Ten Years of Full-Depth Reclamation with Foamed Asphalt in California – An Overview of the Research Investigation, Long-Term Performance, and Lessons Learned

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ABSTRACT: The first full-depth reclamation with foamed asphalt and cement (FDR-FA) project in California was constructed in 2001. The rapid nature of the construction with minimal impacts to traffic compared to conventional reconstruction, together with good early performance prompted the California Department of Transportation to initiate a comprehensive study on the topic, which was undertaken by the University of California Pavement Research Center (UCPRC). The objectives of the study were to determine whether FDR-FA was an appropriate rehabilitation option for highly cracked, thick asphalt pavements. Many rural routes in California have evolved from low-volume agricultural roads that were not designed for current traffic, and regular thin overlays over more than 50 years have resulted in pavements that are difficult to rehabilitate. In 2001, there was very little information available on the use of FDR-FA on thick pavements, with most research undertaken on thin pavements in South Africa. The UCPRC study included laboratory and long-term field studies and culminated in the writing of a series of reports documenting the research and a guideline aimed specifically at using FDR-FA to rehabilitate thick, badly cracked asphalt pavements. The guideline was used as a basis for the writing of specification language. FDR-FA is now considered standard practice in California.

1. Introduction

Full-depth reclamation/recycling (FDR), or deep in-situ recycling (DISR), of damaged asphalt concrete pavement with foamed asphalt and an active filler (FA) to provide a stabilized base for a new asphalt concrete wearing course is a pavement rehabilitation strategy of increasing interest worldwide. It offers a rapid rehabilitation process, with minimal disruption to traffic. Most importantly, it reuses aggregates in the pavement, thereby minimizing the environmental and social impacts associated with extraction and transport of new aggregates.

The California Department of Transportation (Caltrans) built its first project with this technology in 2001 in a 15 km pilot study on Route 20 in Colusa County. Caltrans also approved a University of California Pavement Research Center (UCPRC) study to investigate the use of the technology under California pavement, material, traffic, and environmental conditions, with a special focus on the rehabilitation of thick, severely cracked asphalt pavements.

Most Caltrans FDR-FA projects are undertaken on pavements with thick, cracked asphalt concrete layers, which distinguishes California practice from that of other states and countries investigating and using this technology. Pavement technology in South Africa and Australia, where much of the early research was undertaken, typically relies on good quality granular material or cement-treated base and subbase layers for the primary load-carrying capacity of the pavement, with the thin asphalt concrete (< 50 mm) or aggregate surface treatment layers (chip seals) providing little or no structural integrity. Consequently, in those countries the recycled material consists mostly of recycled natural aggregate and cracked cement-stabilized layers, which was accordingly reflected in their research, experience and guideline
documentation at the time the California study was initiated (1-4). Practice in Europe has been intermediate between that of California and South Africa, with the recycled material generally consisting of a mix of asphalt bound and natural aggregate materials.

2. Study Objective

The objective of the California study was to adapt, modify, and improve existing mix design, structural design, and construction guidelines for full-depth reclamation of cracked asphalt concrete with foamed asphalt and active fillers (FDR-FA) to suit California conditions. The study was to focus on thick, severely cracked asphalt pavements (i.e., the recycled material is predominantly old asphalt concrete). Additional constraints included a requirement that any construction work must be opened to traffic by nightfall, and the requirement that any laboratory testing as part of the mix design or construction quality assurance must be possible with available Caltrans District laboratory equipment, with the exception of the laboratory foaming apparatus. This objective was achieved through a comprehensive four-phase study, which included the following primary elements (5):

- Phase 1
  - Literature review, and technology and research scan.
  - Mechanistic sensitivity analysis.
- Phase 2
  - Assessment of Caltrans projects built to date based on field monitoring and previously collected data.
  - Assessment of planned Caltrans projects prior to construction.
  - Development of a laboratory testing experiment design matrix.
- Phase 3
  - Phased laboratory testing to identify specimen preparation and test methods, assess performance, and compile information for mix design, structural design, and construction guidelines.
- Phase 4
  - Preparation of project selection, mix design, structural design, and construction guidelines.

3. Literature Review

A literature review (6), undertaken in 2004, of current practice revealed that, although considerable research had been carried out on the use of full-depth reclamation with foamed asphalt on pavements consisting of relatively thick granular layers and thin surface treatments, very little research had been carried out on full-depth reclamation of thick asphalt pavements with foamed asphalt (multiple overlays over a relatively weak base or subgrade).

4. Mechanistic Sensitivity Analysis

A mechanistic sensitivity analysis was carried out to identify key variables in the design of recycled pavements consisting primarily of recycled thick asphalt pavement (6). The findings of the literature review and the sensitivity analysis were used to formulate a work plan for laboratory and field studies that would address the issues specific to recycling these thick asphalt pavements. The findings resulting from the sensitivity analysis can be summarized as follows:

- The presence of an aggregate or cement-treated subbase will have a significantly beneficial influence on the performance of an FDR-FA layer with an asphalt concrete
surfacing. Reduced life can be expected if the milling depth breaks through the existing aggregate or cement-treated base into the subgrade. Retaining a portion of the existing base layer should be considered when identifying candidate projects and preparing structural designs incorporating a foamed asphalt layer. On roads with no base, or thin existing aggregate base layers, consideration can be given to importing a layer of aggregate base material, spreading it on the surface to the desired thickness, and then incorporating it into the recycled layer in order to retain the existing base as a subbase in the new structure.

- Increasing the thickness of the recycled layer (i.e., increasing the recycling depth) will be beneficial, provided that adequate compaction can be achieved at the bottom of the layer.
- Foamed asphalt layer designs with lower binder and cement contents (i.e., similar behavior to granular materials) should only be considered for pavements with an underlying relatively stiff (e.g., cement-treated) subbase.
- Depending on certain structural and material characteristics, increasing foamed asphalt stiffness by adding an active filler (typically cement or lime) can either reduce or increase the fatigue life of structures. A sensitivity analysis is necessary to determine whether flexibility or stiffness is more desirable for a specific structure.

5. Assessment of Caltrans Projects Constructed Prior to 2006

A number of FDR-FA projects constructed prior to 2006 as well as a number of planned projects were visited to assess early performance and identify any problems that required additional investigation or research as part of the overall study. A summary of four of the project reviews is provided below. Visual assessments and Falling Weight Deflectometer (FWD) testing continued throughout the study in the spring and fall each year to gather longer term performance data.

- **State Route 20.** This road was rehabilitated using FDR-FA in 2001. The project is 15 km long and carries about 11,000 AADT. The mix design consisted of 2.5 percent foamed asphalt and 1.5 percent cement. The recycled base was surfaced with 45 mm hot-mix asphalt and a 20 mm open-graded friction course. This was the first FDR-FA project constructed in California. After five years of service, the project was performing well, although some fatigue cracking was observed on sections of the road adjacent to rice fields (Figure 1). FWD measurements in these areas indicated that the stiffness of the pavement structure fluctuated seasonally and corresponded with wetting and drying cycles. Observations from this experiment resulted in a phase of laboratory testing to assess moisture sensitivity of FDR-FA mixes and mechanisms contributing to moisture related damage.

![Figure 1: Fatigue cracking in outer wheel path associated with adjacent agriculture practice](image-url)
• **State Route 89.** This road was rehabilitated in 2002. The project is 16 km long and carries about 3,000 AADT. The mix design consisted of 2.5 percent foamed asphalt and 1.0 percent cement, and the road was surfaced with 45 mm hot-mix asphalt. This early FDR-FA project is located in the high Sierra Mountains and is subject to frequent freeze-thaw cycles. After four years of service, the project was performing well, although some longitudinal and alligator cracking was observed in the outer wheel path, attributed to water ingress from the unsealed shoulders (Figure 2). Some transverse cracks were also visible at regular intervals, attributed to low temperature related distress in the asphalt surfacing. One isolated area of fatigue cracking associated with a high water table/weak subgrade was also recorded. Observations from this experiment resulted in phases of laboratory testing to assess moisture sensitivity of FDR-FA mixes, minimum tensile strengths, effects of asphalt binder grade, and temperature sensitivity of FDR-FA bases.

![Figure 2: Fatigue cracking in outer wheel path associated with moisture ingress from shoulder](image)

• **State Route 33/1.** This road was rehabilitated in 2005. The project is 18 km long and carries 2,000 AADT (± 50 percent trucks). The mix design consisted of 3.0 percent foamed asphalt with no active filler. The recycled base was surfaced with 60 mm gap-graded rubberized hot-mix asphalt and a 25 mm rubberized open-graded friction course. This was the first FDR foamed asphalt project built without an active filler and the road was pre-pulverization before stabilizing. Severe distress in the form of alligator cracking and deformation was observed within 12 months after construction (2005) on a number of sections of the road (Figure 3). A forensic investigation attributed this distress to a combination of poor drainage (blocked culverts and filled-in side drains), weak subgrade, incomplete drying of the recycled layer (studies have shown that foamed asphalt-treated layers only gain strength when the compaction moisture has dried back sufficiently), and the absence of active filler, which may have also contributed to the poor initial strength. Areas of deformation continued to appear throughout the period of evaluation. FWD measurements indicated that these problems were all associated with weak subgrades and low base stiffness, and not with the surfacing. Observations from this experiment resulted in a phase of laboratory testing to understand the role of active filler and the effects of “curing” of the foamed asphalt.
Figure 3: Severe distress associated with mix design, weak subgrade, poor drainage and construction.

- **State Route 33/2.** The road was rehabilitated in 2006 and is a continuation of the State Route 33/1 project. The project is 15 km long and carries 1,000 AADT. The mix design consisted of 2.8 percent foamed asphalt and 2.0 percent cement kiln dust. The recycled base is surfaced with 45 mm hot-mix asphalt. This section was built 12 months after SR 33/1. Pre-pulverization was permitted, and an active filler was used. No distress was observed in the first 12 months, apart from some isolated cracking associated with slope instability. Construction was monitored and a number of concerns were noted with respect to the addition of water, quality control behind the recyclers, and the lack of attention given to drainage. Observations from this experiment resulted in a phase of laboratory testing to assess the mechanisms associated with the addition of mixing moisture and compaction moisture, and one to assess different active fillers. Observations of construction practices were used to relate laboratory tests to construction practices and ultimately in the preparation of construction guidelines and standard specifications for FDR-FA projects.

FWD measurements on all of the sections indicated that the asphalt concrete layer stiffness was influenced by temperature, with the values comparable between the different test subsections. Asphalt concrete stiffnesses on distressed and intact subsections on the same project were not significantly different. The moisture content in the pavement structure had a significant influence on the foamed asphalt layer stiffness, with differences as high as 40 percent between wet and dry seasons, which was of a higher relative magnitude than the seasonal variation of subgrade stiffness. The effects of temperature on foamed asphalt mix stiffness were quantified by field measurements. The average temperature sensitivity coefficient on the sections on State Route 33 was 0.016 MPa/°C. Observations from these field assessments and later investigations formed the basis for project selection guidelines (7,8).

6. Laboratory Testing

A comprehensive laboratory investigation was carried out in four phases in conjunction with continued field assessments (6). Although a comprehensive factorial design was prepared at the beginning of the study, it was clear that the number of tests required to complete the full factorial was impractical in terms of material requirements and laboratory resources. A phased approach was therefore adopted, which entailed a series of small experiments based on a series of partial factorial experimental designs. By following this approach, the research team was able to gain an understanding of key issues influencing the performance of foamed asphalt mixes, and use the findings to adjust the testing program and relevant factorial elements to make the best use of resources.
The testing was carried out on material sourced from two projects. This material consisted of predominantly recycled asphalt pavement (RAP) (± 90 percent) together with a small percentage (± 10 percent) of the natural aggregate from the underlying layer. The aggregates (RAP plus underlying layer) were of granitic origin and quartzitic origin for the two projects respectively, and although representative of a relatively large proportion of California, the results, specifically those pertaining to active and semi-active fillers, are not necessarily applicable for all materials found in the state. No recycling projects were undertaken on other representative aggregate types (e.g., basalt) during the UCPRC study and therefore tests with these materials could not be undertaken. The laboratory testing phases included:

- Phase 1 covered assessment of specimen preparation procedures, test methods, and the development and assessment of analysis techniques. These formed the basis for testing in the later phases of the study. Foamability characteristics of a range of California asphalts, and the temperature sensitivity of mixes were also assessed in this phase. A method to visually evaluate the fracture faces of tested specimens in a consistent way was developed in addition to these assessments.
- Phase 2 covered investigations into the effects of asphalt binder properties, RAP sources, RAP gradations, mixing moisture content, and mixing temperature on foamed asphalt mix properties. It also investigated different laboratory test methods for assessing the strength and stiffness characteristics of foamed asphalt mixes, and the development of an anisotropic model relating laboratory stiffness tests to field stress states. This work was performed on specimens without active or semi-active fillers so that the effects of the asphalt alone could be evaluated.
- Phase 3 extended the objectives of Phase 2 with more detailed investigations on variables related to RAP sources and asphalt binder characteristics.
- Phase 4 focused on the role and effects of active, semi-active, and inert fillers on foamed asphalt mix performance, as well as issues pertaining to curing.

The methodology, results and findings of the laboratory study are documented in various reports (6) and technical papers (9-17). Recommendations arising from the testing formed the basis for the mix design chapter of the California FDR-FA guideline document (7). Key lessons learned from the laboratory testing include, but are not limited to:

- The Indirect Tensile Strength (ITS) test is appropriate for mix design testing and performance studies, provided that sufficient replicates are tested, and that tests are repeated if there are significant differences between the replicate specimens of the same mix design and specimen preparation run. This issue was important for conducting mix designs in Caltrans laboratories that only had standard testing equipment.
- Fatigue beam testing using readily available specimen preparation procedures is not appropriate for testing foamed asphalt mixes, unless mixes with relatively high active filler contents are being assessed.
- All testing should be carried out on soaked specimens to obtain a valid indication of likely in-service conditions and to best understand the behavior of the foamed asphalt. Results from testing unsoaked and soaked specimens can be compared to obtain an indication of the moisture sensitivity of the material.
- The aggregate temperature during foam injection and mixing in the laboratory should be maintained in the range of 25°C to 30°C. Poor dispersion of the asphalt and consequent inconsistent results will be obtained at lower temperatures.
- Sufficient material should be retained from the original mix design to check changes associated with the actual binder used in the project if the foamability characteristics of the binder change significantly.
- Foamability should be checked at regular intervals during each day of foaming (e.g., after each tanker change).
• The minimum requirements for the expansion ratio and half-life are 10 times and 12 seconds, respectively.

• An acceptance range of the binder temperature and the foaman tum water-to-asphalt ratio should be determined in the mix design stage to serve as a guideline for construction, instead of defining one "optimum" combination of foaming parameters.

• Analysis of the fracture faces of ITS specimens after testing can provide valuable insights into mix characteristics, simply by visual assessment. These visual procedures should be used by practitioners as a check during mix designs, while quantitative comparisons using digital image processing techniques are more suited to research analyses.

• Fracture face analysis is suitable for comparing asphalt mastic distribution as a function of other mix parameters, such as asphalt type, asphalt content, mixing temperature, mixing moisture content, etc., for foamed asphalt mixes made from recycled aggregates with the same or similar gradations. It is not suited to comparisons of mixes with different parent aggregates, significantly different gradations, fracture faces of specimens prepared with different fabrication procedures or tested using different test procedures, or when portland cement or other active fillers have been included in the mix. Care should also be taken in interpreting the results if dark-colored minerals are present in the aggregates. An example of a fracture face analyses is provided in Figure 4.

(a) Satisfactory mix
(b) Problematic mix: high mixing water content
(c) Problematic mix: high mineral filler content
(d) Problematic mix: low mineral filler content

Figure 4: Typical fracture faces showing different symptoms.
The use of softer asphalt binder grades is encouraged, as these have better dispersion than harder binders for the same or similar foaming characteristics.

The resilient modulus of foamed asphalt mixes is highly dependent on the stress state, but the available laboratory test methods cannot fully simulate the complexity of field stress states.

The Free-Free Resonant Column test and indirect tensile resilient modulus test both yield stress states that are very different compared to those in an FDR-FA pavement. They appear to significantly overestimate the resilient modulus values of foamed asphalt mixes, and thus present problems for their use in pavement design.

In triaxial resilient modulus tests, foamed asphalt (without active filler) transforms the material behavior from that of typical unbound granular materials to that of asphalt-bound materials. Limited increases in the resilient modulus values, attributed to the foamed asphalt treatment, were observed. The magnitude of increase also appeared to be dependent on certain characteristics of the granular materials being treated.

The range of values of tangential Young's modulus for bending in flexural beam tests was similar to the resilient modulus determined from triaxial resilient modulus tests in the unsoaked state. However, the modulus reduction due to water conditioning for beam tests was between 85 and 95 percent, while that of triaxial tests was between 5 and 30 percent.

The triaxial resilient modulus and flexural beam tests each partially represent the stress state in a foamed asphalt-treated base layer under traffic loading. Results of these two test types therefore need to be combined to better understand foamed asphalt mix behaviour.

The mix design fines content (i.e., material finer than 0.075 mm) prior to the application of active filler should not exceed 12 percent as there is no observable improvement in strength or stiffness above this point, and additional binder may be necessary to counter the effects of seasonal moisture fluctuations.

The addition of mineral fines to materials with fines contents between 5 and 12 percent is not recommended unless the laboratory mix design testing (without active filler) indicates that the soaked strengths increase by doing so.

Given that fines content has a significant influence on performance, care should be taken when determining the expected fines content of the pulverized material during mix design. Typically, slabs are removed from test pits during site investigations and these are crushed in the laboratory to obtain an indication of the grading. Observations during the course of the UCPRC study revealed that the actual pulverization process produces higher fines contents than laboratory crushing, which could lead to incorrect mix designs (e.g., low asphalt content). Small cold milling machines should be considered for sampling for mix designs as this will provide more representative material.

Active fillers should be considered in all foamed asphalt FDR projects, as they complement the foamed asphalt by improving early strengths (i.e., supporting traffic within four hours of construction) and reducing the moisture sensitivity of the mineral filler phase. The foamed asphalt improves the ductility of materials treated with cementitious fillers.

Portland cement appears to offer the most advantages compared to the other active fillers tested (lime, cement kiln dust, and Class C flyash). However, insufficient testing was carried out on a range of materials to exclude other fillers, and these should be considered in the mix design until sufficient information has been collected on local materials. Hydrated lime may perform better on materials of basic crystalline origin (e.g. basalt).

Specimens cured for 24-hours (sealed at ambient temperature [20°C]) should be included in the mix design testing along with the 3-day or 7-day unsealed cured (at 40°C) specimens to select the most appropriate active filler, to determine the optimum
active filler content, and to assess the effectiveness of the active filler in developing early strength in the material. Active filler content should generally not be more than 50 percent of the asphalt binder content.

- FDR-FA layers should be allowed to dry back to at least 50 percent of the compaction moisture content before new aggregate layers or the wearing course is placed.
- Adequate drainage measures should be incorporated into the design and construction of recycled roadways.

7. Overview of California FDR-FA Mix Design Procedure
The California FDR-FA mix design procedure was developed from the findings and observations from the laboratory testing phases described above. The key features of the Caltrans mix design procedure include:

- All mix designs must use a foamed asphalt/active filler combination.
- Foamed asphalt and active fillers serve different purposes in the stabilization process, and their application rates are based on separate tests and different criteria.
- The stabilized layer is not a purely asphalt-stabilized or cementitious-stabilized layer (i.e. cement or lime), but rather a "hybrid" with unique properties.
- A single strength test method, namely the indirect tensile strength (ITS) test, is used.
- Two sets of ITS tests are carried out, each with its own curing procedure. One set represents conditions during earlier opening to traffic; the second set assesses longer-term performance considerations.
- Material evaluation is primarily focused on the strength of water-soaked specimens.
- The range of asphalt binder and active filler contents tested is narrower than that in other guidelines, but more emphasis is placed on assessing and controlling variation in mix properties induced by variability in the parent materials and inevitable inconsistencies in laboratory testing.
- Additional testing to refine/optimize the mix design is encouraged.

A typical mix design procedure for FDR-FA applications involves the following eight required tasks and one optional task, each one of which determines the value of one specific design variable from laboratory testing and analysis of the results.

1. Determine the grading of the pulverized material.
2. Select the active filler type(s).
3. Determine the compaction curve of the pulverized material.
4. Select the asphalt binder and determine the foaming parameters.
5. Determine the mixing moisture content (MMC).
6. Determine the asphalt binder content.
7. Determine the active filler content.
8. Determine the reference density for field compaction and minimum strength requirements for as-constructed quality assurance strength tests.
9. Determine the tensile strength retained and temperature sensitivity of the mix design (optional).

8. Long-Term Field Performance
Long-term field performance is being closely assessed on five projects, four on state routes and one on a county road. Construction procedures were closely scrutinized on two of the five projects. Monitoring includes bi-annual visual assessments and FWD testing. Additional projects are being visually assessed on an annual basis. The information gathered was used to prepare the California FDR-FA guideline (7), with specific emphasis on project selection.
and construction guidelines, as well as a chapter on FDR-FA in the Caltrans Standard Specifications. Performance on the five sections is summarized below:

- **State Route 20.** This road continued to perform well. After 10 years of trafficking, fatigue cracking remained limited to areas adjacent to rice fields. FWD measurements continued to show seasonal fluctuation corresponding with wetting and drying cycles.

- **State Route 89.** This section continued to perform well with only minor further deterioration of the earlier observed distresses. Crack sealing was undertaken on an annual basis and a 10 mm-thick pavement preservation micro-surfacing was placed in 2008, six years after construction.

- **State Route 33/1.** This section continued to deteriorate as a result of earlier drainage problems associated with the weak subgrade. Affected sections were patched with full depth asphalt. A number of the patches also showed evidence of distress in later visits. FWD measurements continued to show seasonal fluctuation corresponding with wetting and drying cycles.

- **State Route 33/2.** This section continued to perform well. Some longitudinal and transverse cracking was evident in certain sections (Figure 5). Although no forensic investigation was undertaken on this road, a review of construction records compiled by the author indicated that the distress was probably related to the addition of compaction water and primary compaction procedures that deviated from recommended practice. FWD measurements continued to show seasonal fluctuation corresponding with wetting and drying cycles.

- **County Route 99.** This section was constructed in 2009. The authors were present for the entire construction period and monitored all aspects of the process. FWD measurements were taken on a daily basis between completion of construction of the recycled base and placing of the 50 mm asphalt surfacing. Thereafter, FWD measurements were taken on a twice daily basis for 14 days and thereafter at weekly intervals until stiffness had stabilized (after approximately 25 days). After two years of performance, some isolated areas of distress were observed. These areas were associated with observations of poor dispersion of the foamed asphalt during early-start cold weather construction, and with areas where poor surface finish resulted in ravelling of the surface that was not repaired prior to placing of the hot-mix asphalt.

![Figure 5: Longitudinal crack associated with primary compaction practices.](image-url)
9. Conclusions

A comprehensive study on the full-depth reclamation of thick, severely cracked asphalt pavements using foamed asphalt and cement as a hybrid stabilizer has been completed for the California Department of Transportation by the University of California Pavement Research Center. The investigation included extensive laboratory testing and biannual monitoring of a number of pilot projects. The study culminated in the preparation of interim guidelines for project selection, mix design, structural design, and construction, with a specific emphasis on thick asphalt pavements, which are common in rural areas of California.

The study concluded that full-depth reclamation with foamed asphalt combined with a cementitious filler is an appropriate pavement rehabilitation option for California pavements. It is ideally suited to rehabilitating thick, severely cracked asphalt pavements, common in rural areas. However, all potential projects should be carefully assessed with special care given to subgrade variability, roadside activity, and roadside drainage. Appropriate mix and structural design procedures should be followed, and construction should be strictly controlled to ensure that optimal performance and life are obtained from the pavement. Premature failures will in most instances be attributed to poor project selection (e.g., weak subgrades and/or poor drainage) or to poor construction (e.g., poor asphalt dispersion, incorrect mixing moisture content, poor compaction, or poor surface finish).

Projects are generally limited to roads with an annual average daily traffic volume not exceeding 20,000 vehicles per day, provided that an appropriate structural design can be achieved. This limit is based on traffic control limitations and not pavement design limitations. The technology is particularly suited to pavements where multiple overlays have been placed over relatively weak base course layers, and where cracks reflect through the overlay in a relatively short time. Higher traffic volumes can be considered provided that strength and durability requirements meet or exceed the requirements for the pavement design and suitable traffic control measures can be implemented during construction. Alternatively, the recycled layer can be used as a subbase underneath a new base layer if a pavement structure with higher strength is required.

10. Acknowledgements

This paper describes research activities that were requested and sponsored by the California Department of Transportation (Caltrans), Division of Research and Innovation. Caltrans sponsorship, assistance and interest are gratefully acknowledged. The contents of this paper reflect the views of the authors and do not necessarily reflect the official views or policies of the State of California or the Federal Highway Administration. The UCPRC laboratory staff are also acknowledged.

11. References


