Use of Recycled Concrete Aggregate in PCCP: Literature Search

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16. ABSTRACT

The use of recycled concrete aggregate (RCA) is recommended based on a review of literature that investigated the properties and characteristics of RCA, the physical properties of fresh and hardened concrete containing RCA, the mechanical behavior of concrete containing RCA, and special considerations for concrete pavements using RCA to achieve suitable levels of workability, durability, and strength. The literature also detailed concrete pavement design considerations as well as the successes and failures of trial projects built by other states.

A recommendation is made that RCA be considered for use in Western Washington and that the FHWA Technical Advisory be used as a guide during implementation.

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Executive Summary

The Washington State Department of Transportation (WSDOT) is considering recycling concrete pavements to produce aggregate for new concrete (PCC) pavements. Recycling pavements to produce new pavements conserves natural resources, reduces the impact on dwindling landfill space, reduces disposal costs, and may reduce overall projects costs.

The primary reason for considering recycling, however, is the high quality of the aggregate in our existing pavements. Washington pavements contain some of the highest quality aggregates in the world and this fact has been cited as the reason for the excellent performance of not only the PCC pavements, but also hot mix asphalt (HMA) pavements.

Using recycled concrete aggregate (RCA) can be successful if careful consideration is given to the properties and physical characteristics of the aggregate, the physical properties of the fresh and hardened concrete and the mechanical behavior of the pavement containing RCA as noted below:

Recycled concrete aggregate is angular with rough surfaces, has higher water absorption capacity, lower specific gravity, higher Los Angeles abrasion loss, often fails the sulfate soundness test, but usually passes the magnesium soundness test, and may have higher levels of sodium chloride due to absorption of deicing salts by the cement paste clinging to the rock.

Fresh concrete made with recycled aggregate tends to be very harsh due to the angular shape and rough surface of the aggregate, more prone to slump loss and require higher water contents due to higher absorption of the cement paste attached to the aggregate, and higher air contents due to the greater porosity of the recycled aggregate themselves and to the entrained air in the original mortar.

Hardened concrete made with recycled aggregate has slightly lower compressive strength and flexural strength, a lower stiffness (modulus of elasticity), higher resistance to freeze-thaw due to higher air contents, less potential for D-cracking, increased potential for ASR, equivalent bond strength, higher creep and drying shrinkage than concrete made with virgin aggregates.

Pavements made with RCA aggregates may have problems with excessive midslab cracking, poor load transfer, and durability if proper steps are not taken to combat D-cracking, freeze-thaw and ASR susceptibility.

The workability of mixes made with RCA can be improved by limiting the use of recycled fine aggregate, adding fly as a partial cement replacement and using water reducing agents. Limiting the amount of recycled fine aggregate also improves the durability and strength of concrete made with RCA. Durability can also be improved by using a smaller top size aggregate, using fly ash, blending the RCA with virgin aggregates and using low-alkali cement. Lower strength of mixes made RCA can be overcome by adding water reducing agents, increasing the cement content and as mentioned previously, limiting the amount of recycled fine aggregate in the mix.

Michigan, Wisconsin, Iowa, Minnesota, and Wyoming have built multiple numbers of projects over the years with RCA. Fifteen states having built at least one trial project. The performance

of these projects has been generally good. Performance problems have usually been traced to the marginal quality of the original aggregates. Only one state, Michigan, has a moratorium on the use of RCA due to excessive mid-slab cracking in jointed reinforced concrete pavements built with 41-foot joint spacing. Very few of the states continue to use RCA in their pavements with many electing to use the material in either the base or shoulder material.

The literature suggests that the use of RCA in pavements in Western Washington is worth considering given the hard, durable nature of the virgin aggregates that were used to build the existing pavement on the west side of the state. Many of the performance issues cited in the literature and experienced by other states will not be a problem due to our excellent aggregates or will not show up because of our existing mix design and construction practices.

Introduction

The Washington State Department of Transportation (WSDOT) is considering using recycled concrete aggregate (RCA) as a substitute for some of the virgin aggregate used to produce hydraulic cement concrete pavement (PCCP). The source of this aggregate would be existing PCCP that has reached the end of its structural life and must be replaced. The sections of I-5 through the Seattle urban corridor would be an example of a location that might benefit from recycling the aggregate from the existing pavement into the replacement pavement. There are many reasons for considering using the existing pavement as a source of aggregate for the new pavement.

- Dwindling supplies of high-quality, virgin aggregates.
- Dwindling landfill space.
- Increased disposal costs.
- Sustainability (conservation of natural resources).
- Overall reduction in project costs.

The Literature

The primary source for the information in this investigation is an unpublished report by Dr. Mark Snyder, formerly associated with the University of Minnesota, now a consultant working out of Bridgeville, PA. This unpublished report was background work for an in depth field investigation of nine projects that was published 1994. These same projects were surveyed again in 2006 and reported on at the 2009 TRB Annual Meeting. Additional information on various States experiences obtained through e-mail contacts in 2006 with follow-ups in 2009. The Federal Highway Administration provided the final source of information in the form of a 2007 technical advisory that provided guidance to the states on the use of RCA in hydraulic-cement concrete pavements.

Study Outline

Information from each source will be presented followed by a discussion of how the information may or may not affect the use of RCA in Washington State. Recommendations for the potential incorporation of RCA into Washington State pavements complete the report.

Snyder 2006 Unpublished Report

Properties and Characteristics of Recycled Concrete Aggregate

A concrete pavement's strength and performance is very dependent on the aggregates used to produce the concrete. Recycled concrete aggregates are different in many ways from virgin aggregates as shown in Table 1.

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

Shape and Texture
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.

Absorption Capacity
The amount of water that an aggregate can absorb is called absorption capacity. The porous nature of the cement paste portion of the recycled aggregates increases its absorption capacity. Workability (slump) can suffer with high absorption capacities resulting in a decrease in the time available to place and finish the concrete. Adding additional 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.

Specific Gravity
Specific gravity is a measure of the density of an aggregate. The lower specific gravity of RCA is due to the crushed mortar present in and on the aggregate particles which makes it less dense than virgin aggregates because of its porosity and entrained air structure. The smaller particles tend to have lower specific gravities than the larger particles, thus limiting the amount of recycled fine aggregates in a mix can increase the specific gravity.

L.A. Abrasion Mass Loss
The Los Angeles abrasion test (ASTM C 131) measures the amount of pulverization that takes place for a given aggregate. In general, the greater the loss the softer the aggregate and the less suitable it is for concrete. The loss for RCA is usually higher than natural aggregates, but is well within the limits recommended by ASTM.

Sulfate Soundness Mass Loss
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 1. 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.

Chloride Content
Pavements with long-term exposure to deicing salts map produce RCA with high levels of sodium chloride (NaCl). 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.

Summary
Recycled concrete aggregate is angular with rough surfaces, has higher water absorption capacity, lower specific gravity, higher Los Angeles abrasion loss, often fails the sulfate soundness test, but usually passes the magnesium soundness test, and may have higher levels of sodium chloride due to absorption of deicing salts by the cement paste clinging to the rock.

Physical Properties of Fresh Concrete Containing RCA

The important properties of fresh concrete containing RCA are shown in Table 2.

{PRIVATE **}Property**	**RCA Mixes**
Workability	Poor workability and harshness when both coarse and fine fractions are used. Rapid loss of slump. Problem can be alleviated by using only the coarse fraction combined with natural fines.
Water Content	Typically higher for RCA mixes due to greater absorption. Setting water content may be difficult due to the variable absorption.
Air Content	Tends to be higher and more variable due to higher porosity of RCA and entrained air in original mortar.

Workability

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 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.

Water Content

Increased water contents are required for mixtures containing RCA due, as mentioned previously, the high absorption capacity of the paste clinging to the aggregates. The higher and more variable absorption capacity also makes it difficult to determine the water content which in turn leads to variation in the strength of the hardened concrete.

Air Content

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

Summary

Fresh concrete made with recycled aggregate tends to be very harsh due to the angular shape and rough surface of the aggregate, more prone to slump loss and require higher water contents due to higher absorption of the cement paste attached to the aggregate, and higher air contents due to the greater porosity of the recycled aggregate themselves and to the entrained air in the original mortar than concrete made with virgin aggregates.

Physical Properties of Hardened Concrete Containing RCA

The pavements built with concrete containing RCA must have the strength and durability of conventional concrete if it is to be a viable alternative. Table 3 summarizes the physical properties of mixes containing RCA and the following sections describe these important strength, durability and deformation properties.

{PRIVATE }**Property**		**RCA Mixes**
Compressive Strength		Generally slightly lower due to the reduction of the percent of natural aggregates.
Flexural Strength		Generally slightly lower, but it varies depending on the quality of the original aggregate and the amount of recycled fine aggregate used.
Modulus of Elasticity		Generally 20 to 40 percent lower than mixes with natural aggregates due to the lower elastic modulus of the RCA particles.
Durability	Freeze-Thaw	Superior to virgin aggregate mixes.
	D-Cracking	Reduced potential due to the crushing of original aggregate to smaller sizes.
	ASR	Increased potential due to increased surface areas of the aggregates that have been crushed.
Bond Strength with Reinforcement		Equal to virgin aggregate mixes, but reduced if recycles fines are used.
Creep		Higher due to the higher cement paste fraction.
Drying Shrinkage		Higher due to the higher cement paste fraction.

Compressive Strength
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, other 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.

Flexural Strength
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.

Modulus of Elasticity
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.

Durability

Overall the durability of concretes containing RCA is equal to or better than that of the original concrete. This is examined for the three properties freeze-thaw resistance, d-cracking susceptibility, and ASR susceptibility.

Freeze-Thaw Durability

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.

D-Cracking Susceptibility

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.

Alkali-Silica Reaction

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 between Concrete and Reinforcement

Bond strength reductions have not been noted with only recycled coarse aggregate is used; however, when recycled fines are used reductions have need reported. The additional water required to produce a workable mix in concretes using recycled fines is blamed for this reduced bond strength.

Creep

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

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 that have higher paste contents and thus have increased shrinkage. Mix designs that use both coarse and fine aggregates have the highest drying shrinkage.

Summary
Hardened concrete made with recycled aggregate has slightly lower compressive strength and flexural strength, a lower stiffness (modulus of elasticity), higher resistance to freeze-thaw due to higher air contents, less potential for to D-cracking, increased potential for ASR, equivalent bond strength, higher creep and drying shrinkage than concrete made with virgin aggregates.

Mechanical Behavior of Concrete Containing RCA

The behavior of pavements constructed with RCA mixes has been observed to be different than those constructed with conventional mixes. Recycling seems to affect slab cracking, load transfer and durability as noted in the following sections and summarized in Table 4.

{PRIVATE }**Property**	**RCA PCCP**
Slab Cracking	Excessive amounts of midslab cracking reported in JPCP due to higher shrinkage and greater thermal expansion and contraction with RCA mixes, however, the problem may have been acerbated by excessively long joint spacing.
Load Transfer	Poor load transfer capacity due to: • Smaller sized coarse aggregate requires only small crack openings to loose all of their grain interlock • Lower percentage of natural aggregate particles which have greater load transfer capability • Poor abrasion resistance of the paste portion of the RCA pavements results in rapid loss of load transfer
Durability	Not usually a problem if the proper steps are taken to deal with D-cracking susceptible aggregates, freeze-thaw susceptibility and ASR susceptibility.

Slab Cracking
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

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.

Durability

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 there are steps that can be taken to reduce or eliminate the effects of both as noted previously.

Summary

Pavements made with RCA aggregates may have problems with excessive midslab cracking, poor load transfer, but generally no problems with durability if proper steps are taken to combat D-cracking, freeze-thaw and ASR susceptibility.

Special Considerations for Concrete Pavements Using RCA to Achieve Suitable Levels of Workability, Durability and Strength

Table 5 summarizes the special considerations that are necessary for achieving suitable levels of workability, durability, and strength in a concrete mix utilizing recycled concrete aggregate. Most of these have been discussed at length in the previous sections of this report; however, a brief review of the most important considerations is warranted.

{PRIVATE }Desired Mix Property	Design Concerns	Responsible RCA Characteristic	Possible Solutions
Workability	Harsh mix emerges when RCA fines are used in mix	• Angularity of fine RCA • High absorption of fine RCA	▪ Use natural fines or limit RCA to 30 percent ▪ Use fly ash as partial cement replacement ▪ Add water reducing agent
	Rapid loss in workability during concrete placement	• High absorption of fine RCA	Same as above
Durability	Recycled aggregate less durable	Aggregate consists of aggregate and cement (less virgin material)	▪ Use fly ash ▪ Use a smaller top size ▪ Decrease w/c
	Existing pavement with D-cracking	n/a	▪ Crush to smaller maximum size ▪ Use fly ash in mix to improve durability
	Existing pavement with reactive aggregates	n/a	▪ Use fly ash in mix to improve durability ▪ Consider blending of RCA and virgin aggregates ▪ Use a low-alkali cement
Strength	Strengths from RCA mixes are lower than conventional mixes	• Recycled fine aggregate • Softer cement particles as aggregate	▪ Limit amount of recycled fine aggregate ▪ Add water reducing agent ▪ Increase cement content
	Washing of RCA required for strength	• Deleterious materials in RCA	▪ No conclusive differences in strength between washed and unwashed processes

Workability

The workability of the mix can influence the finished pavement with respect to strength, durability and initial smoothness. Increasing the water content of the mix to increase workability will produce a weaker, more porous cement paste if not accompanied by increases in cement content. Using water reducing admixture and fly ash can get around the workability issues without sacrificing strength and increasing costs. Using natural fines or limiting the RCA fines to 30 percent is also very effective in eliminating the workability problem.

Durability
Problems with freeze-thaw durability, D-cracking susceptibility, and reactive aggregates can be eliminated or minimized through the use smaller top size aggregates, adding fly ash to the mix, blending the RCA with natural aggregates or using low-alkali cement.

Strength
Concrete strength is the criteria by which most agencies specify mix designs. Mixtures utilizing RCA generally have lower strengths than those using natural aggregates. The following list of modifications might be warranted to achieve the desired strength in mixes using RCA:

- Use a water-reducing agent to increase workability without increasing the water/cement ratio.
- Increase the cement content.
- Use fly ash as a partial substitute for cement.
- Eliminate or reduce the amount of recycled fines.

A concern that RCA should be washed to remove deleterious materials that might adversely affect concrete strength has not been born out by studies that have used both washed and unwashed RCA.

Concrete Pavement Design

Relatively little work has been done on examining the need for compatibility between concrete pavement design and concrete mixtures containing RCA. Table 6 provides example guidelines that could be developed for each major design element for a concrete mixture containing RCA.

{PRIVATE }**Concrete Pavement Design Element**	**Design Recommendation**
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 used. • blend of RCA and virgin aggregate used. • greater amount of reinforcement used.
Slab Thickness	Thickness 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.
Joint Spacing	Shorter joint spacing may be desirable to reduce the amount of crack opening.
Load Transfer	Dowels recommended for transverse joints; load transfer at cracks (for reinforced pavements) must consider factors listed in section on *Pavement Type*.
Joint Sealant Reservoir Design	New recommendations may be needed due to increased drying shrinkage.
Base Type	For JPCP, conventional base types appropriate. For reinforced pavements, consider the use of a strong, durable, non-erodible base.
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.
Shoulder Type	Same as for conventional mix design.

States Experience with RCA in Concrete Pavement

Information collected by Mark Snyder from states that built trial projects in the early 1980's to the middle 1990's is summarized in Table 7.

Table 7. State projects using RCA in PCCP

State	Highway/ Location	Year Recycled	Remarks	Performance
Colorado	I-70/I-76 Denver N.	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
Michigan	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	
Minnesota	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.	1990-92	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

Wyoming	I-80, Rock Springs Vic.	1986	JPCP into JPCP	Good
	I-80, Rock Springs Vic.	1987	JPCP into JPCP	Good
	I-80, Cheyenne Vic.	1987	JPCP into JPCP	Good
	I-80, MP Pine Bluffs Vic.	1987	JPCP into JPCP	Fair
	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	

Additional performance information from the primary users of RCA from Table 7 is summarized below:

Iowa

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

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.

Minnesota

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

Wisconsin

- Variety of processes used, JRCP into CRCP, JRCP into JPCP, JRCP into JRCP, CRCP into CRCP.
- Performance is generally good and many of the section 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.

Wyoming

- All project recycled JPCP into JPCP.
- Successfully used ASR aggregates.
- Later projects used dowel joints.

1994 Survey Results by Snyder and Others

Cuttell, G. D., Snyder, M. B., Vandenbossche, J. M., and Wade, M. J. "Performance of Rigid Pavements Containing Recycled Concrete Aggregate". Transportation Research Record 1574. Transportation Research Board. Washington, D.C. 1997.

Mark Snyder and others selected nine projects from Table 7 to conduce a comprehensive field data collection program. 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, retrieval of pavement cores, and estimation of the present serviceability rating.

The conclusions and recommendations from the field survey as reported in Transportation Research Record 1574 are:

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 affects 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 after nine years of service.

Recommendations

- More thoroughly 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.

2006 Survey Results by Snyder and Others

Gress, D.L., Snyder, M.B. and Sturtevant, J. R. "Performance of Rigid Pavements Containing Recycled Concrete Aggregates – 2006 Update*"*. Transportation Research Board 86th Annual Meeting. January 2007.

The same projects were resurveyed in 2006 by Mark Snyder and Others. The conclusions and recommendations are listed below:

Conclusions

- Pavements with RCA are equivalent in all aspects to pavements built with conventional aggregates.
- Load transfer devices improve the performance of RCA pavements.
- Pavements built with RCA have equivalent performance to pavements made with conventional aggregates.

Recommendations

- 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.
- Concrete being considered for recycling into RCA must be evaluated for existing distress and accommodations make to mitigate same.
- Minnesota had high reclaimed mortar content and experienced a higher percentage of slab cracking than in a corresponding control section that did not use RCA.
- Doweled pavements exhibited excellent load transfer, undoweled poor load transfer. Dowel bars should be used on all RCA pavements.
- Freeze-thaw damage not visibly on any of the projects in spite of some not following FHWA recommendations of a minimum cement content of 565 lb/yd^3.

WSDOT Surveys of State Experience with RCA in Concrete Pavements

Information was collected via e-mail from a number of States in 2006 on their use of RCA in concrete pavements. Below is a listing of the responses.

Colorado

- Contact - Tim Aschenbrener, Project Development Branch Manager, 2/27/2006.
- RCA used in the past in base courses and mixes and it worked well, but there is no documentation.

Idaho

- Contact - Mike Santi, Assist. Materials Engineer, 2/27/06.
- RCA used on one project on I-84 near Mountain Home in 1990-91.
- No RCA fine aggregate used.
- Mix was harsh and required more water.
- Have not used since, but would consider if Contractor proposed.

Illinois

- Contact - Amy Schutzbach, Research Engineer, 2/24/2006.
- Recommendations are based on report by Roesler and Huntley, Performance of I-57 Recycled Concrete Pavements, January 2009, Illinois Center for Transportation Report ICT-09-032.
- 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-life paving operation.

Iowa

- Contact – Chris Brakke, Pavement Design and Management Engineer, 6/4/2009
- Most of the RCA project in Iowa were built by counties, only a few by the DOT
- RCA is currently being used in bases.

South Carolina

- Contact - Andrew Johnson, State Pavement Design Engineer, 2/22/2006.
- 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.

Texas

- Contact - Moon Won, Transportation Engineer, 2/25/2006.
- Used on IH-10 in Houston in 1995 – CRCP.
- Used both coarse and fine aggregate, no virgin aggregates.
- Approximately 30% old mortar attached to recycled aggregate.
- Compressive and tensile strengths lower than concrete made with virgin aggregate.

- Density lower, water absorption higher.
- Moisture control was difficult, 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.

Virginia

- Contact - Mohamed K. Elfino, Assist. State Materials Engineer, 2/28/2006.
- 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.

Wyoming

- Contact - Bob Rothwell, Assist. State Materials Engr.,2/28/2006, E-mail.
- RCA used on 8-11 projects as of 2006.
- All projects undoweled JPCP.
- RCA coarse aggregate limited to 60% with remainder virgin aggregate.
- RCA fine aggregate limited to 15%.
- Cement content requirement increase by 1/2 sack.
- Some issues with ASR that were handled without problems.
- Mostly JPCP into JPCP between 1985 and 1994.

The states that were most active in the trials of RCA from the Snyder study were contacted again in 2009 to determine what current use was being made of RCA. The responses are listed below.

Minnesota

- Contact - Ben Worel, MnROAD Operations Engineer, 2/19/2009.
- 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.

Michigan

- Contact - Alan Robords, Supervising Geologist, Aggregate Quality Control, 2/19/2009.
- 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.

Wisconsin

- Contact - Irene Battagliz, Pavement Research and Warranty Engineer, 2/24/2009.
- 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.

Wyoming

- Contact - Bob Rothwell, Assist. State Materials Engineer, 3/13/2009.
- Four projects added to list since Snyder completed survey in 1994. One project had issues with aggregate polishing, but they were with the virgin aggregate added to the mix, not the RAC.

Table 8 is in the same format as Table 7 and contains additional RCA trial projects from Idaho, Oregon, South Carolina, Texas and Wyoming collected from e-mail correspondence in 2006 and 2009.

State	Highway/ Location	Year Recycled	Remarks	Performance
Idaho	I-85, Mountain Home	1990-91	Coarse agg. Only, mix harsh, required more water	Good
Oregon	I-84, Le Grande	?	CRCP, WB lane	
South Carolina	I-95, Florence	2003-2004	Doweled the new JPCP	Good
Texas	IH-10, Houston	1995	CRCP into CRCP	Good
Wyoming	I-80 Telephone Canyon	1997	Added by Bob Rothwell, WYDOT	Good
	I-80 Laramie Marginal	1997	Added by Bob Rothwell, WYDOT	Good
	I-25 Cheyenne Marginal	1999	Added by Bob Rothwell, WYDOT	Good
	I-25 Cheyenne Marginal	2001	Added by Bob Rothwell, WYDOT	Good

The performance of the pavements built with RCA has been generally good. Several states reported that there was virtually no difference in the performance of the pavements containing RCA and control section built with virgin aggregates. Only the state of Michigan has discontinued the use of RCA in pavements due to premature failures or poor performance (moratorium issued in 1991).

While many of the states that have experimented with the use of RCA in concrete pavements, almost none are planning to build additional projects. Many states are using the RCA in bases and in shoulders. The one exception is Minnesota which plans to reconstruction two of the MnROAD test cells reusing the aggregates from previous cells. Other states are reusing their RCA in bases and other non-mainline pavement applications. Wisconsin and Idaho allow the contractor to choose between using the RCA in the pavement or in the base.

FHWA Technical Advisory

FHWA produced a technical advisory in 2007 that addresses the use of RCA in hydraulic cement concrete pavements. The advisory is a very good compilation of the issues involved and steps that should be taken to address those issues.

1. **What is the purpose and scope of this Technical Advisory?** This Technical Advisory issues information on state-of-the-practice and guidance for the use of recycled concrete pavement as aggregate in concrete used for pavements.
2. **Does this Technical Advisory supersede another Technical Advisory?** No. This is a new Technical Advisory.
3. **What are the key definitions?**
   a. **Recycled concrete aggregate (RCA)**. RCA is granular material manufactured by removing, crushing, and processing hydraulic-cement concrete (see paragraph 3b) pavement for reuse with a hydraulic cementing medium to produce fresh paving concrete. The aggregate retained on the 4.75 mm (No. 4) sieve is called coarse aggregate; material passing the 4.75 mm (No. 4) sieve is called fine aggregate.
   b. **Hydraulic-cement concrete**. Historically, the term "portland cement concrete" or "PCC" has been used to describe pavements that use portland cement, a specific type of hydraulic cement, as the binder. Because of the widespread use of blended cements and supplementary cementitious materials, the term "portland cement" no longer accurately describes the binder. In this Technical Advisory, the broader, generic term "hydraulic-cement concrete" is used.
4. **What is the background on recycling concrete as aggregate for concrete pavement?**
   a. Disposal of existing concrete pavements is often a problem faced on many pavement reconstruction projects. Recycling concrete, as an aggregate product, is common practice by several State Departments of Transportation (DOTs), private industry, and many foreign agencies. The Federal Highway Administration (FHWA) Policy Memorandum "Formal Policy on the Use of Recycled Materials," dated February 7, 2002, states that reusing the material used to build the original highway system "... makes sound economic, environmental, and engineering sense." It also emphasizes that recycled materials must be used in an appropriate manner that "... shall not affect the performance, safety or the environment of the highway system." Environmental issues and costs associated with removal and disposal of old concrete must be addressed early in the project development.
   b. Options for dealing with the old pavement include the following:
      1. (1) Removal from the site and disposal in a landfill, or usage in other environmentally favorable ways such as riprap.
      2. (2) Construction of an overlay on top of the old pavement.
      3. (3) Cracking and seating or rubblizing the old pavement, and constructing new pavement on top of it.
      4. (4) Processing the removed pavement into an aggregate product for use in granular or stabilized base, subbase, or shoulder materials.
      5. (5) Processing the removed concrete pavement into a RCA suitable for use as bedding, backfill, granular embankment, or in asphalt or hydraulic-cement concrete with lower performance expectations.
      6. (6) Processing the removed concrete pavement into a high-quality RCA product suitable for use in high performance hydraulic-cement concrete or asphalt.
   c. Discussions of the first five alternatives in paragraph 4b appear in other technical literature. This Technical Advisory deals only with a portion of the final alternative,

recycling removed pavement, from a known source, into a high-quality aggregate product for use as aggregate in high performance hydraulic-cement concrete pavement.

5. **How can removed concrete pavement be processed into aggregate suitable for new concrete pavement?** The first step in processing removed concrete pavement into aggregate suitable for new concrete pavement is to demolish the concrete pavement and remove the demolished material to a processing site. Initial processing removes steel, soil, and other contaminant material from the concrete. The demolished concrete is then crushed and sized by screening operations that result in an aggregate product that meets the specified grading requirements. Fine impurities, such as soil and loose cement mortar, should be removed by special crushing operations, washing, dry or wet screening or hydraulic sizing. Lightweight contaminates, such as wood or porous chert, may require the use of other aggregate beneficiation methods, such as hydraulic separation. Except for removing steel, impurities, and contaminates, this process is identical to the process used to produce aggregate from virgin stone materials.
6. **Can concrete exhibiting materials related distress (MRD) be recycled for use in new concrete pavements?** Yes. Concrete exhibiting MRD may be recycled for use in new concrete pavements only if the distress mechanism is recognized prior to design, and proper mitigation measures are implemented in the new pavement to insure that the MRD will not recur. 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 (see paragraph 14o). The most common MRDs are Alkali-Silica Reaction (ASR) and D-cracking.
    a. ASR occurs when certain siliceous aggregates react with alkalis in the concrete paste to form gel that expands after absorbing water. Gel expansion can cause the concrete to crack. 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 ASR (see paragraph 14k).
    b. 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 (see paragraph 14k).
7. **What are the requirements for insuring the quality of RCA?**
    a. In order to produce high quality concrete for the new application, RCA aggregate should:
        1. (1) 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;
        2. (2) Be free of harmful components such as chlorides and reactive materials unless mitigation measures are taken to prevent recurrence of MRD in the new concrete; and
        3. (3) Have an absorption of less than 10 percent.
    b. In general, the recycled materials used for concrete paving projects must meet the same quality requirements normally used for virgin aggregate. (See American Society for Testing and Materials (ASTM) C 33, "Standard Specification for Concrete Aggregates",or American Society of State Highway and Transportation Officials (AASHTO) M 80, "Coarse Aggregate for Portland Cement Concrete" and AASHTO M 6, "Fine Aggregate for Portland Cement Concrete"). Coarse RCA should meet the appropriate grading requirements. Fine RCA will be somewhat more coarse and angular than needed to produce good concrete. Because of the degradation of new concrete properties discussed in the following sections of this Advisory, use of fine RCA is not recommended. If, however, fine RCA must be used, it should be blended with a finer natural sand to improve performance.

c. Density of RCA will typically be slightly less than that of the original material used. This will have an effect on proportioning the new concrete. Expect RCA to have higher water absorption than that of the original aggregate.
d. The Los Angeles Abrasion Test (ASTM C 131, "Standard Test Method for Resistance to Degradation of Small-Size Coarse Aggregate by Abrasion and Impact in the Los Angeles Machine") is used to determine an aggregate's resistance to breakdown during handling and mixing. RCA produced from all but the poorest quality recycled concrete should have little trouble meeting the abrasion requirements of ASTM C 33 or AASHTO M 80. Abrasion loss should be less than 5 percent.
e. Freeze-thaw durability is primarily a function of the amount of entrained air and the quality of the air void system. If the concrete to be recycled has poor resistance to freeze-thaw action, the new concrete can be expected to have reduced freeze-thaw durability. The freeze-thaw durability of hydraulic-cement concrete with RCA is also impacted by the effect the RCA has on the effectiveness of air-entraining admixtures in the new concrete. A North Carolina study indicates that as the percentage of recycled fine aggregate increased, the air content of the fresh concrete decreased (see paragraph 14d). To meet target air contents, higher dosages of air entraining agent are needed for concrete mixtures utilizing fine and coarse recycled aggregates; other States have found that it is not possible to produce a mixture that satisfied target air content requirements (see paragraph 14d). 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.
f. 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 (JPC) pavement, use of epoxy-coated, stainless steel, and stainless steel clad or fiber reinforced plastic (FRP) dowels should be considered to mitigate the potential corrosion.
g. 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 (see paragraph 14n).
h. 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 (ACI 555, "Removal and Reuse of Hardened Concrete") 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."
i. Laboratory and field trials of the concrete mixture must be conducted to insure that the properties of the mixture containing RCA meet job requirements.

8. **What are the properties of new concrete when RCAs are used?** RCA can have a profound impact on the properties of both fresh and hardened hydraulic-cement concrete. Tables 1, 2, and 3 summarize available information on the effect of RCA on properties of new concrete. In general, as is the case with virgin aggregates, improving the quality of RCA will lessen or eliminate any negative impact on the required engineering properties of the new concrete.
9. **What pavement design issues need additional consideration when using RCA in concrete?** The pavement designer must be aware of potential strength reduction, increased shrinkage potential, and possible changes in the thermal characteristics of hydraulic-cement concrete produced with RCA. These properties may require the designer to increase pavement thickness or change joint spacing to accommodate the use of RCA in the project. The differences in some

concrete properties may be beneficial to the performance of the pavement, depending on the particular design and environment. Prior to design, the properties of the specific concrete proposed for use should be determined. These design inputs can then be used in a mechanistic-empirical design procedure that accounts for temperature and shrinkage in determining joint spacing.

10. **What mixture design and proportioning issues should be considered when proportioning concrete using RCA?**
    a. 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 containing fine and coarse RCA may require up to 15 percent more water (see paragraph 14a).
    b. In the event that fine RCA is used, a blended fine aggregate with no more than 30 percent fine RCA is recommended. This may reduce the water demand by about 10 percent compared to a similar concrete with 100 percent fine RCA. Fine RCA should not be used in concrete where freeze-thaw durability is required.
11. **What production issues should be considered when making concrete with RCA?** Concrete containing RCA can be batched, mixed, delivered, placed, and finished using methods commonly used for concrete containing virgin aggregate. The primary caution for production is dealing with the increased water demand of RCA, even though proper processing should have removed the fine material prior to concrete production. RCA should be presoaked to help maintain uniformity of absorbed water during production. It should be stored and moistened using procedures commonly used for light weight and slag aggregate, such as continuous sprinkling prior to batching.
12. **What construction issues should be addressed when paving with concrete containing recycled aggregates?** If the procedures described above for production of the RCA and the concrete are followed, construction issues should not be different from issues encountered when paving with concrete manufactured with virgin aggregate. Failure to properly address aggregate processing, water demand, or air entrainment will significantly increase the likelihood of problems in placing and finishing the new pavement.
13. **What are the costs associated with using high-quality RCA?** Recycling demonstrates good environmental stewardship, and it may reduce the cost of a paving project, but economic and environmental costs are different on each project. Recycling existing pavement for use as RCA for new concrete pavement may or may not present the best recycling solution. Factors to be considered include availability and cost of virgin aggregate, processing and quality control costs to manufacture high-quality recycled aggregate for use in new concrete, hauling and tipping fees for land-fill disposal of old pavement, comparison with costs of lower-value recycling alternatives, and job specific environmental issues. The quantity of RCA available on a project may not be sufficient to fill the requirements of the new paving project. Pavement sections containing RCA may be thicker or require shorter joint spacing, which may increase the cost of the new pavement.
14. **Are there any reference materials on the use of recycled concrete as aggregate?** The following references apply to using recycled demolished concrete as aggregate for concrete:

    a. American Concrete Institute (ACI) Committee 555, "Removal and Reuse of Hardened Concrete,"ACI 555R-01, American Concrete Institute, Farmington Hills, MI, 2001.
    b. American Concrete Paving Association (ACPA), "Recycling Concrete Pavement,"TB014P, American Concrete Pavement Association, Skokie, IL, 1993, 19 Pages.
    c. ASTM Committee C9, "Standard Specification for Concrete Aggregate,"ASTM C 33, ASTM International, West Conshohocken, PA, 2003.

d. Ahmad, S.H., "Properties of Concrete Made with North Carolina Recycled Coarse and Fine Aggregate, “Center for Transportation Engineering Studies, North Carolina State University, Raleigh, NC, 1996.
e. AASHTO Subcommittee on Materials, "Fine Aggregate for Portland Cement Concrete," AASHTO M 6, American Association of State Highway and Transportation Officials, Washington, DC, 2001.
f. AASHTO Subcommittee on Materials, "Coarse Aggregate for Portland Cement Concrete," AASHTO M 80, American Association of State Highway and Transportation Officials, Washington, DC, 2001.
g. Environmental Council of Concrete Organizations (ECCO), "Recycling Concrete and Masonry,"EV22, Skokie, IL, 1999, 12 Pages.
h. FHWA Policy Memorandum "Formal Policy on the Use of Recycled Materials," February 7, 2002.
i. FHWA Survey, Recycled Concrete Aggregate National Review, May 24, 2005.
j. Klieger, P. and Lamond, J.F., "Significance of Tests and Properties of Concrete-Making Materials," STP 169C, ASTM International, West Conshohocken, PA, 1994.
k. Kosmatka, S., Kerkoff, B. and Panarese, W., "Design and Control of Concrete Mixtures, 14th Edition," Portland Cement Association, Skokie, IL 2002.
l. Melton, J.S., "Guidance for Recycling Concrete Aggregate Used in the Highway Environment," ACI SP-219, American Concrete Institute, Farmington Hills, MI, 2001.
m. National Cooperative Highway Research Program (NCHRP), "2002 Design Guide, Design of New and Rehabilitated Pavement Structures," NCHRP 1-37-A, Transportation Research Board, Washington, DC, 2003.
n. Stark, David, “The Use of Recycled-Concrete from Concrete Exhibiting Alkali-Aggregate Reactivity," Research and Development Bulletin RD114, Portland Cement Association, 1996.
o. Van Dam, T.J., Sutter, L.L., Smith, K.D., Wade, M.J., and Peterson, K.R., "Guidelines for Detection, Analysis and Treatment of Materials-Related Distress in Concrete Pavements Vol. 2: Guidelines Description and Use," FHWA-RD-01-164, Federal Highway Administration, McLean, VA, August 2002.
p. Yrjanson, William A., NCHRP Synthesis 154; "Recycling of Portland Cement Concrete Pavement," Transportation Research Board, Washington, D.C., December 1989.

Table 1. Effect of RCA on Mechanical Properties of Concrete		
Property	**Range of expected changes from similar mixtures using virgin aggregates. (ACI 555R)**	
	Coarse RCA only	**Coarse and Fine RCA**
Compressive Strength	5% to 24% less	15% to 40% less
Strength Variation	Slightly greater	Slightly greater
Modulus of Elasticity	10% to 33% less	25% to 40% less
Creep	30% to 60% greater	30% to 60% greater
Tensile Strength	10% less	10% to 20% less
Permeability	200% to 500% greater	200% to 500% greater
Thermal Expansion	Somewhat less than expected for coarse aggregate used	Somewhat less than expected for coarse aggregate used
Specific Gravity	5% to 10% lower	5% to 10% lower

Table 2. Effect of RCA on Fresh Concrete Properties		
Property	**Range of expected changes from similar mixtures using virgin aggregates. (ACI 555R)**	
	Coarse RCA only	**Coarse and Fine RCA**
Water Demand	Greater	Much greater
Drying Shrinkage	20% to 50% more	70% to 100% more
Finishability	More difficult	More difficult

Table 3. Effect of RCA on Concrete Durability		
Property	**Range of expected changes from similar mixtures using virgin aggregates. (ACI 555R)**	
	Coarse RCA only	**Coarse and Fine RCA**
Corrosion Rate	May be faster	May be faster
Freeze-thaw Durability	Dependent on air void system	Dependent on air void system
Carbonization	65% greater	65% greater
Sulfate Resistance	Dependent on mixture	Dependent on mixture

FHWA web site address for technical advisory:
http://www.fhwa.dot.gov/legsregs/directives/techadvs/t504037.htm

Discussion

There does not seem to be any roadblocks to the use of RCA in pavements in Washington State. The performance problems experienced by other states that have used RCA would not likely happen in Washington if we continued to employ our current standard practices with our mix designs, pavement designs and construction control methods. Table 9 lists problems noted by the reference materials and the solution proposed for overcoming or minimizing the problem in Washington State.

Problem	Solution
Angular and Rough Shape and Texture	Using crushing operations that remove the majority of the mortar from the original aggregate and limit or eliminate the use of recycled fine aggregate.
High Absorption of Water	Limit use of recycled fines and limit amount of old mortar clinging to the aggregate particles by methods used for crushing
Low Specific Gravity	Limit or eliminate the use of recycled fines
High LA Abrasion Loss	Within limits recommended by ASTM, however, removal of the mortar will lower the losses.
Sulfate Soundness Mass Loss and Magnesium Sulfate Mass Loss	Generally not a problem in the state, however, most states waive the tests.
High Chloride Content	WSDOT pavements are generally not high in chlorides
Poor Workability	Limit use of recycled fines and continue our practice of using fly ash in all of our mixes
Rapid Slump Loss	Limiting recycled fine aggregate, removing most of the old mortar will combat this problem.
Increased Water Demand	Add more cement or fly ash
Higher Air Content	Learning curve required in adjusting air contents to compensate for the air already entrained in the paste attached to the aggregate. Remove paste.
Lower Compressive Strengths	Most current mixes normally exceed requirements
Lower Flexural Strengths	Most current mixes normally exceed requirements
Lower Modulus of Elasticity (Stiffness)	Limit use of recycled fines.
D-Cracking	Never been a problem in Washington State.
ASR Reaction	Never been a problem in Washington State.
Lower Bond Strength With Reinforcement Steel	JPCP does not have reinforcing steel.
Higher Rates of Creep	Not generally a problem in pavements
Higher Drying Shrinkage	Limit use of recycled fine aggregates, use more fly ash, lower water contents.
Midslab Cracking	Should not be a problem due to WSDOT short joint

	spacing.
Poor Load Transfer	Dowels required in all new PCCP.

Recommendations for WSDOT

The literature indicates that the majority of problems occurred where the original concrete or aggregate was of marginal quality. The aggregates that compose our older pavements in Western Washington are some of the hardest and most durable aggregates in the world. Washington would, therefore, be one of the states that would be expected to have the least problems using RCA in its concrete pavements. That does not mean that caution should not be practiced in the use of RCA in our concrete pavements. Crushing methods used to produce the aggregates should be those that eliminate as much of the mortar from the aggregate as possible. Conventional aggregate gradations should continue to be used with the RCA. Eliminating or limiting the amount of recycled fine aggregate is necessary to improve the workability of the mix and decrease the water demand and issues associated with fluctuations in the water needs of the mix. Fly ash and water reducers should continue to be employed in all mixes to increase workability and maintain low water/cement ratios. Additional cement may need to be added to compensate for the lower strengths normally found when RCA is used; however, our standard practice of requiring mix designs from contractors should handle this issue. Dowel bars are recommended for all pavements that use RCA; and again this should not result in any changes in our design policy which requires the use of dowel in all new construction. Finally, the FHWA Technical Advisory is an excellent guide on the use of RCA and should be used as a primary reference when RCA is implemented.