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Summary and Recommendations toward Implementing Innovations Based on Selected Presentations at the Asphalt Rubber Pavement Conference (AR2006), October 2006

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UCPRC staff attended the 2006 RPA conference in Palm Springs, CA. This document contains brief summaries of the technical papers/presentations given in both the technical and practical portions of the event. Items within specific papers that may be implementable by Caltrans are noted. Suggestions for future research, development, and information dissemination are given.</td></tr>
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GLOSSARY

Below are basic definitions for commonly found terms in the summary and the proceedings. The reader is urged to do further research on any of these terms if interest is warranted.

Asphalt Concrete Friction Course (AR-ACFC)	An open-graded friction course utilized by the state of Arizona as a noise reducing layer.
Asphalt rubber (AR)	An asphalt concrete mix produced with crumb rubber through the wet process – see wet process.
Asphalt Rubber Stress Absorbing Membrane Interlayers (AR-SAMI)	A reflection crack and waterproofing layer composed of asphalt rubber binder with a single layer of uniform chips. Similar to a chip seal.
American Society for Testing and Materials (ASTM)	Governing body for standards development in the United States
Binder	Asphalt cement. May be modified with polymers or rubber.
Conventional asphalt concrete	Asphalt concrete made with unmodified asphalt cement. Other names commonly used for this are conventional DGAC and conventional HMA.
Crumb rubber modifier (CRM)	Small rubber particles produced from shredding rubber tires. Various gradations of this material are used worldwide.
Cement Treated Base (CTB)	CTB is a mix generally used with asphalt concrete pavements, composed of aggregate, portland cement, and water and is specified as either Class A or Class B by Caltrans. It can be either plant mixed or road mixed.
Dense Graded Asphalt Concrete (DGAC)	Another name for conventional asphalt concrete.
Dynamic Modulus (E*)	Dynamic modulus (E*) refers to the bending stiffness under repeated loading of a viscoelastic material which has both magnitude and phase components. With viscoelastic materials, there is a time lag between the applied stress and resulting strain (and vice-versa) in the material. The time lag is represented by the phase component of E*, noted as ϕ.
Dry process	Modification of asphalt concrete mixtures by use of granulated or ground rubber/crumb rubber. The rubber is used as a portion of the fine aggregate.
Elastic modulus	The stiffness of an asphalt concrete mix as measured by the ratio of applied stress to resulting strain within the material.
Extender Oil	An aromatic oil used to supplement the reaction of the asphalt and the crumb rubber modifier
Indirect Tensile Test (IDT)	An asphalt concrete performance test in which tensile capabilities are determined from compressive forces placed upon an edge loaded asphalt concrete core.
International Roughness Index (IRI)	A measurement unit used to illustrate the relative “roughness” of a pavement. It is measured in inches/mile or mm/km and is a summation of deviations from the horizontal plane over a given distance.

Marshall test	An asphalt mix design procedure commonly used in the eastern and middle portions of the United States.
Mechanistic-Empirical (ME)	Refers to the concept of designing and characterizing pavements using both the mechanical/physical properties of the materials as well as the actual measured field and laboratory performance.
Modified Binder (MB)	Generic term describing asphalt binders that have incorporated into them either polymers, rubbers, or other "modifiers" in order to enhance performance.
Open-graded Asphalt Concrete (OGAC)	An asphalt layer primarily used to minimize standing water and water splash and for drainage when used as a base layer.
Open-graded Friction Course (OGFC)	An asphalt surfacing layer placed to aid friction and water splash issues. Arizona has placed this material (AR-ACFC) on many of their PCC pavements.
Polyphosphoric Acid (PPA)	An additive extensively used in the chemical modification of both conventional and polymer modified binders.
Porous pavements	Pavements that are designed to promote water runoff and/or capture. A wide range of performance capabilities exist for this type of pavement, ranging from open-graded surfaces to fully permeable pavements.
RAC	Caltrans name for Rubberized Asphalt Concrete
RAC-G	Caltrans name for Rubberized Asphalt Concrete with a gap gradation
RAC-O	Caltrans name for Rubberized Asphalt Concrete with an open gradation. Binder content is typically about 20% higher than conventional DGAC.
RAC-O-HB	Caltrans name for Rubberized Asphalt Concrete with an open gradation and even <u>h</u>igher <u>b</u>inder content. Binder content is typically about 65% higher than conventional DGAC.
Raveling	The pavement distress in which surface aggregate is dislodged or worn away due to aging and hardening of the asphalt binder and/or tire wear.
RUMAC	Dry process CRM modified mix Caltrans uses for pavement rehabilitation projects.
SBS and SBR	Refers to the polymer additive or mixes modified with Styrene Butadiene Styrene and Styrene Butadiene Rubber
SGC	Superpave Gyratory Compactor
Spread rate	Refers to the amount of binder placed per unit area in chip seals or SAMIs. Also refers to amount of chips placed per unit area.
Stiffness	Another term for Modulus. Stiffness refers to the degree of bending of an asphalt mix for a given load.
Strain	Change of length per unit length. Permanent strain in asphalt concrete results in rutting within an asphalt mix
Stress	Applied load per unit area
Stress Absorbing Membrane Interlayer (SAMI)	A reflection crack and waterproofing layer composed of conventional asphalt binder with a single layer of uniform chips. Similar to a chip seal.

Terminal blend	A rubber modified asphalt concrete in which the crumb rubber is blended with the asphalt at an asphalt distribution terminal. This process allows for holding the mix for extended periods of time. Typical the blend contains less than 10% crumb rubber along with extender oils and small amounts of polymer modifiers.
Texas Gyratory Compactor (TGC)	A specific compactor used by TxDOT for mix testing.
Traffic Index (TI)	A measure of traffic count over the course of a pavement lifetime. Higher TIs indicate higher traffic levels.
Voids in the Mineral Aggregate (VMA)	The volume of voids as a percent of the entire specimen between the aggregate particles in a compacted asphalt concrete mix, including air voids and effective (but not absorbed) binder.
Wet process	Modification of asphalt cement by blending crumb rubber into the cement through agitation. The rubber reacts through absorption of aromatic oils from the asphalt cement into the polymer chains of the rubber. Typically a set mixing or agitation time is required for “digestion.”

1.0 BACKGROUND AND OVERVIEW

The Asphalt Rubber Pavement Conference (AR2006) held in Cathedral City, California from October 25–27, 2006, provided a forum for the world's leading experts on asphalt rubber in government, industry, and academia to present information and recommendations on innovations in the use of this material. Increased use of crumb rubber is mandated in California under Assembly Bill 338. This conference was sponsored by the Rubber Pavement Association (RPA), the California Department of Transportation (Caltrans), and other organizations.

One of the driving forces behind AR2006 was the Caltrans Office of Pavement Preservation (OPP) in the Headquarters Division of Maintenance, which had identified a need to scan available practices and new technologies for the use of asphalt rubber in pavements. As part of this effort, OPP asked the University of California Pavement Research Center (UCPRC) to attend AR2006 and to provide services as outlined in an agreed-upon work plan (*Work Plan for: "Summary and Recommendations Toward Implementing Innovations Based on Selected Presentations at the Asphalt Rubber Pavement Conference [AR2006], October 2006").* Services provided by the UCPRC focused on reviewing papers, attending the conference (talking with authors and other participants), and preparing a summary and recommendations for OPP. These services are funded largely under Task Order 1018 between the Caltrans Division of Research and Innovation (DRI) and the California Center for Innovative Transportation (CCIT). Some additional funding was provided under Strategic Plan Element 2.3 of the UCPRC's contract with DRI.

The focus of this document is to provide an independent and objective summary and a set of recommendations to Caltrans on implementable—as well as promising—innovations for further use of asphalt rubber based upon selected presentations at AR2006. Of key interest is highlighting those innovations and recommendations that:

(i) Are implementable,
(ii) Need further development, and
(iii) Need further research.

Specifically implementable techniques or materials are those that may be readily utilized by Caltrans with minimal effort. It is important to keep in mind that many of the implementable techniques recommended in this summary are already being used by Caltrans at some level. Innovations that need further development are those that have shown promise in California or other states, but are not fully proven in the judgments of the authors. Those concepts identified as needing further research are promising and novel research ideas that are in the early stages and with additional work may be very effective. A fourth category that reviewers called "general information," was identified after reviewing the papers (which were not available before the conference due to copyright concerns).

The professional judgment of the UCPRC reviewers serves as the basis of the comments made in this paper. Their review revealed that seven of the papers presented have direct implementable content for Caltrans, seven of the papers contain ideas that with further development could be utilized, and the ideas in the rest of the papers need further research or provided general information. All the papers have merit, but the content and processes they discuss are in various stages of progress. Where appropriate, details of these papers are highlighted.

This summary may be considered a stand-alone document. However, it may also be used in conjunction with the DVD from the conference (which the Rubber Pavements Association expects to distribute to Caltrans in February 2007) for further detail and education. It is recommended that those interested in specific papers or information read the official proceedings from the conference.

Asphalt Rubber (AR) is defined by ASTM as a material that contains a minimum of 15% reclaimed tire rubber. California in its specifications, calls for 20+/-2% crumb rubber modifier by total binder mass (includes 75% CRM and 25% HNR). The type and size of rubber particles as well as method of manufacture are also defined. The State of Arizona has successfully used AR in its pavement surfacings for several years. The Arizona Department of Transportation (ADOT) attributes its use of thin AR overlays for noise reduction for the entire highway network in Phoenix because of its confidence in the material. The State of California has also had good success with AR and over a longer period of time (beginning in the late 1970s). Texas, Florida, and other states have also had experience with AR. Many of the papers presented in this conference were based upon work by or for ADOT and by or for Caltrans.

Although AR is the most widely used rubber modified asphalt pavement system (used in chip seals and mixes), there are many other civil engineering uses for scrap tire rubber (some of these were not included in the conference). For example, small particle size rubber used in terminal blend binders shows significant promise and allows for the use of rubber in dense graded asphalt mixes. Scrap rubber shreds have been used as embankment fill for landfill projects, particularly on weak compressive soils due to the lightweight nature of the material. Again, due to the lightweight nature of the material, scrap rubber has been used as backfill for retaining walls and bridge abutments, yielding thinner less costly wall construction projects. Scrap rubber has also been used for drainage backfill as well as for numerous surfacing applications.

2.0 REVIEW OF PAPERS FROM TECHNICAL SESSIONS AND APPLICATION TRACK

2.1 Review and Discussion of Technical Session Papers

During the course of the 3-day AR2006 conference, UCPRC staff reviewed the papers, attended the sessions, and spoke with authors. For this document, the 34 papers that were reviewed have been divided into sections that closely align with the sessions held at the conference.

- General Usage and Applications
- Pavement Performance and Design
- Recycling and Environmental Aspects
- Rehabilitation and Noise Reduction
- Mix Properties
- Binder Properties

Pertinent papers from each of these topics are presented in this section. Implementation recommendations for selected papers are presented where pertinent. Papers noted to be readily implementable are denoted with an asterisk (*).

2.1.1 General Usage and Applications

35 Years of Asphalt-Rubber Use in Arizona
Authors: A. Zareh, G. B. Way

The emphasis of this presentation and paper was on the use of asphalt rubber (AR) in Arizona and how the authors have assessed its success. When using crumb rubber in asphalt binders, Mr. Way stated the importance of using base binder 1 to 2 grades softer than that used in conventional asphalt concrete pavement. For example if 76-16 is needed, then use 64-16 as the base stock for the AR. The authors felt that AR provided good skid resistance and lower maintenance costs. From a graph in the paper, maintenance costs for AR and conventional dense graded mix were comparable for the first 5 years, however after that the dense graded mix costs rose considerably faster than the AR costs. Also shown are results from Mu Meter skid testing. AR performed better than HMA initially and over the life of the pavements tested. However, both AR and HMA showed good skid resistance test values. An additional benefit of this material mentioned by the speaker is that CO_2 emission studies have shown that lower rates of CO_2 are emitted into the atmosphere from the use of AR. The lower CO_2 emissions could be from the use of lower quantities of aggregates, but the paper makes no specific reference to this claim.

The Urban Heat Island Effect and Impact of AR-ACFC Overlays on PCC Pavements

Authors: M. Belshe, K. Kaloush, J. Golden

The authors cite the importance of minimizing the urban heat island effect and the part that AR plays in it. In using the darker AR-OGFC there is an increased surface temperature during the daytime, but reduced surface temperature at night time (explained by the porosity and lower thermal mass). Traffic is felt to have an aeration effect and the relative coolness of the pavement is due to the high air-void content and the lower thermal mass of the surface mix. Without the AR surfacing, the PCC surface would be 3–8ºF higher. The authors believe this increased temperature would result in increased truck and warping/curling damage due to greater slab stresses than would be experienced without the overlay. While the insulating effects of overlays on PCC is not a new concept, the idea that the AR surface could provide such benefits is fairly dramatic. The increase in PCC lifetime is unknown and this is a complex issue that could use further research. In conducting this research, the authors deployed a network of "iButton" thermal sensors to record pavement temperatures. Caltrans may want to follow up with these researchers for further conclusions on this work.

Influence of Temperature Variation on the Reflective Cracking Behaviour of Asphalt Overlays

Authors: M. Minhoto, J. Pais, P. Periera

The paper evaluated the performance of AR mix vs. conventional AC mix in fatigue using finite element method (FEM) modeling considering primarily temperature but also traffic loading. It was found that the difference in damage rate between AR and conventional AC mix seems to be larger in winter than in summer, due to the reduced stiffness of the AR and more closed joints in the lower pavement layer. Further research is needed because it is not apparent whether this is a cyclic/dynamic loading situation or just static loading at different temperatures. There may be other questions about the model, as well.

Asphalt Rubber in New Pavement Construction and Design

Authors: J. Sousa, G. Way, S. Shatnawi, C. Dantas

This paper advocates the use of asphalt rubber in new pavements and that, as designers, we are not taking proper advantage of these materials. The authors emphasize the need to develop new design methodologies (based on minimizing reflective cracking) and laboratory tests for AR since material performance is not well characterized by traditional models, such as fatigue models or in tests such as the Marshall test.

When designing new pavements with an AR surface layer, it is usually necessary to provide sound base support to control the strain and use AR as the shield to stop cracks from propagating to the surface. However traditional design for new pavements uses strain at the bottom of the underlying AC layer to control fatigue and strain at the top of subgrade to control subgrade rutting. This usually leads to very thick AC layers. However, since thin AR overlays in Arizona perform very well in both fatigue and rutting, it is necessary to have a better way to incorporate the AR surface layer into the design. One way is to convert the AR surface layer into an equivalent conventional AC layer. Another alternative is to design the AR surface as an overlay and assume the underlying AC will crack soon. Again, AZ does not allow reduced thickness when using AR mixes.

Evaluation of Tire Wear Emissions, Roughness and Friction Characteristics of Asphalt Rubber Friction Course Pavements

Authors: O. Alexandrova, J. Allen, K. Kaloush

This paper evaluated tire wear emissions from portland cement concrete (PCC) and Asphalt Rubber–Asphalt Concrete Friction Course (AR-ACFC), which was overlaid on the same PCC, surfaces within the Deck Park Tunnel in Phoenix, Arizona. Vehicle emissions of PM10 and PM2.5 particulates were measured as they have been found to affect human health. It was found that AR-ACFC has higher friction and lower International Roughness Index (IRI) than PCC, but resulted in less tire wear emissions.

* Multi-Layer Pavement Strategies Utilizing Asphalt Rubber Binder

Author: J. Van Kirk

As the title suggests, this paper looks at the use of multi-layer systems to produce long-life rehabilitation projects with the use of asphalt rubber binder. The author has found that an AR SAMI interlayer followed by an AR gap-graded overlay has provided good performance over badly distressed pavements. In combination with conventional asphalt concrete leveling course the performance is further enhanced. In the presentation the author mentioned that this added performance was at least in part due to the waterproofing benefit of the SAMI. The base materials studied in this paper did not break down as much as expected because they had been kept relatively dry.

The SAMI suggested by the author contains 9.5 mm chips with 2-3 l/m^2 of binder, which is considerably higher than conventional chip binder spread rate of 1.4-1.8 l/m^2. The author claims significant cost savings to agencies along with the potential benefit of minimizing grade and height problems, commonly encountered with thick conventional overlays. Two examples are cited in the paper where the use of multi-layer strategies saved the client 40% over the cost of a conventional treatment. The author provides references to previous papers where he discusses potential cost savings in more detail. While these savings are substantial, it is helpful to look at multi-generational costs when making comparison between alternatives. This strategy may still be less expensive, but a longer term analysis would verify this.

Implementable Items

- Use of this design strategy. This pavement strategy has been shown to perform well in lower volume, lower truck traffic roadways provided that proper construction is ensured. Adequate construction controls and monitoring are required for success.

2.1.2 Pavement Performance and Design

Asphalt Rubber Mixtures in Portugal: Practical Application and Performance
Authors: M. De Lurdes Antunes, F. Batista, P. Fonseca

The authors studied the performance of field and laboratory produced wet process AR specimens. Four point bending beam tests along with rolling wheel rutting tests were performed. The findings indicate that significantly higher strain levels are allowable for a given number of cycles to failure than in conventional asphalt mixes. It was found that the AR stiffness increased significantly during the first six years of service and that the authors' laboratory aging process was able to mimic this performance. The authors felt that both the new and aged AR specimens performed better than conventional mixtures. With respect to rutting, AR deformation resistance increased with aging, as expected with the binder stiffening.

In constructing these pavements, it is suggested that the compaction equipment closely follow laydown as these materials cool quickly and that strict compaction temperature guidelines be followed. Asphalt plants using this technique must be specially adapted to control the reaction between the asphalt and the crumb rubber and this reaction must be kept under strict control.

Performance of a Test Track Using Crumb Rubber Asphalt and Other Modifiers
Authors: G. Martinez, B. Caicedo, D. Gonzalez, L. Celis

This paper looks at ways to modify Colombian asphalt binders with asphalt rubber techniques. Test track studies were performed using wheel loading (1.5E6 ESALS [80kN]). It was found that while the dry process performed better in the laboratory, its field performance was not comparable to the wet process. According to the authors, the wet process "presented huge advantages" compared to unmodified mixtures and had "better performance than the commercial polymer modified mixes with SBS and SBR."

Structural Design Considerations for Rubberized Asphalt Mixes

Authors: T. Bressette, H. Zhou, S. B. Seeds, R. G. Hicks

This study examined performance and design issues regarding conventional and AR mixtures through modeling numerous structural sections with mechanistic techniques. Well established fatigue (University of California) and rutting (Asphalt Institute) models were used to determine appropriate strains and performance predictions. It was found that for low traffic index (TI) pavements, RAC-G fatigue performance was better than DGAC regardless of subgrade soil strength. For higher traffic levels (TI >8), DGAC mixes outperformed RAC-G mixes in terms of fatigue and rutting. For structural overlays, the structural benefit of the RAC overlay varies with thickness. RAC-G overlays provide the most benefit in thin layers and Caltrans recommendations regarding reduced thickness are valid. For new designs, the authors recommend that a structural design be developed that is necessary to provide adequate cover and that thickness not be reduced when using asphalt rubber mixes.

It should be noted that UCPRC provided the AR and conventional beam fatigue equations (repetitions to 50% loss of stiffness) to the authors and reviewed the results.

Conventional ME analysis using fatigue failure criteria of 50% loss of stiffness was used in this paper along with a converted shift factor to account for crack propagation and boundary conditions. There were strong doubts from some conference participants whether the approach used captures the full benefits of AR performance. Questions were asked whether this approach ignored the crack propagation benefits of AR. This suggests that additional research should be done to understand the differences in crack propagation between conventional asphalt and AR.

Laboratory Characterization and Full-Scale Accelerated Performance Testing of Crumb Rubber Asphalts and Other Modified Asphalt Systems

Authors: X. Qi, A. Shenoy, G. Al-Khateeb, T. Arnold, N. Gibson, J. Youtcheff, T. Harman

This paper tries to relate laboratory performance of binder and mix to rutting and fatigue performance of different mixes in Accelerated Loading Facility (ALF) tests. The purpose is to find a performance test to help characterize AR binder. No SHRP binder test was found that gives good correlation to rutting or fatigue performance in ALF tests.

ALF test results showed that the AR section provided the largest number of cycles to failure of all 12 sections tested. The authors also note that the AR section had a significantly stiffer base layer supporting it than the other test sections. Therefore, a concern regarding this work is that fatigue cracking is not only determined by mix property, but structural capacity as well. The authors state that it is difficult and possibly unwise to try to find a direct correlation between mix property and ALF fatigue cracking performance without considering the in-situ strain. Again, AR tends to defy or at least stretch many of the conventional "rules" of pavement performance, so further research in this regard is relevant. It was also felt that healing in the modified binder seems to be significant because of the higher binder content used.

2.1.3 Recycling and Environmental Aspects

*** Study and Application of Asphalt Rubber and Rubberized Pavement in China**
Authors: H. Wen-Yuan, C. Yung-Chieh, X. Li-Ting

This paper summarizes trends of using AR mixtures in China, where the authors used the combination of conventional and AR mixes. For an existing PCC pavement or CTB base, an AR-SAMI can be placed first to prevent water infiltration, then followed by a conventional DGAC structure layer, with an AR friction layer at the top.

In the dry process, the authors found great success with the use of very fine rubber powder (40, 80, 120 mesh), even on high traffic roads. The rubber proportion used was 20 percent of the binder or 1 percent of the total mix by weight. Based on their observations of 30 km of (mostly) dry process pavement they suggest that this very fine material allows for better reaction with asphalt and hence better compaction properties, mix stability, and integrity.

Implementable Items

- Use of fine rubber powder in dry process with less than 1 percent by weight of total mix after validation with materials available in California.
- Use of thin AR overlay over a conventional structural overlay on Rubber SAMI to minimize reflection cracking.
- Use of precoated chips.

Energy Consumption of Alternative Scrap Tire Uses
Authors: J. Sousa, G. B., Way, D. Carlson

The authors state that using scrap tires in asphalt rubber is by far the most beneficial method of reuse to society in terms of energy savings, when compared to alternate daily cover (ADC) and tire derived fuel. The authors compared these three end uses and indicated potential energy savings gained by using granulated tire rubber as a modifier to asphalt pavement. The speaker cited the potential for

$200,000,000 in annual cost savings should the entire network (11,000 lane miles) be rehabilitated with AR. The author states that this savings is equivalent to the entire Caltrans yearly Maintenance budget.

Taiwan's Experience on Asphalt Rubber Pavement
Authors: C. Chiu, C. Pan

This paper presents experiences in Taiwan using Arizona DOT (ADOT) gap-graded and open-graded AR mixes for flexible pavement rehabilitation. The climate for this area was high temperatures, no freeze, and significant summer rain, leading to concerns about moisture damage. The AR-GG mix had as-built air-void content of around 4 percent, which is much lower than that of conventional mix in the control section due to differences in compaction controls. The mix contained 1 percent portland cement as mineral filler. Overall material cost was 30 percent higher than conventional asphalt concrete. After 42 to 46 months, the AR mixes are performing well with insignificant pop-off for AR-GG and some oil spotting (bleeding) for AR-OG. Future plans for use of AR will be based upon political decisions.

2.1.4 Rehabilitation and Noise Reduction

***Asphalt Rubber Chip Seal Evaluation in California (scheduled but not presented)**
Authors: L. Rouen, B. Toepfer

This paper first presented findings from a review of five AR chip seal projects that had exhibited bleeding, primarily in the number two truck lane, then discussed field validation of these findings. It was concluded that the following factors may have caused the bleeding: high truck volume, high binder spread rate in wheelpaths of truck lanes, aggregate embedment into the underlying pavement, and highway geometry, notably tight curves and steep grades, which lead to vehicle acceleration and deceleration. The use of extender oil was also found to increase bleeding in hot areas.

Implementable Items

Recommendations taken directly from this paper for changes in AR chip seal practice include:

- Use more uniformly graded aggregate,
- Use PG70-10 asphalt in high temperatures,
- Reduce or eliminate the use of extender oil,
- Establish a maximum ADT for chip seal applications,
- Specify that contractors use a variable rate spreader bar that can be adjusted to apply binder at a reduced rate in the wheelpath areas.

* Asphalt-Rubber Gap Graded Mix Design Concepts
Authors: J. Sousa, G.B. Way, A. Zareh

This paper presented the concepts and evolution of gap-graded mix designs for AR in Arizona. Arizona went from Hveem designs in the 1960s to Marshall designs from the 1980s to the 2000s. The speaker cited the balancing act that mix design entails – balancing the two opposing forces of cracking and rutting along with mechanical damage such as raveling. Arizona had experimented with open-graded friction course (OGFC) mixes in the 1950s and 1960s. Inconsistent performance of these mixes and their design being an "art form" led to the idea of using a new mix type. It was found that OGFCs were prone to drain down at high temperatures as well as raveling.

AR does not drain down, but these mixes need good quality aggregate to avoid rutting potential. Consequently, gap-graded mixes were developed. These mixes contain higher binder contents (7%-8%) than conventional mixes and have high VMA (minimum 19%), but not consistently high stabilities. The authors are confident in the performance of this mix and it has been used throughout the State of Arizona to overlay their interstate system.

Implementable Items
- ARFC (open-graded) and ARAC (gap-graded) mixes have shown good success in Arizona. They are also used in California.
- California uses Type II binder in their mixes and the use of these gap-graded mixes is recommended.

Tire/Road Noise Relationship with Viscoelastic Properties of Asphalt Mixtures
Authors: K. Biligiri, A. Sotil, K. Kaloush, J. Golden

The objective of the study was to analyze the dynamic modulus test parameters for dense-graded conventional asphalt and asphalt rubber (AR) mixtures to assess if any of the parameters are indicative of the mix's tire/road noise characteristics. The paper examined dynamic modulus (E*), phase angle (ϕ), relationship between E* and ϕ, use of phase angle as a noise discriminator, relationship between E' (storage modulus) and E'' (loss modulus), and correlation of phase angle and highway noise sound intensity. It was found that the phase angle is potentially a noise discriminate factor between DGAC and open-graded/gap-graded asphalt rubber mixtures. The average peak phase angles for each mix type correlated well with the sound intensity measured for each mix/surface type.

* Asphalt-Rubber Open Graded Mix Reduces Tire Pavement Noise

Authors: A. Zareh, G. Way, K. Kaloush

The State of Arizona has developed a Quiet Pavement Program where conventional AC and PCC surfaces are overlaid by a 25 mm ARFC. The ARFC was found to reduce noise by 3 to 5 dB compared to DGAC, and by 6 to 12 dB compared to PCC pavement. It was decided to overlay around 11,000 lane-km of PCC pavement with 25 mm of ARFC to reduce noise. The authors feel this program has been very successful.

Implementable Items

- Mix corresponding to ADOT ARFC, RAC-O has been used as part of Caltrans Quieter Pavement Program.

Performance Evaluation of Asphalt Rubber and Its Use in Old Concrete Pavement Overlays

Authors: R. Cao, Z. Guo, Q. Bai (presented by J. Sousa)

In this paper, the wet-process production method for asphalt rubber is described. The use of 10 mm Asphalt Rubber Stress Absorbing Membrane Interlayers (AR-SAMI) layers were studied in laboratory fatigue and shear as well as in field conditions. Mix designs were produced with the SHRP (Superpave) Dynamic Shear Rheometer (DSR) and Bending Beam Rheometer (BBR) tests to select the AR binder. However, SuperPave binder tests may not be a good indicator for mix performance, as shown in the paper by Xicheng Qi. According to Superpave binder test results, CRM from truck tires is better than car tires, the #20 particle size is better than #40 and #60, and Pen 70 is better than Pen 90. Recommended levels of CRM are between 16% and 18%. From the field experience of 10 months, the asphalt rubber has outperformed conventional mixes when used as overlays on old concrete pavements. This strategy, used in Arizona, could potentially be used elsewhere after further validation.

* An Update on the Asphalt Rubber Pavement Preservation Strategies Used in California

Authors: S. Shatnawi, A. Stonex, R. G. Hicks

This paper focused on asphalt rubber chip seals, asphalt rubber hot mixes (both open-graded and gap-graded surface mixtures), and thin bonded overlay as preservation strategies. Specifically of interest were strategies utilizing wet process, Type II binder materials. The paper also emphasized specifications, mix design, material requirements, job selection criteria, and application parameters.

While the specifics of these techniques are beyond the scope of this document, a few highlights are discussed here. These changes are also being incorporated into the new Caltrans specifications. The materials and systems identified were asphalt rubber chip seals, composed of asphalt rubber binder with

0.55–0.65 g/sy binder and chips spread at 28–40 lb/sy. It is recommended these chips be precoated to minimize dust problems and enhance binder adhesion.

Asphalt rubber hot mixes with both RAC-O and RAC-G surfaces have shown good success in the state. Increased performance of Rubberized Asphalt Concrete – Open-graded (RAC-O) and Rubberized Asphalt Concrete – Open-graded – High Binder (RAC-O-HB) is due to the higher level of binder present in these mixes than in conventional RAC mixes. RAC-O has 20% more binder and RAC-O-HB has 65% more binder than conventional, leading to thicker films and added durability. Open-graded mixes can last 10 years, but the noise benefits may dissipate with time. There is the additional benefit of rumble factor effects in that the noise emitted from the pavements is lower in frequency if the higher frequencies are absorbed by the pavements. It is mentioned that sound walls can reflect noise to up to 1 mile away and that removing noise at the source is helpful.

Caltrans has seen good performance with RAC-G surfaces as evidenced by studies that looked at the performance history of over 200 RAC-G projects in California. These surfaces were constructed with 50 percent thickness reduction compared to conventional asphalt concrete. However, delamination was reported in a recent project constructed in nighttime hours.

Thin bonded overlays using AR materials have been used successfully in California. To construct these systems, a heavy polymer modified emulsion is used as a tack coat to foster adhesion of the polymer modified gap-graded or open-graded hot mix. In order to use RAC-G as the surfacing however, further development is required.

Implementable Items

- Changes to the wet process specification
- Potentially expanded use of RAC-O and RAC-G as surfacings
- Chip seal specification modifications

Items for Further Development

- Use of RAC-G in thin bonded overlays.
- Requirement for developing an asphalt rubber binder design profile that includes results of tests on samples obtained at designated intervals over a 24-hour period to establish specification compliance.

2.1.5 Mix Properties

Effect of Crumb Rubber on the Aging of Asphalt Binders
Authors: S. Lee, S. Amirkhanian, K. Shatanawi

The author used gel-permeation chromatography (GPC) to detect the molecular size distribution change of CRM binders and unmodified binders before and after aging. Based on the change in large molecular size (LMS), virgin binder and rubber modified binders were found to have very similar aging levels. In binders with rubber modification, the rubber absorbed the lower molecular weight maltenes leaving the residual asphalt binder containing a higher proportion of the heavier weight asphaltenes. This result requires more validation so the authors can generalize the results of this study to various rubber particle sizes and binder sources.

*** Laboratory Evaluation of Asphalt Rubber Modified Mixes**
Authors: M. C. Cook, T. Bressette, S. Holikatti, H. Zhou, R.G. Hicks

Rutting and fatigue performance of asphalt rubber modified mixes were evaluated using SST (AASHTO T320), flexural beam bending fatigue (AASHTO T321), and Hamburg Wheel Track Test (AASHTO T324).

Mixes used include:

- Rubberized Asphalt Concrete – Gap-graded (RAC-G),
- Rubber Modified Asphalt Concrete – Gap-graded (RUMAC-GG),
- Modified Binder – Gap-graded (MB-G),
- Modified Binder – Dense-graded (MB-D), and
- Conventional Dense-graded Asphalt Concrete (DGAC).

It was found that all asphalt rubber modified mixes except for the MB-G and MB-D mixes in the Hamburg Wheel Track Device performed at least equally well as if not better than the conventional DGAC mix.

Implementable Item

- Asphalt rubber modified mixes, including RAC-G, RUMAC-GG, MG-G, and MB-D should continue to be used in applications that are most cost-effective.

Effect of Compaction Temperature on Rubberized Asphalt Mixes

Authors: S. Lee, S. Amirkhanian, K. Shatanawi

It was found in this laboratory experiment that gyratory compaction temperatures used (116°C, 135°C, 154°C, and 173°C) significantly affected the volumetric properties of the rubberized mixtures, but not those of conventional mixtures with virgin and SBS-modified binders. It is recommended to conduct another study with higher rubber percentages (greater than 15%) and various crumb rubber sizes to evaluate the mechanical properties of rubberized mixes and correlate the volumetric properties of the mixes at different compaction temperatures. As shown by other authors in this conference, an adequate and sustained temperature level is imperative for proper compaction.

Mix Design Procedure for Crumb Rubber Modified Hot Mix Asphalt Concrete

Authors: V. Swami, V. Tandon

The paper dealt with evaluating and modifying the existing Tex-232-F procedure and determining its suitability for performance testing of CRM-HMAC. The paper also identified problems and provided solutions to the current procedure (Tex-232-F) and identified the influence of compaction devices. Currently, the state specifies Static Creep Test and Hamburg Wheel Tracking Device to evaluate such mixtures. Differences in compaction procedures, laboratory- versus plant-prepared mixes, and plant- versus plant-produced mixes have shown varying performance. It was found that in comparing specimens produced from the SGC and TGC, that the TGC did show signs of influence on specimen performance based upon increased compaction temperature. Specifically, different mixes may not meet the acceptance criterion for static creep testing; however, these mixes may meet the requirements specified by the TxDot specification with the Hamburg Wheel Tracking Device. The authors recommend further research in this area.

Predictive Equations to Evaluate Thermal Fracture of Asphalt Rubber Mixtures

Authors: A. Zborowski, K. Kaloush

The existing thermal cracking model in AASHTO Mechanistic Empirical Pavement Design Guide (MEPDG) using tensile strength was found to underestimate the crack resistance of AR mixtures in Arizona. While the AR has lower tensile strength it possesses a much greater ductility than conventional. This added ductility offsets the lower tensile strength and results in better long-term thermal cracking performance in the field. It was recommended to use total fracture energy and initial creep compliance in addition to tensile strength and the slope of the creep compliance to predict thermal cracking. The IDT was modified so that the additional parameters can be measured. Subsequent research will focus on developing a new thermal cracking model.

Performance of Wet Process Method Alternatives: Terminal or Continuous Blend
Authors: L. Fontes, P. Periera, J. Pais, G. Triches

Binders in wet process (called "continuous blend" in this paper) had 21% CRM, while binders in terminal blend had 15% or 20% CRM. In contrast to mixtures produced in wet process, it was found that asphalt-rubber mixtures produced with terminal blend process presented better rutting performance but worse fatigue performance. More study of terminal blends is recommended.

Mechanical Properties of Hot Mixture Asphalts with Crumb Rubber and Other Modifiers
Authors: G. Martinez, B. Caicedo, D. Gonzalez, L. Celis

The paper reports laboratory performance of asphalt rubber mixtures using Colombian asphalt binder. Compared to polymer modified binder (PMB) mixture, AR mixtures showed the same performance in fatigue and rutting, but with less moisture susceptibility. One exception was that AR mixture produced with dry process was less resistant to fatigue than the mixture made with unmodified binder. These findings are not consistent with the other papers in the conference.

2.1.6 Binder Properties

Influence of Crumb Rubber Gradation on Asphalt-Rubber Properties
Authors: S. A. Dantas Neto, M. Farias, J. Pais, P. A. A. Pereira

Crumb rubber gradation can have a tremendous influence on the performance of asphalt rubber mixture performance. In this paper, the authors studied this issue and found that by using smaller particles with higher specific surface, increases in rotational viscosity, softening point, and resilience of the samples were noted. These smaller particles allowed for greater contact area between the rubber particles and the lighter fraction of the binders, leading to greater absorption. Larger particles may also lead to problems in the field likely due to compaction difficulties. While not cited in the paper, the author discussed the use of rubber from truck tires, which contains more natural rubber and interacts better with the asphalt binder.

Optimizing the Use of Crumb Rubber by Binary Modification
Authors: H. Ajideh, B. Burris, H. Bahia

The proprietary method of modification described by the authors has shown increases in performance life of crumb rubber modified binders. This very specific oxidation technique adjusts the molecular structure of the asphalt, allowing a reduction in the amount of rubber required to achieve high performance properties. The authors have found that binary modification of the asphalt under repeated cyclic loading with the DSR does not change the short-term aging properties but it does increase the binder fatigue life significantly. Also noted was the decreased permanent strain at 100 cycles for binary modified mixes versus mixes with no additives. The speaker noted that a 76-22 binary mix "feels like" a 58-x mix. This technique allows for the use of 2-5% rubber in the binder.

There were concerns from some conference participants about the techniques and data presented in this paper. The fact that such very low concentrations of rubber apparently produced such significant performance gains was questioned. While this technique shows potential, the authors do not yet have supporting field data. Further research into this technique is recommended.

Laboratory Investigation of Dimensional Changes of Crumb Rubber Reacting with Asphalt Binder

Authors: F. Xiao, B.J. Putman, S. Amirkhanian

This paper presents the study on permanent physical dimensional changes of CRM particles after blending with asphalt binder. It was found that blending led to decreases in both size and mass of CRM particles, and liberation of short fibers and filler materials included in the rubber compounds. This is attributed to the breakdown, or depolymerization of the rubber particles in hot asphalt binder.

Crumb Rubber Modification of Binders: Interaction and Particle Effects

Authors: B.J. Putman, S. N. Amirkhanian

The authors explain how crumb rubber modifiers interact with the asphalt binders through a two-fold process: rubber particle swelling and the removal of light fractions of binder. Tests were performed using a modified rotational viscometer (with larger plate spacing) and shear rheometer to establish these interaction effects. With increased rubber contents regardless of size, viscosity increased. For a given rubber content, smaller sized rubber particles showed higher viscosities than larger particles.

The authors referred to the binders being "drained" of their crumb rubber content (crumb rubber was extracted from binder) and compared them with unmodified binders. It is reported that the crumb rubber particles absorb some of the lighter fractions of the binders due to the particle-binder interaction. This is evidenced by increased viscosity of drained versus unmodified binders. The authors called this phenomenon the "interaction effect" (IE). It was realized that the IE alone could not account for the increased viscosity of modified binders, but a "particle effect" (PE) was occurring as well. The PE represented the filler nature of the crumb rubber particles, so the higher the crumb rubber content, the higher the PE was found to be.

Creep Flow Behavior of Asphalt Rubber Binder: The Zero-Shear Viscosity Analysis (ZSV)

Authors: F. Guiliani, F. Merusi, I. Antunes

This paper pointed out the different creep behaviors demonstrated by binders modified with various amounts of CRM. The test was able to distinguish between traditional binders and rubber modified binders through a difference in the ZSV numeric value. However, measuring ZSV for binders with 20 percent of CRM required some approximation because they show non-Newtonian creep flow. This is a promising technique and can potentially be used to optimize the percentage of CRM in binders.

Role of Polyphosphoric Acid in the Transition from Asphalt Rubber to Terminal Blend of Rubberized Asphalt

Authors: I. Antunes, F. Guiliani

The authors start this paper by noting the ease of production of terminal blend binders compared to asphalt rubber binders. They focus their work on whether it is possible to make terminal blend binders that show performance comparable to asphalt rubber binders. The terminal blend binders possess a smaller fraction of rubber (10%) plus extender oil and perhaps additives such as SBS. The authors found, for a given rubber content, adding Polyphosphoric Acid (PPA) resulted in higher viscosity, resilience, and softening point but lower penetration values. The authors found that the inclusion of PPA in terminal blends, while providing a significant improvement in performance over conventional asphalt concrete, it did not measure up to that of asphalt rubber. While the addition of the PPA modifier shows promise, the authors caution about the potential hazards and constraints of working with this material.

Aging Studies of Asphalt-Rubber Binder (scheduled but not presented)

Authors: C. Lima, L. Tome, C. Filho, S. Soares, J. Soares

The authors use a DSR and a Fourier Transform Infrared (FTIR) spectrometer to study the aging of unmodified and rubber-modified binder, considering the effect of extender oil. It was found that CRM acted as an anti-oxidant in the aging process, perhaps due to the carbon black added to the rubber. The extender oil seemed to reduce aging by reacting with the asphalt rubber binder. DSR results showed that AR binders have better fatigue performance than unmodified binder.

2.2 Application Track (Practical Sessions) Overview

The Application Track at the Asphalt Rubber Conference contained several presentations on the practical aspects of asphalt rubber systems. The UCPRC staff attended these sessions as well as the tour that included stops at Granite's mining and crushing operations, hot mix facilities, and asphalt rubber project sites. No written documentation from the practical program was available to UCPRC staff to review following the conference.

Some of the presentations in the Application Track were promotional in nature, but most offered useful information on the experiences of contractors and agencies involved in the construction and performance of asphalt rubber systems. Helpful information on scrap tire processing as well as RAC grants and grant applications was also presented. In the opinion of the UCPRC staff, the most significant contributions were the presentations by:

- Anne Stonex of MACTEC on "Asphalt Rubber Binder and Mix Design and Testing"
- Jordan Main of Granite Construction on "Emission Studies"
- Terrie Bressette of Caltrans on "Caltrans Asphalt Rubber Design Guide"
- Jack Van Kirk of Basic Resources on "Long Term Performance"
- Bruce Rymer of Caltrans on "Noise Reduction"
- K. Brian Rickey of Sully-Miller Contracting Co. on "Recyclability"

It is recommended that the reader view these presentations on the AR2006 DVD, released by the RPA in February 2007, for complete details. Brief summaries of these selected presentations are given below. Specific implementable items are marked with an asterisk *.

Asphalt Rubber Binder, Mix Design and Testing
Anne Stonex, MACTEC

This presentation focused primarily on general information and best practices for using CRM modified materials. Selected items of importance based upon her experience include:

- * In field conditions it is essential not to directly substitute a no-agitation binder for a high viscosity binder in RAC due their different viscosities and behavior. The general appearance difference, described as "tapioca" versus smooth should be readily recognized by inspectors and field personnel. Proper training of these individuals should be conducted.
- Caltrans is updating Section 39 to include RAC-G with high viscosity asphalt rubber binders to facilitate information retrieval.

- * Do not use a modified asphalt cement as a base for CRM mixtures.
- With submittals it is important to gather as much information as possible, particularly if there are field discrepancies.
- * It is recommended that RAC grant applicants obtain the Binder Design Profile which ensures that the binder has been tested for 24 hour stability. This is very important should there be unforeseen field delays.
- With the binder profile, it is important not to design near the limits because it is as likely as not to be outside these limits when produced.
- * Viscosity is the "go – no go" test in the field.
- * Resilience is a very good way of determining how well the material will perform, particularly in regard to fatigue and reflection cracking concerns.

Emission Studies

Jordan Main, Granite Construction

Concerns over emission air quality from RAC projects prompted a recent small sample study in Caltrans District 1. Relevant findings in their comparison of rubber modified mixes with conventional mixes are:

- Overall there is no significant difference between the emissions from RAC projects and conventional projects.
- Many contaminants and parameters were evaluated including particulate matter, PAH, VOC, NO_x, CO, O_2, CO_2, stack flow rates, and moisture contents.
- In general, for the four mixes tested (DGAC, RAC-G, Type D MB, and RUMAC), all had much lower emissions than required by AP-42 (standard emission factors).
- Specifically, however, benzene, which is highly toxic, showed an emission level for wet process materials twice that recommended in AP-42 and roughly 1.5 times that of the conventional process. A couple of explanations for this high level include that a diesel fueled plant wasn't fully combusting in the dryer and that the wet process mix was the only one to use asphalt extender oil with high volatile content. However, the presenter stated that the commenters from the local air districts were not concerned with the levels measured.
- When comparing odor production from the four materials, it was found that the odor was "not significantly stronger than conventional asphalt production" and was most prevalent near loaded haul trucks and load out areas.
- Results may be viewed in the Lake County Air Quality Management District (LCAQMD) Summary Report dated 10/11/06.

Rubber in Reclaimed Asphalt Pavement

K. Brian Rickey, Sully-Miller Contracting Co.

The presenter discussed the use of recycled rubber materials in future rehabilitation and construction projects. He did not present specific data, but stated that:

- Nine states have or are undertaking studies into the use of rubber asphalt materials as RAP. The presenter said there are limited reproducible opportunities for data analysis because of the differences in rubber percentages, gradations, and applications.
- Due to the limited data available, conclusions are also limited, but he stated that the general direction of using rubber pavements as RAP, based upon the pilot projects to date is positive, however further research is necessary. The industry is not ready to develop specifications based upon the current data.
- Caltrans is updating Section 39 to include the use of up to 15% RAP for HMA. This is expected to go into effect in 2007. However, the presenter mentions it is premature to assume that this same amount will be specified for rubber mixes.
- The presenter referred to a Caltrans pilot project report as saying that “hot plant recycling is an excellent candidate for development and implementation, but laboratory and field evaluation are necessary to promote success”.

Caltrans Asphalt Rubber Design Guide

Terrie Bressette, Caltrans

The presentation discussed the updated “Caltrans Asphalt Rubber Design Guide,” which the presenter sees as a tool to convey information, to serve as a marketing device, and as a means of spreading knowledge of the subject. Ultimately, the purpose of the guide is to improve the success rate of asphalt rubber projects. A few key points that were made in this presentation include:

- In projects where a high level of quality control was provided, Caltrans has successfully placed these materials in the most extreme climates in the state from Death Valley to Mono Lake to Donner Summit. As Caltrans has compelled districts to use AR and as contractors have become more familiar with these materials the quality of the projects has increased. In general however, these mixes don’t work well in cold or wet weather or for long hauls because temperature control is crucial, and they don’t tolerate considerable handwork.
- * When there are failures with these projects, these failures can also be attributed to strategy selection errors and not necessarily material issues. Personnel should be trained in the proper use and application of these materials.

- * There are definite tradeoffs between added cost and enhanced performance/longer service lives for the AR pavements that can help engineers in selecting appropriate pavement strategies. Unit costs for AR overlay are about 1.5 times the cost of conventional AC for overlays and about 3 times the cost for chip seals. However the additional costs are countered by added durability and increased service life. There is substantial evidence that these materials perform well when applied correctly.

Long Term Performance of Asphalt Rubber

Jack Van Kirk, Basic Resources

The presenter strongly believes in asphalt rubber and shows tremendous confidence in the success and long-term performance of the product. He noted that while many people feel this is a "new" product, it has been around since the 1960s in varying capacities, with gap-graded usage starting in the early 1990s. A few key points to consider from his talk:

- * The presenter believes that crumb rubber binders can be used in dense graded mixes. Much of the success shown in the early projects, particularly the I-80 study in the 1980s has been with dense graded mixes.
- * The multi-layer strategies have shown promise. Two layer systems (45 mm RAC-G over AR Chip Seal) and three layer systems (45 mm RAC-G over AR Chip Seal over 25 mm leveling course) have been successfully constructed and have performed well as evidenced by examples cited of pavements performing well for over 15 years. Traffic loading on these pavements was not discussed.
- From a performance standpoint, the presenter discussed how cracked rubber pavements in winter will heal with hot temperatures and the kneading of vehicle traffic.
- Additionally, maintenance on these asphalt rubber sections was minimal to none in comparison to adjacent pavement sections. He states that this lower maintenance cost results in increased safety to the agency and users.
- * Due to reduction in layer thicknesses and use of SAMIs and other thin layers, there is a savings in energy and natural resources when using these products.

Noise Reduction Studies

Bruce Rymer, Caltrans

The presenter discussed the effects of pavement material type on pavement noise and how noise can be reduced by deliberately selecting and designing surfacing materials. These quiet pavements have shown considerable noise reduction benefits that can last up to 7 to 10 years. Wayside (side of the road at 50 ft away) and onboard sound intensity (OBSI, next to tire) measurements were used in the research.

Automobile road noise measurements have been well researched and documented while truck road noise requires further work. Key points from his presentation include:

- * Noise reductions of up to 6dB were noted when using RAC-O when compared to DGAC.
- * Pavement acoustics may be considered as a design parameter when designing mixes.
- * It was found that transverse texture, regardless of whether it is in the pavement or the tire is a main cause of high pavement noise. Removing transverse texture on the pavement has a more marked effect (about 8dB) on noise than removing transverse texture from the tire (about 1dB).
- Additional research is essential to quantify the noise reduction due to quiet pavements under traffic from truck tires.
- * The use of quiet pavements to replace sound walls is a controversial issue because the FHWA does not recognize quiet pavements as a solution to reducing noise levels. The quiet pavement pilot project is showing solid evidence of a noise reduction method. However, it is imperative that if noise walls are to be replaced by quiet pavements maintenance plans be put in place to keep this noise reduction in perpetuity.

Granite Construction Plant Tour

The tour of facilities and project sites convinced UCPRC staff that material preparation and construction capabilities are available to build successful asphalt rubber systems. Contractors experienced in the construction of AR systems using approved QC/QA procedures should have little difficulty producing quality products. However, a mechanism such as test strip requirements should be in place to assure Caltrans and other agencies that quality work can be achieved by contractors with less experience working with asphalt rubber systems.

3.0 SUMMARY AND RECOMMENDATIONS

The AR2006 Conference highlighted a significant number of advances in the use of crumb rubber to modify asphalt binder and its subsequent use in asphalt mix applications. Overall, the conference provided information that could increase competence and build confidence in the use of asphalt rubber for a variety of pavement strategies. Additionally, some of the implementable items presented in the conference will aid in the implementation of AB338. A sampling of these items includes:

- Continue to use of Asphalt rubber modified mixes, including RAC-G, RUMAC-GG, MB-G in applications that are most cost-effective,
- Use RAC-O for quiet pavement applications,
- Develop modifications to the wet process and chip seal specifications to further enhance performance and promote usage of asphalt rubber materials, and
- Use more RAC-O-HB strategies.

Approximately 34 papers were presented in this conference with another 14 or so papers published in the conference proceedings. It is evident from these papers that a significant amount of work went into the research presented and that the authors are fully committed to their findings.

Based upon the printed papers, speaker presentations, and conversations with authors and conference delegates, many recommendations may be made regarding the use of crumb rubber modification in asphalt concrete pavements. Recommendations based on the UCPRC review and subsequent discussions with authors are shown in Table 1, which shows that several topics look implementable (7), some warrant development (7), and a few papers (3) gave general information. The remaining (17) need further research.

Table 1: Summary Table of Selected Papers and Recommendations

Section Topic Paper Title and Author	Implementable	Need Further Development	Need Further Research	General Info.	Function ** (see end of table)
General Usage and Applications					
35 Years of Asphalt-Rubber Use in Arizona Authors: A. Zareh, G. B. Way				x	
The Urban Heat Island Effect and Impact of AR-ACFC Overlays on PCC Pavements Authors: M. Belshe, K. Kaloush, J. Golden			x		
Influence of Temperature Variation on the Reflective Cracking Behaviour of Asphalt Overlays Authors: M. Minhoto, J. Pais, P. Periera			x		
Asphalt Rubber in New Pavement Construction and Design Authors: J. Sousa, G. Way, S. Shatnawi, C. Dantas			x		
Evaluation of Tire Wear Emissions, Roughness and Friction Characteristics of Asphalt Rubber Friction Course Pavements Authors: O. Alexandrova, J. Allen, K. Kaloush			x		
Multi-Layer Pavement Strategies Utilizing Asphalt Rubber Binder (not in program) Author: J. Van Kirk	x				
Implementable Items • Use of this design strategy. This pavement strategy has been shown to perform well in lower volume, lower truck traffic roadways provided proper construction is ensured. Without adequate construction controls and monitoring, success is questionable.					1
Pavement Performance and Design					
Asphalt Rubber Mixtures in Portugal: Practical Application and Performance Authors: M. De Lurdes Antunes, F. Batista, P. Fonseca		x			
Performance of a Test Track Using Crumb Rubber Asphalt and Other Modifiers Authors: G. Martinez, B. Caicedo, D. Gonzalez, L. Celis			x		
Structural Design Considerations for Rubberized Asphalt Mixes Authors: T. Bressette, H. Zhou, S. B. Seeds, R. G. Hicks			x		
Laboratory Characterization and Full-Scale Accelerated Performance Testing of Crumb Rubber Asphalts and Other Modified Asphalt Systems Authors: X. Qi, A. Shenoy, G. Al-Khateeb, T. Arnold, N. Gibson, J. Youtcheff, T. Harman		x			
Recycling and Environmental Aspects					
Study and Application of Asphalt Rubber and Rubberized Pavement in China Authors: H. Wen-Yuan, C. Yung-Chieh, X. Li-Ting	x				
Implementable Items • Use of fine rubber powder in dry process with less than 1 percent by weight of total mix after					1, 2

Section Topic **Paper Title and Author**	**Implementable**	**Need Further Development**	**Need Further Research**	**General Info.**	**Function **** **(see end of table)**
validation with materials available in California. • Use of thin AR overlay and structural overlay on Rubber SAMI to minimize reflection cracking. • Use of precoated chips.					
Energy Consumption of Alternative Scrap Tire Uses J. Sousa, G. B., Way, D. Carlson				**x**	
Taiwan's Experience on Asphalt Rubber Pavement Authors: C. Chiu, C. Pan				**x**	
Rehabilitation and Noise Reduction					
Asphalt Rubber Chip Seal Evaluation in California (scheduled but not presented) Authors: L. Rouen, B. Toepfer	**x**				
Implementable Items Recommendations taken directly from this paper for changes in AR chip seal practice include: • more uniformly graded aggregate, • a PG70-10 asphalt in high temperatures, • reduce or eliminate the use of extender oil, • establish a maximum ADT for chip seal applications, and • specify that contractors use a variable rate spreader bar that can be adjusted to apply binder at a reduced rate in the wheel path areas.					**3**
Asphalt-Rubber Gap-graded Mix Design Concepts Authors: J. Sousa, G.B., Way, A. Zareh	**x**				
Implementable Items • ARFC (open-graded) and ARAC (gap-graded) mixes have shown good success in Arizona. California uses Type II binder in their mixes and the use of these gap-graded mixes is recommended.					**1**
Tire/Road Noise Relationship with Viscoelastic Properties of Asphalt Mixtures Authors: K. Biligiri, A. Sotil, K. Kaloush, J. Golden			**x**		
Asphalt-Rubber Open Graded Mix Reduces Tire Pavement Noise Authors: A. Zareh, G. Way, K. Kaloush	**x**				
Implementable Items • Mix corresponding to ARFC, RAC-O has been used for as part of Caltrans Quieter Pavement Program.					**1, 2**
Performance Evaluation of Asphalt Rubber and Its Use in Old Concrete Pavement Overlays Authors: R. Cao, Z. Guo, Q. Bai (presented by J. Sousa)			**x**		
An Update on the Asphalt Rubber Pavement Preservation Strategies Used in California Authors: S. Shatnawi, A. Stonex, R. G. Hicks	**x**				
Implementable Items • Changes to the wet process specification • Continued use of RAC-O and RAC-G as surfacings • Chip seal specification modifications **Items for further development** • Use of RAC-G in thin bonded overlays. • A requirement for developing an asphalt rubber binder design profile that includes results of tests					**1, 2, 3**

Section Topic Paper Title and Author	Implementable	Need Further Development	Need Further Research	General Info.	Function ** (see end of table)
on samples obtained at designated intervals over a 24 hour period to establish specification compliance.					
Effect of Crumb Rubber on the Aging of Asphalt Binders Authors: S. Lee, S. Amirkhanian, K. Shatanawi			x		
Mix Properties					
Laboratory Evaluation of Asphalt Rubber Modified Mixes Authors: M. C. Cook, T. Bressette, S. Holikatti, H. Zhou, R.G. Hicks	x				
Implementable Items • Asphalt rubber modified mixes, including RAC-G, RUMAC-GG, MG-G, and MB-D should continue to be used in applications that are most cost-effective.					**2, 3**
Effect of Compaction Temperature on Rubberized Asphalt Mixes Authors: S. Lee, S. Amirkhanian, K. Shatanawi			x		
Mix Design Procedure for Crumb Rubber Modified Hot Mix Asphalt Concrete Authors: V. Swami, V. Tandon		x			
Predictive Equations to Evaluate Thermal Fracture of Asphalt Rubber Mixtures Authors: A. Zborowski, K. Kaloush			x		
Performance of Wet Process Method Alternatives: Terminal or Continuous Blend Authors: L. Fontes, P. Periera, J. Pais, G. Triches		x			
Mechanical Properties of Hot Mixture Asphalts with Crumb rubber and other Modifiers Authors: G. Martinez, B. Caicedo, D. Gonzalez, L. Celis			x		
Binder Properties					
Influence of Crumb Rubber Gradation on Asphalt-Rubber Properties Authors: S. A. Dantas Neto, M. Farias, J. Pais, P. A. Pereira		x			
Optimizing the Use of Crumb Rubber by Binary Modification H. Ajideh, B. Burris, H. Bahia		x			
Laboratory Investigation of Dimensional Changes of Crumb Rubber Reacting with Asphalt Binder Authors: F. Ziao, B.J. Putman, S. Amirkhanian			x		
Crumb Rubber Modification of Binders: Interaction and Particle Effects Authors: B.J. Putman, S. N. Amirkhanian			x		
Creep Flow Behavior of Asphalt Rubber Binder. The Zero-Shear Viscosity Analysis Authors: F. Guiliani, F. Merusi, I. Antunes			x		
Role of Polyphosphoric Acid in the Transition from Asphalt Rubber to Terminal Blend of Rubberized Asphalt Authors: I. Antunes, F. Guiliani		x			

Section Topic **Paper Title and Author**	**Implementable**	**Need Further Development**	**Need Further Research**	**General Info.**	**Function **** (see end of table)
Rheological Behavior of Asphalt with Crumbed Rubber and other Modifiers Authors: G. Martinez, B. Caicedo, L. Celis, D. Gonzalez			**x**		
Aging Studies of Asphalt-Rubber Binder (scheduled but not presented) Authors: C. Lima, L. Tome, C. Filho, S. Soares, J. Soares			**x**		

**** Function:**

1) Helps advocate potential increase in use of Asphalt Rubber as directed in AB338.
2) Builds confidence in using Asphalt Rubber.
3) Increases technical competence in using Asphalt Rubber.

3.1 Additional Suggestions and Recommendations from AR2006

The comments below are additional research and development applications that were put forth by various presenters at AR2006 either during presentations or in the papers. Since this summary focused primarily on implementable items, it was felt that a brief summary of some of the areas that need further research would be helpful. Note that much of this research is being conducted by universities and other state agencies.

<u>Applications, Design, and Testing</u>

- Caltrans and ADOT could help promote asphalt rubber OGFCs as many states have had bad experiences with these materials.
- There is a need to develop new design methodologies and laboratory tests for AR since material performance is not well-characterized by traditional models (such as fatigue models) or in tests (such as the Marshall test). This research is needed in applications ranging from new construction to maintenance and rehabilitation.
- Others have reported satisfactory performance on projects with AR SAMI interlayers. Additional controlled full-scale studies (HVS testing) could be performed to enhance design and construction details.

Materials Evaluation

- Further study into CO_2 emission studies. The previous studies have shown that lower rates of CO_2 are emitted into the atmosphere from the use of AR.
- Further study into the insulating effects of overlays on and the potential increase in PCC lifetime gained. This is a complex issue.
- Further research into terminal blends should be explored due their relative ease of manufacture. Terminal blends are used but to a limited extent in California. The intent is to use them more in dense graded mixes in the future. The PG Task Force is working on specifications for terminal blend asphalts that will be very similar to those of PG polymer modified asphalts. The question is how they perform in comparison to polymer modified mixes. Caltrans plans a laboratory study, possibly with the Asphalt Institute, to measure fatigue and rut resistance of mixes using terminal blend and polymer modified binders. A similar laboratory study is being planned to evaluate PPA. Studies into these potential modifiers such as PPA and others could enhance performance.
- Continued research on new thermal cracking models for AR mixtures to help explain their performance relative to thermal cracking. A few specific items to address are:
    - Addressing the effect of binder content versus the effect of CRM modification. Specifically, how do different binder contents change the thermal behavior of mixtures with CRM modifications? This is essential to separate out the effects (and benefits) of increased binder content with CRM modified mixtures.
    - Study thermal fatigue under controlled stress testing (closer to field conditions) and with long term oven aged (LTOA) specimens, as thermal fatigue is more likely after several years of service
    - Look at thermal fatigue resistance with different base asphalt cements.
- Further study into environmental assessment of vehicle emissions of particulates from AR pavements, since particulates affect human health.
- Further study into fatigue and rutting models as they pertain to AR mixtures. There was enough debate at the conference to at least warrant looking into this. Testing for reflection cracking is the major need
- Moisture sensitivity research into AR performance that would include laboratory test development, which then would be calibrated to field performance.
- Peak phase angles have been well-correlated to sound intensity of each mix. Further study could perhaps lead to *a priori* knowledge of mix noise characteristics.

- Further research into the usage and effects of extender oil. The benefits, performance, and risks with using this material should be looked into.
- Application of binary modified binders with crumb rubber modifiers has shown promise. While this is proprietary, the long-term potential for this product may be significant.

Each of the categories specified in Table 2 reflects actions that should be carried forward for the benefit of the State of California. Based upon the core competencies of the principal groups that address research and training needs for the state, we suggest the following task delineation to best take advantage of each activity.

Table 2: Suggested Actions and Agents to Aid AR Implementation

Item	**Group**
Research	UCPRC, Chico State, PPTG, Consultants, national research programs such as NCHRP, State DOT pooled fund studies
Implementation to local governments	Chico State, PPTG
Technology transfer to industry	Chico State, PPTG, Industry Organizations
Disseminate knowledge internally within Caltrans	Caltrans, ITS Tech Transfer, CCIT, Consultants