FEASIBILITY OF RECYCLING RUBBER-MODIFIED PAVING MATERIALS

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EXECUTIVE SUMMARY

Recycling has proved to be a sound, economical method of conserving and reusing scarce material resources used in AC pavement construction. Considerable experience with recycling conventional AC mixtures indicates that the resulting recycled pavements can generally perform at least as well as most new pavements made with virgin materials. Review of the limited literature related to recycling of CRM-modified paving materials and personal interviews with agency and industry representatives indicate that these materials can also be recovered and recycled to provide serviceable pavements.

The types of recycling considered for use by Caltrans, in order of feasibility of development and implementation, include the following: full depth pavement reclamation, hot plant recycling, cold in-place recycling, and hot in-place recycling.

Caltrans is already using full depth reclamation for flexible pavement rehabilitation, and it appears that RAC and CRM-modified materials can readily be incorporated in the resulting improved base course. Although some refinements for determining compatibility and dosage of stabilizing additives may be useful, this approach to recycling RAC and CRM-modified materials can be implemented immediately.

Recycling reclaimed CRM-modified materials using central AC mixing plants (hot plant recycling) appears to have high potential for successful development and field implementation in a relatively short time frame. Use of central AC plants facilitates control and proportioning of the reclaimed materials along with virgin AC mix components for production of recycled AC mixes, and provides appropriate emissions control systems. Based on the extensive and apparent generally successful use of 15% RAP by mass of total mix in a variety of types of mixes throughout the U.S. and limited, but generally successful experience with CRM-modified materials, it appears that the key to implementation of hot plant recycling of CRM-modified material is development of appropriate laboratory mix design methods.

Based on limited experience in California and Kansas, cold in-place recycling (CIPR) of pavements that include CRM materials may be used on a limited trial basis to provide improved base courses for roadways with relatively low traffic volumes that would be overlaid with AC or RAC-G mixes as part of their rehabilitation strategy. However, further development is needed to resolve issues with mix design and compatibility of asphalt emulsions with the reclaimed CRM-modified materials before routine use of this method should be considered.

It is suggested that evaluation of hot in-place recycling (HIPR) be reserved for future development, and build on the experience gained during implementation of the other three approaches to reclaiming and recycling CRM-modified materials. HIPR raises concerns regarding effects of extender oil on emissions and possible adverse effects of commonly used recycling agents on CRM-modified materials.

Plans for laboratory testing to develop and verify a Hveem mix design procedure for hot plant recycling of reclaimed CRM-modified pavement materials, and for field validation of production and performance of such mixes are discussed in this report. These plans may also be applied to development of procedures for CIPR and HIPR of reclaimed CRM-modified materials.

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1.0 INTRODUCTION

1.1 BACKGROUND

There is a strong demand for information on recycling rubberized asphalt concrete (RAC) pavements for use in planning, design, and life-cycle cost analysis of the various reconstruction and rehabilitation alternatives. Caltrans and various counties and municipalities in California have constructed numerous RAC pavements over the past 20 years, some of which may now be candidates for rehabilitation and/or recycling. However, there are no guidelines as to the handling of RAC pavements when they reach the end of their service life. Not only do these pavements represent a sizeable investment of relatively scarce resources, but there are also logistical and economic issues related to disposal of large quantities of scrap bituminous paving materials. To promote the use of RAC, it is necessary to determine its reuse potential in new asphalt concrete (AC) mixtures with hot and/or cold recycling.

Reclaimed asphalt pavement (RAP) is widely used throughout the United States to preserve investment by reutilizing valuable aggregate assets. FHWA and AASHTO support and promote the appropriate use of recycled materials in highway construction in public policy statements and the resolution of the AASHTO Standing Committee on Highways on "Use of Recycled Materials". Considerable research and experience are already available regarding recycling of conventional AC materials that are directly applicable to planning and initiating a preliminary laboratory testing program for investigating the feasibility of recycling RAC.

Although Caltrans has developed an SSP for Recycled Asphalt Concrete, Department experience with recycling of conventional or modified AC mixtures is limited to a handful of projects.

1.2 TERMINOLOGY

A variety of terminology has been used to describe CRM-modified asphalt materials and products, which has caused some confusion over time. Terminology related to reclaimed and recycled pavement materials also varies. To promote clear understanding of this report, the following terminology is used throughout.

Crumb Rubber Modifier (CRM) - Scrap rubber produced from scrap tire rubber and other components, if required, and processed for use in wet or dry process modification of asphalt paving materials.

RAC – Rubberized (i.e. CRM-modified) Asphalt Concrete

RAP – Reclaimed Asphalt Pavement

Reclaimed RAC – Reclaimed wet process or dry process rubberized asphalt concrete

Recycled AC- Asphalt concrete that includes RAP or Reclaimed RAC

Virgin AC – Asphalt concrete that does not include RAP or Reclaimed RAC

Wet Process - A term which describes the method of modifying asphalt cement with CRM. The wet process requires thorough mixing of the CRM in hot asphalt cement and holding the resulting blend at elevated temperatures for a minimum period of time to permit an interaction between the CRM and asphalt.

Wet Process-No Agitation - The term "terminal blend" is often used to describe CRM-modified binders that do not require constant agitation to keep discrete rubber particles uniformly distributed in the hot asphalt cement, including MB materials.

Wet Process-High Viscosity - CRM-modified binders that maintain or exceed a minimum rotational viscosity threshold of 1500 cPs or 1.5 Pa•s at elevated temperatures over the interaction period. These materials require agitation to keep the CRM particles evenly distributed.

Dry Process -The dry process includes CRM as a substitute for 1 to 3 % of the aggregate in the AC mix, not as a modifier of the asphalt cement.

Full Depth Reclamation - a type of pavement rehabilitation in which the entire thickness of asphalt concrete and a designated thickness of the underlying materials (base, subbase and/or subgrade) are pulverized and mixed in place to provide an improved, uniform granular base material from 4 to 12 inches deep, which may be stabilized using foamed asphalt or other stabilizing agents.

Cold In-Place Recycling (CIPR or CIR) – a rehabilitation treatment involving cold milling of the pavement surface and remixing with the addition of asphalt emulsion, portland cement, or other modifiers to improve mixture properties as needed, followed by screeding and compaction of the reprocessed material. Although typically performed in one continuous operation, some contractors and agencies may use a two-pass process.

Hot In-Place Recycling – (HIPR or HIR) - a rehabilitation treatment used to correct asphalt pavement surface distress, including: heating; removal and processing (crushing/screening) of the existing asphalt concrete to the desired depth; mixing with new aggregate materials, new asphalt cement and/or recycling agents; and placing and compacting to meet specification requirements.

1.3 SCOPE

The scope for this feasibility study includes the following:

- Report on literature review.
- Report results of interviews with users and contractors in North America who have experience with recycling RAC-type mixes to supplement the literature.
- Propose a laboratory testing plan to evaluate and/or develop Hveem mix design procedures for incorporating reclaimed RAC pavement into recycled AC paving mixtures.
- Tailor a field validation plan based on "Generic Experimental Design for Product/Strategy Evaluation - Crumb Rubber Modified Materials" to include full-scale recycled AC mix production and placement to verify that laboratory mix design procedures are valid and to identify any plant or field operational issues with incorporating reclaimed RAC pavement into recycled AC paving mixtures.

1.4 OBJECTIVES

The primary objective of this effort is to determine if RAC pavements can be reclaimed and recycled to produce new recycled AC pavements that meet or exceed current performance standards. The results of this study are intended to help eliminate the concerns regarding "recyclability" that have acted as barriers to increasing Caltrans use of RAC.

2.0 LITERATURE REVIEW

The literature review for this task considered the experiences and practices related to recycling conventional AC materials, but focused on the recycling of CRM-modified paving materials.

2.1 CONVENTIONAL RAP

There is considerable literature available regarding recycling of conventional AC materials. Most of the valuable research in this area has been reviewed and summarized as part of Phase 1 of NCHRP Project 9-12, "Incorporation of Reclaimed Asphalt Pavement in the Superpave System" completed in 2001. A review of the NCHRP 9-12 annotated bibliography and of current practice indicates that use of RAP has become routine in a number of states throughout the U.S. and that satisfactory mix design procedures have been developed. With few exceptions, the literature indicates the engineering properties and performance of properly designed recycled AC paving materials are comparable to conventional new AC pavements. This has been determined through the use of a variety of laboratory test and assessment methods including resilient modulus, indirect tensile strength and creep modulus, flexural strength and fatigue, moisture sensitivity, pulse velocity, Corps of Engineers gyratory stability index and gyratory elasto-plastic index, and dynamic modulus. Field performance has been evaluated using pavement condition surveys, falling weight deflectometer, roughness/ride indices, and frictional characteristics and has generally been found to be comparable to that provided by virgin paving materials (McDaniel and Anderson, NCHRP 9-12 Final Report Appendix A (NCHRP Web Document 30)). There seems to be little current research on the use of RAP. The NCHRP 9-12 researchers speculate that the reason is because the mix design and construction methods developed to date generally appear to be working and further effort is not currently required.

Prior to NCHRP 9-12, the FHWA Superpave Mixtures Expert Task Group had provided guidelines for including RAP in Superpave mixture design procedures (Mixtures ETG March 1997). These guidelines were based on existing practice and experience with use of RAP in Marshall, Hveem, and other types of mix design procedures. The recommendations follow a tiered approach as follows:

1. RAP content ≤ 15% by mass of total mixture: Treat the RAP as "black rock" and select the asphalt binder grade based on climate and traffic, so that it is the same grade as would be used for a standard mix design using only virgin materials.

2. RAP content 16 to 25% by mass of total mixture: Use the next softer grade of asphalt cement than would be selected for use in a virgin mix design.

3. RAP content >25% by mass of total mixture: Select asphalt binder grade by recovering and testing the asphalt from the RAP mix and using appropriate asphalt cement blending charts to obtain the desired binder properties for high and low temperature requirements.

The findings of NCHRP 9-12 validated these guidelines. NCHRP Report 452 (McDaniel and Anderson, 2001) presented the same RAP content tiers for their mid-grade recovered binder (PG xx-16) as did the FHWA/ETG guidelines.

2.2 RECYCLING WITH CRM MATERIALS

The recycling of CRM-modified materials has been an area of interest since CRM was first used in asphalt paving materials. Some state DOTs have used RAC-type materials in limited recycling experiments or demonstration projects including: Arizona (MACTEC's Materials Survey Questionnaire (July 2004)); Wisconsin (Solberg and Lyford, 1987, Bischoff and Toepel, 2004); Texas (Crockford et al 1995); Florida (MACTEC's Materials Survey Questionnaire (July 2004)); New Jersey (Baker and Connolly, 1995); Michigan (Gunkel, 1994); Mississippi (Albritton, Barstis and Gatlin 1999); Kansas (Fager 2001); and the Province of Ontario (Emery 1994, 1995, 1997). The respective studies include different types of wet process binders and/or various gradations of crumb rubber modifier (CRM) as an aggregate substitute (dry process). The CRM content of the reclaimed RAC varied widely and some studies did not provide this information. One of the few common features of these experiments was general success based on the following results:

- The recycled AC mixtures could be plant-produced using reclaimed RAC.
- The recycled AC mixtures could be placed and compacted using conventional equipment and practices.
- The resulting recycled pavements typically appeared to perform at least as well as conventional mixes that included conventional RAP.
- Results of emissions test during production of recycled mixes were typically similar to those for conventional virgin and RAP mixes and rarely exceeded EPA limits.

These results indicate that a wide range of CRM-modified paving materials have been successfully recycled, which supports the feasibility of recycling RAC in California. Due to the concerns regarding possible emissions from recycling CRM-modified paving materials, many of the studies include an assessment of the emissions, results of which are presented in this review.

Wisconsin

The first documented attempt at using CRM in recycled mixes appears to have been a 1987 Wisconsin DOT experiment which included projects on US 12 and STH 35 (Solberg and Lyford, 1987; Bischoff and Toepel, 2004). For each project, a wet process high viscosity CRM-modified binder was used to design and construct a dense-graded mix that included 65% virgin aggregate and 35% conventional DGAC RAP. The binder consisted of 200-300 penetration grade asphalt cement with 22% scrap tire CRM by weight of the asphalt. The corresponding CRM content was 0.8% by total weight of mix. Conventional recycled AC mix sections, made with 35% and 50% conventional DGAC RAP, respectively, for US 12 and STH 35, were also constructed as controls. Due to the dense gradation of the US 12 mix, there was not sufficient void space in the mix to include enough of the high viscosity binder to satisfy the demand of the combined aggregate and RAP for asphalt cement. Due to these mixture voids constraints, the high viscosity binder content used was the same as the asphalt cement content of the dense-graded AC control sections. This was

not enough to compensate for the amount of the modified binder that is CRM and not asphalt. The low CRM-modified binder content resulted in an "under-asphalted" mixture which did not provide adequate resistance to reflective cracking. The performance of the resulting RAC pavement on US 12 was poor. For the STH 35 mix, the high viscosity binder content was 1% higher than the asphalt cement content for the conventional DGAC mixture with 50% RAP and performance was improved. The DOT recognized the need for increased CRM-modified binder content based on overall results of this initial experiment. Emissions test were not performed, but WisDOT did report visible emissions ("blue smoke") during production of the CRM-modified mixtures. No discussion of the possible causes was provided, but higher than customary AC plant mixing temperatures were probably a contributing factor.

In 1993, WisDOT initiated a research study to evaluate the recyclability of reclaimed RAC (Bischoff and Toepel, 2004). A 3,200-foot section of the STH 35 RAC mix (conventional RAP with CRM-modified binder) was milled to a depth of two inches. The milling operator reported that the RAC mix was somewhat harder to mill than typical DGAC, but it was removed with conventional equipment. The reclaimed RAC was hauled to an AC plant, and included as 25% by weight of virgin aggregate in a recycled 50-blow Marshall AC mix with 5.5% of 120-150 penetration grade asphalt cement added by total weight of mix. The resulting CRM content of the new recycled AC mix was 0.15% by total weight of mix. Three 2600-foot test sections and a control section were constructed as shown in Table 1.

Table 1. 1993 Reclaimed RAC Test Sections Wisconsin STH 35

Description	Surface Course	Lower Course
Control	1.5 in of Virgin DGAC	3 in of Virgin DGAC
Test Section 1	1.5 in of Virgin DGAC	3 in of Recycled AC w/ Reclaimed RAC
Test Section 2	1.5 in of Recycled AC w/ Reclaimed RAC	3 in of Recycled AC w/ Reclaimed RAC
Test Section 3	1.5 in of Recycled AC w/ Reclaimed RAC	1.5 in of Virgin DGAC

The construction of the recycled mix including reclaimed RAC went fairly smoothly. Only minor problems were encountered, which were attributed primarily to lack of experience with paving RAC mixes, but were easily overcome. Performance evaluations were conducted over a 10-year period that included rut, ride (IRI), friction (skid resistance) measurements, and visual inspection of pavement surface distress including surveys of longitudinal and transverse cracking in randomly selected 500-foot long performance evaluation sections (PES). Discrepancies in performance were observed within each test section, and the southbound lane performed better than the northbound throughout the project.

After 10 years of service, average rut depths of the respective control and test sections were 0.08 and 0.07 inch, which WisDOT considers insignificant. Ten-year IRI values for all sections were less than 1.5 m/km which indicates a smooth ride. Friction testing performed in years 3, 5, and 6 indicated consistently good skid resistance for both surface mixes; the virgin DGAC yielded friction numbers of 56 and 57, and the mix with reclaimed RAC was measured at 55. The primary difference between northbound and southbound distress were amount and severity of cracking; southbound had a total of only 15 severe transverse cracks for all sections. Test Section 1 had the highest total transverse cracking, followed in order by the control and Test Sections 2 and 3. Longitudinal cracking measured includes paving joints and cracking in the wheel paths, some of which photos indicate may be fatigue-related. Longitudinal cracking was more extensive than

transverse, and Test Section 3 exhibited the most severe cracking. However the authors (Bischoff and Toepel, 2004) indicate that the 500-foot evaluation sections "may not be truly representative of the longitudinal cracking present in the entire 2600-foot sections" due to discrepancies within the respective sections. Pavement Distress Index (PDI) values represent overall pavement condition of the PES; values below 70 indicate acceptable condition. After 10 years of service, the PES for Control and Test Sections 1 and 2 performed similarly with PDI values of 55 or 56. Test Section 3 did not perform as quite as well, as indicated by a PDI of 66.

Using the reclaimed RAC in the 1993 mixtures reduced the project cost by 14% compared to using virgin AC. However the RAC placed in 1987 cost 52% more per ton than conventional DGAC. Emissions data showed that recycling a pavement that contains scrap tire rubber does not appear to pose a threat to the health of the workers or to the environment. The researchers concluded that reclaimed RAC can be successfully used in surface and lower course mixes (Bischoff and Toepel, 2004).

Kansas

In 1991, Kansas DOT included conventional DGAC RAP in dry process CRM-modified mixes placed on US 59. The CRM content was calculated based on the total asphalt cement binder content of the RAP and virgin mix rather than by aggregate weight as customary, and the CRM was added dry to the recycled AC mix. Mix designs were developed for 30% RAP/70% virgin with an AC-5 additive and 50%RAP/50% virgin with RA-100 asphalt rejuvenator. Cold weather shut down construction after one lift of the control and test sections were placed. Subsequent raveling may have been a function of either cold-weather construction or CRM content (respectively 10% and 12% CRM by weight of asphalt cement) and the exposed surface was treated with a diluted asphalt emulsion as a remedy (Fager, 2001). Binder content was reportedly increased upon resumption of paving in the spring to prevent raveling, but no content values are presented in the report. The control and 30% RAP/70% virgin mixture test sections were constructed with no serious problems.

However, the RA-100 rejuvenator did not work in the 50%RAP/50% virgin mix. Regardless of how much was added, the CRM seemed to completely absorb the RA-100 and the mix remained too dry. Because CRM content was specified as a fixed ratio of the total asphalt content (asphalt in the RAP plus virgin asphalt added during recycled AC production), more CRM was added when the asphalt content was increased which kept the mix dry. Virgin mix and AC-5 were substituted to eliminate the rejuvenator. KDOT determined that for the dry process, CRM content needed to be based on the weight of RAP and virgin aggregate, independent of asphalt content. Crack and rut surveys from 1993 through 1997 indicated that the control mixes performed better than the test sections. No emissions tests were reported.

In 2003, some of the RAC pavement (wet process high viscosity binder) on I-135 in McPherson County, Kansas, was used in a cold in-place recycling (CIPR) project. Donald C. Drickey, District Engineer for KDOT District 2, made a presentation about the CIPR of RAC at the 2004 meeting of the Asphalt Recycling and Reclaiming Association (ARRA)

The original construction in 1994 included three RAC-G test sections consisting of coarse base and fine surface layers, and a conventional DGAC control section with typical KDOT mixes as shown in Table 2. CRM content of the binder was 13% by total binder weight, 14.9% by weight of asphalt cement. Target binder content for the RAC-G base course mix was 7.0% by total weight of mix. For the RAC-G surface course mix, both 7% and 8% binder by total weight of mix were listed in Fager's 2001 KDOT report that summarizes 10 years of Kansas experience with CRM. The RAC

material rutted in the wheel paths shortly after construction; slurry seals were applied as a remedy in 1996 and 1999, and at spot locations in 2001. A December 2, 2004 telephone interview with Drickey indicated that much of the distress was related to stripping and aggregate degradation which also manifested in the conventional DGAC pavements constructed with the same aggregate materials.

Table 2. 1994 KDOT I-135, McPherson County RAC & Control Pavement Cross-Sections

Section ID	Surface Course	Base Course	Subbase
1	1.5 in Fine RAC-G	12.5 in Coarse RAC-G	6 in Lime-treated subgrade
2	1.5 in Fine RAC-G	5.5 in Coarse RAC-G	9 in Rubblized PCCP
3	1.5 in Fine RAC-G	7.5 in Coarse RAC-G	9 in Rubblized PCCP
4 – Control	1.0 in BM-1T (Conventional DGAC)	8.0 in BM-2C (Conventional DGAC)	9 in Rubblized PCCP

The emulsion supplier performed the mix design for the 2003 CIPR project using samples of millings from the RAC-G pavements which included both fine and coarse reclaimed RAC-G materials, hydrated lime as an anti-stripping admixture, and CSS-Special emulsified asphalt. A Superpave Gyratory Compactor (SGC) was used to compact mixture specimens for volumetric analysis and Marshall stability testing. A design content of 2.5 to 3% CSS-Special by dry weight of reclaimed RAC was selected. Some indications of potential mix tenderness were observed during the mix design process and Marshall stability results were relatively low, ranging from 950 to 1220 pounds. Since the recycled material was intended to serve as a base course under 6.3 inches (160 mm) of conventional AC, KDOT decided to proceed with CIPR of the RAC.

Drickey reported that using a wheeled rather than track-driven HMA laydown machine to spread the CIPR RAC material caused some minor rutting "as the pavement temperature climbed during hot summer days". However, the effects were minor and the first 60-mm thick layer of conventional 19 mm AC served as a leveling course that was placed and compacted directly on the CIPR RAC with no problems. No problems were encountered during placement and compaction of the next two lifts of AC (60 mm of 19 mm mix and 40 mm of 9.5 mm mix) and Drickey reported that the pavement surface currently looks good. KDOT considers this to be a successful project and may construct a similar CIPR project on I-135 in 2005 that would include reclaimed RAC materials in the base course, surfaced with conventional AC pavement.

New Jersey

Another early experiment with reclaiming and recycling RAC was conducted by the New Jersey DOT in 1992 (Smith 1992, Baker and Connolly 1995). A fine gap-graded, dry process PlusRide mix with 3% CRM by aggregate weight raveled shortly after placement in the City of Newark in 1991. It was milled off and stockpiled for future recycling, and replaced with more PlusRide. In 1992, NJDOT developed a mix design that used 20% of the stockpiled reclaimed RAC in a fine aggregate surface course that met NJDOT requirements for standard I-5 AC mix gradation. Mix designs were developed for the surface course mixture containing the reclaimed RAC and for a control mixture that contained conventional RAP. The composition of the two mixes and NJDOT's specifications for I-5 fine aggregate surface course are shown in Table 3. The recycled mix design treated the reclaimed RAC material as "black rock" and determined the asphalt content as for a virgin mix, with no adjustment for the asphalt content of the RAC.

A comparison of the recycled mixes shows that the reclaimed RAC mixture had nearly one percent higher asphalt cement content than the conventional RAP mixture. The increase is due to the additional surface area of the 0.46 percent crumb rubber by weight (100 percent passing the No. 6 sieve) present in the rubber RAP mixture. Marshall laboratory tests of the mixes revealed similar results for each mixture. However, the reclaimed RAC mixture did show higher Marshall flow values compared to the conventional RAP mixture (Baker and Connolly 1995).

Table 3. Sieve Analysis for the NJDOT Reclaimed Dry Process RAC Project (Baker and Connolly 1995)

Sieve Size (% passing)	**RAP Fine Aggregate Surface Course Mix**	**Reclaimed RAC Fine Aggregate Surface Course Mix**	**NJDOT I-5 Specification**
12.7 mm	100	100	100
9.5 mm	99	98	80-100
No. 4	64	68	55-75
No. 8	44.5	45.5	30-60
No. 16	32	32	20-45
No. 30	25	25	15-35
No. 50	17	17	10-30
No. 200	6.4	6.5	4-10
Asphalt Content % by mix weight	5.55	6.4	5-10
Rubber Content % by mix weight	--	0.46	--

Limited stack emissions testing was performed to measure carbon monoxide (CO), total hydrocarbons (as methane) and particulates, during recycled AC mix production in a counter flow drum plant. Results for total hydrocarbons, particulates, and 3 of 4 CO tests were well within limits; one CO reading, 500.6 parts per million exceeded the limit 500 ppm. Similar fluctuations in CO had reportedly been observed during conventional AC production (Smith, 1992), and may have been related to AC plant operations.

The mix containing the reclaimed PlusRide RAC was reportedly placed as a nominal 1.5 to 2-inch thick overlay over cobblestones on a one-mile section of Ferry Street in Newark. This is one of only two entry/exit routes to Newark, and traffic volumes are high with 30 to 40% heavy trucks according to an e-mail transmittal dated September 16, 2004 from Joe Smith of Rutgers University and formerly with NJDOT. The project was recognized by the NJ Asphalt Paving Association and received the Innovative Hot Mix Asphalt Project Award at the 1993 Rutgers University Asphalt Paving Conference. The condition of the recycled pavement in 2002 was reportedly deteriorating, but Smith indicated that the performance of the thin overlay had been considered satisfactory for the extreme traffic conditions.

Texas

The Texas DOT (TxDOT) reclaimed and recycled RAC mixes in several projects in 1993; hot-in-place recycling was used on IH-20 in Tyler, Texas and central plant mixing was used to produce mixes including reclaimed RAC that were placed on Loop 1604 and IH-10 in San Antonio (Crockford et al, 1995). Very little information is provided on the Tyler project except that it was a dense-graded mixture with a high viscosity binder. Although emissions tests were not performed,

the authors recommended that emission controls should be required for hot in-place recycling (HIPR) of CRM-modified paving materials.

For the IH-10 project, issues with the job mix formula and construction led to premature failure of a RAC mix made with a wet process high viscosity CRM-modified binder (18% CRM by total weight, 22% by weight of AC-10 asphalt) that was placed as a mill-and-fill inlay. Based on construction data (Crockford et al, 1995, Appendix B) overall average binder content of the RAC was approximately 7.9%, yielding an overall average CRM content of 1.4% by total weight of mix. Only at the end of construction in 1992 when the frontage roads were paved did it become clear to TxDOT that a coarser, more gap-graded mix would serve better than the mix that had been placed on the IH-10 main line. Therefore, when the main line inlay failed within one year of construction, a coarser gap-gradation such as had been used on the frontage roads was used in test sections on Loop 1604 which included millings from the failed IH-10 RAC pavement. This type of gradation became the basis for TxDOT's Coarse Matrix High Binder (CMHB) system.

Based on the success of the mixes on the IH-10 frontage road and the Loop 1604, in 1993 the failed RAC mix was removed from the outer lane of IH-10 by milling, reclaimed, and incorporated into a virgin CMHB mix at 30% by total weight, and 5.7% asphalt by total weight. This recycled mix replaced the failed inlay, and after two years was reported by the Texas Transportation Institute (TTI) as performing satisfactorily (Crockford et al, 1995). TxDOT reported in its response to MACTEC's Materials Survey Questionnaire (July 2004) that performance of the reclaimed RAC mix was considered to be the same as that of conventional AC, indicating that it is currently satisfactory. Stack emissions data indicated that emissions during production of recycled mixes with reclaimed RAC are no worse than those measured during production of conventional AC. The report provides a number of recommendations for mix design including reclaimed RAC materials that will be considered.

Michigan

Another early RAC recycling effort was conducted by the Michigan DOT in 1993 along M-50 near Lansing. Two CRM-modified mixes including fine-graded (minus 300 μm (No. 50) sieve size) CRM were constructed: conventional DGAC with 20% reclaimed RAC by total mix weight, and RAC with a wet process CRM-modified binder and 20% reclaimed RAC. Stack emissions at the AC plant were tested and background air quality and worker exposure were measured at the pavement laydown location. Results of stack emissions tests demonstrated no significant increase in pollutant emissions during production of virgin or recycled materials containing CRM (Gunkel, 1994, and telephone conversation with Chuck Van Deusen, Consultant, September 28, 2004)

This project evaluated exposure of paving workers to three standard dense-graded control mixes, two made with 200-250 pen asphalt (≈ AC-2.5) with and without conventional RAP, and one with 85-100 pen (≈ AC-10) asphalt; two mixes made with no agitation wet process binder (made by a continuous blending method), including one with reclaimed RAC; one dry process CRM mix; and one conventional mix containing reclaimed RAC. Exposure assessments were performed for particulate matter, benzene soluble organics, 17 polynuclear aromatic hydrocarbons (PAHs), volatile organic compounds (VOCs), 1,3-Butadiene and styrene that are rubber components, and nitrosamines. Medical assessments were confounded by discrepancies between reports and interviews. Conclusions stated that there was no clear pattern to indicate that CRM-modified binders or mixes increase paving workers' exposure to hazardous compounds. For all samples and all mixes, virgin and recycled, workers' exposure to the hazardous compounds evaluated was significantly lower than the established exposure limits. MDOT representatives indicated the CRM recycling appeared to be successful (Flynn, 1994)

Mississippi

The Mississippi Department of Transportation conducted a CRM-modified asphalt material field evaluation in two phases. The first phase involved the construction of a RAC binder course and surface layer for a new roadway section. Three levels of CRM content, respectively 8, 10, and 12% by weight of binder were used in 500-foot test sections. The second phase of the project was planned to evaluate feasibility of recycling the resulting RAC pavement into a new surface course. Performance of the RAC sections was monitored for two years (Albritton, Barstis, and Gatlin 1999).

An AC-20 asphalt cement was used in the CRM-modified binders because adding CRM to AC-30 yielded binders that were too stiff. Phase 2 of the study included construction of three test sections with 15% reclaimed RAC by total mix weight and of a control section made with 11% reclaimed RAC. Prior to the placement of the recycled mixes, areas of base failure attributed to subgrade and subbase saturation by heavy rain were repaired by patching.

Tests of the RAC surface placed in Phase 1 indicated that skid numbers increased with increasing amounts of CRM in the mix. Initial falling weight deflectometer (FWD) tests revealed excessively high deflection values for all Phase 1 test sections and the control section. However, initial rutting and IRI measurements indicated a very smooth pavement with no ruts. Testing of the recycled pavement at 20 months of age showed no trends in the skid numbers with respect to CRM content. Researchers speculated that this difference from Phase 1 results might be due to the effects of traffic and the lower concentrations of CRM in the recycled mix (i.e. the section with 8% CRM in Phase 1 would include only 1.2% CRM in Phase 2). The study noted that the rutting observed in the reclaimed RAC sections was minimal for the length of time (approximately 26 months) that the section was monitored, considering the high deflection values measured throughout the project.

Florida

In response to MACTEC's Materials Survey Questionnaire (July 2004), Florida DOT reported that it had milled and recycled RAC pavements in AC hot plants without problems. According to Florida DOT, "The solution to pollution is dilution". CRM is typically present in only the top ½ to 1-inch of the pavement structure, and the typical milling depth of 3 to 4 inches includes conventional AC materials as well as CRM, which are blended together. The resulting proportion of CRM-modified material may range from about 12.5 to 33% of the total blend of reclaimed pavement materials, and includes either 5% or 12% CRM by weight of asphalt cement, equivalent to about 0.3 or 0.7% CRM by total mix weight. The amount of reclaimed material used in the mix is typically ≤ 30% by weight of aggregate, which dilutes the amount of CRM included in the recycled mix to about 0.1 to 0.2% by total weight. However, FDOT typically does not recycle asphalt rubber SAMIs, but turns that material over to FDOT Maintenance for miscellaneous use.

Arizona

Arizona DOT reported (MACTEC's Materials Survey Questionnaire (July 2004)) that it has recently successfully completed a very limited "proof of concept type test" for hot in-place recycling (HIPR) of an open-graded "asphalt rubber friction course" (ARFC according to ADOT terminology) mix made with 9.0 to 9.5% of high viscosity CRM-modified binder by total mix weight. The ARFC material is similar to Caltrans RAC O-HB, but the CRM-modified binder

consists solely of asphalt cement with 20% tire rubber by weight of asphalt and no extender oil is included.

The test section is located on a two-lane rural highway southeast of Phoenix. Jim Delton of ADOT stated that the purpose was to assess ARFC behavior when subjected to heating, scarification, and remixing in-place. There was nothing wrong with the approximately three-year old existing ARFC (nominal compacted thickness was 5/8-inch), but a nearby conventional HIPR project made it convenient to use this location. The HIPR machine had to be charged with conventional fine-graded DGAC to get the process started, so the first portion includes a combination of ARFC and DGAC which "looks good," according to Delton. Once started, the HIPR process continued for about 200 feet. The work consisted solely of rework, remix, repaving of the ARFC that was there. No material was added in the process and no overlay applied. The ARFC produced minimal smoke and the material was very workable. Although the contractor had been concerned that the CRM-modified binder would gum up the scarifiers and the rest of the equipment, no problems occurred. Delton reported that it has been a few months since he's seen this section, but it looked very good upon completion and at subsequent later viewings. ADOT is planning to do a project using reclaimed ARFC in a virgin open-graded mix, and also plans to perform HIPR on a 14-year old ARFC mix.

Ontario, Canada

Between 1990 and 1994, the Province of Ontario constructed two projects in which CRM was added dry during cold-in-place recycling of conventional pavements. One of the generic dry process (RUMAC) experimental projects placed in 1990 failed and was plant recycled in 1991. As of 1994, performance of the plant-recycled RUMAC pavement was variable, indicated by a range of ratings from "somewhat poor to very good" (Emery 1994). The cold-in-place recycled (CIPR) mixes with CRM added failed by widespread rutting and raveling shortly after being opened to traffic. Both were reprocessed with additional asphalt emulsion and overlaid with a conventional DGAC surface (Emery 1994). The reprocessed CIPR mixes appeared to provide a suitable base for conventional DGAC. Researchers concluded that appropriate mix design was particularly critical to performance of CIPR RUMAC mixes, and that it was necessary to oven-age the proposed mixture to evaluate and compensate for absorption of the asphalt emulsion by the dry CRM particles (Emery 1995, 1997).

California

Caltrans

Caltrans has been experimenting with various methods of recycling conventional and CRM-modified paving materials, including hot plant recycling, and forms of hot and cold in-place recycling (HIPR and CIPR) including full depth reclamation. According to former Caltrans engineer Jack Van Kirk, Caltrans experimented with recycling CRM-modified materials on two projects in the early 1990s.

A 1994 project on Rt. 40 in District 8 reportedly included reclaiming and recycling a RAC pavement. However District 8 personnel assigned to search for related records in response to inquiries have not yet reported finding any information in the files.

The other Caltrans recycling project was located in District 3 on Rt. 89 near Sierraville and it included an asphalt rubber chip seal. A telephone conversation with Ms. Sheree Edwards (currently Caltrans HQ Maintenance) on December 1, 2004 indicated that a considerable quantity

of elastomeric crack sealer was milled up during removal of the top two inches of the asphalt pavement at this site in 1993. The CRM-modified chip seal material on the surface did not seem to cause any problems, in contrast to those caused by "ropes" of crack sealer that were mixed in with the millings. Ms. Edwards reported that during hot plant recycling of the RAP and chip seal material into a conventional recycled AC mix, ropes of crack sealer had to be manually removed from the RAP feed belt into the plant. Ms. Edwards reported that the resulting recycled mix looked acceptable immediately after placement. However, in a subsequent telephone conversation, Joe Peterson, Caltrans District 3 Materials Engineer, reported that the pavement failed severely within one or two years after construction. No specific information regarding the type or cause of failure could be readily located in the District 3 files and it is not clear if the plant-recycled pavement was subsequently removed and replaced or simply overlaid. An adjacent pavement section also surfaced with asphalt rubber chip seal was recycled cold in-place as a base course and overlaid with AC.

Peterson has also been evaluating use of foamed asphalt as a stabilizer for full depth reclamation (FDR), a type of pavement rehabilitation in which the entire thickness of asphalt concrete and a designated thickness of the underlying materials (base, subbase and/or subgrade) are pulverized and mixed in place to provide an improved, uniform granular base material (ARRA Manual 2001) from 4 to 12 inches deep. He described rehabilitation of a badly distressed AC pavement in a low traffic area in the Delta, where subgrades are peat-like, weak and unstable. The AC was pulverized and treated in-place with foamed asphalt about 2-1/2 years ago and is performing well with only an asphalt rubber chip seal surface.

Peterson reported no information to indicate that RAC materials have been encountered in any of the FDR projects completed to date, but would not be surprised if they had. He does not believe that RAC materials would interfere with pulverization and foamed asphalt stabilization operations conducted at ambient temperatures, and there are no indications that they should.

City of Los Angeles

Municipalities in California have also done some limited recycling of RAC materials. The City of Los Angeles Bureau of Street Maintenance conducted the Olympic Boulevard Asphalt Rubber Recycling Project for the City of LA Department of Public Works in 1994 (City of Los Angeles, 1995). The project had two primary goals:

1. Determine the recyclability of asphalt rubber utilizing conventional mix design methodology and microwave technology; and
2. Determine the air quality impact of grinding, transporting, and processing RAC materials and to resolve safety questions regarding the recycling of asphalt rubber materials.

Conventional mix designs and microwave heating technology were used in the study. The Bureau enlisted the assistance of the City of Los Angeles, Department of General Services, Standards Division to test the asphalt according to the Marshall mix design method and criteria and consulted with the Asphalt Institute regarding the mix design procedures and construction practices. The impact method of compaction used in the Marshall method differs from the kneading compaction of the Hveem method used by Caltrans, but volumetric analyses are performed in the same manner for both design methods.

The original RAC pavement was constructed in 1982 on Olympic Boulevard from Indiana Street to Calada Street using a "wet process asphalt rubber which had been made at the City's Asphalt

Plant". The asphalt on the south side of the street was reportedly made with 3% CRM and the asphalt on the north side of the street was made with 1-1/2% CRM by weight of dry aggregate. (NOTE: The rubber content values in the report are described as if for the dry process, which includes up to 3% rubber by weight of dry aggregate. Typically for wet process CRM-modified binders, the percent CRM by weight of asphalt and the binder content of the mix are identified.)

The RAC pavement was milled and the millings were taken to the City's Asphalt Plant and the City's contract Cyclean Plant. At the Cyclean Plant, the millings were heated by microwave prior to mixing with the virgin aggregate and asphalt cement. At the City's Asphalt Plant, the milled RAC was heated as normal and added at 17.6% by weight of virgin aggregate. Asphalt content test data indicate an average of 6.6% asphalt cement by total weight of millings and aggregate was added.
On November 30, 1994 and December 1, 1994, the recycled AC mix made with reclaimed RAC was used to repave Olympic Boulevard. Samples were tested for gradation, Marshall stability and flow, and density using a nuclear gauge. The results showed that the recycled AC made with RAC reclaimed from Olympic Boulevard met specifications and passed all tests, and that RAC is recyclable using either microwave technology or conventional mix design technology.

The air quality was tested by the City's industrial hygienist as the RAC material was milled, processed and used for repaving. The industrial hygienist utilized Cal/OSHA standards and guidelines established by the American Conference of Governmental Industrial Hygienists. The City's industrial hygienist's report stated that, "Employees exposure to dust was evaluated during the grinding by the profiler since dust is the major exposure during this process. Air sampling for other contaminants was done during the paving operation or at the plant during the mixing. Employee exposures to air contaminants were well below the CAL/OSHA permissible exposure limits (PEL), and in most cases they were below the detection limit".

Industry Experience

Representatives from industry were also interviewed regarding experience with pavement recycling in California, including reclaiming and recycling CRM-modified materials.

In December 2004, Jim O'Kane of Pavement Recycling Systems (PRS) reported limited recent experience with cold recycling of RAC in their Lancaster, CA yard. PRS used a Reflex emulsion from Koch Materials and a stockpile of millings that contained CRM to pave the yard. (NOTE: Source of the millings was not identified and it is not certain whether the CRM came from a RAC mix, chip seal or interlayer). Although initial mix design tests showed considerable volume change in mix specimens compacted with a Superpave gyratory compactor (30 gyrations), PRS elected to proceed. There were no problems with crushing, screening or blending the millings and the emulsion. The processed RAC material also appeared to "behave well" during the lay down operation, although Scott Metcalf of Koch Pavement Solutions indicated that compaction was not achieved. After several days of limited truck traffic, raveling occurred that seemed to consist primarily of small pieces of uncoated CRM particles on the surface. Because this yard is only used for equipment storage and parking, it was left as is. PRS believes that if the recycled mix had not been trafficked during the curing period and then had been covered with a hot mix overlay, it might have performed better. (NOTE: An AC overlay would typically be required to accommodate trucks or heavy equipment).

O'Kane remarked that he believed that CRM-modified materials could be also be recycled by pulverizing and mixing in-place with existing AC and base course materials to provide an improved base, which supports Peterson's approach in District 3.

In a telephone conversation on December 9, Scott Metcalf reported another experience with cold recycling of CRM-modified materials on Highway 111 in the Palm Springs/Cathedral City area, which he identified as the highest traffic volume CIPR project in the U.S., with about 50,000 vehicles per day traveling this route. The existing pavement was surfaced with an asphalt rubber chip seal and milling depth was 3 inches, so the relative proportion of CRM-modified to conventional AC material was small. The laboratory mix design called for a relatively high emulsion content of 3.2% by weight of millings. Although the compacted mix design specimens appeared rich and dense, air void content was high: 11 to 12%. The mix specimens indicated slight swelling in the molds, but the recycled mix was compacted in-place without apparent problems. Slight raveling of the CIPR surface was observed prior to overlaying which was remedied by application of a fog seal. The CIPR material was overlaid with RAC and is reportedly performing very well.

Based on his experience, Metcalf recommended that for CIPR, reclaimed CRM-modified materials should not be used in surface courses, but may be included in base courses that will be surfaced with conventional AC. He stated that mixes made with no-agitation CRM-modified binders might be an exception, as the CRM contents are typically too low to have significant effects on the properties of the resulting recycled mix.

Metcalf also offered some comments about hot in-place recycling (HIPR) of CRM-modified materials. He thinks that smoke generation related to the incorporated extender oil may be an issue during construction. In addition, rejuvenating additives should be avoided due to potential to interact directly with the CRM particles (as occurred in Kansas). In the Arizona DOT's "proof of concept" experiment with recycling a RAC O-HB-type mix there were no reports of excessive smoke, but ADOT does not allow use of extender oils in their CRM-modified binders.

2.3 SUMMARY AND RECOMMENDATIONS

The majority of the limited number of studies on the use of reclaimed CRM-modified materials in recycled asphalt paving mixtures indicate that reclaimed CRM-modified materials can be successfully recovered, recycled, and incorporated into other bituminous paving mixes. Results of tests on AC plant emissions and worker exposure conducted during production and placement of recycled mixes including reclaimed CRM-modified paving materials do not indicate adverse impacts on health and safety. Most of the studies recommend development of a standard mix design method for recycled mixes including reclaimed CRM-modified materials. Recycling appears to be a feasible approach to continued value-added use of CRM in pavements which can reduce the life-cycle cost of CRM-modified materials and allow better estimation of their salvage value.

The types of recycling considered for use by Caltrans include the following:

1. **Full depth reclamation**, a type of pavement rehabilitation which recycles in-place the entire thickness of the existing pavement structure including CRM-modified materials, asphalt concrete and a designated thickness of the underlying materials (base, subbase and/or subgrade) to provide an improved base course. Stabilizing additives may be included and a bituminous surface course is typically required.
2. **Hot plant recycling**, where the reclaimed CRM-modified materials can be sized, mixed, maintained, and controlled in stockpiles and added to virgin aggregate and asphalt cement materials under controlled conditions according to a laboratory mix design to provide a suitable recycled AC paving mixture.

3. **Cold in-place recycling** according to a laboratory mix design based on samples from the existing pavement, which may be limited to the upper RAC or AC pavement layers (including surface treatments or seals) or extend to full depth reclamation.
4. **Hot in-place recycling** according to a laboratory mix design based on samples from the existing pavement including CRM-modified layers, whether RAC, chip seal or interlayer.

The following recommendations are based on review of the limited literature and interviews with agency and industry representatives who have worked with CRM-modified asphalt paving materials.

Full depth reclamation is already being performed by Caltrans as a pavement rehabilitation strategy, particularly in District 3 where foamed asphalt appears to be performing well as a stabilizer. Although there is no documentation that CRM-modified materials have been incorporated in existing FDR projects, no obstacles to their inclusion are evident at this time.

It is recommended that Caltrans continue to use this approach to pavement rehabilitation where it is deemed appropriate, and that the presence of CRM in the pavement structure should not be considered an obstacle to recycling the pavement structure in-place. Mix designs are developed for evaluation of effects of selected stabilizing additives and determination of appropriate dosage. However, additives that include petroleum solvents, rejuvenators, or extender oils that may cause CRM particles to swell should not be used when CRM is present. Mix design test results and observations of specimen behavior, particularly volume change after compaction, should indicate if proposed additives are compatible with samples of the site materials used in the design.

Hot plant recycling of conventional AC materials is being performed to a limited extent in California. Based on the literature review, it appears feasible to include reclaimed CRM-modified materials in recycled AC mixes and to expect that the resulting pavements will provide satisfactory performance. Using a hot plant for recycled mix production allows better control of the component materials than can be achieved under field conditions. Kansas DOT's experience with rejuvenators indicates that such additives should be avoided when using high viscosity CRM-modified binders. Instead, relatively soft grades of asphalt cement should be used. However, current work in progress at Clemson University by Shen, Amirkhanian and Lee (presented in a Poster Session at the 2005 Transportation Research Board Meeting but not yet published) indicates that rejuvenators may be suitable for use with reclaimed RAC material that includes no-agitation CRM-modified binders. Based on the extensive and apparent generally successful use of 15% RAP by weight of total mix in a variety of types of mixes throughout the U.S., hot plant recycling has high potential for successful development and field implementation in a relatively short time frame. These factors indicate that hot plant recycling is an excellent candidate for development and implementation by Caltrans, but laboratory evaluation and field validation are necessary to promote success.

Since Caltrans allows addition of up to 15% RAP in large-volume AC projects, the effects of using recycled CRM-modified AC should be investigated forthwith.

Cold in-place recycling experience in California seems to support results of CIPR of CRM-modified materials observed in Kansas and Ontario. Reclaimed CRM-modified materials can be used to make functional CIPR base courses to be surfaced with conventional AC, but issues with stability and raveling of the resulting recycled mixes have not been resolved. It appears that additional work will be required to develop appropriate methods of mix design, including evaluation of appropriate compaction methods. Scott Metcalf stated that it may also be necessary to develop different asphalt emulsion formulations to improve cold-in-place recycling of CRM-

modified materials. Swelling of compacted lab specimens indicates that some of the currently available emulsions may interact with the CRM particles even at ambient temperatures.

Pending future developments, CIPR of pavement structures including CRM may be used on a limited trial basis to provide improved base courses for roadways with relatively low traffic volumes that would be overlaid with AC or RAC-G mixes as part of their rehabilitation strategy. Experience in Kansas indicates that CIPR of CRM-modified materials may be performed over rubblized pavements with satisfactory results (see Table 2 on page 7 of this report).

Hot in-place recycling of CRM-modified materials appears to date to be limited to ADOT's very preliminary proof of concept test. Because of the potential for the extender oil in the CRM-modified to generate blue smoke, possible issues with use of rejuvenating agents, limited experience available and the variable conditions that may be encountered in field operations, this approach should probably be reserved for future development, and build on the experience gained during implementation of the other three approaches to reclaiming and recycling CRM-modified materials that have been considered herein.

3.0 RESEARCH APPROACH FOR EVALUATING FEASIBILITY OF RECYCLING

Based on the findings of NCHRP 9-12 (McDaniel and Anderson, 2001), it is proposed that a similar tiered approach be used, with reclaimed RAC contents of 15% and 25% by total mass of mix, equivalent to about 19% and 36% by dry weight of aggregate, respectively. No major difficulties are anticipated in incorporating 15% reclaimed RAC into recycled DGAC mixes, although some modifications to Hveem mix design procedures may be needed. The primary changes would likely be in specific requirements for volumetric recycled AC mixture properties such as air voids content, voids in mineral aggregate (VMA), voids filled with asphalt (VFA), dust-to-binder content ratio, etc. Therefore, the first mix design trials would be to incorporate 15% reclaimed RAC into recycled DGAC; based on the results, the effects of adding 25% reclaimed RAP will then be evaluated.

The Caltrans SSP for Contractor's optional use of Recycled AC limits RAP content to a maximum 15% by dry weight of aggregate. The proposed approach will show what can be expected at higher reclaimed RAC contents which are typical of extensive current national practice for conventional mixes, and provide useful information that should also apply to lower reclaimed RAC contents. However, it would not be useful to consider adding more than 25% reclaimed RAC by total weight. Properties of recovered CRM-modified asphalt binders do not represent the binder systems present in the RAC mix, which would make selection of appropriate virgin binder grade unnecessarily complicated.

There is not any persuasive reason to use reclaimed RAC in virgin RAC if it can be mixed into DGAC instead. Mix design procedures using two CRM-modified materials could easily become complicated and compatibility issues could arise. Furthermore, RAC into RAC would not increase use of scrap tire CRM.

In-Place Recycling Mix Design and Implementation

Once it has been established that reclaimed RAC can be successfully incorporated into hot plant recycled DGAC pavements, Caltrans may wish to consider expanding the options for reclaiming

and recycling RAC pavements to include cold-in-place and then perhaps hot-in-place recycling of RAC. The same types of protocols established in the hot plant recycling study would be used to develop mix designs for these applications, and for field validation of the resulting recycled pavement products.

3.1 EXPERIMENTAL PLAN FOR LABORATORY MIX DESIGN DEVELOPMENT

The mix design method for including reclaimed RAC in recycled DGAC needs to be valid for any type of aggregate likely to be used in DGAC anywhere in the state and thus should be developed using at least three different primary aggregate types and/or sources available in different parts of California. The types of virgin aggregate materials that will be used to develop the recycled DGAC mix designs do not need to be the same type or source of aggregate that is in the reclaimed RAC. It would be ideal if the reclaimed RAC and virgin DGAC materials used in the laboratory study corresponded to materials that would be included in the Field Evaluation phase, but this may be very difficult to accomplish.

The hypothesis for the proposed laboratory experiment is as follows:

"At respective levels of 15% and 25% reclaimed RAC content by total mass of mix, recommended guidelines for including conventional RAP in conventional DGAC paving mixtures may be applied to including reclaimed RAC in recycled DGAC mixtures."

To test this hypothesis, the following work elements are proposed.

1. Coordinate with Caltrans and Industry to obtain sufficient quantities of milled reclaimed RAC materials to complete the expected laboratory work, including round robin and validation testing by other laboratories to establish that the proposed design method can be reproduced and used by others. Obtain a minimum of 2,000 pounds of each of the three different RAC mixes that represent different types and/or sources of aggregates available in different regions of the state.

Aggregate A	Aggregate B	Aggregate C
Reclaimed RAC A	Reclaimed RAC B	Reclaimed RAC C

2. Determine the gradation and binder content (by extraction, not ignition) of each reclaimed RAC material by laboratory testing according to standard Caltrans test methods, modified as necessary to recover and account for remaining discrete CRM particles. Use the results to determine if additional processing (lab crushing) is needed prior to mixing with virgin aggregates, and repeat gradation analysis as needed.
3. Obtain at least two current successful Caltrans-approved DGAC mix designs (DGAC #1 and DGAC #2) for use as control mixes and as virgin mixes to which the different reclaimed RAC materials will be added. A successful design is considered to be an AC mix that was produced and constructed in compliance with the mix design and specifications and that has provided satisfactory pavement performance. It is not necessary that aggregate types or sources used in the mix design match those in the reclaimed RAC.

4. Obtain at least 30 gallons of each of the respective asphalt cement materials (same refinery source and grade) used in the Caltrans-approved DGAC designs.
5. Obtain virgin aggregates from the original suppliers that correspond to those designated in the respective Caltrans-approved mix designs. Obtain at least 2,000 pounds of each aggregate component in each mix to assure sufficient quantities will be available to complete the laboratory testing necessary to develop and to validate the mix design method, including round robin testing by Caltrans Central and District labs and private laboratories.
6. Validate the existing Caltrans-approved mix designs with the aggregate and asphalt cement samples obtained to verify compliance with original mix design parameters and provide reference values for comparison with recycled DGAC designs developed.
7. Develop recycled DGAC mix designs with the combinations of materials shown in the following mix design matrix. Mix designs must meet Caltrans requirements for DGAC including Hveem stability and provide appropriate volumetric properties. Complete Phase 1 before starting Phase 2.

Laboratory Mix Design Matrix

Reclaimed RAC Material	Phase 1		Phase 2	
	DGAC #1	DGAC #2	DGAC #1	DGAC #2
RAC A	15%	15%	25%	25%
RAC B	15%	15%	25%	25%
RAC C	15%	15%	25%	25%

8. Mix designs that meet Caltrans requirements for DGAC including Hveem stability, and that provide appropriate volumetric properties will be considered to be successful laboratory results. At the discretion of Caltrans, successful lab mix designs may be subjected to laboratory performance tests (repeated shear and fatigue) at TransLab and/or the University of California before proceeding with the proposed field validation study.
9. To validate that the mix design procedures developed are reproducible, a program of round robin testing is proposed that would include Caltrans laboratories and private Caltrans-qualified laboratories. Any of the successful recycled AC mix designs developed could be used. In addition, testing of the corresponding Caltrans-approved DGAC mix design should also be included as a comparison. MACTEC would prepare samples of the virgin aggregates and asphalt cement, reclaimed RAC, and any other mix components for distribution by Caltrans. Pertinent recycled DGAC and DGAC mix designs showing target asphalt binder content, target composite aggregate gradation and individual aggregate and reclaimed RAC gradation information would also be included. MACTEC would also provide statistical analysis of the round robin results. However, based on MACTEC's work with the Arizona DOT to develop a standard mix design method for gap-graded asphalt rubber concrete (GG-AR AC) mixtures, each participating laboratory would have to fabricate and test at least three replicate design sets for the control and recycled DGAC mixes to provide sufficient

data regarding repeatability and reproducibility of the proposed recycled DGAC mix design method.

Expected Outcome

The expected outcome of the laboratory phase of the project is a Hveem mix design procedure for incorporating CRM-modified mixtures into recycled AC mixtures.

3.2 EXPERIMENTAL PLAN FOR FIELD VALIDATION

Purpose

The purpose of the field validation phase of the study is to evaluate under actual field conditions the plant production and performance of recycled DGAC paving mixtures produced from a combination of virgin aggregates and asphalt cement and reclaimed RAC. Of particular interest are operational aspects of reclaiming and recycling RAC materials, including impacts of CRM-modification on milling equipment and efficiency, handling of reclaimed RAC and chip seal materials, introduction of such materials into the AC plant, emissions, etc.

Experimental Plan

The experimental plan shall be developed according to the "Generic Experimental Design for Product/Strategy Evaluation - Crumb Rubber Modified Materials" developed for Caltrans by MACTEC. Flexibility is a requirement for conducting field experiments, and it may be necessary to make some changes depending on findings of the laboratory study, the availability of candidate projects and the ability of the respective districts to support the experiment. However, maintaining a sound experimental and data collection plan is essential to obtain useful results, and the effects of any changes to the proposed evaluation plan should be carefully considered.

3.3 EXPECTED DELIVERABLES

The expected deliverables from the validation phase are long term items. The only short term deliverable for this project is the laboratory mix design procedure. The long term deliverables are as follows:

- a direct comparison of field performance of traditional DGAC overlays with recycled DGAC overlays constructed using a combination of virgin asphalt mix and recycled RAC;
- assessment of the influence of overlay thickness on the performance comparison of conventional DGAC mixes and mixes made with recycled RAC;
- comparison of field performance with laboratory performance test results; and
- overall cost comparison.

Five years is not sufficient to determine or compare the long-term performance of the recycled RAC mixes; however, any serious deficiencies are likely to manifest within that period. Therefore, it is recommended that these projects continue to be evaluated after the initial 5-year monitoring period has been completed, for the life of the subject recycled AC pavements.

4.0 SUMMARY

Recycling has proved to be a sound, economical method of conserving and reusing scarce material resources used in AC pavement construction. Considerable experience with recycling conventional AC mixtures indicates that the resulting recycled pavements can generally perform at least as well as most virgin pavements. Review of the literature related to recycling of CRM-modified paving materials indicate that these materials can also be recovered and recycled to provide serviceable pavements.

A plan for laboratory testing to develop and verify a Hveem mix design procedure for incorporating reclaimed RAC pavement materials into hot plant recycled DGAC mixtures has been proposed, along with a plan for field validation of production and performance of such mixes. The proposed study will provide Caltrans with the necessary tools to promote recycling of RAC and CRM-modified asphalt paving materials, and to substantially increase the amount of these materials that can be recycled into new Caltrans pavements.

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