006/09 Washington DOT Survey

State	Highway/ Location	Year Recycled	Remarks	Performance
Idaho	I-85, Mountain Home	1990-91	Coarse aggregate only, harsh mix, required more water	Good
Oregon	I-84, Le Grande		CRCP WB Lane	
South Carolina	I-95, Florence	2003-04	Doweled the new JPCP	Good
Texas	IH-10, Houston	1995	CRCP into CRCP	Good

Wyoming	I-80, Telephone Canyon	1997		Good
	I-80, Laramie Marginal	1997		Good
	I-25, Cheyenne Marginal	1999		Good
	I-25, Cheyenne Marginal	2001		Good

1.1.4 2011 Survey by Iowa State University

In 2011, a survey was conducted by Iowa State University (Garber et al. 2011) to assess the current use of RCA in concrete paving mixtures. The survey consisted of sixteen questions. Twenty-five states and one Canadian province responded out of which Maine and British Columbia indicated that they do not use PCC pavements much. Some selected questions and responses are given in Table 3.

Based on the results of the survey, some states showed interest in learning more about how to use RCA in new concrete paving mixtures. Barriers (obstacles and misperceptions) that limit the use of RCA in new concrete paving mixtures can be grouped as compliance, quality, or production related. Compliance barriers include the inability for RCA to meet state specifications for aggregate soundness, abrasion, gradation, and strength. In addition, there was a concern expressed that ASR would be a problem. Barriers associated with quality include maintaining consistency and the perception that RCA is a waste material not worthy of use in new concrete paving mixtures. Production barriers include storage, workability, supply, removing debris, and location of processing equipment.

Table 3. Selected Responses from 2011 Iowa State University Survey

State	Experience with RCA	Barriers faced with RCA	What specs will RCA not meet?	Production challenges
Alabama	Spec allows; never done	Supply; quality & consistency; lack of experience	LA abrasion; sodium soundness	N/A
Alaska	N/A	Lack of specification; uniformity; cleanness	N/A	N/A
California	N/A	Spec. not allow; negative impact on performance; unknowns not researched yet	N/A	N/A
Colorado	Aggregate base course; pipe bedding; benefit is	None	None; higher flexure	Virgin aggregate is cheap

	unknown; low bidder's choice			
Florida	Used in HMA on interstate; graded aggregate base; in non-structural concrete, pipe bedding	Coefficient of Thermal expansion when mixed RCA sources; deleterious materials e.g. asbestos	None	Nonexistence of large scale producers
Illinois	8-mi interstate section in 1986; viable rehab option;	Low elastic modulus; high drying shrinkage; workability	N/A	N/A
Indiana	Use as a base/subbase	D-cracking; variability in quality and aggregate properties; influence on concrete properties (water demand, workability, placement, strength, durability)	AP aggregate quality requirements	What to do with fines; only using INDOT concrete sources
Iowa	1977 research; curling	High absorption; harsh mix; operational burden, another type of aggregate	N/A	N/A
Kansas	Perceived cost savings; harsh mix; has to meet all virgin aggregate requirements	D-cracking & ASR; insufficient supply; used in CTB; harsh mix	LA abrasion might be a problem	Insufficient supply; used in 4-in base; harsh mix
Louisiana	Used on I-12; gradation & cleanliness were problem; lack of experience; unsuccessful, overlaid	Bad past experience	Not allowed in PCCP but base	None
Minnesota	80s and at MnROAD in 2010 in composite; on I-35 in 1997, unwashed, difficulty obtaining w/c 0.40, drying shrinkage cracking	Water demand; uniformity & absorption; deterioration (e.g. ASR, D-cracking, de-icer distress)	Maximum w/c	None
Mississippi	Used as a base and as HMA aggregate; save virgin material; high	No new PCC construction; not allowed in new PCCP; not used in other applications	N/A	N/A

	absorption, not cost-effective for HMA			
Missouri	N/A	Anticipated problems: lack of consistent strength; lack of soundness; verifiable source approval	Not tested one yet	N/A
New Jersey	N/A	Mixture from different sources; quality might be questionable	ASR verification	N/A
New Mexico	N/A	ASR is extensive; long-term validation needed	ASR mitigation	Fractionation & stockpiling issues
New York	Specs allow but quality verification cost prevents its use; used in base and subbase	Insufficient amount; testing/evaluation cost is high; material quality/consistency is very low	Soundness; gradation; absorption	Managing stockpile; saturating & draining; maintaining uniform absorption
North Dakota	25 years ago; existing road crushed reused in new; less virgin aggregate	Durability; perception based on past experience; lack of experienced contractor and staff	N/A	N/A
Ohio	Pavements, sidewalks, median, barrier; 15 years ago in Toledo, performing well Only coarse; limit absorption to 7%	Specs require; quality of material; developing a workable mix; QC to maintain consistent mix	Absorption < 7%; LA abrasion < 50%; Cl content <1.5%; spec. grav. variation < 0.1; absorption variation < 0.8%	N/A
Oregon	High absorption; watering of stockpiles	No specs; cost might be higher compared to virgin	N/A	N/A
South Carolina	10 miles on I-95 in 2001; coarse aggregate in new mix; high absorption w/ high variation; performing well	Existing concrete is allowed in reconstruction	Soundness but waived for RCA	Elimination of foreign material; stockpile management; absorption

South Dakota	Only as aggregate base	Quality; ASR	#200 sieve fraction; LA abrasion; sodium sulfate soundness	N/A
Texas	Coarse RCA up to 100%; fine RCA up to 20% for nonstructural, up to 100% for base; cost saving drives the use	Overlays instead of recycling; contaminants in RCA; lack of tests ensuring durability; local zoning restriction of crushers; water demand	Depends on the project	Restriction of crusher's location
Utah	As base aggregate	No specs; quality concerns; ASR; soundness; C33	N/A	N/A
Wisconsin	Can use up to 100% RCA as coarse aggregate in new concrete; RCA as fine aggregate in new concrete is prohibited, due to extremely high absorption values (causing fluctuating water demand) and mixture harshness; RCA must be from the existing project; RCA is allowed at contractor discretion; RCA is prohibited in structures; Benefits – reduces demand for virgin aggregate Disadvantage – RCA increases water demand due to higher absorption and higher angularity (harshness)	Contractor discretion; usually as base or subbase	N/A	Maintaining uniform slump due to absorption; prevented by watering the stockpiles

1.1.5 2012 Survey for Caltrans

Caltrans sponsored a study to learn about different states' practices, policy and research related to concrete recycling. The study was conducted by CTC & Associates, LLC (CTC & Associates 2012). The investigation focused on two parts: Returned Plastic Concrete and Crushed Concrete. The focus of this summary is only on crushed concrete.

It was found that the use of crushed concrete as aggregate for transportation applications is a common practice among DOTs but it is not universally permitted, and restrictions vary from state to state. Some issues include performance, processing and material availability. The state survey showed that among the 30 state respondents, 10 allowed the use of crushed concrete as aggregate for new concrete pavements.

Other key survey findings include the following.

- The most commonly permitted applications for crushed concrete are "fill, embankments or noise barriers" and "pavement base or subbase layers." The latter is the most commonly used application.
- Only a few agencies indicated that they allowed the use of crushed concrete for lean base.
- Most agencies noted the same specifications for crushed concrete as with other aggregate types.
- About half of the respondents discussed problems in using crushed concrete as aggregates, including high pH levels related to the alkali-silica reaction (ASR) and groundwater leaching; high absorption of crushed asphalt concrete; and debris and contamination.
- Fewer than half of the respondents have considered expanding the use of crushed concrete as aggregate, with several citing availability as a barrier to expanded use of crushed concrete as aggregate.
- Percent weight limitations on crushed concrete vary by agencies. Those agencies that nominally allow 100 percent typically have restrictions: limitations to coarse aggregate, requirements that sources must be known and usage on only certain applications.

Thirteen agencies provided follow-up comments. Among the issues mentioned were high pH levels (related to the ASR) and groundwater leaching, high absorption, debris and contamination, mechanical properties, such as high creep and effects on flexural strength, and chemical reactions with the RCA. Detailed responses follow:

1.1.5.1 Delaware

- We don't use crushed concrete in new concrete because of ASR.

1.1.5.2 District of Columbia

- Not allowed in undercut areas where groundwater and soft materials are encountered. Also not allowed in underdrains around filter fabrics.

1.1.5.3 Florida

- Minor- some contamination which involves revisiting the source to offer suggestions on extra cleaning or pre-screening (selecting) material.

1.1.5.4 Georgia

- Determination of maximum dry density and optimum moisture requires special attention apparently due to high absorption of the material.

1.1.5.5 Illinois

- High absorption of AC in HMA. High water demand in PCC. Concern of road salt contamination in PCC. Concern of high alkalis from existing and new cement when making PCC (ASR).

1.1.5.6 Louisiana

- Ensuring only PCC is used for the raw material is difficult to monitor and virtually impossible to detect once crushed and blended.

1.1.5.7 Maryland

- pH issues. If pH is measured at 12.5 Standard Units or above, it is considered hazardous materials by the Maryland Department of the Environment.

1.1.5.8 Michigan

- Leachate.

1.1.5.9 New York

- Concerns with source and material characteristics, based on ASR problems and mixture handling from higher absorptions (long ago) lead to the current requirements.

1.1.5.10 Ohio

- Ohio does not allow the use of RCA as a replacement for aggregate base. There are environmental runoff issues and we have had issues with the RCA re-cementing and causing a change in support of the above concrete pavement. That leads to cracking and deterioration of the concrete pavement.

1.1.5.11 Oklahoma

- Problems with contamination from construction debris and soil when crushed concrete came from a source that collected general construction demolition waste.

1.1.5.12 Pennsylvania

- A recent investigation of settled concrete pavement indicated a possible reaction between recycled concrete aggregate used as subbase material when slag aggregate was used as an open-graded subbase drainage layer on top of the recycled concrete layer.

1.1.5.13 Texas

- We have learned positive and negative lessons. In light of higher creep values, recycled concrete aggregates are no longer allowed in structural concrete. In addition, the project showed recycled fine aggregate has an adverse effect on flexural strength. We also learned that the material is highly absorbent, making moisture control of recycled aggregate critical. We recommended being selective in what is crushed, maintaining uniformity of material types in stockpiles and aggressively monitoring moisture for success in using recycled aggregate in concrete paving applications.

In addition to the interviews with state officials, some interviews were conducted with experts to highlight current and near-term activities to advance the state of the art in and promote the practice of using crushed concrete as aggregate. These interviews are summarized below.

1.1.5.14 David Gress, Associate Director of Recycled Materials Resource Center

- Gress provided some reference to literature presenting the comparative performance of pavements built from recycled and virgin aggregate; those built from RCA were found to perform as well or better than their controls (Van Dam et al. 2012).

- He also discussed latest trends in crushed concrete reuse among DOTs, describing how many are not taking full advantage of the latest technology, but instead are using it as a low value aggregate such as pavement base material. He described a move at FHWA toward promoting use of multiple-lift concrete pavements - a practice once common in the United States and still common in Europe.

- FHWA is soliciting proposals for a five-year program titled “Technology Transfer of Concrete Pavement Technologies” to promote the two-lift procedure as high priority. For a two-lift concrete pavement, recycled concrete can be effectively used as aggregate in constructing the thicker bottom lift, which is then covered by a thin top lift made of high-quality aggregate. Using a concrete with lower elastic modulus in the bottom lift increases the fatigue life of the pavement, thus reducing life-cycle costs. Virgin aggregate can be imported as needed for the thin (one- to two-inch) top layer designed for noise reduction or improved skid resistance. Gress noted that this technique has the tremendous advantages of sustainable design and lower costs.

1.1.5.15 Colin Lobo, National Ready Mixed Concrete Association

- Lobo described efforts at AASHTO to update the relevant specification (AASHTO MP16, Standard Specification for Reclaimed Concrete Aggregate for Use as Coarse Aggregate in Hydraulic Cement Concrete)

1.1.5.16 Mohamed Mahgoub, Chair of ACI Committee 555 (Concrete with Recycled Materials)

- Mahgoub discussed efforts to provide updated guidelines on best practices for recycled concrete aggregate (RCA).

1.1.6 Summary of Findings from Various State Surveys

Table 4 provides a list of the states which at least on one survey have indicated that they use RCA in PCC pavement. Although 23 states appear on the list, upon further inspection it can be found that many of them may allow the use of RCA in PCC pavements but have never built one or else have built a limited number (often just one) project.

It appears that in the time period between the late 1970's to the mid 1990's many projects (more than 100) were built, but this activity has significantly slowed down since. Tracking the history of the states who were most active in building projects we find that Michigan (who built the most number of projects) placed a moratorium on using RCA in PCC pavements in 1991. It is now only allowed in lower-risk applications such as curb and gutter, sidewalks, barriers etc. Michigan experienced some problems with mid-slab transverse cracking, but most of this was attributed to design features rather than the RCA itself. In Wisconsin, contractors are electing to use RCA in the base and shoulders, not in the pavements. Iowa indicated the majority of their trial projects were built by counties rather than the DOT. They noted some mid-slab transverse cracking, and now the RCA is mainly used in the base.

Among the most active states in using RCA in PCC pavements it might be said that Minnesota currently has the most favorable outlook. Among the issues noted by Minnesota, were the extra cost of washing the aggregates, and maintaining a water-cement ratio of 0.40. Minnesota built trial sections of composite RCA pavements using the two-lift approach at the MnROAD test facility in 2010.

It is recognized that sustainable development is promoted by using recycled material such as recycled concrete aggregates (RCA) in construction. Currently, the majority of states consume most of their RCA in base courses. Very few new PCC pavements have been built with RCA. Some observations or perceptions include ASR potential, variability in quality, high absorption, and the effect on mechanical properties. The fact that there is a large volume of research but only limited implementation seems to suggest that there is a technology transfer problem, that is, many of the perceived problems may already have solutions in the completed research. FHWA is currently promoting the two-lift approach where RCA can be used in the lower lift and higher quality aggregate can be used in the thinner upper lift. It remains to be seen if this will become popular in the US in the coming years.

Table 4. States that use RCA in PCC Pavements According to Surveys

State	1994 Snyder / Comment		2004 FHWA	2006/09 WashDOT Survey / Comment		2011 Iowa State / Comment		2012 Caltrans / Comment	
Alabama	N		N			Y	Spec allows. Never done	Y	Spec allow
Colorado	Y	1 project 1982	Y	Y	Used in past. No documentation.	N	Base course	Y	
Connecticut	Y	1 project 1979	N						
Idaho	N		Y	Y	1 project 1990. Not used since. Would consider if contractor suggested				
Illinois	Y	1 project 1986	Y	Y	20 year performance of 1 project good	N	1 project	Y	
Indiana	N		N			N	Use as base/subbase	Y	
Iowa	Y	16 projects 1976-1993. Some mid-slab transverse cracking	N	N	Most projects built by counties. Now used in base.	N		N	
Kansas	Y	3 projects 1985-1990	N			N			
Michigan	Y	30 projects 1981-1994. Moratorium in 1991	Y	N	Can only be used in curb, sidewalk, barrier etc.			N	
Minnesota	Y	14 projects 1980-1988. Good performance.	Y	Y	Mainly used in base. Two new MNROAD cells	Y	Added I-35 project in 1997. Two MnROAD cells in 2010.		
Nevada	N		N					Y	Permitted
New York	N		N			Y	Specs allows	Y	Spec allow

State	1994 Snyder / Comment		2004 FHWA	2006/09 WashDOT Survey / Comment		2011 Iowa State / Comment		2012 Caltrans / Comment	
North Dakota	Y	3 projects 1983-1984.	Y			N	25 years ago		
Ohio	N		N			Y	15 years ago in Toledo. Performing well	Y	Spec allow
Oklahoma	Y	2 projects 1983-1988.	N					Y	
Oregon	N		N	Y	1 project.	N	No spec	N	
South Carolina	N		Y	Y	1 project 2003. Encouraging as coarse aggregate No fines.	Y	Only 1 project 10 miles on I-95	Y	
Texas	N		Y	Y	1 project 1995. Good performance. Limit fines to 20%.	Y	1 project	Y	
Virginia	N		Y	N	Only used in cement stabilized subbase				
West Virginia	N		Y						
Wisconsin	Y	17 projects 1983-1993. Good performance.	N	N	Contractors elect to put it in base, shoulders	N			
Wyoming	Y	10 projects 1985-1994. Good performance	Y	Y	4 additional projects				

1.2 GENERAL LITERATURE REVIEW

1.2.1 Mark Snyder (2006) as reported in Anderson et al. (2009)

A large amount of work conducted by Mark Snyder was documented in an unpublished report in 2006 and is reproduced in Anderson et al. 2009. The work gives a lot of information on many aspects such as characteristics of the aggregates, fresh concrete properties, hardened concrete properties, and performance of pavements. Some physical properties and characteristics of RCA are given in Table 5.

RCA aggregates, both coarse and fine, tend to be very angular and rough due to the crushing of the virgin aggregate particles and the presence of cement paste that continues to cling to the surfaces of the aggregate. Concrete mixes with angular and rough particles tend to be harsh and difficult to finish. The harshness can be minimized by not using recycled fines. The use of admixtures such as fly ash or water reducers can also minimize the harshness of RCA mixes. The porous nature of the cement paste portion of the recycled aggregates increases its absorption capacity. Workability can suffer with high absorption capacities resulting in a decrease in the time available to place and finish the concrete. Adding water to the mix by pre-wetting the aggregate is one solution that has been used. Limiting the use of recycled fine aggregate will also reduce the absorption capacity of the aggregate.

Table 5. Properties and Characteristics of RCA versus Virgin Aggregates

Property	Virgin Aggregates	RCA
Shape and texture	Well rounded, smooth (gravels) to angular, rough (crushed rock)	Angular with rough surface
Absorption capacity	0.8 – 3.7 %	3.7 – 8.7 %
Specific gravity	2.4 – 2.9	2.1 – 2.4
LA Abrasion Loss	15 – 30 %	20 – 45%
Sodium Sulfate Soundness Loss	7 – 21 %	18 – 59%
Magnesium Sulfate Soundness Loss	4 – 7 %	1 – 9 %
Chloride content	0 – 1.2 kg/m^3	0.6 – 7.1 kg/m^3

Soundness tests are performed on aggregates to provide an indication of an aggregate's resistance to weathering and other environmental effects. RCA commonly fail the sodium sulfate soundness test while passing the magnesium sulfate soundness test as indicated in Table 5. This contradiction between the results of the two test methods brings into question if they are applicable to RCA. Many agencies waive soundness testing on RCA. Pavements with long-term exposure to deicing salts may produce RCA with high levels of sodium chloride. There is concern that RCA with high chloride contents may affect the durability of the new concrete and the corrosion of steel in new concrete. If there is a concern it is suggested that the fine aggregate be washed and that epoxy-coated steel or other corrosion resistant steels be used for reinforcement.

Concrete mixtures with both coarse and fine recycled aggregates can be very harsh and difficult to work due to the highly angular and rough surface of the RCA. Additional water is required in order to obtain the same degree of workability as a mix containing conventional aggregates, especially when both coarse and fine recycled aggregates are used. Increasing the water content will necessitate an increase in the cement content to produce a cement paste that is equivalent to mixes made with conventional aggregates. The result is a more costly mix design.

Workability can be improved by reducing (down to about 30%) or eliminating the amount of recycled fines in favor of natural fines, using water reducers, adding fly ash or a combination of all three. Using fly ash alone may not provide a workable mix and a reduction in the percentage or elimination of the recycled fines may be necessary. Slump loss is commonly observed for mixtures containing RCA due to its high absorption characteristics. Solutions include presoaking the aggregates or pre-wetting the stockpile. The higher and more variable absorption capacity of RCA also makes it difficult to determine the water content which in turn leads to variation in the strength of the hardened concrete. Higher and more variable air contents are common in fresh concrete made with RCA. This is due to the higher porosity of the recycled aggregates themselves and to the entrained air in the original mortar. Therefore, the target air content of mixtures containing RCA must be higher to achieve the same durability as conventional mixes.

Compressive strengths of concrete containing RCA are generally slightly lower than concretes made with natural aggregates; however, there is little agreement on the magnitude of the strength reduction. Some studies cite two to ten percent lower compressive strengths, others report similar and sometimes higher strengths depending upon the water-cement ratios for the mixes. The higher air content normally found in mixes containing RCA may also lead to lower strength values. Reports indicate that the use of recycled coarse aggregate reduces the flexural strength by up to eight percent at the same water-cement ratio, and that this reduction increases if recycled fines are also used. The quality of the concrete used to produce the RCA has a strong influence on flexural strength, which relies most heavily on the paste-aggregate bond strength. The stiffness or modulus of elasticity of concretes made with RCA is 20 to 40 percent lower than that of conventional concrete at the same water-cement ratio. This reduction can be even greater when recycled fines are also used. The reduction in modulus of elasticity is due to the fact that recycled aggregates typically have lower elastic moduli than natural aggregates. A reduction in modulus of elasticity in pavement applications is not a serious concern from a fatigue standpoint, as the lower modulus should result in lower tensile stresses in the slab. On the deflection side, the lower modulus may result in increased corner deflections, which could result in more pumping and faulting at joints.

Various users have reported increase freeze-thaw resistance due to the higher entrained air contents that result from the air entrainment contained in the RCA aggregate. RCA should be tested prior to use to determine the potential for each particular source. In general the D-cracking susceptibility of RCA is less because the aggregate that is susceptible is crushed to a smaller size in producing the RCA. The addition of fly ash has also been shown to reduce the D-cracking potential by increasing the workability of the mix which allows the use of less water, thereby rendering the mix less permeable. Using natural sands rather than recycled sands also has been shown to be effective in reducing the D-cracking potential. ASR potential is higher in mixtures that use RCA because more aggregate surfaces are exposed for the reaction by the crushing operation. This can be combated by using low alkali, Type II cement, blending the RCA with quality conventional aggregates, and using fly ash in the mix to reduce the expansion of the recycled concrete pavement.

Bond strength reductions between concrete and steel have not been noted when only coarse RCA is used; however, when recycled fines are used reductions have been reported. The additional water required to produce a workable mix in concretes using recycled fines is blamed for this reduced bond strength. The creep potential of concrete is generally proportional to the paste content of the mix. RCA mixtures, which contain more paste than conventional mixes, have a 20 to 40 percent higher creep potential. Creep is generally not a major concern in highway pavements. Drying shrinkage in concrete is dependent upon the amount of excess water present in the fresh cement paste and the ability of the aggregate to restrain the paste from shrinking. Higher water-cement ratios, higher paste contents, and lower coarse aggregate contents will all tend to increase shrinkage. Mixtures with RCA have higher paste contents and thus have increased shrinkage. Mix designs that use both coarse and fine aggregates have the highest drying shrinkage.

There has been considerable success in using RCA on paving rehabilitation projects; however, there have been some reported cases where the use of RCA has resulted in a decrease in performance of the pavement. Excessive amounts of midslab cracking in jointed plain concrete pavement (JPCP) have been reported with the problem traced back to the higher shrinkage and greater thermal expansion/contraction properties of the concrete containing RCA. Midslab cracking in JPCP often leads to failure of the pavement due to a loss of load transfer. Abrasion resistance in RCA has been found to be less than in natural aggregates. The faces of transverse joints or midslab cracks in RCA concrete are more sensitive to abrasion during traffic loading which results in the rapid loss of load transfer capability at these locations. The fracture or cracking of pavements containing RCA often occur at the old paste-aggregate bond interface. The cracks that form are very straight, both in the vertical and horizontal direction. The result is very smooth crack faces with poor load transfer capacity. The absence of natural aggregates in pavements containing RCA further contributes to the poor load transfer capacity of RCA concrete. Loss of load transfer affects performance leading to excessive pumping, faulting, and rapid deterioration of transverse cracks and non-doweled joints under heavy truck traffic.

Load transfer across transverse cracks that develop in individual panels is carried by aggregate interlock through the intimate contact of the roughened faces of the crack. Pavements containing RCA are often deficient in aggregate interlock due to a number of factors including.

- The smaller sized coarse aggregate common with RCA requires only small crack openings to effectively lose all of their grain interlock.
- The use of recycled aggregate reduces the number of natural aggregate particles at the crack face which have a much greater load transfer capability.
- The poor abrasion resistance of the paste portion of the RCA results in greater and more rapid losses of load transfer than when conventional coarse aggregates are used.

Dowel bars at the joints are a necessity for pavements that use RCA and are subject to heavy truck loads.

Recycling concretes containing D-cracking susceptible aggregates can produce a pavement that is less susceptible to durability problems because the aggregates have already endured the majority of the damage. As mentioned previously, reducing the size of the coarse aggregate, adding fly ash to increase workability without increasing the water content, and using natural sands instead of RCA fines all increase the durability of the resultant pavement and its resistance to D-cracking. Freeze-thaw problems and alkali-silica reactions can be a problem that reduces durability, but can be reduced through the use of smaller top size aggregates, adding fly ash to the mix, blending the RCA with natural aggregates or using low-alkali cement.

Snyder also provided some suggestions to consider for pavement design.

1.2.1.1 Pavement Type

- JPCP with short joint spacing may be preferred to prevent transverse cracks and the reliance on aggregate interlock
- JRCP or CRCP may be candidates if:
  - larger top-size aggregate is used.
  - blend of RCA and virgin aggregate is used.
  - greater amount of reinforcement is used.

1.2.1.2 Slab Thickness

- Thickness is the same as for conventional design, although the use of two-layer slabs (i.e., lower layer of recycled concrete with upper wearing layer of high-quality virgin aggregate) should be investigated.

1.2.1.3 Joint Spacing

- Shorter joint spacing may be desirable to reduce the amount of crack opening.

1.2.1.4 Load Transfer

- Dowels recommended for transverse joints; load transfer at cracks (for reinforced pavements) must consider factors listed in the section on Pavement Type.

1.2.1.5 Joint Sealant Reservoir Design

- New recommendations may be needed due to increased drying shrinkage.

1.2.1.6 Base Type

- For JPCP, conventional base types appropriate.
- For reinforced pavements, consider the use of a strong, durable, non-erodible base.

1.2.1.7 Reinforcement

- Increased longitudinal steel reinforcing may be required in JRCP and CRCP to hold the cracks tightly together so that aggregate interlock can be maintained.

1.2.1.8 Shoulder Type

- Same as for conventional mix design.

1.2.2 Mark Snyder in Cuttell et al. (1997)

In 1994, Snyder and others performed field evaluation on nine projects selected from Table 1 (Cuttell et al. 1997). In particular, these sections were: Connecticut: I-84 Waterbury; Kansas: K-7 Johnson Co.; Minnesota: I-94 Brandon, I-90 Beaver Creek, US 59 Worthington, US 52 Zumbrota (Goodhue Co.); Wisconsin: I-94 Menomonie, I-90 Beloit (Rock Co.); and Wyoming: I-80 Pine Bluffs. The nine projects represented a broad range of pavement design, traffic loads, and environmental conditions for pavements that had performed acceptably, as well as those that did not perform acceptably. Five of the nine projects involved a recycled section and a corresponding control section (construction at about the same time using virgin aggregates). The remaining four projects included two with a recycled section, one with a comparison of mechanical load transfer differences between two recycled sections and one with a comparison of foundations support differences between two recycled sections.

The field survey included pavement condition and drainage surveys, photographic documentation of pavement conditions, measurement of slab deflections and joint or crack load transfer using a falling weight deflectometer (FWD), retrieval of pavement cores, and estimation of the present serviceability rating (PSR).

The conclusions and recommendations from the field work were as follows.

1.2.2.1 Conclusions

- Performance was comparable between recycled and conventional pavements when similar amounts of virgin aggregates were used.
- Load transfer was affected by the use of RCA due to the effects that the inclusion of old mortar has on thermal expansion and contraction, shrinkage and crack face texture.
- Recurrent D-cracking was not observed on any of the projects.
- Recurrent ASR was present in small localized areas in one project (Wyoming) after nine years of service.

1.2.2.2 Recommendations

- More thorough evaluation and testing should be conducted on RCA than conventional virgin aggregates.
- Removal of most mortar from the original aggregate appears to result in improved PCC properties.

- Maximizing recovery of reclaimed materials by adjusting gradation limits may result in workability, durability, and strength problems.
- Pavement joint layout and load transfer systems should be designed to take into consideration the high drying shrinkage and coefficient of thermal expansion values as well as the reduced volumetric surface texture potential of the pavement containing RCA.

1.2.3 Mark Snyder in Gress et al. (2008)

The same projects that were surveyed in 1994 were resurveyed in 2006 by Snyder and others (Gress et al. 2008 and Sturtevant 2007). In addition, two new RCA pavement sections were added: Illinois: I-57 Effingham; and Iowa: US 75 Rock Rapids (Lyon Co.). Such factors as ASR, maximum aggregate size, RCA mortar content and load transfer dowels affected pavement performance. Additionally, multiple pavements were rehabilitated since the 1994 study with diamond grinding and retrofitting of dowel bars for load transfer, which had a positive effect on performance. The conclusions and recommendations are listed below.

1.2.3.1 Conclusions

- It is possible to make pavements with RCA which are equivalent in all aspects to pavements built with conventional aggregates.
- Load transfer devices improve the performance of RCA pavements.
- Pavements built with RCA can be made to have equivalent performance to pavements made with conventional aggregates.
- RCA pavements can be effectively rehabilitated resulting in equal or better PSR ratings than with conventional pavements.
- Even though 10 out of the 16 pavements tested were found to have ASR their performance at the time of the 2006 survey was comparable to controls and pavements without ASR.
- The remaining expansion potential of 8 out of the10 pavements that were identified having ASR were found to be significant suggesting the pavements will continue to undergo expansion in the future.

1.2.3.2 Recommendations

- As with conventional pavements, load transfer devices should be used independent of traffic.
- Joint spacing should be kept as short as possible to minimize transverse cracking caused by increased shrinkage and thermal properties.
- RCA crushed with processes that reduce the reclaimed mortar content will behave more like virgin aggregates in terms of workability, strength and volumetric stability.
- Processes that maximize reclamation efficiency will have greater amounts of reclaimed mortar, which may require adjustments in the mixture proportioning to produce concrete with similar properties to that obtained using natural aggregate.
- All concrete being considered for recycling into RCA must be evaluated for existing distress. If potential ASR expansion is confirmed the proposed recycled concrete pavement must be properly mitigated to achieve maximum service life.

1.2.4 Ideker et al. (2013, 2014)

A joint research effort between four universities (Oregon State, Wyoming, Laval, and Ryerson) was primarily focused on laboratory investigation of ASR in RCA (Ideker et al. 2013, 2014). The major points of this research are discussed further. While ASR can jeopardize the durability of concrete, it can be mitigated if the virgin aggregate is initially identified as reactive. However, it has been shown that adding recycled concrete that has exhibited ASR in the field requires higher ratios of mitigating agents (Scott and Gress, 2003; Stark, 1996). Common mitigation measures include Class C or F fly ash, silica fume, lithium nitrate, blast furnace slag, and/or low alkali cement. This issue highlights the need for a standard test that will quickly and efficiently determine the potential field reactivity of RCA. Currently, no such test exists. In addition to the potentially reactive RCA tested in the project, it was necessary to combine RCA in mortar mixtures with nonreactive fine aggregate. The research focused primarily on RCA that exhibited ASR in field conditions. RCA in this project was used as a replacement for virgin aggregate at 25%, 50% and 100% replacement levels.

The most used accelerated test method for ASR on virgin aggregates is the ASTM C1260 Accelerated Mortar Bar Test (AMBT). Another available test is the ASTM C 1293, but was not an option for this study due to the yearlong required testing period. The other options, such as ASTM C1260 offer a faster testing period but often at the expense of accuracy (Thomas et al. 2006). Since it has been shown that, on average, aggregates expand more quickly in warmer conditions than cooler conditions (Fournier et al. 2009), and these accelerated tests require extreme temperatures for testing, results are obtained faster. While it can produce false results, ASTM C 1260 is generally accepted as a good screening test for aggregates (Fournier et al. 2006).

The best approach for accurate prediction of reactivity is the use of several complimentary tests.

However, when separate tests produce opposite results (e.g., one passing result and one failing result), the test with the worst result, or the most conservative result, should be taken into consideration and preference should be given to the more reliable, longer-term ASTM C 1293 test results (Berube and Fournier 2007). Another concern when using RCA is that the level of processing during the crushing activities may affect its reactivity. It has been shown that additional crushing procedures increase the amount of cracks in the original coarse aggregate of the RCA (Nagataki et al. 2004). This may expose fresh reaction sites within the RCA for ASR to occur.

It is important to note that ASTM C 1260 test is only applicable to mortar. Therefore, if the reactivity of a coarse aggregate is to be assessed with this test method, the aggregate must be crushed to meet the gradation standards of the test. As a result, it is possible to expose and remove reactive phases during the crushing, sieving and washing process required by the standard. This may lead to inaccurate reactivity predictions for field structures containing potentially reactive coarse aggregates (Thomas et al., 2006). The consensus among many ASR researchers and engineers is to use an expansion limit of 0.10% after 14 days of immersion in the sodium hydroxide soak solution to indicate aggregate reactivity (Thomas et. al, 2007).

By ASTM C 1260 standards, aggregates are classified by day 14 as reactive; however, it has been suggested that researchers continue the test for 28 days for further observation (Fournier, 2006). Because the test conditions are harsh, the rate of expansion can increase between 14 and 28 days. This means a specimen may pass within 14 days and fail within 28 days. Such examples contribute to false negative results that are widely reported in the literature. Although ASTM C 1260 does not provide guidance on 28-day measurements for a classification, this speculation may help engineers recommend conservative treatment options.

Malvar and Lenke (2006) developed a chemical index to determine the amount of fly ash required to mitigate ASR in concrete made with natural aggregates. The equation was developed by examining the results of combinations of a wide range of cements, fly ashes and various reactive aggregates in the AMBT. The chemical index uses the characteristics of the particular fly ash and cement to predict how much fly ash, by weight percent replacement of cement, will be required to mitigate ASR for a particular combination of cement and aggregate. In essence, this can provide a strong starting point to eliminate the need for vast quantities of testing where an optimum dosage can be predicted and then that dosage rate (and rates slightly higher and slightly lower) can be tested to confirm the amount of fly ash needed to control the reaction.

Overall it was found that modifications to standard aggregate testing and characterization standards were necessary for testing RCA. This included modifications to standard tests including ASTM C 128, C 305 and C 1260. It was found that the potential for alkali silica reactivity did exist for new concrete containing RCA. The characteristics of the RCA also had a profound effect on ASR related expansion. RCA with a higher content of reactive coarse or fine aggregate (compared to paste fraction) exhibited greater reaction and would therefore require higher levels of mitigation. Based on testing in this research project precision and bias statements in ASTM C 1260 (for virgin aggregate) do not apply to RCA. (Ideker et al. 2013).

From Phase II of this project the following main conclusions were drawn: 1) The coefficient of variation limits in ASTM C 1260 do not apply to concrete mortar bars incorporating RCA. 2) Generally, as the replacement level of RCA was reduced, the amount of supplementary cementitious material (SCM) needed to control deleterious ASR also decreased for the RCA sources investigated in this study. 3) Ternary blends containing metakaolin resulted in the most significant decrease in expansions compared to the mixtures with no SCMs. 4) The specific amounts of fly ash predicted by the Malvar and Lenke equation needed to control deleterious ASR in concrete incorporating RCA produced conflicting results. In about half of the cases, the chemical index equation was capable of predicting the required amount of fly ash to reduce ASR-related expansion for RCA and fly ash combinations. However, not all RCA followed this trend. 5) The amount of adhered mortar can affect the level of reactivity in an aggregate, and subsequently may affect the efficacy of an SCM to mitigate ASR. (Ideker et al. 2014).

1.2.5 FHWA Technology Deployment Plan (Garber et al. 2011)

Iowa State University developed a Technology Deployment Plan for the FHWA aimed at addressing the barriers that limit the use of RCA in new concrete paving mixtures (Garber et al. 2011). The Plan recognizes barriers grouped into three primary categories: compliance, quality, and production. Commonly cited reasons for limiting the use of RCA in new concrete paving mixtures include agency restrictions, an inability to meet specifications, and lack of consistent quality. Some of these limitations seem to reflect a general lack of knowledge. For example, a common owner-agency concern is the use of RCA from concrete previously exhibiting materials related distress (e.g., ASR or D-cracking). There have been studies, however, that demonstrate how proper mitigation efforts can make RCA from such concrete sources a viable option. Contractors are also concerned that RCA will result in inconsistent quality, which in turn can compromise workability and the ability to meet specifications. Because of concerns about quality, contractors increase the costs for using RCA, making it a less attractive option for new concrete paving mixtures. Educating contractors and owner-agencies about methods for effectively incorporating RCA into new concrete mixtures could help the industry overcome this limitation.

The mortar around the original aggregate affects RCA properties. Because of the increased mortar fraction, the relative density of RCA is less than and porosity is greater than most virgin aggregates. When producing concrete with RCA, the volumetric proportioning and mixing water requirements are affected by the relative density and porosity properties. RCA is more susceptible to mass loss, higher absorption, and freeze-thaw damage when compared to most virgin aggregates because of its increased porosity due to the mortar fraction. RCA strength is typically less than that of virgin aggregate; however, it may have greater strength than some soft virgin aggregates. The strength of RCA depends on the combined strength of the original aggregate and the transition zone between that aggregate and the mortar of the old concrete. It should be noted, however, that although there tends to be increased mass loss associated with RCA, it still commonly meets specified tolerances for LA abrasion testing.

States that allow RCA for use in new concrete paving mixtures typically require that RCA meet the same specifications as virgin aggregates. This could restrict the use of RCA, and some considerations should be made to change some requirements in specifications for virgin aggregates. For example, RCA is prone to fail the soundness requirements and limits on the quantity of fines. European standards for test methods to qualify RCA for use in new concrete mixtures recommend using a magnesium solution for testing RCA durability in freeze-thaw environments. It has been reported that absorption testing for RCA requires more time for accuracy (Meinhold et al. 2001; Gomez et al. 2001; Schouenborg 2004). The process for determining gradation may affect the accuracy of the results because the shaking during sieving causes mortar particles to separate from the original aggregates. Instead, it has been recommended by the Swedish National Testing and Research Institute, the Foundation of Scientific and Industrial Research at Norwegian Institute of Technology, and the Icelandic Building Research Institute to test several smaller samples. The order in which gradation and abrasion testing is done with the same sample affects the results. For abrasion testing or fracture resistance, it is recommended that the sample be tested as a unit (Schouenborg 2004).

A new concrete mixture that includes RCA must be engineered properly in order to achieve required workability, strength, and durability. Concrete designed by simply replacing virgin concrete with RCA will not necessarily perform the same. Fresh concrete containing RCA tends to lose workability faster and is often a harsher mix (Hansen and Narud 1983). A modest acceleration may be observed in setting time, which may be attributed to continued hydration of the old mortar fraction while the new concrete mortar is still plastic. Hardened concrete containing RCA generally has a lower modulus of elasticity, higher coefficient of thermal expansion (CTE), and experiences more drying shrinkage (ACPA 2009; Burke et al. 1992). Concrete strength is often lower when compared to the same mix with virgin aggregates. New concrete may suffer ASR-related distress if RCA is from ASR distressed concrete (FHWA

2007). The development of mixtures to minimize or offset these effects is necessary. Engineering the mix by properly proportioning RCA and virgin aggregate combinations with optimized water content and both chemical and mineral admixtures (i.e. SCMs) will improve the performance of new concrete with RCA.

As more RCA is used in place of virgin aggregate for the same mixture design, noticeable differences in concrete properties such as strength, workability, and durability become apparent.

Research has shown that, when replacing virgin aggregate with RCA, there is a limit at which, when all other mix constituents (e.g., cement, water, air content) are held constant, concrete properties such as strength and durability are affected. In Austria, it is reported that virgin coarse aggregate can be replaced with up to 20% RCA (Sommer 1994). In Australia, up to 30% of virgin coarse aggregate can be replaced by RCA, but only in new concrete mixtures for curbs and sidewalks (CCA Australia 2008). Research in the UK supports the use of 30% replacement of coarse aggregate with RCA and reports that there is little to no effect on concrete properties (Limbachiya et al. 2004). Research in Japan concludes that up to 20% coarse aggregate can be replaced with RCA without affecting concrete properties and that maximum aggregate size should be limited to a range of 16-20 mm (Dosho 2007).

RCA as a fine aggregate is not typically used in new concrete mixtures. It has been reported that

RCA fine material contains increased amounts of contaminants that adversely affect concrete properties (RILEM 2005; Smith et al. 2008). Fine RCA may cause increased shrinkage, reduced strength, and reduced workability. Therefore, most specifications currently in existence that address the use of RCA in new concrete mixtures do not allow the use of RCA as a substitute for fine aggregate.

As is the case for new concrete mixtures with virgin aggregates, the *w/cm* ratio should be optimized for placement and performance. Some research simply suggests that new concrete mixtures with RCA require additional water and cement. However, in order to achieve a workable mix that is strong and durable for paving applications, new concrete mixtures with RCA should be engineered to include chemical and mineral admixtures that minimize the need for additional water and cement (Dosho 2007; Hansen and Narud 1983; Burke et al. 1992).

Research in New Zealand resulted in a method for determining trial batch proportions based on a series of strength curves developed for a range of w/cm ratios for both RCA and virgin aggregate mixes (Zhang and Ingham 2010).

Compressive strength of concrete with RCA is commonly reported as being lower than the strength of concrete made with only virgin aggregates. Reduced concrete strength when RCA is used in place of virgin aggregates is attributed to the mortar fraction around the original aggregate. It has been shown that when a new concrete mixture has a higher *w/cm* and includes RCA with a strong transition zone between the original aggregate and the old concrete mortar fraction, the new concrete will exhibit strengths similar to that of the same mix if virgin aggregate were used. If the w/cm is low and the RCA transition zone is weak, the concrete will have lower strengths than if virgin aggregates were used in the same mix (Otsuki et al. 2003).

In addition to reduced compressive strengths, the relationship between compressive strength and tensile strength is not necessarily the same for concrete with RCA as it is for concrete with virgin aggregates (Sanchez and Gutierrez 2004). For higher *w/cm*, the relationship of compressive strength to tensile strength predicts values that are too high (Tavokali and Soroushian 1996).

For concrete with RCA to achieve a specific strength, the reviewed literature recommends that the RCA come from a source of equal or greater strength; however, even concrete from the same source may not be uniform in strength and this may cause problems in achieving specifications (Hansen and Narud 1983). Minimizing the amount of mortar around an aggregate during processing will help increase strength. Mineral admixtures such as fly ash and slag can be used to improve both strength and durability. Limiting the porosity of RCA will also help the concrete achieve required strength (Meinhold et al. 2001).

Concrete paving mixtures that include RCA aggregate can be engineered to perform well in freeze-thaw environments. It has been shown that RCA from previously air-entrained concrete improves concrete performance in such conditions, and the use of fly ash can improve concrete with RCA performance in freeze-thaw environments (Gokce et al. 2004). RCA in concrete does increase the potential for more carbonation and chloride penetration because the transition zone between old mortar and original virgin aggregate is more permeable than virgin aggregate (Otsuki et al. 2003). Mineral admixtures may help decrease carbonation and chloride ingress by densifying the new mortar matrix. ASR can occur in concrete with RCA. Typical mitigation methods (e.g., reduced *w/cm*, addition of mineral admixtures) can work to minimize the potential damaging effects of ASR (Stark 1996).

Consistent workability, strength, and durability of a new concrete paving mixture that includes

RCA depends on good quality control. According to the literature, there are quality control methods specific to RCA that may help to limit material variability and address moisture control.

Stockpiling RCA according to the properties of the source concrete is a technique that minimizes variability. Removing as much of the mortar as possible is another method, which requires optimized crushing methods as discussed previously. Pre-wetting aggregates before mixing is a moisture control method that helps combat the absorptive nature of RCA.

1.2.6 Vancura et al. (2009)

Vancura et al. (2009) produced a review of overlooked research aimed at addressing the concerns preventing the widespread use of RCA in PCC pavements. The review mainly focused on European literature. RCA is more absorptive than natural aggregate because of its recycled mortar content. This makes it less dense and it requires more attention to mix design since each batch of recycled aggregate requires a unique adjustment to satisfy the absorption of the aggregates (Yrjanson 1989). The absorption of both coarse and fine natural aggregate is around 1% or less. The absorption of coarse RCA is around 2% to 5% and that of fine RCA between 6% and 12% (Sani et al. 2005; Shayan and Xu 2003). Research indicates that fly ash is an agent that decreases hardened concrete's permeability (Yang et al. 2008). In order to not compromise the workability of the concrete some suggest simply wetting the aggregate or adding a little more water to the concrete mix (Franke 1994). At a concrete batch plant or even onsite, the aggregate could be tested ahead of time to determine the absorption (Cristofeletti et al. 1994). If such testing is not feasible then sprinkling the RCA for 48 h before incorporating it in a concrete mix ensures that each aggregate batch is fully saturated (Werner 1994).

Recycled concrete fines are small particles of mortar, not durable aggregate and are generally unwelcome in the concrete mix. Their absorption levels alone may cause unpredictability in the wet concrete (Hendricks 1994). Other research indicates that recycled fines decrease workability, demand more water, increase absorption, and decrease strength compared with mixes made with natural fines (Sani et al. 2005; Sommer 1994; Gomez-Soberon 2002). As an exception to the conventional wisdom, a project in Sweden successfully incorporated 100% coarse and fine RCA. This success was attributed to splitting the aggregate into four sizes (0/4, 4/8, 8/16 and 16/32) before incorporating it into the new concrete mix and to ensuring that the old concrete cement paste was 100% saturated before the RCA was incorporated into the concrete mix. Vancura et al. (2009) performed a review of the concrete mix designs in the literature and found that in general, when SCM such as silica fume or fly ash is used, the compressive strength of concrete with RCA is equal to or slightly less than that made with natural aggregates.

RCA concrete offers less restraint to volumetric expansion in response to temperature and moisture fluctuations, primarily due to it lower modulus of elasticity (hence lower stiffness) (Cuttell et al. 1997; Springenschmid and Sodeikat 1998; Huber et al. 2004). Yang et al. (2008) observed that shrinkage was dependent on the amount of mortar left on the original concrete. Though both moisture and thermal gradients are responsible for volume change in PCC pavements, research suggests that the temperature gradient is the primary cause of shrinkage and swelling in PCC containing RCA (Huber et al. 2004). Shrinkage due to carbonation was found to be negligible in RCA concrete (Shayan and Xu 2003).

Initially, the shrinkage rate of conventional concrete exceeds that of RCA concrete, but after approximately 10 days, the shrinkage rate of conventional concrete slows at a quicker rate than that of RCA concrete (Yang et al. 2008). Besides decreasing the amount of mortar attached to the recycled aggregate, both a partial substitution of fly ash for cement and a decrease in the *w/cm* ratio reduced the drying shrinkage and creep of recycled aggregate concrete. Researchers attribute this to a greater long-term strength development due to the pozzolanic reaction of fly ash (Kou et al. 2007). A third factor in decreasing creep and shrinkage is time. The total porosity of concrete made with coarse RCA decreases over a period of 90 days because of the crystallization of products that reduce both the number and size of the pores (Gomez-Soberon 2002).

The reason it is important to limit shrinkage, creep, and warping is more apparent when the structural elements of pavements are considered. Because of the large strains caused by thermal gradients, cracks and joints can contract more given the appropriate conditions. The result is decreased load transferability across the joint or crack leading to early degradation of the pavement (Cuttell et al. 1997). An example of this finding is portrayed by a case study from a stretch of RCA PCC pavement in Minnesota. An RCA pavement section and a natural aggregate control pavement section were placed at about the same time on US-52 near Zumbrota, Minnesota. A sample of the RCA pavement indicated an 83.6% mortar content and the conventional sample revealed a 51.5% mortar content. After only 10 years of service, the RCA section was 88% cracked versus 22% cracked for the control section. After 22 years, the RCA section was 92% cracked and the control section was 24% cracked. Even though the control section was significantly cracked, the performance of the RCA pavement may have been due, in part to the high mortar content of the recycled aggregate.

In Europe, concrete that exhibits D-cracking or ASR distress would not be used as RCA in PCC; however, in the US there have been efforts to utilize such pavements. For example, in Minnesota, a 16-mi rehabilitation project on US-59 between Worthington and Fulda was the first known project to recycle concrete pavement that failed extensively from D-cracking (Yrjanson 1989). Laboratory research identified that the original virgin coarse aggregate had shown poor durability and subsequently the concrete pavements containing this aggregate were D-cracked. In response, MnDOT limited the size of the recycled coarse aggregate to 19 mm (3/4 in.) for dilation reduction. Research also showed that fly ash could be used to reduce the chances of D-cracking. In laboratory studies, concrete pavement mixes with fly ash substituted for cement as 0%, 10%, and 20% by weight of cement were tested by to observe freeze thaw durability. The mixture with 20% fly ash replacement showed a greatly reduced potential for D-cracking (Yrjanson 1989).

The 1994 and 2006 follow-up studies conducted by Mark Snyder and others described pavement sections, two in Minnesota and one in Kansas, that were constructed with previously D-cracked pavement (Cuttell et al. 1997; Gress et al. 2009). The Minnesota section (MN-2) that contained less than 10% recycled mortar content showed no signs of recurrent D-cracking after 22 years.

The other Minnesota section (MN-3) showed no signs of recurrent D-cracking after 26 years. The MN-3 section ultimately failed because of joint faulting and was rehabilitated in 2004. The coarse RCA used for both Minnesota projects was limited to a maximum size of l 9 mm (3/4 in).

The Kansas section (KS-1), which, in addition to coarse RCA, incorporated 25% recycled fines into its mix and allowed a maximum coarse RCA size of 38 mm (1.5 in), had a different outcome. Whereas after 9 years no recurrent D-cracking was observed, by 2002 the section was rehabilitated with a bituminous overlay because of recurrent D-cracking.

The same reports also details the recycling of an existing PCC pavement with ASR problems in Wyoming (WY-1) for new PCC pavement. In this project, the coarse RCA contained less than l0% mortar content and 25% of natural fines was replaced with recycled concrete fines. Also important in the mix design was the use of ASR mitigation techniques such as using low-alkali cement and Class F fly ash. The original l994 study reported that uranyl acetate testing found a moderate amount of silica gel in the mortar around aggregate particles of the RCA section and minimal amounts of silica gel in the control section. By 2006 there was visual evidence of localized ASR surface cracking, indicating minor ASR after more than 20 years. The possible conclusions from this case study are that the ASR mitigation techniques prevented more severe recurrent ASR and that using 100% natural fines may have prevented or lessened the recurrence.

It has become common practice to place a bituminous overlay to rehabilitate concrete pavements. This overlay is usually scraped away prior to recycling the concrete pavement. A study in Austria investigated the effects of asphalt content (binder) incorporated with RCA. Although asphalt contents of up to 20% did not significantly reduce the pavement's flexural strength and asphalt contents of up to 33% did not compromise shrinkage and swelling behavior, asphalt contents of more than 20% impaired the pavement's frost resistance (Sommer 1994). Ultimately, Austria limited to l 0% the amount of 4/32-mm asphalt particles in the recycled aggregate used in PCC pavement mixes.

In some European countries, most notably Austria, RCA is used as coarse aggregate for the bottom layer of composite concrete-on-concrete pavement. In 1989 Austria pioneered this practice by developing a system to recycle the existing concrete pavement along the Al motorway between Vienna and Salzburg. Today, Austria requires the use of recycled concrete in the lower layer of its two-course PCC pavements. This system entails using the 4/32-mm crushed coarse aggregates for the new roadway and the 0/4-mm fines to stabilize the frost layer (Krenn and Stinglhammer 1994). German engineers replaced a 6-km section of the A9 motorway near

Dessau. RCA was used as coarse aggregate in the bottom lift of a two-lift PCC pavement. The specific experience that persuaded the Germans to experiment with RCA despite their not having standard specifications for its use was Austria's suggestion to eliminate recycled concrete fines from the mix for the lower lifts because of the fines' negative effect on workability (Gomez-Soberon 2002). Another Austrian-inspired RCA PCC project was constructed on the A27 motorway in Lower Saxony, Germany. Coarse RCA was used in the lower lift of a two-lift pavement in 6-km sections (Franke 1994). Later in the 1990s, German researchers confirmed the resistance of RCA PCC pavement to deicing salt penetration through observation of the in-field performance of the pavement along the A93 motorway in Bavaria. A single-layer concrete pavement with 100% coarse RCA (no recycled fines) survived the particularly hard winter of 1995-1996 and showed no deterioration (Springenschmid et al. 1998). In a final example from Germany, sections of the A9 motorway constructed with RCA PCC were observed to have a higher resistance to cracking than their conventional counterparts undergoing similar environmental conditions. Two hypotheses were proposed for this phenomenon: first, recycled aggregate's rough surface has the ability to create a better bond with the new mortar than the natural aggregate, and second, there may be a local reduction in the water-to-cement ratio near the bond area because of the porosity of the recycled cement paste (Springenschmid et al. 1998).

Iowa State University conducted an investigation into two-lift PCC pavement (Cable and Frentress 2004) to provide recommendations and guidelines for the adoption of these pavements into U.S. practice. One of the caveats of this review was the additional expense of the construction of two layer PCC pavements in the United States given the need for equipment and expertise that are not familiar to American pavement engineers and contractors. One immediate cost-saving measure would be the use of RCA in the lower of the two PCC lifts.

1.2.7 Michigan Tech Study, Van Dam et al. 2011

Michigan Tech University performed a research study for the Michigan DOT (Van Dam et al. 2011). As noted previously, Michigan currently limits the use of RCA to bound and unbound drainable bases. Some of the performance issues on the early projects developed because of the unique characteristics and properties of RCA materials, such as increased absorption, lower specific gravity, and reduced abrasion resistance. In the chapter about using RCA in PCC mixture it is noted that 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 RCA 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 RCA. As the RCA particle size decreases, the relative volume of mortar increases, which is why the influence on concrete behavior becomes more apparent as smaller sized RCA 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 RCA.

When using only coarse RCA, the major impact is the increased water demand. The angular and rough surface texture of RCA is the major contributor to increasing water demand, although the increased absorption capacity due to the reclaimed mortar also plays a role. If using only coarse RCA, 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). If both coarse and fine RCA are used, all fresh concrete properties are affected even more significantly. One other concern with fresh concrete properties is the potential for early setting due to the presence of unhydrated cement in the RCA 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 RCA), they are of lesser consequence in concrete mixtures in which only the coarse RCA is used.

The concrete compressive and tensile strengths, as well as modulus of elasticity, are influenced by the use of coarse RCA. 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 RCA. 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.

The coefficient of thermal expansion (CTE) of hydrated cement paste is considerably higher than that of natural coarse aggregates. As a result, as the reclaimed mortar volume of the RCA increases, so does the CTE of concrete made from the RCA. It has been reported that the CTE of concrete made with RCA is typically 10 percent higher than that made with natural aggregate. 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. 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 RCA 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 RCA 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 RCA 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 RCA 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 RCA.

Pavement design details that may require adjustment to address some of the unique characteristics of concrete made with RCA include increased pavement thickness and decreased joint spacing. These are primarily due to decreased concrete strength (if not addressed through mixture design), increased CTE resulting in higher curling stresses, and increased drying shrinkage.

In addition, MDOT experience has shown that concrete made with RCA 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

RCA, 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 RCA 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 RCA.

1.2.8 Washington DOT Study, Wen et al. (2014)

Washington State University conducted a research study for the Washington DOT to evaluate the suitability of using RCA in new concrete pavements (Wen et al. 2014). RCA was obtained from sources with original high quality material. Variable included percent replacement of coarse natural aggregate with RCA (0%, 15%, 30% and 45%), and percent replacement of portland cement with type F fly ash (0% or 20%). RCA had lower specific gravities (2.54) and higher absorption capacities (3.41%) than those for the coarse natural aggregates (2.63 and 1.17%) due to the presence of adhered mortar on the RCA. The adhered mortar was also largely the cause of the increased Los Angeles abrasion loss for the RCA (about 23%) in comparison to that for the natural aggregate (15%). The degradation factor is a measure of abrasion loss under wet conditions. Washington DOT requires a degradation factor above 30. The degradation values were significantly improved after washing off fines and met the minimum requirement but were only around 58 for 100% RCA, and about 75 for 15%, 30%, and 45% RCA. One of the sources had an average 14-day ASR expansion on mortar bars greater than 0.1%. An inference from this result is that ASR reactivity may be an issue with using RCA. This could be because of the original or remaining alkali levels in the recycled aggregates, or from the crushing process which can expose new surfaces whose ASR reactivity has not yet been depleted.

A total of 20 different batches of concrete mixtures were tested. For batches not containing fly ash the *w/cm* ratio was about 0.44, while for the batches containing fly ash the *w/cm* ratio was about 0.40. There was a general trend of decreasing slump with increasing RCA content, and two of the mixtures containing 45% RCA (but no fly ash) needed water-reducing admixture to obtain a slump between 1 to 3 in. Fly ash on the other hand increases the workability allowing the *w/cm* ratio to be lower at 0.40. There appeared to be no significant effect on the air-entrainment of the mixture keeping in mind that an air-entraining agent was added to keep the air entrainment between 4 to 7%. The concrete mixtures all had 28-day compressive strengths greater than the Washington DOT 4000 psi minimum but there was no obvious relationship between RCA content and compressive strength. All mixtures met the 14-day modulus of rupture (MOR) minimum requirement of 650 psi. RCA content did not appear to have a significant on the MOR. There was no immediately visible trend between RCA content and coefficient of thermal expansion. Data showed that the drying shrinkage strain be increased from 0 to 30% over the reference concrete at 45% RCA replacement. Finally, it was recommended that Washington DOT may consider using RCA in PCC pavements at the 45% replacement level.

1.2.9 Other Literature

Hansen (1995) conducted a study at the University of Michigan to investigate the causes of distress in RCA pavements at two project locations. One of the sections also contained a control pea stone aggregate section. A performance evaluation of the test sections indicated that traffic loading and pavement thickness played a major role in the deterioration of several of the pavement sections. Using a thicker pavement slab can help to reduce pavement damage. The effect of the foundation layers on recycled concrete performance was not conclusive, though it was seen that excessive deflection can cause significant damage to the pavement. Good compaction of base and subbase layers is advantageous as is a stiff subgrade. Uniform foundation stiffness can reduce stress concentrations in the slab. Load transfer efficiency across cracks and transverse joints had a significant effect on slab performance. High load transfer across cracks is indicative of good aggregate interlock and adequate foundation support. Load transfer across joints is indicative of properly working joints with the doweled connections moving as they are designed to do. Poor load transfer across joints indicates ineffective joints. Because of the aggregate/paste mix in recycled aggregates, the long-term shearing resistance of the aggregate may be lower than for many virgin aggregates. This could in turn lead to a decrease in aggregate interlock, causing more rapid deterioration of existing cracks. In the case of pea stone concrete, small aggregate size and rounded aggregate shape led to poor aggregate interlock. This project also showed the sensitivity of recycled concretes to both field conditions and environmental factors. Data showed that hot weather during placement was associated with recycled sections that deteriorated rapidly, while a better product was produced during cooler placement weather. Early shrinkage cracking and inhomogeneous concrete were noted for the sections placed at high temperatures. It is probable that the quality of the recycled aggregate plays a major role in the performance of the new concrete. The use of freeze-thaw testing is an accepted method for aggregate durability testing and can be applied to recycled aggregates. Because of the high absorption capacity of many recycled aggregates, freeze-thaw dilation may be excessive. The use of large size premium virgin aggregate in conjunction with recycled aggregate can increase aggregate durability as well as improve aggregate interlock and abrasion resistance.

A paper presents the aspects of mix design, construction, and challenges faced in the two-lift construction of test cells at the MnROAD test facility (Tomkins et al. 2011). One of the pavements consists of a low-cost aggregate PCC topped by a high-quality exposed aggregate concrete PCC; while the other consists of an RCA PCC mix topped by exposed aggregate concrete. This is further discussed in Akkari and Izevbekhai (2012). Another study discussed concrete sustainability practices at MnDOT and projected some possible savings that can be derived from recycled aggregate usage (Izevbekhai 2012). The study also determined that the use of higher pozzolanic substitution, well-graded aggregates, and a low *w/c* ratio are reasonable and realistic sustainable practices.

Akkari et al. (2013) suggested that in RCA concrete, the interfacial transition zone (ITZ) may be enhanced as bleed water is absorbed by the RCA. Gradations were “as received” but limited to a maximum size of 38 mm (1.5 in) and minimum size of 4.75 mm (0.19 in). A counting of the fractured aggregates in the exposed faces of cracked flexural beams suggested an enhancement of the ITZ in recycled aggregate. To eliminate counting error, the authors developed and used an aggregate avoidance index method to evaluate the fractured faces. Results indicated lower aggregate avoidance indices for higher recycled aggregate content, thus validating the enhancement of the ITZ.

Cross et al. (1996) reported on the Kansas demonstration project using RCA in PCCP. Four test sections were evaluated including two control sections, one section with cement treated base (CTB) with RCA, and one with RCA in both the PCCP and CTB. An HMA shoulder using RCA as coarse aggregate was also constructed. The test sections were monitored over a 10-year period for performance including faulting, roughness, load transfer, and friction measurements. Faulting, roughness, performance level, and joint distress measurements from KDOT’s 1995 pavement condition survey were used to compare the performance of the recycled sections with PCCP of similar age and traffic in the same area of the state. All test sections performed well, with the CTB and PCCP sections with RCA aggregates showing slightly more distress.

Gress and Kozikowski (2000) evaluated techniques and procedures for assessing the ASR expansion potential of concrete that was made from RCA, was known to have ASR, or was capable of ASR under conditions of increased alkalinity. Laboratory tests included evaluating prisms characterized by variable surface-to-volume ratios, increased temperature, microwave energy, and increased alkali content. Standard 280-mm (11-in.) prisms with 76.2-mm (3-in.) faces, which were cast with four 6.35-mm (0.5-in.) parallel longitudinal holes, were shown to accelerate ASR and to lower the coefficient of variation of the expansion data. The expansions of 76.2-mm (3-in.) concrete cubes were found to be greatly accelerated, compared with standard prisms. Modified AASHTO T303 and modified ASTM 1293 conditions were found to effectively accelerate ASR in concrete prisms cast with holes. Prisms that were sealed in evacuated plastic bags with water were found to effectively accelerate ASR expansion.

Li and Gress (2006) researched the use of fly ash to mitigate ASR in concrete made with RCA that comes from concrete with a known ASR history. Modified ASTM C 1260 and C 1567 with different aggregate grading showed that a 25% cement substitution with a Class F fly ash controlled the expansion under 0.10% at 28 days. Pore solution and thermal gravimetric analysis revealed both calcium hydroxide and alkalis are reduced by fly ash substitution. Calcium depletion alone is a sufficient condition for ASR arrest, but the substitution level, depending on the portland cement, can be as high as 60% and unusable in field concrete. Approximately 25% fly ash substitution was required to lower the pH to a range of 13.28 to 13.32, a presumed ASR threshold range. The effect of alkali reducing appears to be more pivotal than calcium consumption. Although alkalis were found to be present in the RCA, it was not shown that it was available to the pore solution. This suggests that alkali concentration in the new paste and the old RCA matrix are approximately equal and therefore in equilibrium with each other.

Bekoe et al. (2010) evaluated the feasibility of using RCA in concrete pavement application. Concrete containing 0%, 25%, and 50% RCA was produced in the laboratory and properties vital to the performance of concrete pavement were evaluated. Results from the laboratory testing program indicate that the compressive strength and elastic modulus are reduced slightly as the percentage of RCA increases. The flexural strength, splitting tensile strength, and CTE are about the same for concrete containing virgin aggregate and RCA. The free shrinkage increases slightly as the percentage of RCA increases. With the measured properties, a finite element analysis was performed to determine how the concretes containing the different amounts of RCA would perform if they were used in a typical concrete pavement in Florida. Analysis from the finite element model determined the maximum stresses under critical temperature and load conditions. Potential performance of the pavements was evaluated based on the computed maximum stress to flexural strength ratio. The maximum stress to flexural strength ratio in the pavement was found to stay about the same as the percentage of RCA increases. This indicates that RCA can be used in concrete pavement without affecting its performance.

Rizvi et al. (2010) performed a study to incorporate RCA into pervious concrete. The research methodology involved substituting the coarse aggregate in the pervious concrete with 15%, 30%, 50%, and 100% RCA. Cylinders were cast in the laboratory for each percentage of RCA and a control mix containing only virgin aggregate. Fresh concrete tests were done, and the cylinders were tested for compressive strength, permeability, and void content. Testing showed that pervious concrete containing 15% RCA had strength, permeability, and void content that were very similar to those of the control mix. Samples that contained 30% RCA or greater had a significant loss in strength and increase in permeability and void content. Based on the specific mix design and RCA quality used in this research, the recommendation is that the optimum percentage of RCA in pervious concrete be 15% direct replacement of virgin coarse aggregate.

Roesler et al. (2011) reported on the RCA test pavement constructed by Illinois on I-57 near Effingham (the same project previously studied by Mark Snyder in 2006) constructed between 1986 and 1987. It was a 10-in CRCP. Functional and structural data, including FWD tests, visual distress surveys, surface profiles, and skid numbers were collected periodically throughout the service life of the pavement. FWD results indicated that the pavement section exhibited excellent load carrying, with an average load transfer efficiency greater than 90% across the transverse cracks. The prominent distress was longitudinal cracking, which appeared over the reinforcement bars in all lanes. This abnormal cracking pattern had been noted for many years and had been attributed to problems with the original tube feeding process. The section developed a significant amount of localized distresses and patches over its last 5 years as a result of further deterioration of the longitudinal cracking. A petrographic examination concluded that no deleterious ASR had occurred in the pavement and that the air void system had been normal. The mean transverse crack spacing was approximately 1.5 ft, which was significantly shorter than normal CRCP and was attributed to the greater drying shrinkage potential of recycled concrete aggregate. Functionally, the pavement showed good skid resistance and fair-to-good ride quality. The overall performance of this CRCP section exceeded the performance of roughly 50% of the 10-in. CRCP within Illinois in terms of age and 25% in terms of traffic. In June 2010, this CRCP section was overlaid with 3.5 in. of asphalt concrete.

Butler et al. (2012) performed a study to investigate the effect of coarse aggregate properties on the main mixture proportion parameters (i.e., cement content, water demand, and *w/c* ratio). Four aggregate types were investigated: one control virgin aggregate source and three RCAs produced from the crushing of hardened concrete. Numerous aggregate tests, including density, absorption, abrasion resistance, adhered mortar content, and crushing value, were performed. Fourteen mixture proportions were developed with the use of three mixture proportion scenarios (control, direct replacement, and strength based) and two compressive strength levels (40 and 60 MPa). The effect of RCA on compressive strength and workability was evaluated by replacement of natural coarse aggregate with RCA. Contrary to numerous studies, one of the RCA concretes had compressive strengths up to 12% higher than the equivalent control mixture. Mixture proportions (water, cement, and *w/c* ratio) were later adjusted to ensure that the RCA concretes had compressive strength and slump values similar to the control concretes. Variations in water demand, cement content, and *w/c* ratio could then be directly attributed to the properties of the RCA source. One of the RCA concrete required less cement (and a higher *w/c* ratio) to achieve strengths and slumps similar to the control concrete.

Butler et al. (2013) present guidelines for using RCA as a full or partial replacement for natural coarse aggregate in new concrete. Several international standards and guidelines for the use of RCA in concrete are reviewed and contrasted to identify areas in which further development is required. The main results of an extensive experimental research program by the authors are summarized to provide a basis for the development of a framework for using RCA in structural concrete. Several RCA performance classes are proposed, each with a specific set of requirements and suitable applications. The proposed performance classes define further requirements and guidance for the use of RCA beyond the requirements of Canadian Standards Association A23.1 and ASTM C33. The authors propose a detailed decision tree to allow engineers, concrete producers, aggregate suppliers, and contractors to assess whether a particular RCA source is suitable for use in reinforced concrete or plain concrete or as fill material.

According to one report, RCA will reduce the CTE of concrete (Smith and Tighe 2009). This would result in a performance increase of concrete because there would be less expansion and shrinkage with temperature change.

CHAPTER 2: LONG-TERM PERFORMANCE OF RCA PAVEMENTS

Sustainability practices dictate that, whenever possible, materials should be recycled and reused. In fact, the American Society of Civil Engineers Code of Ethics Canon 1 requires civil engineers to consider sustainability in any design. In addition, studies indicate that the natural aggregate resources in the Twin Cities area are being rapidly depleted or built upon, and thus should be conserved by using alternative materials when possible. The Minnesota Department of Transportation is quite progressive in this regard and allows the use of recycled concrete, asphalt, glass, and brick in various applications. Although in Minnesota, as well as in all other states in the US, the primary use of recycled concrete aggregate (RCA) is in base courses, there are a number of pavements in the Minnesota network as well as some cells in the MnROAD test facility which contain RCA as a primary aggregate. However, the long-term performance of such sections has not been formally evaluated against the performance of similar conventional concrete pavements.

In Chapter 1, the state-of-the-practice regarding the use of RCA in concrete pavements was determined through various past and recent surveys of State DOT's in addition to a general literature review including both American and European literature. Although 23 states reported using RCA in pavements in one survey or another, upon further inspection it was found that many of them may allow the use of RCA in PCC pavements but have never built one or else have built a limited number (often just one) project. It appears that in the time period between the late 1970's to the mid 1990's many projects (more than 100) were built, but this activity has significantly slowed down since. Tracking the history of the states who were most active in building projects we find that Michigan (who built the most number of projects) placed a moratorium on using RCA in PCC pavements in 1991. It is now only allowed in lower-risk applications such as curb and gutter, sidewalks, barriers etc. Michigan experienced some problems with mid-slab transverse cracking, but most of this was attributed to design features rather than the RCA itself. In Wisconsin, contractors are electing to use RCA in the base and shoulders, not in the pavements. Iowa indicated the majority of their trial projects were built by counties rather than the DOT. They noted some mid-slab transverse cracking, and now the RCA is mainly used in the base.

Among the most active states in using RCA in PCC pavements it might be said that Minnesota currently has the most favorable outlook. Among the issues noted by Minnesota, were the extra cost of washing the aggregates, and maintaining a water-cement ratio of 0.40. Minnesota built trial sections of composite RCA pavements using the two-lift approach at the MnROAD test facility in 2010.

No previous work was found where the long-term performance of RCA sections was formally evaluated against conventional concrete sections based upon a large database. A few reports exist where field evaluations including petrographic analyses of a limited number of RCA pavements were performed and sometimes compared to a control. For example in the work of Mark Snyder et al. 1994 and 2006, the performance of RCA pavements seemed to be relatively good. In cases where more cracking was observed relative to a control, it was mainly attributed to the reclaimed mortar content. Another potentially significant demerit of using RCA as suggested by Snyder may be a deficiency in aggregate interlock due to a number of factors including.

- The smaller sized coarse aggregate common with RCA requires only small crack openings to effectively lose all of their grain interlock.

- The use of recycled aggregate reduces the number of natural aggregate particles at the crack face which have a much greater load transfer capability.
- The poor abrasion resistance of the paste portion of the RCA results in greater and more rapid losses of load transfer than when conventional coarse aggregates are used.

In addition to these main points, researchers have extensively studied various mechanical properties of RCA concrete which could potentially lead to a difference in performance.

There are a significant number of projects in Minnesota consisting of concrete pavements made with recycled concrete aggregate (RCA). These pavements were constructed during the 1980s and 1990s and most of them are still in service. Performance data have been collected for these pavement sections by the Minnesota Department of Transportation (MnDOT) on a regular basis. The objective of this portion of the project was to evaluate the performance data and determine if there is any statistically significant difference between the performance of pavements containing RCA and concrete pavements constructed with regular aggregate. In addition, the data available for the MnROAD Test Cells 70, 71, and 72 that were built using the two-lift process in 2010 was examined.

2.1 METHODOLOGY

First, a list of all RCA projects was developed by manually searching the Concrete Pavement Evaluation System (COPES) for all instances of the word “Recycled” under aggregates. A second source of information was the reports from previous studies conducted by Mark Snyder et al. in 1994 and 2006. In some instances some discrepancies were noted where a pavement was identified by COPES as containing RCA but not Snyder and vice versa. Table A1 of the Appendix gives the list of RCA Pavements together with information about the thickness, joint spacing, maximum aggregate size, and concrete mix design. Figure A1 in the Appendix shows a map of the RCA locations. A total of 219.2 miles of RCA pavements were identified in this step.

The next step was to evaluate the available pavement performance data for the RCA sections. The total number of miles for which data were obtained was 211.934. The following performance measures were available:

2.1.1 International Roughness Index (IRI)

An objective measure of the roughness of the pavement is obtained through the International Roughness Index (IRI) measured by the front lasers on a specially equipped MnDOT van. This simulates a standard vehicle traveling down the roadway and is equal to the total anticipated vertical movement of this vehicle accumulated over the length of the section. The IRI is typically reported in units of inches/mile (vertical inches of movement per mile traveled). The higher the IRI is, the rougher the roadway.

2.1.2 Ride Quality Index (RQI)

The IRI is converted to a Ride Quality Index through a regression equation which is intended to capture a typical road-user's perception of the level of comfort in driving over a pavement section. The RQI can be calculated for concrete pavements using the following equation (Janisch 2006):

$$RQI = \begin{cases} 6.634 - 0.353\sqrt{IRI} & \text{IRI in in/mi} \\ 6.634 - 2.813\sqrt{IRI} & \text{IRI in m/km} \end{cases} \tag{1}$$

The RQI is on a scale of 0 to 5 with 5 being excellent. Pavements are normally designed for a terminal RQI of 2.5. Once the RQI has reached 2.5, this generally signifies that a major Concrete Pavement Rehabilitation (CPR) must be performed. The RQI is used as the primary indicator of the condition of MnDOT's pavements in its Pavement Condition Annual Report, and is also the basis for predicting the remaining service life of a pavement.

2.1.3 Surface Rating (SR)

Surface Rating (SR) is used as the indicator for pavement distress. It varies between 0 to 4 with 4 being excellent. For jointed concrete pavement, the distresses which are considered include transverse joint spalling, longitudinal joint spalling, faulted joints, cracked panels, broken panels, faulted panels, overlaid panels, patched panels, and D-cracked panels. The percentage of each distress in a 500-foot sample is determined and multiplied by a weighting factor to give a weighted percentage. The weighting factors are higher for higher severity levels of the same distress and higher for distress types that indicate more serious problems exist in the roadway such as alligator cracking and broken panels. Once all of the weighted percentages are calculated, they are summed to give the Total Weighted Distress (TWD). The SR is then calculated as follows (Janisch 2006).

$$SR = e^{(1.386 - 0.045TWD)} \tag{2}$$

2.1.4 Pavement Quality Index (PQI)

Pavement Quality Index (PQI) is the index that attempts to provide an overall condition rating based on both ride quality and distress. It ranges between 0 to 4.5 with 4.5 being excellent. The PQI can be calculated using (Janisch 2006).

$$PQI = \sqrt{RQI \times SR} \tag{3}$$

While all four indexes were tracked, the RQI was the main index of interest in this study. The RQI is used to report MnDOT's network pavement performance. An RQI value of 2.5 is one of the triggers for pavement management decisions on when to rehabilitate a section. While distresses can also necessitate a pavement rehabilitation and influence the selection of the appropriate treatment, it was found that SR did not change as rapidly as RQI, often still being close to 4.0 when the RQI had deteriorated to 2.5. In Figures 3 and 8 where the three indexes (RQI, PQI, and SR) are plotted for RCA and non-RCA sections respectively, it can be seen that the RQI curve sits below the SR curve. On average, it appears that the RQI deteriorates faster and is more likely to reach trigger levels sooner. Thus, RQI was the primary index used for the modeling discussed later in the report. Also, it should be noted that rehabilitation activities are not necessarily triggered by pavement condition. Corridor-wide improvements and new alignments may sometimes override a condition based intervention.

2.2 MISSING DATA AND NON-CORRESPONDING DATA

Pavement condition data were regularly collected on an annual basis since 2000 and 2001; however, prior to that it was common to find missing intermediate data points. Since RQI was the most frequently reported data, linear interpolation between surrounding points was used to fill in the missing data points. When RQI data was missing at the beginning of the series, linear extrapolation based on the three subsequent readings was used. This scheme was also used for apparently non-corresponding data. For example, say the first year reading shows 2.1 while the second year data shows 3.6, the most plausible explanation is that the first reading is a remnant from the old concrete pavement and therefore this data point would also be replaced by extrapolation. In other words, a reading had been taken earlier that year on the old concrete pavement, but no subsequent reading was taken that same year on the new pavement that was constructed later that year. Because the most infrequently reported measure was SR, it was decided to interpolate and extrapolate values of PQI similar to the RQI scheme and then calculate SR from Equation 3. The reason for SR being reported less frequently is that it is only determined on about 60% of the network on an annual basis due to limited manpower. Any missing values of IRI were back-calculated using Equation 1.

After obtaining the data for RCA sections, a similar database was obtained for non-RCA sections. Because pavement performance may vary by the time period of construction due to changes in specifications, techniques etc. it was decided to evaluate only new concrete construction built during the 1980s and 1990s. This resulted in a database of about 459 miles. The dataset was then further reduced by excluding pavements with AADT in excess of about 90,000 or less than 2,000 thus keeping the range of AADT approximately the same as that of the RCA dataset. This resulted in a database of about 391 miles. In order to keep the dataset manageable, the size was truncated to 211.752 miles, roughly the same size as the database for RCA sections. Random sampling was performed by assigning numbers to each section and then using the RAND() function in Excel to sort the data. During this process, seven sections (totaling 3.1 miles) were found to have apparent zero service lives i.e. they start out below RQI of 2.5 and never improve beyond that during the time of record. These sections were considered to be anomalies and were not selected as part of the final random sample.

Both datasets, i.e. the RCA and non-RCA, were analyzed to determine the time required to reach RQI of 2.5. Because fluctuations were often observed e.g. a section could go from RQI of 2.5 back to 2.7, the time to reach the first major CPR was taken as the point where the pavement's RQI had been less than or equal to 2.5 for three consecutive years. In many instances, a pavement had not reached the terminal RQI during the observed period of time. In other cases a pavement may have been rehabilitated before reaching RQI of 2.5. For these situations, it became necessary to forecast the time to reach RQI of 2.5. Two different methods were used namely exponential smoothing or exponentially weighted moving average (EWMA), and autoregressive integrated moving average (ARIMA). A conservative approach was taken and the smaller of the two predictions was used as the controlling value. In addition, an upper limit of 60 years was implemented; that is, if the prediction exceeded 60 years it was deemed unrealistic and the recorded value was 60 years.

The analytic methods used include exponential smoothing, ARIMA, and Markov:

2.3 EXPONENTIAL SMOOTHING

The triple exponential smoothing approach for forecasting can be summarized by:

$$s_t = \alpha \frac{x_t}{c_{t-L}} + (1-\alpha)(s_{t-1} + b_{t-1}) \tag{4}$$

$$b_t = \beta(s_t - s_{t-1}) + (1-\beta) b_{t-1} \tag{5}$$

$$c_t = \gamma \frac{x_t}{s_t} + (1-\gamma) c_{t-L} \tag{6}$$

$$F_{t+m} = (s_t + m b_t) c_{t-L+m} \tag{7}$$

Where:

x is the observation,
s is the smoothed observation,
b is the trend factor,
c is the seasonal index,
F is the forecast at *m* periods ahead,
t is an index denoting a time period,
L is the number of periods in a season, and
α, β, γ are constants (that typically range from 0.1 to 0.3) that must be estimated to minimize the mean squared errors.

The exponential smoothing forecast were performed with the statistics software SYSTAT. Additional details about the exponential smoothing method can be found in textbooks (e.g. Washington et al. 2003, Bisgaard and Kulahci 2011).

2.4 ARIMA MODELING

ARIMA models are generally denoted as ARIMA(p,d,q) where *p* is the number of autoregressive terms, *d* is the number of nonseasonal differences needed for stationarity, and *q* is the number of lagged forecast errors in the prediction equation.

First let *y* denote the *d*th difference of *Y*. This means

If d = 0: $y_t = Y_t$ (8)
If d = 1: $y_t = Y_t - Y_{t-1}$ (9)
If d = 2: $y_t = (Y_t - Y_{t-1}) - (Y_{t-1} - Y_{t-2})$ (10)

Then the general forecasting equation is given by

$$\hat{y}_t = a_t + \phi_1 y_{t-1} + \ldots + \phi_p y_{t-p} - \theta_1 a_{t-1} \ldots - \theta_q a_{t-q} \tag{11}$$

where $\hat{y}_t$ is the forecasted value, y is the differenced value of the original data Y, ϕ are the autoregressive parameters, θ are the moving average parameters taken here to be negative following the Box-Jenkins convention, a_t are the error or noise terms, t is an index denoting time and p and q are as defined previously. The modeling process usually begins by examining the degree of differencing required to remove non-stationarity. Next, some decision about the number of autoregressive and/or moving parameters required is made. This can be done by examining the autocorrelation and partial autocorrelation functions, in addition to observing the goodness of fit which can be obtained from software. For this study, the statistics software SYSTAT was used for the ARIMA modeling and the ARIMA(2,1,1) model was found to adequately model the behavior. Additional details about the ARIMA method can be found in textbooks (e.g. Washington et al. 2003, Bisgaard and Kulahci 2011).

2.5 MARKOV MODEL

The Markov model considers events to be correlated with the immediately preceding event. A classic example is that the probability of a certain type of weather e.g. rainy on any given day is dependent on the type of weather on the previous day e.g. rainy, sunny, snowy. Some researchers have used this concept in the pavement management field (Chou et al. 2008, Wang et al. 1994). First a finite number of condition states must be defined. For this project, five states were chosen as shown in Table 6.

Table 6. Condition States Based on RQI for Markov Model

Condition State	RQI Range	Approximate MnDOT Descriptive Category
1	≥ 4.1	Very Good
2	3.6 – 4.0	Good
3	3.1 – 3.5	Good
4	2.6 – 3.0	Fair
5	≤ 2.5	Poor to Fair

All of the obtained RQI values from the MnDOT databases were placed in their respective condition state. The sum of the miles in each condition state was then determined. The next step was to determine the probabilities of transitioning from one condition state to another. For this purpose, the number of miles transitioning from each condition state to another had to be determined. This was accomplished by importing Excel data into MATLAB, and running a MATLAB code. The worst condition state i.e. state 5 was treated as an “absorbing” state. In other words, once a pavement deteriorates to condition state 5, the probability of it returning to a better condition state is taken as zero, therefore the probability of it remaining in state 5 the following year is 1 (or 100%). The transition probabilities i.e. the probability of transitioning from state *i* to state *j* are then calculated using:

$$P_{ij} = \frac{\text{Total Miles from State i to State j}}{\text{Total Miles in State i}} \tag{12}$$

The P_{ij} values can be recorded in a matrix form and this is referred to as the transitional probability matrix. The P_{ij} values are subject to the following constraints

$$\begin{gathered} P_{ij} \geq 0 \text{ for all i and j} \\ \sum_{j=1}^{n} P_{ij} = 1 \text{ for all i} \end{gathered} \tag{13}$$

where n is the total number of condition states.

Since the RQI values are recorded on an annual basis, the transition period is one year; therefore, this is the one-year transition matrix. By multiplying the one-year matrix, predicted condition in future years can be obtained e.g. $P^2 = P \times P, P^3 = P \times P \times P$, etc. A condition matrix, i.e. a matrix showing the proportion of miles in each condition state can be multiplied by the transition matrix to obtain the predicted distribution of conditions in the subsequent years. In many Markov chains, a stationary distribution may be found after a large number of periods, i.e. after many years, the expected condition state distribution will be the same regardless of the initial condition state matrix.

2.6 RESULTS

The RCA sections are listed in order of decreasing time to reach RQI of 2.5 in Table A2 of the Appendix and the corresponding table for non-RCA sections is given in Table A3 of the Appendix. The histogram showing the frequency distribution for RCA sections is presented in Figure 1 together with the probability density function. This diagram is by the number of miles. A similar histogram by the number of observations is shown in Fig A2 in the Appendix. The probability density function shows an approximately normal distribution with a slightly longer and fatter right tail.

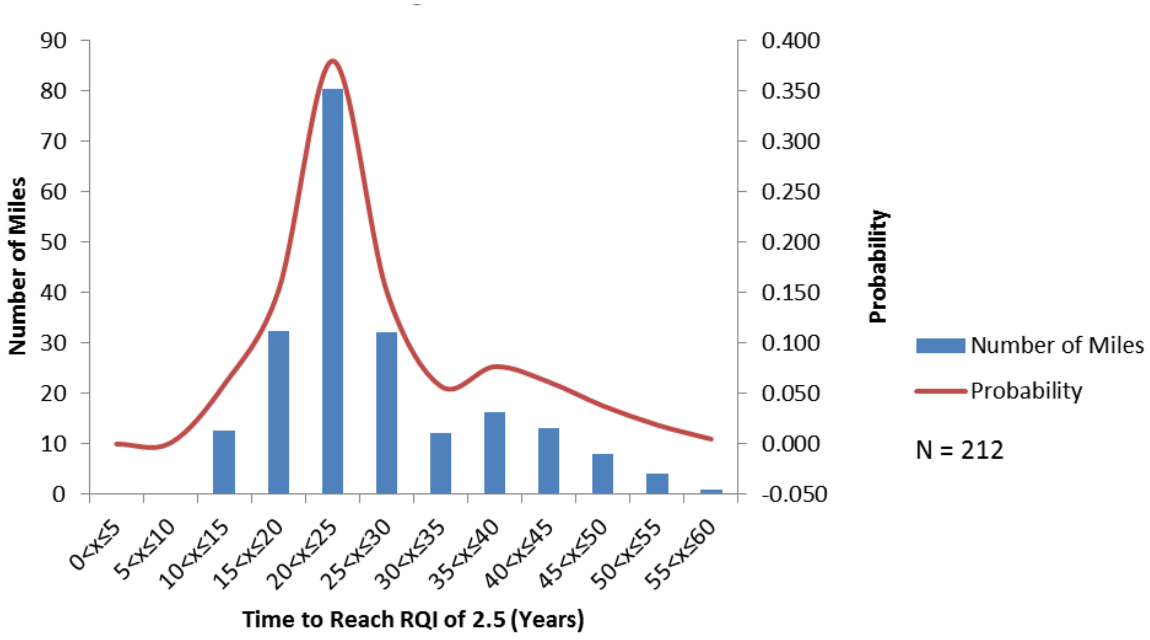

Figure 1. Histogram for time to reach RQI of 2.5 for RCA sections by miles.

The corresponding histogram by miles for non-RCA sections is shown in Figure 2. The histogram by the number of observations for non-RCA sections is shown in Figure A3 in the Appendix. The probability density function show an approximate normal distribution with a fatter right tail. An upturn is seen at the end due to a significant number of pavements with a 60-year time to reach major CPR.

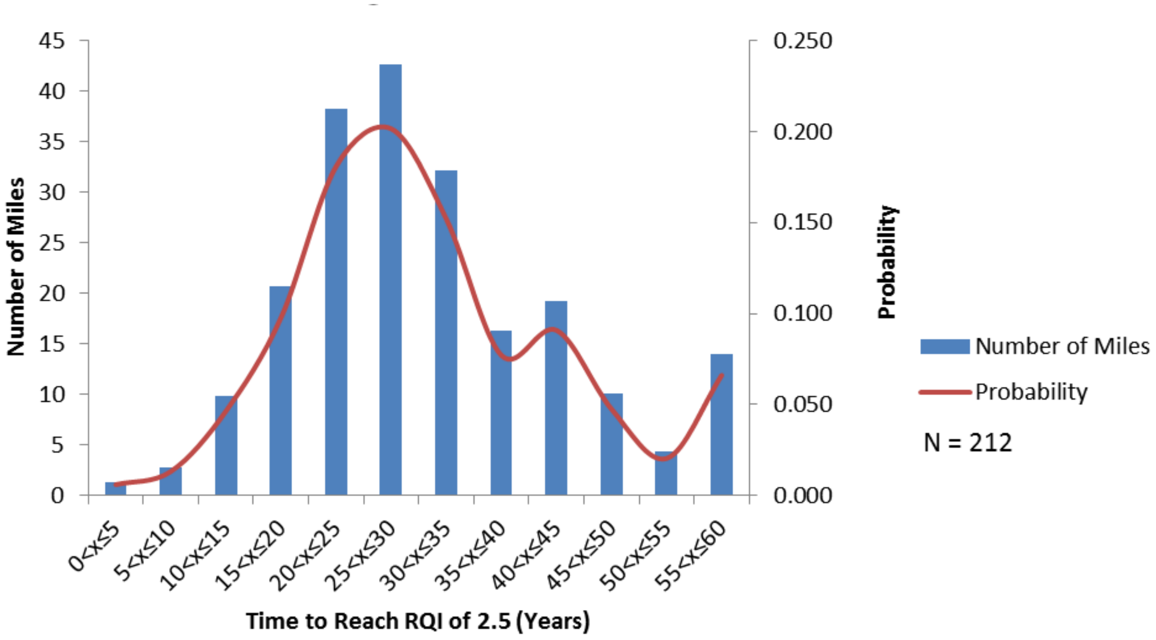

Figure 2. Histogram for time to reach RQI of 2.5 for non-RCA sections by miles.

The summary statistics for RCA sections is presented in Table 7. The time to reach major CPR i.e. RQI of 2.5 or less for at least 3 years ranged between 8 and 60 with a mean of 27. Using the one sided *z*-test for large samples with the sample mean as an estimator of the population mean, and standard deviation of the sample as an estimator for the standard deviation of the population; we are 95% confident that the true mean (population mean) of RCA pavements is larger than 26. We are 95% confident that the true mean is less than 28. Using the two-sided *z*-test, we are 95% confident that the true mean lies between 26 and 28.

The summary statistics for non-RCA sections is presented in Table 3. The time to reach major CPR ranged between 5 and 60 with a mean of 32. Using the one sided *z*-test for large samples with the sample mean as an estimator of the population mean, and standard deviation of the sample as an estimator for the standard deviation of the population; we are 95% confident that the true mean of non-RCA pavements is larger than 30. We are 95% confident that the true mean is less than 33. Using the two-sided *z*-test, we are 95% confident that the true mean lies between 30 and 33.

Table 7. Summary Statistics for Time to Reach RQI of 2.5 (in Years) for RCA Sections

Maximum	60
Minimum	8
Mean by observations	27
Variance by observations	90
Standard deviation by observations	9
Mean by miles	27
Variance by miles	91
Standard deviation by miles	10
Lower 95% CL (one-sided) by miles	26
Upper 95% CL (one-sided) by miles	28
Lower 95% CL (two-sided) by miles	26
Upper 95% CL (two-sided) by miles	28

Notes: 211.934 centerline miles, 231 observations

Table 8. Summary Statistics for Time to Reach RQI of 2.5 (in Years) for non-RCA Sections

Maximum	60
Minimum	5
Mean by observations	30
Variance by observations	152
Standard deviation by observations	12

Mean by miles	32
Variance by miles	148
Standard deviation by miles	12
Lower 95% CL (one-sided) by miles	30
Upper 95% CL (one-sided) by miles	33
Lower 95% CL (two-sided) by miles	30
Upper 95% CL (two-sided) by miles	33

Notes: 211.752 centerline miles, 245 observations

The tests to check if the difference between the population means of RCA and non-RCA sections are real or statistically significant are summarized in Table 9. We are 95% confident that the difference in means ($\mu_{\text{non-RCA}} - \mu_{\text{RCA}}$) will be more than 2.35 years. We are 95% confident that the difference in means will be less than 6.51 years. Both interval limits are positive, so this implies that the non-RCA sections have a higher time to reach major CPR i.e. perform better than RCA sections. Finally, hypothesis testing was performed. The null hypothesis $H_o : \mu_1 - \mu_2 = D_o$ was set up as $H_o : \mu_{non-RCA} - \mu_{RCA} = 0$

That is the null hypothesis was that there is no difference between the population means. The z-test statistic is

$$\frac{\mu_1 - \mu_2 - D_o}{\sqrt{\frac{\sigma_1^2}{n_1} + \frac{\sigma_2^2}{n_2}}} \tag{14}$$

This results in a test statistic of 4.2. Since this exceeds $z_{0.025}$ which is 1.96, we can reject the null hypothesis at the 5% significance level. That is, the evidence suggests that the difference between the means is real, and the RCA sections performance is worse compared to the non-RCA sections. A Kolmogorov-Smirnov test was performed to check if the distributions of the two sample sets (using data by the number of observations) were similar. The null hypothesis is that the distributions are the same. The computed D-statistic was 0.227, while the D-critical value at a 95% confidence limit with sample sizes of 231 and 245 is 0.123. Since the D-statistic is greater than D-critical we reject the null hypothesis and conclude that the distributions are not similar.

Table 9. Significance Test for Difference in RCA and non-RCA Section Means

Lower 95% CL for ($\mu_{\text{non}} - \mu_{\text{RCA}}$)	2.35
Upper 95% CL for ($\mu_{\text{non}} - \mu_{\text{RCA}}$)	6.51
H_o: $\mu_{\text{non}} - \mu_{\text{RCA}} = 0$ test statistic	4.2
$z_{0.025}$ (5% SL)	1.96
Result	Reject Null Hypothesis, i.e. there is a real difference in mean time to reach RQI of 2.5 between non-RCA and RCA sections

The average index value by years for RQI, SR, and PQI for RCA sections are shown in Figure 3. As expected there is a trend of deterioration i.e. the values decrease with time. The data show a definite upturn around 23 years or so. This is due to the influence of a large enough number of major CPR taking place and improving the index value, thus causing the average to move higher. For this reason, the individual indexes are plotted again in Figures 4 to 6 up to 22 years only. Figure 7 shows the average IRI value over time. Note that a simple linear regression equation as shown in Figure 4 predicts the average time to reach RQI of 2.5 or less for three consecutive years is 30 years.

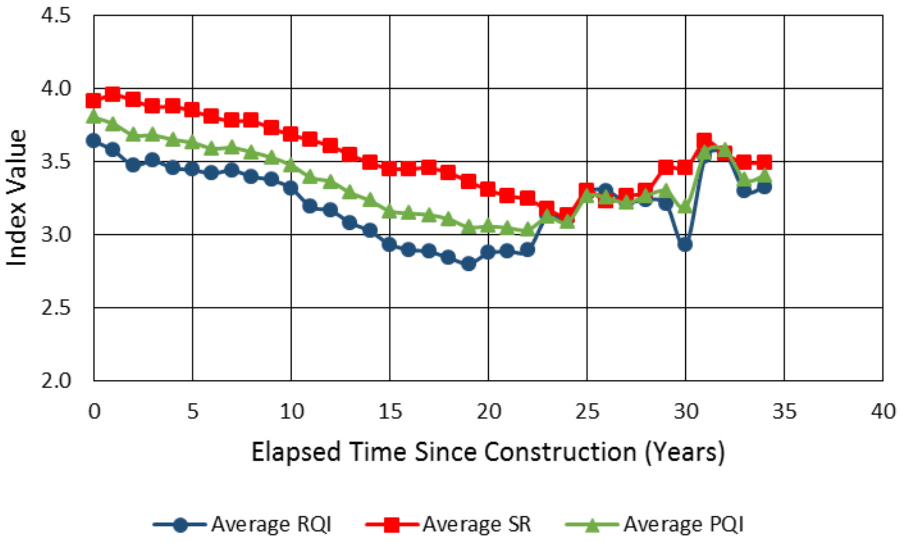

Figure 3. Average index values of RQI, SR, and PQI for RCA sections over time.

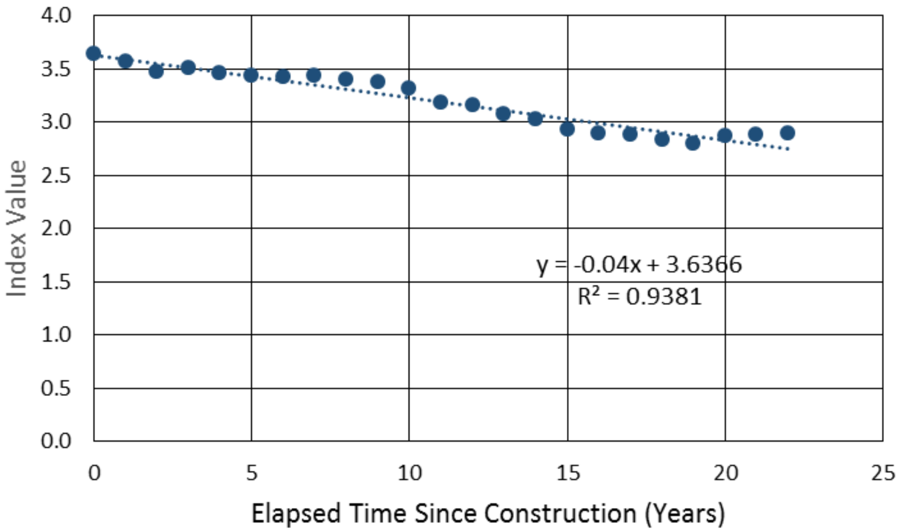

Figure 4. Average RQI value for RCA sections over time.

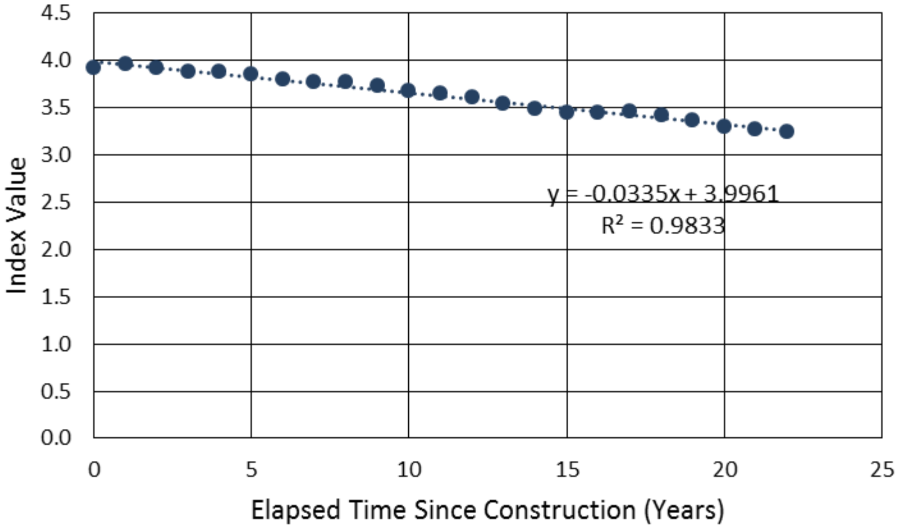

Figure 5. Average SR value for RCA sections over time.

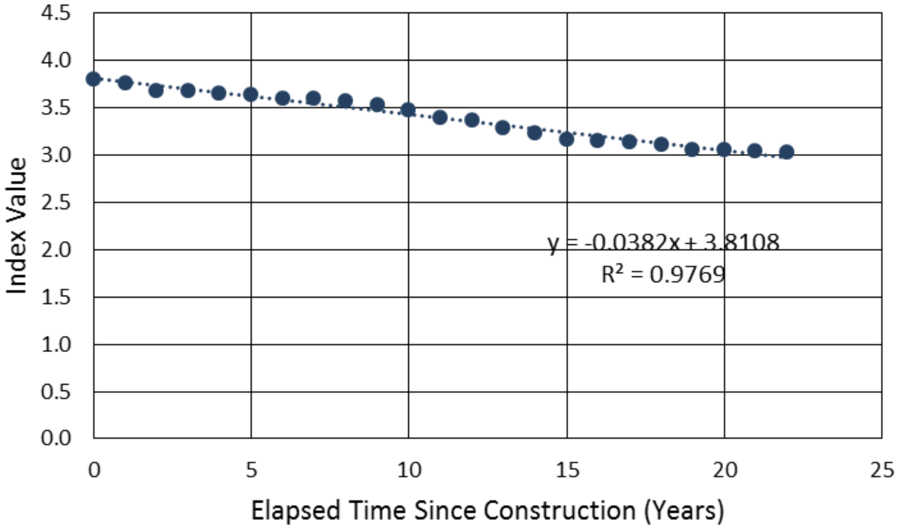

Figure 6. Average PQI values for RCA sections over time.

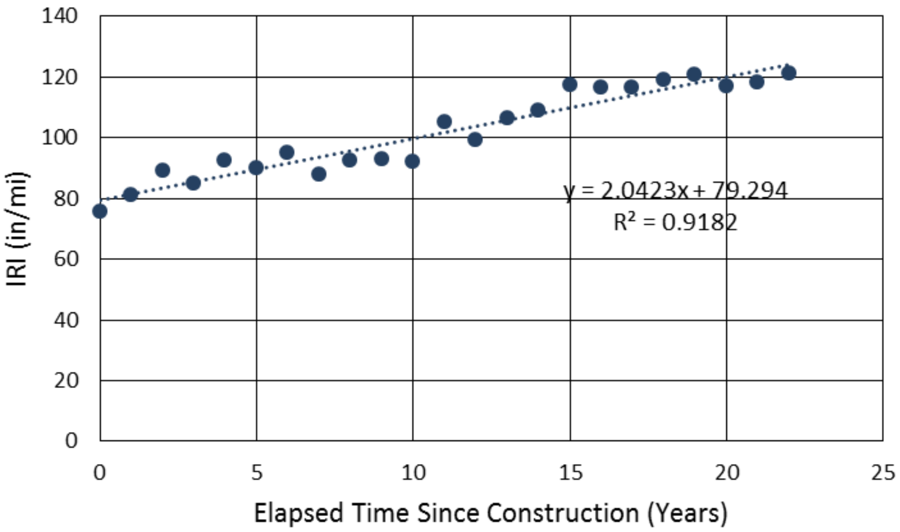

Figure 7. Average IRI for RCA sections over time.

The average index value by years for RQI, SR, and PQI for non-RCA sections are shown in Figure 8. As expected there is a trend of deterioration i.e. the values decrease with time. The data show somewhat of an upturn around 28 years or so. This is due to the influence of a large enough number of major CPR taking place and improving the index value, thus causing the average to move higher. For this reason, the individual indexes are plotted again in Figures 9 to 11 up to 27 years only. Figure 12 shows the average IRI value over time. Note that a simple linear regression equation as shown in Figure 9 predicts the average time to reach RQI of 2.5 or less for three consecutive years is 37 years.

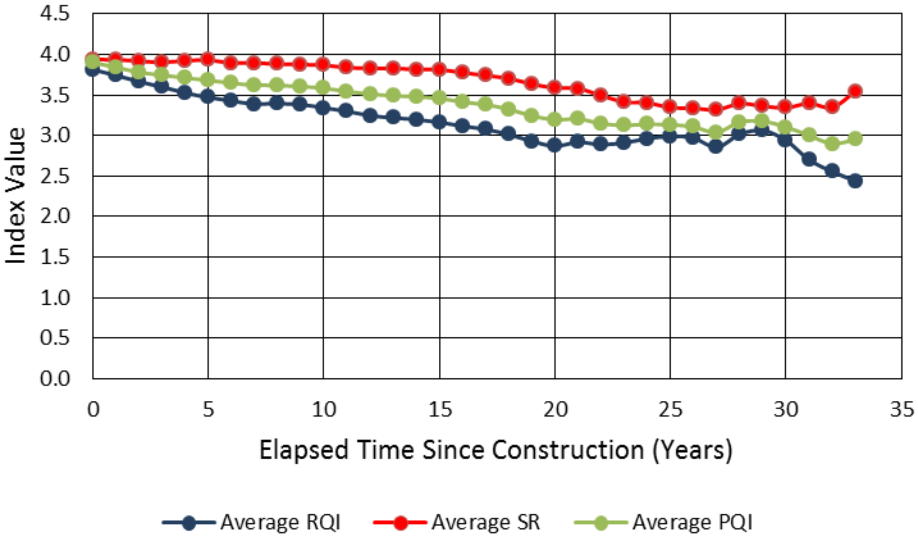

Figure 8. Average index values of RQI, SR, and PQI for non-RCA sections over time

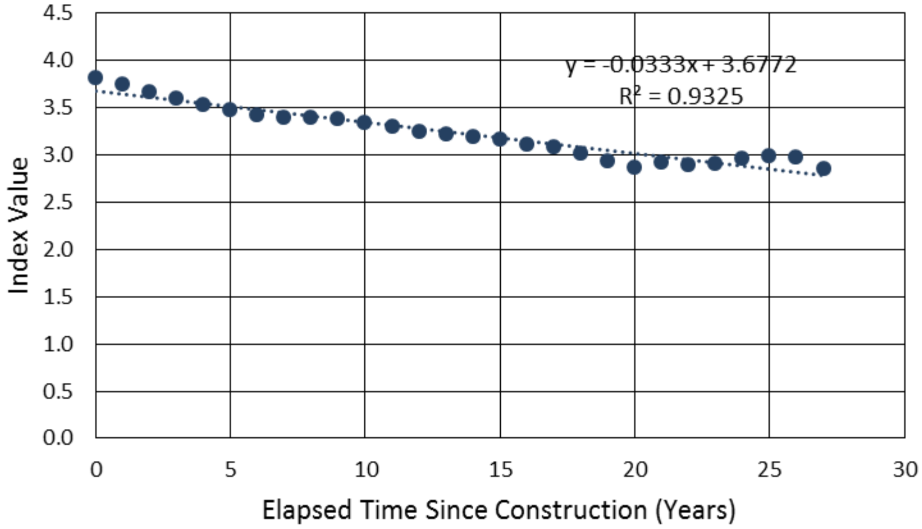

Figure 9. Average RQI value for non-RCA sections over time.

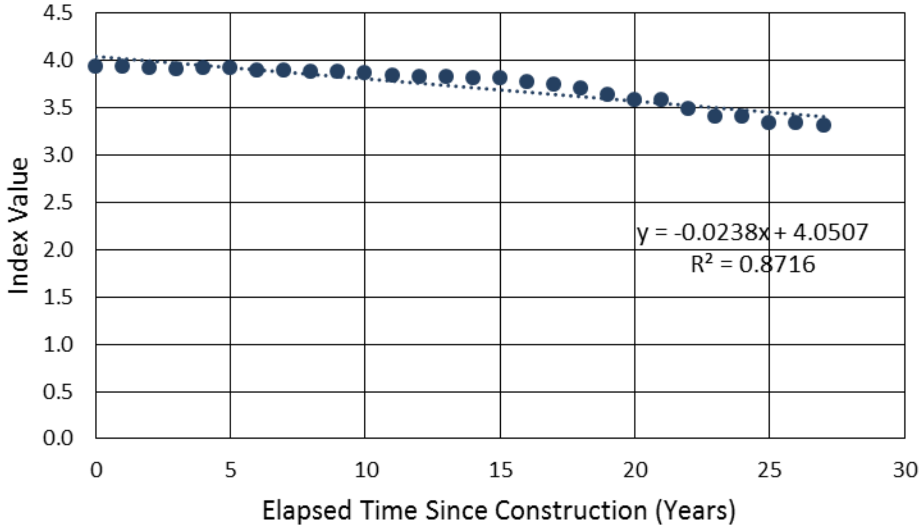

Figure 10. Average SR value for non-RCA sections over time.

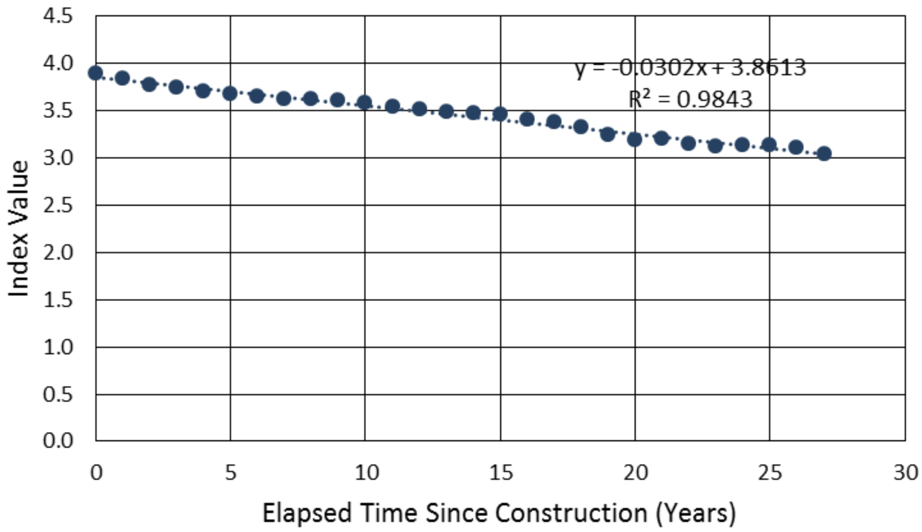

Figure 11. Average PQI value for non-RCA sections over time.

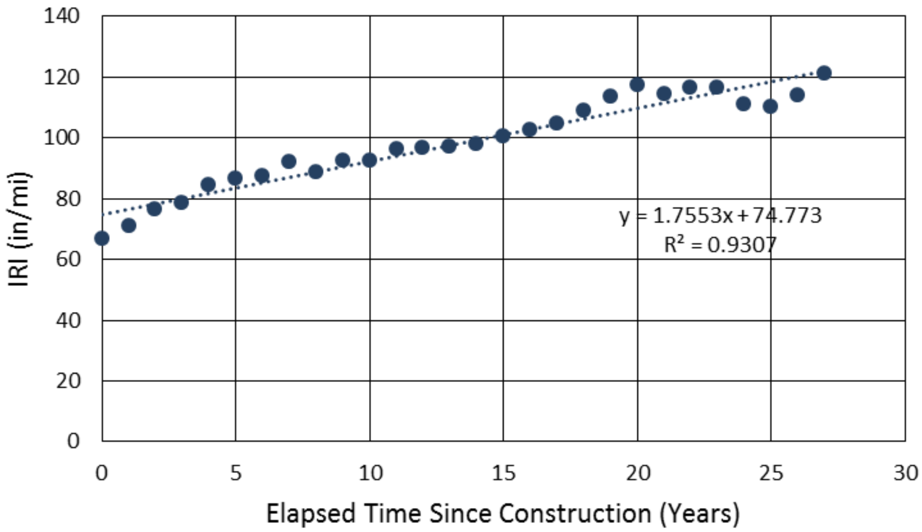

Figure 12. Average IRI for RCA sections over time.

In order to develop the Markov transitional probability matrix for RCA sections, first the number of miles transitioning from one state to another had to be counted. The results are given in the matrix below. Note that the worst condition state i.e. state 5 was treated as an absorbing state so all instances of state 5 are recorded in the last element (5,5).

$$\begin{bmatrix} 50.099 & 64.516 & 8.727 & 0 & 0 \\ 22.065 & 1001.6 & 409.304 & 10.678 & 0.932 \\ 8.292 & 277.198 & 1400.2 & 332.899 & 6.768 \\ 2.931 & 43.379 & 169.085 & 796.763 & 193.342 \\ 0 & 0 & 0 & 0 & 576.519 \end{bmatrix}$$

The one-year transitional probability matrix for RCA sections was then developed as shown. The interpretation of these numbers can be illustrated as follows. For example, if we consider the second row of the matrix; if a pavement section is currently in condition state 2, in the next year the probability that it will improve back to state 1 is 1.5% (0.015); the probability that it will remain in state 2 is 69.3% (0.693); the probability that it will deteriorate to state 3 is 28.3% (0.283); the probability that it will go directly to state 4 is 0.7% (0.007); and the probability that it will go directly to state 5 is 0.06% (0.0006).

$$P = \begin{bmatrix} 0.40618 & 0.523066 & 0.070754 & 0 & 0 \\ 0.015274 & 0.693351 & 0.283338 & 0.007392 & 0.000645 \\ 0.004094 & 0.136864 & 0.691335 & 0.164366 & 0.003342 \\ 0.002431 & 0.035984 & 0.140261 & 0.66094 & 0.160383 \\ 0 & 0 & 0 & 0 & 1 \end{bmatrix}$$

By multiplying a condition matrix by the transitional probability matrix, the expected condition distribution in the subsequent year can be established. For example, the initial condition matrix for RCA sections is given below. It simply shows the percentage of RCA pavements in each condition state in their initial year of construction. For example, 21.5% of pavement miles were in state 1, 43.2% were in state 2 etc. By multiplying the percentages by the midpoint RQI of each state, an average RQI can be computed. For the initial condition matrix, the average RQI is 3.7.

$$C_0 = \{0.215706 \quad 0.432177 \quad 0.253288 \quad 0.087806 \quad 0.011022\}$$

By multiplying the initial condition matrix by the transitional probability matrix, we obtain the expected condition distribution in the 1st year after construction. The average RQI is 3.5.

$$C_1 = \{0.095467 \quad 0.450305 \quad 0.325137 \quad 0.102861 \quad 0.02623\}$$

To obtain C_2 we multiply C_1 by P^2 and so on and so forth. The average RQI is 3.4.

$$C_2 = \{0.047236 \quad 0.410356 \quad 0.373549 \quad 0.124755 \quad 0.044104\}$$

The Markov model approaches a stationary distribution after a large number of years; that is, the condition matrix will no longer change significantly and would not depend on the initial condition matrix. For example the 36th year condition matrix for RCA sections finally gives an average RQI of 2.5.

$$C_{36} = \{0.002952 \quad 0.068701 \quad 0.105571 \quad 0.06019 \quad 0.762586\}$$

In Figure 13, the actual average RQI variation for RCA sections is plotted together with the Markov predicted average RQI. Good agreement between the two can be seen. In Figure 14, the probabilistic behavior curves for each condition state can be seen. This curve can be formed starting with an initial condition matrix (1,0,0,0,0) for state 1, (0,1,0,0,0) for state 2 etc. The percentage of pavement miles for the given state in subsequent years is then tracked. For example, by observing Figure 14 it can be said that if we started with 100 miles in state 1, after one year in service, only about 40 would remain in state 1. After two years, only about 17 would remain in state 1; after three years, only about 8 would remain in state 1 etc.

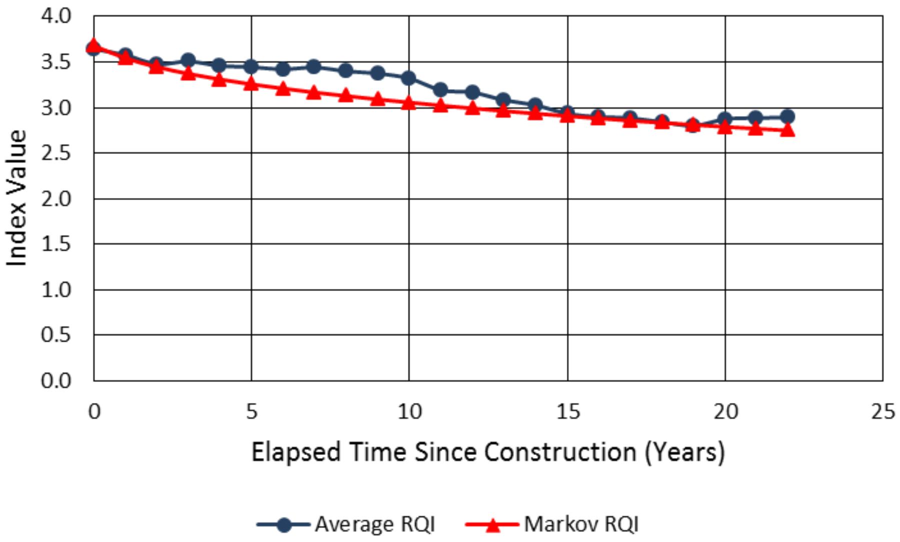

Figure 13. Actual and Markov predicted average RQI values for RCA sections.

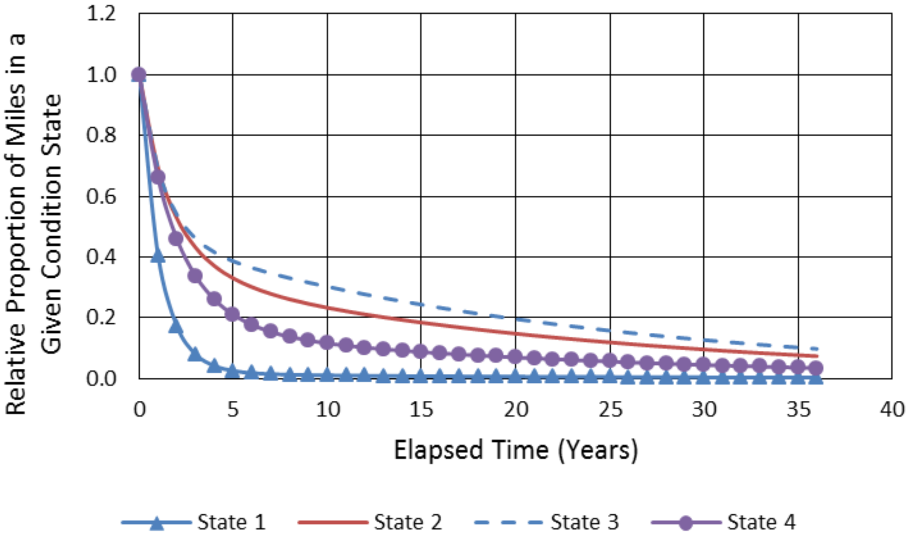

Figure 14. Markov probabilistic behavior curves for RCA sections.

In order to develop the Markov transitional probability matrix for non-RCA sections, first the number of miles transitioning from one state to another had to be counted. The results are given in the matrix below.

$$\begin{bmatrix} 183.457 & 110.284 & 7.919 & 0 & 0 \\ 50.99 & 1069.3 & 336.561 & 8.663 & 0.932 \\ 2.942 & 179.03 & 1327.1 & 253.608 & 2.404 \\ 3.178 & 25.799 & 121.417 & 748.376 & 100.955 \\ 0 & 0 & 0 & 0 & 343.619 \end{bmatrix}$$

The one-year transitional probability matrix for non-RCA sections is given below

$$P = \begin{bmatrix} 0.608158 & 0.36559 & 0.026251 & 0 & 0 \\ 0.034771 & 0.729178 & 0.229508 & 0.005907 & 0.000636 \\ 0.001667 & 0.101429 & 0.751862 & 0.14368 & 0.001362 \\ 0.003179 & 0.025806 & 0.12145 & 0.748582 & 0.100983 \\ 0 & 0 & 0 & 0 & 1 \end{bmatrix}$$

The initial condition matrix for non-RCA sections is given below. The average RQI is 3.8. Thus, the non-RCA sections have a slightly better average starting RQI than RCA sections (3.8 vs 3.7).

$$C_0 = \{0.314217 \quad 0.49609 \quad 0.164504 \quad 0.023306 \quad 0.001884\}$$

After one year in service the condition matrix is given below. The average RQI is 3.7.

$$C_1 = \{0.208691 \quad 0.493899 \quad 0.24862 \quad 0.044013 \quad 0.004777\}$$

For comparison with the RCA sections, the 36th year condition matrix for non-RCA sections is given below. The average RQI is 2.7 showing that the non-RCA sections are performing slightly better (2.7 vs 2.5).

$$C_{36} = \{0.011664 \quad 0.10272 \quad 0.173047 \quad 0.114787 \quad 0.597781\}$$

In Figure 15, the actual average RQI variation for non-RCA sections is plotted together with the Markov predicted average RQI for the first 28 years. Good agreement between the two can be seen. In Figure 16, the probabilistic behavior curves for each condition state can be seen. For example, by observing Figure 16 it can be said that if we started with 100 miles in state 1, after one year in service, only about 60 would remain in state 1. After two years, only about 38 would remain in state 1; after three years, only about 25 would remain in state 1 etc. Comparing the probabilistic behavior curves of the non-RCA sections vs the RCA sections it appears that the non-RCA sections deteriorate at a slower rate as a larger proportion of the best condition states (1 & 2) are retained over the first few years.

Finally, an investigation of the effect of AADT, percent trucks, and truck AADT on the time to reach major CPR was performed. Figures A4 to A6 in the Appendix show the time to reach major CPR versus AADT, percent trucks, and truck AADT respectively for RCA sections. The corresponding diagrams for the non-RCA sections are shown in Figures A7 to A9. In all cases, only a weak correlation was found and in some instances, the opposite trend to what might be expected was found i.e. the value of the independent variable (time to reach major CPR) increasing with the dependent variable (e.g. truck AADT in Figure A9).

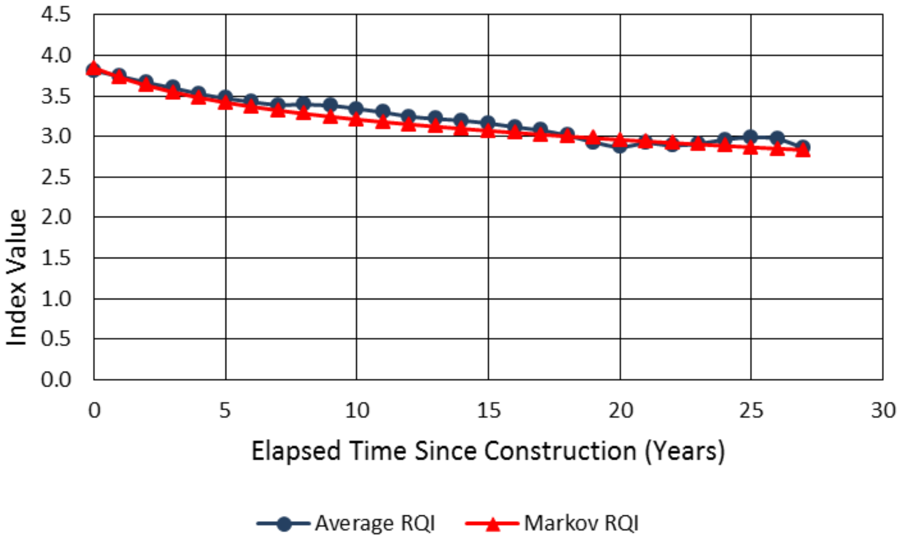

Figure 15. Actual and Markov predicted average RQI values for non-RCA sections.

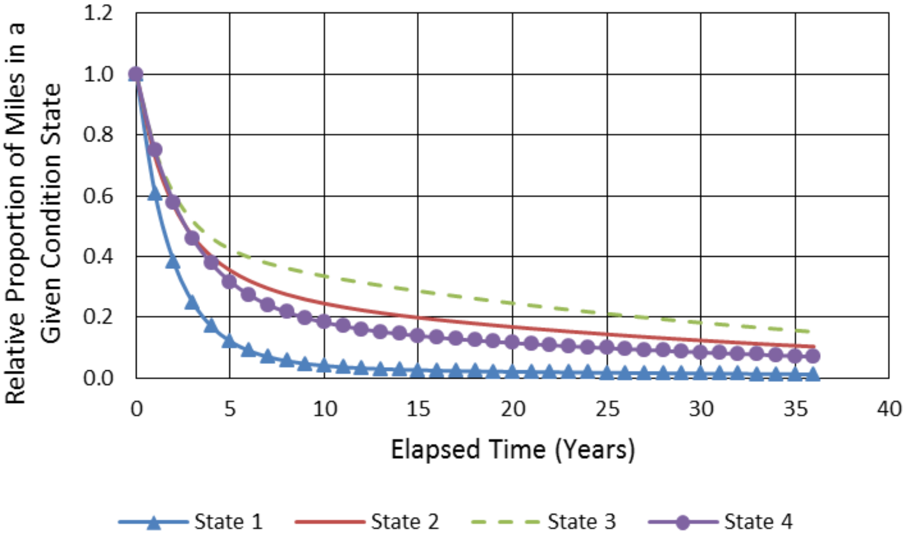

Figure 16. Markov probabilistic behavior curves for non-RCA sections.

2.7 MNROAD SHRP-II CELLS 70, 71, 72

In 2010, three innovative composite test cells were created at the MnROAD test facility. They were constructed using a two-lift procedure. Their construction and early performance are described in detail in Akkari and Izevbekhai 2011. Test cell 70 was created with a hot mix asphalt (HMA) over a recycled aggregate concrete, test cell 71 utilized a diamond grind concrete over a recycled aggregate concrete, and test cell 72 consisted of a exposed aggregate concrete over a low cost concrete (with a low cement content).

Figure 17 shows the average RQI for the three test cells. These were calculated using Equation 1 utilizing the IRI measured with the ROLINE laser on the Lightweight Inertial Surface Analyzer (LISA). Since the cells were only constructed in 2010, sufficient data are not yet available to make an accurate long-term forecast. In general, test cell 70 and 71 appear to be performing well with both test cells possibly showing a very slight decreasing trend. Cell 72 began with a much lower initial RQI and seems to be showing a decreasing trend. There does appear to be some seasonality in the data; however, this is complicated by the fact that the data are not recorded at consistent time intervals. The summer months (June, July) seem to have the highest values. Triple exponential smoothing was performed on the data and the estimates for time to reach RQI of 2.5 or less for three consecutive years were approximately 35 years for cell 70, 17 years for cell 71, and 11 years for cell 72. If the 17 year predicted time holds true for cell 71 then it would be well below the average for regular one lift RCA pavements (27 years).

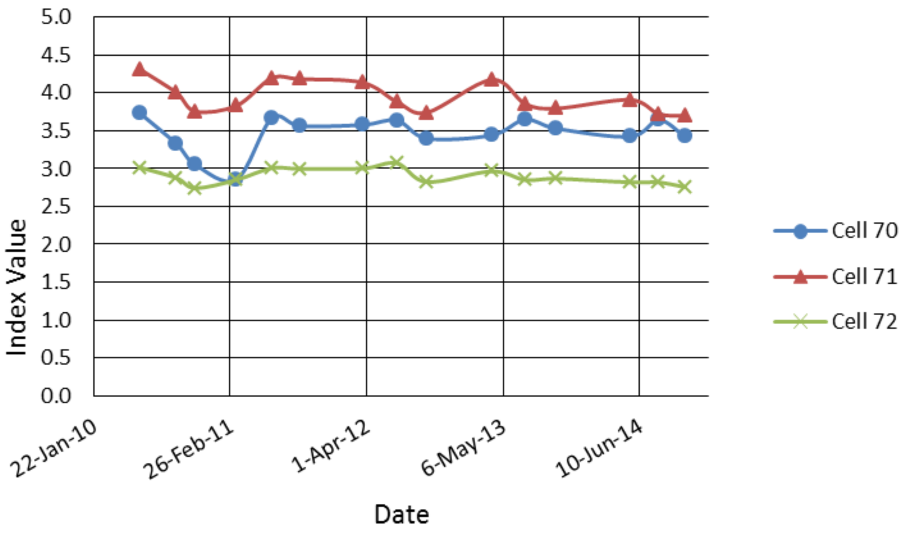

Figure 17. Average RQI for MnROAD test cells 70, 71, and 72.

2.8 CHAPTER SUMMARY

The long-term performance of concrete pavement sections created with RCA was evaluated and compared with that of concrete pavements created with regular aggregates constructed during the same time period (1980’s and 1990’s) and with a similar range of AADT. In the case of RCA sections, the evaluated sample size of approximately 212 miles constituted almost the entire population of RCA sections. In the case of the non-RCA sections, the randomly selected sample of approximately 212 miles also constituted a large sample size. In many instances the pavements had not reached the terminal condition of RQI during the time of record or may have been rehabilitated before reaching that condition. In these cases, the predicted time to reach RQI of 2.5 was obtained by triple exponential smoothing and ARIMA modeling. The mean time to reach the condition of major CPR (i.e. RQI of 2.5) for RCA sections was found to be 27 years and for non-RCA sections was 32 years. The difference in means was found to be statistically significant, i.e. the RCA sections require a major CPR at an earlier age than non-RCA sections.

Markov transitional probability matrices were developed for both the RCA sections and non-RCA sections. Markov predicted average RQI values were found to match the actual average RQI behavior very closely in the first 23 to 29 years or so. Beyond that the actual average RQI tended to be apparently influenced by sections being rehabilitated and therefore dramatically improving the RQI. Also, the Markov model approaches a stationary distribution after a large number of years therefore the predicted deterioration rates will slow down significantly. Nonetheless, the Markov predicted time for average RQI to reach 2.5 was higher for non-RCA sections. In addition, the Markov probabilistic behavior curves indicate a faster rate of deterioration during the initial years for RCA sections than non-RCA sections. This could potentially mean that RCA sections may require minor repairs more often than non-RCA sections.

Some of the hypotheses proposed in the literature that predicted that RCA sections may perform worse than non-RCA sections, as previously discussed in Chapter 1, may be possible explanations. These include poorer abrasion resistance due to the attachment of non-durable mortar around the main aggregate as well as in the recycled fines, and poorer aggregate interlock due to smaller aggregate top size and poor abrasion resistance which may have necessitated techniques such as shorter joint spacing. In addition, it has been reported that due to difficulties with workability during the construction with RCA aggregates in the 1980s and 1990s, additional water may have been added to improve the slump. This was due to the high amount of fines and varying levels of saturation of aggregates. The additional water may have increased the water-cement ratio, thus potentially decreasing the durability of the concrete.

The potential economic implications of RCA sections lasting a shorter amount of time before major CPR as well as possibly more frequent minor repairs compared to non-RCA sections are discussed in Chapter 4.

CHAPTER 3: MATERIALS AND CONSTRUCTABILITY OF RCA PAVEMENTS

This chapter presents the findings of the project team regarding the material properties of recycled concrete aggregate and the constructability of concrete pavements using these aggregates. One of the main concerns is the interaction of mix proportioning and absorption of the recycled aggregate, and the resulting ability of the contractor to maintain the water-cementitious ratio at an appropriate level.

3.1 PHYSICAL PROPERTIES

The material properties evaluated as part of this project included the aggregate properties such as gradation, specific gravity, absorption, and abrasion resistance. These were measured on samples of recycled concrete aggregates with a small amount of asphalt concrete. The RCA was obtained from the Olmsted County State Aid Highway 4 Reconstruction Project near Rochester, Minnesota in 2015. The existing pavement that was crushed into aggregate had been placed in 1976 and conformed to the 1972 MnDOT Construction Specifications for Concrete, and had been in service for about 39 years before being crushed up. For the natural aggregate comparisons, virgin crushed dolomitic limestone aggregates from Northwood, Iowa were obtained from the Cemstone Corporation Ready-mix Plant in Mankato, Minnesota. In addition, for the fine aggregates, a fine river sand from Henderson, Minnesota (Pit No. 72016) was also obtained from the Cemstone Corporation Ready-mix plant.

In addition, nine cores were extracted from pavements in Minnesota which were constructed in the 1980s and early 1990s using recycled concrete aggregates in the pavement layer.

Figure 18. Recycled concrete aggregate (including fines) is obtained from a stockpile.

The materials testing plan included physical tests and gradations of the coarse and fine fractions of each aggregate (defined as retained or passing the #4 sieve, respectively). The tests and associated laboratory procedures used are given in Table 10. Multiple specimens were tested for each material and property to characterize variability in the results. The information in the remainder of this section presents the properties of the recycled concrete aggregate and of the crushed limestone used in the laboratory studies.

Table 10. Materials Testing Plan

	Material Property	MnDOT Laboratory Manual Testing Method
Coarse Aggregate	Specific Gravity and Absorption	1204
	Gradation	1202
	Abrasion Resistance (Los Angeles Rattler)	1210
Fine Aggregate	Specific Gravity and Absorption	1205
	Gradation	1203
	Abrasion Resistance (Micro Deval)	1217

3.1.1 Specific Gravity and Absorption

The specific gravity testing was completed according to MnDOT Lab Manual methods 1204 and 1205 for coarse and fine aggregates, respectively. Table 11 provides specific gravity and absorption information for the recycled concrete aggregate and natural crushed limestone used in the laboratory portion of the study.

Table 11. Coarse Aggregate Specific Gravity and Absorption

	Bulk, SSD		Absorption, %	
	Natural	Recycled	Natural	Recycled
Coarse	2.783	2.468	0.62	3.90
Fine	2.645	2.308	0.84	9.00

One additional study was conducted to determine the observed absorption rate of the coarse recycled concrete aggregates after various periods of soaking time. The MnDOT Lab Manual 1204 requires a soaking time of 48 ±4 hours prior to conducting the specific gravity and absorption testing. However, in a concrete batch plant the aggregates are often in very dry conditions and water for aggregate absorption is introduced at the time of mixing. As can be seen in Figure 19, the “observed” absorption rate increases with time after soaking begins (the time when water is introduced to the container of aggregates) for at least two hours before reaching its maximum value that would be measured after more than 48 hours of soaking. One additional hypothesis was that the process of mixing aggregates in a concrete batch plant could cause a more rapid increase in the observed absorption rate. To address this, a second set of absorption tests were conducted where the aggregates were subjected to agitation in water with a laboratory concrete mixer during the first three minutes of the test. This set of data is also shown in Figure 19, but does not show an increase in observed absorption (in fact, there seems to be a slight decrease at some soak times, but most of these are within the acceptable range of error for absorption tests according to MnDOT Lab Manual 1204).

One important idea from this test is that any additional water included in the batching process to account for aggregate absorption may be present as free water in the paste for several hours before being fully absorbed into the aggregates. These results lend further weight to the recommendations later in this chapter to keep recycled concrete aggregate stockpiles saturated prior to their use in concrete.

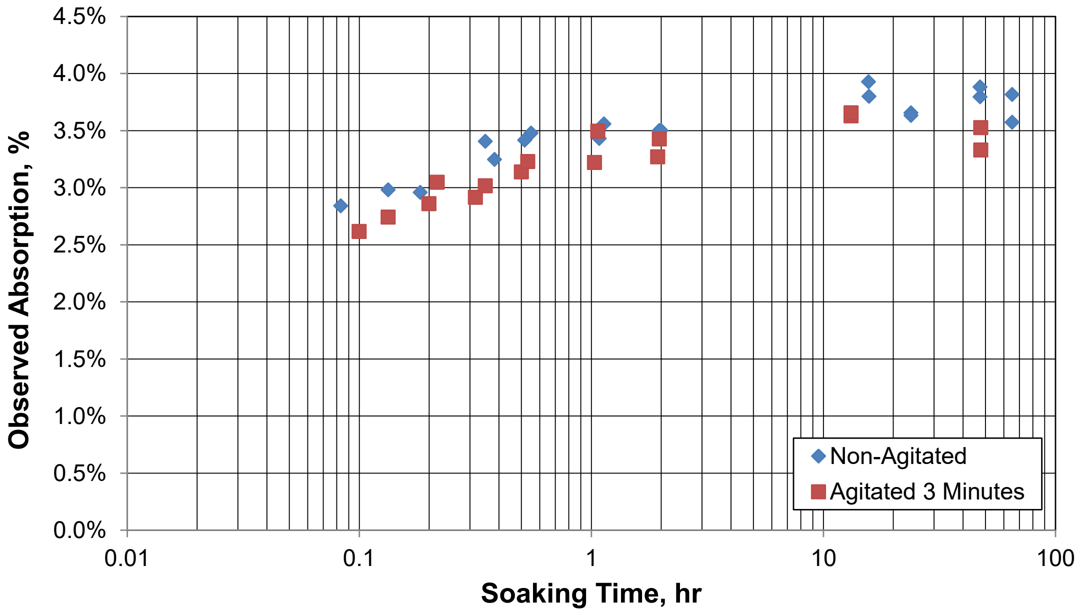

Figure 19. Observed coarse aggregate absorption at various soaking times.

3.1.2 Abrasion Resistance

The results for the LAR and Micro-Deval tests are shown in Table 12. The coarse RCA obtained for the laboratory study lost an average of 41% in the LAR test (MnDOT Lab Manual 1210) which just exceeds the allowable loss according to MnDOT specification 3137 (Coarse Aggregates for Portland Cement Concrete). While the Micro Deval test has not been required by MnDOT for several years, the test was conducted and the results are shown in the table. Various sources indicate levels of acceptable loss in fine aggregates with the Micro-Deval apparatus of 13 to 20 percent (Rogers, 1991, Richard, 1997).

Table 12. Abrasion Resistance of Aggregates Used in Laboratory Study

	Coarse (LAR)		Fine (Micro Deval)	
	Natural	**Recycled**	**Natural**	**Recycled**
Average Percent Loss	25	41	7.7	14.1

3.1.3 Asphalt Content

Another concern when using recycled concrete as aggregate in new concrete is the proportion of asphalt concrete in the crushed material. The samples obtained for the laboratory testing in this project contained about 8% percent asphalt concrete by weight. Assuming that the asphalt mixture included in the RCA is at no more than 6% asphalt cement, the total in the RCA material would be about 0.5%, which is much less than the 1% maximum recommended by the FHWA (2007). In order to investigate if the small amount of asphalt may have any effect on mechanical properties, two identical concrete mixtures containing 100% coarse RCA and a water-cementitious ratio of 0.35 were created. In one of the mixtures, any aggregate that visibly appeared to contain asphalt was discarded manually prior to batching. The results showed that there is little to no difference in the compressive strength and shrinkage strain, thus the effect of the asphalt can be expected to be negligible in this series of experiments.

3.1.4 Gradation

The gradations of the RCA and crushed limestone aggregates (as sampled from the stockpiles) for use in the laboratory study are shown in Table 13 and Figure 20. In the case of the recycled concrete aggregate, the stockpile was being used in base layer construction, and the crushed limestone was taken from the stockpiles of a concrete supplier to the paving industry. For the laboratory study described later in this report, the fine aggregate was used without further processing or grading, and the gradations are reported below. The fine aggregates were separated by size and recombined at a specific gradation reported in the section on the laboratory study.

Table 13. Fine Aggregate Gradation, Percent Retained

Sieve Opening	Natural	Recycled
#4	0.0%	0.0%
#8	8.1%	30.7%
#16	21.2%	19.2%
#30	30.7%	14.8%
#50	22.8%	12.2%
#100	15.5%	6.9%
#200	0.7%	3.8%
Pan	0.2%	10.9%

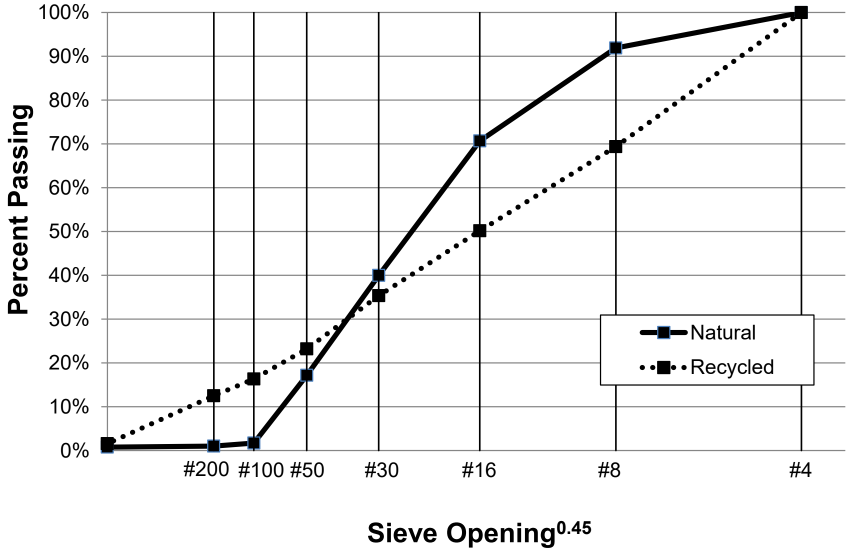

Figure 20. Fine aggregate gradation, as sampled from the stockpile.

The aggregate gradation met the recommendations for optimized graded aggregate or the so-called tarantula curve as shown in Figure 21. Note that for the coarse aggregate sizes (#4 and larger) the aggregates were sieved to ensure the same gradation between the RCA and natural aggregates; however, the fine aggregates were taken as they were without sieving. It can be seen from Figure 21 that the RCA contained finer size particles than the natural aggregates.

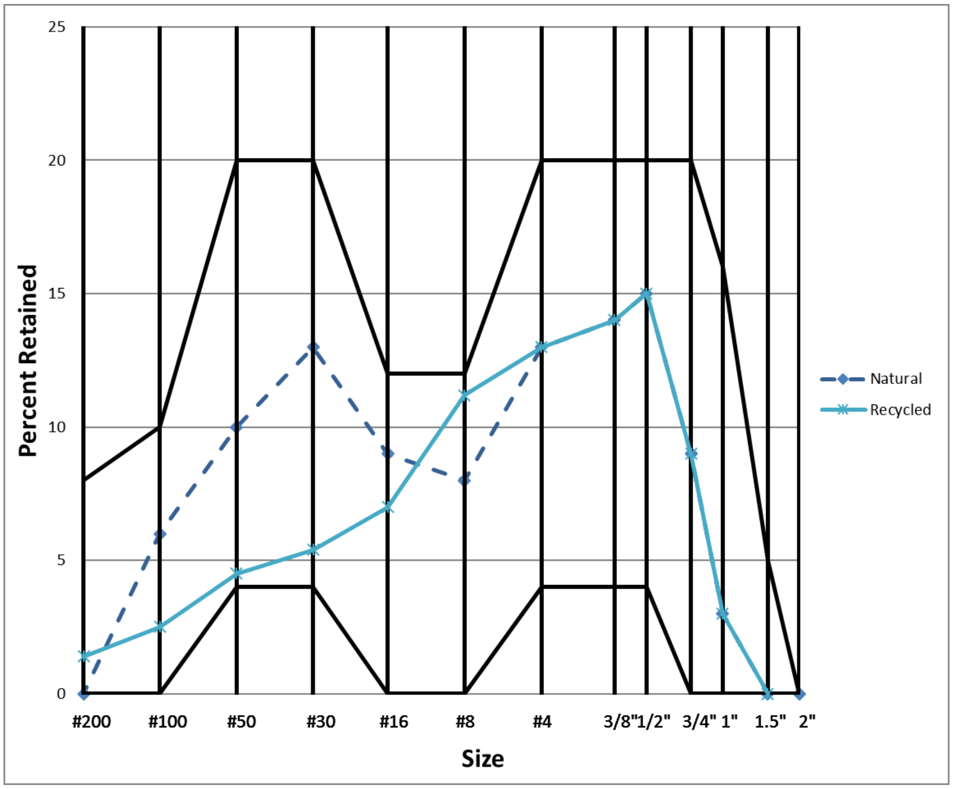

Figure 21. Aggregate Gradation.

3.2 EXPERIMENTAL PROGRAM

In 2000, MnDOT experimented by designing a project for a 60-year life. That included adding 1-inch additional thickness, required well-graded aggregate using 8-18, permeability requirements of no greater than 2500 coulombs at 28 days, increased target air content of 8.5%, and stainless steel dowel bars. The target air content was later modified to 7%. The high performance concrete (HPC) mix specifications included a water-cementitious ratio of 0.40 or less, and a minimum cementitious content of 530 lb/cy. It was also understood that most of these mixes would contain fly ash (Type C/F) or slag. Through the mid 2000's MnDOT tested concrete cores for permeability and determined that the quality of the concrete whether it was a high performance mix design or a regular mix design had similar properties, so MnDOT eliminated the HPC mix that included trial batching and a permeability requirement. MnDOT also did not add an additional inch of thickness after those early trials. The only remaining item was the stainless steel dowel bars which are still specified in most metro area projects to this day.

An experimental matrix was developed to evaluate the differences in the fresh and hardened properties of concrete made from varying proportions of RCA in the mixture. It is important to note that all mixture proportions were developed based on volume rather than mass. Recycled concrete aggregates replaced natural aggregates on a volume basis, and the quantities were subsequently converted to weight for batching purposes. Nine different concrete mixes were made, according to the matrix shown in Table 14.

Table 14. Experimental Program – Concrete Mixture Variations

Mix No.	Recycled Replacement – Coarse	Recycled Replacement – Fine	30% Class C Fly Ash Replacement?	Saturated or Dry Aggregates?
B1	0%	0%	Y	Dry
B2	100%	0%	Y	Dry
B3	100%	100%	Y	Dry
B4	50%	50%	Y	Dry
B5	50%	0%	Y	Dry
B6	50%	50%	N	Dry
B7	100%	100%	N	Dry
B8	100%	100%	Y	Saturated
B9	50%	50%	Y	Saturated

For easy identification, a six-character designation scheme for the mixes was developed, as follows.

- The first and second characters indicate the percent coarse aggregate replacement: 0, 5, or 1 for 0%, 50% or 100% replacement (by volume), respectively.
- The third and fourth characters indicate the percent fine aggregate replacement: 0, 5, or 1 for 0%, 50% or 100% replacement (by volume), respectively.
- The fifth character indicates whether 30% of the cement in the base mix is replaced by a Class C fly ash (A for Ash or N for None).
- The sixth character indicates whether the aggregates were dry or saturated at the time of mixing (D for dry or W for wet).

The mixture proportions are given in Table 15. Mix B1 was the control mix approximating a typical MnDOT high performance mix. High range water reducer Type F was used to facilitate the mixing of otherwise harsh mixtures, though the dosage rates were fairly low to avoid excessive slump. The effects of various components in the mixture were evaluated with the following comparisons.

- The effect of coarse aggregate replacement was studied by creating mixes B5 (50% coarse RCA) and B2 (100% coarse RCA).
- The effect of adding recycled fines was studied using mixes B6 (50% coarse RCA, 50% fine RCA), and B3 (100% coarse RCA, 100% fine RCA).
- Although the benefits of adding fly ash such as impermeability, workability, and ASR reduction are well documented, there is a potential looming shortage of fly ash in the US due to the unprecedented rate at which coal plants are being shut down. For this reason, two mixes were created without fly ash, namely B6 (50% coarse RCA, 50% fine RCA), and B7 (100% coarse RCA, 100% fine RCA).

- One method that has been attempted in the earlier literature to address the workability issues with RCA has been to keep the stockpiles wet. To study this effect as well as any possible benefits from internal curing, mixes B9 (50% coarse RCA, 50% fine RCA) and B8 (100% coarse RCA, 100% fine RCA) were created where the RCA were soaked under water for 24 hours prior to mixing.

Table 15. Concrete Mixture Proportions

Mix Number	B1	B2	B3	B4	B5	B6	B7	B8	B9
Mix Designation	0C0F AD	1C0F AD	1C1F AD	5C5F AD	5C0F AD	5C5F ND	1C1F ND	1C1F AW	5C5F AW
Component	**Mixture Proportions, lb/yd^3**								
Cement	410	410	410	410	410	598	598	410	410
Fly Ash	175	175	175	175	175	0	0	175	175
Water	217	217	217	217	217	221	221	217	217
Natural Coarse Aggregate	1,819	0	0	909	909	909	0	0	915
Natural Fine Aggregate	1,309	1,309	0	655	1,309	655	0	0	660
Recycled Coarse Aggregate	0	1,560	1,560	780	780	780	1,560	1,623	811
Recycled Fine Aggregate	0	0	1,048	524	0	524	1,048	1,152	576
	Admixture, fl oz/yd^3								
Air Entraining Admixture	13.3	16.6	13.3	14.9	16.6	16.6	16.6	16.6	16.6
High Range Water Reducer Type F	12.4	24.9	16.6	24.9	20.7	37.3	41.5	24.9	39.0

Several trial batches were mixed in order to determine the appropriate dosage for the admixtures to obtain the proper air content and slump. Once the admixture dosages were determined, the test mixes were produced and the testing was begun.

3.2.1 Mechanical Properties of RCA Concrete

This experimental program was performed to evaluate some basic properties of RCA and concrete made with RCA. This was motivated by the desire to explore behavior at low water-cementitious material ratios meeting MnDOT high performance specifications, to evaluate the beneficial use of chemical admixtures, and also to explore new optimized aggregate gradations.

The compressive strength of concrete made with recycled aggregates is generally reported to be lower than that of concrete made with natural aggregates. For example, at 100% coarse replacement, several researchers found 2-25% lower compressive strength at the same w/cm ratio (Verian et al. 2013). While the compressive strength itself may not be a major factor in concrete pavements, it is strongly correlated with other important properties such as flexural strength and modulus of elasticity. The flexural strength is an important property for resistance to tensile stresses as well as the fatigue life. Some reports indicate that flexural strength decreases by about 8% at the same w/cm (Anderson et al. 2009).

The decreasing trend of compressive strength and tensile strength in concrete with increased RCA content may be explained by the presence of two kinds of interfacial transition zones (ITZ) in concrete made with RCA. The ITZ represents the bond between aggregate and paste and is often weaker than either the aggregate or hydrated cement paste. In normal concrete, the ITZ occurs between aggregate and mortar while in concrete with RCA, the ITZ occurs between the original aggregate and old mortar and between the reclaimed mortar and new mortar (Verian et al. 2013).

The stiffness or modulus of elasticity of concretes made with RCA can be 20-40% lower than that of conventional concrete at the same water-cement ratio. This reduction can be even greater when recycled fines are also used. A reduction in modulus of elasticity in pavement applications is not a serious concern from a fatigue standpoint, as the lower modulus should result in lower tensile stresses in the slab. On the deflection side, the lower modulus may result in increased corner deflections, which could result in more pumping and faulting at joints (Anderson et. 2009).

Sturtevant et al. (2007) found that the coefficient of thermal expansion (CTE) was generally higher for pavement with recycled concrete than the control pavement. Temperature gradients may cause curling and warping of pavements. High CTE may increase the potential for mid-slab cracking and increase the rate of crack deterioration due to higher stresses and/or greater crack widths. Cores retrieved and tested from several test sites from around U.S. indicated that the CTE is approximately 10% higher on RCA concrete compared with that of normal concrete (Wade et al. 1997).

Because of restraint at the bottom of the pavement, shrinkage can cause a warping of the pavement. Higher drying shrinkage has been reported in RCA concrete. Drying shrinkage in concrete is dependent upon the amount of excess water present in the fresh cement paste and the ability of the aggregate to restrain the paste from shrinking. Higher water-cement ratios, higher paste contents, and lower coarse aggregate contents will all tend to increase shrinkage. Mixtures with RCA have higher paste contents and thus have increased shrinkage. Mix designs that use both recycled coarse and fine aggregates have the highest drying shrinkage (Anderson et al. 2009).

It has been reported that RCA fine material contains increased amounts of contaminants that adversely affect concrete properties (RILEM 2004). Fine RCA may cause increased shrinkage, reduced strength, and reduced workability. Therefore, most specifications currently in existence that address the use of RCA in new concrete mixtures do not allow the use of RCA as a substitute for fine aggregate.

While much literature exists concerning the behavior of RCA concrete under statically applied load, there is substantially less information on the behavior under dynamic load. Researchers have studied the flexural fatigue performance of plain concrete with normal aggregates to obtain empirical relationships between stress level (S), number of cycles to failure (N), and probability of failure (P). The stress level is the ratio of maximum applied stress to the flexural strength of the material i.e.

$$S = \frac{f_{\max}}{f_r} \tag{15}$$

For example, the PCA has developed the following equations which have about 10% probability of failure (PCA 1984):

For

$$S \geq 0.55,\ \log_{10}(N) = 11.737 - 12.077(S) \tag{16}$$

For

$$0.45 < S < 0.55,\ N = \left(\frac{4.2577}{S - 0.4235}\right)^{3.268} \tag{17}$$

And for

$S \leq 0.45$, number of repetitions is unlimited.

The ACPA have developed an equation as follows:

$$\log_{10} N = \left[\frac{-S^{-10.24}\log_{10}(1-P)}{0.0112}\right]^{0.217} \tag{18}$$

Oh (1986) developed the equation

$$S = A + B \log_{10} N \text{ with } A = 1.1339 \text{ and } B = -0.0889 \tag{19}$$

Singh and Arora (2015) have studied the flexural fatigue performance of concrete made with RCA. They have obtained the parameters for Equation 19 for 100% RCA as A = 1.152 and B = -0.098. In another study, they have found that the 2 million cycle endurance limit for stress level *S* was 0.58 for normal aggregate concrete, 0.56 for 50% RCA concrete, and 0.50 for 100% RCA concrete.

3.2.2 Fresh Concrete Properties

The unit weights, slumps, and air contents are presented in Table 16. All of the mixes turned out to be relatively stiff except mix B9. The difficult workability issues presented a challenge. In general, it was noted that mixes that were relatively more fluid under vibration gave higher air entrainment readings using the pressure meter while those that did not respond well to vibration gave lower readings. It should also be noted that there are questions regarding the use of the pressure meter when using lightweight, porous aggregates. If a large excess supply of aggregates had been available, it may have been possible to create a large number of batches and discard the waste until the optimum combination of high range water reducer and air entraining agent could be obtained as this is an iterative process.

Table 16. Fresh Concrete Properties

Mix Number	B1	B2	B3	B4	B5	B6	B7	B8	B9
Mix Designation	0C0F AD	1C0F AD	1C1F AD	5C5F AD	5C0F AD	5C5F ND	1C1F ND	1C1F AW	5C5F AW
Theoretical Unit Weight (7% air), lb/cf	146.3	138.6	132	139.2	142.5	139.8	132.7	132.4	139.4
Theoretical Unit Weight (air-free basis) , lb/cf	156.5	148.3	141.2	148.9	152.5	149.6	142.0	141.7	149.2
Actual Unit Weight, lb/cf	152.6	140.6	136.6	148.2	142.5	148.8	139.4	137.6	139.2
Gravimetric Air Content, %	2.5	5.2	3.3	0.5	6.5	0.5	1.8	2.9	6.7
Slump, in	1.0	2.0	0.0	0.5	1.5	0.5	0.0	2.0	5.0
Air Entrainment by Pressure Meter, %	2.5	5.5	5.5	2.5	8.5	2.0	2.0	3.0	7.0

3.2.2.1 Workability

After the creation of the mixes, a potential method was evaluated that could make it easier when dealing with difficult mixes like these. This is the so-called box test developed by Cook et al. (2014). A concrete mixture for a slip formed pavement must be stiff enough to hold an edge after leaving the paver, but workable enough to be consolidated by vibration. This method represents a simple and economical test method to evaluate the ability of a mixture to consolidate under vibration and subsequently hold a vertical edge under its own weight. This information is not available from the slump test alone. The box is a 12-inch cube and the four vertical sides are formed by two L-shaped walls that are clamped together. The basic steps of the test are to fill the box to a height of 9.5 in. A one-inch diameter vibrator as specified by Cook et al. is then placed in the box while counting 3 seconds in and 3 seconds out. The walls are then removed to evaluate the surface voids on the sides. It is suggested that if there are between 10 to 30% surface voids the mixture can be called good. If this is not achieved, the material is added back to the mixer where more water reducing admixture can be added. The air test is not run until the mix passes the box test. This test method was evaluated on only one of the batches, namely mix B4 (50% coarse RCA, 50% fine RCA). The process of the test is represented in Figures 22 through 29 below. The test was found to be more useful than slump test for pavement mixes.

Figure 22. Photo of Mix B4 in the mixer with 15 mL HRWR (15.2 fl oz/yd^3).

Figure 23. The box is filled prior to vibration.

Figure 24. The concrete is vibrated for 3 seconds in and 3 seconds out.

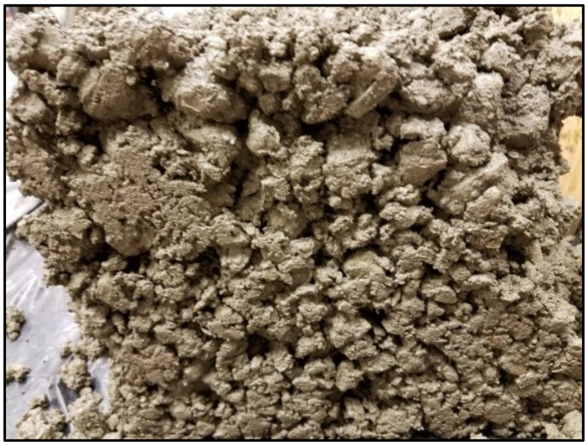

Figure 25. The surface voids are evaluated. This is obviously not adequate at this stage.

Figure 26. 30.4 fl oz/yd^3: Too many surface voids.

Figure 27. 49.7 fl oz/yd^3: About 50% surface voids.

Figure 28. 60.9 fl oz/yd^3: Bottom portion is fairly well consolidated – optimum dosage.

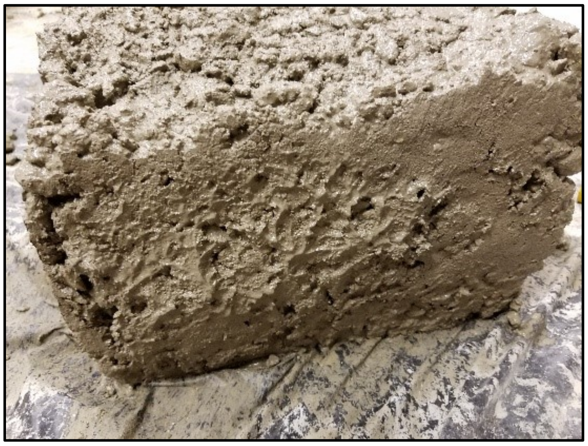

Figure 29. 76.1 fl oz/yd^3: edge slump is observed.

3.2.2.2 Water-Cementitious Materials Ratio

MnDOT offers contractors an incentive for achieving a water-cementitious material ratio less than 0.40. The w/cm is taken from contractor batch tickets, and verified by MnDOT using the microwave oven test. For this laboratory study, the w/cm was determined in the mix proportioning stage, and the materials weighed out and mixed in the lab. The w/cm for each mix was verified similar to the MnDOT method in the field using the microwave test. Four samples were taken for each mix, each consisting of approximately 1500g of material. The concrete is placed on a fiberglass cloth in a glass pan in a microwave oven with a power rating of 900W. Since two microwave ovens were available, two of the samples were sealed with plastic wrap while the test was begun with the other two samples.

After 5 minutes the sample is removed and the material is broken up with a tamping rod. The sample is returned to the microwave for another 5 minutes. Thereafter, weight readings are taken in two-minute intervals until the mass loss is less than 1g. After the first two samples had been heated for 10 minutes, the next two samples were then heated for 10 minutes before switching back to the first two samples. The total water content is adjusted for the absorption of the aggregates and then divided by the cement content from the mix design. It was noted that after the samples had been heated for 15 minutes or so, some of the asphalt-containing aggregates began to get liquefied. The results from the microwave tests are presented in Table 17.

In the testing to develop the ASTM standard, Rebelo (2014) reports that for low water-cement ratio between 0.4 to 0.5, the error was within 0.05 of the w/cm. For the case of design w/cm of 0.37, this would equate to a 13.5% error. By examining Table 17, it can be seen that all of the average errors are within 13.5% except for Batch 8 and Batch 9. Therefore, the microwave test seems to be a suitable test for RCA concretes. As noted previously the moisture content was difficult to control for mixes B8 and B9 as the RCA was presoaked for 24 hours. Prior to mixing an attempt was made to bring the aggregates to the SSD condition. While this is relatively easy for coarse aggregates where the water can be decanted and the aggregates towel dried, it is difficult and time consuming for the fines. Although moisture content corrections were applied, they may not have been entirely representative resulting in extra water in the mix. In addition, such treatment is not feasible in full-scale concrete production in the field.

Table 17. Microwave Test Results for w/cm

Mix	Test No.	Actual w/cm	Error, %	Average w/cm	Average Error, %
B1 0C0FAD	1	0.35	-5.4	0.34	-8.8
	2	0.32	-13.5		
	3	0.33	-10.8		
	4	0.35	-5.4		
B2 1C0FAD	1	0.33	-10.8	0.36	-3.4
	2	0.37	0.0		

	3	0.38	2.7		
	4	0.35	-5.4		
B3 1C1FAD	1	0.33	-10.8	0.36	-3.4
	2	0.32	-13.5		
	3	0.38	2.7		
	4	0.4	8.1		
B4 5C5FAD	1	0.38	2.7	0.37	-1.4
	2	0.36	-2.7		
	3	0.34	-8.1		
	4	0.38	2.7		
B5 5C0FAD	1	0.33	-10.8	0.36	-4.1
	2	0.38	2.7		
	3	0.34	-8.1		
	4	0.37	0.0		
B6 5C5FND	1	0.37	0.0	0.39	4.1
	2	0.38	2.7		
	3	0.35	-5.4		
	4	0.44	18.9		
B7 1C1FND	1	0.43	16.2	0.42	13.5
	2	0.41	10.8		
	3	0.4	8.1		
	4	0.44	18.9		
B8 1C1FAW	1	0.48	29.7	0.47	27.0
	2	0.49	32.4		
	3	0.44	18.9		
	4	0.47	27.0		
B9 5C5FAW	1	0.44	18.9	0.43	14.9
	2	0.41	10.8		
	3	0.44	18.9		
	4	0.41	10.8		

3.2.3 Hardened Concrete Properties

Over a period of weeks, the concrete samples from each mix were tested for compressive strength development, drying shrinkage, and coefficient of thermal expansion. Additional tests were performed to evaluate the flexural strength and chloride penetrability via the electrical resistivity test. Comparisons between the control mix and those with varying levels of recycled aggregates are discussed in the next few sections.

3.2.3.1 Compressive Strength

Two 4x8-in cylinders were tested for each batch at each of 7, 14, and 28 days since casting. Cylinders were demolded after 24 hours and cured in a saturated lime bath until testing. The results from the compressive strength tests for 7, 14, and 28 days are shown in Figures 30 through 32. It can be seen that there is a dramatic loss in strength for all mixes containing RCA with respect to the control mix. It could be expected that at lower w/cm the difference in strength between RCA concrete and normal aggregate concrete would be more pronounced due to a difference in strength of the new ITZ versus the old ITZ. In particular, considering the 28-day compressive strength, the control mix achieved an average compressive strength of 8393 psi. The strength of the 50% coarse RCA mix (5C0FAD) was 32% lower than the control mix, and the 100% coarse RCA mix (1C0FAD) was 43% lower.

Adding recycled fines can be seen to further decrease the strength. For example, from Figure 32, the strength of 5C5FAD is less than 5C0FAD and likewise the strength of 1C1FAD is less compared to 1C0FAD. The mixes without fly ash are very similar to the corresponding mixes with fly ash, which can be seen by comparing 5C5FAD vs 5C5FND, and 1C1FAD vs 1C1FND. Only two mixes did not achieve at least a 4000 psi compressive strength at 28 days. This was due to the difficulty controlling the moisture content as discussed before.

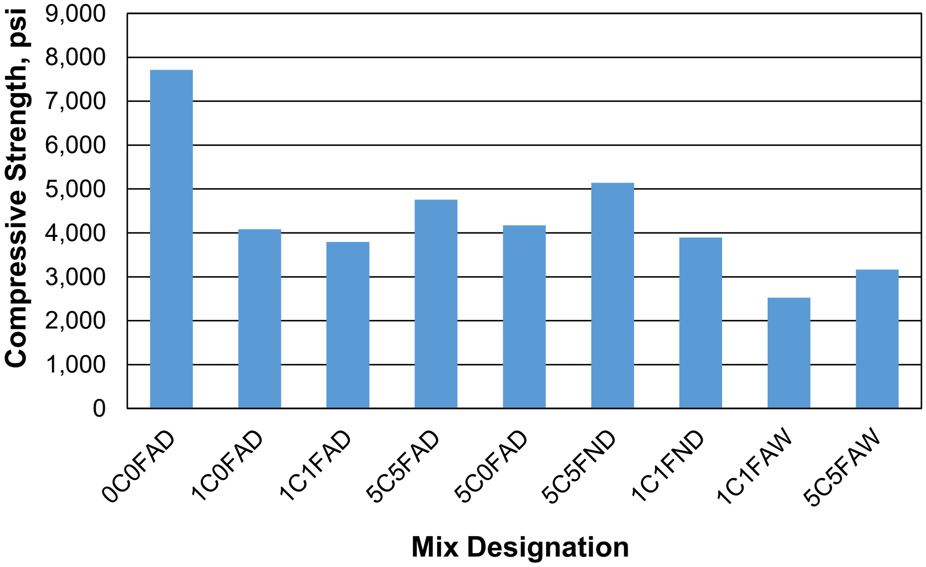

Figure 30. Seven day compressive strength results.

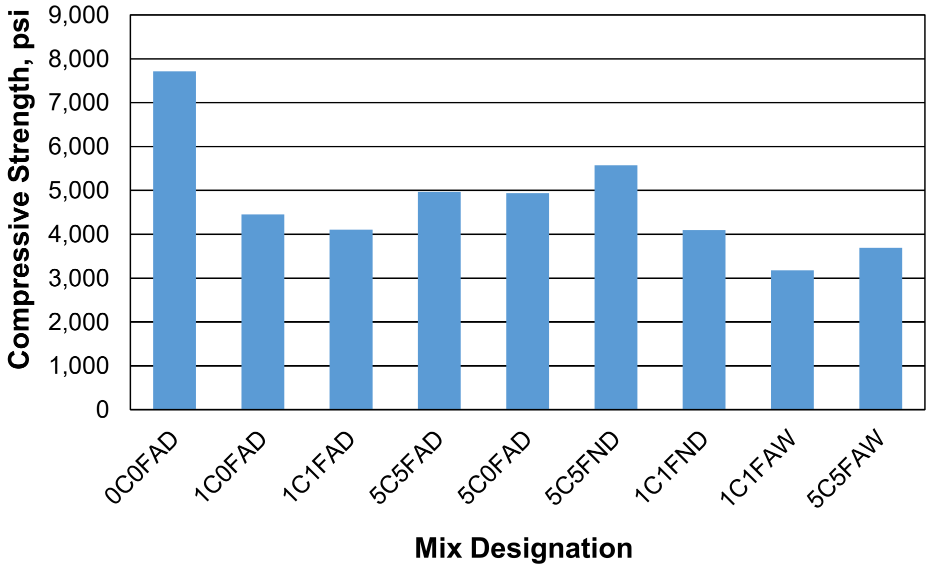

Figure 31. Fourteen day compressive strength results.

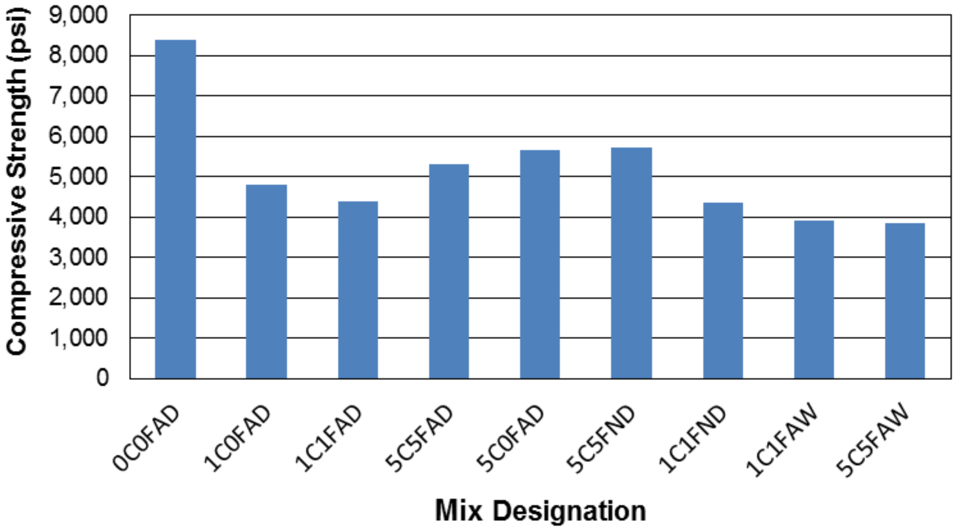

Figure 32. Twenty-eight day compressive strength results.

3.2.3.2 Drying Shrinkage

The drying shrinkage of each mix was evaluated using standard 3x3x11.25-inch concrete prisms. The prisms were demolded after 24 hours then cured in a saturated lime bath for two days before being dried in an environment with temperature 22.2°C and approximately 55% relative humidity. The results can be seen in Figure 33. It can be observed that addition of recycled fines has a profoundly negative effect on the shrinkage of the concrete. The lowest three curves correspond to mixes that did not contain any recycled fines. The best performance is from the control mix. The next mix with 50% coarse RCA performed almost as well as the control with both having an ultimate shrinkage less than 300 microstrains. The next best performance is from the mix with 100% coarse RCA with an ultimate shrinkage strain of 370 microstrains. Comparing the mixes where only the proportion of coarse RCA changes, the ultimate drying shrinkage increased about 1% with 50% coarse RCA (5C0FAD), and by 32% with 100% coarse RCA (1C0FAD). These results are as expected as the coarse RCA contains adhered mortar. The middle three curves correspond to 50% fine RCA replacement. There was similar performance between the mixes with and without fly ash, and the worst was the mix with pre-wetted RCA. The top 3 curves (worst performance) consisted of the 100% RCA fines with their ultimate shrinkage strains. Based on these results, it can be recommended that fine RCA should not be used.

3.2.3.3 Coefficient of Thermal Expansion

The CTE was tested using the samples from the drying shrinkage test, after its conclusion. As expected, and as indicated in the literature, the samples with more RCA exhibited higher CTE than the control sample. Table 18 gives the CTE of each mix, with the data sorted by CTE. It can be seen in the data that the mix without RCA has the lowest CTE, and that the next lowest is the mix with only 50% coarse RCA. In fact, comparing mixes by proportion of coarse RCA only, the correlation with CTE is consistent. A comparison by proportion of fine RCA in the mix is similar, with one exception.

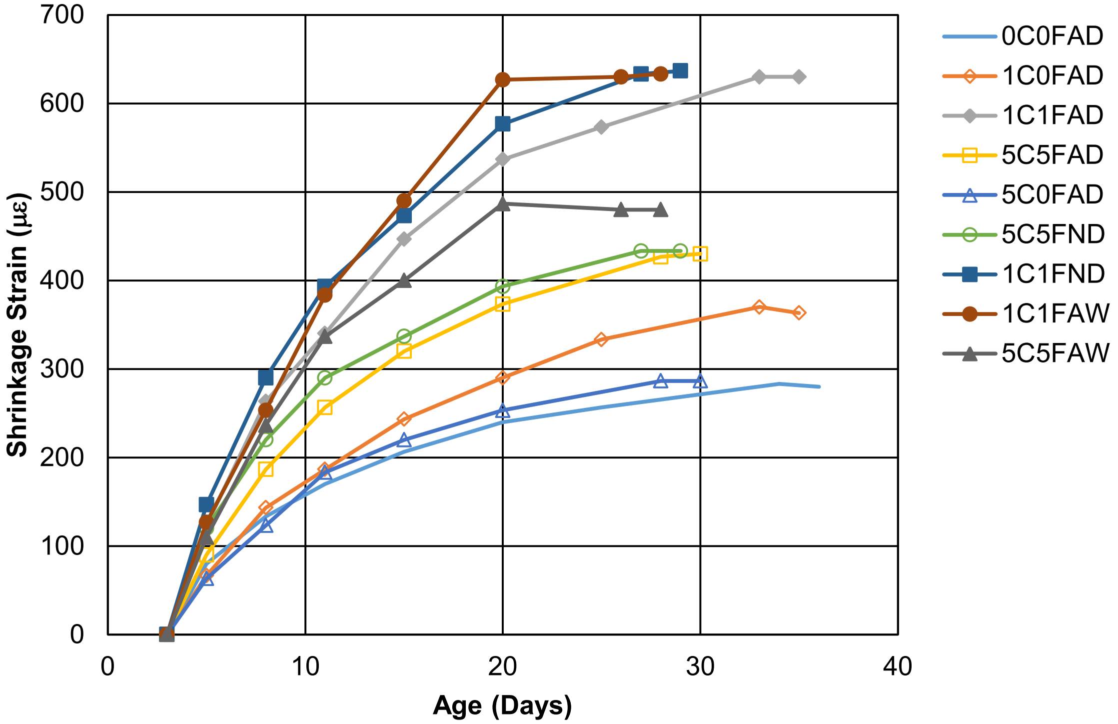

Figure 33. Drying shrinkage strain of the concrete mixes.

As indicated in the literature (Sturtevant, 2007 and Wade et al., 1997) the CTE is generally higher for concrete with RCA than for the control mix. In the CTE tests conducted for this project, and comparing mixes where only the proportion of coarse RCA changes, the CTE increased less than 1% with 50% coarse RCA (5C0FAD), and by 11% with 100% coarse RCA (1C0FAD).

Table 18. Coefficient of Thermal Expansion Test Results

Mix Designation	Description	CTE, Deg C^{-1}
0C0FAD	0% Coarse RCA 0% Fine RCA	11.5 $\mu\varepsilon$
5C0FAD	50% Coarse RCA 0% Fine RCA	11.5 $\mu\varepsilon$
5C5FAW	50% Coarse RCA 50% Fine RCA	11.9 $\mu\varepsilon$
5C5FAD	50% Coarse RCA 50% Fine RCA	12.1 $\mu\varepsilon$
5C5FND	50% Coarse RCA 50% Fine RCA	12.4 $\mu\varepsilon$
1C0FAD	100% Coarse RCA 0% Fine RCA	12.8 $\mu\varepsilon$
1C1FAW	100% Coarse RCA 100% Fine RCA	13.0 $\mu\varepsilon$
1C1FAD	100% Coarse RCA 100% Fine RCA	13.3 $\mu\varepsilon$
1C1FND	100% Coarse RCA 100% Fine RCA	13.6 $\mu\varepsilon$

3.2.4 Additional Concrete Mixtures

In order to determine if the small asphalt content might have had an impact on the mechanical properties of the concrete, it was decided to create two additional concrete mixtures with 100% coarse RCA. One of the mixtures, “B2 Bit” would contain the RCA aggregate in the “as is” condition, while the second mixture “B2 No Bit” would contain RCA aggregate where the particles containing asphalt were picked out by hand. Some observations by MnDOT personnel have found relatively good performance of pavements with a compressive strength of 6000 psi. Reviewing the previous results, it can be seen that the 50% coarse RCA mix was already at that level at 28 days (5667 psi). In order to bring up the strength of the 100% coarse RCA mixes, the w/cm ratio for B2 Bit and B2 No Bit was brought down from 0.37 to 0.35. In addition, because the control mix with 0% RCA had a very high strength of 8393 psi, a second % RCA mix “B1 New” was created by increasing the w/cm ratio from 0.37 to 0.39. The mixture proportions for these additional mixes are shown in Table 19.

The results of the compressive strength test for the additional concrete mixtures are shown in Figure 34. It can be seen that both mixes with 100% coarse RCA reached approximately 7000 psi strength at 28 days, and there does not seem to be a significant difference with the presence of bituminous particles. The new 0% RCA mix, B1 New, achieved a 28-day compressive strength of only 4240 psi.

Table 19. Mixture Proportions for Additional Concrete Mixtures

Mix Name	**B1 New**	**B2 Bit**	**B2 No Bit**
Mix Designation	0C0FAD	1C0FAD	1C0FAD
Component	**Mixture Proportions, lb/yd³**		
Cement	400	420	420
Fly Ash	169	182	182
Water	221.9	210.7	210.7
Natural Coarse Aggregate	1818.7	0	0
Natural Fine Aggregate	1308.9	1308.9	1308.9
Recycled Coarse Aggregate	0.0	1559.6	1559.6
Recycled Fine Aggregate	0.0	0.0	0.0
	Admixture, fl oz/yd³		
AEA	20.9	26.1	26.1
HRWR	13.0	104.3	104.3

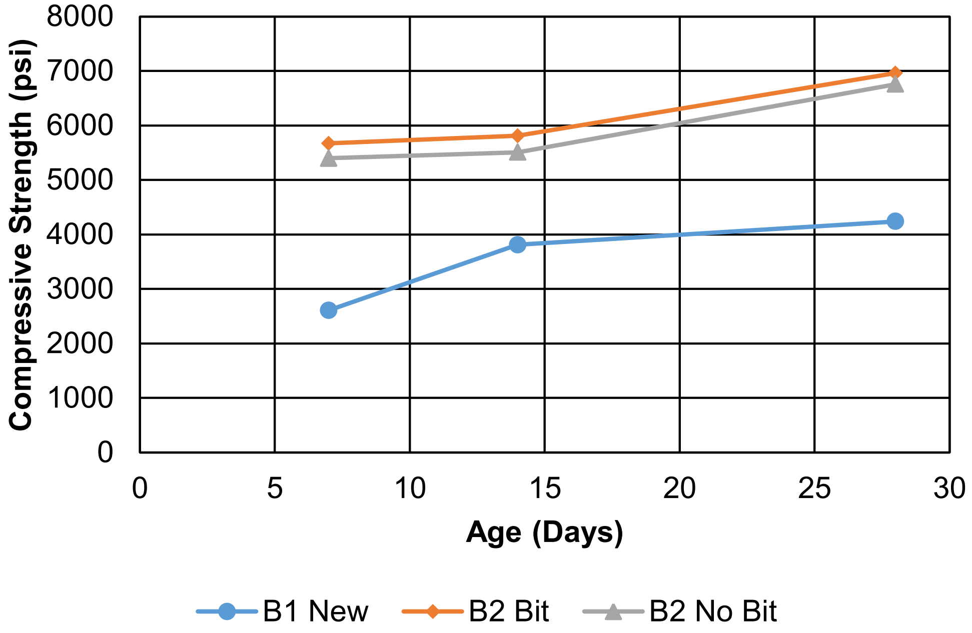

Figure 34. Compressive strength of additional concrete mixtures.

The results of the drying shrinkage test for mixes B2 Bit and B2 No Bit are shown in Figure 35. It can be seen that the overall performance of the two mixes were fairly similar again illustrating the fact that there seems to be little effect of the asphalt content. For comparison, the curves for the original control mix 0C0FAD and original 100% coarse RCA mix 1C0FAD are shown. The performance of the new B2 mixes show much improvement over the original and are close to the values for the original control mix 0C0FAD.

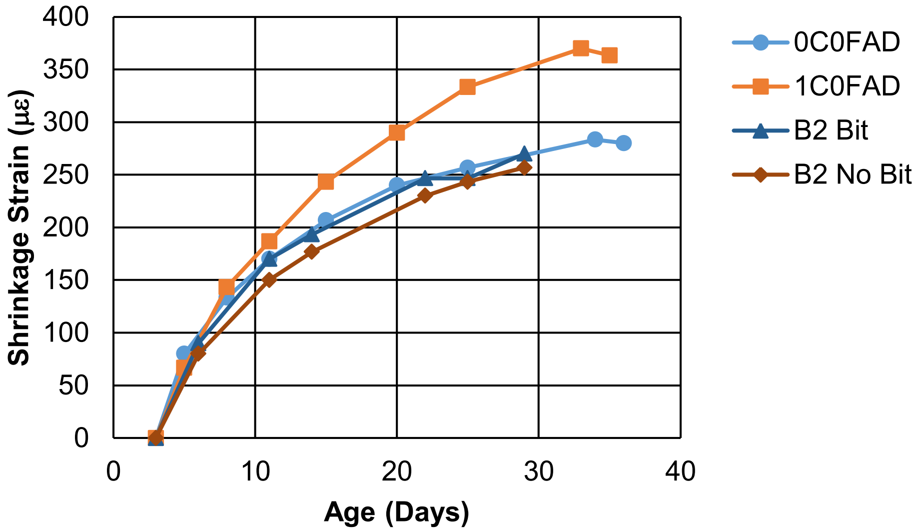

Figure 35. Shrinkage strain for B2 Bit and B2 No Bit.

3.2.4.1 Electrical Resistivity

Electrical resistivity measurements were performed on all of the prism specimens after completion of the shrinkage tests. The surface resistivity measurements were performed using a Proceq Resistivity Meter which utilizes the four-probe Wenner array method. Surface resistivity measurements have been found to be correlated with the rapid chloride permeability test, and low permeability is generally associated with increased durability. The results of the surface resistivity measurements are shown in Table 20. It can be seen that the mixes without fly ash seem to have significantly lower surface resistivity values.

Table 20. Surface Resistivity (kΩ-cm) Measurements

Mix	S1	S2	S3	Age (Days)
0C0FAD	217	122.2	132	105
1C0FAD	173.1	151	101.8	104
1C1FAD	112.1	88.4	77.3	104
5C5FAD	122	90.1	69.1	99

5C0FAD	214	133.4	151	99
5C5FND	60.5	43.5	55	98
1C1FND	64.3	47.5	44.2	98
1C1FAW	106	72.2	83	97
5C5FAW	152	102	131	97
B2 - No Bit	63.7	66.7	79.8	23
B2 - Bit	60.7	75.4	64.4	23
B1 - New	83.8	57.8	107.5	22

The chloride penetrability classification according to both AASHTO TP 95 (surface resistivity) and ASTM C1202 (rapid chloride permeability) is given in Table 21. It can be seen that all of the concrete mixes in this study will fall in the very low chloride penetrability range.

Table 21. Chloride Penetrability Classification

Chloride Ion Penetrability	AASHTO TP 95 (kΩ-cm)	ASTM C1202 (Coulombs)
High	< 12	> 4000
Moderate	12-21	2000-4000
Low	21-37	1000-2000
Very Low	37-254	100-1000
Negligible	> 254	< 100

3.2.4.2 Flexural Strength

The flexural strength of the concrete mixes was evaluated by testing three 3x3x11.25-inch beams for each mix. The beams were tested in a third-point loading configuration. The beams were approximately 180 days old at the time of testing. The results are shown in Figure 36. Once again it can be seen there was a reduction in flexural strength with respect to the control mix. Reductions in strength occur with increasing volumes of RCA. For example, considering the mixes where only coarse RCA were used, the flexural strength of 5C0FAD and 1C0FAD were 17% and 20% lower than the strength of the control mix, respectively. The addition of fine RCA further decreases the flexural strength. For example, the strength of 5C5FAD is less than 5C0FAD and the strength of 1C1FAD is less than 1C0FAD. The flexural strengths (at an age of about 150 days) of the newer concrete mixes were 563 psi, 732 psi, and 784 psi for B1 New, B2 No Bit, and B2 Bit respectively. This shows once again that there seems to be little effect of the bituminous particles on the strength.

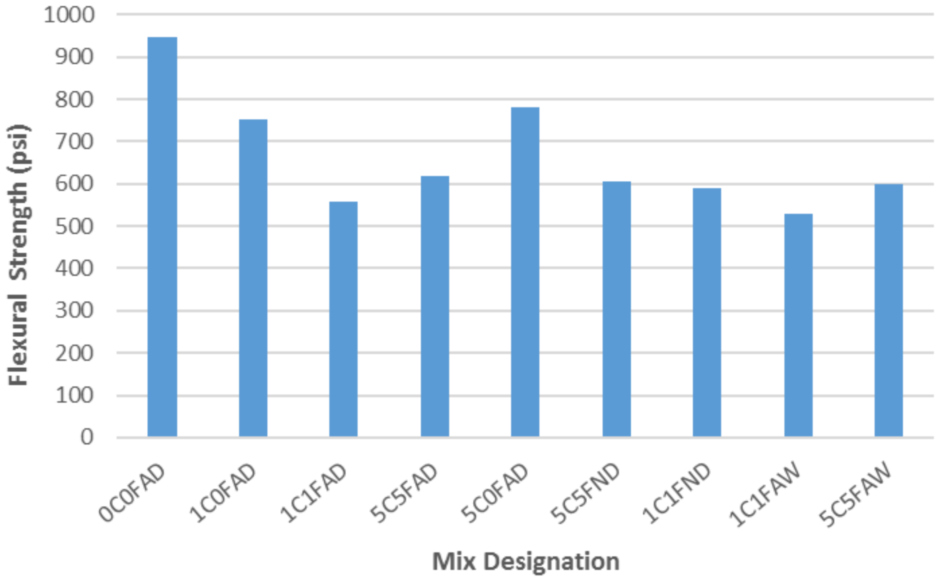

Figure 36. One hundred-eighty-day flexural strength results.

3.3 DISCUSSION

Based on the experimental results, the information in Chapter 2 showing decreased service lives for RCA pavements, and the other results reported in the literature, it is recommend that recycled fines should not be used in new concrete mixtures. Recycled fines usually have a negative effect on the strength, shrinkage, and workability of the mix. Coarse RCA replacements can be used; however, if expecting to achieve a similar service performance with conventional concrete, some changes in the mix or structural design should be implemented. Although the fatigue life of concrete using recycled aggregate has not been well studied, similar performance to concrete pavement with natural aggregate could be obtained by increasing the pavement thickness and leaving the mix design unchanged, or increasing the concrete strength and leaving the thickness unchanged. These two options are presented below, followed by recommendations on joint spacing to compensate for changes in thermal coefficient.

3.3.1 Pavement Thickness

As far as the thickness design is concerned, a rough estimate can be made as follows considering just the traffic loading stresses: first the modulus of rupture, f_r is needed. A typical relationship recommended by the American Concrete Institute (ACI) may be used:

$$f_r = 7.5\sqrt{f_c'} \tag{20}$$

The stress ratio, *S* given in Singh and Arora (2016) for the 2-million cycle endurance limit is used as a guide for the difference in flexural fatigue performance as the percentage of coarse RCA increases. Next, from Equation 20, the maximum allowable stress f_{max} can be obtained. From classical bending theories, stress is known to vary inversely with the square of the thickness e.g. from

$$\sigma = \frac{Mc}{I} = \frac{M\left(h/2\right)}{bh^3/12} = \frac{6M}{bh^2} \tag{21}$$

Using any value for *M* and *b*, the required thickness of the different concrete mix designs normalized with respect to the control mix can be obtained. The results are shown in Table 22. Thus it can be seen that to achieve the same fatigue performance life, the thickness of the 50% RCA concrete pavement should be about 12% greater than the control mix pavement, while the 100% RCA pavement should be about 24% thicker. Table 23 shows the corresponding values using this recommendation for typical pavement thicknesses.

Table 22. Calculations to determine equivalent thickness to achieve similar fatigue life

Mix Type	f_c'	f_r	S	f_{max}	Normalized thickness
Normal	8393	687	0.58	399	1.00
50% RCA	5667	565	0.56	316	1.12
100% RCA	4809	520	0.50	260	1.24

Table 23. Thickness increase based on recommendation from Table 22.

Mix Type	Suggested Thickness, in			
Normal	7	8	9	10
50% RCA	7.9	9.0	10.1	11.2
100% RCA	8.7	9.9	11.1	12.4

It is recognized that adding 12% to 24% to the thickness of a pavement slab can add a lot to the initial cost of construction. As an example, assuming a 9-inch slab with 50% RCA from Table 23, with a cost of \$75/cy for the concrete delivered on site. The additional 1.1-inch thickness represents 0.031 cy per sy of pavement (1.1 in / 36 sy-in per cy). This could add \$2.29 per sy of pavement (\$75/cy * 0.031 cy per sy) to achieve this additional thickness. More details are provided in Chapter 4.

3.3.2 Mix Design

As an alternative to increasing the pavement thickness to compensate for lower concrete strength (and potentially to be more cost effective), the mix design could be altered to increase strength without changing the thickness of the slab. Many mix designs used in concrete pavements in Minnesota use 585 pcy of cementitious material (often 410 pcy cement and 175 pcy fly ash for a 30% replacement ratio). Mix designs should be modified individually to determine an appropriate compensation for the decrease in strength due to the use of recycled aggregates. However, as an example of the potential magnitude of additional cost, consider an additional 100 pcy of cement at a cost of \$110 / ton. The following table shows the addition of cement and water to increase the mix strength, and a corresponding decrease in aggregate and air to maintain the same volume.

Table 24. Volume and Cost Computation for additional Cement.

	Specific Gravity (assumed)	Cost (assumed)	Weight, pcy	Volume, cf	Cost, $/cy
+ Cement	3.15	$110/ton	+ 100	+0.51	+ $5.50
+ Water	1.00	Negligible	+40	+0.64	
- Air (assume 6%)		Negligible		-0.06	
- Natural Aggregates	2.65	$15/ton (average)	-180	-1.09	- $1.35
Net Change			-40	0.0	+ $4.15

The $4.15/cy additional cost for concrete of a higher strength would add $1.04/sy at a thickness of 9 in. Compared to the increased thickness option, at $2.29/sy the increased strength option is very economical.

3.3.3 Joint Spacing

For mixes with up to 50% coarse RCA, the standard joint spacing of 15 ft can probably be used as the shrinkage strain and coefficient of thermal expansion only deviated from that of the control by about 1%. For mixes with 100% coarse RCA, the shrinkage strain increased by 32% and the CTE increased by 11% over the control mix; therefore, it is recommended to decrease the joint spacing in this case to reduce curling and warping and the potential for increased cracking. It was found that a joint spacing of 12 ft gives approximately the same total expansion as the control mix and is recommended for this case. It should also be noted that 12 ft and 15 ft are the two standard spacings available for selection in the Minnesota mechanistic-empirical based design software MnPave-Rigid.

3.3.4 Petrographic Analysis

Nine cores were taken with the assistance of MnDOT District 7 staff. District 7 had suspected possible ASR in several concrete pavements throughout the district, and worked with the project team to identify appropriate locations to obtain the cores. The cores were chosen based on the time from construction to the first major CPR, ranging from 5 years to more than 30 years in the samples obtained. Information concerning location and the pavement segment from which the cores were extracted is given in Table 25. In order to have minimum disruption to traffic, lower AADT roads were selected.

Table 25. Core and Highway Segment Locations

Core	Route	Segment MP Begin	Segment MP End	Core RP
1	MN60-D	50.640	54.172	51.005
2	US59-U	25.009	26.014	25.731
3	US59-D	12.163	12.551	12.326
4	US59-I	12.163	12.551	12.404
5	MN15-U	17.987	19.992	19.000
6	MN15-U	20.642	21.696	21.010
7	US169-U	25.617	27.875	26.000
8	US169-U	38.580	39.604	39.000
9	MN19	92.980	97.260	96.000

Table 26 provides basic information regarding the performance of the pavement segments. In three cases, cores 4, 5, and 8 a discrepancy was noted (i.e. the pavement was expected to contain RCA per COPES but none was detected, or RCA was detected when none was expected). Otherwise, nothing out of the ordinary was detected from the petrographic analysis. The area from which core 4 was taken was repaved in 2013, and so the concrete taken from that area is likely not the same as was placed in 1980.

Most of the parameters were within reasonable ranges for this age of concrete, and no real material distresses were observed. The disruption due to ASR was minimal, ettringite formation was normal, and the depth of carbonation was relatively low. The range of estimated water-cementitious ratio (0.37 – 0.42) reported by the petrographic analysis seems considerably lower than what is reported in the mix designs for these sections of pavement. In the Chapter 2 discussion as to why the service life of the RCA pavements might be less than that of the non-RCA pavements, it had been noted by some of the personnel who had been present during their construction in the 1980s that extra water may have been added on-site to account for the workability loss due to variability in absorption and degree of saturation of the RCA. Based on the results of the petrographic analysis, at least for these pavements, it does not appear that extra water had been added. In fact, the observed water-cementitious ratio was less than that of the mix design.

Table 26. Section Performance

Core	Time to first Major CPR Actual, yrs	Time to first Major CPR Predicted, yrs	AADT	Year constructed	RCA per COPES?	RCA detected?
1	22	24	4846	1987	Yes	Yes
2	6	24	3521	1980	Yes	Yes

3	5	NA	4053	1980	No	No
4	5	NA	4014	1980	Yes	No
5	>30	20	4514	1984	Yes	No
6	7	19	4145	1984	Yes	Yes
7	>23	42	2585	1991	Yes	Yes
8	>21	32	2534	1994	No	Yes
9	>21	52	2400	1993	Yes	Yes

Table 27. Mix Design Parameters from Submitted Mix Designs

3	Water, lb/cy	Cement, lb/cy	Fly Ash, lb/cy	w/cm	Coarse Aggregate, lb/cy	Fine Aggregate, lb/cy
1	260	472	83	0.47	1683	1200
2	255	465	109	0.44	1653	1198
3	255	465	109	0.44	1653	1198
4	255	465	109	0.44	1653	1198
5	285	596	0	0.48	1796	1163
6	258	497	0	0.52	1918	1104
7	290	512	90	0.48	1578	1200
8	260	472	83	0.47	1697	1200
9	282	502	88	0.48	1616	1200

Table 28. Parameters Estimated by the Petrographic Analysis

Core	Air Content, %	Paste Content, %	Aggregate Content, %	RCA % of Aggregate	RCA % of Total Mix
1	4.8	25.9	69.3	33	23
2	9.4	25.2	65.3	42	28
3	7.4	20.4	72.2	0	0
4	6.7	25.0	68.3	0	0
5	4.9	25.8	69.3	0	0
6	8.8	23.9	67.3	42	28
7	5.4	24.0	70.6	18	13

8	5.9	26.5	67.6	27	18
9	7.0	29.3	63.7	37	23

Table 27 gives the basic mix design information obtained from the mix designs for the concrete as submitted to MnDOT, while Table 28 provides the estimated mix parameters, such as air content, paste content, aggregate content, RCA percentage of the aggregate, and RCA percentage of the total volume from the petrographic analysis. There does appear to be some correlation of better performance with lower design w/cm, measured air content, and lower percentage of RCA of the aggregate. Table 29 provides additional estimated parameters obtained from the petrographic analysis.

Table 29. Additional Parameters Estimated by the Petrographic Analysis

Core	Spacing Factor, in	Specific Surface, in^2/in^3	Maximum Aggregate Size, in	Fly Ash Replacement of Cement, %	Aggregate Type	Color Difference of Paste
1	0.023	367	0.75	33	Gravel (mix of granite, carbonates, schist)	Light gray, dark gray within RCA
2	0.006	482	0.75	42	Gravel (mix of granite, carbonates, schist)	Medium gray, light gray in RCA
3	0.004	741	1	0	Quartzite	Two toned, upper part light gray, lower part bluish gray
4	0.006	635	1	0	Quartzite	Two toned, upper part light gray, lower part bluish gray
5	0.016	548	1	0	Quartzite	Light medium gray
6	0.006	444	0.75	42	Gravel (mix of granite, carbonates, schist)	Medium gray, same in RCA

7	0.015	548	1	18	Quartzite	Light gray, dark gray in RCA
8	0.014	563	1	27	Quartzite	Light gray, dark gray in RCA
9	0.01	435	0.75	37	Gravel (mix of granite, carbonates, schist)	Medium gray, same in RCA

3.4 CONSTRUCTION OF CONCRETE PAVEMENTS WITH RCA

This section contains a review of the literature and of best practices relating to the construction of portland cement concrete pavements with recycled concrete aggregates. It presents ideas for preparing, handling, and processing, recycled concrete aggregates, as well as information on pavement design and construction using these aggregates.

3.4.1 Recycled Aggregate Properties

An FHWA Technical Advisory report (FHWA, 2007) indicates that crushed RCA should have the following properties to be included in a high-quality concrete.

- Free of harmful components such as soil, asphalt, and steel.
- More than 90% of the material should be cement paste and aggregate. Asphalt content should be less than 1%.
- Free of chlorides and reactive materials (unless mitigation measures are taken to prevent recurrent or materials-related distress.
- Have an absorption rate less than 10%.

The FHWA Technical Advisory also recommends against using RCA fines, due to the lower quality concrete usually produced when the fines are included, such as decreased strength, increased shrinkage and thermal coefficient, etc. Consideration should also be given to the RCA material susceptibility to ASR, freeze-thaw durability problems, abrasion resistance, and the presence of chlorides. It is recommended that laboratory and field trial batches be conducted to verify that concrete made with a specific RCA material will meet project specifications. The technical advisory recommends that RCA fines not be used in areas where freeze-thaw durability is necessary.

Tayabji et al. (2012) suggested that the recycled material should be obtained from a single source, to be more confident in the properties and in the variability of those properties. It is best if the source of the RCA is from another pavement, with the assumption that construction and materials specifications at the time of the original pavement's placement will be of similar nature to current specifications. The authors also recommend that the RCA not be obtained from a commercial recycle yard which may include concrete contaminated with unknown chemicals, industrial waste, or other reactive materials.

ASTM C 33 (ASTM, 2011) indicates that “in general, the recycled materials used for concrete paving projects must meet the same quality requirements normally used for virgin aggregate.” An addition to this is suggested in ACI 325.9R (2015) to add “unless the lower-quality recycled material is used in the lower layer of a two-course pavement.”

FHWA (2007) suggests that RCA exhibiting materials related distress may be recycled and used in new concrete pavements, but only if the distress mechanisms are recognized prior to design, and if proper mitigation measures are implemented. It suggests that the materials engineer should visit the recycling location to observe the type and extent of distresses, and to collect samples for further study.

3.4.2 Processing

The recycled concrete pavement must be crushed and sized, graded, and further processed, possibly with wet screening or hydraulic sizing. The additional processing not normally conducted on virgin aggregates includes removal of loose cement mortar, removal of lightweight materials such as wood, soil, or other porous stone. Besides the additional steps to remove these contaminants, the processing of RCA should be the same, and use the same equipment, as processing natural aggregates.

3.4.3 Mix Proportioning

The FHWA Technical Advisory report includes many suggestions for mixture proportioning to accommodate for the detrimental effects on some properties.

- May use additional cementitious materials to reach the required or desired strength.
- The presence of coarse RCA may require about 5% more water. Concrete made with RCA fines may require about 15% more water.
- Keep in mind that the specific gravity of RCA concrete is usually lower than concrete made with natural aggregates.
- If RCA fines must be used, they should be blended with natural fines to mitigate the detrimental effects. In blended fine aggregates, no more than about 30% of the fines should be RCA. Remember to adjust the water accordingly.
- Conduct trial batches to test for workability, strength, shrinkage, thermal coefficient. Concrete pavements with poor levels of these properties may need design modifications to attain the performance expected of a concrete pavement.

3.4.4 Pavement Design

Several reports describe differences in pavement design that should be considered when using recycled concrete aggregate. A report by the Michigan Department of Transportation (MDOT, 2011) recommends design modifications such as increased pavement thickness and decreased joint spacing, as were suggested in previous sections of this report. The MDOT report suggests that RCA concrete should not be used in jointed concrete pavement, or that dowels should be used across every joint in pavements where RCA is used, due to possible poor aggregate interlock across the crack faces. The low abrasion resistance noted in this report and in others is the primary reason for the low aggregate interlock. The MDOT report discusses the two-layer concrete pavement, where the lower lift is built with lower quality aggregates and the surface lift is built with high-quality natural aggregate.

3.4.5 Concrete Properties

A report by ACI Committee 555 (Concrete with Recycled Materials) (ACI, 2001) includes discussion on the effects of RCA on various properties of concrete, including fresh concrete properties, mechanical properties, and durability. More specifically, the following are mentioned.

With coarse RCA only

- Compressive strength: 5-24% lower
- Tensile strength: about 10% lower
- Elastic modulus: 10-33% lower
- Creep: 30-60% greater
- Permeability: 200-500% greater
- Drying shrinkage: 20-50% more

With coarse and fine RCA

- Compressive strength: 15-40% lower
- Tensile strength: 10-20% lower
- Elastic modulus: 25-40% lower
- Creep: 30-60% greater
- Permeability: 200-500% greater
- Drying shrinkage: 70-100% more

These effects should be considered when designing a concrete pavement using RCA materials. As mentioned, a program of trial batches should be conducted to ensure the properties of the concrete will meet required specifications.

3.4.6 Stockpile Management

Many authors suggest using proper stockpile management with recycled concrete aggregates. This often means the implementation of procedures commonly used for lightweight or slag aggregates, such as continuous sprinkling to maintain a saturated state prior to batching.

3.4.7 Summary of Costs, Benefits and other Potential Uses

This section includes a list of items that should be considered when determining the financial viability of using recycled concrete aggregates in new concrete. Actual costs are not given here, as this is intended to highlight the concepts and ideas behind the decisions. Items in this are intended to be those which differ from the processing and usage of natural crushed stone products.

Costs

- Demolition
- Transporting material (if not processed on-site and in-place)
- Removal of steel, soil, and other contaminants
- Crushing, sizing, washing
- Evaluation of RCA materials for suitability in the new concrete
- Stockpile management for an additional aggregate or two (coarse and possibly fines)
- Possible increased need for quality control testing
- Possible need for thicker PCC pavement slab
- Additional joint sawing (if shorter slabs are needed)
- Additional uncertainty in the design and construction

Opportunity Costs – By using RCA in the concrete, what benefits are not realized?

- Most RCA that is used in pavements is placed in the base or subbase layer. If this is not available because it was used in the PCC layer, new or other recycled material must be purchased and transported to the site. Purchasing new aggregates for the base or subbase layer may still be more economical than new aggregates for the concrete layer since these aggregates are normally of lower quality and cost.
- Similarly, RCA fines can often be used in shouldering, and so any diversion from this use would be considered an opportunity cost for their use in concrete. However, since RCA fines are not recommended for concrete, this may not be an issue.
- There are other beneficial uses of recycled concrete aggregates, including noise barriers, embankment fill, riprap, drainage structures, and new concrete for uses other than concrete pavements layers. These could include base layers, shoulders, median barriers, sidewalks, curb and gutter, and many varieties of lean- or econo-crete types of concrete. RCA fines can also be used for fill in subgrade corrections (ACPA, 1993).

Benefits

- Potentially significant savings due to decreased need for new aggregate to be purchased and transported to the site.
- Although most recycled concrete is not sent to landfills, if a concrete pavement is to be removed and not recycled on site, the costs of demolition and crushing should be included here. If a demolished concrete pavement would otherwise be sent to a landfill, the costs of transportation and landfill tipping fees would be saved by recycling the material on site.

3.5 CHAPTER SUMMARY

Various tests were conducted to evaluate the properties of RCA as well as concrete made with RCA in comparison to concrete with natural limestone aggregate. The absorptions were approximately 3% for the coarse RCA and 9% for the fine RCA. Abrasion losses measured from the LAR were approximately 41% for the RCA vs 25% for the crushed limestone aggregate.

Compared to concrete mixtures made in the 1980's, more modern mixtures have evolved significantly, most notably in the use of lower water-cementitious ratios, optimized gradation of aggregates, and the use of admixtures. In order to evaluate the effects of RCA, a series of concrete mixes with w/cm of 0.37 was created with varying amounts of coarse and fine RCA replacements. A significant reduction in twenty-eight day compressive strengths was observed, of about 32% for 50% coarse RCA replacement and 43% for 100% coarse RCA replacement. This level of strength decrease seems to be higher than most reported in the literature. It must be noted that most of the tests from the literature tend to be at higher water-cementitious ratios (> 0.42). It is possible that the difference in strengths can be more pronounced at lower w/cm due to the difference in the strengths of the old ITZ versus the new ITZ.

The ultimate drying shrinkage strain for 50% coarse RCA concrete was approximately the same as the control at about 290 microstrain. At 100% coarse RCA replacement, the shrinkage strain increased to about 380 microstrain. In light of the results presented in Chapter 2 which showed a shorter service life for RCA sections than non-RCA sections, as well as the differences in mechanical properties noted here, it may not be appropriate simply to use the same mix design or structural design for the RCA and non-RCA pavements and expect similar fatigue performance. As an example, using the predicted values of flexural strength together with research results regarding the flexural fatigue performance of RCA concrete, in this report it is suggested either to increase the thickness by an appropriate amount to reduce flexural stresses, or to increase the strength of the concrete to counteract the expected decrease in strength due to the RCA. In addition, the joint spacing was recommended to be reduced from 15 ft to 12 ft for 100% coarse RCA pavement.

Because of significant increase in drying shrinkage, and further lowering of compressive strength, coupled with the challenges in workability, it is not recommended to use RCA fines. The box test was found to be a more useful test than the slump test in evaluating the workability of mixtures for slip form paving and is recommended during the trial batch process for RCA mixtures although it is equally valuable for normal concrete mixes.

The microwave test was found to be suitable for RCA as well as non-RCA mixes. At the target w/cm of 0.37 most of the errors were within 0.05 (13.5% error in this case). This matches closely to what was observed during developmental testing for the ASTM standard at w/cm between 0.40 and 0.55.

Some of the past literature has suggested pre-wetting the stockpiles of RCA to account for the variability in absorption. The moisture content would have to be monitored closely for this method and may work for coarse RCA only but would be difficult for the fine RCA. Based on the results obtained, this may not be necessary as the RCA can be added in the dry condition with water added for the absorption, and any necessary adjustments in workability can be made with the water reducing admixture.

Petrographic analysis of several cores of existing pavements with a range of lives until the first major CPR were performed. No special material-related distresses were observed for the RCA pavements. There did appear to be some correlation of better performance with lower design w/cm, measured air content, and lower percentage of RCA of the aggregate.

CHAPTER 4: ECONOMICS OF USING RECYCLED CONCRETE AGGREGATES

Donalson et al. (2011) performed a sustainability assessment of using RCA versus virgin limestone aggregate (VLA) in base courses from the perspective of environmental, social, and economic aspects. The environmental impact was found to demonstrate a reduced impact in favor of recycled concrete aggregate in process energy and disposal (viz. fuel used to haul concrete to landfill) at -0.01 and 0.04 metric tons of carbon dioxide equivalents, respectively. The delivered price of the material has been found to primarily differ in the transportation costs as the processing procedures have been found to be similar. For a hypothetical scenario in Florida, the delivered cost was $12.75 per ton for RCA and $13.20 per ton for VLA (based on a 30-mile haul distance for the VLA). For the social impact, the leachability of several chemicals for both RCA and VLA were evaluated. It was found that RCA leaches less harmful and less toxic amounts of chemicals than VLA; however, in both cases the actual amount of constituent reaching the groundwater is negligible compared to groundwater contamination limits of the EPA.

Ram et al. (2011), in a report developed for the Michigan Department of Transportation, performed lifecycle cost analysis (LCCA) to evaluate the use of RCA in concrete pavements. Pavements constructed using RCA in the paving concrete exhibited comparable performance (in terms of life-cycle agency costs) to sections with natural coarse aggregates at lower traffic volumes; however, at higher traffic volumes the majority of them underwent major rehabilitation or reconstruction activities after about 20 years of service. Michigan's initial trials of RCA pavements were often JRCP and suffered mid-slab transverse cracking that may have been due to some combination of small top size aggregate, poor aggregate interlock due to adhered mortar, long joint spacing, and too little reinforcement. The average agency cost for level I (<6000 AADT, ~9 in average thickness) pavements was almost the same at about $15,000 on an annual worth basis for both natural aggregate and RCA concrete for a 50-year analysis period. For level III (>10,000 AADT, ~11 in thickness) pavements the average agency cost was about $14,600 for natural aggregate and about $12,170 for RCA. Thus, the agency costs seem to be approximately the same or slightly better for RCA when evaluated over a longer period of time, even after considering the 20-year service life of some of their RCA pavements.

Horvath (2004) developed a lifecycle analysis (LCA) framework in Excel that also performs LCCA for the Recycled Material Resource Center. The tool name is PaLATE. A user-guide of sorts for this tool was developed as part of a Master's Thesis by Nathman (2008).

Verian et al. (2013) performed a benefit-cost analysis and developed a useful spreadsheet to evaluate initial material costs associated with RCA use for the Indiana DOT. For the base aggregate, two different gradations are considered, #8 and #53. When concrete is crushed to aggregate, there is 50% waste (i.e. fines) for the #8 and 40% waste for the #53 gradation. Some other assumed values in their analysis included: $5/ton RCA crushing costs, $9.50/ton concrete natural aggregate, $9.50/ton base #8, $9/ton base #53, hauling cost $0.35/ton/mile, and landfill cost $2/ton. The haul distances assumed were: old project & crushing operation 10 miles, crushing & delivery point 7.4 miles, project & landfill 50 miles, and natural aggregate source & delivery point 21 miles. Under these assumptions, for example for 50% coarse RCA in the concrete, and 100% RCA in the base, they achieve a net cost savings of about $2.50/ton of aggregate.

Hu et al. (2014) performed a review of two-lift construction in the US. A survey of contractors showed that most would favor using a second batch plant instead of adding bins for the first plant. In addition, a second slip-form paver is required for the wet-wet method of construction. Despite the increased equipment and labor costs, the three most recent two-lift construction projects in the US (Kansas 2008, Minnesota 2010, and Illinois 2012) showed a net saving compared to the conventional concrete alternative. The positive data are due to the substantial saving from the reduced aggregate costs and concrete cost used in the bottom lift, together with the positive bidding climate currently seen in the U.S. The Minnesota project consisting of MnROAD Cells 71 and 72 on the I-94 mainline showed concrete costs of $71.07/cy concrete costs, $2.61/sy paving costs, and $20.38/sy net costs for the conventional concrete compared to $62.66/cy, $4.28/sy paving costs, and $19.94 /sy net costs for the two-lift construction.

4.1 LIFE CYCLE COST ANALYSIS

Lifecycle Cost Analysis (LCCA) is a widely used technique in the US for comparing pavement alternatives, often used to compare asphalt and concrete alternatives. From engineering economics theory, alternatives can be compared equivalently by future worth, present worth, or annual worth. In LCCA for pavement alternatives, it is most common to compare present worth (or net present value) or annual worth (or effective uniform annual cost). It is useful to review the relationships between some of these values as given by Equations 22 through 24.

$$F = P\left(1+i\right)^{n}$$

F = Future worth; P = Present worth (22)

i = Annual discount rate; n = number of years

$$P = \frac{F}{\left(1+i\right)^{n}} \tag{23}$$

$$A = P\left[\frac{i\left(1+i\right)^{n}}{\left(1+i\right)^{n}-1}\right] \tag{24}$$

$A =$ Annual worth

4.1.1 Real Discount Rate

The real discount rate is a function of both the interest rate and inflation rate and is given by:

$$i = \frac{1+i_{int}}{1+i_{\mathrm{inf}}} - 1 \tag{25}$$

In this study, the latest discount rate for 30 years as reported by the Office of Management and Budget (OMB) which is 1.5% was used. It is suggested by OMB that for analysis periods longer than 30 years, the 30-year value should still be used.

4.1.2 Analysis Period

It is normally suggested to use a relatively long analysis period to be able to capture the effects of various maintenance activities. In this study, the analysis period has been chosen to be 50 years which is a reasonable timeline considering the long expected service lives of new concrete pavements in Minnesota. The analysis presented in Chapter 2 indicated that RCA pavements had an average time to major CPR of 27 years and non-RCA pavements had an average time to major CPR of 32 years. Thus, the non-RCA pavements had about 18.5% more longevity. Concrete mix designs have changed significantly since the 1980's, most notably in the use of lower water-cementitious ratios. Utilizing the mix designs that were developed in Chapter 3, a reasonable expected time to major CPR of 50 years has been assumed for 50%RCA pavements, and the time to major CPR for non-RCA pavements has been taken as 59 years (that is about 18.5% longer). The 100% RCA pavement's expected time to major CPR has been taken as 46 years, thus, a major CPR would occur during the analysis period.

4.1.3 Initial Costs

One of the major differences between the alternatives considered was the concrete mix design. While the unit price of concrete as a whole (e.g. in \$ per cy or \$ per sy) is normally reported in bids and is readily available e.g. in MnDOT average bid prices, it does not allow the nuances of changes in mix design to be accounted for in the LCCA. For example, the difference in cost for RCA versus natural aggregate within the mix cannot be evaluated with the lump sum value of concrete, and thus the mix must be broken down into its components.

Additional initial costs considered were the saw cuts of joints and dowel bars. These needed to be included because some of the alternatives called for a 12 ft joint spacing instead of 15 ft standard joint spacing.

It is also realized that there is an effect of "economies of scale." For example, in the MnDOT average bid prices, it is often found that unit costs are less for larger quantities. For this reason, a minimum length of 7 miles for a new paving project was assumed in this analysis.

4.1.4 Annual Maintenance Costs

Annual maintenance costs have been assumed to be the same for all alternatives and have not been included for the analysis.

4.1.5 Future Costs

In Chapter 2 it was found that the frequency of minor CPR for both RCA and non-RCA pavements were fairly similar and thus they have not been included in this analysis. One of the alternatives was assumed to have a major CPR at 46 years. The CPR technique has been assumed to be diamond grinding. The future cost can be converted to present worth using Equation 23 and to annual worth using Equation 24.

In the case that any of the alternatives have some remaining service life at the end of the analysis period, one of the techniques to account for this is to calculate the residual value. The residual value is given by:

$$\text{Residual Value} = \frac{\text{Remaining Service Life}}{\text{Expected Service Life}} \times \text{Initial Cost} \qquad (26)$$

The residual value can then be converted to present worth using Equation 23 and to annual worth using Equation 24.

4.1.6 Scenario Considered

It should be noted that when comparing alternatives with LCCA, any costs that are constant between the alternatives need not be considered. In fact, if the constant costs *are* included, it will tend to lessen the differences of the various alternatives considered. Annual maintenance and minor CPR have not been included. Similarly, the landfill disposal of non-useable RCA (taken to be only the fines) would be constant between all the alternatives and has not been calculated. Using data from Verian et al. 2013, the amount of non-useable RCA (fines) has been taken as 40%.

The old PCCP to be recycled has been assumed to be 7 miles long by 24 ft wide by 10 in thick. The base of the new PCCP to be constructed has been assumed to be 7 miles by 24 ft wide by 8 in thick class 5 aggregate. All of the new PCCP alternatives are 7 miles long and 24 ft wide. The hauling distance between the natural aggregate sources and the delivery point has been assumed to be 30 miles.

The new conventional concrete pavement (Alternative 1) had a thickness of 9 in. In Chapter 3, it was suggested that in order to achieve similar fatigue performance as the conventional concrete, pavement thickness be increased by 12% for 50% RCA concrete and 24% for 100% RCA concrete. In lieu of increasing the thickness, the concrete mix could also be strengthened by increasing the cementitious material content and decreasing the water-cementitious (w/cm) ratio. Based on the laboratory testing, it is suggested that the w/cm ratio be decreased to 0.36 for 50% RCA concrete and 0.35 for 100% RCA concrete to achieve similar fatigue performance as the conventional concrete (with w/cm of 0.37). Also, because of higher drying shrinkage and higher coefficient of thermal expansion, it was recommended to reduce the joint spacing from 15 ft to 12 ft for 100% RCA concrete at the w/cm of 0.37; however, at w/cm of 0.35 the shrinkage and thermal expansion of the 100% RCA mix were similar to that of the conventional concrete therefore the joint spacing could remain at the standard 15 ft value.

The LCCA calculations were set up in a spreadsheet. The unit costs assumed are given in Table 30 and the unit weights for some of the materials is given in Table 31.

The concrete mix designs utilized in this chapter are those reported in the Chapter 3 experimental program. The two mixes for the two-lift construction have been copied from the MnROAD test cell mixes (Akkari 2011). The mix designs are summarized in Table 32.

Table 30. Unit Costs Assumed in LCCA

Material/process	Unit Cost	Unit	Reference
RCA	$8.75	ton	Izevbekhai (2015)
Natural aggregate for concrete	$22.00	ton	Sibley Aggregate, Kraemer Mining MN (2016)
Aggregate for EAC	$20	ton	Izevbekhai (2015)
Natural aggregate for base class 5	$16.77	ton	MNDOT average bid (2014)
Sand	$5	ton	PaLATE, producers websites
Cement	$110	ton	PaLATE, Cemstone (2016)
Flyash	$90	ton	PaLATE, Cemstone (2016)
Water	$36.88	Mgal	MNDOT average bid (2014)
High range water reducer	$1000	ton	Internet search (2016)
Haulage	$0.35	ton/mile	Verian et al. (2013)
Sawcut	$4.83	LF	MNDOT average bid (2014)
Dowels	$6.18	ea	MNDOT average bid (2014)
Landfill fee	$4	ton	Midwest Asphalt (2016)
Premium for 2-Lift	$1.66	SY	MnROAD Test Cell (Hu et al)
Diamond Grinding	$2.30	SY	MNDOT average bid (2014)

Table 31. Unit Weights of Materials Used

Material	Unit Weight, ton/cy
Natural Aggregate for Concrete	2.33
Natural Aggregate for Class 5 Base	2.33
Aggregate for Exposed Aggregate Concrete	2.33
Natural Fine Aggregate	2.21
Recycled Coarse Aggregate	2.00

4.1.7 Alternatives Considered

A total of eight alternatives were considered in the LCCA, namely:

1. Conventional concrete pavement with no RCA in the concrete with an expected life till first major CPR of 59 years.
2. 50% coarse RCA in the concrete with similar structural design as (1), but with an expected life to first major CPR reduced to 50 years.
3. 50% coarse RCA in the concrete with a 12% thicker design than (1) and similar life expectancy of 59 years to first major CPR.
4. 50% coarse RCA in the concrete with a lower w/cm ratio (0.36) and similar structural design as (1) with a similar life expectancy of 59 years to first major CPR.
5. 100% coarse RCA with similar structural design as (1) but with reduced joint spacing of 12 ft and reduced life to first major CPR of 46 years.
6. 100% coarse RCA in the concrete with a 24% increase in thickness from (1) and reduced joint spacing of 12 ft and similar life expectancy of 59 years to first major CPR.
7. 100% coarse RCA in the concrete with a lower w/cm ratio (0.35) and similar structural design as (1) with a similar life expectancy of 59 years to first major CPR.
8. Two-lift construction that has 50% RCA in the lower lift and exposed aggregate concrete in the top lift with a similar life expectancy to first major CPR as (1), i.e. 59 years.

Table 32. Concrete Mix Proportions (lb/cy)

Alternative in which used	1	2 & 3	4	5 & 6	7	8	
Mix Description	0% RCA	50% RCA, w/c = 0.37	50% RCA, w/c = 0.36	100% RCA, w/c = 0.37	100% RCA, w/c = 0.35	Lower Lift Mix	Top Lift Mix
Cement	410	410	417	410	420	360	616
Fly Ash	175	175	178	175	182	240	109
Water	216	217	214	216	211	234	283
Natural Coarse Aggregate	1819	909	909	0	909	825	1976
Natural Fine Aggregate	1309	1309	1309	1309	1309	1200	843
Recycled Coarse Aggregate	0	780	780	1560	1560	920	0
High Range Water Reducer	0.83	1.38	3.03	1.66	5.64	0.88	0.88
w/cm	0.37	0.37	0.36	0.37	0.35	0.39	0.39

4.1.8 Round 1 of Analysis

The practice of utilizing crushed RCA in the base is common in Minnesota; however, there may not be enough quantity of RCA obtained locally on a project to satisfy the demand for the base course (up to 75% of the blend can be RCA according to MnDOT Standard Specifications) let alone in the concrete. In round 1 of the analysis, the priority usage of the locally crushed RCA was in the concrete pavement. If there was any RCA remaining, it was then applied to the base course.

4.1.9 Round 2 of Analysis

A review of several aggregate suppliers in Minnesota revealed that class 5 recycled concrete base could be purchased at a very low cost (average of about $5.25 per ton). This is significantly less than the $16.77 per ton for natural class 5 base (MnDOT average bid price). In light of this fact, a second round of LCCA was performed assuming that the contractor would purchase enough extra RCA base aggregate to make all of the bases 75% recycled and 25% natural.

As examples, Tables 33 through 35 show the spreadsheet analysis for three out of the total of sixteen different alternatives evaluated by the project team.

Table 33. Mix Analysis – Alternative 1 (0% RCA, 15 ft Joint Spacing)

	Length, mi	Width, ft	Thickness, in	Area, sy	Volume, cy	Useable %	Waste	Useable Vol, cy	Waste Vol, cy
Old PCCP	7	24	10	98,560	27,378	60%	40%	16,427	10,951
New PCCP	7	24	9	98,560	24,640				

						Volume of Remaining RCA, cy	% Recycled Material	% Natural Material
Base	7	24	8	98,560	21,902	16,427	75%	25%

Concrete Mix Components	Weight, pcy	Volume, cy	Total Project Volume, cy	Total Weight for Project, tons	Cost	Concrete Cost, $/cy
Cement	410	0.08	1,904	5,051	$209,391	
Fly Ash	175	0.04	948	2,156	$194,040	
Water	216	0.13	3,166	2,667	$23.6	
Natural Coarse Aggregate	1,819	0.39	9,617	22,406	$492,928	
Natural Fine Aggregate	1,309	0.30	7,299	16,126	$80,628	
Recycled Coarse Aggregate	0	0.00	0	0	$0	
HRWR	0.83	0.000	12	10	$10,226	
						$40.07

Table 34. Mix Analysis – Alternative 2 (50% RCA, 15 ft Joint Spacing)

	Length, mi	Width, ft	Thickness, in	Area, sy	Volume, cy	Useable %	Waste	Useable Vol, cy	Waste Vol, cy
Old PCCP	7	24	10	98,560	27,378	60%	40%	16,427	10,951
New PCCP	7	24	9	98,560	24,640				

						Volume of Remaining RCA, cy	% Recycled Material	% Natural Material
Base	7	24	8	98,560	21,902	11,618	53%	47%

Concrete Mix Components	Weight, pcy	Volume, cy	Total Project Volume, cy	Total Weight for Project, tons	Cost	Concrete Cost, $/cy
Cement	410	0.08	1,904	5,051	$209,391	
Fly Ash	175	0.04	948	2,156	$194,040	
Water	217	0.13	3,166	2,673	$23.6	
Natural Coarse Aggregate	909	0.20	4,808	11,199	$246,375	
Natural Fine Aggregate	1,309	0.30	7,299	16,127	$80,634	
Recycled Coarse Aggregate	780	0.20	4,808	9,610	$84,084	
HRWR	1.38	0.001	20	17	$17,002	
						$33.75

Table 35. Mix Analysis – Alternative 7 (100% RCA, 15 ft Joint Spacing, reduced w/cm)

	Length, mi	Width, ft	Thickness, in	Area, sy	Volume, cy	Useable %	Waste	Useable Vol, cy	Waste Vol, cy
Old PCCP	7	24	10	98,560	27,378	60%	40%	16,427	10,951
New PCCP	7	24	9	98,560	24,640				

						Volume of Remaining RCA, cy	% Recycled Material	% Natural Material
Base	7	24	8	98,560	21,902	6,810	31%	69%

Concrete Mix Components	Weight, pcy	Volume, cy	Total Project Volume, cy	Total Weight for Project, tons	Cost	Concrete Cost, $/cy
Cement	420	0.08	1,950	5,174	$214,498	
Fly Ash	182	0.04	986	2,242	$201,802	
Water	211	0.13	3,081	2,600	$23.0	
Natural Coarse Aggregate	0	0.00	0	0	$0	
Natural Fine Aggregate	1,309	0.30	7,299	16,126	$80,629	
Recycled Coarse Aggregate	1,560	0.39	9,617	19,214	$168,122	
HRWR	5.64	0.003	81	69	$69,485	
						$29.81

The second part of the spreadsheet performs the economic analysis and is shown in Tables 36 through 38.

Table 36. Economic Analysis – Alternative 1 (0% RCA, 15 ft Joint Spacing)

Hauling Distances and Costs	Distance, mi	Cost, $
Crushing Old Concrete	0	0
Delivery of RCA	0	0
Delivery of Natural Aggregate	30	$538,541

Initial Costs	Total Cost, $	Unit Cost, $/sy
Concrete	$977,012	
Recycled Portion of Base	$287,467	
Natural Portion of Base	$213,952	
Haulage	$538,541	
Sawcutting	$285,627	
Dowels	$365,460	
Total Initial Cost	$2,668,060	$ 27.07

Analysis Results		per sy
Expected time to Major CPR, yrs	59	
Analysis Period, yrs	50	
Remaining Service Life, yrs	9	
Residual Value, $	$ 480,251	
Present Value of Residual Value, $	$ 221,121	
Cost of Major CPR, $		0
Present Value of Major CPR, $		0
Total NPV	$2,439,938	$ 24.76
Equiv. Uniform Annual Cost	$69,713	$ 0.71

Table 37. Economic Analysis – Alternative 2 (50% RCA, 15 ft Joint Spacing)

Hauling Distances and Costs	Distance, mi	Cost, $
Crushing Old Concrete	0	0
Delivery of RCA	0	0
Delivery of Natural Aggregate	30	$538,517

Initial Costs	Total Cost, $	Unit Cost, $/sy
Concrete	$814,548	
Recycled Portion of Base	$203,320	
Natural Portion of Base	$401,836	
Haulage	$538,517	
Sawcutting	$285,627	
Dowels	$365,460	
Total Initial Cost	$2,609,309	$ 26.47

Analysis Results		per sy
Expected time to Major CPR, yrs	50	
Analysis Period, yrs	50	
Remaining Service Life, yrs	0	
Residual Value, $	$ -	
Present Value of Residual Value, $	$ -	
Cost of Major CPR, $	$ 226,689	$ 2.30
Present Value of Major CPR, $	$ 107,678	$ 1.09
Total NPV	$2,716,987	$ 27.57
Equiv. Uniform Annual Cost	$77,629	$ 0.79

Table 38. Economic Analysis – Alternative 7 (100% RCA, 15 ft Spacing, reduced w/cm)

Hauling Distances and Costs	Distance, mi	Cost, $
Crushing Old Concrete	0	0
Delivery of RCA	0	0
Delivery of Natural Aggregate	30	$538,555

Initial Costs	Total Cost, $	Unit Cost, $/sy
Concrete	$665,074	
Recycled Portion of Base	$119,173	
Natural Portion of Base	$589,720	
Haulage	$538,555	
Sawcutting	$285,627	
Dowels	$365,460	
Total Initial Cost	$2,563,609	$ 26.01

Analysis Results		per sy
Expected time to Major CPR, yrs	59	
Analysis Period, yrs	50	
Remaining Service Life, yrs	9	
Residual Value, $	$ 461,450	$ 4.68
Present Value of Residual Value, $	$ 219,191	$ 2.22
Cost of Major CPR, $		0
Present Value of Major CPR, $		0
Total NPV	$2,344,419	$ 23.79
Equiv. Uniform Annual Cost	$66,984	$ 0.68

4.2 RESULTS

The results of the first round of LCCA are presented in Table 39 in increasing order of costs from left to right. The results clearly indicate that the use of RCA in concrete can be economical with two of the alternatives being less costly than the conventional concrete alternative. It can be seen that pavement longevity is valuable, with those alternatives with lower expected lives to the first major CPR being among the most expensive. When evaluating the option of improving life expectancy either by thickening the pavement slab or modifying the concrete mix to a stronger design, the latter proved to be more economical. The most economical alternative overall was number 7, which was the 100% RCA mix with a lower w/cm ratio. Although, with this alternative we are increasing the cementitious content which is an expensive component of the concrete, the benefit achieved by substituting the less expensive RCA for the natural aggregate outweighs this. As natural aggregate costs for concrete tend to be higher than the natural aggregate costs for bases, it seems to make good economic sense to utilize the locally available crushed RCA from a project first in the concrete rather than the base course. Alternatives 6 and 5 both with 100% RCA are adversely impacted with the need to reduce joint spacing from 15 ft to 12 ft with correspondingly higher costs for sawcuts and dowel bars. The two-lift construction finished somewhere near the middle demonstrating that savings in material costs can help to offset increased labor and equipment costs. It should be noted however; that there is not enough historical data to have much knowledge on the long-term performance, predicted service life, and maintenance activities for the two-lift pavement.

Table 39. Results of LCCA for Round 1

	Alternative							
	7	4	1	3	8	2	6	5
Net Present Value (millions)	$2.344	$2.393	$2.440	$2.531	$2.606	$2.717	$2.759	$2.821
NPV (per SY)	$23.79	$24.27	$24.76	$25.68	$26.44	$27.57	$27.99	$28.62
Annual Cost	$66,984	$68,358	$69,713	$72,326	$74,447	$77,629	$78,829	$80,606
Annual Cost (per SY)	$0.68	$0.69	$0.71	$0.73	$0.76	$0.79	$0.80	$0.82
Assumed Life to 1st Major CPR	59	59	59	59	59	50	59	46
Thickness	9	9	9	10.08	9	9	11.16	9
Joint Spacing	15	15	15	15	15	15	12	12
% RCA in concrete	100	50	0	50	31	50	100	100
% RCA in base	31	53	75	50	59	53	21	31
Concrete cost (per CY)	$29.81	$34.85	$40.07	$33.75	$19.91	$33.75	$27.30	$27.30

As noted previously, it was found that class 5 RCA for base was available from several aggregate suppliers at a substantially lower price than natural aggregate for class 5 base. A second round of analysis was performed assuming the contractor would purchase extra RCA from offsite to achieve the maximum allowable recycled content of 75% recycled in the base. The results of this analysis are shown in Table 40 with the cost increasing from left to right. All of the costs are significantly reduced compared to Table 39. Under this scenario, the fact that RCA use in concrete can be highly economical is even more pronounced with most alternatives proving less costly than the conventional concrete pavement (alternative 1). The most economical alternatives were unchanged from round 1, i.e. Alternatives 7 and 4. The trends seen previously also held here. When looking at the alternatives containing RCA, the most expensive ones tend to be the ones with shorter life expectancy to first major CPR. It appears to be cheaper to change the mix design to a stronger more durable mix than to increase the thickness of the pavement.

4.3 OTHER COSTS

The previous sections have described the major components that should be included in any life cycle cost analysis for concrete pavements made with natural or with recycled concrete aggregates. Those sections mentioned costs associated with concrete pavement construction including

- Purchasing aggregate,
- Crushing where needed,
- All other concrete-making materials (cement, fly ash, water, etc.),
- Joint dowels and sawcutting,
- Hauling, and
- Landfill charges, where applicable.

Table 40. Results of LCCA for Round 2 (Extra RCA purchased for base)

	Alternative							
	7	**4**	**6**	**3**	**5**	**8**	**1**	**2**
Net Present Value (millions)	$1.878	$2.159	$2.181	$2.270	$2.311	$2.431	$2.440	$2.462
NPV (per SY)	$19.05	$21.91	$22.12	$23.03	$23.45	$24.66	$24.76	$24.98
Annual Cost	$53,657	$61,695	$62,303	$64,862	$66,033	$69,454	$69,713	$70,342
Annual Cost (per SY)	$0.54	$0.63	$0.63	$0.66	$0.67	$0.70	$0.71	$0.71
% RCA in concrete	100	50	100	50	100	31	0	50
% RCA in base	75	75	75	75	75	75	75	75

The majority of these expenses can be quantified without great effort, particularly when the cost analysis is conducted by a contractor with an intimate knowledge of these items and their likely costs. In addition to these expenses, other less tangible items should be considered when assessing the feasibility of using recycled concrete aggregates for use in new concrete. These include the following.

- **Stockpile Management**

  When construction project documents call for the use of recycled concrete materials, the contractor must make arrangements for additional physical space for stockpiles and the additional labor and equipment to manage them. In cases where the old concrete is removed, crushed, and reused in place, there is still a need for moving the material out of the roadway while other components of the pavement structure are built. In those cases, space must be made available to the side of the roadway under construction and the material must be deposited there during or after crushing and then moved to a batch plant and returned in the new concrete for placement.

- **Accounting Procedures**

  A cost item that arises and is often considered less prominently than the others is the accounting procedures and standards that must be followed by contractors and producers of recycled materials. These costs are also borne by owners of natural aggregates as well.

  Proper accounting standards require that any recycled material owned by a producer or contractor must be entered as an asset in the owner's accounting system. In essence, a stockpile of recycled material owned by a producer or contractor is unsold goods that are carried on the balance sheet. During the construction season, these assets are not held by the owner very long, when they are being used that season in the construction of an new concrete pavement. However, when the contractor or producer retains ownership over a winter, between construction seasons, it becomes a longer-term asset, again recognized as "unsold goods" that can be detrimental to the overall accounting practices of the owner.

- **Alternative Beneficial Uses**

  As has been discussed previously in this report, there are other uses for recycled concrete aggregates. One of the most common of these uses is as a replacement for natural aggregate the base layer. As shown in the economic analyses earlier in this report, since any available RCA material is usually used in the base layer, a decision must be made to use it as an aggregate in the new concrete layer rather than in the base. In either case, the trade-off between using the recycled concrete material in the base or the surface layer means that additional aggregate must be brought to the site from elsewhere. The cost of the additional aggregate is likely to be different in order to meet specification requirements for concrete or for base material, and this should be considered in the analysis.

When recycled coarse aggregates are used in the concrete layer, a large amount of fines are left to be used or wasted. Other uses for recycled concrete fine materials include stabilization of subgrade materials, shouldering materials, and other stabilization methods. Decisions to use the fine and/or coarse recycled materials should consider the various alternative uses and the potential unanticipated costs to the project.

4.4 SUSTAINABILITY OF RCA PAVEMENTS

The triple bottom line principles by which sustainability can be measured are economic, environmental, and social benefits. According to the FHWA, the goal of sustainability is the satisfaction of basic social and economic needs, both present and future, and the responsible use of natural resources, all while maintaining or improving the well-being of the environment on which life depends. A sustainable highway should satisfy lifecycle functional requirements of societal development and economic growth while reducing negative impacts to the environment and consumption of natural resources.

4.5 FHWA INVEST SOFTWARE

The FHWA have developed a tool to assist highway agencies measure the sustainability level of their projects. The tool is called the Infrastructure Voluntary Evaluation Sustainability Tool (INVEST). The current version is Version 1.2. It is based on a scorecard format with points being awarded across multiple categories spanning all the way from project planning through construction. Various achievement levels are attainable as shown in Table 41. In this respect, the tool somewhat resembles the popular LEED rating system which is widely utilized in building projects.

Table 41. INVEST Project Development Achievement Levels

Achievement Level	Fraction of Total Points Possible	Points Required					
		Paving	Urban Basic	Urban Extended	Rural Basic	Rural Extended	Scenic and Recreational
No. of Available Points		63	136	171	119	153	136
Platinum	60%	38	82	103	71	92	82
Gold	50%	32	68	86	60	77	68
Silver	40%	25	54	69	48	61	54
Bronze	30%	19	41	52	36	46	41

Criteria within the FHWA INVEST modules encompass aspects from all three sustainability principles. For example, for the project development (PD) module the criteria are categorized as shown in Table 42.

Table 42. Project Development Criteria by Sustainability Principle

Criterion Number and Title	Max No. of Points	Triple Bottom Line Principles		
		Social	Environmental	Economic
PD-01: Economic Analyses	5	X	X	X
PD-02: Life-Cycle Cost Analyses	3		X	X
PD-03: Context-Sensitive Project Development	10	X	X	X
PD-04: Highway and Traffic Safety	10	X		X
PD-05: Educational Outreach	2	X	X	X
PD-06: Tracking Environmental Commitments	5	X	X	
PD-07: Habitat Restoration	7		X	
PD-08: Stormwater Quality and Flow Control	6		X	
PD-09: Ecological Connectivity	4	X	X	X
PD-10: Pedestrian Facilities	3	X	X	X
PD-11: Bicycle Facilities	3	X	X	X
PD-12: Transit and HOV Facilities	5	X	X	X
PD-13: Freight Mobility	7		X	X
PD-14: ITS for Systems Operations	5	X	X	X
PD-15: Historic, Archaeological, and Cultural Preservation	3	X		
PD-16: Scenic, Natural, or Recreational Qualities	3	X		
PD-17: Energy Efficiency	8		X	X
PD-18: Site Vegetation, Maintenance and Irrigation	6		X	X
PD-19: Reduce, Reuse, and Repurpose Materials	12		X	X
PD-20: Recycle Materials	10		X	X
PD-21: Earthwork Balance	5		X	X
PD-22: Long-Life Pavement	7		X	X
PD-23: Reduced Energy and Emissions in Pavement Materials	3	X	X	X
PD-24: Permeable Pavement	2		X	X
PD-25: Construction Environmental Training	1	X	X	

PD-26: Construction Equipment Emission Reduction	2	X	X	
PD-27: Construction Noise Mitigation	2	X	X	
PD-28: Construction Quality Control Plan	5		X	X
PD-29: Construction Waste Management	3		X	X
PD-30: Low Impact Development	3		X	
PD-31: Infrastructure Resiliency Planning and Design	12	X	X	X
PD-32: Light Pollution	3	X	X	
PD-33: Noise Abatement	5	X	X	

An evaluation of the alternatives considered in the economic analysis part of this report was performed to determine if there was any difference in sustainability levels under the criteria of the PD module as listed in Table 42. The criteria that were investigated were PD-01 Economic Analyses, PD-02 Life-Cycle Cost Analyses, PD-19 Reduce, Reuse, and Repurpose Materials, PD-20 Recycle Materials, PD-22 Long-Life Pavement, PD-23 Reduced Energy and Emissions, PD-29 Construction Waste Management. The analysis revealed that all of the alternatives considered were similar and there is no advantage given in FHWA INVEST per se for utilizing the RCA in the concrete versus utilizing it in the base course. For example, under criterion PD-20.1, up to 5 points can be earned if the average recycled content (ARC) is 50% or more.

$$ARC(\%) = \frac{\left(\sum r_n\right)}{\left(\sum W_n\right)} \times 100\% \qquad (27)$$

where r_n = total weight or volume of RAP or RCA,
W_n = total weight or volume of either all existing pavement materials or bedding, backfill, and granular embankment materials per the method of recycling used,
n = number of materials considered in accordance with the method used.

For all of the alternatives considered, about 60% of the existing pavement material was used as RCA either in the new concrete or in the base, thus all would score 5 points under this criterion.

However, it can be seen that a sustainable project can easily be developed using RCA. As an example, a custom score card was created in INVEST including 11 default core areas specified by INVEST. The results from Alternative 7, the 100% RCA mix with w/cm of 0.35 are shown in Table 43. The project scored a total of 50 points out of 68 which corresponds to 73% resulting in an achievement of Platinum status. If the project were scored on the Urban Basic scorecard, this would be guaranteed at least a Bronze status and is very close the Silver status level. The detailed questions answered in the survey is included at the end of this report as an appendix.

Table 43. Score for 100% RCA Mix in INVEST Custom Scorecard

Criteria	Points possible	Score
PD-01 Economic Analyses	5	5
PD-02 Lifecycle Cost Analyses	3	1
PD-04 Highway and Traffic Safety	10	10
PD-06 Tracking Environmental Commitments	5	5
PD-19 Reduce, Reuse and Repurpose Materials	12	8
PD-20 Recycle Materials	10	5
PD-22 Long-Life Pavement	7	7
PD-23 Reduced Energy and Emissions in Pavement Materials	3	3
PD-24 Permeable Pavement	2	0
PD-26 Construction Equipment Emission Reduction	2	1
PD-28 Construction Quality Control Plan	5	5
PD-29 Construction Waste Management	4	0
Total	68	50

4.6 PALATE

PaLATE is an excel-based tool to perform lifecycle analysis (LCA). It was developed for the Recycled Material Resource Center. A comparison of Alternative 7 (100% RCA mix) against Alternative 1 (conventional concrete) was performed in PaLATE. The results for Alternative 7 are given in Table 44, while the results for Alternative 1 are given in Table 45. The output includes several parameters such as energy consumption, water consumption, various emissions, potential leachates, and human toxicity. It can be seen that in most cases the values are fairly similar and in many cases the 100% RCA mix appears to have more environmental benefit.

Table 44. Alternative 7 (100% RCA Mix) LCA Results from PaLATE

	Materials Production	Materials Transportation	Processes (Equipment)	Totals
Energy (MJ)	42,795,721	2,344,953	428,198	45,568,872
Water Consumption (kg)	15,869	399	42	16,310
CO_2 (mg) = GWP	3,158	175	32	3,365
NO_x (kg)	36,892	9,419	677	46,988

PM_{10} (kg)	16,926	1,837	48	18,811
SO_2 (kg)	24,146	565	45	24,756
CO (kg)	19,626	785	146	20,557
Hg (g)	60	2	0	62
Pb (g)	3,679	79	14	3,772
RCRA Hazardous Waste Generated (kg)	65,314	16,897	3,085	85,296
Human Toxicity Potential (cancer)	1,447,558	50,266	0	1,497,824
Human Toxicity Potential (non-cancer)	6,478,853,388	61,668,441	0	6,540,521,829

Table 45. Alternative 1 (Conventional Mix) LCA Results from PaLATE

	Materials Production	Materials Transportation	Processes (Equipment)	Totals
Energy (MJ)	42,764,915	2,413,647	423,103	45,601,665
Water Consumption (kg)	15,870	411	41	16,322
CO_2 (mg) = GWP	2,987	180	32	3,199
NO_x (kg)	36,498	9,691	669	46,858
PM_{10} (kg)	17,218	1,890	48	19,156
SO_2 (kg)	23,966	581	44	24,592
CO (kg)	19,554	808	144	20,506
Hg (g)	60	2	0	62
Pb (g)	3,662	81	14	3,758
RCRA Hazardous Waste Generated (kg)	64,543	17,392	3,049	84,984
Human Toxicity Potential (cancer)	1,758,923	51,738	0	1,810,661
Human Toxicity Potential (non-cancer)	10,433,611,888	63,474,965	0	10,497,086,852

4.7 CHAPTER SUMMARY

An economic analysis using the LCCA approach shows that it can be very economical to use RCA in new concrete pavement construction. The practice of utilizing crushed RCA in the base course is already quite common in Minnesota; however, because the natural aggregate for concrete may be more expensive than that for base courses it may make good economic sense to substitute RCA for natural aggregate in concrete.

Long-life pavements tend to be more economical then shorter-life pavements (with lower initial costs) in the long run. Concrete pavements made with RCA may have shorter life spans than those of their conventional concrete counterparts at the same w/cm ratio. To achieve similar performance, one option may be to change the structural design e.g. increase the thickness while another option may be to strengthen the mix e.g. by increasing the cementitious material and decreasing the w/cm ratio. The LCCA performed in this report tends to favor the option of strengthening the concrete mix.

In most cases, the amount of RCA available from crushing an existing PCCP locally is expected to be less than what is needed to construct both the new concrete pavement as well as the base course. At current rates, the cost of purchasing recycled concrete base is significantly less than that of natural aggregates; therefore, if the contractor purchases extra RCA to make the entire base up to 70% recycled, then the project becomes even more economical.

Economics is just one of the triple bottom line principles of sustainability, the others being environment and social aspects. One comprehensive tool for assessing sustainability is the FHWA INVEST tool. The utilization of a large amount of RCA material either in the base or the new concrete can qualify a project for several points in the INVEST program, thus indicating the sustainable impact of using RCA.

Environmental and social impacts were also evaluated utilizing the LCA framework in the PaLATE program. The use of a large amount of RCA in the concrete had several advantages over the conventional concrete for example in decreased human toxicity potential, reduced energy consumption, and some reduced emissions.

CHAPTER 5: GUIDELINES FOR USING RCA IN CONCRETE PAVEMENTS

The use of recycled concrete aggregate (RCA) in the construction of new concrete pavements was proven to be a sustainable practice, as discussed in Chapter 4 of this research project. In particular, lifecycle cost analysis showed that this was an economical alternative. Therefore, the practice of using RCA in new concrete should be encouraged. Minnesota is one of the states which has built the most number of new concrete pavements using RCA, yet there are no MnDOT specifications addressing this issue. The lack of specifications may seem to imply that this practice is not allowed or encouraged and may have contractors shying away from its use.

In this chapter, first a review of existing guidelines or specifications by various agencies as well as information in the literature was performed. Finally, recommendations are given at the end of the chapter which MnDOT may wish to consider in shaping any possible future specification regarding the use of recycled concrete aggregate in new concrete pavement construction.

The authors feel that the emphasis should be on mixture proportioning and producing a concrete with satisfactory strength and durability properties rather than specifying multiple tests on the RCA itself. It has been shown by the authors and other researchers that it is possible to create strong and durable concrete mixtures using RCA as coarse aggregate in volume replacement levels of coarse aggregate up to 100%.

5.1 REVIEW OF EXISTING GUIDELINES

A review of guidelines or specifications of various agencies as well as recommendations in the literature regarding the use of RCA in concrete was performed and is summarized in this section. Many of these have been mentioned in previous sections of this report, and are repeated in summary here. These recommendations cover material properties, materials handling, stockpiling, and construction practices. Some of the comments in this chapter are not specifically intended for RCA, but have similar implications for the use of RCA materials.

5.1.1 ACI 325

The American Concrete Institute (ACI) Committee 325 – Concrete Pavements only briefly mentions the topic of RCA in its “Guide for Construction of Concrete Pavements” (ACI 2015). It states that these materials possess properties that are different from natural aggregates, so they should be adequately characterized and carefully evaluated before incorporating into a construction project. In general, recycled materials to be used as aggregate for pavement concrete should meet the same requirements as virgin aggregate materials e.g. ASTM C33, unless the lower-quality recycled material is used in the lower layer of a two-course pavement.

5.1.2 ACI 555

ACI Committee 555 – Concrete with Recycled Materials has one chapter dedicated to the production of new concrete using RCA in its report "Removal and Reuse of Hardened Concrete" (ACI 2001). For *abrasion loss*, it uses the ASTM C33 criteria of <50% for general construction and <40% for crushed stone under pavements. It states that all but the poorest quality recycled concrete can be expected to pass this requirement. The *sulfate soundness* test could be performed on the RCA. For *contaminants*, the maximum allowable amounts of impurities are given in Table 46.

Table 46. Maximum Allowable Amounts of Impurities in RCA (ACI 555R-01)

Type of Aggregate	Plasters, clay lumps, and other impurities of densities < 3300 lb/yd^3 (1950 kg/m^3), lb/yd^3 (kg/m^3)	Asphalt, plastics, paints, cloth, paper, and similar material particles retained on a 0.047 in (1.2 mm) sieve (also other impurities of densities < 2000 lb/yd^3 [1200 kg/m^3]), lb/yd^3 (kg/m^3)
Recycled Coarse	17 (10)	3 (2)
Recycled Fine	17 (10)	3 (2)

In the next section of the report, the effects of RCA on hardened concrete properties are discussed. For recycled coarse and natural sand combinations, *compressive strengths* were reduced anywhere from 5 to 39%. For recycled coarse and recycled fines combinations, compressive strengths were lowered by 15 to 40%. The majority of strength loss was brought about by the portion of RCA smaller than the #8 sieve (2 mm); therefore, the use of RCA fines in concrete production may be prohibited.

The *modulus of elasticity* was lower by about 10 to 33% when only coarse RCA was used. *Creep* increased by 30 to 60%. *Drying shrinkage* was about 20 to 50% more for concretes with coarse RCA only. *Tensile strength and flexural strength* was reduced less than 10% but in one study was up to 20%. Many studies found that *freeze-thaw resistance* was approximately the same. The rate of *carbonation* was found to be 65% when using RCA that had already suffered carbonation.

It could be noted that many of the detrimental properties of using RCA could be offset by proper mixture proportioning and in particular by lowering the water-cementitious ratio. The following guidelines were given in ACI 555R-01.

- To determine a target mean strength on the basis of a required strength, a higher standard deviation (700 psi [4.83 MPa]) should be used when designing a concrete with recycled concrete aggregates of variable quality than when recycled aggregate of uniform quality or virgin aggregates are used;
- At the design stage, it may be assumed that the w/c for a required compressive strength will be the same for recycled aggregate concrete as for a conventional concrete when coarse recycled aggregate is used with conventional sand. If trial mixtures show that the compressive strength is lower than assumed, an adjustment to a lower w/c should be made;

- For the same slump, the free water requirement of recycled coarse aggregate concrete is 5% more than for conventional concrete;
- Specific gravity, unit weight, and absorption of aggregates should be determined before mixture proportion studies;
- The mixture proportion should be based on the measured density of the recycled aggregates intended in the job concrete;
- The sand-to-aggregate ratio for recycled aggregate concrete is the same as when using virgin materials;
- Trial mixtures are absolutely mandatory. If the placing will include confined spaces and irregular form shapes, trial placements should also be included;
- An important requirement of all recycled aggregate concrete is presoaking the aggregates to offset the high water absorption of the recycled aggregates; and
- Materials smaller than No. 8 sieve (approximately 2 mm) should be eliminated from aggregates prior to production.

5.1.3 FHWA Technical Advisory T5040.37

The Federal Highway Administration Technical Advisory T5040.37 has produced a report “Use of Recycled Concrete Pavement as Aggregate in Hydraulic-Cement Concrete Pavement” FHWA (2007). This report heavily references ACI 555R-01. The use of fine RCA is not recommended. It states that RCA should

- Be free of harmful components such as soil, asphalt, and steel. More than 90% of the material should be cement paste and aggregate. Asphalt content should be less than 1 percent;
- Be free of harmful components such as chlorides and reactive materials unless mitigation measures are taken to prevent recurrence of material related distress (MRD) in the new concrete; and
- Have an absorption of less than 10 percent.

In general, the RCA should meet the same requirements as for virgin aggregate e.g. ASTM C33. The LAR abrasion loss should be less than 50%. Freeze-thaw testing (ASTM C 666, "Standard Test Method for Resistance of Concrete to Rapid Freezing and Thawing") should be done as part of the evaluation and qualification of concrete mixtures containing RCA, in areas where resistance to freeze-thaw action is required. RCA derived from concrete containing more than 0.04 kg of chloride ion per cubic meter (0.06 lbs of chloride ion per cubic yard) should not be used in concrete for Continuously Reinforced or Jointed Reinforced concrete pavement because accelerated steel corrosion could lead to early pavement failure. In doweled jointed plain concrete pavement (JPCP), use of epoxy-coated, stainless steel, and stainless steel clad or fiber reinforced plastic (FRP) dowels should be considered to mitigate the potential corrosion. Alkalis from deicer salt within the RCA must be considered if the RCA is prone to ASR, and it is to be used as an aggregate in concrete.

Shrinkage and thermal expansion characteristics of concrete containing RCA should be determined prior to pavement design so that the actual parameters can be used in the design process. Typically, concrete containing RCA will have a higher drying shrinkage and a higher coefficient of thermal expansion but testing must be performed on the proposed mixture to quantify the actual values. The most commonly used shrinkage test for concrete is ASTM C 157, "Standard Test Method for Length of Change of Hardened Hydraulic-Cement Mortar and Concrete." The coefficient of thermal expansion of concrete can be determined using methods described in AASHTO TP 60, "Standard Method Test for Coefficient of Thermal Expansion of Hydraulic Cement Concrete." Laboratory and field trials of the concrete mixture must be conducted to insure that the properties of the mixture containing RCA meet job requirements.

Mixture design and proportioning of concrete containing RCA is accomplished using the same procedures used for concrete containing virgin aggregates. The water/cementitious material ratio should be 0.45 or less and a water-reducing admixture should be used. Additional cementitious material may be required to produce the required strength. Concrete containing coarse RCA may require approximately 5 percent more water than a similar concrete containing virgin coarse aggregate.

Concrete exhibiting MRD may be recycled for use in new concrete pavements only if the distress mechanism is recognized prior to project design, and proper mitigation measures are implemented to insure that the MRD will not recur in the new pavement. As part of the decision making process for recycling the old concrete pavement, a materials engineer should visit the site and observe the type and extent of distress. Pavement samples should be taken for laboratory evaluation. Using supplementary cementitious materials (i.e., fly ash or ground granulated blast furnace slag), or lithium admixture in the new concrete mixtures will help to mitigate Alkali-Silica Reaction (ASR). D-cracking is the result of water freezing in certain porous aggregates. The common mitigation method used by highway agencies is to reduce the maximum size of the aggregates subject to D-cracking. When pavement containing a D-cracking aggregate is recycled, the demolished concrete may require additional crushing to reduce the maximum aggregate size.

5.1.4 AASHTO MP 16-13

The American Association of State Highway Transportation Officials (AASHTO) has produced a Standard Specification for Reclaimed Concrete Aggregate for Use as Coarse Aggregate in Hydraulic Cement Concrete (AASHTO 2015). For the deleterious material content specification, three exposure categories, A, B, and C are defined as in Table 47.

Table 47. Exposure Classifications (AASHTO MP 16-13)

Typical Uses (Suggested)	Weathering Exposure	Class of Aggregate
Concrete pavements, cement-treated base courses, sidewalks, median barriers, curbings, and other nonstructural applications	Severe	A
	Moderate	B
	Negligible	C

The limits for deleterious materials is then given as in Table 48.

Table 48. Limits for Deleterious Substances (AASHTO MP 16-13)

	Maximum Allowable %				
Class Designation	Clay Lumps & Friable Particles	Chert (< 2.4 sp gr SSD)	Sum of Clay Lumps, Friable Particles, & Chert (< 2.4 sp gr SSD)	Other Deleterious Substances	Coal & Lignite
A	2.0	3.0	2.0	0.3	0.2
B	3.0	5.0	3.0	0.3	0.2
C	3.0	8.0	5.0	0.3	0.2

Some of the physical property limits specified by AASHTO MP 16-13 are summarized in Table 49.

Table 49. Physical Property Limits (AASHTO MP 15-13)

Property	Limit
LA Abrasion Loss, %	50
Soundness Loss, % (only if local experience shows test to be applicable)	12 (sodium sulfate) 18 (magnesium sulfate)
Amount of Material Finer than 75-µm (No. 200), %	1.5
Chloride Ion Content	0.6 lb/yd^3 of concrete

Other limitations on the physical properties of the RCA were given:

- RCA for use in concrete that will be subjected to in-service wetting, extended exposure to humid atmosphere, or contact with moist ground shall not contain any materials that are reactive with alkali components in the cement in an amount sufficient to cause excessive expansion of mortar or concrete. Except, if such materials are present in injurious amounts, the coarse aggregate may be used with the addition of a material that has been shown to prevent harmful expansion due to the alkali-aggregate reaction. Alkali reactivity shall be tested in accordance with AASHTO T 303 when alkali-silica reaction is suspected, and in accordance with ASTM C586 when alkali-carbonate reaction is suspected.
- RCA for use in concrete that will be subjected to freeze-thaw action shall not contain aggregate components that expand and result in D-cracking of the concrete. When potential D-cracking is suspected, the reclaimed concrete aggregate shall be tested in accordance with AASHTO T 161.
- RCA shall meet the flat and elongated particle requirements of the specifying jurisdiction.
- RCA shall be tested in accordance with T 85 to establish the specific gravity and absorption. For specific gravity, the total variability of tests from minimum value to maximum value shall not exceed 0.100; and for absorption, the total variability of tests from minimum value to maximum

value shall not exceed 0.8 percent. Aggregates that have specific gravity and absorption values that fall outside of these limits shall be stockpiled separately, and the limits stated above shall apply to the new stockpile.

Additionally, some requirements that have been imposed on the quality control aspects are:

- If the contractor/supplier wishes to use RCA, or combinations of RCA and other approved aggregate materials, a request shall be made to the engineer for approval. The percentage of combined materials shall be established as part of a pre-submitted blended aggregate combination. At the engineer’s discretion, revised hydraulic cement concrete mix designs shall be required when percentages of materials change.
- The contractor/supplier of RCA shall develop and implement a quality control plan for aggregate production. The quality control plan shall detail the production procedures, testing methods, and testing frequencies that will be used to ensure that RCA meets the requirements of the specification.
- The quality control plan will detail the production procedures and methods to ensure consistent production of aggregate from reclaimed concrete.
- Detail methods to ensure that reclaimed concrete source materials are not contaminated with extraneous solid waste or hazardous materials. Methods and criteria for examining reclaimed concrete materials prior to use should be established.
- Stockpiling will be required to assist in qualitatively and quantitatively identifying the presence of deleterious materials. Stockpiling can also be used as a means to qualitatively assess the uniformity of the material. The stockpile may represent all or part of the material to be used on a project and should be constructed in a manner that will minimize segregation and permit visual examination and representative sampling of the material.
- If reclaimed concrete aggregate is blended with other approved aggregates, this shall be accomplished by mechanical interlock blending or belt blending to ensure uniform proportioning.
- RCA shall be saturated with water for a time period that is sufficient to saturate all particles, prior to introducing the reclaimed concrete aggregate into a concrete mix, by means of a water-sprinkling system or another approved method. At the time of batching, the reclaimed concrete aggregate shall contain water in excess of the saturated surface-dry condition.
- Provision shall also be made for the free drainage of excess water.

5.1.5 Butler et al. 2013

Butler et al. 2013 have presented some guidelines for the use of RCA. Their findings were based on experiments conducted on three different sources of RCA.

- RCA-1 derived from crushing of municipal concrete sidewalks, curb and gutter structures;
- RCA-2 derived from crushing of concrete apron and terminal structures at Pearson International Airport in Toronto, Canada; and
- RCA-3 derived from crushing of hardened returned concrete (approximately one year old) at a ready-mix concrete plant.

The RCA classification guidelines consist of three levels of assessment:

1. Determine whether the particular RCA source satisfies the existing standard specifications for natural or virgin coarse aggregates in concrete (Canadian Standards Association).
2. Determine the specific performance class to which the RCA belongs (see Table 50).
3. Based on the performance class, determine whether the RCA source is suitable for use in reinforced concrete (Class A), unreinforced concrete (Class B), or as fill material (Class C).

Class A aggregates could further be divided into two categories: Class A1 already meets the specifications for natural or virgin aggregates and therefore can be used unconditionally for this application; while Class A2 fails to meet some of the specifications for natural aggregate and must undergo the second level of assessment (Table 50) to determine if it is acceptable. Note that an aggregate must meet three out of the four criteria in Table 50 to achieve the appropriate designation. Also note that abrasion loss in Butler et al 2013 has been given in Micro-Deval. The authors of the current report have proposed a correlation equation between the Micro-Deval and Los Angeles Rattler based on the best-fit line of over 800 data points presented in Cuelho et al. 2008. The utilized equation is given by Equation 28.

$$\frac{LAR\_\%\_Loss}{40} = 0.283\frac{MD\_\%\_Loss}{18} + 0.45 \tag{28}$$

Table 50. Proposed Aggregate Property Limits for RCA (Butler et al. 2013)

Aggregate Property	Class A2	Class B	Class C
Relative Density (oven-dry)	≥ 2.3	2.0 to 2.3	< 2.0
% Adhered Mortar	≤ 50%	> 50%	> 50%
Absorption	≤ 3%	3 to 6%	≥ 6%
Abrasion Loss (Micro-Deval)	19 to 22%	22 to 25%	> 25%
Abrasion Loss (LAR) (conversion done by Reza & Wilde)	30 to 32%	32 to 34%	> 34%

5.1.6 Verian et al. 2013

Verian et al. 2013 performed an experimental study on the use of RCA in concrete for the Indiana Department of Transportation. Some of the strategies discussed to improve the performance of RCA in concrete included the following.

- Two-stage mixing instead of normal mixing. In normal mixing, fine aggregate, cement, coarse aggregate (RCA & natural), and all of the water are mixed for approximately 120 seconds. In two-stage mixing, fine aggregate plus coarse aggregate are first mixed for 60 seconds then half of the water is added and further mixing is done for 60 seconds; next cement is added and mixed for 30 seconds, then the remaining half of the water is added and mixed for 120 seconds. This gives a total mixing time of 270 seconds. During the first stage of mixing a layer of cement

slurry forms on the surface of recycled aggregate that fills the cracks and voids and eventually creates a better interfacial transition zone.
- Reducing the mortar content that clings to the aggregate can be done by crushing the old concrete to a maximum size aggregate that is less than the maximum size of the original aggregate in the old concrete.
- Adjustments to concrete mixture proportions.

The recommendations put forth to the Indiana DOT included:

- RCA should be required to meet existing INDOT requirements for #8 AP aggregates. In addition, the following conditions are recommended: The Brine Freeze and Thaw Soundness requirements should be used in place of the Sodium Sulfate Soundness for acceptance; and RCA materials having absorption values between 5.0 and 6.0 percent that pass AP testing may be used if proper handling techniques are employed, including pre-wetting of RCA stockpiles.
- RCA produced from existing INDOT concrete pavements is preferred, and those pavements should be evaluated prior to recycling to identify any existing materials related distresses that could impair the RCA's long-term durability. If the concrete pavement was placed prior to the establishment of INDOT AP quality aggregate standards and freeze-thaw durability is a concern, then cores taken at the joints and examined by a trained concrete petrographer can establish whether the aggregate has been freeze-thaw durable.
- RCA from variable and unknown sources should not be allowed unless they can be tested and shown consistently to have properties passing INDOT's AP standard and specifications for aggregates used in concrete pavements.
- The approval process for the use of RCA in INDOT pavement concrete should include field trial batches to ensure the ability of achieving workable concrete with the desired w/cm and air content.
- The determination of moisture content of RCA at time of batching is critical for proper adjustments of the mix water. It should be noted that if the moisture content of the RCA is less than SSD condition, then slump may change quickly after initial batching as water is absorbed.
- A quality paving concrete that meets INDOT specifications can be produced using some amount of RCA as a replacement for AP coarse aggregate. Replacement levels of up to 30% RCA for plain concrete and up to 50% for concrete containing approximately 20% Class C fly ash can result in paving concrete with properties very similar to concrete without RCA while using common batching and construction practices for producing quality paving concrete. Good quality concretes containing 100% RCA can be produced but the use of mineral and chemical admixtures is recommended and extra attention to appropriate proportioning is needed.
- It is recommended that RCA be pre-wetted (i.e. aggregate piles should be kept moist, near SSD) and the aggregate moisture content determined with good accuracy.
- The use of fly ash is recommended in RCA concrete, especially at higher aggregate replacement levels since it has been proven that fly ash generally improves the mechanical and durability properties of most concrete mixtures.
- Using the pressure meter to determine the fresh air content in RCA mixtures is valid, but additional side-by-side measurements with the volumetric method are recommended until greater confidence is achieved with a variety of RCA mixtures and RCA sources.

- The water-soluble chloride content of RCA should be determined for each RCA source as RCA can contain water soluble chlorides at levels that are higher than many natural aggregates. Elevated chlorides in the mixture can interfere with set time, admixture behavior, certain test results and corrosion of steel in the concrete. If corrosion of steel is a potential concern as in reinforced concrete elements then recommendations for maximum total chloride content given in ACI 222 Corrosion of Metals in Concrete should be followed.
- Use caution in interpreting the results of electrical conductance/resistance test for estimating penetrability/ permeability of concrete that contains RCA as RCA can contribute additional ions to the paste that may interfere with obtaining test results that accurately reflect penetrability/ permeability.
- If the RCA is from more than one source then the range of specific gravity and absorption values of the RCA sources should be determined in accordance to AASHTO T 85, and the range of values obtained shall be reported. If variations in absorption or specific gravities preclude satisfactory production of PCC mixtures, independent stockpiles of materials will be sampled, tested, and approved prior to use. It is recommended that the guidelines provided by AASHTO MP 16-13 be followed.
- When a variety of options for using RCA are available, an economic analysis can be conducted to determine the optimal use of resources and realize maximum cost savings.
- Encourage the use of RCA as a viable alternative to natural coarse aggregate in concrete paving mixtures. The use and availability of RCA can keep aggregate costs competitive and result in measurable savings for new concrete pavement construction, especially in regions in which quality natural aggregates are less available.

5.1.7 Stark 1996

- The following conclusions were presented by Stark (1996) in a report by the Portland Cement Association about the use of RCA from concrete exhibiting alkali-silica reactivity.
- Recycled concrete used as coarse aggregate in new concrete possesses potential for ASR in the new concrete if the original concrete contained aggregate that was susceptible to ASR.
- The alkali content of the cement in the original concrete where expansion due to ASR developed had little bearing on expansions due to ASR in new concrete containing the original concrete as recycled coarse aggregate.
- The alkali content of the cement in the new concrete containing recycled concrete as coarse aggregate had a significant effect on subsequent expansions due to ASR. However, the use of low-alkali cement without fly ash did not always reduce expansions due to ASR to safe levels.
- The use of a low-lime ASTM Class F fly ash in new concrete containing recycled concrete as coarse aggregate greatly reduced expansions due to ASR in the new concrete. However, to bring expansions to less than the test criterion, without exception, also required the use of low-alkali cement with the fly ash. It is not certain whether such stringent methods would be required for other, less reactive, recycled concretes used as coarse aggregate.
- The pavement engineer should not assume that, because expansive ASR did not develop in original concrete to be recycled as aggregate, it will not develop in the new concrete. Petrographic examination of the original concrete is recommended in this judgment.

5.1.8 Wen et al. 2015

A paper by Wen et al. in the Transportation Research Record (Wen et al., 2015) discussed the use of RCA in new concrete pavements, and developed the following conclusions.

- Test results showed that up to a 45% replacement of coarse natural aggregate with RCA had no significant effect on any of the hardened concrete properties tested.
- RCA should be washed and sieved to remove fine particles prior to being used as a replacement for natural aggregates in new concrete.
- Each RCA source should be tested for ASR following the crushing process, and mitigated as necessary.

This final recommendation seems somewhat impractical from an operational perspective, when quick ASR testing can take 16 days or more, and a good understanding of the ASR potential of the RCA material could take 12 months.

5.1.9 Garber et al. 2011

In *Technology Deployment Plan for the Use of Recycled Concrete Aggregates in Concrete Paving Mixtures* (Garber et al., 2011) described research done in several other countries, and provides recommendations from other researchers.

Researchers in Japan developed a method for indexing the quality of RCA materials. The researchers divided RCA materials into three classes: High, Middle, and Low quality. To be used in concrete applications, an RCA material must meet the criteria for High Quality. The classification is based on relative density and absorption, but the material also must meet requirements for abrasion, shape, quantity of fines, and chloride content. RILEM also recognizes three categories of RCA, based on absorption, density, sulfate content, and other durability-related properties.

The Japanese research also suggests that “up to 20 percent of coarse aggregate can be replaced with RCA without affecting concrete properties” and that maximum aggregate size should be limited to 16 to 20 mm. In Australia and the UK, up to 30 percent of coarse aggregate may be replaced with RCA. The UK researchers indicate that at this level “there is little to no effect on concrete properties.”

5.1.10 Other Research

Conclusions and recommendations similar to those mentioned above were found in many reports and journals. A few notable comments include the following.

- Limiting the amount of RCA fines to 25% can minimize water demand increase by approximately 15% (Buck, 1973)
- Increasing total air content by 1% can assure a good air-void system (Vandenbossche and Snyder, 1993)
- Use a volumetric method for air content (Roll-a-meter or air-void analyzer) to avoid potential problems associated with pressure methods (Fick, 2008);

- The American Concrete Paving Association suggests that pavement designers may use normal mix design methods when using RCA, but that they should "be careful" using RCA fines.

Current MnDOT Specifications

The current edition of MnDOT's Standard Specifications for Construction (2016) address the use of recycled concrete aggregate in materials and pavement layers other than the concrete surface layer. These include the following.

- **Drainable Bases (3136.A.1)**

  Virgin aggregates are required in drainable base layers "unless modified by the Contract to allow for recycled aggregates."

- **Shoulders (3138.2.D.3)**

  While recycled concrete materials are allowable for surface and base courses, this subsection restricts their use to shoulders only. Tables 3138-3, 3138-4, and 3138-5 provide gradation requirements for aggregates to be used in these applications, with recycled material content of less than 25%, 25% to less than 75%, and 75% or more, respectively.

- **Permeable Asphalt Stabilized Stress Relief Course (PASSRC) and Permeable Asphalt Stabilized Base (PASB) (3139.3)**

  While the scope of this report does not include asphaltic materials, it is notable that recycled materials "including glass, concrete, bituminous, shingles, ash, and steel slag" are not allowable in these layers.

- **Ultra-Thin Bonded Wearing Course (UTBWC) (3139.4)**

  Similar to the bituminous layers mentioned above, the same restrictions on recycled materials exist as for PASSRC and PASB).

- **Micro-Surfacing (3139.5)**

  Similar to the bituminous layers mentioned above, the same restrictions on recycled materials exist as for PASSRC and PASB).

- **Granular Material (3149.A.2)**

  "For products not required to be 100% virgin aggregates, the Contractor may substitute recycled aggregates…" Recycled aggregates are only allowable if they consist of "recycled asphalt pavement (RAP), recycled concrete materials, and recycled aggregate materials;" and if the recycled concrete material is "no greater than 75% of the material blend" and "no greater than 10 percent masonry block".

- **Riprap (3601.2.A.1)**

  Additionally, recycled concrete is not allowable for riprap applications “unless otherwise allowed 4by the contract.”

5.2 CHAPTER SUMMARY

The use of RCA in concrete pavements can be a sustainable practice; however, current MnDOT Standard Specifications do not address the issue. The AASHTO Provisional Standard MP16-13 represents a move forward at the national level to address the issue. The focus will be on establishing proper concrete mixture proportioning and testing rather than excessive testing of the aggregates themselves. This is because it has been proven that high-strength and durable concrete mixtures can be created using RCA as coarse aggregate. To prevent the lowest quality materials being used for RCA, an abrasion loss limit is suggested together with a limit on deleterious material content. The following is a suggestion by the authors for MnDOT to consider as a possible inclusion in the Standard Specifications. It is broken down into two parts: Specifications and Commentary.

5.2.1 Proposed Specifications for Use of Recycled Concrete Aggregate in New Concrete Pavement

- Preference shall be given to aggregates made from demolished concrete pavements which were previously constructed in conformance to the applicable MnDOT Standard Specifications at the time of construction.
- RCA shall be tested in accordance with MnDOT 1204 to establish the specific gravity and absorption. For specific gravity, the total variability of tests from minimum value to maximum value shall not exceed 0.100; and for absorption, the total variability of tests from minimum value to maximum value shall not exceed 0.8 percent. Aggregates that have specific gravity and absorption values that fall outside of these limits shall be stockpiled separately, and the limits stated above shall apply to the new stockpile (AASHTO MP 16-13).
- The use of recycled concrete aggregate as fine aggregate in the construction of new concrete pavements shall not be permitted. That is, recycled concrete material passing the No. 4 sieve shall not be allowed.
- RCA can be used to replace natural coarse aggregate in volume amounts up to 100% provided that:
    - Proper concrete mixture proportioning is performed and aggregate replacements are done by volume not mass;
    - Trial batches are created to evaluate proper workability and air-entrainment levels;
    - Test cylinders are created to demonstrate that concrete with RCA achieves similar strength levels as a conventional concrete mixture. Typically, the concrete with RCA must be made with a lower water-to-cementitious materials ratio to achieve similar strength with a comparable conventional concrete mixture.
- Deleterious material content shall be limited in accordance with Table 1 of AASHTO MP 16-13 (Table 48 in this report).

- RCA should have an abrasion loss of less than 50% when measured with the Los Angeles Rattler (MnDOT 1210).
- RCA obtained from old concrete pavements may already be at an advanced level of carbonation or have been subjected to chloride ion penetration; therefore
- New concrete pavement made with RCA should be Jointed Plain Concrete Pavement (JPCP) only. When dowel bars are used, they should be of stainless steel or other high-performance (corrosion resistant) material; otherwise the chloride ion content tested in accordance with AASHTO T 260 shall be less than 0.60 lb/yd^3 of concrete.
- The use of supplementary cementitious materials such as fly ash is highly recommended.
- RCA for use in concrete shall not contain any materials that are reactive with alkali components in the cement in an amount sufficient to cause excessive expansion of mortar or concrete. Except, if such materials are present in injurious amounts, the coarse aggregate may be used with the addition of a material that has been shown to prevent harmful expansion due to the alkali-aggregate reaction. Alkali reactivity shall be tested in accordance with AASHTO T 303 when alkali-silica reaction is suspected, and in accordance with ASTM C586 when alkali-carbonate reaction is suspected.
- RCA for use in concrete that will be subjected to freeze-thaw action shall not contain aggregate components that expand and result in D-cracking of the concrete. When potential D-cracking is suspected, the reclaimed concrete aggregate shall be tested in accordance with AASHTO T 161. Appropriate mitigation techniques similar to that applied for natural aggregate shall be applied.

5.2.2 Commentary to the Specifications

The use of recycled concrete aggregates in new concrete mixtures is a sustainable practice which includes economic benefits. Recycled fines are mainly non-durable mortar particles which tend to create problems such as increased shrinkage and creep as well as workability issues. For this reason, the use of recycled fines is not permitted in the construction of new concrete pavements.

Mortar content that adheres to the coarse aggregate is one of the reasons that concrete made with RCA exhibits less compressive strength and flexural strength, lower modulus of elasticity, increased shrinkage, increased creep, and higher coefficient of thermal expansion when compared with conventional concrete made with natural aggregates. One of the suggested techniques to reduce the amount of adhered mortar is to crush the RCA to a maximum size less than that of the original aggregate (with due consideration for minimum aggregate size for aggregate interlock at joints of JPCP).

Nonetheless it is possible to create concrete mixtures that are high-strength and durable using RCA. Proper mixture proportioning and trial batches are essential to developing durable and high-strength concrete mixtures. The use of fly ash is highly recommended due to its capabilities in reducing alkali-aggregate reaction and improving workability. Mechanical properties can be improved by lowering the water-to-cementitious material ratio. Admixture dosages must be evaluated to achieve proper workability and air-entrainment. The box test has been found to be a useful test when evaluating concrete mixtures containing RCA.

When RCA from different sources is used on the same project, variability in specific gravity and absorption can make concrete mixture proportioning difficult. Thus, when there is high variability from sample to sample, separate stockpiles must be maintained.

RCA may be made from an old concrete that has been subjected to carbonation and chloride ion ingress. For this reason, it is recommended that stainless steel or other high-performance (corrosion resistant) dowel bars be used. In lieu of this, a test should be performed to ensure that the chloride ion content is sufficiently low to prevent any corrosion problems.

RCA aggregates made from concrete exhibiting alkali-aggregate related distress or D-cracking have been successfully used in new concrete pavement construction. Appropriate mitigation techniques should be employed such as adding supplementary cementitious materials to mitigate alkali-aggregate reaction and crushing aggregates to a smaller size for D-cracking control.

CHAPTER 6: RECOMMENDATIONS AND CONCLUSIONS

Utilizing recycled concrete aggregate in new concrete pavement construction can impact the triple bottom line principles of sustainability – economic, environmental, and social benefits – in a positive manner. This practice should be encouraged especially during a time of dwindling natural aggregate resources across the nation. The use of RCA in the base course is already a well-established practice; however, utilizing RCA in the concrete itself will provide even more benefit. From an economic standpoint, the aggregate specified for concrete is typically of a higher quality (more expensive) than that specified for the base; therefore, substituting the RCA for aggregate in the concrete makes good economic sense. Lifecycle cost analysis showed that the utilization of RCA in the concrete can be economical; this is despite the fact that in order to achieve similar performance to a conventional concrete pavement with natural aggregates, the concrete mix must be strengthened, e.g. by adding cementitious content and lowering the water-cementitious material ratio.

One comprehensive tool for assessing sustainability is the FHWA INVEST tool. The utilization of a large amount of RCA material either in the base or the new concrete can qualify a project for several points in the INVEST program, thus indicating the sustainable impact of using RCA. Environmental and social impacts were also evaluated utilizing a lifecycle analysis framework. The use of a large amount of RCA in the concrete had several advantages over the conventional concrete, for example, in decreased human toxicity potential, reduced energy consumption, and some reduced emissions.

The early trial projects built in Minnesota in the 1980s using the RCA in the concrete pavement perhaps did not give due consideration in the design phase to the differences between concrete made with RCA and concrete made with natural aggregates. Therefore, somewhat unsurprisingly the long-term performance of the RCA pavements was found to be a little bit worse (27 years vs 32 years) compared to the conventional concrete pavements when assessed based on the time to when a major concrete pavement restoration was required. Nevertheless, the RCA pavements have performed satisfactorily with most still in service. Economic considerations are one of the principles of sustainable design and lifecycle cost analysis will favor longer-lasting pavements. In future designs using RCA in the concrete, adjustments should be made to the concrete mix design to overcome this deficiency in performance.

Some recommendations were given that could possibly be considered in developing any future specifications regarding the use of RCA in concrete. Recycled fines are mainly non-durable mortar particles that tend to create problems such as excessive shrinkage and creep as well as workability issues. For this reason, it has been recommended that the use of recycled fines not be permitted in the construction of new concrete pavements.

Mortar content that adheres to the coarse aggregate is one of the reasons that concrete made with RCA exhibits less compressive strength and flexural strength, lower modulus of elasticity, increased shrinkage, increased creep, and higher coefficient of thermal expansion when compared with conventional concrete made with natural aggregates. One of the suggested techniques to reduce the amount of adhered mortar is to crush the RCA to a maximum size less than that of the original aggregate (with due consideration for minimum aggregate size for aggregate interlock at joints of JPCP).

It is possible to create concrete mixtures that are high-strength and durable using RCA. Proper mixture proportioning and trial batches are essential to developing durable and high-strength concrete mixtures. The use of fly ash is highly recommended due to its capabilities in reducing alkali-aggregate reaction and improving workability. Mechanical properties can be improved by lowering the water-to-cementitious material ratio. Admixture dosages must be evaluated to achieve proper workability and air-entrainment. The box test has been found to be a useful test when evaluating concrete mixtures containing RCA. This test along with other promising tests such as the Vibrating Kelly Ball test for workability and electrical resistivity tests for durability assessments may form a portfolio of tests useful for evaluating concrete paving mixtures.

When RCA from different sources is used on the same project, variability in specific gravity and absorption can make concrete mixture proportioning difficult. Thus, when there is high variability from sample to sample, separate stockpiles should be maintained.

RCA may be made from an old concrete that has been subjected to carbonation and chloride ion ingress. For this reason, it is recommended that stainless steel or other high-performance (corrosion resistant) dowel bars be used. In lieu of this, a test should be performed to ensure that the chloride ion content is sufficiently low to prevent any corrosion problems. RCA aggregates made from concrete exhibiting alkali-aggregate related distress or D-cracking have been successfully used in new concrete pavement construction. Appropriate mitigation techniques should be employed such as adding supplementary cementitious materials to mitigate alkali-aggregate reaction and crushing aggregates to a smaller size for D-cracking control.

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APPENDIX A. RCA PAVEMENT TEST SECTIONS IN MINNESOTA

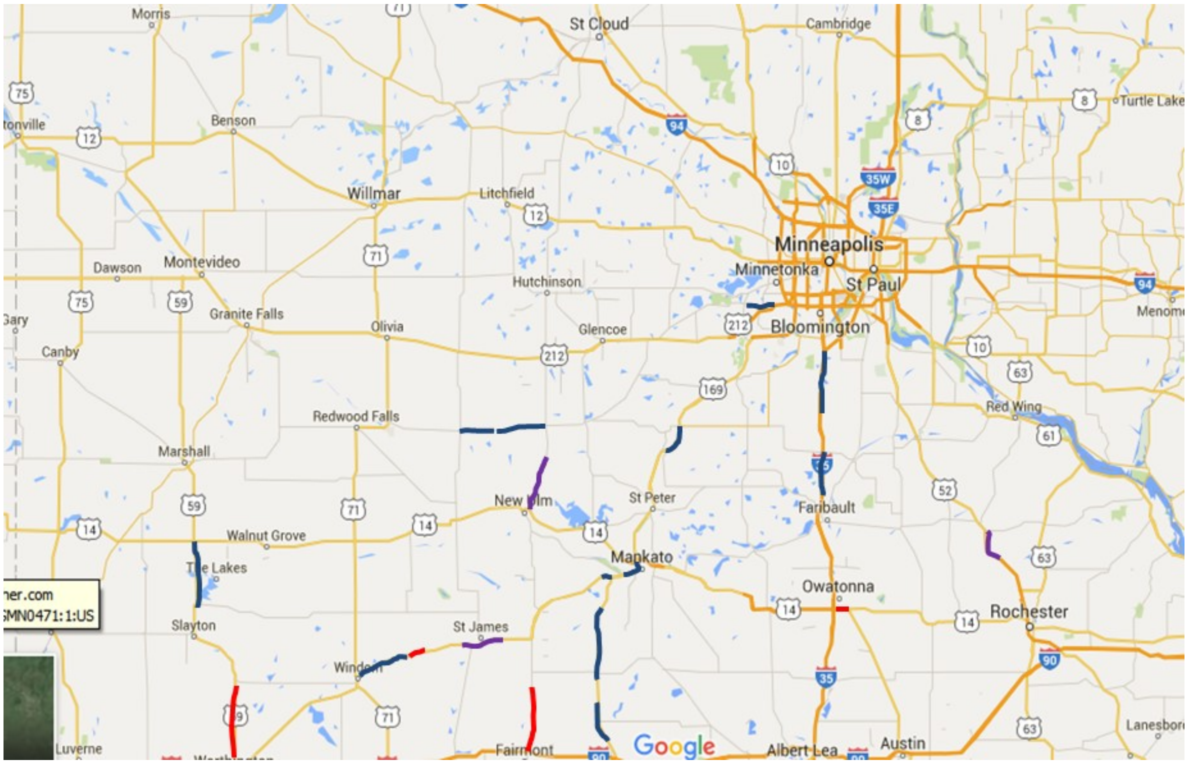

Figure A1. Map showing the locations of RCA sections in Minnesota

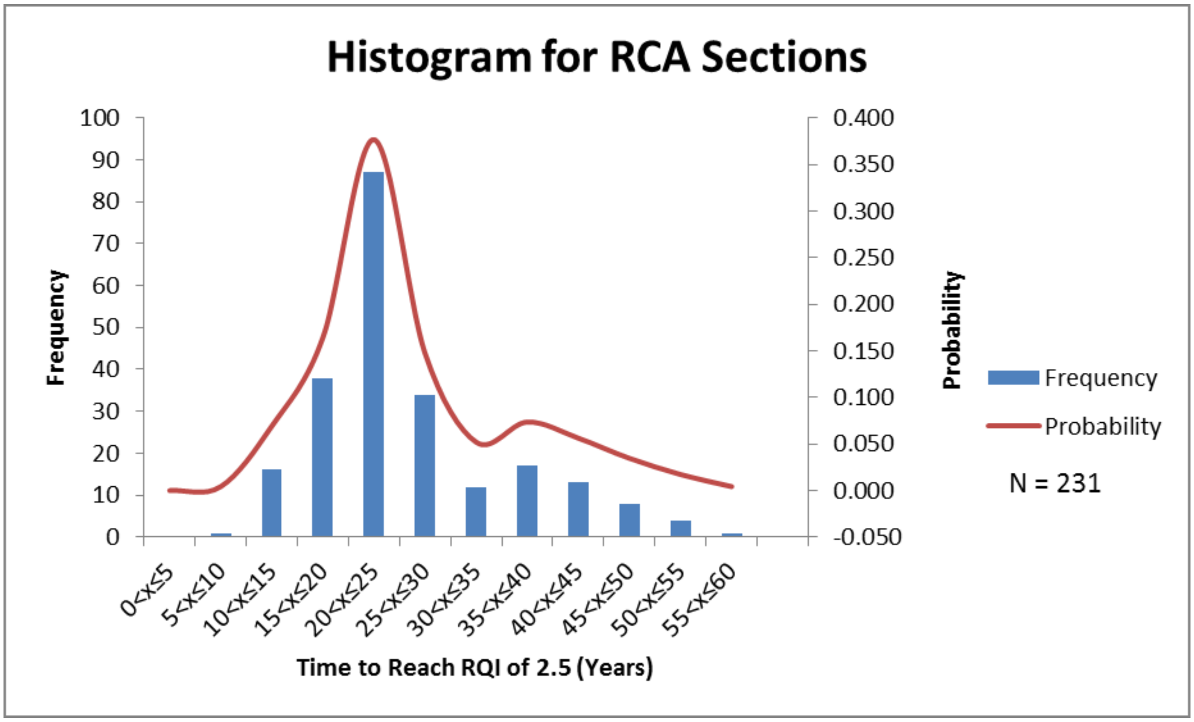

Figure A2 Histogram for time to reach RQI of 2.5 for RCA sections by number of observations

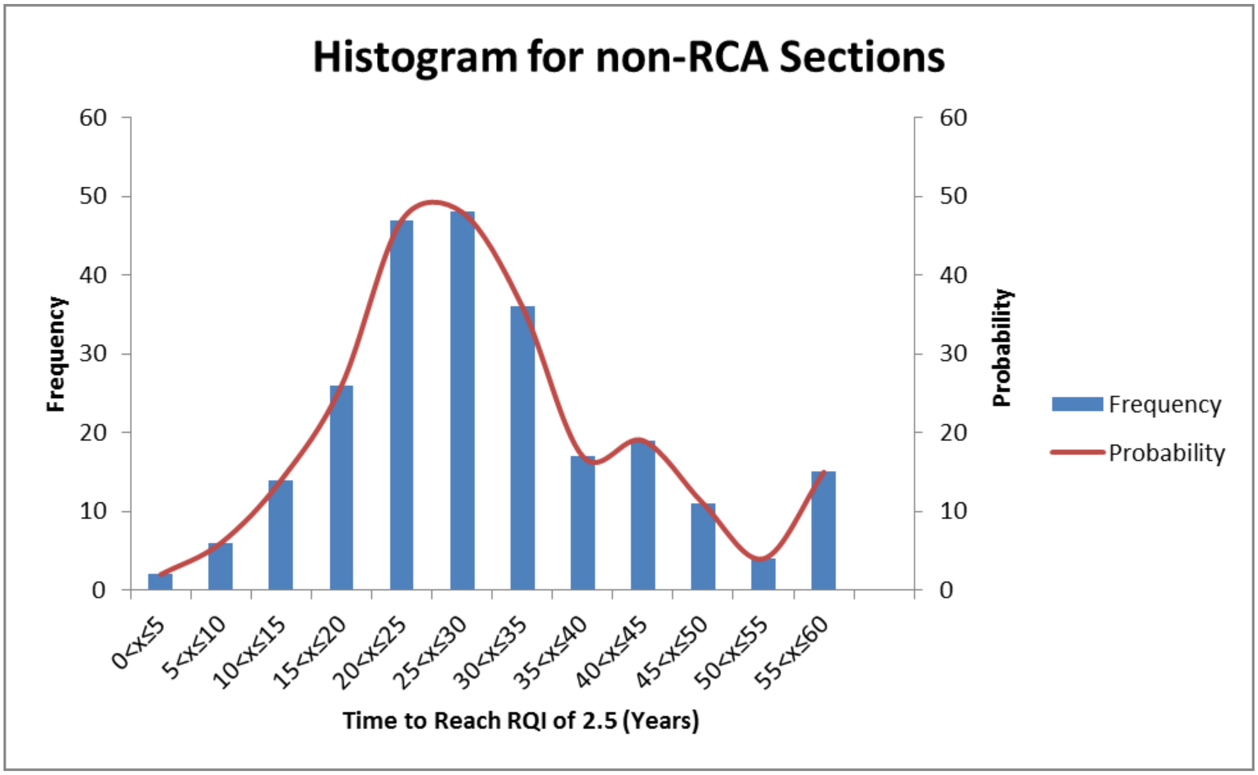

Figure A3 Histogram for time to reach RQI of 2.5 for non-RCA sections by observations

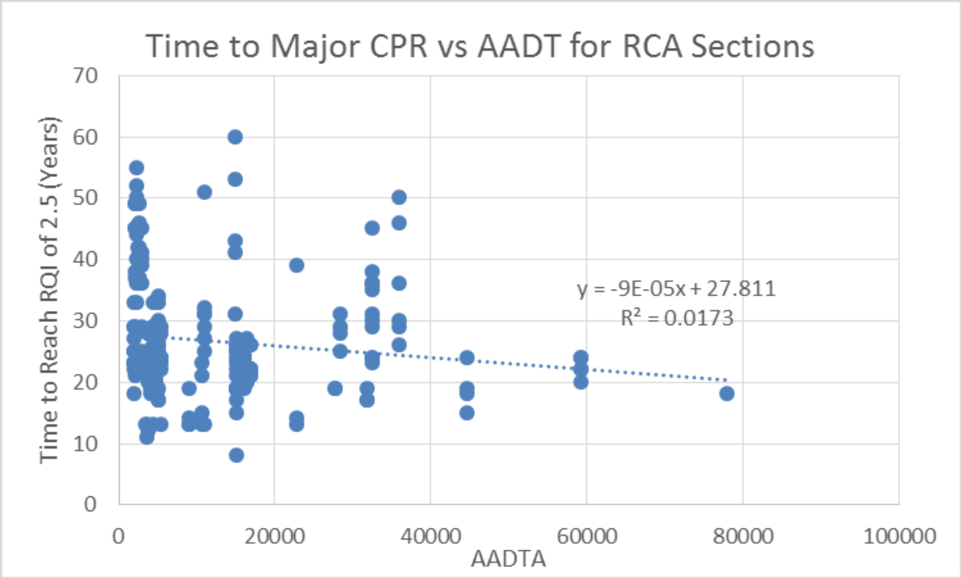

Figure A4 Time to reach RQI of 2.5 vs AADT for RCA sections

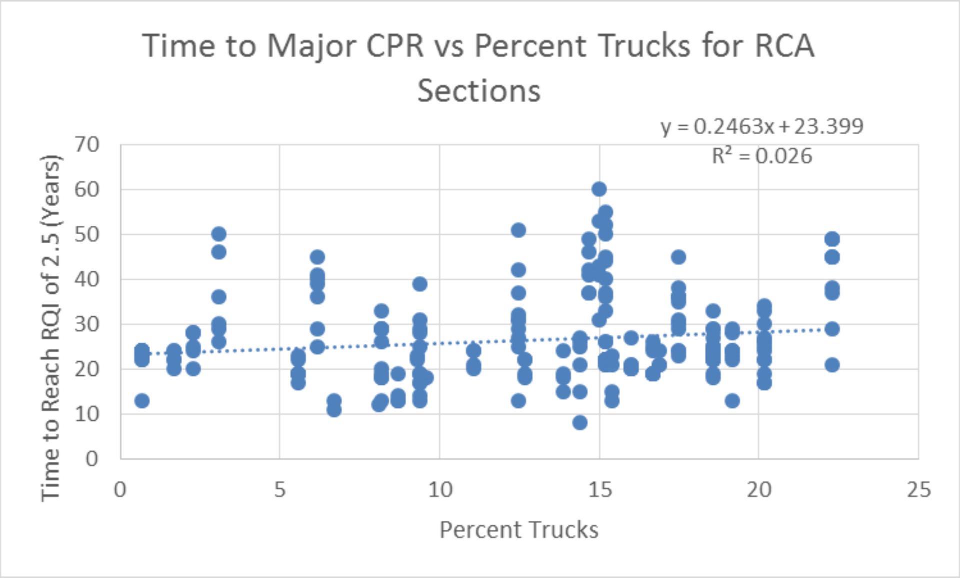

Figure A5 Time to reach RQI of 2.5 vs percent trucks for RCA sections

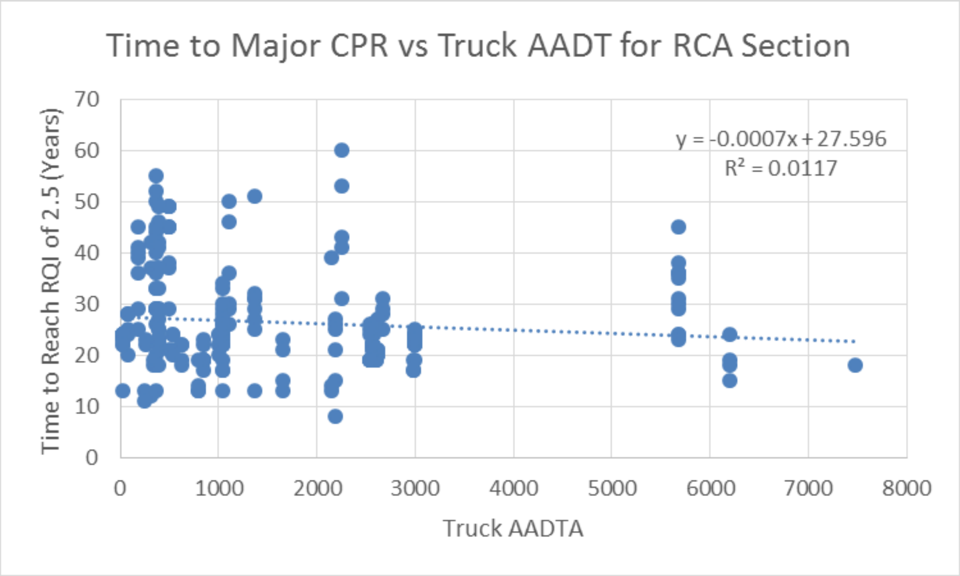

Figure A6 Time to reach RQI of 2.5 vs truck AADT for RCA sections

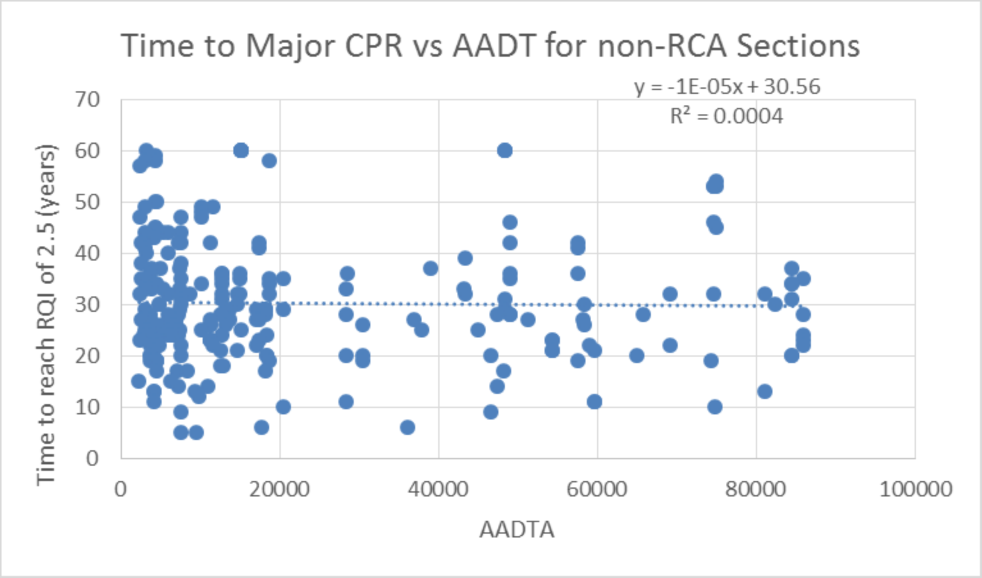

Figure A7 Time to reach RQI of 2.5 vs AADT for non-RCA sections

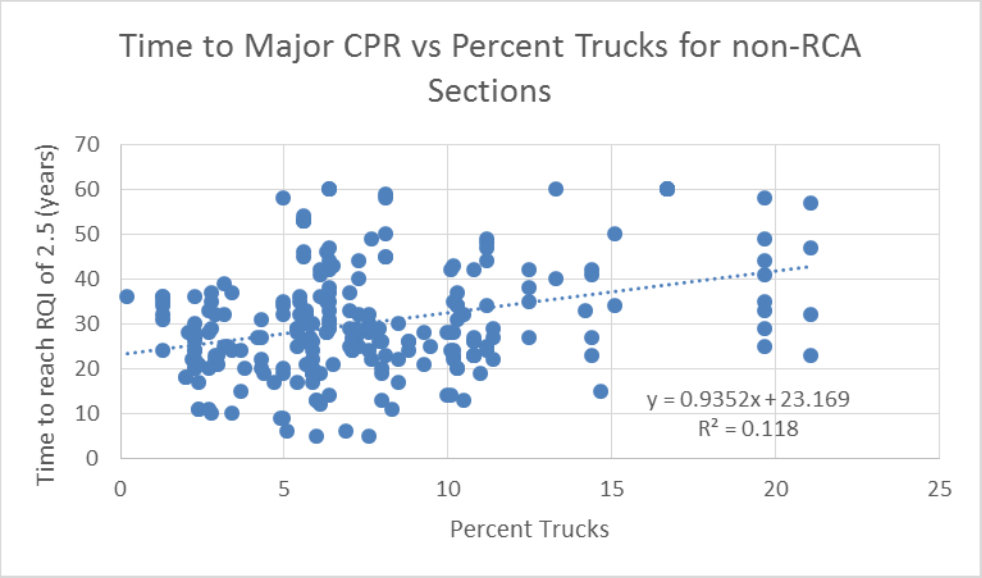

Figure A8 Time to reach RQI of 2.5 vs percent trucks for non-RCA sections

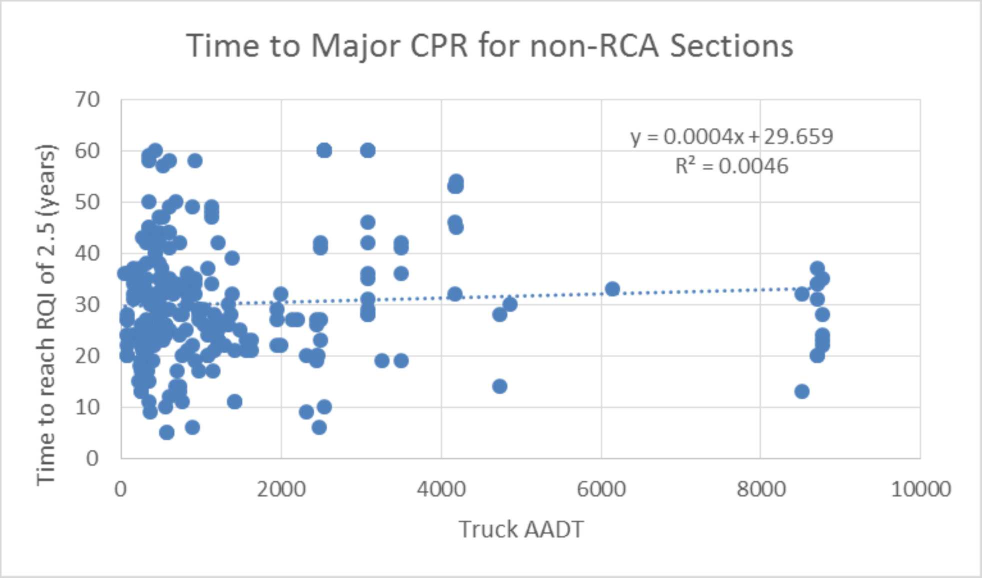

Figure A9 Time to reach RQI of 2.5 vs truck AADT for non-RCA sections

APPENDIX B. PAVEMENT TEST SECTION PERFORMANCE ANALYSIS

This appendix contains the details of the performance analysis conducted on the test sections constructed in Minnesota in the 1980s and 1990s.

				Time to RQI of 2.5, years									
Segment	MP Begin	MP End	Length, mi	Controlling	ARIMA (2,1,1)	EWM	Actual	Time to 1st Major CPR	AADTA	PCT Truck	Truck AADTA	Year Mile	Error^2 * Weight
IS94-I	34.972	35.969	0.997	60	60	60	>21	>21	15,045	15.0	2,257	59.820	3589
MN19-U	94.104	95.103	0.999	55	60	55	>21	>21	2,400	15.2	365	54.945	3022
IS94-I	34.972	35.969	0.997	53	57	53	>21	>21	15,045	15.0	2,257	52.841	2801
MN19-U	95.103	96.091	0.988	52	60	52	>21	>21	2,400	15.2	365	51.376	2672
IS90-I	0.999	1.998	0.999	51	46	51	>29	14	11,002	12.5	1,375	50.949	2598
MN19-U	93.089	94.104	1.015	50	50	51	>21	>21	2,400	15.2	365	50.750	2538
MN5-I	47.067	48.014	0.947	50	60	50	>23	>23	36,062	3.1	1,118	47.350	2368
US169-U	28.605	29.603	0.998	49	60	49	>22	>22	2,257	22.3	503	48.902	2396
US169-U	29.603	30.617	1.014	49	60	49	>22	>22	2,257	22.3	503	49.686	2435
US169-U	35.583	36.583	1.000	49	60	49	>22	>22	2,257	22.3	503	49.000	2401
MN19-U	106.103	107.103	1.000	49	57	49	>22	>22	2,664	14.7	392	49.000	2401
MN19-U	108.098	109.093	0.995	46	59	46	>22	>22	2,664	14.7	392	45.770	2105
MN5-I	46.066	47.067	1.001	46	50	46	>23	>23	36,062	3.1	1,118	46.046	2118
US169-U	14.613	15.613	1.000	45	48	45	>22	16	2,952	6.2	183	45.000	2025
US169-U	30.617	31.602	0.985	45	57	45	>22	>22	2,257	22.3	503	44.325	1995
US169-U	33.593	34.586	0.993	45	54	45	>22	>22	2,257	22.3	503	44.685	2011
US169-U	36.583	37.861	1.278	45	54	45	>22	>22	2,257	22.3	503	57.510	2588
MN19-U	97.358	98.088	0.730	45	46	45	>21	>21	2,400	15.2	365	32.850	1478
IS35-D	65.044	66.045	1.001	45	45	51	>24	22	32,529	17.5	5,693	45.045	2027
MN19-U	98.088	99.093	1.005	44	56	44	>21	>21	2,400	15.2	365	44.220	1946
IS94-I	33.972	34.972	1.000	43	53	43	>21	>21	15,045	15.0	2,257	43.000	1849
US169-U	25.617	26.618	1.001	42	42	42	>23	>23	2,585	12.5	323	42.042	1766
MN19-U	104.103	105.108	1.005	42	48	42	>22	>22	2,664	14.7	392	42.210	1773
US169-U	13.613	14.613	1.000	41	51	41	>22	16	2,952	6.2	183	41.000	1681
MN19-U	105.108	106.103	0.995	41	46	41	>22	>22	2,664	14.7	392	40.795	1673
IS94-I	32.973	33.972	0.999	41	41	43	>21	>21	15,045	15.0	2,257	40.959	1679
US169-U	15.613	16.619	1.006	40	45	40	>22	16	2,952	6.2	183	40.240	1610
MN19-U	101.108	102.098	0.990	40	46	40	>21	>21	2,400	15.2	365	39.600	1584
US169-U	12.619	13.613	0.994	39	60	39	>22	16	2,952	6.2	183	38.766	1512
US52-D	75.379	76.220	0.841	39	40	39	>24	22	22,904	9.4	2,153	32.799	1279
US169-U	34.586	35.583	0.997	38	50	38	>22	>22	2,257	22.3	503	37.886	1440
IS35-D	64.045	65.044	0.999	38	38	39	>24	22	32,529	17.5	5,693	37.962	1443
US169-U	26.618	27.857	1.239	37	37	39	>23	>23	2,585	12.5	323	45.843	1696
US169-U	31.602	32.596	0.994	37	59	37	>22	>22	2,257	22.3	503	36.778	1361
MN19-U	99.093	100.103	1.010	37	45	37	>21	>21	2,400	15.2	365	37.370	1383
MN19-U	107.103	108.098	0.995	37	42	37	>22	>22	2,664	14.7	392	36.815	1362
MN19-U	109.093	109.511	0.418	37	48	37	>22	>22	2,664	14.7	392	15.466	572
US169-U	12.332	12.619	0.287	36	57	36	>22	16	2,952	6.2	183	10.332	372
MN19-U	100.103	101.108	1.005	36	42	36	>21	>21	2,400	15.2	365	36.180	1302
IS35-D	62.810	64.045	1.235	36	38	36	>24	22	32,529	17.5	5,693	44.460	1601
IS35-D	66.045	67.046	1.001	36	36	36	>24	22	32,529	17.5	5,693	36.036	1297
IS35-D	67.046	68.046	1.000	36	36	39	>24	22	32,529	17.5	5,693	36.000	1296
MN5-I	44.834	46.066	1.232	36	38	36	>23	>23	36,062	3.1	1,118	44.352	1597
IS35-I	64.045	65.044	0.999	35	37	35	>24	22	32,529	17.5	5,693	34.965	1224
MN60-U	57.006	58.196	1.190	34	36	34	>22	22	5,200	20.2	1,050	40.460	1376
MN15-U	12.966	13.985	1.019	33	37	33	>30	>30	4,514	8.2	370	33.627	1110
MN19-U	96.091	97.358	1.267	33	40	33	>21	>21	2,400	15.2	365	41.811	1380
US59-U	52.016	53.007	0.991	33	33	35	>20	18	2,100	18.6	391	32.703	1079
MN60-U	55.006	56.006	0.834	33	35	33	>22	22	5,200	20.2	1,050	27.522	908
IS90-D	0.000	0.999	0.999	32	32	32	32	21	11,002	12.5	1,375	31.968	1023
IS35-I	65.044	66.045	1.001	31	31	31	>24	22	32,529	17.5	5,693	31.031	962
US52-D	67.722	68.375	0.653	31	41	31	>25	23	28,403	9.4	2,670	20.243	628
IS90-D	1.998	2.996	0.998	31	31	31	>29	21	11,002	12.5	1,375	30.938	959
IS90-I	1.998	2.996	0.998	31	31	31	>29	14	11,002	12.5	1,375	30.938	959
IS94-I	31.805	32.973	1.168	31	33	31	>21	>21	15,045	15.0	2,257	36.208	1122
IS35-D	68.046	68.492	0.446	30	30	35	>24	22	32,529	17.5	5,693	13.380	401
MN5-D	47.067	48.014	0.947	30	38	30	>23	>23	36,062	3.1	1,118	28.410	852
MN60-U	61.006	61.917	0.911	30	30	30	>21	21	5,200	20.2	1,050	27.330	820
MN15-U	13.985	14.982	0.997	29	29	29	29	>30	4,514	8.2	370	28.913	838
MN15-U	14.982	15.982	1.000	29	29	29	29	>30	4,514	8.2	370	29.000	841
MN15-U	15.982	16.985	1.003	29	29	29	29	>30	4,514	8.2	370	29.087	844
MN15-U	17.987	18.986	0.999	29	29	29	29	>30	4,514	8.2	370	28.971	840
US169-U	17.616	18.765	1.149	29	30	29	>22	16	2,952	6.2	183	33.321	966

				Time to RQI of 2.5, years									
Segment	MP Begin	MP End	Length, mi	Controlling	ARIMA (2,1,1)	EWM	Actual	Time to 1st Major CPR	AADTA	PCT Truck	Truck AADTA	Year Mile	Error^2 * Weight
US169-U	27.857	28.605	0.748	29	33	29	>22	>22	2,257	22.3	503	21.692	629
IS35-I	62.810	64.045	1.235	29	30	29	>24	22	32,529	17.5	5,693	35.815	1039
US52-D	68.375	69.389	1.014	29	32	29	>25	23	28,403	9.4	2,670	29.406	853
IS90-D	2.996	3.903	0.907	29	33	29	>29	21	11,002	12.5	1,375	26.303	763
US59-U	51.009	52.016	1.007	29	30	29	>20	18	2,100	18.6	391	29.203	847
US59-U	58.022	58.660	0.638	29	29	34	>20	18	2,100	18.6	391	18.502	537
MN5-D	46.066	47.067	1.001	29	33	29	>23	>23	36,062	3.1	1,118	29.029	842
MN60-U	48.931	49.842	0.911	29	29	30	>19	>19	5,459	19.2	1,048	26.419	766
MN15-U	60.835	61.690	0.855	28	28	28	28	28	3,776	2.3	87	23.940	670
MN15-U	62.622	63.554	0.932	28	28	28	28	28	3,776	2.3	87	26.096	731
MN15-U	63.554	64.486	0.932	28	28	28	28	28	3,776	2.3	87	26.096	731
US52-D	69.389	70.376	0.987	28	31	28	>25	23	28,403	9.4	2,670	27.636	774
MN60-U	46.931	47.932	1.001	28	28	30	>19	19	5,459	19.2	1,048	28.028	785
US169-I	78.521	79.519	0.998	27	30	27	>18	9	15,223	14.4	2,192	26.946	728
IS90-D	0.999	1.998	0.999	27	29	27	>29	21	11,002	12.5	1,375	26.973	728
US59-U	53.007	54.013	1.006	27	27	27	>20	18	2,100	18.6	391	27.162	733
IS94-D	59.963	60.963	1.000	27	27	27	>21	21	16,414	16.0	2,626	27.000	729
MN60-U	56.006	57.006	1.000	27	27	27	>22	22	5,200	20.2	1,050	27.000	729
MN15-U	16.985	17.987	1.002	26	26	26	26	>30	4,514	8.2	370	26.052	677
US169-D	79.519	79.986	0.467	26	28	26	>18	9	15,223	14.4	2,192	12.142	316
IS94-I	58.965	59.963	0.998	26	26	26	>22	22	16,914	15.2	2,571	25.948	675
IS94-I	59.963	60.963	1.000	26	26	26	>22	22	16,914	15.2	2,571	26.000	676
IS94-I	68.965	69.968	1.003	26	26	26	>19	19	15,236	16.7	2,544	26.078	678
MN5-D	44.834	46.066	1.232	26	26	26	>23	>23	36,062	3.1	1,118	32.032	833
MN60-I	58.196	58.908	0.712	26	34	26	>22	22	5,200	20.2	1,050	18.512	481
MN60-U	60.006	61.006	1.000	26	26	26	26	21	5,200	20.2	1,050	26.000	676
MN15-U	61.690	62.622	0.932	25	25	25	25	25	3,776	2.3	87	23.300	583
US169-U	16.619	17.616	0.997	25	30	25	>22	16	2,952	6.2	183	24.925	623
US169-I	79.519	79.986	0.467	25	29	25	>18	9	15,223	14.4	2,192	11.675	292
US52-D	70.376	71.026	0.650	25	25	25	25	23	28,403	9.4	2,670	16.250	406
IS90-I	2.996	3.903	0.907	25	29	25	>29	14	11,002	12.5	1,375	22.675	567
US59-U	50.009	51.009	1.000	25	25	29	>20	18	2,100	18.6	391	25.000	625
US59-U	54.013	55.015	1.002	25	25	26	>20	18	2,100	18.6	391	25.050	626
IS94-D	85.945	86.949	1.004	25	27	25	>19	19	16,119	18.6	2,998	25.100	628
IS94-I	69.968	70.966	0.998	25	25	28	>19	19	15,236	16.7	2,544	24.950	624
MN60-U	54.172	55.006	0.834	25	25	25	>22	22	5,200	20.2	1,050	20.850	521
MN15-U	64.486	65.418	0.932	24	24	24	24	28	3,776	2.3	87	22.368	537
IS35-I	66.045	67.046	1.001	24	24	24	24	22	32,529	17.5	5,693	24.024	577
IS35-I	67.046	68.046	1.000	24	24	24	24	22	32,529	17.5	5,693	24.000	576
IS35-I	80.834	81.363	0.529	24	24	24	24	24	44,678	13.9	6,210	12.696	305
IS35-I	81.363	82.001	0.638	24	24	24	24	21	59,354	1.7	1,009	15.312	367
IS35-I	84.003	85.002	0.999	24	24	24	24	21	59,354	1.7	1,009	23.976	575
US59-U	13.004	14.010	1.006	24	24	24	24	6	3,521	0.7	25	24.144	579
US59-U	14.010	15.005	0.995	24	24	24	24	6	3,521	0.7	25	23.880	573
US59-U	15.005	15.997	0.992	24	24	24	24	6	3,521	0.7	25	23.808	571
US59-U	15.997	17.001	1.004	24	24	24	24	6	3,521	0.7	25	24.096	578
US59-U	17.001	18.008	1.007	24	24	24	24	6	3,521	0.7	25	24.168	580
US59-U	20.000	21.003	1.003	24	24	24	24	6	3,521	0.7	25	24.072	578
US59-U	21.003	22.001	0.998	24	24	24	24	6	3,521	0.7	25	23.952	575
US59-U	22.001	23.005	1.004	24	24	24	24	6	3,521	0.7	25	24.096	578
US59-U	23.005	24.006	1.001	24	24	24	24	6	3,521	0.7	25	24.024	577
US59-U	24.006	25.009	1.003	24	24	24	24	6	3,521	0.7	25	24.072	578
IS94-D	80.961	81.959	0.998	24	24	24	24	21	15,334	16.9	2,591	23.952	575
IS94-D	83.030	83.952	0.922	24	25	24	>19	19	16,119	18.6	2,998	22.128	531
IS94-D	86.949	87.950	1.001	24	28	24	>18	19	16,119	18.6	2,998	24.024	577
IS94-D	87.950	88.947	0.997	24	25	24	>18	19	16,119	18.6	2,998	23.928	574
IS94-D	90.945	91.942	0.997	24	24	23	>19	19	16,119	18.6	2,998	23.928	574
IS94-I	67.964	68.965	1.001	24	24	24	>19	19	15,236	16.7	2,544	24.024	577
MN60-D	50.961	51.976	1.015	24	24	24	>22	22	4,846	11.1	538	24.360	585
MN60-D	52.991	54.172	1.181	24	24	24	>22	22	4,846	11.1	538	28.344	680
MN60-I	58.908	59.270	0.362	24	24	24	24	>27	5,200	20.2	1,050	8.688	209
MN60-U	42.932	43.931	0.999	24	24	26	>19	19	5,459	19.2	1,048	23.976	575
MN60-U	43.931	44.941	1.010	24	24	24	>19	19	5,459	19.2	1,048	24.240	582

				Time to RQI of 2.5, years									
Segment	MP Begin	MP End	Length, mi	Controlling	ARIMA (2,1,1)	EWM	Actual	Time to 1st Major CPR	AADTA	PCT Truck	Truck AADTA	Year Mile	Error^2 * Weight
MN60-U	47.932	48.931	0.999	24	24	29	>19	19	5,459	19.2	1,048	23.976	575
IS35-I	68.046	68.492	0.446	23	23	23	23	22	32,529	17.5	5,693	10.258	236
US59-U	17.001	18.008	1.007	23	23	23	23	6	3,521	0.7	25	23.161	533
US59-U	18.999	20.000	1.001	23	23	23	23	6	3,521	0.7	25	23.023	530
US59-U	26.674	27.013	0.339	23	23	23	23	6	2,829	9.3	263	7.797	179
US59-U	47.088	48.016	0.928	23	25	23	>20	18	2,100	18.6	391	21.344	491
US59-U	48.016	49.008	0.992	23	23	23	>20	18	2,100	18.6	391	22.816	525
US59-U	56.018	57.018	1.000	23	23	23	>20	18	2,100	18.6	391	23.000	529
US59-U	57.018	58.022	1.004	23	23	23	>20	18	2,100	18.6	391	23.092	531
IS94-D	78.961	79.958	0.997	23	23	23	23	22	15,222	5.6	852	22.931	527
IS94-D	90.945	91.942	0.997	23	24	23	>19	19	16,119	18.6	2,998	22.931	527
IS94-D	92.938	93.939	1.001	23	23	23	>19	19	16,119	18.6	2,998	23.023	530
IS94-D	93.939	94.938	0.999	23	23	23	>19	19	16,119	18.6	2,998	22.977	528
IS94-D	95.936	96.263	0.327	23	23	23	>19	19	16,119	18.6	2,998	7.521	173
MN60-D	41.945	42.579	0.634	23	23	23	23	>24	10,801	15.4	1,663	14.582	335
MN60-U	44.941	45.933	0.992	23	23	23	>19	19	5,459	19.2	1,048	22.816	525
IS35-I	82.001	83.005	1.004	22	22	22	22	21	59,354	1.7	1,009	22.088	486
IS35-I	83.005	84.003	0.998	22	22	22	22	21	59,354	1.7	1,009	21.956	483
US59-U	24.006	25.009	1.003	22	22	22	22	6	3,521	0.7	25	22.066	485
US59-U	26.014	26.674	0.660	22	22	22	22	6	3,521	0.7	25	14.520	319
US59-U	27.013	28.178	1.165	22	22	22	22	6	2,829	9.3	263	25.630	564
US59-U	49.008	50.009	1.001	22	22	22	>20	18	2,100	18.6	391	22.022	484
IS94-D	71.961	72.963	1.002	22	22	22	22	22	15,222	5.6	852	22.044	485
IS94-D	84.952	85.945	0.993	22	23	22	>18	19	16,119	18.6	2,998	21.846	481
IS94-D	87.950	88.947	0.997	22	22	22	>19	19	16,119	18.6	2,998	21.934	483
IS94-D	89.947	90.945	0.998	22	22	24	>19	19	16,119	18.6	2,998	21.956	483
IS94-D	94.938	95.936	0.998	22	22	22	>19	19	16,119	18.6	2,998	21.956	483
IS94-I	50.972	51.972	1.000	22	22	22	22	22	16,914	15.2	2,571	22.000	484
IS94-I	51.972	52.973	1.001	22	22	22	22	22	16,914	15.2	2,571	22.022	484
IS94-I	52.973	53.974	1.001	22	22	22	22	22	16,914	15.2	2,571	22.022	484
IS94-I	53.974	54.971	0.997	22	22	22	22	22	16,914	15.2	2,571	21.934	483
IS94-I	55.969	56.969	1.000	22	22	22	22	22	16,914	15.2	2,571	22.000	484
IS94-I	56.969	57.965	0.996	22	22	22	22	22	16,914	15.2	2,571	21.912	482
IS94-I	57.965	58.965	1.000	22	22	22	22	22	16,914	15.2	2,571	22.000	484
IS94-I	60.963	62.108	1.145	22	22	22	22	22	16,914	15.2	2,571	25.190	554
MN60-D	58.196	58.908	0.712	22	22	22	22	22	5,200	20.2	1,050	15.664	345
MN60-D	58.908	59.270	0.362	22	22	22	22	22	5,200	20.2	1,050	7.964	175
MN60-I	50.961	51.976	1.015	22	22	22	22	22	4,959	12.7	630	22.330	491
MN60-I	52.991	54.172	1.181	22	22	22	22	>22	4,959	12.7	630	25.982	572
MN60-U	45.933	46.931	0.998	22	22	22	>19	19	5,459	19.2	1,048	21.956	483
US169-U	32.596	33.593	0.997	21	21	21	21	>22	2,257	22.3	503	20.937	440
US169-D	78.521	79.519	0.998	21	23	21	>18	9	15,223	14.4	2,192	20.958	440
IS94-D	58.965	59.963	0.998	21	21	21	21	21	16,414	16.0	2,626	20.958	440
IS94-D	60.963	62.108	1.145	21	21	21	21	21	16,414	16.0	2,626	24.045	505
IS94-D	79.958	80.961	1.003	21	21	21	21	21	15,334	16.9	2,591	21.063	442
IS94-D	81.959	83.030	1.071	21	21	21	21	21	15,334	16.9	2,591	22.491	472
IS94-I	50.603	50.972	0.369	21	21	21	21	22	16,914	15.2	2,571	7.749	163
IS94-I	54.971	55.969	0.998	21	21	21	21	22	16,914	15.2	2,571	20.958	440
MN60-D	51.976	52.991	1.015	21	21	21	21	22	4,846	11.1	538	21.315	448
MN60-I	41.945	42.579	0.634	21	21	21	21	>24	10,801	15.4	1,663	13.314	280
MN15-U	18.986	19.992	1.006	20	20	20	20	>30	4,514	8.2	370	20.120	402
MN15-U	65.418	66.350	0.932	20	20	20	20	26	3,776	2.3	87	18.640	373
IS35-I	85.002	85.495	0.493	20	20	20	20	21	59,354	1.7	1,009	9.860	197
IS94-D	56.257	56.969	0.712	20	20	20	20	21	16,414	16.0	2,626	14.240	285
IS94-D	56.969	57.965	0.996	20	20	20	20	21	16,414	16.0	2,626	19.920	398
IS94-D	57.965	58.965	1.000	20	20	20	20	21	16,414	16.0	2,626	20.000	400
MN60-D	50.640	50.961	0.321	20	20	20	20	22	4,846	11.1	538	6.420	128
MN15-U	20.996	21.696	0.700	19	19	19	19	7	4,145	8.2	340	13.300	253
IS35-I	77.803	78.999	1.196	19	19	19	19	24	44,678	13.9	6,210	22.724	432
US52-D	64.385	64.783	0.398	19	19	19	19	26	31,846	9.4	2,994	7.562	144
US52-D	67.024	67.389	0.365	19	19	19	19	26	27,802	9.4	2,613	6.935	132
US52-D	67.389	67.722	0.333	19	19	19	19	26	27,802	9.4	2,613	6.327	120
IS94-D	73.962	74.961	0.999	19	19	19	19	22	15,222	5.6	852	18.981	361

				Time to RQI of 2.5, years									
Segment	MP Begin	MP End	Length, mi	Controlling	ARIMA (2,1,1)	EWM	Actual	Time to 1st Major CPR	AADTA	PCT Truck	Truck AADTA	Year Mile	Error^2 * Weight
IS94-D	74.961	75.958	0.997	19	19	19	19	22	15,222	5.6	852	18.943	360
IS94-D	75.958	76.960	1.002	19	19	19	19	22	15,222	5.6	852	19.038	362
IS94-D	76.960	77.960	1.000	19	19	19	19	22	15,222	5.6	852	19.000	361
IS94-D	77.960	78.961	1.001	19	19	19	19	22	15,222	5.6	852	19.019	361
IS94-D	83.952	84.952	1.000	19	19	19	19	19	16,119	18.6	2,998	19.000	361
IS94-I	62.108	62.963	0.855	19	19	19	19	19	15,236	16.7	2,544	16.245	309
IS94-I	62.963	63.963	1.000	19	19	19	19	19	15,236	16.7	2,544	19.000	361
IS94-I	63.963	64.963	1.000	19	19	19	19	19	15,236	16.7	2,544	19.000	361
IS94-I	64.963	65.963	1.000	19	19	19	19	19	15,236	16.7	2,544	19.000	361
IS94-I	65.963	66.963	1.000	19	19	19	19	19	15,236	16.7	2,544	19.000	361
IS94-I	66.963	67.964	1.001	19	19	19	19	19	15,236	16.7	2,544	19.019	361
MN60-I	51.976	52.991	1.015	19	19	19	19	22	4,959	12.7	630	19.285	366
MN60-I	92.357	93.370	1.013	19	19	19	19	20	9,138	8.7	795	19.247	366
MN60-U	61.917	63.099	1.182	19	19	19	19	21	5,200	20.2	1,050	22.458	427
MN15-U	19.992	20.642	0.650	18	18	18	18	>30	4,514	8.2	370	11.700	211
MN15-U	20.642	20.996	0.354	18	18	18	18	7	4,145	8.2	340	6.372	115
IS35-I	80.000	80.834	0.834	18	18	18	18	24	44,678	13.9	6,210	15.012	270
IS35-D	84.829	85.495	0.666	18	18	18	18	>22	78,000	9.6	7,488	11.988	216
US59-U	55.015	56.018	1.003	18	18	18	18	18	2,100	18.6	391	18.054	325
MN60-I	49.842	50.961	1.119	18	18	18	18	22	4,959	12.7	630	20.142	363
US52-D	62.952	63.397	0.445	17	17	17	17	26	31,846	9.4	2,994	7.565	129
US52-D	63.397	64.385	0.988	17	17	17	17	26	31,846	9.4	2,994	16.796	286
IS94-D	72.963	73.962	0.999	17	17	17	17	22	15,222	5.6	852	16.983	289
MN60-U	59.270	60.006	0.736	17	17	17	17	21	5,200	20.2	1,050	12.512	213
MN60-U	63.099	64.127	1.028	17	17	17	17	21	5,200	20.2	1,050	17.476	297
US169-I	78.326	78.521	0.195	15	15	15	15	9	15,223	14.4	2,192	2.925	44
IS35-I	78.999	80.000	1.001	15	15	15	15	24	44,678	13.9	6,210	15.015	225
MN60-I	41.309	41.945	0.636	15	15	15	15	>24	10,801	15.4	1,663	9.540	143
US52-D	74.383	75.379	0.996	14	14	14	14	22	22,904	9.4	2,153	13.944	195
MN60-D	93.370	93.930	0.560	14	14	14	14	20	9,138	8.7	795	7.840	110
MN15-U	21.696	22.743	1.047	13	13	13	13	>30	4,504	8.2	369	13.611	177
US169-U	18.765	19.615	0.850	13	13	13	13	>22	3,681	6.7	247	11.050	144
US52-D	73.376	74.383	1.007	13	13	13	13	22	22,904	9.4	2,153	13.091	170
IS90-I	0.000	0.999	0.999	13	13	13	13	14	11,002	12.5	1,375	12.987	169
US59-U	12.656	13.004	0.348	13	13	13	13	6	3,521	0.7	25	4.524	59
MN60-D	41.309	41.945	0.636	13	13	13	13	>24	10,801	15.4	1,663	8.268	107
MN60-D	92.357	93.370	1.013	13	13	13	13	20	9,138	8.7	795	13.169	171
MN60-I	93.370	93.930	0.560	13	13	13	13	20	9,138	8.7	795	7.280	95
MN60-U	42.579	42.932	0.353	13	13	13	13	19	5,459	19.2	1,048	4.589	60
MN15-U	22.743	24.249	1.506	12	12	12	12	7	3,931	8.1	318	18.072	217
US169-U	18.765	19.615	0.850	11	11	11	11	>22	3,681	6.7	247	9.350	103
US169-D	78.326	78.521	0.195	8	8	8	8	9	15,223	14.4	2,192	1.560	12

APPENDIX C. FHWA INVEST ANALYSIS

INVEST
ECONOMIC • SOCIAL • ENVIRONMENTAL

100% RCA Custom - Oct 23, 2016

Module: Project Development

Scorecard: Custom

Points: 50

Criteria | Points

OM-01 **Internal Sustainability Plan**

0/15

Focus on sustainability improvements within the agency’s internal operations that affect all three principles of the triple bottom line.

OM-01.1 Does the agency have a sustainability commitment endorsed by senior executives?

OM-01.2 Has the agency developed a comprehensive internal sustainability plan that includes goals, performance metrics, quantifiable targets, strategies, and actions?

OM-01.3 Is the Comprehensive Internal Sustainability Plan integrated with coordination, implementation, and/or monitoring and tracking?

OM-01.4a Is sustainability training provided for staff, including an introduction to the Comprehensive Internal Sustainability Plan?

OM-01.4b Does the agency have an employee or an employee committee that promotes sustainability? OM-01.5a Does the agency implement at least two Travel Demand Management options?

OM-01.5b Does the agency provide support for alternative fuel vehicles used for commuting?

OM-01.6 Does the agency have a CISP per OM-02.2 and does it monitor progress towards goals for at least one year after goal establishment and show measurable advancement towards stated goals?

Scoring Notes
Next Actions

OM-02 **Electrical Energy Efficiency and Use**

0/15

Reduce the consumption of fossil fuels during operation and maintenance of agency owned and/or operated facilities through improvements in efficiency and the use and/or generation of renewable energy sources.

OM-02.1 Does the agency set energy reduction or renewable energy usage goals?

OM-02.2 Has the agency developed a documented plan that outlines how the energy reduction and renewable energy goals set above will be accomplished?

OM-02.3 Does the agency maintain an electricity monitoring system for operations and maintenance that tracks electricity usage for all highway facilities?

OM-02.4a Has the agency implemented an employee awareness program?
OM-02.4b Does the agency employ a representative or maintain an employee committee focused on the reduction of energy consumption and sustainability?

OM-02.5a Does the agency execute a contract for a minimum of two years of renewable energy, or create and operate renewable energy facilities within the agency-owned properties to meet the selected goal?

Next Actions
Scoring Notes

OM-03 **Vehicle Fuel Efficiency and Use**

0/15

Reduce fossil fuel use and emissions in vehicles used for operations and maintenance.

OM-03.1 Has the agency set goals for fossil fuel use reduction and set a time frame in which these goals should be achieved?

OM-03.2 Does the agency have a documented fleet management plan?

OM-03.3 Is the agency actively testing the use of alternative fuels or reduction methods?

OM-03.4 Does the agency have a fleet tracking program, spreadsheet, or other document that monitors vehicle use and fuel consumption?

OM-03.5 Does the agency have a fleet tracking system and has it used it to demonstrate progress for at least one year?

Scoring Notes
Next Actions

OM-04 **Reduce, Reuse and Recycle**

0/15

Create and pursue a formal recycling and reuse plan for agency operated facilities and maintenance activities.

OM-04.1 Has the agency set goals for operation and maintenance material reduction, reuse, and recycling?

OM-04.2 Does the agency have a documented plan that outlines how the reduce, reuse, and recycle goals will be accomplished?

OM-04.3 Does the agency track the waste streams and report the amount of waste produced and the amount of material reduced, reused, and recycled?

OM-04.4 Has the agency tracked progress toward these goals with the performance measurement system for at least one year and shown progress toward stated goals?

Scoring Notes
Next Actions

OM-05 **Safety Management**

0/15

Maximize the safety of the existing roadway network through a systematic and comprehensive review of safety data and the allocation of resources in planning and programming to support safety in operations and maintenance.

OM-05.1a Is the agency a state agency or a regional agency?

OM-05.1b In identifying the safety performance metrics for the reduction of fatal and serious injuries in the state or region, which of the following applies?

OM-05.2a Has the agency set goals and targets for each of the safety performance metrics identified for the reduction in fatal and serious injuries?

OM-05.3a Does the agency have a plan to support the reduction in fatal and serious injuries in the state or region?

OM-05.4 Is the agency a state agency or a regional agency?

OM-05.5 Is the agency measuring progress and monitoring performance?

Scoring Notes
Next Actions

OM-06 **Environmental Commitments Tracking System** 0/15

Ensure that environmental commitments made during project development related to operations and maintenance are documented, tracked, and fulfilled.

OM-06.1 Does the agency use a Comprehensive Environmental Compliance Tracking System (ECTS)? OM-06.2 Are any of the key features identified integrated into the ECTS?

OM-06.3 Does the agency require use of ECTS? OM-06.4 Does the agency have a GIS-based ECTS?

OM-06.5a Are goals set for compliance with environmental commitments and set a time frame in which these goals should be achieved?

Scoring Notes
Next Actions

OM-07 **Pavement Management System** 0/15

Leverage a pavement management system to balance activities that extend the life and function of pavements with impacts to the human and natural environment.

OM-07.1 Does the agency have a pavement management system (PMS)?

OM-07.2a Is pavement network performance tracked using one of the common metrics identified?

OM-07.2b Does the agency have measures related to project timeliness of rehabilitation, preservation, and maintenance activities?

OM-07.3 Does the agency set pavement system performance goals and monitor progress toward goals? OM-07.4 Does the agency have a PMS and leverage data to demonstrate sustainable outcomes?

OM-07.5 Does the agency have a PMS and consider sustainable pavement solutions?

Scoring Notes
Next Actions

OM-08 **Bridge Management System** 0/15

Leverage a bridge management system (BMS) to balance activities that extend the life and function of bridges with impacts to the human and natural environment.

OM-08.1 Does the agency have a Bridge Management System (BMS)? OM-08.2 Is bridge network performance tracked?

OM-08.3 Does the agency set bridge system performance goals and monitor progress toward goals? OM-08.4 Is a BMS used and are data leveraged to demonstrate sustainable outcomes?

Scoring Notes
Next Actions

OM-09 **Maintenance Management System** 0/15

Leverage a Maintenance Management System (MMS) to inventory, assess, analyze, plan, program, implement, and monitor maintenance activities to effectively and efficiently extend the life of the system, improve the service, and reduce the impacts to the human and natural environment.

OM-09.1 Are any of the key elements identified integrated into the Maintenance Management System (MMS)? OM-09.2 Does the agency Leverage vehicle-based technologies to connect to MMS?

OM-09.3 Does the agency's MMS integrate their PMS, BMS, RMP, and TCMP?

OM-09.4 Does the agency's MMS tie into its PMS and BMS and exchange information?

OM-09.5a Does the agency have a MQA program that relates highway maintenance to highway performance?

Scoring Notes
Next Actions

OM-10 **Highway Infrastructure Preservation and Maintenance** 0/15

Make paved roadway surfaces, bridges, tunnels, roadsides, and their appurtenance facilities last longer and perform better by undertaking preservation and routine maintenance on them.

OM-10.1 Has the agency implemented an Road Maintenance Plan (RMP)?

OM-10.2a Is appropriate funding allocated to accomplish preventative maintenance, routine maintenance, and repair activities in the RMP and annual work plan?

OM-10.2b Does the RMP highlight activities that contribute to sustainability during maintenance and operations?

OM-10.2c Does the RMP include activities that contribute to sustainability of infrastructure assets.

OM-10.3a Does the plan include performance measures that can be used to monitor the effects of plan implementation?

Scoring Notes
Next Actions

OM-11 **Traffic Control Infrastructure Maintenance** 0/15

Increase safety and operational efficiency by maintaining roadway traffic controls.

OM-11.1 Has the agency implemented a Traffic Control Maintenance Plan (TCMP)?

OM-11.2a Has the agency established quantifiable performance metrics for the TCMP?

OM-11.3a Does the agency set quantifiable goals relating to the metrics above for agency traffic control devices?

OM-11.4a Does the TCMP specifically address sustainability and highlight procedures, specifications, and activities that contribute to sustainability during preservation and maintenance activities?

OM-11.4b Does the TCMP specifically address sustainability and include procedures, specifications, or measures that contribute to the sustainability of infrastructure assets?

Scoring Notes
Next Actions

OM-12 **Road Weather Management Program** 0/15

Plan, implement, and monitor a road weather management program (including snow and ice control) to reduce environmental impacts with continued or better level of service.

OM-12.1a Has a RWMP been developed that includes strategies that can be used to mitigate the effects of weather on traffic?

OM-12.2a Has the agency established quantifiable performance metrics for the RWMP program? OM-12.3 Has the agency implemented a Roadway Weather Information System (RWIS)?

OM-12.4a Does the agency have an RWMP that includes, at a minimum, the listed elements specific to snow and ice control?

OM-12.5 Does the agency successfully implement a Materials Management Plan to monitor quantities of salt applied and level of service?

OM-12.6 Has the agency implemented a Maintenance Decision Support System?

Scoring Notes
Next Actions

OM-13 **Transportation Management and Operations**

0/15

Maximize the utility of the existing roadway network through use of technology and management of operations strategies.

OM-13.1 Has the agency taken enhanced or expedited measures to improve mobility and user level of service?

OM-13.2 How many categories of ITS technologies were utilized on this project? See Table OM-13.2.A and its instructions.

OM-13.3 Has the agency tailored the National ITS Architecture to create a regional architecture based on agency-specific needs?

OM-13.4 Has the agency integrated a system to ensure the needs of M&O strategies are fully considered in roadway infrastructure design?

OM-13.5a Have performance metrics been established, including at least one each related to safety, mobility, and integration of M&O strategies into design?

Scoring Notes
Next Actions

OM-14 **Work Zone Traffic Control**

0/15

Plan, implement, and monitor Work Zone Traffic Control (WZTC) methods that maximize safety of workers and system users with continued or better level of service.

OM-14.1 Does the agency have a Work Zone Traffic Control Program (WZTC)?

OM-14.2a Does the agency have quantifiable performance metrics for the WZTC program? OM-14.3 Are Intelligent Transportation Systems (ITS) used to anticipate and reduce congestion? OM-14.4 Does the agency Apply and Review ITS Technologies and Innovations?
OM-14.5 Does the agency use contracting incentives or dis-incentives to encourage contractors to reduce and optimize construction timelines?

OM-14.6 Does the agency use a public involvement or WZTC representative to communicate regularly with property owners and businesses affected by work?

OM-14.7 Does the agency participate in National Work Zone Awareness Week and develop a campaign to promote work zone safety awareness?

Scoring Notes
Next Actions

PD-01 **Economic Analyses**

5/5

Using the principles of benefit-cost analysis (BCA) or economic impact analysis (EIA), provide evidence that the benefits, including environmental, economic, and social benefits, justify the full life-cycle costs.

PD-01.1a Was a benefit-cost analysis (BCA) for the project completed using minimum acceptable industry practices?
Yes (2 points)

PD-01.1b Was an Economic Impact Analysis (EIA) completed that meets all the listed requirements? Yes (3 points)

Scoring Notes
Track your scoring notes here. For example, "Based on May 2, 2012 Technical Report (attached)."

Next Actions
Record future actions here. For example, "Coordinate with HQ and ensure specifications meet requirements."

PD-02 **Lifecycle Cost Analyses** 1/3

Reduce life-cycle costs and resource consumption through the informed use of life-cycle cost analyses of key project features during the decision-making process for the project.

PD-02.1a Was an LCCA performed for all pavement structure alternatives in accordance with the method described in the FHWA's Technical Bulletin for Life-Cycle Cost Analysis?
Yes (1 point)

PD-02.1b Was an LCCA performed for all stormwater infrastructure alternatives considered? No (0 points)

PD-02.1c Was an LCCA performed for the project's major feature (bridges, tunnels, retaining walls, or other items not listed in the preceding options) for each of the alternatives considered?
No (0 points)

Scoring Notes
Track your scoring notes here. For example, "Based on May 2, 2012 Technical Report (attached)."

Next Actions
Record future actions here. For example, "Coordinate with HQ and ensure specifications meet requirements."

PD-03 **Context Sensitive Project Development** 0/10

Deliver projects that harmonize transportation requirements and community values through effective decision- making and thoughtful design.

PD-03.1 Did the project development process generally follow the six-step CSS framework described in NCHRP report 480 and NCHRP report 642, or an equivalent process?

PD-03.2 Did the project development process feature a "cradle-to-grave" project team that included planners, traffic engineers, public involvement specialists, design engineers, environmental experts, safety specialists, landscape architects, right-of-way staff, freight experts, construction engineers, and others to work on projects who worked together to achieve the desired CSS-based vision for the project?

PD-03.3 As a result of CSS-influenced project development process, were external "champions" for the project created in the affected community who were engaged and proactive in supporting it?

PD-03.4 Was acceptance achieved among project stakeholders on the problems, opportunities, and needs that the project should address and the resulting vision or goals for addressing them?

PD-03.5 Do project features consider the appropriate scale of the project? PD-03.6 Did the project remove objectionable or distracting views?

PD-03.7 Did the project integrate context sensitive aesthetic treatments?

PD-03.8 Were aethetics for structural items incorporated into the design of the project?

Scoring Notes
Next Actions

PD-04 **Highway and Traffic Safety** 0/10

Safeguard human health by incorporating science-based quantitative safety analysis processes within project development that will reduce serious injuries and fatalities within the project footprint.

PD-04.1 Were human factors considerations incorporated?

Interactions between road users and the roadway using fundamentals captured in Chapter 2 of the Highway Safety Manual and the Human Factors Guideline for Road Systems (NCHRP Report 600 series) were evaluated, documented, and incorporated. (2 points)

PD-04.2 Was awareness built among the public regarding contributing factors to crashes? Yes (1 point)

PD-04.3 Does the agency conduct explicit consideration of safety using quantitative, scientifically proven methods?
Yes (0 points)

PD-04.3a Was the project type established during scoping of project alternatives through a quantitative and statistically reliable process?
Yes (1 point)
10/10
PD-04.3b Were project design and/or operational alternatives developed and evaluated using explicit consideration of substantive safety through quantitative, statistically reliable methods?
Yes (2 points)

PD-04.3c Were quantitative and statistically reliable methods and knowledge used to assess substantive safety performance in the development of preliminary and final design details?
Yes (3 points)

PD-04.4 Was a statistically reliable, science-based method used to evaluate the safety effectiveness of the implemented project?
Yes (1 point)

Scoring Notes
Track your scoring notes here. For example, "Based on May 2, 2012 Technical Report (attached)."

Next Actions
Record future actions here. For example, "Coordinate with HQ and ensure specifications meet requirements."

PD-05 **Educational Outreach** 0/2

Increase public, agency, and stakeholder awareness of the integration of the principles of sustainability into roadway planning, design, and construction.

PD-05.1 Did this project incorporate public educational outreach that promotes and educates the public about sustainability by installing or performing a minimum of two different elements from Table PD-05.1.A?

Scoring Notes
Next Actions

PD-06 **Tracking Environmental Commitments** 5/5

Ensure that environmental commitments made by the project are completed and documented in accordance with all applicable laws, regulations, and issued permits.

PD-06.1a Was a comprehensive environmental compliance tracking system used for the project and related facilities?
Yes (2 points)

PD-06.1b Does the environmental tracking system have a formal mechanism to communicate commitments from transportation planning through design, construction and maintenance?
Yes (1 point)

PD-06.2 Has the principal project constructor assigned an independent environmental compliance monitor who will provide quality assurance services and report directly to and make recommendations to the regulatory and Lead Agencies?
Yes (2 points)

Scoring Notes
Track your scoring notes here. For example, "Based on May 2, 2012 Technical Report (attached)."

Next Actions

Record future actions here. For example, "Coordinate with HQ and ensure specifications meet requirements."

PD-07 Habitat Restoration

0/7

Avoid, minimize, rectify, reduce, and compensate the loss and alteration of natural (stream and terrestrial) habitat caused by project construction and/or restore, preserve, and protect natural habitat beyond regulatory requirements.

PD-07.1 Was project-specific mitigation or mitigation banking used on this project? Use Table PD-07.1.A to determine the points earned.

PD-07.2 Were high quality aquatic resources (HQAR) avoided or were the impacts minimized on this project? Use Table PD-07.2.A to determine the points earned.

PD-07.3 Were high quality environmental resources avoided or were the impacts minimized on this project? Use Table PD-07.3.A to determine the points earned.

Scoring Notes
Next Actions

PD-08 Stormwater Quality and Flow Control

0/6

Improve stormwater quality from the impacts of the project and control flow to minimize their erosive effects on receiving water bodies and related water resources, using management methods and practices that reduce the impacts associated with development and redevelopment.

PD-08.1 Did the project treat at least 80% of the total runoff volume? Use Tables PD-08.1.A and PD-08.1.B to determine points.

PD-08.2 Did the project manage the flow from at least 80 percent of the total runoff volume, and is flow control based on controlling peak flows or durations from the project site? Use Tables PD-08.2.A and PD-08.1.B to determine points.

Scoring Notes
Next Actions

PD-09 Ecological Connectivity

0/15

Avoid, minimize, or enhance wildlife, amphibian, and aquatic species passage access, and mobility, and reduce vehicle-wildlife collisions and related accidents.

PD-09.1P Was a site-specific ecological assessment of the roadway project using GIS data or regional expertise conducted?

Scoring Notes
Next Actions

PD-10 Pedestrian Facilities

0/3

Provide safe, comfortable, convenient, and connected pedestrian facilities for people of all ages and abilities within the project footprint.

PD-10.1P Were all facilities upgraded to meet ADA standards and do responses below exclude any projects to upgrade facilities to ADA standards?

Scoring Notes
Next Actions

PD-11 Bicycle Facilities

0/3

Provide safe, comfortable, convenient, and connected bicycling facilities within the project footprint.

PD-11.1 Were missing bicycle connections installed per master plan or other relevant documents? PD-11.2 Were bicycle features installed that are safe, comfortable, convenient and connected?

Scoring Notes
Next Actions

PD-12 **Transit and HOV Facilities** 0/5

Promote use of public transit and carpools in communities by providing new transit and high occupancy vehicle (HOV) facilities, or by upgrading existing facilities within the project footprint.

PD-12.1 Were Transit and HOV facilities installed on this project that are consistent with the need, purpose, and appropriateness for transit and HOV access within the project footprint? Use Table PD-12.1.A to determine points.

Scoring Notes
Next Actions

PD-13 **Freight Mobility** 0/7

Enhance mobility of freight movements, decrease fuel consumption and emissions impacts, and reduce freight-related noise.

PD-13.1 Were freight facilities installed on this project consistent with the need, purpose, and appropriateness for freight mobility within the project footprint? Use Table PD-13.1.A to determine points.

Scoring Notes
Next Actions

PD-14 **ITS for System Operations** 0/5

Improve the efficiency of transportation systems through deployment of technology and without adding infrastructure capacity in order to reduce emissions and energy use, and improve economic and social needs.

PD-14.1 Were one or more allowable ITS applications installed? Use Table PD-14.1.A to determine points.

Scoring Notes
Next Actions

PD-15 **Historic, Archaeological, and Cultural Preservation** 0/3

Preserve, protect, or enhance cultural and historic assets, and/or feature National Scenic Byways Program (NSBP) historic, archaeological, or cultural intrinsic qualities in a roadway.

PD-15.1P Is any part of the project or resource listed in the NRHP or been determined eligible for the NHRP by a State, Local, or Tribal Historic Preservation Officer?

Scoring Notes
Next Actions

PD-16 **Scenic, Natural, or Recreational Qualities** 0/3

Preserve, protect, and/or enhance routes designated with significant scenic, natural, and/or recreational qualities in order to enhance the public enjoyment of facilities.

PD-16.1P Is any portion of the project along one of America's Byways®, a State Scenic Byway, an Indian Tribe Scenic Byway, or other route that was designated or officially recognized as such?

Scoring Notes
Next Actions

PD-17 **Energy Efficiency**

0/8

Reduce energy consumption of lighting systems through the installation of efficient fixtures and the creation and use of renewable energy.

PD-17.1 Were energy needs evaluated for the project?

PD-17.2 Was the energy consumption on the project reduced through the installation of energy efficient lighting and signal fixtures and through the installation of autonomous, on-site, renewable power sources?

PD-17.3 Was a plan established for auditing energy use after project completion as part of operations and maintenance?

Scoring Notes
Next Actions

PD-18 **Site Vegetation, Maintenance and Irrigation**

0/6

Promote sustainable site vegetation within the project footprint by selecting plants and maintenance methods that benefit the ecosystem.

PD-18.1P Does all site vegetation use non-invasive species only, use non-noxious species only, use seeding that does not require consistent mowing for a viable stand of grass, and minimize disturbance of native species?

Scoring Notes
Next Actions

PD-19 **Reduce, Reuse and Repurpose Materials**

8/12

Reduce lifecycle impacts from extraction and production of virgin materials by recycling materials.

PD-19 Points for different methods are cumulative; however, this criterion shall not exceed a total of twelve points. Points exceeding twelve will not contribute to overall score.
I understand. (0 points)

PD-19.1 Was remaining service life increased through pavement preservation activities? Points are awarded per Table PD-19.1.A. (4 points)

PD-19.2 Was the amount of new pavement materials needed reduced? Points are awarded per Table PD-19.2.A. 3 (3 points)

PD-19.3 Was remaining service life increased through bridge preservation activities? Points are awarded per Table PD-19.3.A. No (0 points)

PD-19.4 Was remaining service life increased through retrofitting existing bridge structures? Points are awarded per Table PD-19.3.A. No (0 points)

PD-19.5 Were existing pavements, structures, or structural elements reused for a new use? Points are awarded per Table PD-19.5.A. No (0 points)

PD-19.6a Were foundry sand or other industrial by-products used in pipe bedding and backfill? No (0 points)

PD-19.7 Was a project-specific plan for the recycling and reuse plan developed as described? Yes (1 point)

Scoring Notes
Track your scoring notes here. For example, "Based on May 2, 2012 Technical Report (attached)."

Next Actions
Record future actions here. For example, "Coordinate with HQ and ensure specifications meet requirements."

PD-20 **Recycle Materials**

5/10

Reduce lifecycle impacts from extraction, production, and transportation of virgin materials by recycling materials.

PD-20 Points for different methods are cumulative; however, this criterion shall not exceed a total of ten points. Points exceeding ten will not contribute to overall score.
I understand. (0 points)

PD-20.1 Was RAP or RCA used in new pavement lifts, granular base course, or embankments? Points are awarded per Tables PD-20.1.A or PD-20.1.B.
(5 points)

PD-20.2 Were pavement materials recycled in place using cold-in-place recycling, hot-in-place recycling, and full depth reclamation methods? Points are awarded per Table PD-20.2.A.
No (0 points)

PD-20.3 Did the project reuse subbase granular material as subgrade embankment or as part of the new subbase? Points are awarded per Table PD-20.3.A.
No (0 points)

PD-20.4 Did the project relocate and reuse at least 90 percent of the minor structural elements, including existing luminaires, signal poles, and sign structures that are required to be removed and/or relocated onsite? No (0 points)

PD-20.5 Did the project salvage or relocate existing buildings? No (0 points)

Next Actions
Record future actions here. For example, "Coordinate with HQ and ensure specifications meet requirements."

Scoring Notes
Track your scoring notes here. For example, "Based on May 2, 2012 Technical Report (attached)."

PD-21 Earthwork Balance

0/5

Reduce the need for transport of earthen materials by balancing cut and fill quantities.

PD-21.1a Are the design cut and fill volumes or the actual construction cut and fill volumes balanced to within 10%?

PD-21.2 Has an earthwork management plan been established, implemented and actively managed on this project?

PD-21.3 Has topsoil been preserved or reused on this project?

Scoring Notes
Next Actions

PD-22 Long-Life Pavement

7/7

Minimize life-cycle costs by designing long-lasting pavement structures.

PD-22 Points for different methods are cumulative; however, this criterion shall not exceed a total of seven points. Points exceeding seven will not contribute to overall score.
I understand. (0 points)

PD-22.1 Which of the following describes how long-life pavement was used on this project? Long-life pavement was used for at least 75 percent of the surface area of regularly trafficked lanes. (5 points)

PD-22.2 Was the asphalt density of 100 percent of the total new or reconstructed pavement increased to a minimum of 94 percent?
No (0 points)

PD-22.3 Was a performance-based pay incentive for pavement smoothness used on this project? Yes (2 points)

Scoring Notes
Track your scoring notes here. For example, "Based on May 2, 2012 Technical Report (attached)."

Next Actions

Record future actions here. For example, "Coordinate with HQ and ensure specifications meet requirements."

PD-23 **Reduced Energy and Emissions in Pavement Materials** 3/3

Reduce energy use in the production of pavement materials.

PD-23 Points for different methods are cumulative; however, this criterion shall not exceed a total of three points. Points exceeding three will not contribute to overall score.
I understand. (0 points)

PD-23.1 Was at least 50 percent of the total project pavement material (by weight) a low-energy material from asphalt production?
No (0 points)

PD-23.2 Was at least 50 percent of the total project pavement material (by weight) a low-energy material from cement production?
PD-23.2a Yes, cement production using an ENERGY STAR® certified plant was used. (3 points)

PD-23.3 Was at least 50 percent of the total project pavement material (by weight) a low-energy material from concrete production?
PD-23.3b Yes, concrete production occurred in an NRMCA Sustainable concrete plant. (3 points)

Scoring Notes
Track your scoring notes here. For example, "Based on May 2, 2012 Technical Report (attached)."

Next Actions
Record future actions here. For example, "Coordinate with HQ and ensure specifications meet requirements."

PD-24 **Permeable Pavement** 0/2

Improve flow control and quality of stormwater runoff through use of permeable pavement technologies.

PD-24.1and2P Does the project include a maintenance plan for permeable pavements and are permeable pavements placed in areas where no sand will be used for snow and ice control or pavement sealing?
No (0 points)

Scoring Notes
Track your scoring notes here. For example, "Based on May 2, 2012 Technical Report (attached)."

Next Actions
Record future actions here. For example, "Coordinate with HQ and ensure specifications meet requirements."

PD-25 **Construction Environmental Training** 0/1

Provide construction personnel with the knowledge to identify environmental issues and best practice methods to minimize impacts to the human and natural environment.

PD-25.1 Did the owner require the Contractor to plan and implement a formal environmental awareness training program during construction to ensure the project stay in compliance with environmental laws, regulations, and policies?

Scoring Notes
Next Actions

PD-26 **Construction Equipment Emission Reduction** 1/2

Reduce air emissions from non-road construction equipment.

PD-26.1 Were one or more methods implemented to reduce non-road emissions? Points are awarded per Table PD-26.1.A.
1 (1 point)

Scoring Notes
Track your scoring notes here. For example, "Based on May 2, 2012 Technical Report (attached)."

Next Actions

Record future actions here. For example, "Coordinate with HQ and ensure specifications meet requirements."

PD-27 **Construction Noise Mitigation** 0/2

Reduce annoyance or disturbance to surrounding neighborhoods and environments from road construction noise.

PD-27.1 Is the contractor required to establish, implement, and maintain a formal Noise Mitigation Plan (NMP) during roadway construction?

PD-27.2 Has the contractor monitored noise and the effectiveness of mitigation measures at the receptors throughout construction to ensure compliance with the NMP?

Scoring Notes
Next Actions

PD-28 **Construction Quality Control Plan** 5/5

Improve quality by requiring the contractor to have a formal Quality Control Plan (QCP).

PD-28.1 Is the Contractor required to plan and implement quality control measures throughout construction with
5/5
care and for materials above and beyond what is typically required by specifications and regulations? Yes (3 points)

PD-28.2 Does the contract leverage the use of Quality Price Adjustment Clauses to link payment and performance of the constructed products?
Yes (2 points)

Scoring Notes
Track your scoring notes here. For example, "Based on May 2, 2012 Technical Report (attached)."

Next Actions
Record future actions here. For example, "Coordinate with HQ and ensure specifications meet requirements."

PD-29 **Construction Waste Management** 0/4

Utilize a management plan for road construction waste materials to minimize the amount of construction-related waste destined for landfill.

PD-29.1 Is the contractor required to establish, implement, and maintain a formal Construction and Demolition Waste Management Plan (CWMP) during roadway construction, or its functional equivalent?

PD-29.2 Can the owner demonstrate that a percentage of the construction waste has been diverted from landfills?

PD-29.3 Were excess materials hauled directly to other project sites for recycling on those projects?

Scoring Notes
Next Actions

PD-30 **Low Impact Development** 0/3

Use low impact development stormwater management methods that reduce the impacts associated with development and redevelopment and that mimic natural hydrology.

PD-30.1 Did the project use effective BMPs or stormwater management techniques that mimic natural hydrology to treat pollutants? Use Tables PD-30.1.A and PD-30.1.B and PD-30.1.C to determine points.

Scoring Notes
Next Actions

PD-31 **Infrastructure Resiliency Planning and Design** 0/12

Respond to vulnerabilities and risks associated with current and future hazards (including those associated with climate change) to ensure transportation system reliability and resiliency.

PD-31.1 Did the project incorporate consideration of climate change at a project-specific level in project development and environmental reviews?

PD-31.2 Did the project incorporate future consideration of climate change effects in the design process?

PD-31.3 Did the project mitigate the effects of GHG emissions through design efforts above and beyond requirements and regulations?

Scoring Notes
Next Actions

PD-32 **Light Pollution** 0/3

To safely illuminate roadways while minimizing unnecessary and potentially harmful illumination of the surrounding sky, communities, and habitat.

PD-32.1 Were the uplighting ratings met on this project per Table PD-32.1.A? PD-32.2 Were the backlighting ratings met on this project per Table PD-32.2.A? PD-32.3 Were the glare ratings met on this project per Table PD-32.3.A?

Scoring Notes
Next Actions

PD-33 **Noise Abatement** 0/5

Reduce traffic noise impacts to surrounding communities and environments.

PD-33 Points for different noise abatement methods are cumulative; however, this criterion shall not exceed a total of five points. Points exceeding five will not contribute to overall score.

PD-33.1 Was a specialized noise barrier used on this project?

PD-33.2 Were traffic system management techniques used to reduce existing noise levels? PD-33.3 Were buffer zones provided for adjacent noise sensitive receptors?
PD-33.4 Were quiet pavements used on the project? Use Table PD-33.4.A to determine the points earned. PD-33.5 Were plantings used as a sight screen to separate noise receptors from the project?

Scoring Notes
Next Actions

SPR-01 **Integrated Planning: Economic Development and Land Use (for Regions)** 0/15

Integrate statewide and metropolitan Long Range Transportation Plans (LRTP) with regional and/or local land use plans and economic development forecasts and goals. Proactively encourage and facilitate sustainability through the coordination of transportation, land use, and economic development planning.

SPR-01.1a Has the agency developed goals and objectives for the integration of metropolitan and/or statewide transportation planning with economic development and land use planning above and beyond current requirements?

SPR-01.2a Does the agency regularly engage land use and economic development agencies in its jurisdiction throughout the transportation planning process?

SPR-01.3 Does the agency use best practice quantitative methods to analyze and evaluate the performance of alternative land use/ transportation scenarios?

SPR-01.4 Does the agency provide institutional leadership in encouraging transportation planning that is consistent with land use and economic development plans and that supports sustainability principles?

SPR-01.5 Can the agency demonstrate sustainable outcomes?

Scoring Notes
Next Actions

SPR-02 **Integrated Planning: Natural Environment (for Regions)** 0/15

Integrate ecological considerations into the transportation planning process, including the development of long range transportation plans (LRTP), corridor plans, and the TIP. Proactively support and enhance long-term ecological function through the coordination of transportation and natural resource planning.

SPR-02.1a Has the agency developed goals and objectives that meet the requirement for the integration of metropolitan and/or statewide transportation planning with applicable environmental plans, policies, and goals?

SPR-02.2a Does the agency go above and beyond current consultation requirements by regularly engaging natural resource and regulatory agencies?

SPR-02.3 Does the agency apply system or landscape-scale evaluation techniques using natural resource data? SPR-02.4 Can the agency demonstrate sustainable outcomes?

Scoring Notes
Next Actions

SPR-03 **Integrated Planning: Social (for Regions)** 0/15

The agency's Long Range Transportation Plan (LRTP) is consistent with and supportive of the community's vision and goals. When considered in an integrated fashion, these plans, goals and visions support sustainability principles. The agency applies context-sensitive principles to the planning process to achieve solutions that balance multiple objectives to meet stakeholder needs.

SPR-03.1 Do the metropolitan and/or statewide transportation planning agencies share the community's vision for overall sustainability efforts; are transportation-related goals and objectives are consistent with that vision?

SPR-03.2 Does the agency successfully identify a diverse range of stakeholders and public participants?

SPR-03.3a Does the agency use a transparent process to inform stakeholders how their input will be used and then follow through accordingly?

SPR-03.3b Does the agency demonstrate to stakeholders how their input was used to inform and affect transportation planning decisions?

SPR-03.4 Can the agency demonstrate sustainable outcomes?

Scoring Notes
Next Actions

SPR-04 **Integrated Planning: Bonus (for Regions)** 0/10

The agency has a continuing, cooperative, and comprehensive (3-C) transportation planning process. Planners and professionals from multiple disciplines and agencies (e.g., land use, transportation, economic development, energy, natural resources, community development, equity, housing, and public health) work together to incorporate and apply all three sustainability principles when preparing and evaluating plans.

SPR-04.1 Does the agency's transportation planning occur within an integrated and collaborative planning process?

Scoring Notes

Next Actions

SPR-05 **Access and Affordability (for Regions)** 0/15

Enhance accessibility and affordability of the transportation system to all users and by multiple modes.

SPR-05.1a Do system planning documents analyze physical access and identify specific population groups or areas where this is an issue?

SP-05.1b Do system planning documents analyze access and equity and identify specific populations or areas where this is an issue?

SPR-05.1c Do system planning documents analyze affordability and identify specific populations or areas where this is an issue?

SPR-05.1d Do system planning documents include documentation of targeted, enhanced outreach or communication that has been used to engage these population groups or areas in the transportation planning process?

SPR-05.2a Does the agency use travel model, census, geospatial, and other data to quantitatively evaluate the nature and distribution of accessibility and affordability concerns in its jurisdiction?

SPR-05.2b Does the agency analyze how its transportation planning documents address or improves issues?

SPR-05.3a Does the LRTP include sustainability-related performance measures that can be used to monitor the effects of plan implementation on transportation accessibility and affordability?

Scoring Notes
Next Actions

SPR-06 **Safety Planning (for Regions)** 0/15

Agency integrates quantitative measures of safety into regional planning policies, ordinances, activities, projects, and programs, and across all modes and jurisdictions.

SPR-06.1 Does the agency collaborate and participate in the development and implementation of the State Strategic Highway Safety Plan?

SP-06.2a Has the agency incorporated the Toward Zero Death (TZD) vision and implementing TZD as part of its transportation planning activities?

SPR-06.2b Has the agency developed strategies/plans to support TZD?

SPR-06.3 Does the agency develop a plan that incorporates safety into short- and long-range transportation planning?

SPR-06.4 Does the agency integrate quantitative safety performance measures into the transportation planning process?

SPR-06.5a Does the agency incorporate and integrate quantitative safety considerations into the selection and evaluation of strategies for different user groups?

SPR-06.5b Does the agency select strategies that include systemic treatments with proven effectiveness in reducing fatalities and serious injuries?

SPR-06.6 Does the agency integrate statistically sound approaches to determine projected safety performance into the long-range transportation planning process?

SP-06.7a Does the agency system plan or program include safety-related performance measures?

Scoring Notes

Next Actions

SPR-07 **Multimodal Transportation and Public Health (for Regions)** 0/15

Expand travel choices and modal options by enhancing the extent and connectivity of multimodal infrastructure. Support and enhance public health by investing in active transportation modes.

SPR-07.1a Has the agency developed goals and objectives for enhancing the extent and connectivity of multimodal infrastructure within its jurisdiction?

SPR-07.1b Has the agency developed goals and objectives related to active transportation and the improvement of public health?

SPR-07.2 Does the agency regularly engage public health and active mode stakeholders?

SPR-07.3a Does the agency's planning process include and prioritize active, non-motorized transportation projects and programs as a component of the LRTP?

SPR-07.3c Has the agency evaluated the health impacts of the LRTP to determine whether the planned transportation investments will help the agency to meet its public health and active transportation goals?

SPR-07.4 Does the agency evaluate its progress toward meeting its multimodal and public health goals and makes adjustments as necessary?

Scoring Notes
Next Actions

SPR-08 **Freight and Goods Access & Mobility (for Regions)** 0/15

Implement a transportation plan that meets freight access and mobility needs while also supporting triple bottom line sustainability principles.

SPR-08.1a Does the agency include in system plans, specific provisions for maintaining and improving freight reliability and connectivity between modes and to freight generators for both inter- and intra-city freight, in

ways that enhance sustainability?

SPR-08.1b Does the agency consider multimodal freight mobility needs in the planning process?

SPR-08.2a Does the agency regularly engage freight service providers, stakeholders, workers, and representative in developing transportation planning documents?

SPR-08.3a Does the agency include and monitor freight access performance measures in planning documents? SPR-08.3b Does the agency include and monitor freight mobility performance measures in planning documents?

SPR-08.4a Does the agency provide for planning, evaluating, maintaining and improving intermodal freight connectors and linkages to freight generators at all levels?

SPR-08.4b Does the agency provide for planning, evaluating, maintaining, and enhancing freight mobility utilizing appropriate quantitative measures and monitoring for freight modes?

SPR-08.4c Does the agency monitor progress toward goals for at least one year and show measurable advancement toward goals?

Scoring Notes
Next Actions

SPR-09 **Travel Demand Management (for Regions)** 0/15

Reduce vehicle travel demand throughout the system.

SPR-09.1a Has the agency developed quantifiable TDM goals and objectives for reducing travel demand for the transportation network within its jurisdiction?

SPR-09.2 Is the agency implementing a comprehensive TDM program that includes several of the various types of TDM strategies described?

SPR-09.3 Does the agency have quantifiable TDM performance measures and can the agency demonstrate ongoing monitoring of its TDM program?

SPR-09.4 Can the agency demonstrate sustainable outcomes?

Scoring Notes
Next Actions

SPR-10 **Air Quality & Emissions (for Regions)**

0/15

To plan, implement, and monitor multimodal strategies to reduce emissions and to establish a process to document emissions reductions.

SPR-10.1 Has the agency developed goals and objectives for the reduction of air emissions in transportation planning documents?

SPR-10.2 Does the agency regularly engage partner agencies throughout the transportation planning process?

SPR-10.3 Is the agency implementing multimodal strategies as part of a transportation plan to reduce emissions?

SPR-10.4 Was an emissions analysis performed?

Scoring Notes
Next Actions

SPR-11 **Energy and Fuels (for Regions)**

0/15

Reduce the energy and fossil fuel consumption from the transportation sector and document it in the transportation planning process.

SPR-11.1a Has the agency developed energy and/or fossil fuel reduction goals and objectives for the transportation system within its jurisdiction?

SPR-11.2a Has the agency developed and does the agency maintain a baseline inventory of current energy and/or fossil-fuel consumption from transportation?

SPR-11.3 Is the agency developing a plan and implementing strategies to reduce transportation-related energy and/or fossil fuel usage?

SPR-11.4 Does the agency develop performance measures, monitor progress and demonstrate sustainable outcomes?

Scoring Notes
Next Actions

SPR-12 **Financial Sustainability (for Regions)**

0/15

Evaluate and document that financial commitments made across transportation system plans are reasonable and affordable.

SPR-12.1 Is an inter-agency, cooperative approach for advanced revenue forecasting practices used? SPR-12.2 Is an inter-agency, cooperative approach for advanced project estimating practices used?

Scoring Notes
Next Actions

SPR-13 **Analysis Methods (for Regions)**

0/15

Agencies adopt and incentivize best practices in land use, socioeconomic and transportation systems analysis methods.

SPR-13.1a Does the agency demonstrate that the analysis has a strong foundation in observed data suitable for developing tools which model the land use, socioeconomic, transport, and environmental systems?

SPR-13.2 Does the agency have a current strategic plan, analysis program, or equivalent?

SP-13.3a Does the agency's organizational structure include a technical committee to review data collection/ quality, planning assumptions, and forecasting methods?

SP-13.3b Has the agency convened a peer review of its analysis methods? SPR-13.3c Has the agency convened a peer review of its travel demand model?

Scoring Notes
Next Actions

SPR-14 **Transportation Systems Management and Operations (for Regions)** 0/15

Optimize the efficiency of the existing transportation system.

SPR-14.1a Has the agency developed clearly defined goals and objectives for improving the efficiency of the transportation system within its jurisdiction?

SPR-14.2a Are TSM&O strategies included in the LRTP, or other planning documents, as appropriate? SPR-14.2b Does the LRTP, or equivalent, include a discussion of the impacts of including TSM&O strategies? SPR-14.2c Are the TSM&O strategies considered and prioritized in the LRTP, or other planning documents? SPR-14.3 Has the agency implemented or is the agency funding TSM&O strategies?

SPR-14.4 Does the agency include TSM&O performance measures in planning documents?

SPR-14.5 Does the agency monitor progress toward goals for at least one year and can the agency show measurable advancement toward goals?

Scoring Notes
Next Actions

SPR-15 **Linking Asset Management and Planning (for Regions)** 0/15

Leverage transportation asset management data and methods within the transportation planning process to make informed, cost-effective program decisions and better use existing transportation assets.

SPR-15.1 Has the agency developed clearly defined goals and objectives for linking asset management and planning in their planning documents?

SPR-15.2 Does the agency cooperate with partner agencies to integrate their asset management data and economic analysis to prioritize investments?

SPR-15.3 Does the agency leverage performance-based planning and programming components of asset management to analyze and evaluate trade-offs in long-range transportation planning processes?

SPR-15.4a Does the agency prioritize transportation decisions that support maintenance and good repair of existing transportation assets?

SPR-15.4b Does the agency monitor progress toward goals for at least one year and can the agency show measurable advancement toward goals?

Scoring Notes
Next Actions

SPR-16 **Infrastructure Resiliency (for Regions)** 0/15

Anticipate, assess, and plan to respond to vulnerabilities and risks associated with current and future hazards (including those associated with climate change) to ensure multi-modal transportation system reliability and resiliency. Identify a range of vulnerability and risks to both existing and planned transportation infrastructure.

SPR-16.1a Has the agency developed goals and objectives consistent with partner agencies for infrastructure resiliency in transportation planning documents?

SPR-16.2 Does the agency regularly coordinate with partner agencies within its jurisdiction throughout the transportation planning process, to reduce barriers and further the prospects for implementation of strategies to address infrastructure resiliency?

SPR-16.3 Does the agency coordinate with partner agencies to collect infrastructure vulnerability and risk assessments into planning documents and identify and inventory necessary event-based transportation plans that need to be developed as a result?

SP-16.4 Does the agency coordinate with partner agencies to develop appropriate strategies to address transportation events related to hazard events?

SPR-16.5 Does the agency have infrastructure resiliency performance measures incorporated into its transportation planning documents?

SPR-16.6 Does the agency monitor progress towards goals for at least one year and can the agency show measurable advancement towards goals?

Scoring Notes
Next Actions

SPR-17 **Linking Planning and NEPA (for Regions)** 0/15

Integrate system planning process information, analysis, and decisions with the project-level environmental review process, and reference it in NEPA documentation.

SPR-17.1 Has the agency developed landscape-level goals and objectives for linking system and corridor
0/15
planning with NEPA documentation and implementing PEL best practices?

SPR-17.2 Does the agency have documented procedures that link system-level planning analyses to project- level NEPA analysis?

SPR-17.3 Can the agency document communication from executive management to staff level regarding the agency's commitment to strengthening planning and environmental linkages?

SPR-17.4 Are NEPA practitioners consulted during system-level planning?

SPR-17.5a Do planning processes, including long-range, corridor, and sub-area studies, feature components that use NEPA principles and methods, including at least four of those listed?

SPR-17.5b Does the agency systematically and successfully incorporate information from the system-level planning process into project-level documents?

SPR-17.6a Do planning and policy documents include PEL implementation performance measures?

Scoring Notes
Next Actions

SPS-01 **Integrated Planning: Economic Development and Land Use (for States)** 0/15

Integrate statewide and metropolitan Long Range Transportation Plans (LRTP) with statewide, regional, and/or local land use plans and economic development forecasts and goals. Proactively encourage and facilitate sustainability through the coordination of transportation, land use, and economic development planning.

SPS-01.1a Has the agency developed goals and objectives for the integration of metropolitan and/or statewide transportation planning with economic development and land use planning above and beyond current requirements?

SPS-01.2a Does the agency regularly engage land use and economic development agencies in its jurisdiction throughout the transportation planning process?

SPS-01.3 Does the agency use best practice quantitative methods to analyze and evaluate the performance of alternative land use/ transportation scenarios?

SPS-01.4 Does the agency provide institutional leadership in encouraging transportation planning that is consistent with land use and economic development plans and that supports sustainability principles?

SPS-01.5 Can the agency demonstrate sustainable outcomes?

Scoring Notes
Next Actions

SPS-02 **Integrated Planning: Natural Environment (for States)**

0/15

Integrate ecological considerations into the transportation planning process, including the development of long range transportation plans (LRTP), corridor plans, and the STIP. Proactively support and enhance long-term ecological function through the coordination of transportation and natural resource planning.

SPS-02.1a Has the agency developed goals and objectives that meet the requirement for the integration of metropolitan and/or statewide transportation planning with applicable environmental plans, policies, and goals?

SPS-02.2a Does the agency go above and beyond current consultation requirements by regularly engaging
0/15
natural resource and regulatory agencies?

SPS-02.3 Does the agency apply system or landscape-scale evaluation techniques using natural resource data? SPS-02.4 Can the agency demonstrate sustainable outcomes?

Scoring Notes
Next Actions

SPS-03 **Integrated Planning: Social (for States)**

0/15

The agency's Long Range Transportation Plan (LRTP) is consistent with and supportive of the community's vision and goals. When considered in an integrated fashion, these plans, goals and visions support sustainability principles. The agency applies context-sensitive principles to the planning process to achieve solutions that balance multiple objectives to meet stakeholder needs.

SPS-03.1 Do the metropolitan and/or statewide transportation planning agencies share the community's vision for overall sustainability efforts; are transportation-related goals and objectives are consistent with that vision?

SPS-03.2 Does the agency successfully identify a diverse range of stakeholders and public participants?

SPS-03.3a Does the agency use a transparent process to inform stakeholders how their input will be used and then follow through accordingly?

SPS-03.3b Does the agency demonstrate to stakeholders how their input was used to inform and affect transportation planning decisions?

SPS-03.4 Can the agency demonstrate sustainable outcomes?

Scoring Notes
Next Actions

SPS-04 **Integrated Planning: Bonus (for States)**

0/10

The agency has a continuing, cooperative, and comprehensive (3-C) transportation planning process. Planners and professionals from multiple disciplines and agencies (e.g., land use, transportation, economic development, energy, natural resources, community development, equity, housing, and public health) work together to incorporate and apply all three sustainability principles when preparing and evaluating plans.

SPS-04.1 Does the agency's transportation planning occur within an integrated and collaborative planning process?

Scoring Notes
Next Actions

SPS-05 **Access and Affordability (for States)**

0/15

Enhance accessibility and affordability of the transportation system to all users and by multiple modes.

SPS-05.1a Does the agency aggregate and synthesize available and relevant physical access data and analyses from state and partner agencies, such as MPOs or COGs, into system planning documents?

SPS-05.1b Does the agency aggregate and synthesize available and relevant access and equity data and analyses from state and partner agencies, such as MPOs or COGs, into system planning documents?

SPS-05.1c Does the agency aggregate and synthesize available and relevant affordability data and analyses

0/15

from state and partner agencies, such as MPOs or COGs, into system planning documents?

SPS-01.1d Does the planning document include documentation of outreach with partner agencies and stakeholders as appropriate to coordinate information and analyses sharing for all dimensions of accessibility included in SPS-05.1a, SPS-05.1b and SPS-05.1c?

SPS-05.2a Does the agency integrate travel model, census, geospatial, and other data to quantitatively evaluate the nature and distribution of accessibility and affordability concerns in its jurisdiction?

SPS-05.2b Does the agency analyze how its transportation planning documents address or improves concerns/issues into the development of plans and policies?

SPS-05.3a Does the LRTP include performance measures that can be used to monitor the effects of plan implementation on transportation accessibility and affordability?

Scoring Notes
Next Actions

SPS-06 **Safety Planning (for States)**

0/15

Agency integrates quantitative measures of safety into regional planning policies, ordinances, activities, projects, and programs, and across all modes and jurisdictions.

SPS-06.1 Does the agency collaborate with partner agencies in the development and implementation of the State Strategic Highway Safety Plan?

SPS-06.2a Has the agency incorporated the Toward Zero Death (TZD) vision and implementing TZD as part of its transportation planning activities?

SPS-06.2b Has the agency developed strategies/plans to support TZD?

SPS-06.3 Does the agency Develop a Plan that Incorporates Safety into Short- and Long-Range Transportation Planning?

SPS-06.4 Does the agency integrate quantitative safety performance measures into the transportation planning process?

SPS-06.5a Does agency incorporate and integrate quantitative safety considerations into the selection and evaluation of strategies for different user groups?

SPS-06.5b Does the agency select strategies that include systemic treatments with proven effectiveness in reducing fatal and serious injuries?

SPS-06.6 Does the agency integrate statistically sound approaches to determine projected safety performance into the long-range transportation planning process?

SPS-06.7a Does the agency actively participate and support the state Traffic Records Coordinating Committee (TRCC) and jointly fund initiatives related to improvement of data management and linkage initiatives?

SPS-06.7b Does the agency develop, maintain, and use GIS-based data files for the entire public roadway system, crash* and non-crash information?

SPS-06.7c Does the agency create, maintain, and use GIS-based data for safety analysis and for use in the consideration of safety as part of the long-range transportation planning process?

Scoring Notes
Next Actions

SPS-07 **Multimodal Transportation and Public Health (for States)** 0/15

Expand travel choices and modal options by enhancing the extent and connectivity of multimodal infrastructure. Support and enhance public health by investing in active transportation modes.

SPS-07.1a Has the agency developed goals and objectives for enhancing the extent and connectivity of multimodal infrastructure within its jurisdiction?

SPS-07.1b Has the agency developed goals and objectives related to active transportation and the improvement of public health?

SPS-07.2 Does the agency regularly engage public health and active mode stakeholders?

SPS-07.3a Does the agency's planning process include and prioritize active, non-motorized transportation projects and programs as a component of the LRTP?

SPS-07.3c Has the agency evaluated the health impacts of the LRTP to determine whether the planned transportation investments will help the agency to meet its public health and active transportation goals?

SPS-07.4 Does the agency evaluate its progress toward meeting its multimodal and public health goals and makes adjustments as necessary?

Scoring Notes
Next Actions

SPS-08 **Freight and Goods Access & Mobility (for States)** 0/15

Implement a transportation plan that meets freight access and mobility needs while also supporting triple bottom line sustainability principles.

SPS-08.1a Does the agency include in the LRTP or other appropriate plan specific goals for maintaining and improving freight connectivity between modes and to freight generators for both inter- and intra-city freight, in ways that enhance sustainability?

SPS-08.1b Does the agency consider multimodal freight mobility needs in the planning process?

SPS-08.2a Does the agency regularly engage freight service providers, stakeholders, workers, and representative in developing transportation planning documents?

SPS-08.3a Does the agency include and monitor freight access performance measures in planning documents? SPS-08.3b Does the agency include and monitor freight mobility performance measures in planning documents?

SPS-08.4a Are measures and criteria to encourage coordination among the freight modes in ways that enhance sustainability are included in planning documents?

SPS-08.4b Does the agency provide for planning, evaluating, maintaining and enhancing freight mobility utilizing appropriate quantitative measures and monitoring for freight modes?

SPS-08.4c Does the agency monitor progress towards goals for at least one year and can the agency show measurable advancement towards stated goals?

Scoring Notes
Next Actions

SPS-09 **Travel Demand Management (for States)** 0/15

Reduce vehicle travel demand throughout the system.

SPS-09.1a Does the agency include a goal and objective to coordinate and support TDM activities of its regional and metropolitan partner agencies?

SPS-09.1b Has the agency developed quantifiable TDM goals and objectives for reducing travel demand for the transportation network within its jurisdiction?

SPS-09.2 Is the agency implementing a comprehensive TDM program that includes several of the various types of TDM strategies described?

SPS-09.3 Does the agency have quantifiable TDM performance measures and can the agency demonstrate ongoing monitoring of its TDM program?

SPS-09.4 Does the agency monitor progress towards goals for at least one year and can the agency show measurable advancement towards goals?

Scoring Notes
Next Actions

SPS-10 **Air Quality & Emissions (for States)** 0/15

To plan, implement, and monitor multimodal strategies to reduce emissions and to establish a process to document emissions reductions.

SPS-10.1 Has the agency developed goals and objectives consistent with partner agencies for the reduction of air emissions in transportation planning documents?

SPS-10.2 Does the agency regularly coordinate with partner agencies throughout the transportation planning process, to reduce barriers and further the prospects for implementation of strategies to improve air quality?

SPS-10.3a Does the agency partner with the state environmental agency, MPO or other regional planning organization and/or local jurisdictions to coordinate and implement transportation demand management strategies?

SPS-10.3b Does the agency partner with the state environmental agency, MPO or other regional planning organization and/or local jurisdictions to coordinate and implement transportation system management strategies to reduce emissions, including congestion relief and traffic management strategies?

SPS-10.3c Does the agency partner with the state environmental agency, MPO or other regional planning organization(s) to coordinate and implement vehicle technologies including diesel emissions reduction strategies and clean vehicle strategies?

SPS-10.3d Does the agency support policies and investments that support the development of infrastructure for fuel technologies?

SPS-10.4 Does the agency have quantifiable air emissions performance measures incorporated into its transportation planning documents?

SPS-10.5 Does the agency monitor progress towards goals for at least one year and can the agency show measurable advancement towards goals?

Scoring Notes
Next Actions

SPS-11 **Energy and Fuels (for States)**

0/15

Reduce the energy and fossil fuel consumption from the transportation sector and document it in the transportation
0/15
planning process.

SPS-11.1a Has the agency developed energy and/or fossil fuel reduction goals and objectives for the transportation system within its jurisdiction?

SPS-11.2a Does the agency cooperate with partner agencies to develop and maintain a baseline inventory of current energy and/or fossil-fuel consumption from transportation?

SPS-11.3a Does the agency coordinate with partner agencies and integrate energy and fossil fuel reduction strategies in the LRTP, and does the LRTP includes a discussion of the impacts of including these strategies?

SPS-11.3b Does the agency coordinate with partner agencies and integrate transportation strategies to reduce transportation-related energy and fossil fuel consumption and related emissions?

SPS-11.4a Had the agency incorporated energy and fossil fuel reduction performance measures into the transportation planning process?

SPS-11.4b Does the agency monitor progress towards goals for at least one year and can the agency show measurable advancement towards goals?

Scoring Notes
Next Actions

SPS-12 **Financial Sustainability (for States)**

0/15

Evaluate and document that financial commitments made across transportation system plans are reasonable and affordable.

SPS-12.1 Is an inter-agency, cooperative approach for advanced revenue forecasting practices used? SPS-12.2 Is an inter-agency, cooperative approach for advanced project estimating practices used?

Scoring Notes
Next Actions

SPS-13 **Analysis Methods (for States)**

0/15

Agencies adopt and incentivize best practices in land use, socioeconomic and transportation systems analysis methods.

SPS-13.1a Does the agency demonstrate that the analysis has a strong foundation in observed data suitable for developing tools which model the land use, socioeconomic, transport, and environmental systems?

SPS-13.2a Does the program include a specific multi-year development program for maintaining transportation data resources and improving analysis methods?

SPS-13.2b Does the program include specifications for the data resources and methods that explicitly address sustainability principles?

SPS-13.2c Does the program include identification of an adequate level of funding required to implement the data collection and modeling tasks, which is also reflected in the appropriate work plan?

SPS-13.2d Does the program identify and include resources which include support for experienced technical management and a mix of technical staff and/or contract staff?

SPS-13.3a Does the agency's organizational structure include a technical committee to ensure the technical review of data collection/ quality, planning assumptions, and forecasting methods?
0/15
SPS-13.3b Has the agency convened a peer review of its analysis methods? SPS-13.3c Has the agency convened a peer review of the travel model?

Scoring Notes
Next Actions

SPS-14 **Transportation Systems Management and Operations (for States)**

0/15

Optimize the efficiency of the existing transportation system.

SPS-14.1a Has the agency developed clearly defined goals and objectives for improving the efficiency of the transportation system within its jurisdiction?

SPS-14.2a Are TSM&O strategies included in the LRTP, STIP, or other planning documents, as appropriate? SPS-14.2b Does the LRTP, or equivalent, include a discussion of the impacts of including TSM&O strategies?
SPS-14.2c Are the TSM&O strategies considered and prioritized in the LRTP, STIP, or other planning documents?

SPS-14.3 Has the agency implemented or is the agency funding TSM&O strategies? SPS-14.4 Does the agency include TSM&O performance measures in planning documents?
SPS-14.5 Does the agency monitor progress towards goals for at least one year and can the agency show measurable advancement towards goals?

Scoring Notes
Next Actions

SPS-15 **Linking Asset Management and Planning (for States)**

0/15

Leverage transportation asset management data and methods within the transportation planning process to make informed, cost-effective program decisions and better use existing transportation assets.

SPS-15.1 Has the agency developed clearly defined goals and objectives for linking planning in their planning documents?

SPS-15.2 Does the agency incorporate asset management data and economic analysis to prioritize investments?

SPS-15.3 Does the agency leverage performance-based planning and programming components of asset management to analyze and evaluate tradeoffs in long-range transportation planning processes?

SPS-15.4a Does the agency prioritize transportation decisions that support the maintenance and good repair of existing transportation assets?

SPS-15.4b Does the agency monitor progress towards goals for at least one year and can the agency show measurable advancement towards goals?

Scoring Notes
Next Actions

SPS-16 **Infrastructure Resiliency (for States)** 0/15

Anticipate, assess, and plan to respond to vulnerabilities and risks associated with current and future hazards (including those associated with climate change) to ensure multi-modal transportation system reliability and resiliency. Identify a range of vulnerability and risks to both existing and planned transportation infrastructure.

SPS-16.1 Has the agency conducted a system-level assessment of potential hazards? SPS-16.2 Has the agency conducted a vulnerability assessment of its assets?

SPS-16.3 Has the agency conducted a risk assessment of its assets? SPS-16.4 Has the agency developed and implemented adaptation strategies?

SPS-16.5 Does the agency regularly coordinate with partner agencies within its jurisdiction throughout the transportation planning process?

SPS-16.6 Does the agency have a formal mechanism to evaluate and prioritize infrastructure improvements?

Scoring Notes
Next Actions

SPS-17 **Linking Planning and NEPA (for States)** 0/15

Integrate system planning process information, analysis, and decisions with the project-level environmental review process, and reference it in NEPA documentation.

SPS-17.1 Has the agency developed landscape-level goals and objectives for linking system and corridor planning with NEPA documentation and implementing PEL best practices?

SPS-17.2 Does the agency have documented procedures that link system-level planning analyses to project- level NEPA analysis?

SPS-17.3 Can the agency document communication from executive management to staff level regarding the agency's commitment to strengthening planning and environmental linkages?

SPS-17.4 Are NEPA practitioners consulted during system-level planning?

SPS-17.5 Does the agency successfully incorporate information into project-level NEPA documents? SPS-17.6a Do planning and policy documents include PEL implementation performance measures?

Scoring Notes
Next Actions