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Performance Based Specifications: Literature Review on Increasing Crumb Rubber Usage by Adding Small Amounts of Crumb Rubber Modifier in Hot Mix Asphalt

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Performance Based Specifications: Literature Review on Increasing Crumb Rubber Usage by Adding Small Amounts of Crumb Rubber Modifier in Hot Mix Asphalt

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Partnered Pavement Research Center (PPRC) Project 4.61 (DRISI Task 3024):
Increasing Crumb Rubber Usage by Using Small Amounts of CRM in HMA

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16. ABSTRACT

A comprehensive review of the literature covering more than 100 published journal articles, conference proceedings, and reports found that although considerable research has been undertaken to understand the advantages and disadvantages of using recycled tire rubber to modify asphalt binders, no published information on PG+X-type initiatives (i.e., focused more on using additional waste tires in asphalt mixes rather than on improving performance of the binder and mix) was found. A number of states have specifications that allow tire rubber as a substitution for styrene-butadiene-styrene (SBS) modification (e.g., California [PG-M], Florida [PG-ARB], and Louisiana [PG-CRM]). The quantities of rubber added and the properties of the rubber particles used are similar to one of the four approaches discussed in this Technical Memorandum: PG+X Approach-1. No published research on adding very small quantities (i.e., less than 0.5 percent by total weight of the mix) in a dry process was located.

Preliminary indications from this literature review and from early laboratory testing as part of the study include the following:

- The properties of binders modified according to Approach-1, Approach-2, and Approach-4 properties are likely to be influenced by both rubber particle content and rubber particle size. The properties of mixes prepared using Approach-3 are also likely to be influenced by these parameters.
- It is unlikely that the PG grading of the PG+X binders prepared according to Approach-1, Approach-2 and Approach-4 will be the same as the base binder. A one grade bump can be expected if five percent rubber by weight of the binder is added and two grade bumps are possible if ten percent rubber is added.
- In Approach-2 and Approach-3, the use of smaller rubber particles (i.e., less than 1.0 mm) will probably have less effect on the binder and mix properties than the use of larger particles (i.e., up to 2.36 mm).
- Although the objective of the PG+X initiative is to use more recycled tire rubber in asphalt pavements, some benefits in terms of improved rutting, cracking, and moisture resistance performance are still likely despite the small quantities of rubber used.

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PROJECT OBJECTIVES

The objective of this project is to provide the information needed for Caltrans to decide whether and how to move forward with each of four approaches for adding small amounts of crumb rubber modifier to all hot mix asphalt, and the technologies required to follow these approaches. This goal will be achieved through completion of the following tasks:

1. Identification of various types of materials that may fall within each of the four categories.
2. Review of available literature regarding past or present technologies identified, including specifications, reports, and any other information (written or oral) that can be gathered.
3. Identification of any issues regarding specification testing.
4. Testing and analysis of example materials to determine their capability of meeting Superpave PG specifications, comparison with currently specified materials in terms of expected performance, and if a material cannot meet all specifications, information regarding the likely effect on performance. This will include asphalt binder and mix testing.
5. Evaluation of effects of mix properties on pavement performance in different thicknesses of overlays and new/reconstructed asphalt pavements using *CalME* for different levels of traffic and different climate regions.
6. A life cycle cost analysis (LCCA) that includes identification of cost and performance data, and analysis of net present value, with sensitivity analysis, for materials within each category (not funded in this phase of the study).
7. A life cycle analysis (LCA) that includes development of environmental flow data, calculation of impacts, and interpretation and reporting of the results (not funded in this phase of the study).
8. Assistance with development of test methods, methods of determining rubber content, specification language, and guidelines (not funded in this phase of the study).
9. Reporting of all results.

This technical memorandum provides an update on work completed to date on Tasks 1 and 2.

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1. INTRODUCTION

1.1 Background

California is faced with the challenge of annually diverting more than 40 million of the state's scrap tires from disposal. The California Department of Resources, Recycling, and Recovery (CalRecycle) is responsible for finding new uses of waste tires. In 2010, CalRecycle estimated that of the approximately 41.1 million reusable waste tires generated in California, 33 million of them (81 percent) were diverted through various alternatives that included reuse, retreading, and combustion.

In 2005, the Legislature passed and the Governor signed AB 338, which requires the California Department of Transportation (Caltrans) to make use of a specific weight of crumb rubber per metric ton of the total amount of asphalt paving materials it uses each year. Specifically, as of 2013 Caltrans is required to use, on an annual average, 11.58 lb (5.2 kg) of crumb rubber per metric ton of the total amount of asphalt paving materials Caltrans placed in the course of construction and repair of the state highway system.

In 2006, the Federal Highway Administration (FHWA) Recycled Materials Policy was established. This policy states that recycled materials should get first consideration in materials selection, and that the determination of what recycled materials are used should include an initial review of engineering and environmental suitability and a subsequent assessment of economic benefit, and that any restrictions prohibiting the use of recycled materials without a technical basis should be removed from the specifications.

Caltrans mission statement includes the goals of sustainability and stewardship, as a means to preserve and enhance California's resources and assets. As part of this mission, Caltrans has proposed reducing landfill disposal of scrap tires by requiring that all asphalt concrete contain a relatively small amount of crumb rubber modifier (CRM). A "relatively small amount" of CRM has been defined as between five and ten percent by weight of the asphalt binder with the resulting modified binder termed "PG+X", where "X" is the amount of CRM added and "PG+X" implies that the PG grading of the base binder should not change after the addition of the CRM. The proposal also considers an alternative dry process addition of between 0.25 and 0.5 percent CRM by weight of the aggregate. This proposed increase in the CRM is driven primarily by environmental considerations and not for enhanced performance, as has been the historical approach. However, Caltrans will continue to use CRM to modify the asphalt binders used in gap- and open-graded mixes to improve performance and durability.

1.2 Proposed Approaches for Adding Small Amounts of CRM

Caltrans has identified the following four approaches (these four approaches are in a different order than what was shown in the original Caltrans Project Scoping document) for using small amounts of CRM in dense-graded asphalt concrete (i.e., Type A hot mix asphalt [HMA]) while still meeting current Caltrans Section 39 specifications:

Approach-1: Wet Process with No Agitation, Complete Digestion
Caltrans PG+X for unmodified binders and meeting all current PG specifications, with addition of the CRM not resulting in a change to the PG grading of the base binder. It is anticipated that binders that already meet the current Caltrans PG-M specification would fall into this category.

Approach-2: Wet Process with Agitation, Incomplete Digestion
Caltrans PG+X for asphalt rubber binders and meeting anticipated PG specifications for asphalt rubber binders with changes to some components of the specification (e.g., solubility). Addition of the rubber should not result in a change to the PG grading of the base binder. It is anticipated that binders prepared using the same approach currently followed to prepare the asphalt rubber binders used in gap- and open-graded mixes (i.e., rubber particles smaller than 2.36 mm [passing the #8 sieve]) and in chip seals (i.e., rubber particles smaller than 1.4 mm [passing the #14 sieve]), but with lower CRM contents, will fall into this category.

Approach-3: Dry Process
Addition of between 0.25 and 0.5 percent CRM per ton of asphalt concrete mix (~ 5 to 10 lb/ton [2.3 to 4.5 kg/ton]) using a dry process. Mixes containing this rubber must still meet all Caltrans specifications. The PG grading of the binder should not be affected if this approach is followed.

Approach-4: Wet Process with Agitation, Complete Digestion
Same as Approach-2, but using other recycled tire rubber formulations typically with a finer rubber particle size, such as devulcanized tire rubber, which can be field-blended to achieve a binder containing between five and ten percent CRM (by weight of the binder) that still meets PG specifications, with potentially some relaxation for solubility. Addition of the CRM should not result in a change to the PG grading of the base binder.

1.3 Problem Statements

At this time there is no comprehensive list of all materials, past and current, that may fall into each of the four approaches listed in Section 1.2. Prior to the preparation of this technical memorandum, the literature had not been reviewed to gather information regarding properties, performance, variability, and any potential issues with specific reference to the four approaches.

There are no performance-related laboratory test results or field performance data for the binders or mixes for the four approaches and the materials that may fall under each of them. Caltrans does not have field construction experience with these specific approaches, but it does have extensive experience with using CRM in gap- and open-graded mixes and in PG M mixes.

1.4 Study Objective/Goal

Caltrans has requested that the UCPRC evaluate the technical feasibility, life cycle cost analysis (LCCA), and life cycle assessment (LCA) environmental impacts of each of these approaches. Caltrans has also requested the assistance of UCPRC with the development of test methods, specification language and guidelines, if applicable. The goal of the project is to provide the information needed for Caltrans to decide whether and how to move forward with each of the four approaches and the technologies required to follow them. This goal will be achieved through completion of the following tasks:

1. Identification of various types of materials that may fall within each of the four approaches.
2. Review of the available literature regarding past or present technologies identified, including specifications, reports, and any other information (written or oral) that can be gathered.
3. Identification of any issues regarding specification testing.
4. Testing and analysis of example materials to determine whether they are capable of meeting Superpave PG specifications, comparison with currently specified materials in terms of expected performance, and if a material cannot meet all specifications, information regarding the likely effect on performance. This will include asphalt binder and mix testing. It should be noted that the primary focus of laboratory testing will be on accommodating additional CRM in binder/mixes and not on improving performance of the binder and mix, in line with the terms of reference provided to the UCPRC.
5. *CalME* evaluation of the effects of mix properties on performance of new/reconstructed asphalt pavements and existing pavements with overlays of different thicknesses. Different levels of traffic and different climate regions will be considered.
6. An LCCA that includes identification of cost and performance data, and analysis of net present value, with sensitivity analysis, for materials within each category (not funded in this phase of the study).
7. An LCA that includes development of environmental flow data, calculation of impacts, and interpretation and reporting of the results (not funded in this phase of the study).
8. Assistance with development of test methods, methods of determining rubber content, specification language, and guidelines (not funded in this phase of the study).
9. Reporting of all results.

Approach-1, Approach-3 and Approach-4 will be investigated in all tasks. Approach-2 will initially be investigated through the end of Task 2. Thereafter, any further testing on Approach-2 will only continue once a PG-type specification for asphalt rubber binders has been agreed to by the Caltrans Rock Products Committee.

This technical memorandum provides an update on work completed to date on Tasks 1 and 2.

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2. TASK 1: IDENTIFY PROCESSES AND MATERIALS

2.1 Materials for Approach-1

Based on the California Asphalt Rubber Usage Guideline *(1)*, a PG+X rubberized binder for Approach-1 would be produced using a “wet process with no agitation” method. In this process, hot asphalt binder and CRM (typically passing the #60 [250 μm] or finer sieve) would be blended in the refinery or at an asphalt binder terminal. No subsequent agitation with a special auger or paddles would be required to disperse the rubber particles in the binder phase because rubber particles are usually digested (i.e., broken and melted in) or dispersed uniformly by circulation of the binder within the storage tank. This approach will likely require that the CRM particles be smaller than 250 μm and fully digested in the binder to be able to pass the solubility test at the 99 percent minimum. Approach-1 materials would be subject to meeting both performance grade binder and dense-grade mix testing specifications.

PG grading tests can be performed on this type of binder following the specified procedure in the AASHTO or ASTM standards for conventional asphalt binder without any modification of testing equipment, methods, or grading criteria.

2.2 Materials for Approach-2

According to the California Asphalt Rubber Usage Guideline, Approach-2 PG+X binders would be categorized as “wet process, field-blended binder with agitation”. This binder would be produced following the same methods used to produce the asphalt rubber binders that are currently used in gap- and open-graded rubberized asphalt concrete mixes and in rubberized chip seals. The apparent main difference from current asphalt rubber binder specifications would be that the CRM content is between 5 and 10 percent by weight of the binder, instead of between 18 and 22 percent. Approach-2 materials would be subject to meeting both performance grade binder (with the possible relaxation of solubility requirements) and dense-grade mix testing specifications. Any proposed PG binder-type grading specifications would need to factor in the presence of larger rubber particles and higher mix production temperatures, which will require adjustments to dynamic shear rheometer (DSR), rolling thin film oven (RTFO), and bending beam rheometer (BBR) testing procedures.

PG grading tests and procedures are currently being developed at the UCPRC for testing asphalt rubber binders with particle sizes up to 2.36 mm in size (i.e., passing the #8 sieve).

2.3 Materials for Approach-3

Based on the California Asphalt Binder Usage Guideline, crumb rubber used in this approach would act as a portion of the aggregate structure when used in the dry process. The rubber content in this standard dry process is normally between one and three percent by total weight of the mix; however, PG-X mixes would typically only contain between 0.25 and 0.5 percent by total weight of the mix. Consequently, the need to alter the gradation of the mix to accommodate the rubber particles, which have significantly lower densities than the granular aggregates, is unlikely. Different sizes of crumb rubber can be used. Given that the rubber is not being used to modify the binder, Approach-3 materials would be subject to meeting dense-grade mix testing specifications only.

2.4 Materials for Approach-4

According to the California Asphalt Rubber Usage Guideline, Approach-4 PG+X binders would also be categorized as "wet process, field-blended binder with agitation". However, these binders would differ from Approach-2 binders in that finer gradation rubber particles would be used to reduce reaction time and to provide a more homogenous binder. Devulcanized and other commercially available recycled tire products will also be investigated as Approach-4 materials. Approach-4 materials would be subject to meeting both performance grade binder and dense-grade mix testing specifications, but with some relaxation for certain attributes (e.g., solubility in binder tests).

3. TASK 2: LITERATURE AND KNOWLEDGE REVIEW

3.1 Introduction

This literature review is based on a search of available reports, journals, specifications, and other written documentation identified through search engines and information databases, and in the paper documents available in the UCPRC library.

Although there is considerable published information on the modification of asphalt binders and mixes using recycled tire rubber, the literature review found very limited information specifically relevant to the goals of the PG+X initiative (i.e. adding small amounts of CRM to asphalt binder). Key issues that may be relevant in terms of identifying testing procedures and interpreting test results are summarized below.

3.2 States Permitting the Use of Recycled Tire Rubber in Binder Modification

Published information documenting research on the use of recycled tire rubber in asphalt binder and mixes was sourced from numerous states including Arkansas, Arizona, California, Florida, Georgia, Kansas, Louisiana, Massachusetts, Michigan, Mississippi, New Jersey, Texas, and Wisconsin. The experience of transportation departments in Florida and Louisiana that are applicable to Approach-1 and potentially applicable to Approach-4 PG+X binders are summarized below:

- The Florida Department of Transportation (DOT) started using rubber modified binders in the late 1990s. Up to 5 percent crumb rubber modifier (CRM) passing the 300 µm (#50) sieve is permitted in dense-graded mixes, and up to 12 percent CRM passing the 600 µm (#30) sieve was permitted in open-graded mixes. Long-term monitoring of pavement sections showed that these mixes produced with tire rubber-modified binders exhibited a better friction index, better rutting resistance, and better durability *(2)*. Florida's new PG 76-22 Asphalt Rubber Binder (ARB) Specification requires a minimum of 7 percent CRM by weight of binder and must meet all AASHTO M 320 criteria except solubility, which has been removed as a requirement. Accelerated wheel load and laboratory testing results *(3)* indicated that PG 76-22 (ARB) dense-graded mixes provide similar rutting and cracking resistance to PG 76-22 styrene-butadiene-styrene (SBS) modified mixes.
- Louisiana DOT adds about 9 percent terminal-blended CRM into unmodified PG 64-22 binders to produce PG 76-22 CRM binders. Laboratory and accelerated wheel load test results *(4)* indicated that the CRM binder provides comparable performance to PG 76-22 PM (SBS) modified binders in terms of AASHTO M 320 criteria. Louisiana does not have a solubility requirement for tire rubber-modified binders.

3.3 Factors Effecting Binder Rheology Specific to PG+X Binders

3.3.1 Effect of Rubber Grinding Method

All states using recycled tire rubber as an asphalt modifier appear to require ambient-ground tire rubber.

3.3.2 Effect of Rubber Content on Binder Properties

Considerable published research has been conducted on this topic, however, only the literature focusing on rubber contents below 10 percent by weight of the binder was reviewed *(5-14)*. All of these studies noted clear changes in binder rheology after the addition of as little as three percent rubber by weight of the binder, with the degree of change increasing with increasing rubber content. Key rheological properties affected include higher viscosity, increased stiffness, reduced phase angle, lower creep stiffness, increased penetration, and reduced storage stability when compared to the control base binder containing no rubber. The m-value property did not appear to be influenced by increasing the rubber content by up to 10 percent. Increasing rubber content also affected mix properties, with increased resistance to rutting, fatigue cracking, and low-temperature cracking being recorded.

3.3.3 Effect of Rubber Particle Size on Binder Properties

The surface area of rubber particles increases with decreasing particle size. Consequently, smaller particles are likely to interact with the base binder more effectively than larger particles, leading to potentially shorter reaction times at lower blending temperatures and to improved stability (i.e., the period before separation of the rubber particles from the asphalt begins). Larger particle surface areas also facilitate absorption of the light oils in the base binder, which promotes digestion of the rubber. Several published studies have focused on evaluating the impact of rubber particle size on the properties of asphalt rubber binders *(15-21)*. Unfortunately there was little standardization of the sizes of rubber particles assessed (75 µm up to 2.36 mm [#200 up to #8 sieve]) with no clear distinction of the boundary between what was considered to be fine and coarse. However, the studies generally concluded that digestion times, phase angle, and fatigue cracking resistance decreased with decreasing particle size, while stability, viscosity, stiffness, and rutting resistance all increased with decreasing particle size. Low-temperature creep stiffness did not appear to be significantly influenced by rubber particle size. Binder contents in mixes also tended to decrease with decreasing rubber particle size used in the binder given that gaps in the aggregate gradation can be smaller.

3.4 Dry Process Rubberized Asphalt Mixes

Most published research on dry process rubberized asphalt mixes has focused on comparisons of performance between dry and wet processes, based on expectations of performance improvement rather than PG+X-type initiatives that use small amounts of CRM primarily as a means of using more waste tires.

Most studies used higher percentages of rubber than is expected in PG+X mixes (i.e., typically higher than an equivalent of 0.5 percent by weight of the mix). Key findings that were documented *(22-29)* in studies comparing dry and wet processes generally included the following:

- The dry rubber did not effectively react with the asphalt binder
- Dry process mixes had poorer compaction (i.e., higher air void contents)
- Dry process mixes had poor distribution of the rubber through the mix
- Dry process mixes exhibited poorer cohesion between the binder and the aggregate leading to increased moisture sensitivity
- Dry process mixes generally had poorer rutting and fatigue cracking resistance, and higher variability in performance parameters.
- The differences in performance between the two processes lessened in significance with decreasing rubber content and decreasing rubber particle size.
- Dry process mixes were considerably cheaper to produce than wet process mixes given the ease of adding it to the mix and the absence of a need for any significant plant modifications.

One study *(30)* investigated adding 0.5 percent rubber by total weight of the mix in a dry process to a mix produced with terminal blend rubber-modified binder with the objective of increasing total rubber content. The rubber particles used in the tests were smaller than 1.18 mm (i.e., passing the #16 sieve) and were treated with extender oils before being added to the mix. Tests were carried out to compare rutting and cracking performance of the mixes with and without addition of the dry process rubber. The results indicated that the rutting performance of the dry process mix diminished, but the fatigue cracking resistance improved.

3.5 Engineered Rubber Products

Engineered rubber projects include devulcanized tire rubber as well as a number of proprietary formulations made from waste tires that can be used to modify asphalt. Simplification of the blending process is usually the primary reason for their use *(31-33)*. A number of published studies have compared devulcanized rubber-modified binders with conventional asphalt rubber binders and with SBS-modified binders *(34-36)*. Findings from these studies indicate that devulcanized rubber-modified binders can be prepared at lower temperatures than conventional binders and that they generally have lower high-temperature viscosities. No differences in rutting and cracking performance or in moisture resistance were noted between the three binder types.

3.6 Binder Testing Issues

The UCPRC is currently working on the development of a Superpave-type performance grading testing procedure for asphalt rubber binders *(37)*. The standard AASHTO M 320 procedure is not considered appropriate given that the maximum rubber particle size permitted in the Caltrans specifications (i.e., 100 percent passing the #8 [2.36 mm] sieve) exceeds by a considerable margin the maximum recommended size for testing with a 25 mm parallel plate geometry in a DSR. The gap size should be a minimum of four times the size of the maximum particle size. A concentric cylinder geometry with a 6 mm gap is currently being investigated along with modified procedures for RTFO aging and BBR specimen preparation procedures.

A parallel study by a Caltrans task group is investigating using 25 mm parallel plate geometry with a 3 mm gap *(38)*. However, this study is primarily focused on asphalt rubber binders used in chip seals, where the maximum rubber particle size is limited to 1.0 mm (i.e., passing the #14 [1.4 mm] sieve) to prevent spray nozzle blockages.

3.7 Mix Testing Issues

No references to any significant potential issues with regard to testing mixes prepared using any of the proposed PG+X approaches were found during the literature review and none are anticipated. However, based on a general discussion in the literature, the following factors should be taken into consideration during any future mix testing:

- A hold time may still be required after compacting specimens (gyratory or rolling wheel) prepared with rubber-modified binders, given the tendency of the rubber in the specimens to expand while still hot. A similar hold time to that listed in the current Caltrans specifications is proposed as an interim measure.
- At least three replicates should be tested in any procedure given that the very small amounts of rubber being added may have little to no effect on some test results. Test results and comparisons of results of control and modified specimens need to be interpreted with care given that the variation in results may be within the precision and bias range of a given test (i.e., what appears to be a difference in performance between a control specimen and a specimen prepared with a rubber-modified binder may be attributable to the expected variability in test results for that test).
- Adding between 0.25 and 0.5 percent rubber by total weight of the mix to the mix ingredients prepared for compacting laboratory test specifications may not be representative of production-scale mixes. Between 18 and 37 g of rubber is added to the 7.0 kg of aggregate typically required to prepare gyratory-compacted specimens.

4. TASK 4: LABORATORY TESTING

4.1 Introduction

Answers to the following questions are being explored in this task:

- What processes and materials are expected to meet either the required specifications or the modified specifications, if they are changed in Project Task 3 (Identification of any issues regarding specification testing).
- What is the expected effect on binder performance (Approach-1 and Approach-4 initially, Approach-2 at a later date) and mix performance (Approach-1, Approach-3, and Approach-4 initially, Approach-2 at a later date) of the materials permitted in these specifications compared with currently unmodified materials specified by Caltrans?

It should be noted that the laboratory testing work plan was prepared based on initial discussions between Caltrans and the UCPRC that centered on the PG+X initiative being focused more on using additional waste tires in asphalt mixes rather than on improving performance of the binder and mix. It should also be noted that the budget and schedule of this project do not permit testing of all possible materials within each category.

4.2 Proposed Work Plan

4.2.1 Approach-1

The following binder tests are recommended to evaluate and characterize the properties of the PG+X wet process, no agitation binders. Tests will be performed on both the PG+X binders and their respective base binders.

1. PG grading. All PG grading tests will be performed and specification criteria checked.
2. Permanent deformation and damage properties of asphalt binder. Multiple stress creep and recovery (MSCR) and linear amplitude sweep (LAS) tests will be performed for comprehensive characterization of the binders for permanent deformation and fatigue damage, respectively.
3. Adhesive properties of the asphalt binder. The binder bond strength (BBS) test will be performed. Characterization of the adhesive properties of the binder is not included in the current PG grading system, but it is critical in terms of defining the contribution of the binder in assessing the overall moisture sensitivity of asphalt mixtures. Currently, there is a draft AASHTO standard procedure available for the BBS test. The test will be performed under both wet and dry conditions.
4. Chemical analysis of base binder and PG+X binders using Fourier Transform Infrared (FTIR) spectroscopy and other possible methods.

The experimental plan for the binder testing will include the factors and factorial levels listed in Table 4.1. The PG+X wet process, no agitation binders will be provided by binder suppliers, as-ready for testing.

Suppliers will also provide the base binder and all the ingredients used in the production of the PG+X binders.

Table 4.1: Approach-1 Binders: Testing Factors and Factorial Level

Factor	Factorial Levels	Details
Binder grade	2	PG 64-XX and PG 70-XX
Binder source	2	Two refineries, minimum one from California
Crumb rubber content	3	0, 5, and 10% by total weight of binder
Crumb rubber size	1	Passing 250 µm (#60)
Total number of binders: 12		

Asphalt mix testing is also recommended to gain a clear understanding of the effects of using PG+X wet process, no agitation rubberized binder compared to conventional unmodified binders. The following tests using a dense-graded asphalt mix are recommended:

- Mix design and mix volumetrics (based on the Superpave mix design approach) to meet Caltrans specifications
- Stiffness and permanent deformation characterization using dynamic modulus and repeated load triaxial tests
- Fatigue cracking characterization using flexural fatigue and semicircular beam (SCB) tests
- Low-temperature cracking characterization using the thermal stress and strain test (UTSST)

The experimental plan for mix testing will include the factors and factorial levels listed in Table 4.2. It is recommended that the beam fatigue and UTSST tests be performed at two or more different aging levels to evaluate the long-term aging performance of the binder in the mix. Mixes will be prepared in the UCPRC laboratory.

Table 4.2: Approach-1 Mixes: Factors and Factorial Level

Factor	Factorial Levels	Details
Binder grade	2	PG 64-XX and PG 70-XX
Binder source	1	California refinery
Crumb rubber content	3	0, and 5, and 10% by total weight of binder
Crumb rubber size	1	Passing 250 µm (#60)
Aggregate source and gradation	1	Crushed alluvial with dense gradation with 15% RAP
Aging conditions	2	For UTSST only
Total number of mixes: 6 (12 for UTSST)		

4.2.2 Approach-2

This approach will be covered in a later study once the PG-type grading system for asphalt rubber binder with particles up to 2.36 mm (passing the #8 sieve) is finalized.

4.2.3 Approach-3

The same tests listed for Approach-1 are recommended to evaluate and characterize the properties of dry process mixes, with the following additional considerations:

- The effects of rubber content and rubber particle size on the mix design and on performance should be evaluated. Both parameters are expected to have an influence on test results.
- Compaction of dry process mixes may still require a hold time while the specimens cool to prevent expansion after the load is released.

The experimental plan for this phase of the study will tentatively include the factors and factorial levels listed in Table 4.3. The mix production, construction issues, and performance of test sections should be evaluated in at least four pilot projects. The dry process loose mixes will be collected from the pilot projects for further testing in the UCPRC laboratory.

Table 4.3: Approach-3 Mixes: Factors and Factorial Level

Factor	Factorial Level	Details
Base binder	1	Project dependent
Crumb rubber content	2	0 and 0.5% by total weight of the mix
Crumb rubber size	2	Current gradations of crumb rubber used in production of asphalt rubber binders for gap- and open-graded mixes (<2.36 mm [#8]) and for chip seals (<1.4 mm [#14]) as specified by Caltrans
Aggregate source and gradation	1	Crushed alluvial with dense gradation with 15% RAP
Asphalt plant	2	Drum plant and batch plant
Total number of mixes: 8		

4.2.4 Approach-4

Approach-4 binders were initially planned to be prepared by a local supplier using a full-scale or scaled field production unit. Although small quantities of binder were produced for binder testing, pilot production runs indicated that producing this binder in the quantities required for mix testing was not feasible. A commercially available devulcanized rubber pellet product that would theoretically meet the Approach-4 requirements is therefore being tested instead.

The same binder and mix tests listed for Approach-1 are recommended for evaluating and characterizing the properties of the Approach-4 binders. The experimental plans for this phase of the study will likely include the factors and factorial levels listed in Table 4.4 and Table 4.5.

Table 4.4: Approach-4 Binders: Factors and Factorial Level

Factor	Factorial Level	Details
Binder grade and source	1	PG 64-22
Rubber modifier source	2	PG+X specific and proprietary supplier
Rubber modifier content	3	0, 5, and 10 percent by total weight of binder
Extender oil content	1	As specified by product supplier
Total number of binders: 6		

Table 4.5: Approach-4 Mixes: Factors and Factorial Level

Factor	Factorial Levels	Details
Binder grade and source	1	PG 64-22
Rubber modifier source	1	Proprietary supplier
Rubber modifier content	3	0, 5, and 10 percent by total weight of binder
Aggregate source and gradation	1	Crushed alluvial with dense gradation with 15% RAP
Aging conditions	2	For UTSST only
Total number of mixes: 3 (6 for UTSST)		

4.3 Testing Status

4.3.1 Approach-1

Material acquisition and testing completed to date for Approach-1 materials is as follows:

- The two binders were received from the suppliers.
- PG grading and MSCR tests have been completed, and LAS, BBR, BBS, and FTIR testing is in progress.
- Mix design and specimen preparation are complete for one binder source. Hamburg wheel track tests are complete. Rutting and cracking performance testing is in progress.

Findings to date indicate that adding small quantities of rubber to the binder will result in a high-temperature PG grade bump in most instances.

4.3.2 Approach-2

No testing has been undertaken on Approach-2 materials.

4.3.3 Approach-3

Although mix testing is planned to be carried out on plant-produced mixes only, given the very small quantities of rubber being added, preliminary mix testing was carried out to assess the feasibility of producing Approach-3 mixes in the laboratory. To date, one mix with one rubber content (0.5 percent by weight of total mix) with particle size less than 2.36 mm (passing the #8 sieve [i.e., typically used in binders prepared from gap- and open-graded binders]) was produced. The results indicate that higher binder contents may be required to meet air void targets (an increase of 1.5 percent in this test). The voids filled with mineral aggregate (VMA) and voids filled with asphalt (VFA) specification parameters were not met in this initial mix design, despite the higher binder content. The test is currently being repeated using rubber particles passing the 1.4 mm (#14) sieve (i.e., typically used in chip seal binders) to determine whether the mix design requirements can be met with smaller rubber particles.

4.3.4 Approach-4

Material acquisition and testing completed to date for Approach-4 materials is as follows:

- The two binders were received from the suppliers.
- PG grading and MSCR tests have been completed on the binder prepared by the local supplier, and LAS, BBR, BBS, and FTIR testing is in progress. Testing on the proprietary devulcanized product is in progress.
- No mix testing has been undertaken on the Approach-4 materials.

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5. CONCLUSIONS

A comprehensive review of the literature covering more than 100 published journal articles, conference proceedings, and reports found that although considerable research has been undertaken to understand the advantages and disadvantages of using recycled tire rubber to modify asphalt binders, no published information on PG+X-type initiatives (i.e., focused more on using additional waste tires in asphalt mixes rather than on improving performance of the binder and mix) was found. A number of states have specifications that allow tire rubber as a substitute for styrene-butadiene-styrene (SBS) modification (e.g., California [PG-M], Florida [PG-ARB], and Louisiana [PG-CRM]). The quantities of rubber added and the properties of the rubber particles used are similar to the PG+X Approach-1 discussed in this technical memorandum. No published research on adding very small quantities (i.e., less than 0.5 percent by total weight of the mix) in a dry process was located.

Preliminary indications from this literature review and from early laboratory test results include the following:

- The properties of binders modified according to Approach-1, Approach-2 and Approach-4 are likely to be influenced by both rubber particle content and rubber particle size. The properties of mixes prepared using Approach-3 are also likely to be influenced by these parameters.
- It is unlikely that the PG grading of the PG+X binders prepared according to Approach-1, Approach-2, and Approach-4 will be the same as the base binder. One grade bump can be expected if 5 percent rubber by weight of the binder is added and two grade bumps are possible if up to 10 percent rubber is added.
- In Approach-2 and Approach-3, the use of smaller rubber particles (i.e., less than 1.0 mm) will probably have less effect on binder and mix properties than larger particles (i.e., up to 2.36 mm).
- Although the objective of the PG+X initiative is to use more recycled tire rubber in asphalt pavements, some benefits in terms of improved rutting, cracking, and moisture resistance performance are still likely despite the small quantities of rubber used.

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