A Research Summary on Recycled Crushed Concrete Aggregate (RCA)

for Use in

Cast In-Place Concrete Pavement (CICP)

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Work Product Final Report
Concrete Task Group, Pavement & Materials Partnering Committee

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Executive Summary

Caltrans desired to evaluate the potential for using recycled crushed concrete aggregate (RCA) in concrete pavements to achieve economic benefit, enhance sustainability, reduce waste, and conserve natural resources without comprising the quality and performance of the finished product that should be equivalent to the concrete pavements consisting only non-recycled materials. Over 80 RCA related papers, articles, reports, books, manuals, and 40 State DOT's practices on RCA use were reviewed, and garnered multiple key factors that need to be considered in using RCA in concrete pavements including sources, cleaning procedure, crushing process, moisture, abrasion, absorption, hydration, workability, and durability. The pavement designer must be aware of potential to reduced strength, increased shrinkage, and possible changes in the thermal characteristics of concrete containing RCA, if proper procedures and applications are not followed. RCA can be considered engineered materials and can be used to produce concrete for pavements, if RCA is produced through proper methods and meets the specified requirements of aggregates for concrete. Based on the literature search information and state of practices across the nation, it is recommended to use only the coarse fractions of RCA to manufacture concrete and use at the bottom of concrete pavement through two-lift construction practice. Later, it can be extended to full depth concrete pavement, when more positive pavement performance data are available for RCA used concrete pavements.

Introduction

The study on recycled crushed concrete aggregate (RCA) for use in cast in-place concrete pavements (CICP) was initiated under pavement and materials partnering committee (PMPC) to evaluate the potential for using RCA in new concrete pavements and work include gathering information pertaining to the use of RCA and analyze information to address pavement performance issues, greenhouse gas (GHG) carbon savings, and reuse resources. The authorized scope of work consisted following milestones:

1. Literature search and report on findings
2. Draft specification proposal
3. Recommendation/Design guidance on where use is appropriate
4. Research summary

The summary of each milestone including conclusions and recommendations are presented under each Milestone sections. This document fulfills the requirements of the final milestone "Report Summary". The PMPC approved work product scoping document and time extension is presented in Appendix-1.

1.0 Literature Search and Report on Findings

Over 80 papers, articles, reports, books, manuals, and 40 State DOTs practices on the use of RCA to manufacture concrete were reviewed and key characteristics of RCA influencing properties of concrete and performance of concrete pavements were identified and analyzed to draw diligent conclusions for the use of RCA in concrete pavements in Caltrans projects. A brief summary of conclusions and recommendations from literature search are listed below:

1.1 Conclusions

- RCA promotes sustainability by reducing construction waste, conserving natural aggregate, and reducing greenhouse gas emission and energy consumption.
- The service life of concrete pavement is not significantly lowered when using up to 30 percent fine RCA replacement.
- RCA has different properties compared to natural aggregate (NA) aka virgin aggregate (VA) due to the presence of reclaimed mortar in the fines and adhered mortar on the aggregate particles. RCA particles are angular shaped and rough textured. Numerous studies have been conducted examining the properties of RCA mixtures at different replacement levels up to 100 percent. Most of studies have shown insignificant effect on concrete properties when using less than 30 percent coarse RCA.
- The effects on fresh concrete from the use of RCA include lower workability and higher air content. The effects on hardened concrete properties of RCA include lower strength (compressive, flexural, and tensile strength); higher shrinkage, creep, coefficient of thermal expansion (CTE) and permeability; lower modulus of elasticity and lower density. Typically, RCA mixtures are less durable than NA or VA mixtures.
- RCA for concrete pavement must be considered as an engineered material due to their different physical and chemical properties and their impact on the plastic and hardened properties of concrete pavement. Recent studies recommend modifying concrete mix designs by using chemical and/ or mineral admixtures to improve workability, strength, and durability. The use of superplasticizers can improve the workability of RCA mixtures. Caltrans mandates the use of at least 15 percent fly ash as supplementary cementitious materials (SCMs) in concrete pavement mixtures. The use of fly ash reduces the w/cm ratio and mitigates alkali silica reaction (ASR), thus improving mechanical and durability properties.
- Several studies on RCA concrete pavements showed comparable performance when compared to a control pavement using NA or VA, even with RCA sourced from D-cracked and ASR-damaged pavements. However, a good quality source is a governing factor for pavement performance.
- RCA manufacturing plants require large storage space for demolished concrete, crushing, processing, cleaning and treatment units, and storage areas for the crushed concrete aggregates.
- Jaw crushers can be used to remove any embedded steel reinforcement and dowels. Jaw crushing minimizes the amount of fines produced whereas Impact and Cone crushers yield higher percentage of coarse RCA with relatively less adhered mortar while creating more fines.
- The washing/cleaning operations of RCA require large volumes of water, treatment plants, and time. Careful attention to the washing process should be taken before recycling the existing RCA. The cost of cleaning process units with acceptable treatment plants should be taken in consideration.
- From the literature review, laboratory test results and lessons learned from pilots, it would be prudent to start projects with RCA by reviewing results from Caltrans projects approved in 2015 in Los Angeles (LA) County.

- RCA can be used in the bottom lift of two-lift concrete pavements. The successful construction of I-210 in LA has proven that RCA is a useful product that can provide satisfactory performance when used in concrete mixtures.
- Several available tools and software can be used to estimate costs savings and environmental benefits with the use of RCA in concrete pavements.

1.2 Recommendations

- The sources of RCA for new concrete pavement should be from sources that originally had good quality control. Good RCA could come from recycled concrete pavement rubbles, hardened returned plastic concrete (crushed concrete aggregate) intended for use in concrete pavements, etc.
- RCA should be clean and uncontaminated.
- Based upon this literature search, up to 30 percent replacement of natural coarse aggregate (NCA) or virgin coarse aggregate (VCA) with quality coarse RCA would be acceptable and the performance of the concrete would not be compromised. Additional studies should be conducted to verify that a 45 percent replacement of NCA or VCA with RCA can produce a suitable mix for a new PCCP. Mix designs should be tested to ensure that the RCA concrete mix meets the specifications for concrete pavement to determine a limit for coarse RCA.
- RCA properties can be characterized by using standard tests and specification requirements.
- Alkali Silica Reaction (ASR) can be mitigated by using SCMs as a substitute for cement in RCA concrete mixes. The use of SCMs to mitigate ASR is specified in Section 90-1.02B(3) of standard specifications and different options are provided based on the SCMs type in the mix.
- Review the specifications from successful RCA implementations used by other states to develop pilot specifications for using RCA in concrete pavements for California. Texas, Illinois, and other States had successful RCA pavement projects which may give Caltrans some example specifications.
- Any strength reduction could be compensated with an increase in pavement thickness and/or by increasing the percentage of reinforcement for continuously reinforced concrete pavement (CRCP).
- Use RCA in the bottom lift of two-lift concrete pavements.

A complete literature search report is presented in Appendix-2.

2.0 Specification Proposal for Application of RCA in Concrete Pavement

The RCA Working Group evaluated many possible options to use RCA in concrete pavements and reached consensus to use RCA to manufacture concrete for pavements with following requirements:

- Use only coarse RCA in the bottom lift of two-lift concrete pavements.

- Use maximum 30 percent of coarse RCA replacing natural or virgin coarse aggregates to manufacture concrete for pavements.
- For both lifts, to determine the minimum content of cementitious materials or the maximum ratio of water to cementitious materials, use modulus of rupture values of at least 570 psi for 28 days age and at least 650 psi for 42 days age.
- Coarse RCA must meet gradation specified in section 90-1.02C(4)(b) except RCA must have less than 5 percent passing No. 4 sieve.
- Do not use RCA as a source for fine aggregate.
- RCA can be used as innocuous aggregate in Section 90-1.02B(3) Equation-1, if tested under ASTM C1260 and maximum expansion is 0.15 percent.
- Maintain RCA moisture above saturated surface dry condition for a minimum of 12 hours before batching.
- The thickness of the top lift must be minimum 3 inches and the maximum aggregate size for the top lift must be 1 inch.
- The target slump as tested under CT 556 for the bottom lift must be 1 inch and for the top lift must be 1.5 inch.
- The source of RCA must be from the existing concrete pavement within the approved construction area of the project or other pavement projects or concrete placed in other structures with the same performance requirements or returned plastic hardened concrete (CCA) or any combination of the above.

A complete proposed specification for two-lift concrete pavements is presented in Appendix-3.

3.0 Design Guide

A summary of guidance for use of RCA in concrete pavements is briefed below, a complete guide is presented in Appendix-4.

3.1 Production

The RCA must be manufactured from any of the following source or combination thereof:

I. Existing concrete pavement within the approved construction area of the project.
II. Existing concrete with equal or better quality than the new concrete, mainly derived from
    - concrete structures
    - returned plastic hardened concrete (CCA)

The RCA should be manufactured by removing and separating asphaltic materials, joint sealants, reinforcing steel bars, steel mesh, tie bars, and/or dowel bars and other contaminants from the concrete. Perform necessary crushing, screening, washing, and beneficiation methods to produce coarse aggregate with consistent qualities and properties. Jaw crushers can be used to remove any embedded steel reinforcements and dowels. Generally, jaw crushing minimizes production of fines, whereas Impact and Cone crusher produces more fines but yield higher percentage of coarse RCA with relatively less adhered mortar.

3.2 Characteristics of RCA

I. Shape and Texture

Both coarse and fine RCA tend to be very angular and rough due to the crushing of hardened concrete and adherence of mortar to the aggregate particles. This tends to create harshness and poor finishing ability for concrete mixtures. The harshness can be minimized by limiting the amount of recycled fines, utilizing fly ash, and/or other SCMs, and adding chemical admixtures such as superplasticizers, water reducers, and viscosity modifying additives.

II. Specific Gravity (SG)

The RCA particle size governs specific gravity, gradation, and absorption. In general, SG for virgin aggregate (VA) ranges from 2.4 to 2.9, whereas for RCA ranges from 2.1 to 2.5. The SG of combined aggerates may be reduced up to 10 percent with the replacement of coarse VA with that same percentage of coarse RCA. The amount of fines consisting of crushed mortar in RCA is the main contributor for the reduction of specific gravities.

III. Aggregate Gradation

RCA can be processed to produce the same gradation as with VA.

IV. Porosity

Aggregate quality highly depends upon RCA porosity. The increased porosity of RCA is attributed to the presence of adhered mortar that consequently lower elastic modulus and toughness. In addition, higher porosity can lead to stress concentration under external load and may reduce its strength.

V. Absorption

The water absorption of RCA is higher due to higher porosity and greater surface area of the reclaimed mortar. Typically, RCA absorbs more water compared to VA and higher absorption capacities can lead to a loss of workability in concrete.

VI. Mortar Content

The higher mortar content in RCA may contribute to increased absorption capacity and decreased SG. Higher absorption can lead to higher shrinkage which has the potential to make the concrete pavement more susceptible to increased cracking. The attached old mortar creates greater aggregate-paste interfaces known as interfacial transition zone (ITZ). ITZ in RCA includes the bonds between aggregate-old mortar, aggregate-new mortar, and old mortar-new mortar. ITZ is the weak area in concrete where failure initiates.

VII. Los Angeles (LA) Abrasion

LA abrasion test is used to determine the toughness and abrasion characteristics of aggregate. In general, percent loss in LA abrasion testing for RCA ranges from 25 to 45 percent, while loss for virgin aggregates ranges from 15 to 30 percent.

VIII. Sodium Sulfate Soundness

Sodium sulfate soundness test is used to evaluate the ability of aggregate to resist excessive change in volume under physical conditions and to identify poor performing aggregates as part of source approval. RCA typically passes magnesium sulfate testing, but often fails sodium sulfate soundness testing.

IX. Alkali Silica Reactivity (ASR)
RCA can be used as innocuous aggregate in Section 90-1.02B(3) Equation-1, if RCA is tested under ASTM C1293 and maximum expansion is 0.04 percent or tested under ASTM C1260 and maximum expansion is 0.15 percent.

RCA can be produced to meet the same standard aggregate quality and grading requirements, if they are processed and handled properly. The tests in Table 1 are to be performed on the individual RCA aggregate for reference purposes only. The tests in Table 2 are to be performed on the combined RCA and virgin aggregates for acceptance testing. It is recommended that both sets of tests be performed prior to the RCA concrete mix prequalification and during RCA concrete production.

Table 1. Quality Characteristics and Test Methods of RCA (Report only)

Quality characteristic	**Test method**
LA Abrasion (max %)	California Test 211
Cleanness Value (min %)	California Test 227
Flat and Elongated 3:1 ratio (max %)	California Test 235
Chloride Content (max ppm) Reinforced concrete Non-reinforced concrete	California Test 404
Sodium Soundness (max loss %)	California Test 214
Specific Gravity (max variability)	California Test 206
Absorption (max %)	California Test 206

Table 2. Required Tests and Thresholds for Combined RCA and Virgin Aggregates

Quality characteristic	**Test method**	**Requirement**
LA Abrasion (max %)	California Test 211	45
Cleanness Value (min %)	California Test 227	71
Chloride Content (max ppm) Reinforced concrete Non-reinforced concrete	California Test 404	1000 2000
Sodium Soundness (max loss %)	California Test 214	10

3.3 Effect of RCA on Concrete

The effects of RCA on concrete mix properties can range from negligible to significant, depending on the nature, composition, adherent mortar, and gradation of the RCA. These effects are summarized below:

3.3.1 Effects on Fresh Concrete Properties

I. Workability

The workability of concrete produced with RCA decreases mainly due to higher water absorption capacity and friction potential morphology of RCA. The increased absorption of water reduces available water, resulting in reduced concrete flowability. This mixture harshness is attributed to RCA's angularity, shape, and relatively high surface roughness which can be mitigated with proper processing. The reduced workability will have a direct impact on concrete placement time and workmanship efficiency. Overall, RCA concrete mixtures may require 5 percent more water with the replacement of coarse RCA only. If both coarse and fine RCA are used, the water requirement may increase up to 15 percent to compensate for the higher absorption of water by the RCA.

Several methods could be used to improve workability including limiting the use of fine RCA, utilizing a water-reducing admixture, and incorporating supplementary cementitious material (SCM) into the mixture. Workability can also be maintained by prewetting the stockpile and frequently monitoring the moisture content of RCA stockpiles before mixing.

II. Air Content

Concrete produced with RCA tends to yield inconsistent air contents due to the potential existence of higher levels of entrained and entrapped air within the adhered cement mortar. As a result, target air content for RCA concrete should be raised to achieve the same durability as normal mixtures in geographical areas where required.

III. Drying Shrinkage

Concrete produced with RCA tends to have higher absorption due to the porous adhered mortar. Drying shrinkage increases with RCA percentage primarily due to the increased adhered mortar content. Increased drying shrinkage causes an increase in concrete pavement moisture warping stresses when other factors remain constant.

3.3.2 Effects on Hardened Concrete Properties

I. Compressive and tensile strength

In general, strengths of concrete decreases as the percentage of RCA increases in a concrete mixture. When replacing 100 percent of virgin coarse aggregate with coarse RCA, compressive and tensile strengths are reduced by 24 percent and 10 percent, respectively when compared to concrete made with 100 percent virgin aggregates. Similarly, by replacing 100 percent of both virgin coarse and fine aggregates with RCA, compressive and tensile strengths were found to decrease by 40 percent and 20 percent, respectively. Replacing up to 30 percent of the coarse virgin aggregate with RCA has an insignificant effect on the concrete strength.

II. Creep

Typically, creep increases with RCA percentage due to the higher proportion of paste content in RCA. The creep of RCA concrete is 30 to 60 percent higher than virgin aggregate concrete. Higher creep values are beneficial in concrete pavement in reducing long term curling and warping stresses caused by temperature and moisture gradients.

III. Modulus of Elasticity (MOE)

Most studies have shown that RCA has lower MOE than virgin aggregate concrete, and it decreases with increase in RCA percentage. The static MOE of RCA concrete is mainly affected by reclaimed mortar content and w/c ratio.

IV. Coefficient of Thermal Expansion (CTE)
The coefficient of thermal expansion of concrete manufactured by using coarse RCA should meet the job specifications and are suitable for the purpose that they are being used. Laboratory and field trials of the concrete mixtures must be completed to document that the CTE performance is in compliance with the requirements of Section 40.

V. Durability of Concrete
In general, the presence of RCA in concrete can adversely affect the pavement durability. A study has found that the carbonation depth of RCA increases with higher RCA replacement. Sufficient air entrainment remains the dominant factor in terms of durability performance when exposed to freezing/thawing cycles, regardless of the RCA replacement levels. RCA has been noted as having an increased potential for alkali silica reactivity (ASR) compared to virgin aggregate. RCA tends to increase in internal surface area during the crushing process which increases the chemical potential and reactivity of the aggregates. The RCA concrete mixture incorporating SCM can significantly improve the resistance to chloride ion penetration.

3.3.3 Applications

RCA may be utilized to produce the following pavement materials in compliance with their respective specification requirements:

I. Aggregate subbases
II. Aggregate bases
III. Cement treated bases
IV. Concrete bases
V. Treated permeable bases
VI. Additional aggregates for reclaimed pavements
VII. Concrete for cast in-placed concrete pavements (two-lift pavements)

3.4 Potential influence of RCA on concrete pavement and their remedial strategies

The potential influences of RCA aggregates on concrete pavement, and their potential remedial strategies are summarized in Table 3.

Table 3. Potential Influence of RCA on Concrete Pavement and Remedial Strategies

Characteristics	**Statements/ Issues**	**Potential Remedial Strategies**
RCA Aggregates:		
Los Angeles Abrasion	Recycled Crushed Concrete Aggregate (RCA) typically has slightly higher abrasion loss compared to virgin aggregate (VA) concrete due to the adhered old mortar.	• Allow RCA from known source with good quality only. • Manufacture RCA through impact or other efficient method to remove the old mortar attached to the RCA.
Cleanness Value	Coarse RCA is relatively clean.	• Limit RCA from known source only. • Allow coarse RCA only. • Wash or air blow coarse RCA.

Absorption	RCA typically has a higher absorption compared to virgin aggregate due to an additional surface area of the old mortar attached to the RCA.	• Maintain RCA in a surface saturated dry (SSD) condition through RCA stockpile management. • Use two-stage mixing approach. • Use coarse RCA only.
Alkali Silica Reactivity (ASR)	RCA could have ASR issues which cause formation of gel by absorbing moisture and expands enough to crack concrete.	• Reject the RCA if ASR is observed in source concrete based on its field performance. • RCA can be used as innocuous aggregate in Section 90-1.02(B)3 Equation-1, if RCA is tested under ASTM C1293 and maximum expansion is 0.04 percent or tested under ASTM C1260 and maximum expansion is 0.15 percent. • To mitigate reactive aggregate, use low-alkali cement, supplementary cementitious materials (SCMs) such as fly ash, ground granulated blast furnace slag (GGBFS), silica fume or treat with lithium nitrate ($LiNO_3$) solution. Limit the total alkali loading in the concrete and add lithium nitrate ($LiNO_3$) in the mix if SCMs amount cannot meet the ASR mitigation requirement
RCA Concrete:		
Unit Weight	RCA **c**oncrete exhibits lower unit weight due to the increased porosity of adhered old mortar in RCA.	• Use proper percentage of RCA from a quality source. • RCA substitution can be done volumetrically (rather than by weight) due to its lower specific gravity. • Remove the old mortar portion attached to the RCA.
Slump	RCA concrete may have a lower slump than virgin aggregate concrete at the same w/c ratio due to their higher absorption, rough surface texture and angularity nature.	• Similar workability can be achieved by controlling aggregate type, aggregate size, shape, texture, and gradation, mixture proportion, temperature at mixing, prewetting RCA and using water-reducing admixture and/ or SCM. • Remove the old mortar portion attached to the RCA.
Air Content	RCA concrete yields a higher air content compared to virgin aggregate concrete due to the potential existence of higher levels of entrained and entrapped air within the adhered cement mortar.	• Air content can be controlled by removing the old attached mortar from RCA, washing or air blowing coarse RCA, using SCMs, etc. • Impact and cone crushers can effectively remove these attached mortars.
W/C Ratio	RCA concrete may have a lower slump than virgin aggregate concrete at the same w/c ratio due to the water absorption by the adhered cement mortar.	• W/C can be reduced by using admixtures and SCM such as fly ash. • Remove the old mortar portion attached to the RCA.

		• To compensate for the extra water absorbed by the RCA, prewetting of the RCA may be utilized. *Note: "adding additional water during concrete mix design" needs clarification and parameters included.
Flexural Strength	RCA concrete may yield a lower flexural strength than virgin aggregate concrete. The proper percentage of RCA replacing virgin aggregates can produce specified flexural strengths.	• Utilize coarse RCA with up to 30 percent replacement of virgin aggregates in concrete mixtures. • Reduce w/c ratio. • Use two-stage mixing approach. • Use RCA from a high-quality source and limit the amount of old mortar clinging to the RCA particles by an effective crushing method.
Compressive Strength	Most studies have reported no effect on compressive strength with up to either 40 percent Coarse RCA or 20 percent Fine RCA. With the increased RCA content beyond the threshold value, the compressive strength tends to decrease.	• Compressive strength can be sustained by improving the RCA using SCMs such as fly ash and/or GGBFS. • Limit the amount of RCA and only use coarse aggregate. • Add water reducing admixture. • Increase cement content. • Utilize two-stage mixing approach.
Modulus of Elasticity (MOE)	Most studies have shown that lower MOE performance is seen in RCA concrete due to the presence of reclaimed mortar adhered to the RCA. MOE performance decreases as RCA percentage increases.	• Lower MOE has positive effect on concrete pavements. Lower modulus can lower tensile stresses in the slab. However, proper design for joint load transfer is required to mitigate possible corner cracks.
Creep	Generally, creep increases with an increased percentage of RCA utilized in a concrete mixture. This is a result of the higher proportion of reclaimed paste adhered to the RCA.	• Higher creep has a positive effect on concrete pavements.
Shrinkage	Higher shrinkage is seen in RCA concrete resulting in higher moisture warping stresses in the concrete pavement.	• Limiting the percentage of RCA can significantly limit the anticipated increase in concrete shrinkage. • Reduce w/c ratio and cement content by using a higher percentage of SCMs. • Reduce the fine aggregate contents.
Coefficient of Thermal Expansion (CTE)	Most studies have shown higher CTE results in RCA concrete than in virgin aggregate concrete. Higher CTE may increase the potential for mid-slab cracking and may increase the rate of deterioration due to higher stresses and/or greater crack widths.	• These concerns can be reduced by limiting the RCA source to only agency projects (i.e. a documented good quality source material).

Permeability	The size and continuity of the pores in hydrated cement paste would control the coefficient of permeability. Permeability increases with an increased RCA percentage. The permeability of RCA concrete can be higher than virgin aggregate concrete. The impact can range from negligible to very large.	• These impacts can be mitigated with a low permeability and a high-quality RCA source, by reducing w/c ratio, limiting air content, and utilizing proper concrete mix design proportioning which include SCMs and admixtures.

Appendices

- Appendix 1: PMPC Approved Work Product Scoping Document and Time Extension
- Appendix 1: Time Extension for RCA Work Group
- Appendix 2: Literature Search and Report on Findings
- Appendix 3: Draft Specification Proposal
- Appendix 4: Design Guidance