August 2006
Research Report: UCPRC-SR-2006-02

Caltrans Partnered Pavement Research Program (PPRC) Summary Report Four Year Period: 2000–2004

Authors:
J. T. Harvey, C. L. Monismith, W. A. Nokes, and N. F. Coetzee

This work was completed as part of Partnered Pavement Research Program Strategic Plan Item 2.3

PREPARED FOR:

California Department of Transportation
Department of Research and Innovation
Sacramento

PREPARED BY:
Pavement Research Center
Institute of Transportation Studies
University of California, Berkeley and
Department of Civil Engineering
University of California, Davis

DOCUMENT RETRIEVAL PAGE		**Report No: UCPRC-SR-2006-02**
Title: Caltrans Partnered Pavement Research Program (PPRC) Summary Report: Four Year Period: 2000–2004		
Authors: J. T. Harvey, C. L. Monismith, W. A. Nokes, and N. F. Coetzee		
Prepared for: Caltrans	**FHWA No.:** CA080295A	**Date:** August 2006
Strategic Plan Element No.: 2.3	**Status:** Final	**Version No:** Stage 6, approved version

Abstract: This report provides a summary of the results of the various studies completed in the Partnered Pavement Research Program (PPRC) during the period 2000–2004. In addition, preliminary findings of investigations, initiated but not yet implemented during this period, are included. The results are based on the combined results of analytical developments, laboratory testing of pavement materials, and HVS tests of full-scale pavement test sections.

Summaries of developments in the following areas are included:

1. *Asphalt Mixes — Materials and Flexible Pavement Studies.* These include studies of mix fatigue, moisture sensitivity, reflection cracking, performance of drained and undrained pavements, and those associated with I-710 freeway rehabilitation.

2. *Concrete — Materials and Rigid Pavement Studies.* These include: evaluation of long-life rehabilitation strategies, results of the SR-14 (Palmdale), HVS rigid pavement studies, dowel retrofit investigations on US-101 and the SR-14 test pavements, studies of the physical properties of fast-setting hydraulic cement concrete (FSHCC), alkali-silica reaction (ASR) accelerated pavement testing, evaluation of maturity method for concrete flexural strength, and *HIPERPAV* for early age cracking in plain jointed concrete pavements.

Also included are: construction-related activities including pay factors for asphalt mixes and use of *CA4PRS; M-E* pavement design and rehabilitation; a summary of databases containing the results of the various investigations; deep in-situ recycling (DISR); pavement management-related activities; permanent deformation response of asphalt mixes; and implementation and technology transfer activities during the 2000–2004 period.

Keywords: Heavy vehicle simulator (HVS) testing, fatigue and permanent deformation of asphalt mixes, reflection cracking, I-710 rehabilitation, fast-setting hydraulic cement concrete physical properties, dowel bar retrofit, M-E pavement design and rehabilitation, databases, pavement management, research implementation.

Proposals for Implementation: Implementation for each of the studies is included in Table 4.

Related documents: See Reference list.

Signatures:

C L. Monismith **2nd Author**	W. A. Nokes **Technical Review**	D. Spinner **Editor**	J. T. Harvey **Principal Investigator**	M. Samadian, **Caltrans Contract Manager**

DISCLAIMER

ACKNOWLEDGMENTS

Many people have been involved in this program during the four-year period and their significant contributions are gratefully acknowledged:

University of California, Berkeley:
A. Ali
M. Bejarano
E. Diaz
D. Eng
I.M. Guada
D. D. Hung
W. Ibbs
D. Kim
E.B. Lee
S. Madanat
A. Monteiro
C. Scheffy

University of California, Davis:
J.T. Harvey

Dynatest, Inc.:
D. Bush (deceased)
P. Millar
P. Ullidtz

Council for Scientific and Industrial Research (CSIR) Transportek, South Africa:
L. du Plessis
A. Heath
J. Lea
F. Long
J. Prozzi

Caltrans Division of Research and Innovation:
T. Hoover
M Samadian
M. Essex
J. Holland
J. Lee
K. Frick

Subcontractors:
J. Roesler (U. of Illinois)
W. Davids (U. of Maine)
L. Kazanovich (U. of Minnesota)
J.P. Mahoney, G. Turkiyah (U. of Washington)
R. Blab, (U. of Vienna)
V. Janoo (CRREL)
S. Weissman (Symplectic Engineering)
A. Mohseni (Consultant)

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

EXECUTIVE SUMMARY

This report provides a summary of the results of the various studies completed during the period of 2000–2004. In addition, preliminary findings of investigations initiated but not yet completed during this period are also included. These results are based on a program which has combined the results of analytical developments, laboratory testing of pavement materials, and the HVS testing of carefully planned, full-scale pavement test sections to provide information to Caltrans to assist its staff in moving forward toward the goal of improved pavement performance. The program has benefited not only from the partnering between the Pavement Research Center, Caltrans, Dynatest Consulting, and the CSIR, but also with many organizations listed in the *Acknowledgments.* The report includes a complete listing of the HVS tests completed as of June 2004; a tabulation of the Strategic Plan Elements according to which the program operates; and a summary of the results of a number of the studies shown in this summary as Table 1, briefly described in the following paragraphs. For convenience, Table 1 has been divided into three parts: 1a. Completed Projects (as of 2004); 1b.In-Progress Projects (as of 2004); and 1c.Completed Projects, Other Funding Sources.

Asphalt Mixes — Materials and Flexible Pavement Studies

Results of the Goal 3 laboratory fatigue studies on RAC-G and AR dense-graded mixes provide useful information for the mechanistic-empirical design procedure (SPE 4.1) under development. In the near term it also provides useful data to develop Gravel Equivalent Factor(s) for AR hot mixes for rehabilitation design alternatives using current methodology.

Results of the Goal 5 study suggest that improved structural pavement design and construction practices (e.g., improved AC compaction) reduce the necessity for the use of ATPB to drain water entering from the pavement surface.

If ATPB is used directly beneath the AC layer, improved mix design of the ATPB is required, e.g., increased binder content, use of a modified binder, and the use of an additive to improve mix moisture sensitivity resistance. Also, a properly designed geotextile (or soil filter) between the ATPB and AB should be incorporated in the pavement structure to preclude clogging of ATPB from the fines of the untreated aggregate base (AB). Systematic cleaning of edge and transverse drains adjacent to the ATPB is a necessity to prevent water being trapped in the ATPB.

Results of studies of the performance characteristics of AB emphasize the importance of improved compaction. It is recommended that AB be compacted to a relative compaction of 100 percent based in the Modified AASHTO Compaction Test (T 180) test. This test is recommended to replace the current CTM 216 procedure since the relationship between field and laboratory compaction test results, both water content and dry density, corresponds more closely to results of the AASHTO T-180 test.

The mix designs for the I-710 Freeway rehabilitation using the simple shear test were subjected to HVS tests prior to construction. Results of these tests indicate that the RSST-CH provides a "reasonable" mix design for the mix containing the PBA-6a* (modified) binder. At 50°C this mix was able to accommodate a significantly larger number of load repetitions (approx. 200,000 to a rut depth of about 8 mm) than a conventional DGAC with a stabilometer "S" value of 43 (approximately 20,000 to a rut depth of 12.5 mm).

A few months after completion of construction of the I-710 project, post-construction interviews were conducted by members of the Caltrans/Industry Long Life Pavement Rehabilitation (LLPR) Flexible Task Group. Results of the interviews stressed the importance of partnering between Caltrans and the Contractor on projects of this type. In addition, the other "lessons learned" resulting from the interviews provide a useful set of recommendations to expedite subsequent LLPR projects.

In the Goal 9 Project (SPE 4.10) to develop improved designs for reflection cracking, the MB Test Road pavement was constructed with a DGAC surface course about 75 mm (3 in.) thick. HVS testing on this pavement provided the cracked AC surface that served as the test sections for the investigation. Overlays were placed using mixes containing AR-4000 asphalt cement (DGAC), asphalt rubber (RAC-G), and three different modified binders containing rubber. By June 2004, rutting studies of the various overlay mixes were completed.

Results of the rutting study, as compared to the results of the earlier Goal 3 study, indicated that the various mixes containing the MB materials exhibited less resistance to rutting than the two Goal 3 overlay mixes. These results suggest that an improved mix design procedure will likely be required, e.g., like that used for the I-710 mixes.

The PCCAS-supported study was conducted to evaluate the influence of the binder parameter $G^* \sin \delta$ in the AASHTO PG binder specification (currently AASHTO M320-04) on pavement fatigue performance. Results showed that this parameter as well as the SSV and SSD parameters (used in the Caltrans PBA Specification) did not differentiate mix performance for the range of binders and asphalt pavement structures analyzed for representative regions in the area encompassed by PCCAS. Based on the results of the study, the recommendation was made to continue using the current specification requirement since there are no data to support its deletion. This finding likely contributed to the decision of Caltrans to adopt the PG binder specification to replace the AR binder specification, effective January 1, 2006.

The AC moisture damage investigation (SPE 4.9), though still in progress, has provided a few preliminary observations. For example, analysis of data from the field survey of projects phase suggests that high air-void contents in the mixes, permitting water retention, contributed significantly to moisture-related distress.

From the laboratory part of the test program, preliminary results of tests using the Hamburg Wheel Tracking Device (HWTD) indicate that the test procedure selected does not clearly distinguish between mixes with different degrees of moisture sensitivity.

Concrete — Materials and Rigid Pavement Studies

Results of the Palmdale (SR-14) test program provided an evaluation of concrete pavement sections constructed using fast-setting hydraulic cement concrete (FSHCC). This investigation provided information on the fatigue response of the FSHCC, and the influence of dowels, tied shoulders, and widened traffic lanes on pavement performance.

Prior to completion of the SR-14 study, HVS 2 was moved temporarily to Northern California to a site on US-101 in Ukiah. The purpose of this test program was to evaluate the efficacy of dowel bar retrofitting of joints (and cracks) in an existing PCC pavement that had been subjected to traffic ($>4.0 \times 10^6$ ESALs) over a period of about thirty-four years (1967–2001). The project included participation of staff from the Washington State DOT (WSDOT). In this case, the PPR Program utilized the expertise of WSDOT in this area to carry out the study. At the same time, it provided WSDOT with information on the expected longer-term loading performance of this method for concrete pavement rehabilitation (an example of the value of partnering).

In the concrete pavement design area, results of pavement analysis studies, together with the results of HVS tests (including those on US-101 at Ukiah and SR-14 at Palmdale) stress the importance of the use of dowels, non-erodible bases, and tied-shoulders or widened outside lanes for heavily trafficked, jointed concrete pavements. Results from the SR-14 site have also demonstrated the effectiveness of dowels in restricting curling movements along transverse joints from daily temperature changes associated with the high desert environments of Southern California. Tie bars produce similar benefits for longitudinal joints.

Performance data obtained from the SR-14 experiment suggest the following to increase the lives of pavements using FSHCC:

1. Shrinkage must be controlled (Caltrans SSP requirements $\leq$ 0.053 percent at seven days) and monitored during construction;
2. Control of curing is important;
3. It is necessary to minimize friction between concrete and base;
4. Flexible (e.g., AC) bases are preferred over rigid bases (e.g., LCB) to permit relaxation of environmental stresses;
5. Joint spacing should not exceed 4.6 m; and

6. It is necessary to take measures to prevent bonding of new slabs placed adjacent to existing slabs.

Analyses of the SR-14 sections have also demonstrated that built-in curl can lead to either bottom-up or top-down load-associated cracking. This curl contributes to load associated longitudinal and corner cracking (versus mid-slab bottom-up transverse cracking — the normal mode assumed for design purposes). While the proposed new design guide (AASHTO 200x) for rigid pavements considers the latter form of cracking, concrete pavement design in California must incorporate considerations of built-in curl to mitigate longitudinal and corner cracking as well.

From a concrete materials standpoint, higher flexural strength [4.5 Mpa (650 psi)] than currently used for design purposes [3.8 Mpa (550 psi)] by Caltrans is extremely desirable. Strengths at this level will reduce the propensity for both load-associated and environmentally induced cracking.

The performance of the dowel bar retrofitted pavement on US-101 as well as test sections on SR-14 have demonstrated the significant improvement in resistance to step faulting under traffic. Substantial increases in ESALs were obtained for these pavements as compared to similar pavement sections without dowels.

For concrete mixes the laboratory investigations have included:

1. Studies of the behavior of FSHCC, including strength, stiffness, fatigue, shrinkage, thermal expansion, and durability characteristics;
2. Evaluation of the program *HIPERPAV*; and
3. Evaluation of the concrete maturity concept.

The mix durability study included evaluation of sulfate resistance [already reported in Reference (1)] and aggregate silica reaction (ASR). The latter study included an evaluation of two tests for ASR, ASTM C 1260 (quick and inexpensive), and ASTM C 1293 (requires one year to complete). For the ASTM C 1293 test, an evaluation of the use of a locally available low-alkali cement with added hydroxide ions suggested that it might be used in lieu of a standard high-alkali cement (not available locally).

The following recommendations resulted from this study:

1. Continue to use ASTM C1260; if aggregate is found reactive, perform ASTM C 1293.
2. Continue the evaluation of the “modified” ASTM C 1293 with a wider range of aggregates; if the similar results are obtained with the additional aggregates, replace current C 1293 with the modified test.

Results of the fatigue test program indicate that the FSHCC exhibits about the same response as conventional PCC. Also, the SR-14 mix exhibited significantly higher free shrinkage relative than mixes containing Type II PCs. These results support the findings from the in-situ strain measurements. It should be emphasized, however, that the use of FSHCC does not necessarily result in higher shrinkage differentials since some of the FSHCCs can have lower shrinkage than Type II PCs. Thus, when using FSHCCs it is important to test the shrinkage characteristics not only initially, but also periodically during the construction process.

From the initial studies using the *HIPERPAV* software, it shows promise in providing guidance for making decisions to reduce the risk of early age cracking. *HIPERPAV*, however, is not a substitute for good construction practices, which include proper joint sawing and slab curing. Moreover, for California, the studies have indicated that the risk of early-age cracking is larger in the desert climate than in the coastal regions. Mix design is also important in that aggregate type selection should be carefully evaluated for each region, and higher strength concrete will definitely reduce the potential for shrinkage cracking.

The results of the Maturity study indicate the there is a reasonable correlation between the maturity indices (TTF and t_e) and flexural strengths measured in the laboratory for the range of mix types studied. At early ages the flexural strength predicted from laboratory curves were similar to measured flexural strengths on field beams for mixes containing Type II cements but were higher than field-measured strengths for mixes with Type III cements. The use of laboratory determined compressive strength versus maturity curves is not recommended to estimate flexural strength. A limited study also suggested that the maturity approach using flexural strengths is probably applicable to mixes with special cements and/or chemical admixtures. It is recommended, however, that field-testing of beams and cylinders should be continued to further validate the procedure.

Construction-Related Activities

An optimal solution for reconstruction of heavily trafficked freeways, particularly in urban corridors in California, has required combining developments in pavement engineering, construction productivity analysis, and traffic simulation. Used together they can provide a solution which balances traffic delay and construction schedule for the rehabilitation while considering different construction windows.

The *CA4PRS* (Construction Productivity Analysis for Pavement Rehabilitation Strategies) software was developed to meet constructability considerations while an existing program, *PARAMICS*, has been utilized to assess traffic impacts. CA4PRS has been designed to estimate the length of freeway that can be rehabilitated or reconstructed within a set of constraints. It considers “what-if” scenarios for major parameters and constraints such as:

- Construction windows: seven- and ten-hour nighttime closures; fifty-five hour weekend closures; continuous weekday closures; and other closed windows required for a specific project;
- Lane closure tactics: partial closures; full closures (counterflow traffic);
- Strategy type: concrete (portland cement concrete or fast-setting hydraulic cement concrete) slab replacement strategies; crack, seat, and asphalt overlay and full-depth asphalt concrete replacement strategies;
- Material constraints: mix design and curing time (concrete) and cooling time (asphalt). (The *CA4PRS* program incorporates the program *MultiCool* to determine cooling rates for HMA as a function of the environment and layer thickness.)
- Pavement structural section profile: thickness of concrete slab or asphalt concrete layers;
- Concrete pavement design: widened truck lanes, various base types (lean concrete base or asphalt concrete base);
- Resource constraints for the contractor: location, capacity, and available pavement equipment; and
- Scheduling constraints: mobilization, demobilization, and traffic control.

The proposed work plan, CPM schedules, resource availability, and traffic pattern of the construction equipment are the main inputs to the analysis. Resource availability and construction traffic patterns are treated as constants in a deterministic analysis module, and treated as random variables in a probabilistic (stochastic) analysis module, which considers variability of the inputs.

Integrating CA4PRS with the traffic simulation program to analyze potential construction and traffic scenarios permit development of quantitative estimates of the optimal (most cost-effective) construction management and traffic control plans. The software also evaluates different pavement structures and construction windows for construction duration. When combined with traffic delay simulation, pavement structures that maximize construction speed without creating unacceptable traffic delays are determined. Evaluation of the impact of various traffic-handling tactics on construction duration can define a procedure to minimize total traffic delay. These data are vital to achieve the three competing goals of longer-life pavement, faster construction, and less traffic delay during freeway reconstruction and rehabilitation projects.

During this four-year period the CA4PRS program has been used for the I-710 project in Long Beach, CA, where long-life asphalt pavements were used for rehabilitation in a series of fifty-five-hour weekend closures. The original time Caltrans estimated for completing the 4.4 km (26.3 lane-km) project required ten weekend closures. The contractor actually completed the project in eight closures; use of the CA4PRS program was instrumental in producing this time savings.

CA4PRS has also been used in the planning of the reconstruction of I-15 at Devore (near San Bernardino, CA). This highway has an average daily traffic of about 110,000, 9 percent of which is trucks, and a total length of 17 lane-kilometers (4.2 km × 2 lanes × 2 directions). The project includes two segments: the first consisting of four lanes and the second three lanes. The existing pavement is 200 mm (8 in.) of concrete with 100 mm (4 in.) of cement-treated base. The new pavement will consist of 290 mm (12 in.) of Type III high early strength concrete with 150 mm (6 in.) of asphalt concrete base.

Evaluation of the total cost (construction cost + traffic handling cost + total user delay cost) based on the construction productivity and traffic analyses were utilized. A number of alternatives were considered; based on the overall comparison and justification, Caltrans District 8 selected continuous closures during weekdays, with durations of seventy-two hours.

In both the I-710 and I-15 projects, the results of analyses, laboratory testing, and HVS test programs were utilized. For the I-710 project, the design of asphalt mixes and full-depth sections took advantage of mix and pavement design methodology developed during the Strategic Highway Research Program (SHRP) and calibrated with HVS tests.

For the I-15 project, the use of widened concrete truck lanes (validated on the SR-14 HVS tests) and asphalt concrete shoulders, rather than tied concrete shoulders, resulted in shorter construction times. In addition, the decision to use the HMA as the base was based on both construction time and environmental stress effects, the latter resulting from analyses of SR-14 test sections.

Currently, Caltrans makes use of pay factors for asphalt concrete construction on QC/QA projects. These factors have been established on the basis of experience. As noted in Reference (1) an investigation was initiated into the development performance of related pay factors. This latter approach utilizes performance equations developed for fatigue cracking from the PPR Program and for rutting from the WesTrack program. The performance equations, in turn, permit determination of performance-based pay factors for AC construction. For rutting, the performance equation includes the influence of asphalt content, air-void content, and aggregate gradation. The performance equations for fatigue include the influence of air-void content, asphalt content, and asphalt concrete thickness.

Costs are established considering only agency cost consequences of delaying or accelerating the time to the next rehabilitation. For the as-constructed mix, the relative performance (RP) — the ratio of off-target ESALs to target ESALs — is determined for both fatigue and rutting. The smallest combined RP of the two distress modes permits determination of the pay factor from the cost model.

To establish the feasibility for the use of this approach, pay factors determined by the methodology were compared with those used by Caltrans. Comparisons were established for approximately eighty projects constructed in the period January 1997 to June 2000. Only a limited number of these projects contained measured rutting and fatigue-cracking data that had been incorporated in the Caltrans Pavement Management System (PMS). Accordingly, a “shadowing” study is underway and awaits the results of additional detail performance data from the PMS.

This blending of the results from the HVS and WesTrack programs provides an example of the synergistic effects that can result from the PPR group being involved in other related projects.

Mechanistic-Empirical Performance Design and Rehabilitation

While mechanistic-empirical (or analytically based) pavement and rehabilitation analysis and design development have been utilized in specific situations, e.g., the I-710 and I-15 freeway rehabilitation projects, there has been a systematic ongoing effort to develop an improved pavement and rehabilitation design system for both flexible and rigid pavements for Caltrans. Elements of this framework are now in place and training of selected Caltrans staff in the use of the methodology is now underway.

The flexible pavement and rehabilitation design methodology has been programmed by Dr. Per Ullidtz and draws on the extensive knowledge that has been developed in this area over the years. The framework for new design includes both fatigue and rutting considerations utilizing the linear sum of cycle ratios concept and the cumulative damage concept reflecting both the effects of traffic loading and environment. It should be noted that for fatigue, the procedure is similar to that incorporated in the new design guide (AASHTO 200x) currently under evaluation. The methodology, however, reflects California conditions; e.g., AC mix characteristics developed in the PPR Program, Caltrans-measured traffic load spectra, and environmental conditions based on California weather station information. Moreover, the results of the HVS test program have played a significant role to ensure that the analysis procedure produces “reasonable” results.

Considerations of rutting in the AC layer differ from that in the new design guide. Estimates of rutting are based on methodology that had been developed during SHRP and refined using WesTrack test results and those obtained from rutting tests in HVS tests under controlled loading and temperature conditions.

The rigid pavement design procedure is patterned after the new design guide making use of traffic, environmental, and mix characteristics for California conditions. In addition, provision is made, depending on environment and potential slab curling, to analyze for both bottom-up and top-down cracking not only in the transverse direction at mid-slab (as in the new design guide), but also in the longitudinal direction and at slab corners. Provision is included for doweled transverse joints, tied concrete shoulders, widened lanes with asphalt shoulders, and various base types (e.g., asphalt concrete as well as lean concrete base). Results of the HVS tests at Palmdale and Ukiah have provided key data to aid in the development of design methodology.

As a part of the M-E program, a number of software programs have been developed or are under development. Table 10 of the report contains a summary of these programs and their expected usage in the M-E design and rehabilitation methodology.

Databases

From the outset of the project, it has been necessary to establish a database or databases to filter and store essential results of the laboratory and field investigations. Table 10 contains a summary of the current databases that are maintained. These include:

1. *Heavy Vehicle Simulator Database,* which contains the results of the completed tests listed in Table 2.
2. *Seasonal Monitoring Database* includes results for eight seasonal monitoring stations established through the PPR Program.
3. *Falling Weight Deflectometer (FWD) Database* includes FWD tests from HVS test sections and field sites.
4. *Laboratory Test Database* contains a summary of the various laboratory tests conducted on the material used in the HVS test program as well as other programs in which the PRC was involved, e.g., WesTrack Test Road and the Pacific Coast Conference on Asphalt Specifications asphalt concrete study.
5. *Weigh-in-Motion (WIM) Database* contains Caltrans ASCII WIM data for the period 1991–2003. This program will be transferred to the Caltrans Traffic Division in September 2004.

Deep In-Situ Recycling (DISR)

DISR activities include: (1) use of recycled AC as untreated aggregate base (AB) and (2) use of foamed asphalt to stabilize a mix consisting of recycled AC and unbound aggregate from the existing pavement.

Working with District 2, three projects using the recycled AC as AB are being evaluated. Initial results from the study on US 395 near Alturas suggests that this is a viable rehabilitation strategy resulting in cost savings and, from initial field measurements, may provide a longer pavement life than the conventional overlay strategy.

For DISR using foamed asphalt, PPR Program staff has been working with District 3 staff to evaluate this alternative. HVS tests were completed on a series of test sections on SR 89 near Truckee. The tests were constructed on a shoulder section; results of the tests indicated that the test sections were not representative of the traveled way. Analyses are underway, however, to evaluate the performance of these sections. Preliminary analyses suggest, for example, that the test sections exhibited seasonal variations that should be considered in any future performance evaluations of foamed asphalt DISR.

Other Technical Activities

The PRC Staff has worked with Caltrans Staff in the development of an enhanced pavement management system (PMS). This activity has included the identification variables required for databases for M-E pavement design and rehabilitation (SPE 4.1, 4.5) and QC/QA reports (SPE 3.1.5) which can be linked to the Caltrans PMS. A report on QC/QA data, for example, will permit validating or modifying the performance-based pay factors for asphalt concrete construction (SPE 3.1.5). Similarly, in order to assess the validity of the M-E system (SPE 4.5), monitoring of pavements designed according to new methodology is essential.

Development of effective mix and pavement design procedures depends on accurate predictions of the pavement system response to different loading conditions. This predictive capability depends on the availability of material models that accurately represent the behavior of the various materials. Thus a longer term study has focused on the formulation of an accurate constitutive law for rutting for asphalt concrete mixes at elevated temperatures. To this end a nonlinear constitutive law for the behavior of asphalt concrete mixes at elevated temperatures has been developed that is suitable for the modeling of both rut initiation as well as rut evolution phases. The model consists of a viscoelastic fluid acting in parallel with an elastoplastic solid and has been designed to account for key aspects of the observed behavior of asphalt concrete mixes. In the longer term this model will be useful to evaluate the rut resistance of mixes for use in heavy duty pavements.

Implementation and Technology Transfer

Implementation activities during this period have included:

1. Interactions with Caltrans and the pavement industry;
2. Working directly with Caltrans Staff on specific projects; and
3. Short courses and special seminars

Members of the PPR Staff have served as members of a number of joint task groups and committees including the following:

1. Moisture Sensitivity Asphalt Concrete Task Group
2. Long-Life Flexible Pavement Rehabilitation Task Group

Results of the developing research have been incorporated in short courses developed under the auspices of the Technology Transfer (T^2) Program of the Institute of Transportation Studies of UC Berkeley. Examples of the short courses include:

1. Asphalt Pavement Fundamentals: Design, Construction, and Rehabilitation (three days)
2. Asphalt Mix and Structural Pavement Design (three days)
3. Concrete Pavement Fundamentals (three days)
4. Compaction, Stabilization, and Drainage of Asphalt Pavement Layers (two days)
5. Controlling Moisture Damage in Asphalt Pavements

Information on these and other courses can be found at the following Web site:

http://www.techtransfer.berkeley.edu.

Recently, because of budget stringencies, new ways of packaging materials for technology transfer have been and are under development. One methodology, recently introduced, has been to take four- to six-hour segments from the first four courses listed above and prepare instructional materials that can be delivered at a specific site requested by Caltrans or other public agencies and industry groups.

Table 1a. Summary of Results: Implementation Recommendations (Completed Projects)

Study	Goal/Strategic Plan Element (SPE)	Type	Objective(s)	Results	Recommendations to Caltrans for Implementation	References
Mix Fatigue Tests	Goal 3	Laboratory Study, Analysis	1. Define the stiffness and fatigue characteristics of mixes used as overlays for both Goal 3 and Goal 5 studies: • Dense-graded asphalt concrete (DGAC) • Rubberized asphalt hot mixes including gap-graded (RAC-G) and dense graded (RAC-DG)	1. Stiffness and fatigue test data for DGAC and both types of RAC mixes: • Mix stiffeners, influence of: - Type of compaction - Degree of compaction - Binder content - Temperature - Aging and moisture effects • Mix fatigue characteristics, influence of: - The above (except conditioning) - Strain level 2. Provides data for Caltrans M-E pavement design and rehabilitation procedure. In the near term data also useful for developing Gravel Equivalent Factors design for RAC mixes.	1. Include this stiffness and fatigue data in Cal ME pavement design and rehabilitation materials catalogue. 2. Determine gravel equivalent factors (based on M-E methodology) for use in assisting Caltrans methodology.	3
Performance of Drained and Undrained Pavements Under Wet Conditions	Goal 5 / SPE 4.3	Accelerated pavement tests with HVS, laboratory tests, analysis	1. Evaluate the behavior of three drained (1) and undrained (2) pavement sections in the saturated condition under HVS loading 2. Investigate influence of compaction conditions (water content and dry density) on the permeability, stiffness, strength, and permanent deformation characteristics of the untreated aggregate base (AB) used in this test series. Compare optimum water contents and maximum dry densities obtained from CTM 216 and Mod. AASHTO T-180.	1. Results from the accelerated tests are as follows: • The ATPB stripped in the presence of water and heavy (HVS) loading. • Clogging of the ATPB with fines from the AB was observed in the wheel path area. Permeability of the ATPB in this area was decreased by three orders of magnitude (1.0 to 0.001 cm/sec). • When the ATPB stripped, increased permanent deformation, as compared to the dry condition, occurred in the section. • Because of stripping, the failure mode for the drained pavement was rutting as compared to fatigue cracking in the undrained section.	1. Reconsider general use of ATPB directly under AC layer in pavement sections. 2. If the decision is made to continue use of ATPB, develop improved mix design procedure and incorporate a filter between ATPB and untreated AB/ASB layer.	4, 5, 6, 7, 8, 9

Study	Goal/Strategic Plan Element (SPE)	Type	Objective(s)	Results	Recommendations to Caltrans for Implementation	References
	Goal 5/ SPE 4.3 (cont.)			1. For specimens compacted by Modified AASHTO T-180 and T-99, the higher degree of compaction achieved in T-180 resulted in: a. Higher stiffness moduli b. Reduced plastic deformations in repeated loading c. Reduced permeability 2. While both CTM 2.6 and AASHTO T-180 produced same maximum dry density, the optimum in water content obtained with CTM 2.6 was approximately 2 percent higher than that obtained with AASHTO T-180.	1. Since the line of optimums for the AASHTO compaction tests coincide more closely with field compaction results for AB's, AASHTO T-180 should replace CTM 216. 2. AB's should be compacted to 100 percent of the T-180 dry density for improved AB performance (N.B. this degree of compaction can be reasonable with current compaction equipment).	10, 11, 12, 13, 14
Long Life Pavement Rehabilitation Program, I-710 Freeway	SPE 2.3	Laboratory Study, Analysis, Accelerated Pavement tests using HVS	1. Prepare mix and structural pavement designs for I-710 Freeway rehabilitation 2. Check rutting performance of mix designs using HVS testing at elevated temperature (50C at 2in. depth) on the mixes to be used in the rehabilitated sections. 3. Work with Caltrans and Contractor Staff to evaluate the CA4 Program and traffic related simulations. 4. Conduct follow-up studies of as-built pavement sections on in-situ performance.	1. Mix and Structural section designs accepted by Caltrans/Industry Flexible Pavement Task Group of the LLPR Committee. 2. CA4PRS Program permitted contractor to complete contract in 8 rather than 10 weekend closures and traffic plan resulted in minimal traffic delays during weekend closures. 3. Partnering between Caltrans, Industry and PRC contributed to successful project.	1. Mix and pavement design proceedings used for I-710 rehabilitation should be continued for use on future major rehabilitation projects. 2. Adopt the CA4PRS for initial planning of all future rehabilitation projects. 3. Continue Caltrans/Industry partnering for future projects of this type.	15, 16, 17, 18

Study	**Goal/Strategic Plan Element (SPE)**	**Type**	**Objective(s)**	**Results**	**Recommendations to Caltrans for Implementation**	**References**
Evaluation of Rigid Pavement Long-Life Rehabilitation Strategies (LLPRS-Rigid)	Goal 4 / SPE 4.2	Laboratory studies, HVS tests, Analyses	Assist implementation of LLPRS-Rigid; evaluate structural designs and FSHCC performance. 1. Evaluate adequacy of structural design options (tied concrete shoulders, doweled joints, widened truck lanes) 2. Assess concrete durability for ASR, sulfate attack, fatigue, and strength gain 3. Measure affects of construction and mix design durability and structural performance.	1. Results of the HVS tests using FSHCC include: a. Shrinkage must be controlled (=<0.053% at 7 days) b. Control of curing conditions important c. Friction between concrete slab and base should be minimized d. In high desert environments of California (e.g. Palmdale) ACB preferred to LCB to reduce effects of environmentally induced stresses. e. Effectiveness of dowels, non-erodable bases and tied concrete shoulders or widened truck lanes. f. Joint spacings in high desert environments should not exceed 4.6m (15ft) 2. Results of the laboratory test program include: a. A detailed database of mechanical properties for FSHCC. b. Compressive and flexural strengths respond differently to environmental factors, thus there is not a unique relation between the two strengths. c. Mixes containing Portland cement have significantly lower coef. of thermal expansion than those with CSA. d. Current Caltrans practice of using ASTM C1260 as a tool for evaluating ASR followed by testing with ASTM C1293 if aggregate is reactive is sound practice. 3. Analysis results included: a. Development of analysis procedure which permits design of pavements to mitigate longitudinal and corner cracking as well as mid-slab cracking.	1. Use large dowels in new rigid pavements. 2. It is not necessary to use FSHCC as the primary material for LLPRS-Rigid; also considered increased use of mixes containing Type III cement in its place. 3. Widened truck lanes can be used as an alternative to tied concrete shoulders. 4. Establish maximum spacings in Highway Design Manual for different environmental regions in California 5. Continue practice of using ASTM C1260 to evaluate aggregates for ASR and the use of ASTM C1293 if aggregate is reactive according to ASTM C1260. 6. Further evaluate ASTM C1293 using the locally available low-acid cement with added hydroxide ions for a milder range of aggregate.	26, 27, 28, 29, 30, 31, 32, 33, 34, 35

Study	**Goal/Strategic Plan Element (SPE)**	**Type**	**Objective(s)**	**Results**	**Recommendations to Caltrans for Implementation**	**References**
Dowel Bar Retrofit (DBR) of Rigid Pavements	Goal 7 / SPE 4.8	HVS tests, Labora-tory tests, Analysis	Establish whether the dowel bar retrofitting is a cost effective rehabilitation strategy for in-service rigid pavements and includes the flowing: 1. HVS testing of an in-service concrete pavement (3 or 4 years) on U.S. 101 at Ukiah and some sections of the Palmdale project on SR 14. 2. Laboratory testing of 3 types of dowel bards for stiffness and corrosion characteristics 3. Finite element modeling of slabs containing dowels	*This project is still in progress; results as of June 2004 are included.* 1. Both the US 101 and SR 14 projects have demonstrated the potential benefits of DBR in terms of extending pavement life (as measured by additional traffic). 2. Four dowels per wheel path are expected to provide better performance than three. 3. The finite element program EVERFE version 2.3 provides a useful methodology to analyze dowel bar performance.	1. Dowel bar retrofit of existing pavements is viable rehabilitation strategy. Its use must however, be selected in the basis of life cycle analysis. 2. Careful construction practices must be followed since the dowel performance is very dependent on proper installation.	36, 37, 38, 39
Analysis of Sensitivity of Plain, Jointed Concrete Pavement (JCP) in California to Early-Age Cracking using *HIPERPAV*	SPE 3.1	Analysis, Field test evaluation	Evaluate the use of *HIPERPAV* by Caltrans as follows: 1. Software evaluation. 2. Field evaluation of instrumented slabs at four sites in the desert environment; and 3. Development of recommendations for mitigation of early-age cracking and use of *HIPERPAV* in California.	1. *HIPERPAV* provides useful guidelines for a range of specific inputs; however not sufficient for JPC durability prediction. 2. Program indicates that improvement of construction practices has most significant impact in reducing early age cracking; proper joint spacings and curing time are key issue. 3. Desert climate more critical than coastal environments. 4. Aggregate type important in desert environments, e.g. gravel versus granite.	1. *HIPERPAV* should be used by limited to PCC at this time. Improvements should include: a. FSHCC; b. Risk (probabilistic) analysis; and c. cumulative damage prediction 2. Improve practices to prevent early-age cracking a. Construction practices including project scheduling of curing and joint saving; b. Desert region requies careful consideration of aggregate selection c. More careful attention to mix design, e.g. use of lower w/c rations, use of superplasticques, and evaluation of fly ash content.	40

Study	Goal/Strategic Plan Element (SPE)	Type	Objective(s)	Results	Recommendations to Caltrans for Implementation	References
Evaluation of the Maturity Method for Flexural Strength Estimation in Concrete Pavement	SPE 3.12	Field, Laboratory	Provide Caltrans with information on the accuracy and feasibility of the Maturity Method for measurement of concrete flexural strength of pavement slabs	1. Maturity Method using laboratory flexural strengths can be implemented. However additional work required for Type III and other high early strength mixes. (special cements and/or chemical admixtures). 2. Use of laboratory established compressive strength versus maturity curves to estimate flexural strength is questionable; relation between compressive and flexural strength not constant for a range in mixes.	1. To calculate maturity, Nurse-Saul method (TTF) adequate; assumed values of Activation Energy (E) and Datum Temperature (T_D) are satisfactory for conventional mixes only. Use flexural specimens. 2. Perform calibration at three temperatures (e.g., 10, 23, 40°C) with specimens cured at 100% relative humidity. 3. Continue fixed testing of beams and cylinders.	41

Table 1b. Summary of Results: Implementation Recommendations (In Progress)

Study	**Goal/Strategic Plan Element (SPE)**	**Type**	**Objective(s)**	**Results**	**Recommendations to Caltrans for Implementation**	**References**
Development of Improved Rehabilitation Designs for Reflection Cracking	Goal 9/ SPE 4.10	Laboratory tests, accelerated pavement tests with HVS, analysis	Investigate reflection cracking of conventional AC, RAC-G, and mixes containing other modified binders (MB) places as overlays on cracked and/or joined pavements and to develop tests, analysis methods, and design procedures to mitigate this form of distress.	*N.B. This project is in progress; results through June 2004 are as follows:* 1. New Pavement Constructed with conventional AC surface on Class 2 aggregate base and 6 sections tested with HVS to establish cracked sections for overlay study. 2. Overlays placed; 6 test locations established including: DGAC (90mm); RAC-G (45mm); MB4 (45mm and 90mm); MB15 (45mm) 3. Rutting tests at 50C using this HVS were completed. All sections exhibited less repetitions to rut depth of 12.5mm at fewer repetitions than Goal 3 sections.	1. While results are not complete consideration should be given to improved mix design procedures for mix using binders formulated according to proposed MB specifications.	19
Investigation of Asphalt Concrete Moisture Damage	Goal 8 / SPE 4.9	Field study, Laboratory study, Analysis, HVS tests	Investigate causes and risk of AC moisture damage in California; investigate measures to mitigate risk.	1. Working (see Goal 4 statement previous page) with the Moisture Sensitivity of Asphalt Concrete Task Group (MSACTG), a joint Caltrans/Industry working group, PRC Staff developed a systematic procedure for moisture identification and a suggested risk map for moisture damage potential considering temperature and precipitation and a moisture sensitivity training course.	Recommendations will be submitted to Caltrans when tests on the field and laboratory specimens are completed. This is anticipated in Fall 2005.	23

Study	**Goal/Strategic Plan Element (SPE)**	**Type**	**Objective(s)**	**Results**	**Recommendations to Caltrans for Implementation**	**References**
Investigation of Asphalt Concrete Moisture Damage *(continued)*				2. Initiated a field survey of projects to develop a database of 200 sites throughout California identified by the MSACTG. 3. Initiated a laboratory test program including: CTM 371, Hamburg Wheel Tracking Device (HWTD), flexural fatigue testing on saturated beams. 4. Preliminary analysis of the field data suggests that high air void contents in pavement sections contributed significantly to moisture damage.		
Pay Factors for Asphalt Concrete Construction	SPE 3.1.5, SPE 4.13	Analysis, Field	Develop pay factors for asphalt concrete based on performance-based relationships.	1. Pay factors developed for fatigue and rutting using performance equations calibrated from HVS tests and the WesTrack test program. 2. Pay factors for fatigue based on degree of compaction, asphalt concrete, and AC layer thickness. 3. Pay factors for rutting based on asphalt content, degree of compaction and percent passing NO. 200 sieve.	Conduct shadowing studies on a number of QC/QA projects approximately 5 years in age and obtain field performance data for both fatigue cracking and rutting. (*N.B. STANTEC* has included approximately 20 projects in the PMS work for DR and I.)	42, 43, 44, 48, 49, 50

Study	Goal/Strategic Plan Element (SPE)	Type	Objective(s)	Results	Recommendations to Caltrans for Implementation	References
Construction Analysis for Pavement Rehabilitation Strategies *(CA4PRS)*	SPE 4.6	Analysis, Field	Develop tools that will permit reduction of construction duration, cost, and traffic delay through improved planning, design, and specifications.	1. CA4PRS Program developed and used to assist Caltrans in the construction planning for the I-710, Long Beach, and I-15, Devore, Long Life pavement rehabilitation projects.	1. Use CA4PRS as a part of the planning for all long life pavement rehabilitation projects and involve design, construction, and traffic staff in this initial planning phase. 2. Have PRC Staff conduct training for District Staff in all Districts in which LLPR projects will be constructed.	45, 46, 51, 52, 53, 54
Development of the First Version of a Mechanistic-Empirical Pavement Rehabilitation Reconstruction and New Pavement Design for Rigid and Flexible Pavements	SPE 4.1	Analysis, Software Development	Improve Caltrans pavement performance for implementation of mechanistic design integrating structural materials and construction elements	1. Flexible pavement design software program developed (calibration underway using results of HVS and WesTrack test programs) 2. Rigid pavement design Software patterned after AASHTO guide software (200X). Includes provisions for evaluation of longitudinal and corner cracking not included in AASHTO 200X software.	1. Use current developments to update rigid pavement design catalogue. 2. Use current developments for I-710 and I-15 projects Structural section designs.	55

Study	**Goal/Strategic Plan Element (SPE)**	**Type**	**Objective(s)**	**Results**	**Recommendations to Caltrans for Implementation**	**References**
Development of the First Version of a Mechanistic-Empirical Pavement Rehabilitation Reconstruction and New Pavement Design for Rigid and Flexible Pavements				3. Associated software developed: a. CalME (Version 1.0) (Flexible) b. RadiCal (Version 1.0) (Rigid) c. EVERFE (Version 2.3) (FEA) d. LEAP 2 (MLEA) e. CDIM (Climate) f. WIMANA (Traffic)		
Pavement Research Databases	SPE 2.2	Analysis, Software Development	Incorporate all data from PRC research activities into relational databases for future use.	1. The following databases are all in operation: a. PRC-HVS b. Fieldsites.mdb c. PRC_FWD.mdb d. Fatigue.mdb e. Shear f. PCC_Lab g. WIMData	1. Notified DR and I Staff of availability of databases.	56, 57, 58

Study	Goal/Strategic Plan Element (SPE)	Type	Objective(s)	Results	Recommendations to Caltrans for Implementation	References
Deep In-Situ Recycling	SPE 2.4.2 Goal 10 (SPE 4.12)	Field evaluation, HVS Tests, Laboratory tests	SPE 2.4.2 Using Recycled Asphalt as Unbound Base. Evaluate rehabilitation strategy involving recycling in-place asphalt concrete and a porting of existing untreated aggregate and using combined materials as base for new AC layer.	1. Two projects in District 2 have been initiated and a third is planned: a. US 395 near Alturas b. SR 70 at Beckwourth c. SR 44 near Poison Lake 2. For US 395 Project, project provided cost savings in terms of time, material, and improved performance.	1. Continue study for SR 70 and SR 44 programs.	59
			SPE 4.12 (Goal 10) Evaluate DISR Foamed Asphalt; develop improved mix and structural design practice.	1. HVS testing of foam test sections on SR 89 at Calpine were completed by June 2004. 2. The pavement structure of the HVS test sections at this site was not representative of the mainline pavement structure. Nevertheless useful results should be obtained from the analyses of the test results.	1. Continue the field HVS test sections at other representative sites; insure that the HVS tests are done in the mainline pavement (requires constructing long-pass section).	60, 61

Table 1c. Summary of Results: Implementation Recommendations (Funding from Other Sources)

Study	Goal/Strategic Plan Element (SPE)	Type	Objective(s)	Results	Recommendations to Caltrans for Implementation	References
Influence of Asphalt Binder Properties on the Fatigue Performance of Asphalt Concrete Pavements	Support provided by PCCAS	Laboratory tests, Analysis	Evaluate the influence of nine binders selected by PCCAS member participants on pavement performance for representative ranges in pavement sections, environmental conditions, and traffic loading.	1. Current AASHTO M320-04 intermediate temperature requirement for G#sinδ on PAV aged binder does not insure adequate performance in fatigue for the wide range of environmental conditions and pavement structures evaluated. 2. In spite of the above, recommendation to retain the current criteria made for the parameters in the binder specification.	1. Adopt current PG binder, i.e., AASHTO M320-04	20, 21, 22

1. INTRODUCTION

In June 2004, the Caltrans Partnered Pavement Research Program (PPRP)[1] completed ten years[2] of research and development (R and D) in the Pavement Engineering area. The program is a joint effort among the California Department of Transportation (Caltrans), the University of California at Berkeley (UCB), University of California at Davis (UCD), the Division of Roads and Transport Technology (Transportek) of the Council of Scientific and Industrial Research (CSIR) of the Republic of South Africa, and Dynatest Consulting, Inc., of Ventura, California. The program has also involved a series of other participants as subcontractors; the Acknowledgements section contains a listing of these other participants.

The program combines the results of analytical developments, laboratory testing of pavement materials, and Heavy Vehicle Simulator (HVS) testing of carefully planned, full-scale pavement test sections to assist Caltrans in moving towards its goal of improved pavement performance on the approximately 80,000 lane-km (50,000 lane-mi.) of highways within its jurisdiction.

The two HVS units purchased by Caltrans in 1994 have been in almost continuous operation since March 1995.[3] One HVS is used to test full-scale pavements in a controlled environment at the UCB Pavement Research Center (PRC), located at the University of California, Berkeley Richmond Field Station (RFS); the other is used for testing in-service pavements. Thus far, the second HVS has been used to test concrete pavement on SR-14 near Palmdale (High Desert, Southern California) and dowel-bar retrofitted jointed (and cracked) concrete pavement on US-101 in Ukiah (Northern California) and SR-14, and to test a deep in-situ recycling project (using foamed asphalt) on SR-89 near Truckee (Central Sierra Nevada mountains east of Sacramento). Figure 1 illustrates the HVS units in operation at the various sites. As of June 2004, a total of seventy-four test sections were completed; Table 2 contains a summary of the completed tests. This total includes forty sections at the RFS site and thirty-four sections at the three field sites. Since March 1995, approximately 60×10^6 repetitions corresponding to 2.9×10^9 ESALs have been applied to these test sections by the two HVS units.

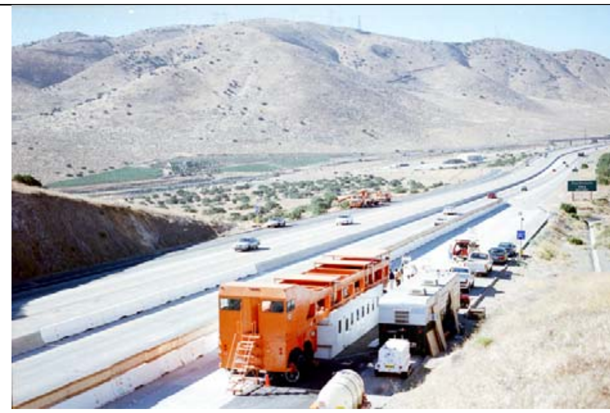
The R and D program, results of which are described in subsequent sections, is based on a strategic plan which is evaluated at about two-year intervals. Problem statements are prepared by the PPRP staff with input from the Pavement Standards Team (the PST, which is made up of Caltrans engineers from Design, Materials, Construction, Maintenance, Research, and Traffic, and which includes both Headquarters and District representatives). The statements are reviewed by the PST and the Pavement Program Steering Committee (PPSC) to which the PST reports. Utilizing a ranking of the problem statements by the PST, new projects are approved and the Strategic Plan is developed and submitted for approval by the PPSC. The most recently approved plan covering the 2000–2004 period was approved in April 2003. In this plan, the project goals from the 1994–2004 period were changed to *Strategic Plan Elements* as summarized in Table 3. These elements are shown with the corresponding goals associated with the HVS test program in Table 2.

The purpose of this report is to provide a brief summary of technical developments completed and in progress during the 2000–2004 period. Technical activities include the analytical developments, laboratory testing of pavement materials, and HVS tests briefly summarized in Table 2. Where appropriate, results of individual programs [Goals or Strategic Plan Elements (SPE)] which cover related areas are combined in order to provide a comprehensive basis for implementable recommendations in specific pavement-related materials, design, and construction areas. Table 4 includes a summary of these results together with recommendations for their implementation. Also included is a section devoted to discussion of implementation and technology transfer activities conducted during the 2000–2004 period as well as the effectiveness of the efforts.

---

[1] During the period 1994–2000, the program was referred to as the California Accelerated Pavement Testing (CAL/APT) Program. In July 2000, the name of the program was changed to the PPRP.
[2] A pilot program was conducted prior to the CAL/APT program in the period 1993–1994 to define the feasibility of this joint effort.
[3] In fall 2000, the two machines were temporarily out of service for upgrades.

HVS1 and 2 at Building 280 RFS, 1998.



HVS2 on SR-14 at Palmdale, 1999.

HVS2 on US-101 dowel bar retrofit sections, Ukiah, California, 2001

HVS 1 and 2 on modified binder test section, RFS, 2003.

HVS2 on SR-89 foamed asphalt test sections, Calpine, California, fall 2003.

HVS2 on SR-89 foamed asphalt test sections, Calpine, California, winter 2004.

Figure 1. Heavy Vehicle Simulators in operation.

Table 2. Summary of Completed HVS Tests

CAL/APT Program Goal	PPRC Strategic Plan Element	Test Sections	Test Location	Pavement Components	Test Purpose
Goal 1		500-503	RFS	Asphalt Concrete (DGAC) Untreated Aggregate Base (AB) Asphalt Treated Permeable Base (ATPB) Untreated Aggregate Subbase (ASB)	Evaluate structural adequacy to traffic loading of flexible pavement designed by existing Caltrans procedure
Goal 3		504-513	RFS	Asphalt Concrete (DGAC) Asphalt rubber (RAC-G) hot mix, gap-graded	Evaluate the rutting propensity of Caltrans surface course mixes at elevated temperatures under different tire types
		514, 515, 517, 518	RFS	Asphalt Concrete (DGAC) Asphalt rubber (RAC-G) hot mix, gap graded	Evaluate the performance of overlays on existing cracked AC pavements and compare the performance of the DGAC and RAC-G overlays to evaluate the equivalence of performance of $h_{RAC-G}=½h_{DGAC}$. Data will also be useful for Goal 9.
Goal 5	4.3	543-545	RFS	Overlaid sections – 514, 515, 517, and 518 with ATPB and AB in saturated state	Evaluate the comparative performance of saturated AB and ATPB under accelerated loading
Implementation	2.3	546, 547	RFS	Overlay of concrete pavement with mixes used in the I-710 rehabilitation	Evaluate the rutting characteristics of the PBA-6a* mix used in the I-710 rehabilitation.

CAL/APT Program Goal	PPRC Strategic Plan Element	Test Sections	Test Location	Pavement Components	Test Purpose
Goal 4	4.1	516	RFS	PCC pavement aggregate base (AB)	Develop experience in installation of instrumentation for Palmdale tests; provide experience for HVS-2 crew for Palmdale program.
		519-541	SR-14, Palmdale	HCC pavement with cement treated and aggregate base	Develop field fatigue characteristics for FSHCC; evaluate various concrete pavement design features and the effects of environment on performance.
Goal 7	4.8	553-555	US-101, Ukiah	In-service PCC pavement with Cement-Treated Base (CTB) and ASB.	Evaluate the performance of an existing PCC pavement in which joints and cracks were retrofitted with dowels.
		556-559	SR-14, Palmdale	HCC pavement constructed for Goal 4.	Evaluate performance of a pavement retrofitted with conventional, fiber reinforced polymer (FRP), and hollow stainless steel dowel bars.

CAL/APT Program Goal	PPRC Strategic Plan Element	Test Sections	Test Location	Pavement Components	Test Purpose
Goal 9	4.10	567-569, 571-573, 575, 576	RFS	New pavement, asphalt concrete (DGAC), granular base (AB) (test pavement for overlays).	Evaluate performance of overlays containing different modified binders (MB) on existing asphalt concrete (DGAC) pavement. Test was comprised of three steps: 1. Crack existing pavement. 2. Rutting evaluation of overlays. 3. Reflection cracking of overlays.
		580-585		(Rutting sections)	
		586-591 (590)[a]		(Cracking sections)	
		552[b] 551[c]	RFS	Same pavement as used for Tests 546 and 547.	Evaluate reflection cracking in asphalt concrete over joints/cracks in PCC pavement.
Goal 10	4.12	593-596	SR-89, Calpine	Asphalt concrete (DGAC) on foamed asphalt base.	Evaluate performance of pavement with foamed asphalt base [deep in-situ recycling (DISR)].

a. Section completed prior to June 2004.
b. Tested using HVS-1.
c. Currently under test with HVS 2 (Fall 2004).

Table 3. PPRC Program, Strategic Plan Elements, PST Recommendations and Priorities in 2004 and 2002

Strategic Plan Element and Project Title	’04 PST [1]	’02 PST [1]
New Proposed Project (’04): Evaluation of Tack Coats of Conventional and Rubberized Mixes	Unfunded [2]	NA
New Proposed Project (’04): Investigation of Improved Open Graded Mix Designs	Fund [2]	NA
Research Services – Basic		
2.1 Development of Partnered Pavement Research Program	Fund	NA
2.2 Pavement Research Database	Fund	NA
2.3 Provide Pavement Technology Advice to Caltrans	Fund	NA
Research Services – Special Forensic Investigations		
2.4.1 Longitudinal Joint Compaction	Complete	4.5
2.4.2 Deep In-Situ Recycling Using Recycled AC as Unbound Base: Field & Lab Testing (US-395)	Fund	4.4
2.4.3 Deep In-Situ Recycling (DISR) Using Foamed Asphalt	Cancelled	4.5
2.4.4 Maintenance Surface Treatments for Noise and Performance: Test Section Layout and Performance Monitoring (SR-138)	Fund	3.2
Research Services – Implementation Projects		
3.1.1 Calibration of *HIPERPAV* for California Conditions	Fund	3
3.1.2 Evaluation of Concrete Maturity Meters	Complete	4.5
3.1.3 Use of the Dynamic Cone Penetrometer (DCP) for Maintenance, Rehabilitation, and Reconstruction Site Evaluation	Fund	3
3.1.4 Quality Assurance Laboratory Testing for AC Long-Life Pavement Mix Designs (I-710)	Fund	3.75
3.1.5 Development of New Asphalt Concrete QC/QA Pay Factor Tables	Fund	4.25
3.2.1/2.3d Calibration Sites for Falling Weight Deflectometers, Profilers, & Skid Resist. Devices	Fund (2.3d)[3]	4.1
3.2.2 Evaluation of Profilers and Automated Distress Data Collection Equipment	Unfunded	4
3.2.3 Process for Evaluating Strategies for Recycling Materials into the Pavement Structure, with First Case Study “Recycling of PCC Grindings Slurry”	Unfunded	3.66
3.2.4 Development of Integrated Databases to Make Pavement Preservation Decisions	Fund	3.6
3.2.5 Documentation of Pavement Performance Data for Pavement Preservation Strategies and Evaluation of Cost-Effectiveness of Such Strategies	Fund	3.6
3.2.6 Development of Improved Patching Procedures for OGAC Overlays	Fund	2.9
3.2.7 Pilot Projects for Compaction Specifications for Aggregate Base and Aggregate Subbase/Use of the Rapid Compaction Control Device (RCCD)	Fund	2.75
3.2.8/2.3d Pilot Projects for Chip Seal Specifications based on South African Design Practice	Fund (2.3d)[3]	2.5
3.2.9/2.3d Development of Guidelines for Effective Maint. Treatment Evaluation Test Sections	Fund (2.3d)[3]	2.3
3.2.10 Mix Design Procedure for Asphalt Concrete Base for Rigid Pavements	Unfunded	2.1
Research Goals		
4.1 Development of First Version of Mechanistic-Empirical Pavement Rehab., Reconstr., & New Pavement Des. Procedure for Rigid & Flexible Pavements (Pre-Calibration of AASHTO 2002)	Fund	3.8
4.2 Evaluation of Rigid Pavement Long-Life Rehabilitation Strategies (LLPRS-Rigid)	Fund	4.2
4.3 Performance of Drained & Undrained Flexible Structures Under Wet Conditions	Complete	2.7
4.4 Development of Asphalt Concrete Rutting Performance Tests and Analysis Procedures	Fund	3.2
4.5 Calibration of Mechanistic-Empirical Design Models	Fund	4
4.6 Development of Rehabilitation Construction Productivity Analysis Products	Fund [2]	2.8
4.7 Verification of Asphalt Concrete Long-Life Pavement Strategies	Fund [2]	3.3
4.8 Dowel Bar Retrofit of Rigid Pavements	Fund	4
4.9 Investigations of Asphalt Concrete Moisture Damage	Fund [2]	4.3
4.10 Development of Improved Rehabilitation Designs for Reflection Cracking	Fund	4.3
4.11 Evaluation of Hydraulic Cem. Con. Mix Des. for Pavements	Cancel	3.2
4.12 Development of Improved Mix and Structural Design and Construction Guidelines for Deep In-Situ Recycling (DISR) of Crack Asphalt Concrete as Stabilized or Unstabilized Bases	Fund [2]	4
4.13 Validation of Asphalt Concrete QC/QA Pay Factors	Unfunded	3.9
4.14 A Framework for Implementing Innovative Contracting Methods for Transportation Infrastructure Rehabilitation/Reconstruction	Fund [2]	2.8
4.15 Development of Integrated Pavement Strategy Decision Support System	Fund [2]	3

[1] ’04 PST are recommendations in Nov. 2004; ’02 PST are rankings from PST in Nov. 2002 (range from 5 = Highest to 1 = Lowest)
[2] PST recommendation (Nov. 2004) to clarify, to reduce tasks, or to evaluate re-scoping project
[3] PST recommendation (Nov. 2004) to identify these as “Corporate” or “Overhead” items linked to Research Services, Element 2.3d

The categories of research are defined below.

Strategic Plan Elements	Element Numbers
Research Services – Basic	2.1 to 2.3
(1) Develop the PPRC program, (2) Continue developing the Pavement Research Database, and (3) Provide pavement technology advice to Caltrans.	
Research Services – Special Forensic Investigations	2.4.1 to 2.4.4
Investigate performance of existing pavement through sampling, laboratory testing, instrumentation, monitoring, analysis, and reporting results.	
Research Services – Implementation Projects	3.1.1 to 3.2.10*
For technologies under evaluation by Caltrans, assist the Department with experiment design, development of specifications, construction management methodology, laboratory tests, and pavement design and analysis methodology.	
Research Goals	4.1 to 4.15
Study especially complex pavement issues that require longer project schedules and more resources for testing and analysis.	

* Elements 3.1.1 to 3.1.4 existed when the 2003 Strategic Plan was formulated. Elements 3.2.1 to 3.2.10 were added in 2003.

Table 4. Summary of Results: Implementation Recommendations (Projects are Combined from Tables 1a, 1b, and 1c and are Listed Chronologically)

Study	Goal/Strategic Plan Element (SPE)	Type	Objective(s)	Results	Recommendations to Caltrans for Implementation	References
Mix Fatigue Tests	Goal 3	Laboratory Study, Analysis	1. Define the stiffness and fatigue characteristics of mixes used as overlays for both Goal 3 and Goal 5 studies: • Dense-graded asphalt concrete (DGAC) • Rubberized asphalt hot mixes including gap-graded (RAC-G) and dense graded (RAC-DG)	1. Stiffness and fatigue test data for DGAC and both types of RAC mixes: • Mix stiffeners, influence of: - Type of compaction - Degree of compaction - Binder content - Temperature - Aging and moisture effects • Mix fatigue characteristics, influence of: - The above (except conditioning) - Strain level 2. Provides data for Caltrans M-E pavement design and rehabilitation procedure. In the near term data also useful for developing Gravel Equivalent Factors design for RAC mixes.	1. Include this stiffness and fatigue data in Cal ME pavement design and rehabilitation materials catalogue. 2. Determine gravel equivalent factors (based on M-E methodology) for use in assisting Caltrans methodology.	3
Performance of Drained and Undrained Pavements Under Wet Conditions	Goal 5 / SPE 4.3	Accelerated pavement tests with HVS, laboratory tests, analysis	1. Evaluate the behavior of three drained (1) and undrained (2) pavement sections in the saturated condition under HVS loading 2. Investigate influence of compaction conditions (water content and dry density) on the permeability, stiffness, strength, and permanent deformation characteristics of the untreated aggregate base (AB) used in this test series. Compare optimum water contents and maximum dry densities obtained from CTM 216 and Mod. AASHTO T-180.	1. Results from the accelerated tests are as follows: • The ATPB stripped in the presence of water and heavy (HVS) loading. • Clogging of the ATPB with fines from the AB was observed in the wheel path area. Permeability of the ATPB in this area was decreased by three orders of magnitude (1.0 to 0.001 cm/sec). • When the ATPB stripped, increased permanent deformation, as compared to the dry condition, occurred in the section. • Because of stripping, the failure mode for the drained pavement was rutting as compared to fatigue cracking in the undrained section.	1. Reconsider general use of ATPB directly under AC layer in pavement sections. 2. If the decision is made to continue use of ATPB, develop improved mix design procedure and incorporate a filter between ATPB and untreated AB/ASB layer.	4, 5, 6, 7, 8, 9

Study	Goal/Strategic Plan Element (SPE)	Type	Objective(s)	Results	Recommendations to Caltrans for Implementation	References
	Goal 5/ SPE 4.3 (cont.)			1. For specimens compacted by Modified AASHTO T-180 and T-99, the higher degree of compaction achieved in T-180 resulted in: a. Higher stiffness moduli b. Reduced plastic deformations in repeated loading c. Reduced permeability 2. While both CTM 2.6 and AASHTO T-180 produced same maximum dry density, the optimum in water content obtained with CTM 2.6 was approximately 2 percent higher than that obtained with AASHTO T-180.	1. Since the line of optimums for the AASHTO compaction tests coincide more closely with field compaction results for AB's, AASHTO T-180 should replace CTM 216. 2. AB's should be compacted to 100 percent of the T-180 dry density for improved AB performance (N.B. this degree of compaction can be reasonable with current compaction equipment).	10, 11, 12, 13, 14
Long Life Pavement Rehabilitation Program, I-710 Freeway	SPE 2.3	Laboratory Study, Analysis, Accelerated Pavement tests using HVS	1. Prepare mix and structural pavement designs for I-710 Freeway rehabilitation 2. Check rutting performance of mix designs using HVS testing at elevated temperature (50C at 2in. depth) on the mixes to be used in the rehabilitated sections. 3. Work with Caltrans and Contractor Staff to evaluate the CA4 Program and traffic related simulations. 4. Conduct follow-up studies of as-built pavement sections on in-situ performance.	1. Mix and Structural section designs accepted by Caltrans/Industry Flexible Pavement Task Group of the LLPR Committee. 2. CA4PRS Program permitted contractor to complete contract in 8 rather than 10 weekend closures and traffic plan resulted in minimal traffic delays during weekend closures. 3. Partnering between Caltrans, Industry and PRC contributed to successful project.	1. Mix and pavement design proceedings used for I-710 rehabilitation should be continued for use on future major rehabilitation projects. 2. Adopt the CA4PRS for initial planning of all future rehabilitation projects. 3. Continue Caltrans/Industry partnering for future projects of this type.	15, 16, 17, 18

Study	Goal/Strategic Plan Element (SPE)	Type	Objective(s)	Results	Recommendations to Caltrans for Implementation	References
Development of Improved Rehabilitation Designs for Reflection Cracking	Goal 9/ SPE 4.10	Laboratory tests, accelerated pavement tests with HVS, analysis	Investigate reflection cracking of conventional AC, RAC-G, and mixes containing other modified binders (MB) places as overlays on cracked and/or joined pavements and to develop tests, analysis methods, and design procedures to mitigate this form of distress.	*N.B. This project is in progress; results through June 2004 are as follows:* 1. New Pavement Constructed with conventional AC surface on Class 2 aggregate base and 6 sections tested with HVS to establish cracked sections for overlay study. 2. Overlays placed; 6 test locations established including: DGAC (90mm); RAC-G (45mm); MB4 (45mm and 90mm); MB15 (45mm) 3. Rutting tests at 50C using this HVS were completed. All sections exhibited less repetitions to rut depth of 12.5mm at fewer repetitions than Goal 3 sections.	1. While results are not complete consideration should be given to improved mix design procedures for mix using binders formulated according to proposed MB specifications.	19
Influence of Asphalt Binder Properties on the Fatigue Performance of Asphalt Concrete Pavements	Support provided by PCCAS	Laboratory tests, Analysis	Evaluate the influence of nine binders selected by PCCAS member participants on pavement performance for representative ranges in pavement sections, environmental conditions and traffic loading.	1. Current AASHTO M320-04 intermediate temperature requirement for G#sinδ on PAV aged binder does not insure adequate performance in fatigue for the wide range of environmental conditions and pavement structures evaluated. 2. In spite of the above, recommendation to retain the current criteria made for the parameters in the binder specification.	1. Adopt current PG binder, i.e., AASHTO M320-04	20, 21, 22

Study	**Goal/Strategic Plan Element (SPE)**	**Type**	**Objective(s)**	**Results**	**Recommendations to Caltrans for Implementation**	**References**
Investigation of Asphalt Concrete Moisture Damage	Goal 8 / SPE 4.9	Field study, Laboratory study, Analysis, HVS tests	Investigate causes and risk of AC moisture damage in California; investigate measures to mitigate risk.	1. Working (see Goal 4 statement previous page) with the Moisture Sensitivity of Asphalt Concrete Task Group (MSACTG), a joint Caltrans/Industry working group, PRC Staff developed a systematic procedure for moisture identification and a suggested risk map for moisture damage potential considering temperature and precipitation and a moisture sensitivity training course. 2. Initiated a field survey of projects to develop a database of 200 sites throughout California identified by the MSACTG. 3. Initiated a laboratory test program including: CTM 371, Hamburg Wheel Tracking Device (HWTD), flexural fatigue testing on saturated beams. 4. Preliminary analysis of the field data suggests that high air void contents in pavement sections contributed significantly to moisture damage.	Recommendations will be submitted to Caltrans when tests on the field and laboratory specimens are completed. This is anticipated in Fall 2005.	23
Evaluation of Rigid Pavement Long-Life Rehabilitation Strategies (LLPRS-Rigid)	Goal 4 / SPE 4.2	Laboratory studies, HVS tests, Analyses	Assist implementation of LLPRS-Rigid; evaluate structural designs and FSHCC performance. 1. Evaluate adequacy of structural design options (tied concrete shoulders, doweled joints, widened truck lanes) 2. Assess concrete durability for ASR, sulfate attack, fatigue, and strength gain Measure affects of	1. Results of the HVS tests using FSHCC include: a. Shrinkage must be controlled (=<0.053% at 7 days) b. Control of curing conditions important c. Friction between concrete slab and base should be minimized d. In high desert environments of California (e.g. Palmdale) ACB preferred to LCB to reduce effects of environmentally induced stresses.	1. Use large dowels in new rigid pavements. 2. It is not necessary to use FSHCC as the primary material for LLPRS-Rigid; also considered increased use of mixes containing Type III cement in its place. 3. Widened truck lanes can be used as an alternative to tied	26, 27, 28, 29, 30, 31, 32, 33, 34, 35

Study	Goal/Strategic Plan Element (SPE)	Type	Objective(s)	Results	Recommendations to Caltrans for Implementation	References
	Goal 4 / SPE 4.2 (cont.)		construction and mix design durability and structural performance.	e. Effectiveness of dowels, non-erodable bases and tied concrete shoulders or widened truck lanes. f. Joint spacings in high desert environments should not exceed 4.6m (15ft) 2. Results of the laboratory test program include: a. A detailed database of mechanical properties for FSHCC. b. Compressive and flexural strengths respond differently to environmental factors, thus there is not a unique relation between the two strengths. c. Mixes containing Portland cement have significantly lower coef. of thermal expansion than those with CSA. d. Current Caltrans practice of using ASTM C1260 as a tool for evaluating ASR followed by testing with ASTM C1293 if aggregate is reactive is sound practice. 3. Analysis results included: a. Development of analysis procedure which permits design of pavements to mitigate longitudinal and corner cracking as well as mid-slab cracking.	concrete shoulders. 4. Establish maximum spacings in Highway Design Manual for different environmental regions in California 5. Continue practice of using ASTM C1260 to evaluate aggregates for ASR and the use of ASTM C1293 if aggregate is reactive according to ASTM C1260. 6. Further evaluate ASTM C1293 using the locally available low-acid cement with added hydroxide ions for a milder range of aggregate.	

Study	Goal/Strategic Plan Element (SPE)	Type	Objective(s)	Results	Recommendations to Caltrans for Implementation	References
Dowel Bar Retrofit (DBR) of Rigid Pavements	Goal 7 / SPE 4.8	HVS tests, Labora-tory tests, Analysis	Establish whether the dowel bar retrofitting is a cost effective rehabilitation strategy for in-service rigid pavements and includes the flowing: 1. HVS testing of an in-service concrete pavement (3 or 4 years) on U.S. 101 at Ukiah and some sections of the Palmdale project on SR 14. 2. Laboratory testing of 3 types of dowel bards for stiffness and corrosion characteristics 3. Finite element modeling of slabs containing dowels	*This project is still in progress; results as of June 2004 are included.* 1. Both the US 101 and SR 14 projects have demonstrated the potential benefits of DBR in terms of extending pavement life (as measured by additional traffic). 2. Four dowels per wheel path are expected to provide better performance than three. 3. The finite element program EVERFE version 2.3 provides a useful methodology to analyze dowel bar performance.	1. Dowel bar retrofit of existing pavements is viable rehabilitation strategy. Its use must however, be selected in the basis of life cycle analysis. 2. Careful construction practices must be followed since the dowel performance is very dependent on proper installation.	36, 37, 38, 39
Analysis of Sensitivity of Plain, Jointed Concrete Pavement (JCP) in California to Early-Age Cracking using *HIPERPAV*	SPE 3.1	Analysis, Field test evaluation	Evaluate the use of *HIPERPAV* by Caltrans as follows: 1. Software evaluation. 2. Field evaluation of instrumented slabs at four sites in the desert environment; and 3. Development of recommendations for mitigation of early-age cracking and use of *HIPERPAV* in California.	1. *HIPERPAV* provides useful guidelines for a range of specific inputs; however not sufficient for JPC durability prediction. 2. Program indicates that improvement of construction practices has most significant impact in reducing early age cracking; proper joint spacings and curing time are key issue. 3. Desert climate more critical than coastal environments. 4. Aggregate type important in desert environments, e.g. gravel versus granite.	1. *HIPERPAV* should be used by limited to PCC at this time. Improvements should include: a. FSHCC; b. Risk (probabilistic) analysis; and c. cumulative damage prediction 2. Improve practices to prevent early-age cracking a. Construction practices including project scheduling of curing and joint saving; b. Desert region requies careful consideration of aggregate selection c. More careful attention to mix design, e.g. use of lower w/c rations, use of superplasticques, and evaluation of fly ash content.	40

Study	Goal/Strategic Plan Element (SPE)	Type	Objective(s)	Results	Recommendations to Caltrans for Implementation	References
Evaluation of the Maturity Method for Flexural Strength Estimation in Concrete Pavement	SPE 3.12	Field, Laboratory	Provide Caltrans with information on the accuracy and feasibility of the Maturity Method for measurement of concrete flexural strength of pavement slabs	1. Maturity Method using laboratory flexural strengths can be implemented. However additional work required for Type III and other high early strength mixes. (special cements and/or chemical admixtures). 2. Use of laboratory established compressive strength versus maturity curves to estimate flexural strength is questionable; relation between compressive and flexural strength not constant for a range in mixes.	1. To calculate maturity, Nurse-Saul method (TTF) adequate; assumed values of Activation Energy (E) and Datum Temperature (T_D) are satisfactory for conventional mixes only. Use flexural specimens. 2. Perform calibration at three temperatures (e.g. 10, 23, 40C) with specimens cured at 100% relative humidity. 3. Continue fixed testing of beams and cylinders.	41
Pay Factors for Asphalt Concrete Construction	SPE 3.1.5, SPE 4.13	Analysis, Field	Develop pay factors for asphalt concrete based on performance-based relationships.	1. Pay factors developed for fatigue and rutting using performance equations calibrated from HVS tests and the WesTrack test program. 2. Pay factors for fatigue based on degree of compaction, asphalt concrete and AC layer thickness. 3. Pay factors for rutting based on asphalt content, degree of compaction and percent passing NO. 200 sieve.	Conduct shadowing studies on a number of QC/QA projects approximately 5 years in age and obtain field performance data for both fatigue cracking and rutting. (*N.B. STANTEC* has included approximately 20 projects in the PMS work for DR and I.)	42, 43, 44, 48, 49, 50
Construction Analysis for Pavement Rehabilitation Strategies (CA4PRS)	SPE 4.6	Analysis, Field	Develop tools that will permit reduction of construction duration, cost, and traffic delay through improved planning, design, and specifications.	1. CA4PRS Program developed and used to assist Caltrans in the construction planning for the I-710, Long Beach, and I-15, Devore, Long Life pavement rehabilitation projects.	1. Use CA4PRS as a part of the planning for all long life pavement rehabilitation projects and involve design, construction, and traffic staff in this initial planning phase. 2. Have PRC Staff conduct training for District Staff in all Districts in which LLPR projects will be constructed.	45, 46, 51. 52, 53, 54

Study	**Goal/Strategic Plan Element (SPE)**	**Type**	**Objective(s)**	**Results**	**Recommendations to Caltrans for Implementation**	**References**
Development of the First Version of a Mechanistic-Empirical Pavement Rehabilitation Reconstruction and New Pavement Design for Rigid and Flexible Pavements	SPE 4.1	Analysis, Software Development	Improve Caltrans pavement performance for implementation of mechanistic design integrating structural materials and construction elements	1. Flexible pavement design software program developed (calibration underway using results of HVS and WesTrack test programs) 2. Rigid pavement design Software patterned after AASHTO guide software (200X). Includes provisions for evaluation of longitudinal and corner cracking not included in AASHTO 200X software. 3. Associated software developed: a. CalME (Version 1.0) (Flexible) b. RadiCal (Version 1.0) (Rigid) c. EVERFE (Version 2.3) (FEA) d. LEAP 2 (MLEA) e. CDIM (Climate) f. WIMANA (Traffic)	1. Use current developments to update rigid pavement design catalogue. 2. Use current developments for I-710 and I-15 projects Structural section designs.	55
Pavement Research Databases	SPE 2.2	Analysis, Software Development	Incorporate all data from PRC research activities into relational databases for future use.	1. The following databases are all in operation: a. PRC-HVS b. Fieldsites.mdb c. PRC_FWD.mdb d. Fatigue.mdb e. Shear f. PCC_Lab g. WIMData	1. Notified DR and I Staff of availability of databases.	56, 57, 58

Study	Goal/Strategic Plan Element (SPE)	Type	Objective(s)	Results	Recommendations to Caltrans for Implementation	References
Deep In-Situ Recycling	SPE 2.4.2 Goal 10(SPE 4.12)	Field evaluation, HVS Tests, Laboratory tests	SPE 2.4.2 Using Recycled Asphalt as Unbound Base. Evaluate rehabilitation strategy involving recycling in-place asphalt concrete and a porting of existing untreated aggregate and using combined materials as base for new AC layer.	1. Two projects in District 2 have been initiated and a third is planned: a. US 395 near Alturas b. SR 70 at Beckwourth c. SR 44 near Poison Lake 2. For US 395 Project, project provided cost savings in terms of time, material, and improved performance.	1. Continue study for SR 70 and SR 44 programs.	59
			SPE 4.12 (Goal 10) Evaluate DISR Foamed Asphalt; develop improved mix and structural design practice.	1. HVS testing of foam test sections on SR 89 at Calpine were completed by June 2004. 2. The pavement structure of the HVS test sections at this site was not representative of the mainline pavement structure. Nevertheless useful results should be obtained from the analyses of the test results.	1. Continue the field HVS test sections at other representative sites; insure that the HVS tests are done in the mainline pavement (requires constructing long-pass section).	60, 61

2. TECHNICAL DEVELOPMENTS

As seen in Table 3, the program is broad-ranging, covering studies of: pavement materials; design and rehabilitation methodologies for flexible and rigid pavements; pavement construction considerations, particularly for freeway rehabilitation; recycling; and aspects of pavement management. A brief summary of the databases resulting from project studies is also included. The program includes an element entitled: *Provide Technology Advice to Caltrans* (SPE 2.3) Brief discussions of examples of this are included in this section where appropriate.

In addition to the completed investigations, significant findings from some of the studies underway that have completion dates that extend into the 2004-2008 period are included.

2.1 Asphalt Mixes—Materials and Flexible Pavement Studies

Pavement sections designed and constructed at the RFS according to Caltrans specifications have included flexible pavements and overlays. Both drained [i.e., with an asphalt-treated permeable base (ATPB) layer] and undrained [i.e., with a standard aggregate base (AB) layer] sections have been evaluated. Following loading to failure of these sections, they were overlaid with either dense-graded asphalt concrete (DGAC) or asphalt rubber hot mix gap-graded (ARHM-GG/RAC-G) to evaluate the current Caltrans method of overlay designs for these two materials. Results of tests on the original sections (Goal 1, Table 2) and overlays on the Goal 1 sections and tested in the "dry" condition (Goal 3, Table 2) were summarized in Reference (1).

Results of the laboratory fatigue tests on the overlay materials [Goal 3 (SPE 4.10)] and the HVS tests on these overlay sections for the condition in which the bases remained saturated during HVS loading [Goal 5 (SPE 4.3)] are briefly summarized in this section. Also included are: preliminary results of a laboratory study of granular base material performance associated with Goal 5; a summary of developments associated with the design and construction of the I-710 freeway from the Pacific Coast Highway to the I-405 freeway (SPE 2.3); results of the Pacific Coast Conference on Asphalt Specifications (PCCAS) supported study on the influence of asphalt binders on simulated flexible pavement performance; and some initial test results from HVS tests on the Modified Binder (MB) Test Road, the first phase of the Goal 9 (SPE 4.10) study concerned with rehabilitation designs to mitigate reflection cracking.

2.1.1 Mix Fatigue Tests (Goal 3)

The testing of asphalt mixes described in this section serves two purposes: first, to answer questions comparing two alternatives; second, to provide data for future use in mechanistic-empirical design procedures. While the Goal 3 HVS tests were reported in Reference (2), the extensive laboratory test program and data analyses to define the stiffness and fatigue response of DGAC and AR hot mixes used in the HVS tests was not completed until 2004 (3). This program has developed important data on the stiffness and fatigue characteristics of both types of mixes. The laboratory test program included tests on mixed specimens prepared as follows: field mixed, field compacted (FMFC); field mixed, laboratory compacted (FMLC); and laboratory mixed, laboratory compacted (LMLC). Two gradings were used for the AR hot mixes, one a gap grading (RAC-G) and the other the same as that used for the laboratory prepared DGAC mix. Mix variables included asphalt content, air-void content, effects of aging and moisture, temperature, and strain level. The resulting data provides useful information for the new (mechanistic-empirical) design procedure under development for Caltrans (SPE 4.1). In the near term, the data will also be useful for developing Gravel Equivalent Factor design data for AR hot mixes for rehabilitation alternatives.

2.1.2 Performance of Drained and Undrained Pavements Under Wet Conditions (Goal 5 [SPE 4.3])

Three test sections from the Goal 3 Study were subjected to HVS loading while the base courses (ATPB or AB) were maintained in a "wet" condition; two contained ARHM-GG (or RAC-G) mixes as the surface course while the third contained DGAC. Details of the test program are contained in References (4, 5, 6, and 7). The three sections had similar pavement lives when both rutting and fatigue criteria are considered. These ranged from 14.3×10^6 to 21.3×10^6 ESALs when the smaller of the two ESAL values for each section is selected.

Results of the accelerated pavement tests can be summarized as follows:

- The ATPB placed between the asphalt concrete and aggregate base *stripped* (the adhesive bond between the aggregate surface and the asphalt binder was broken) in the presence of water and heavy loading.
- Clogging of the ATPB with fines from the aggregate base was observed in the wheelpath area. This resulted in a reduction in permeability of the ATPB by three orders of magnitude (10 mm/s to 0.01 mm/s), which contributed to a saturated condition and accelerated its deterioration.
- While the ATPB initially reduced surface deflections under load, rapid deterioration of the ATPB with load repetitions resulted in similar deflections to those observed in the undrained sections.
- When the ATPB stripped, an increase in permanent deformation was observed as compared to dry conditions.
- Because of the stripping of the ATPB, surface rutting was the prominent failure mode; on the other hand, for the undrained sections, fatigue cracking was the predominant failure mode.

From this test series, the general use of ATPB directly under the dense-graded asphalt concrete layer in the pavement section warrants reconsideration. This recommendation is supported by the results of earlier laboratory tests on representative ATPB mixes (8) and associated analyses and surveys of the field performance of ATPB (9), which include the experience of district personnel with expertise in the maintenance of pavement drainage systems,

Improved compaction in the asphalt concrete layer will reduce its permeability. Improved compaction and increased asphalt concrete layer thickness will also substantially delay crack initiation and propagation in the asphalt concrete layer. Reducing the permeability and the cracking potential of the asphalt concrete will thus reduce the necessity for the ATPB; potentially the use of ATPB could even be eliminated. Despite the steps to reduce the propensity for the surface water to enter the pavement, it must be recognized that drainage layers may still be required to help remove water entering into the pavement structure from the subgrade.

However, a second recommendation is that if ATPB is used directly beneath the asphalt concrete, then improvements should be made to the material to enhance its performance in the presence of water. Increasing binder content, using modified binders such as asphalt rubber, and using an additive such as lime or anti-stripping agent are alternatives that should be considered. Associated with changing mix design requirements is the necessity for incorporation of a properly designed geotextile or soil filter adjacent to the ATPB layer in the pavement structure in order to prevent the ATPB from clogging. Results of the HVS tests in this test series strongly support such a recommendation.

To ensure continued effectiveness of the ATPB when used, systematic maintenance practices for the cleaning of edge and transverse drains must be followed or, if lacking, should be established.

2.1.3 Laboratory Study of Performance Characteristics of Untreated Aggregate Base Materials

A laboratory investigation of the performance characteristics of untreated aggregate base was conducted as a part of the Goal 5 study. This investigation examined the influence of compaction conditions (water content and dry density) on the permeability, strength, stiffness, and permanent deformation characteristics of the aggregate base (AB) used in the Goal 5 tests as well as a recycled aggregate base (RAB) used in the pavement section for the MB test sections to be discussed subsequently. Results of tests on the AB (Reference (10) are summarized in this section.

To define the compaction characteristics of the AB, Modified and Standard AASHTO (AASHTO T180 and T99, respectively) and Caltrans (CTM 216) compaction tests were used. Both the AASHTO T180 and CTM 216 tests produced about the same maximum dry density; however the optimum water content obtained in the CTM 216 procedure was about 2 percent higher [also observed by Hveem in 1957 (11)].

Constant head permeability tests were performed on specimens prepared by the AASHTO T180 and T99 tests. Dry of the optimum water contents for the two compaction efforts, permeabilities of the specimens compacted in the standard test were about two orders of magnitude larger than for specimens compacted in the modified test (approximately 2×10^{-6} versus 2×10^{-4} cm/s).

Results of repeated load axial compression tests (similar to AASHTO P46) also demonstrated the importance of improved compaction. In general, the higher the degree of compaction, the higher the stiffness (modulus) and the lower the amount of plastic strain associated with a specific number of load applications. These differences are larger at water contents less than the optimum for each compactive effort.

From a pavement design/construction standpoint, for improved pavement performance it is recommended that AB be compacted to a dry density 100 percent of the AASHTO T180 dry density. Water contents dry of the optimum water content associated with this compactive effort should be used. This degree of densification can be reasonably obtained with current compaction equipment following good construction procedures. With the reduced permeability associated with the improved compaction, the potential for ingress of water into untreated aggregate bases (with gradings comparable to those used by Caltrans) is reduced.

Extensive field studies (e.g., References 12 and 13) have shown that optimum moisture contents for granular materials (as measured by the line of optimums) compacted in the field correspond more closely with those obtained in the AASHTO tests than in those obtained with CTM 216. Local government agencies in Southern California already base compaction control on the AASHTO tests; their current specifications call for a relative compaction of 95 percent of the AASHTO T180 maximum dry density for granular bases (14). Because this test program showed the importance of controlling both moisture content and dry density (plus the fact that AASHTO T180 and T99 are widely used with excellent ties between laboratory and field compaction), their use in lieu of CTM 216 is recommended but with 100 percent instead of 95 percent compaction.

2.1.4 Long-Life Pavement Rehabilitation Program, I-710 Freeway (SPE 2.3)

After Caltrans started the Long-Life Pavement Rehabilitation Strategies (LLPRS) program in 1998, the Long Beach Freeway, Interstate 710 (I-710), was designated a candidate corridor. The I-710 stood out as an important route because of its age (in service since 1952), its high traffic volume (164,000 vehicles per day), and its heavy truck traffic serving the Port of Long Beach. Project needs included developing asphalt concrete overlay and full-depth designs that could be constructed during a 55-hour closure, designing thinner structural overlays than the thick pavement sections proposed based in Caltrans and Asphalt Institute methods, and identifying materials and designs to meet compaction specifications for the 55-hour closure. The I-710 rehabilitation project provided an opportunity to solve these problems by implementing approaches for asphalt concrete mix design and structural pavement design developed during SHRP and extended through the CAL/APT and PPRC programs. Results of these design aspects are discussed in References (15) and (16), and a summary of the design, construction, and follow up activities to June 2004 are included in Reference (17).

The selected pavement section for the full-depth AC replacement structure consists of: (1) a rut-resistant surface course using a mix containing a 100 percent crushed aggregate and PBA-6a* modified binder for both rutting resistance and improved durability characteristics; (2) an asphalt concrete base course containing an AR-8000 asphalt that provides good stiffness characteristics for structural section; (3) the same mix as in (2) with 0.5 percent more asphalt — termed a "rich-bottom mix" to provide improved fatigue resistance in the lower part of the structural section; and (4) an open-graded asphalt rubber porous friction course (RAC-O) for splash, spray, and hydroplaning resistance and noise reduction as well as for providing a protective layer for the PBA-6a* mix. It is anticipated that this RAC-O surface course will be replaced during the design life of the structure.

Mix designs for both the PBA-6a* and AR-8000 mixes were performed using the SHRP developed simple shear test (18). To assess the rutting performance of the PBA-6a* mix, it was subjected to approximately 170,000 repetitions using the HVS. During the test a pavement temperature of 50ºC (122ºF) was maintained at a depth of 50 mm (2 in.).[4] Results of the test suggest that the PBA-6a* mix should satisfactorily carry the anticipated traffic without excessive deformations (17).

The pavement structures for the cracked and seated portion of the freeway followed Caltrans practice. The structure consists of a leveling course placed on the PCC pavement; this is followed by an application of an asphalt-saturated fabric serving as a membrane interlayer. Additional asphalt concrete and the porous friction course complete the structure. Since the anticipated traffic is significantly greater than that on which current thicknesses are based (i.e., 200×10^6 versus approximately 20×10^6 ESALs), finite element analyses were conducted for a range in the AC thicknesses. Based on these analyses, the overall thickness of the overlay was increased from about 150 mm (6 in.) to 225 mm (9 in.). The mixes used are the same as those for the full-depth AC replacement structure resulting in continuity of the mixes throughout the project.

Successful performance of the pavement structures requires strict attention to pavement construction, including careful control of the mix components during production and the degree of densification during compaction. Results of the QC/QA testing indicated that this objective was achieved.

The constructability program, *CA4PRS* (described subsequently in Section 2.3.2), served as a useful tool to both the Caltrans and Contractor staff in achieving the necessary goals associated with the fifty-five-hour weekend closure. The program provided an estimate of the maximum length of full-depth AC that could be placed in the dig-out areas during a fifty-five-hour closure. For this project, the maximum thickness of AC for a 1000-ft. length of a three-lane freeway would be about 20 in., paving only in the traveled way. Thus, the design originally suggested according to the current HDM procedure (~22 in. of full-depth AC) would likely have required a greater time to complete.

Following completion of the project, interviews were conducted separately with Caltrans staff (one-half day, A.M.) and the Contractor and materials suppliers (one-half day, P.M.). The purpose of the interviews was to determine what went well with the project and which aspects should be considered for improvements on future projects.

The "lessons learned" from the interviews [summarized in Reference (17)] have provided very useful information for both agency and contractor staff who might be involved in future projects of this type.

A major lesson learned is that "partnering" is extremely desirable in a project of this importance to achieve the highest quality possible in the finished pavement structures. High quality is mandatory to achieve performance for the longer time periods associated with this type of pavement rehabilitation.

To track performance, a program of field testing using a Falling Weight Deflectometer (FWD) was instituted in November 2003 to evaluate the structural response of the pavement. Additional FWD testing is planned at intervals into the future to monitor changes in response. This study also includes laboratory shear and fatigue tests of specimens obtained from the constructed pavement.

The process used to arrive at the designs as well as the construction requirements was a "partnered" effort between Caltrans, the asphalt industry in California, and academia through UC Berkeley. This partnering provided an excellent opportunity to successfully implement new ideas and research results on this challenging project in which some of the traditional approaches were insufficient. It is strongly recommended that such cooperation continue in the future!

---

[4] Construction of the test pavement involved partnering between the asphalt industry and the PRC. Industry provided the materials together with funds for mixing and placing of the PBA-6a* and AR-8000 mixes at the RFS.

2.1.5 Development of Improved Rehabilitation Designs for Reflection Cracking (Goal 9 [SPE 4.10])

Similar to the Goal 3 mix fatigue tests mentioned previously (see Section 2.1.1), data are needed for future use of mechanistic-empirical design procedures. To provide that data and to meet more immediate needs, the overall purpose of Goal 9 is to investigate the reflection cracking performance of conventional asphalt concrete together with asphalt rubber and other modified binder mix overlays placed on cracked and/or jointed pavements and to develop tests, analysis methods, and design procedures to mitigate this type of distress.

To evaluate the performance of the various mixes, an accelerated load test program using the HVS together with a laboratory test program was developed (19). This field/laboratory test program consisted of two phases:

- *Phase 1* consisted of constructing a conventional asphalt concrete pavement consisting of a dense-graded asphalt concrete surface (DGAC) and an untreated aggregate base (AB) on the recompacted upper 150 mm (6 in) of the existing subgrade, then subjecting six sections of the pavement to accelerated loading using the HVS to induce fatigue cracking in the AC layer.
- *Phase 2* included placement of a series of mixes as overlays to rehabilitate the cracked test sections. Currently these overlay sections are being subjected to HVS tests to evaluate rutting and cracking in the overlays. Test sections include:

    1. A full-thickness (90 mm) Dense-graded Asphalt Concrete (DGAC) overlay;
    2. A half thickness (45 mm) Rubberized Asphalt Concrete Type G (RAC-G) overlay;
    3. A half thickness (45 mm) Asphalt Concrete Type G-MB4 (RMB4) overlay (with an asphalt rubber binder meeting the requirements for grade MB4);
    4. A full thickness (90 mm) Asphalt Concrete Type G-MB4 (RMB4) overlay (with an asphalt rubber binder meeting the requirements for grade MB4)
    5. A half thickness (45 mm) Asphalt Concrete Type G-MB-15 (RMB-15) overlay (with an asphalt rubber binder with approximately 15 percent rubber)
    6. A half thickness (45 mm) MAC-15 overlay (with an asphalt rubber binder with approximately 15 percent rubber)

Phase 1 and the rutting studies of Phase 2 were completed during the 2000–2004 period. This section includes a summary of the completed work.

Results of the HVS and the laboratory test programs are expected to provide (1) comparisons of the performance of the three modified binder (MB) products with RAC-G and DGAC control overlays and (2) a measure of the relative performance of mixes containing the different modified binders. Results will be used in the development of the mechanistic-empirical (ME) design procedure being developed in SPE 4.1.

Results from the Phase 1 tests include the following:

1. Design and as-constructed thicknesses differed somewhat:
    a. AC: design, 90mm; as-constructed, 79–89mm
    b. AB: design, 410mm; as-constructed, 337–352mm
2. Closely-spaced HWD testing assisted in the location of the six test sections and provided detailed measurements of the moduli of the various test layers as follows: AC, average – 2035 MPa , std. dev. 103 MPa; AB, average-283 MPa, std, dev.-103 MPa; subgrade, average – 98 MPa, std. dev. 37 MPa.
3. Design ESALs (TI-7), 131,000 reps.; HVS test results, 78,500-970,000 reps.
4. Performance measures for the sections included:
    a. Measured crack density, 4.1 – 8.1 m/m^2; measured rut depths, 3.8 – 15.3mm

b. Repetitions to failure based on: combination of fatigue cracking and rutting, four sections; only fatigue cracking, two sections.

Variation in ESALs to failure depended, in part, on the periods when the HVS tests were conduced. Results indicated that the sections tested during the dry/warm season lasted longer than those tested during the wet/cold season when higher moisture contents occurred in the aggregate base.

Following placement of the overlay sections for the Phase 2 study, rutting tests were performed on test sections in the overlays away from the cracked test sections in the existing pavement since the areas directly over the cracked sections have been or will be used for the reflection cracking study. For the rutting studies, HVS tests were conducted when the pavement temperature at a 50 mm (2 in.) depth was 50°C using a 40 kN load on dual tires at 710 kPa tire pressure. Unidirectional loading was used for these tests.

A summary of the test results are as follows:

Table 5. Summary of Goal 9 Overlay Rutting Studies

Goal (SPE)	Mix	Overlay Thickness mm actual/design	HVS applications to 12.5 mm rutting[b]
Goal 9 (SPE 4.10)	DGAC	97/90	>10,000
	RAC-G	50/45	5,800
	MB 15	44/45	3,000
	MB 4	48/45	3,000
	MB 4	90/90	1,800
	MAC 15	46/45	1,400
Goal 3	DGAC	75[a]	>25,000
	RAC-G	38[a]	>20,000
	RAC-G	62[a]	>20,000

a. Design thickness
b. Maximum rut depth

It will be observed that these test sections reached a rut depth of 12.5mm (0.5 in.) at fewer load applications than the mixes used in the Goal 3 study. Until trench section studies are dug when all of the tests have been completed, specific conclusions cannot be drawn. However, from observation of the rutting in some of the sections, selection of binder contents may require different criteria (and test methodology) for future mix designs using these binders.

2.1.6 Influence of Asphalt Binder Properties on the Fatigue Performance of Asphalt Concrete Pavements (Pacific Coast Conference on Asphalt Specifications [PCCAS])

The purpose of this study is to evaluate different asphalt binders with different fatigue parameters and assess their performance as measured by flexural beam fatigue tests. Asphalt beams were prepared by PRC staff. This study was funded primarily by DOTs (including Caltrans) through a pooled fund study with Arizona as the lead state and industry members of the PCCAS. Nevertheless, the results are important to Caltrans, particularly since the study deals with a concern raised a number of years ago regarding the fatigue requirement in the AASHTO PG Binder Specification (20). A summary of the results of the study are contained in Reference (21).

The study included the following elements:

- Selection of nine representative binders used by PCCAS participants. These included the following: two AR-4000 asphalt cements (California Valley and Coastal sources), AC20P polymer modified asphalt (used by the Nevada DOT), PBA-6a* (modified binder), PG 70-28 (modified binder), and a series of PG-graded neat asphalts that included PG 52-28, PG 64-22, PG 64-28, and PG 76-16.

- Development of binder test data including: (1) test data according to the AASHTO 320-03 (MP-1) binder specification; (2) determination of G*sinδ over a range in frequencies at three or four temperatures in the range 5°C to 30°C; and (3) molecular weight distributions using size exclusion chromatography (SEC).
- Preparation and fatigue testing of mixes containing the nine different asphalt binders using a dense-graded aggregate, one binder content, and one degree of compaction (air-void content of 6 percent).
- Analysis of the fatigue performance of the mixes for three pavement structures in four representative environments for the region encompassed by the participants in the PCCAS.
- Evaluation of various binder parameters versus traffic (three levels associated with the three structural pavement sections) and environment on fatigue response.

The pavement sections used in Reference (22) for performance estimates (in terms of ESALs) were designed according to the Caltrans design methodology for asphalt concrete pavements. For performance estimates, multilayer elastic analysis was utilized and only those pavement sections with a subgrade stiffness of 26.5 MPa (~3800 psi.) were used. The stiffness selected would be considered representative of a weak subgrade (Stabilometer R value = 5).

Asphalt concrete stiffnesses were determined using the regression equations for stiffness obtained from flexural stiffness measurements at three temperatures and at 10Hz. The asphalt concrete thickness varies from 90 mm (3.6in.) for 0.13 x 10^6 ESALs (low traffic volume) to 405 mm (16.2 in.) for about 73 x 10^6 ESALs (high traffic volume).

In this study, the nine binders met the current AASHTO 320-03 (MP-1) binder specifications for fatigue. Moreover, with the exception of the thin pavement structure, the performance of the mixes with the nine binders provided adequate computed fatigue performance in the pavement sections for the four environments considered; i.e., the predicted performance in terms of ESALs equaled or exceeded the design traffic volumes for all three sections at a reliability level of 90 percent.

The binder properties evaluated *did not differentiate* mix performance for the range of asphalt concrete pavement structures used for the analyses.

For the current specification parameter G*sinδ, there is no consistent pattern of behavior. Similarly, when the *SSV* (shear susceptibility of viscosity) and *SSD* (shear susceptibility of the phase angle, delta) parameters were evaluated, the binders exhibiting good performance according to the Caltrans PBA specification criteria included three of the nine materials that did not perform as well in the simulated pavement structures as a number of the binders in the poor performance zone.

Based on the results of this study, which are similar to those reported in an earlier PRC study (20) as well as by other investigations, the current AASHTO MP-1 criterion does not ensure adequate performance or preclude it for the nine mixes of three representative pavement structures for a wide range of environmental conditions. The mixes containing the nine binders (short-term aged mixes) performed well in adequately designed structural sections, even though there was a wide range in the abilities of the mixes containing these binders to accommodate traffic as measured in ESALs. For example, for the section containing the 255-mm (10.2 in.) thick AC layer, the computed ESALs ranged from 1.90×10^8 to 9.55×10^{14} ESALs (design ESALs range from 4.5 to 6.0×10^6) in the Santa Barbara, California environment. This example emphasizes the importance of having good design information, e.g., fatigue test data, to develop cost effective designs.

The recommendation resulting from the study is to maintain the current specification requirement for fatigue even though, as noted above, it does not guarantee good performance.

2.1.7 Investigations of Asphalt Concrete Moisture Damage (Goal 8 [SPE 4.9])

In 2001, Caltrans embarked on a project partnering with the asphalt industry to mitigate reported problems of distress in AC pavements attributed to moisture sensitivity through the Moisture Sensitivity of Asphalt Concrete Task Group (MSACTG). The PRC staff has served on a series of sub-task groups in this partnered effort. Activities have included: the development of a systematic procedure to identify moisture sensitivity distress in the field which includes a field survey of projects to develop data for a moisture sensitivity database; development of a testing and treatment matrix as a function of environmental risk; and the development of training courses (six and two-hour courses) for Caltrans and industry staff (23). Because of the concern with current laboratory procedures used to evaluate the susceptibility of mixes to moisture, the PPR Program also initiated an investigation to develop an improved test methodology for mix evaluation.

The procedure to identify moisture sensitivity distress in the field was included in the moisture sensitivity training course (23) taught at two locations during spring 2004 (San Diego and Sacramento).

The *field survey of projects* to develop data for the Moisture Sensitivity Database includes 200 sites throughout the state. At sixty-three of the locations (approximately one-third of the sites) detailed coring was planned for the period June 2004 though May 2005. This program included obtaining both dry and wet cores. Measurements on the cores included moisture contents of dry cores and bulk and theoretical maximum densities for all cores. Eighty percent of the sites were selected because distress presumably related to moisture damage was observed; the other 20 percent were considered as “control” sections, i.e., sections showing no surface distress. By June 2004 approximately 120 of the sites were visited. However, since the list of sites selected for coring was approved by a subcommittee of the MSACTG in late May 2004 only a few locations were completed prior to June 30, 2004 (the remainder of the sites were cored in the period July 2004–May 2005).

Preliminary analysis of the data suggests that high air-void contents in the mixes, which permitted water retention, contributed significantly to moisture-related distress. It is likely that these data will reinforce earlier recommendations stressing the importance of improved AC mix compaction at the time of construction.

The laboratory test program included: an evaluation of the Hamburg Wheel Tracking Device (HWTD); development of a flexural fatigue test on saturated beam specimens to evaluate moisture sensitivity effects; comparisons among the results of tests with the HWTD, flexural fatigue test results, and TSR results using CTM 371. Results of these tests will be completed in the 2004–2005 period.

Completed test results using the HWTD suggest the following: (1) the current test procedure does not clearly distinguish mixes with different degrees of moisture sensitivity; and (2) the test may overestimate the performance of mixes containing conventional asphalt and underestimate performance of mixes containing modified binders.

2.2 Concrete – Materials and Rigid Pavement Studies

As with the asphalt pavements studies, a series of HVS and laboratory tests have been conducted. HVS testing for concrete pavements has included the following:

1. Fast-setting hydraulic cement concrete (FSHCC) jointed pavements on SR-14 near Palmdale, California
2. Dowel-bar retrofitted plain jointed concrete pavement on both US 101 in Ukiah and on SR-14 at the Palmdale site.

A series of laboratory and field studies on concrete mixes were initiated at the same time as the SR-14 HVS test program and included:

1. Studies of behavior of FSHCC, including the strength, stiffness, fatigue, shrinkage, thermal expansion, and durability characteristics;
2. Evaluation of the software program *HIPERPAV*; and
3. Evaluation of the concrete maturity concept.

The laboratory test program on concrete durability has included a study of sulfate resistance on portland cements as well as fast-setting hydraulic cements (summarized in Reference [24, 25]). This program has also included studies of alkali-silica reactivity (ASR), concentrating in the 2000–2004 period on laboratory testing using two different ASTM tests — C 1260 and C 1293.

Associated with the field doweled-joint investigation is a laboratory study to evaluate the mechanical properties and corrosion resistance of various types of dowel bars. Included in this study is the evaluation of segments of concrete pavement taken in the vicinity of a joint that was dowel-bar retrofitted by the Washington State Department of Transportation (WSDOT) approximately eleven years prior (1992) to the sampling date.

Results of the completed investigations as well as the results of completed analytical studies associated with this test program, particularly those related to the SR-14 HVS tests, are summarized in this section.

2.2.1 Evaluation of Rigid Pavement Long-Life Rehabilitation Strategies (LLPRS-Rigid) (Goal 4 [SPE 4.2])

Caltrans' LLPRS, formulated in 1998, included the use of FSHCC to permit sections of rehabilitated concrete pavements to be opened to traffic within four (4) hours of placement. To provide support for this aspect of the LLPRS, two FSHCC pavement test strips — one on the North Tangent and the other on the South Tangent – were constructed on SR-14 near Palmdale. A description of the test sections and instrumentation incorporated in the FSHCC slabs as well as the HVS test plan are described in References (26, 27). The South Tangent sections were used to evaluate the fatigue response of the FSHCC. The North Tangent sections were used to evaluate both load and environmental effects on concrete slab performance with various design features (no dowels plus AC shoulders, dowels plus CC shoulders, and dowels plus widened lanes), and with joint spacings of 3.7, 4.0, 5.5, and 5.8 m (12, 13, 18, and 19 ft.).

The laboratory studies included tests on mixes containing six different hydraulic cements from three categories: (1) portland cement (Type I/II, two Type III materials designated III-A and III-B); (2) two calcium sulfoaluminate cements (CSA-A and CSA-B); and (3) calcium aluminate cement (CA). Construction closure duration and desired time to reach the minimum flexural strength are shown in Table 6.

Table 6. Closure Duration and Time to Reach Minimum Beam Strength for Each Mix

Mix Name	**Cement Type**	**Intended Construction Window**	**Desired Time to Reach Minimum Strength**
Type I/II	Portland Cement Type I/II	New construction, or long-term continuous closure	28 days
Type III-A	Portland Cement Type III	55-hour weekend, or short-term continuous closure	12 to 16 hours
Type III-B	Portland Cement Type III	55-hour weekend, or short-term continuous closure	12 to 16 hours
CSA-A	CSA	7- to 10 hour overnight, or 55-hour weekend	4 to 8 hours
CSA-B	CSA	7- to 10 hour overnight, or 55-hour weekend	4 to 8 hours
CA	CA	7- to 10 hour overnight, or 55-hour weekend	4 to 8 hours

2.2.1.1 SR-14 Pavement Test Program

The South Tangents sections were tested first. A total of twelve HVS loading tests were conducted including: 100-mm layer, three sections; 150-mm layer, five sections; and 200-mm layer, four sections. Loads ranged from 20 to 100 kN (4.5 to 22.5 k) and repetitions to failure from approximately 6×10^4 to 1.2×10^6 depending on the magnitude of the applied loads. HVS loading was bidirectional with the tire located at the edge of the pavement. Failures were predominately corner breaks or longitudinal cracks (one slab in the 200 mm tests exhibited mid-slab transverse cracking).

The North Tangent sections, all with 200-mm-thick concrete layers, included ten HVS test sections: four sections with asphalt shoulder and no dowels, three sections (3.66-m lane width) with doweled joints and tied concrete shoulders; and three sections (4.26-m lane width) with AC shoulders and dowels. Six of the ten sections were subjected to bidirectional loading; unidirectional loading was used for the other four.

While a temperature control box was used on some of the sections, it was concluded that its use is not merited since changing the surface temperature of a relatively small area within the total area of influence complicated the thermal regime.

2.2.1.1.1 Results of HVS Tests

Results of the field performance on the pavements constructed using FSHCC can be summarized as follows (28, 29, 30):

1. Shrinkage must be controlled (adhering to the current Caltrans SSP requirements $\leq$0.053 percent at seven days) and monitored during construction.
2. Control of curing conditions is important.
3. Friction between the base and the concrete slab should be minimized.
4. In environments like the Palmdale site (high desert, Southern California) flexible (i.e., asphalt concrete) bases are preferred over rigid (i.e., lean concrete) bases to permit relaxation of environmentally related stresses.

Results also emphasized the importance of the use of dowels, non-erodable bases, and tied concrete shoulders or widened outside lanes (4.26 m [14 ft.]) with asphalt concrete shoulders. Also, the effectiveness of dowels in restricting curling movements along transverse joints from daily temperature changes in the high desert environment was demonstrated. A similar result was observed with tie bars at longitudinal joints. In addition the results indicate that joint spacings in the high desert environment should not exceed 4.6 m (15 ft.).

2.2.1.1.2 Results of Analytical Studies

The SR-14 sections demonstrate conclusively that slab curling must be considered in concrete pavement design and analysis. Results of the analyses conducted on the test sections indicated that this phenomenon has a significant effect on the load carrying capacity and fatigue life of a concrete pavement. Several factors contribute to the total amount of this curing including: temperature gradient, drying shrinkage gradient, moisture gradient, and creep. The cumulative effect of these components can be defined by an effective built-in temperature difference, EBITD (31). The EBITD is a linear temperature difference between the top and bottom of a concrete slab that produces the same deflection response as the cumulative effects of a nonlinear built-in temperature gradient, nonlinear moisture gradient (reversible), and nonlinear shrinkage gradient, reduced over time by creep.

A procedure was developed to calculate the EBITD using backcalculation based on loaded slab deflections obtained from the falling weight or heavy weight deflectometers (FWD or HWD). Results of these analyses indicated that (32):

- The slabs tested at Palmdale had high EBITD values (-20°C to -35°C) for sections with low restraint (undowelled Sections 519FD through 535FD) and low-to-moderate EBITD values (0°C to -20°C) for sections with higher restraint (dowelled Sections 537FD though 541FD). Restraints due to dowel bars appears to restrict the upward curl of the slabs during early age, likely through tensile creep mechanisms; this results in lower EBITD for dowelled slabs. Large values for the EBITD measured for the Palmdale test slabs resulted from the use of fast-setting, high-early-strength concrete with superplasticizer and approximately 400 kg per cubic meter of high shrinkage cement. The slabs were paved during daytime and in desert conditions with low ambient humidity and high wind speed, which also contributed to the high EBITD.

- The slabs' self-weight also acts as a restraint on its curling. Among slabs with thicknesses greater than 100 mm, the 150 mm slabs exhibited greater EBITD than 200 mm slabs.
- On all sections, the corners of the slab had a larger EBITD compared to the mid-slab edge.
- The doweled sections had more uniform restraint at the joints, resulting in a similar EBITD for both sides of each slab. The variation in EBITD among undoweled slabs was greater because EBITD depends on aggregate interlock restraint, which in turn is not uniform between slabs.

Results from these tests were used to evaluate various fatigue damage models together with the linear summation of cycle ratios cumulative damage hypothesis (a.k.a. "Miner's hypothesis"). Analyses indicate that test slabs cracked at cumulative damage levels significantly different from unity. Accordingly, new models were formulated that incorporate stress range and loading rate along with peak stresses. Coefficients for these models were developed to incorporate transverse cracking, longitudinal cracking, and corner breaks.

The models can also be used for slabs that exhibit high negative EBITD. For slabs susceptible to high shrinkage gradients, microcracking resulting from restraint stresses during early ages can significantly reduce the slab's nominal strength. This early-age restraint can vary considerably from one slab to another. To recognize this variability a procedure to model slab strength reduction as a function of slab size was developed using nonlinear fracture mechanics. This resulted in the introduction of a parameter called the "effective initial crack depth" to characterize the early-age surface microcracking.

To recognize the influence of the above noted factors, analyses have been incorporated into a software analysis program, *RADICAL* (31).[5] This program was developed in order to analyze longitudinal and corner cracking, which are not considered in the NCHRP 1-37A Design Guide. It is expected that *RADICAL* will be used as a supplement to the NCHRP 1-37A Design Guide for mechanistic-empirical analysis of plain jointed concrete pavement. *RADICAL* can be used in conjunction with the concrete thickness design procedure in the *New Design Guide* (NDG). *RADICAL* has the advantage over the NDG in that it permits slab thickness design to mitigate both longitudinal and corner cracking as well as mid-slab cracking (the only mode considered in the NDG).

The SR-14 also included a study of load transfer efficiency (LTE) at joints, which provided the basis for the general observation stated earlier (30). Even after the application of aggressive 150-kN loading onto the test sections, no obvious LTE deterioration could be detected from the sections constructed with dowels, tie bars, and widened lanes. Although extensive cracking developed during the testing, no significant drop in LTE values could be detected after the formation of the cracks. This is an indication of the effectiveness of the dowels to transfer load across joints, even with extensive joint deterioration. The dowels also have a significant influence in controlling slab edge movements.

In contrast to this, the plain aggregate interlock sections (no dowels or tie bars) experienced significant reductions in LTE after the appearance of corner cracks. Significant reduction in pavement life as compared to the reinforced jointed sections was observed. It is recommended that dowels be used in plain jointed concrete pavement to maintain LTE and minimize faulting.

In general the SR-14 field test program and the associated studies have provided significant results which both reinforce some current Caltrans practice and point the way to improved design and construction practices that can contribute significantly to the Caltrans goal of longer life pavement design and rehabilitation.

---

[5] Hiller, J. E. and J. R. Roesler. "Determination of Critical Concrete Pavement Fatigue Damage Locations Using Influence Lines." *Journal of Transportation Engineering*, ASCE, August 2005, pp. 599–607.

2.2.1.2 Strength, Stiffness, Shrinkage, Thermal Expansion, and Fatigue Characteristics

For the six (6) mixes evaluated, design variables included cement type and admixtures, water/cement ratio, and curing conditions. Each of the performance-related properties tested was measured under various conditions to study the effects of important mix design and construction variables. References (33 and 34) detail the results of these studies.

Conclusions from the results of the tests to measure strength, stiffness, shrinkage, and thermal expansion characteristics are as follows:

1. Cement type, curing condition, and water/cement ratio should all be considered important for concrete mix design since all influence strength gain. Cement type is the most important factor, assuming an optimized mix design. Curing conditions (moisture and temperature) are next in terms of influence on concrete strength, followed by water/cement ratio, e.g., a 10-percent increase in water content from the target value can reduce mix strength by more than 10 percent.
2. Compressive and flexural strengths respond differently to environmental factors. A cold environment causes the greatest reduction in compressive strength while a dry condition is most detrimental to flexural strength. Thus, there is not a unique correlation between the two kinds of strengths. A reasonably accurate prediction of flexural strength from compressive strength, or vice versa, is only possible within a range of curing conditions, and does not include many temperature environments encountered in the field. Although the compressive strength test has less variability than the flexural strength test, the tests are not interchangeable if precise strength data are required.
3. The correlation between elastic modulus and compressive strength corresponded to the relation presented in ACI-318 for the portland cement Type I/II mix at twenty-eight days under the standard moist curing. Additional data are needed to extend the conclusion to non-portland cement concrete. The study has shown, however, that for portland concrete cement the correlation at other ages or under other curing conditions does not conform to ACI-318.
4. While mix design has the greatest effect on concrete strength gain, the curing condition is a more important factor in shrinkage than the mix design. Generally, high temperature and low moisture result in greater shrinkage. However, the extent to which temperature and moisture affect shrinkage depends on the cement type. Calcium sulfoaluminate cements from different manufacturers exhibited different amounts of shrinkage due likely to their differences in chemical compositions.
5. Coefficients of thermal expansion by two methods of measurement (ASTM C 531 and U.S. Army Corps of Engineers Test CRD-C39-81 [termed herein CRD])] ranged from 8 to 12×10^{-6}/°C for the group of six mixes included in this study. These results correspond to data reported in the literature. The results of this study showed that the CRD test uses a more reasonable temperature range to measure the coefficient of thermal expansion. According to the CRD method, the mixes containing portland cement have slightly lower coefficients of thermal expansion than those with calcium sulfoaluminate.

Results of the flexural fatigue tests provided the following conclusions:

1. Fast setting concrete mixes (Type III portland cement, calcium sulfoaluminate, and calcium aluminate) exhibit fatigue resistances, i.e., number of cycles to failure, which are similar to or higher than that of the standard Type I/II concrete mix.
2. At the stress ratio of 0.85 the concrete mix with Type III-A cement exhibited the largest fatigue life among all mixes tested. However, at a stress ratio of 0.70, all mixes exhibited similar fatigue lives. The ratio of the log of the average number cycles at 0.85 stress ratio for the mix with Type III-A cement to that of the mix with Type I/II cement is approximately 2 (based on the average of tests on four beams of each material).

3. The mix with Type III-B cement exhibited a shorter fatigue life at the same stress ratio when compared to the mix with Type III-A cement; however, the fatigue life of the mix with Type III-B cement was comparable to that of the standard type mix.
4. The mix with cement CSA B had a slightly larger fatigue life at the same stress ratio when compared to the mix containing cement CSA A, although the difference was not statistically significant. Both mixes with the CSA cements exhibited similar lives to that for the mix with the Type I/II cement.
5. The mix with CA cement showed a larger variation between test specimens than the other mixes. However, the results indicate that the scatter is about the same as for the mix with the Type I/II mix.

2.2.1.3 Accelerated Laboratory Testing for Alkali-Silica Reaction (ASR) (Goal 4 [SPE 4.2])

Alkali-silica reactivity of aggregates in California may cause deterioration of rigid pavements if no preventative measures are used. Some tests used to screen aggregates for potential alkali-silica reactivity are ASTM C 1260 and ASTM C 1293. Both tests are accelerated test methods (tests subjecting materials to conditions that increase the rate of reaction as compared to the rate which would occur in the field). In some cases, such accelerated tests may cause reactions that would not occur in the field, leading to erroneous classification of an aggregate as reactive.

ASTM C 1260 is aggressive because of the high temperature and the high concentration of hydroxide used in the test. A criticism of the test is that it may classify good aggregates as reactive; however, results are obtained in only fourteen days.

A more realistic, yet still accelerated test is ASTM C 1293. The lower concentration of hydroxide and the lower temperature at which the test is run are not as aggressive as the ASTM C 1260 conditions. ASTM C 1293 is more representative of actual field conditions since the test is performed on concrete specimens, unlike ASTM C 1260, which is performed on mortar specimens. However, the major drawback of this test is that it requires a year to complete.

ASTM C 1293 requires high-alkali content cement. This cement was difficult to find in the Western region of the United States, and had to be shipped from Pennsylvania. In addition to problems caused by the lack of a readily available local source for this cement, the cost of shipping such a material from the east coast imposes a substantial cost burden.

Objectives of this investigation (35) have been to:

1. *Compare standard tests.* Identify similarities and differences among results from ASTM C 1293 and ASTM C 1260 performed on a set of the same aggregates.
2. *Develop and evaluate a modified ASTM C 1293 test.* Investigate whether cement available locally in the State of California can be used with the addition of sodium hydroxide to perform a modified ASTM C 1293 as an alternative to importing the expensive high-alkali content cement specified in ASTM C 1293.
3. *Evaluate and compare reactivity phenomena of ASTM C 1293 and ASTM C 1260.* Use microstructural analysis to determine whether the reactions exhibited by ASTM C 1293 and ASTM C 1260 are similar and just occur at different rates or whether the reactions themselves are different.

Aggregates from four different quarries in California were used for this study to prepare specimens. Tests included ASTM C 1260, ASTM C 1293, and a modified version of ASTM C 1293 in which a low-alkali cement was used with added sodium hydroxide. Table 7 provides comparisons among the different tests conditions. Microscopy was used to assist in evaluating the test results. Two of the aggregates were obtained from San Francisco Bay Area sources and two were obtained from Southern California sources.

Conclusions from the research are as follows:

1. *Comparison of Standard Tests.* Results from ASTM C 1260 and ASTM C 1293 indicate that a finding of reactivity using the quick and inexpensive ASTM C 1260 test should be followed by an evaluation using the more lengthy and costly ASTM C 1293. If an aggregate fails both tests, it has a high probability of being reactive in the field.
2. *Evaluation of Modified ASTM C 1293.* The use of the modified ASTM C 1293 (use of a locally available, low-alkali cement with added hydroxide ions) showed that the same conclusion could be drawn as when the standard test is used. The low-alkali cement also seemed to intensify the expansion value for the reactive aggregate only.
3. *Differences in reactivity phenomena of ASTM C 1293 and ASTM C 1260.* The microstructural evaluation of two of the aggregates (sources C and D) found that ASTM C 1260 and ASTM C 1293 cause different phenomena in these aggregates. Because of the high temperature and full saturation used in ASTM C 1260, expansion occurs in the aggregate. The lower temperature and hydroxyl content used in ASTM C 1293 result in cracks forming along the boundary between the aggregate and hardened cement paste, which then propagate through the paste. ASTM C 1260 is a very aggressive test that may identify an aggregate as reactive even though it may never react under conditions more typical of those occurring in the field. This is the basis for recommending that a finding of reactivity with this test should be followed by testing with ASTM C 1293.

Table 7. Comparison of ASTM C 1260, ASTM C 1293, and Field Conditions

Parameter	**Test**			
	Standard Test ASTM C 1260	**Standard Test ASTM C 1293**	**Modified Test ASTM C 1293**	**Typical Field Conditions**
Duration of Test	14 days	1 year	1 year	~5 years or more for ASR to occur
Material Tested	Mortar	Concrete	Concrete	Concrete
Specimen Dimension	25 x 25 x 285 mm	76 x 76 x 285 mm	76 x 76 x 285 mm	Large slabs and structural sections
Moisture Condition	Submerged in solution	100% humidity	100% humidity	Varies depending on climate region
Alkali Exposure	Submerged in 1 mole of NaOH	Total alkali content 1.25% occurring in cement	Total alkali content of 1.25% obtained by adding NaOH to mix water with low alkali cement obtainable in California.	Depends on naturally occurring alkali in pore fluid
Temperature	80°C	38°C	38°C	Varies depending on climate region

Results of the various tests are summarized in Table 8.

Table 8. Comparative Performance

Aggregate Source	Historical ASR Performance	ASTM C 1260 at 14 days	ASTM C 1293 at 1 year	Modified ASTM C 1293 at 1 year
A	No documented cases of ASR in field concrete	Non-reactive	Non-reactive	Non-reactive
B	Not available	Inconclusive	Non-reactive	Non-reactive
C	No documented cases of ASR in field concrete	Reactive	Non-reactive	Non-reactive
D	New quarry, no historical data	Reactive	Potentially Reactive	Potentially Reactive

Based on the results of this investigation the following three recommendations have been made to Caltrans:

1. The current Caltrans practice of using ASTM C 1260 as a tool for evaluating the reactivity of aggregates, followed by testing with ASTM C 1293 when an aggregate is found to be reactive by ASTM C 1260 should continue.
2. The investigation regarding the use of locally available, low-alkali cement with added hydroxide ions (modified ASTM C 1293) should be extended to a wider number of aggregates, and if the results show that this modified version of the test performs well, the modified method should be adopted by Caltrans in place of the current standard ASTM test.
3. The modified ASTM C 1293 test should then be submitted to ASTM for approval.

2.2.2 Dowel Bar Retrofit of Rigid Pavements (Goal 7 [SPE 4.8])

The overall objective of this research goal has been to establish whether the dowel bar retrofit (DBR) rehabilitation strategy can provide adequate pavement performance and if it is cost effective compared to alternative strategies. To achieve this objective specific studies have included (36):

- Determination of the feasibility of the dowel bar retrofit rehabilitation treatment based on the existing condition of the concrete slabs including level of faulting, fatigue cracking, corner cracking, and age of the slabs.
- Evaluation of the load transfer restoration provided by the dowel bar retrofit treatment.
- Determination of the expected life of the treatment based on condition of the slabs at the time of rehabilitation, restored load transfer efficiency, traffic, and climate region.
- Determination of the mechanism(s) of failure of the dowel bars at the end of their useful life.
- Development of a recommended best practice for dowel bar retrofit treatment considering design, materials, and construction.
- Provision of a dowel bar retrofit lifecycle cost analysis procedure for comparison with competing strategies based on existing pavement condition, climate region, and traffic.

This study has included the following investigations, all of which have not been completed at the date of this report:

- Field accelerated pavement testing with HVS 2 at two sites.
- At Ukiah on US-101 to evaluate the efficacy of dowel bar retrofitting of joints (and cracks) in an existing PCC pavement which had been subjected to traffic (>4.0 x 10^6 ESALs) for a period of thirty-four years (1967–2001). This project involved participation by staff of the

State of Washington DOT (WSDOT). (N.B. This represents an excellent example of partnering. In this case, the PPR Program utilized the expertise of the WSDOT in this area to carry out the study. At the same time the study provided WSDOT with information on the expected longer-term loading performance of this form of concrete pavement rehabilitation). The test program was conducted during the period January–May 2001 (37).

- At Palmdale on the SR-14 test sections, the dowel bar retrofitting study included the use of epoxy-coated bars, hollow-stainless steel bars filled with grout, and fiber-reinforced polymer (FRP) dowels. While the majority of the tests were conducted using four dowels in each lane (Caltrans practice), two joints were retrofitted with three epoxy-coated steel dowels (WSDOT practice). (36)
- Laboratory study to permit evaluation of dowel bar corrosion and the stiffness and strength characteristics of additional types of dowel bars not included the field studies. This study is still in progress, and the results were expected in spring 2005.

2.2.2.1 U.S. 101 – Ukiah, Mendocino County Study

This study, on the northbound truck lane with joint faults in the range 6 to 12 mm, included two HVS test sections and two replicate test sections for regular traffic. For one of these test sections the joints were retrofitted with epoxy coated steel dowels. One HVS test section and one replicate test section for regular traffic were designated control sections and were not retrofitted with dowels. All six sections were subjected to diamond grinding to remove faulting.

The control test section (555FD) was subjected to 169,679 load repetitions; dowel bar retrofitted test sections (553FD, 554FD) were subjected to 433,986 and 472,578 load repetitions, respectively. On each section the first 80,000 load repetitions of a 40 kN load was used followed by a 90 kN loading. Because of time restrictions for the closure, none of the HVS test sections were loaded to complete “failure” as defined by cracked slabs or completely degraded dowel bar retrofit assemblies. Load transfer efficiency (LTE), deflections, and cracking were selected as the key performance variables to be monitored during HVS testing. Faulting was not expected because of the bidirectional loading applied and little change in LTE was observed during the loading. Deflection data served as the basis for extrapolating HVS test results to field performance.

All existing slabs in the traffic closure and the test sections were subjected to Falling Weight Deflectometer (FWD) testing both during the day and night (four times over a span of approximately fifteen months).

In general LTE, determined from FWD deflections, was 100 percent at temperatures above 35°C — for both the undoweled and doweled, regardless of its magnitude at lower temperatures. Also, deflection differences between corners and the centerline of transverse joints approached zero at temperatures above 30°C to 35°C. At temperatures below 35°C, a large variance in LTE was observed in the undoweled sections. These results suggest that the majority of faulting damage occurs in California pavements (undoweled) during winter periods and at nights during the rest of the year. For the doweled sections LTE almost never went below 80 percent, and deflections and deflection differences were much smaller than those for the undoweled sections.

Important conclusions from the study include:

1. While the LTE in the undoweled section was not reduced significantly during HVS testing, deflections increased significantly and significant pumping was observed. For the DBR sections, LTE remained constant during loading; however there were measurable increases in deflection at the joints although no pumping was observed. Deflection differences between joints were significant in the undoweled section with little or no differences observed in the DBR sections. These results suggest significant reduction in aggregate interlock in the undoweled section and some aggregate interlock and/or dowel/concrete contact surface degradation for the doweled sections.

2. Results of the tests suggest the DBR sections would permit an additional 1.5 to 2.0 × 10^6 repetitions of the 90 kN load to reach the same joint deflections as the undowelled sections. Based on Caltrans' 4.2 load equivalency factor (Highway Design Manual) this would correspond to an increase of up to 60 × 10^6 ESALs. While this increase in ESALs should be treated with caution at this time, it certainly demonstrates the potential benefits of DBR.
3. Finite element modeling of slabs containing dowels was performed using modifications to the software program *EVERFE* (38), results of which were to be included in a later report. Also a regression equation for faulting referred to as the RIPPER[6] model (39) was evaluated for the US-101 site.

2.2.2.2 SR-14, Palmdale, Los Angeles County

The SR-14 study included four HVS test sections with the following features:

- 556 FD, two transverse joints retrofitted with four epoxy-coated steel dowels in each wheelpath;
- 557 FD, two transverse joints retrofitted with three epoxy-coated steel dowels in each wheelpath;
- 558 FD, two transverse joints and one transverse crack retrofitted with four dowels per wheelpath; one joint and the crack had FRP dowels while one joint had epoxy-coated steel dowels; and
- 559 FD, two transverse joints and one transverse crack retrofitted with four dowels per wheel path; one joint had epoxy-coated steel dowels, one joint had hollow grout-filled stainless steel dowels, and the crack included hollow stainless steel dowels in one wheelpath and epoxy-coated steel dowels in the other.

The HVS test program on SR-14 was completed in March 2003 and the FWD testing in June 2003. All of the data had not been analyzed as of June 2004. However, preliminary analyses indicate the following:

- The HVS and FWD testing indicated that dowel bar retrofit significantly improved the load transfer efficiency and reduced deflections from both loads and environment compared to the undoweled pavements in SR-14 sections. Previous HVS trafficking damaged LTE on undoweled joints, but no significant loss of LTE was found after very heavy trafficking of the HVS on DBR or originally installed dowels. Under FWD testing, the LTE from DBR (four steel dowels per wheelpath) was typically in the range of 85 to 90 percent at lower temperatures before trafficking, whereas for originally installed dowels spaced at 0.3 m across the joint LTE at same temperatures was typically greater than 95 percent.
- Three dowels per wheelpath was found to have significantly lower LTE than four dowels per wheelpath. FRP and grout-filled hollow stainless steel dowels had similar performance to epoxy-coated steel dowels, all with four dowels per wheelpath.
- These results, as well as those obtained elsewhere, demonstrate (using the same spacing centered on the wheelpath) that the performance of plain jointed concrete pavement without dowels can be improved by retrofitting the joints with dowel bars. The results also indicate that four dowels per wheelpath are expected to provide better performance than three dowels per wheelpath, and that FRP and grout-filled hollow stainless steel dowels may provide similar performance to epoxy-coated steel dowels. An extensive laboratory study of FRP dowels is currently underway as noted earlier.

---

[6] RIPPER is an acronym for *R*igid *P*avement *P*erformance.

2.2.2.3 Modeling Studies

Analysis using the RIPPER model for faulting indicated that pavements in climate regions with more days per year with air temperatures greater than 32.2°C (90°F) have the slowest development of faulting. This is due to the closing of joints, greater aggregate interlock, and greater load transfer efficiency (LTE) at those temperatures. The effects on LTE of the higher temperatures were demonstrated at the US-101, Ukiah site. However the model under-predicted the measured faulting at Ukiah for the inputs associated with the site.

The finite element program *EVERFE* Version 2.3 was completed during this period (38). The program provides a 3D finite element analysis tool for calculating stresses, strains, and deformations in rigid pavements caused by traffic and environment. Validation of the program using field data will get underway in the 2004–2008 contract period. *EVERFE* provides, for example, the opportunity to examine the influence of dowel bars of different types as well as dowel misalignment on joint performance.

2.2.3 Analysis of Sensitivity of Plain, Jointed Concrete Pavement (JPC) in California to Early-Age Cracking Using *HIPERPAV* (SPE 3.1)

HIPERPAV is a computer program designed under a Federal Highway Administration (FHWA) research contract to predict early-age behavior of jointed concrete pavements (41). It serves as a design and construction analysis tool for engineers to mitigate cracking in the first seventy-two hours following the placing of new concrete. The program attempts to model to parameters that influence the behavior of concrete pavements and includes the following parameters: mix design, pavement design, construction, and environmental.

A plan has been developed to evaluate the use of *HIPERPAV* by Caltrans to reduce the potential for early-age cracking (41) and includes the following objectives:

1. Evaluation of *HIPERPAV* software, including a critical review of the models in the software, and a sensitivity study of the relative effects of variables included in *HIPERPAV* on early-age cracking for California conditions.
2. Field Validation of *HIPERPAV* in California, including instrumentation and monitoring of slabs on four sites in the California desert, and
3. Development of recommendations for the mitigation of early-age cracking and the use of *HIPERPAV* in California.

Conclusions and recommendations reported herein are based on the completion of the first of the above three objectives. (41)

Although *HIPERPAV* provides accurate qualitative guidelines for a range of certain inputs, it is probably not sufficient for JPC durability prediction for specific projects. Comprehensive durability prediction includes the effects of mechanical, chemical, and thermal degradations after several days of placement of the concrete.

From the sensitivity analyses performed during the study, with the program, it can be concluded that improvement of construction practice has the most significant impact in reducing the risk of early-age cracking. Specifically, proper joint sawing and curing times are key issues for reducing this risk. Overall, the Desert climate region (Daggett) is much more critical for early-age cracking than are the two coastal regions (Los Angeles and Bay Area). However, mix design factors important for the South Coast (Los Angeles) and the Bay Area (San Francisco) regions are less so for the Desert region (Daggett).

In the Desert climate region analysis, the type of aggregate is the primary mix design factor affecting cracking in the pavement. In this case, using gravel (softer) is safer than using granite (harder).

In the South Coast and Bay Area regions, the use of gravel aggregate, fly ash (25 percent), and Type II cement, which is coarser and contains more C_2S, provides a reduced risk of early-age cracking. Higher ultimate strengths obtained by using a lower water/cement ratio also provides a reduced risk of early-age cracking.

In the South Coast and Bay Area regions, it was found that JPC geometry is not particularly critical for early-age cracking if loading is not applied. Other parameters such as time of day of construction and seasonal factors do not show significant impacts on the results.

Based on the study completed to date two recommendations have been made to Caltrans. The first recommends changes to *HIPERPAV* and the second is to modify Caltrans practices to mitigate early age cracking.

Relative to the first recommendation, *HIPERPAV* is limited in its use and applicability for Caltrans. First of all, the range of validity has not been clearly established. Analysis for cases using fast-setting hydraulic cement concrete (FSHCC) has not been developed yet and the models are not adequate for predicting the behavior of Type III mixes. To address these problems, the program application should be extended to FSHCC materials and modeling of autogenous shrinkage.

HIPERPAV software is a deterministic simulation, but there are always risks embedded in the input data. These contain variations in measuring, mixing, etc., accordingly, *HIPERPAV* should include a more comprehensive probabilistic analysis.

The durability prediction for cumulative damage of the pavement is not included in *HIPERPAV*. Given that cumulative damage may have a significant impact on early-age cracking, this should be included in the future version.

In order to better correspond with Caltrans practice, *HIPERPAV* should allow data inputs specific to Caltrans practice, such as beam strengths. These modifications to *HIPERPAV* should then be validated.

Given that the Desert region has the most severe problem with early-age cracking, the second recommendation is that special care should be taken to establish an appropriate design and construction strategy for that region. Among the four main categories of input data, the construction parameters were found to have the largest impact on early-age cracking. Construction practice should be reviewed to ensure proper scheduling of curing and saw cutting of joints during construction.

According to the analysis, aggregate type was the only important mix design variable in the Desert region, so the mix designer should emphasize aggregate type selection. Measurement of coefficient of thermal expansion (CTW) should be considered.

The effect of fly ash content changes depends on the cement type; thus further studies should be performed regarding the influence of fly ash content. *HIPERPAV* predicts that the higher strength concrete with lower fly ash content and low water/cement ratio provides the safest result. To improve mixing, use of a superplasticizer is recommended. A smaller joint spacing is safer than a larger joint spacing; the current Caltrans maximum spacing of 4.6 m is a significant improvement as compared to the previous maximum of 5.8 m.

Overall, the use of *HIPERPAV* as a design tool is worthwhile because it provides a good indication of the correct answers to complex problems that can not be solved intuitively. *HIPERPAV* should not be expected to always predict early-age cracking correctly; however, it does provide guidance in making decisions to reduce the risk of early-age cracking.

2.2.4 Evaluation of the Maturity Method for Flexural Strength Estimation in Concrete Pavement (SPE 3.12)

The objective of this project was to provide Caltrans with information regarding the accuracy and feasibility of the maturity method for the measurement of the concrete flexural strength of pavement slabs. The investigation included: (1) instrumentation of slabs with four different mixes at three concrete pavement construction projects in District 8 to measure maturity; (2) laboratory testing of flexural and compressive strengths to develop maturity-versus-strength curves for each of the four mixes at three different curing temperatures; (3) measurement of maturity in field cast and cured beams and cylinders on each of four field projects, and; (4) testing of strength at several time intervals to compare maturity development in the slab versus field specimens, and to compare strengths predicted from the laboratory maturity curves with beam and cylinder strengths measured in the field specimens. (41)

Temperature histories were measured in the laboratory specimens, field specimens, and field slabs. Maturity was calculated using both the Nurse-Saul (Time-Temperature Factor [TTF]) and Arrhenius (Equivalent Age [t_e]) methods.

The conclusions are as follows (41):

1. Applicability of the maturity method for estimation of flexural strength.
   a. Reasonable correlations have been established between maturity indexes (TTF and t_e) and flexural strength during laboratory calibration of maturity curves for all four mixes included in this study.

   b. Flexural strengths measured in field beams and flexural strengths predicted from the laboratory maturity curves were similar at early ages for the two Type II mixes checked against field beams. For the Type III mix, the field beams exhibited lower strengths than were predicted using the laboratory calibrated maturity curve.

   c. Maturity curves calibrated using data that included later age laboratory beam strengths tended to predict beam strengths that were greater than those measured in the field cured beams in some cases. This may be partly due to the temperature ranges experienced by the field beams. It is possible that these beams developed strength at the extremes of the temperatures used in the calibration of the laboratory maturity curves. It may also be due to differences in moisture conditions between the field and laboratory curing conditions. Field curing under wet sand may produce less humid conditions than the laboratory condition, resulting in lower tensile strengths due to drying shrinkage. However, it is likely that moisture conditions in the slab may be closer to the laboratory curing conditions.

   d. Use of laboratory established compressive strength versus maturity curves to estimate the flexural strength is not recommended because the relation between compressive strength and flexural strength is not consistent across different mixes, and for a given mix may vary considerably with age and other variables.

   e. Results indicate that the maturity method using laboratory flexural strengths can be implemented for estimating flexural strengths for pavement construction. However, additional work is required for successful implementation, especially for Type III and other high early strength mixes.

2. Applicability of the use of the maturity method for Caltrans concrete mixes with special cements and/or chemical admixtures.
   a. Good correlations were found between maturity indexes TTF and t_e and compressive strength of concrete during laboratory calibration of the maturity curves.

   b. Compressive strengths measured in field cylinders and compressive strengths predicted from the laboratory maturity curve matched well for one of the Type II mixes and the Type III mixes. For the other Type II mix (Victorville), the maturity method underestimated the compressive strengths of the field cylinders (i.e., was conservative). These results suggest that the maturity method may be applicable to Caltrans mixes with special cements and or/chemical admixtures.

Implementation recommendations include the following:

1. To calculate maturity:

- The Nurse-Saul (TTF) method provided results similar to the more complex Arrhenius (t_e) method.
- For the mixes considered in this study, the calculation of maturity indexes based on typically assumed values of Activation Energy (E) and Datum Temperature (T_o) appeared satisfactory.
- The experimental determination of E and T_o is recommended for "exotic"/special mixes only.

2. To determine the laboratory calibration:

- Perform the calibration at three temperatures spanning the range of potential field temperatures for which the laboratory calibration curve for that mix may be used. The temperatures of 10°C, 23°C, and 40°C span the approximate range of temperatures encountered on the three instrumented field projects included in this study. This calibration is necessary to be certain that the maturity assumption is true for the given mix. After sufficient field experience is obtained, it may be possible to reduce the laboratory calibration work to one curing temperature.
- Use specimens cured in 100 percent relative humidity conditions.

3. To measure maturity:

- The maturity meter should be installed in the slab close to the shoulder (around 300 mm from the edge) at a 50-mm depth.
- Use of a maturity meter that will provide a complete temperature history, not just the calculated values of one or more maturity indexes at specific ages. With the complete temperature history, the engineer can verify the calculations, double-check the results, and even alter parameters, guaranteeing a greater control of the process.
- Use wireless sensors with a PDA-equipped antenna. Sensors that require wires coming from the slab had the wires cut by construction equipment or laborers tripping over them several times during the study. Several data collection devices left near the slab were damaged by construction equipment or stolen during this study.

4. Continue field testing of beams and cylinders:

- Because of the relatively few projects included in this study, and the high cost of failure of pavements or structures if the maturity method underestimated concrete strength, it is recommended that a limited number of flexural beams continue to be tested for pavements and compressive cylinders for structures. Once sufficient experience is gained with the maturity method, it is likely that the number of specimens to be tested can be reduced considerably.
- Several specimens should be cast from the field mix, cured at 23°C in the laboratory, and tested at several time intervals to confirm that the mix used in the field has a similar maturity curve to the curve developed from materials submitted by the contractor prior to the start of construction.
- Several specimens should be periodically cast and cured in the field. As a check, these specimens should be tested when the critical strength has been estimated to have been achieved in the concrete pavement or structure. Maturity should be measured in these specimens for comparison with the strength predicted from the laboratory curve at the same maturity.

2.3 Construction-Related Activities

In Reference (1), a number of recommendations based on the results of analyses, laboratory tests, and HVS tests were made relative to improved construction practices. These included recommendations related to the compaction requirements for asphalt concrete and to the use of tack coats between asphalt concrete during multiple lift construction.

Both the fatigue analyses and the fatigue performance of the asphalt concrete in the HVS tests emphasized the importance of proper compaction of these layers in the pavement structure. Accordingly, it was strongly recommended that compaction requirements be established to ensure that in-place constructed mix air-void contents do not exceed about 7 percent. This recommendation certainly appears to be reinforced by the moisture sensitivity studies associated with Goal 8 (SPE 4.9).

At the same time, it was recommended that the method specification and relative compaction requirement based on laboratory density be replaced. For example, when using the relative compaction requirement, a reduction in asphalt content from that selected in the laboratory resulted in air-void contents in the range of 10 to 12 percent, even though the method specification or relative compaction requirements were met. The AASHTO T209 "Rice" specific gravity test (ASTM D 2041) was recommended as the replacement procedure. This methodology was also recommended for ARHM-GG mixes used as thin overlays, replacing the current method specification. Currently (2004), the requirement is included in a Caltrans Standard Special Provisions (SSP) and was used to control AC compaction on the I-710 rehabilitation discussed previously (17). Also, the Caltrans version of AASHTO T209 and CTM 309 entitled "Theoretical Maximum Specific Gravity and Density of Bituminous Paving Mixtures," was introduced in June 2004. (42)

In the first four HVS test sections, a weak bond was observed between the first two asphalt concrete lifts. In all cases, this lack of bond was found to significantly degrade pavement performance. The extent to which weak bonding may be prevalent in California pavements has not been determined. The fact that the HVS test pavements were constructed according to standard Caltrans procedures in a controlled environment suggests that a weak bond may contribute to performance problems for in-service pavements under heavy traffic where moisture and temperature fluctuations can also contribute to debonding.

No such slippage was observed in the HVS tests in the overlay sections where a tack coat was used on the existing trafficked pavement prior to the placement of the overlay. Accordingly, the use of a tack coat between all AC layers was recommended and initially implemented in the construction requirements for the I-710 rehabilitation. Recently, the use of a tack coat has become standard procedure.

During the 2000–2004 period, development of performance-related pay factors for asphalt concrete construction (begun in 1997) continued (SPE 4.13). A summary of results obtained during this period is included (43, 44).

Considerable progress has been made with *CA4PRS* (Construction Productivity Analysis for Pavement Rehabilitation Strategies [SPE 4.6], briefly referred to in Section 2.1.4 [45, 46]). In 2003 development of an integrated pavement strategy decision support system was initiated (SPE 4.15). This program includes: (1) studies of cost variance analyses for long-life pavement rehabilitation (LLPR) projects; (2) development of a constrained lifecycle cost analysis procedure; and (3) corridor cost studies to permit development of criteria for selecting LLPR projects based on life-cycle cost analyses (47).

2.3.1 Pay Factors for Asphalt Concrete Construction (SPE 3.1.5 and SPE 4.13)

In 1997, Caltrans introduced the use of a QC/QA procedure in paving contracts using 10,000 or more tonnes of AC. Pay incentives were established on the basis of experience to improve the construction process. These pay factors, developed from experience and by consensus of a number of Caltrans engineers, used asphalt content, degree of compaction, and aggregate gradation. Weighting factors were assigned as follows: 0.3 for asphalt content, 0.4 for degree of compaction, and 0.3 for aggregate gradation parameters. Of this latter parameter, percent passing the No. 200 sieve was assigned a weight of 0.07 of the 0.3 value (approximately 23 percent).

Results obtained from the PPR Program as well as results of other studies conducted by the PRC (48), notably the WesTrack accelerated pavement study (48), have provided the basis for development of performance-related pay factors for fatigue cracking and rutting. The performance model for fatigue resulted from the CAL/APT program (1); the model for rutting is based on results of mix performance at WesTrack (49). For the rutting mode of distress, the system considers the means and variances of asphalt content, air-void content, and aggregate gradation. For fatigue distress, the means and variances of asphalt content, air-void content, and asphalt thickness are included. In estimating fatigue damage under traffic loading, the pavement is treated as a multilayer elastic system. The performance models permit computation of a pavement life, expressed in ESALs, using Monte Carlo simulation (48).

Costs are established using a cost model considering only agency cost consequences of delaying or accelerating the time to the next rehabilitation. For the as-constructed mix, the relative performance (RP) — the ratio of off-target ESALs to target ESALs — is determined for both fatigue and rutting. The shortest RP for the combined RPs (determination of the combined RP is described subsequently) for mix and pavement characteristics considered for a specific distress mode permits determination of the pay factor from the cost model (44).

The performance models have been developed to determine the 10^{th} percentile *in-situ* lives for ruts (15 mm depth) and fatigue cracking (10 percent in wheelpaths) for both expected or on-target construction quality as well as off-target construction quality. The pay factors reflect only the variance attributed to materials and construction.

The pay factors presented reflect full agency cost increments, both for bonuses for superior construction and penalties for inferior construction. Also, the construction quality effect is the date of the first resurfacing/rehabilitation. The RP is determined independently for the rutting and fatigue modes of distress. Since there are a number of factors which influence each distress mode, the combined RPs are determined from the following for rutting and fatigue, respectively:

$$\text{combined } RP_{rut} = RP_{Pwasp} * RP_{Vair} * RP_{P200}$$

$$\text{combined } RP_{fat} = RP_{Pwasp} * RP_{Vair} * RP_{tAC}$$

where P_{wasp} = asphalt content, percent,
V_{air}= air-void content, percent,
P_{200} = percent passing the No. 200 sieve, and
t_{AC}= HMA thickness.

The relative performance that governs the contractor's pay factor is that associated with the shortest life determined from the two distress modes.

An example of the process that can be used to implement performance-based pay factors has been described in Reference (44). Comparisons between pay factors assigned by Caltrans and those determined by the performance-based approach have been made for eighty-plus Caltrans QC/QA projects constructed in 1997.

In order for a decision to be made to change from the experience-based pay factors to performance-based pay factors, extensive field performance data are required. This necessitates the linking of a database containing the initial construction data to the pavement management system containing the field performance data. An excellent example of this tie between materials and construction and field performance data is included in Reference (50).

One of the advantages to the performance-based approach is that it emphasizes the mix and pavement structure characteristics that most affect performance. As an example, the rutting model emphasizes the importance of asphalt content, degree of compaction, and aggregate gradation as defined by the P_{200} fraction while the fatigue model emphasizes degree of compaction, pavement thickness, and asphalt content. While the contractor might consider increasing the binder content somewhat for improved degree of compaction for fatigue, increase of the asphalt content above the design target precludes this because of rutting considerations.

In general, the performance-based approach emphasizes the importance of uniformity in both materials production and placement with reasonable controls placed on inherent variability. Moreover, it emphasizes the importance of adhering to design target values. The methodology also reflects only the materials and construction variance by eliminating the influence of test variance. Study is continuing and recommendations will be given when work is completed.

2.3.2 *Construction Analysis for Pavement Rehabilitation Strategies (CA4PRS)* (SPE 4.6)

CA4PRS (Construction Analysis for Pavement Rehabilitation Strategies) is a constructability analysis software program that has been designed to assist engineers and contractors in estimating the amount of highway pavement that can be rehabilitated or reconstructed for a given project. The program takes into account constraints of pavement materials and design, construction logistics, traffic operations, and time limitations. The development of the software represents a cooperative effort with funding from the FHWA pooled fund SPR-3(098) sponsored by the Four State Pavement Technology Consortium (California, Minnesota, Texas, and Washington). The program has been developed for use as a planning and evaluation tool for Long-life Pavement Rehabilitation (LLPR) Projects. During the 2000–2005 period, the program has been used to assist Caltrans and contractor staff on two rehabilitation projects: (1) I-710 freeway in Long Beach (District 4), and (2) I-15 freeway in Devore (District 8) (51, 52, 53, 54).

The program permits evaluation of many different rehabilitation alternatives for both asphalt concrete (AC) (I-710, Long Beach) and cement concrete (CC) pavements (I-15, Devore). For AC pavement projects such as I-710, *CA4PRS* considers the following parameters:

- Rehabilitation strategy: Crack and seat PCC with AC overlay (CSOL) or full-depth AC replacement (FDAC).
- Construction window: Seven- and ten-hour nighttime closures, fifty-five-hour weekend closures, continuous closure (e.g., seventy-two-hour), or combinations of these.
- Lane closure tactics: Number of lanes to be closed at one time for rehabilitation (includes partial or full closures).
- Materials influences: Cooling time for AC *(Note:* the software program *CalCool*, also developed at the PRC, takes environmental and material factors into account to provide an accurate estimation of AC cooling time and can be integrated with *CA4PRS).*
- Pavement cross-sections: Thickness of AC layers and mix type.
- Logistical resources: Location, capacity, and number of available rehabilitation equipment, including but not limited to excavation equipment, hauling trucks, AC mixing plant(s), hot mix delivery trucks, paving machines, and compaction equipment.
- Scheduling interfaces: Mobilization/demobilization, traffic control time, and activity lead-lag time relationships and buffer sizes.

For PCC pavements, e.g., I-15, considerations include: (1) PCC or FSHCC slab replacement; (2) thickness of concrete slab; (3) widened truck lanes or tied concrete shoulders; (4) base types including LCB or ACB; and (5) concrete curing time.

The proposed work plan, CPM schedules, resource availability, and traffic pattern of the construction equipment are the main inputs to the analysis. Resource availability and construction traffic patterns are treated as constants in a deterministic analysis module and treated as random variables in a probabilistic (stochastic) analysis module, which considers variability of inputs.

CA4PRS has been integrated and combined with a traffic simulation program. By analyzing potential construction and traffic scenarios, the software provides quantitative estimates of the optimal (most cost-effective) construction management and traffic control plans. The software also evaluates different pavement structures and construction windows for construction duration. When combined with traffic delay simulation, pavement structures which maximize construction speed without creating unacceptable traffic delays are determined. Evaluation of the impact of various traffic-handling tactics on construction duration can define a procedure to minimize total traffic delay. These data are vital to achieve the three competing goals of longer life pavement, faster construction, and less traffic delay during freeway reconstruction and rehabilitation projects.

2.3.2.1 I-710 Freeway Rehabilitation

The I-710 freeway rehabilitation construction was accomplished in six construction stages. During the first stage, the median was widened and the old metal beam guardrails were replaced with concrete barriers. The second stage included excavating, widening, and paving the outside shoulders up to the existing pavement grade. The remaining four stages involved the main work of rehabilitating the four full-depth asphalt concrete (FDAC) sections under the overpasses and the two AC overlays of the cracked and seated PCC (CSOL) sections.

Prior to the start of the mainline rehabilitation, the PRC team used *CA4PRS* to estimate that the maximum production capability in the fifty-five-hour weekend closures was one CSOL section (about 1.3 km) and one FDAC section (about 0.4 km). However, the *CA4PRS* analysis indicated that the contractor's initial plan of rehabilitating two FDAC sections and one CSOL section in one fifty-five-hour closure was overly optimistic. The contractor revised his plan before beginning the mainline work to match the *CA4PRS* production estimate.

The original Caltrans time estimate for completing the 4.4 km (26.3 lane-km) project was ten weekend closures. The contractor actually completed the project in eight closures. Use of *CA4PRS* was instrumental in achieving this time savings.

Changes in traffic performance (volume, speed, and travel times) were measured for weekends before and during construction. The results indicate that efforts to inform the public of detours, as indicated in the Caltrans Traffic Management Plan (TMP), resulted in significantly lower traffic demand in the construction work zone (CWZ). Despite initial concerns about traffic delay, there was no significant congestion and traffic operated at free-flow speeds during construction weekends throughout the surrounding network, including the I-710 Corridor, neighboring freeways, and detour arterials. The studies conducted for this project[7] by the PRC team emphasize the usefulness of this approach for transportation agencies and contractors in developing integrated construction and traffic management plans for rapid highway rehabilitation projects that maximize construction productivity and minimize traffic delay in high volume situations.

Overall, the construction productivity data collected indicates that the rehabilitation plans developed by Caltrans and the contractor were accurate and reliable. Almost all rehabilitation activities were completed as scheduled and the freeway was reopened to the public by 5 a.m. Monday after each closure. Traffic measurement data indicate that the Caltrans TMP minimized the impact of construction on drivers.

2.3.2.2 I-15 Freeway Rehabilitation

For the I-15 freeway rehabilitation, *CA4PRS* was used during the planning and design of a project to rebuild 4.2 km of deteriorated PCC truck lanes. Construction of the project was scheduled to start during September 2004. Caltrans decided to implement two single-roadbed continuous closures (about 200 hours for each closure) with round-the-clock operations, the most economical in terms of both agency and road-user (traffic delay) costs compared to ten-hour nighttime weekday closures, fifty-five-hour weekend closures, and seventy-two-hour weekday closures. The scenario selection was based on production schedules predicted by *CA4PRS*, traffic delay analyses with several tools (i.e., the Highway Capacity Manual, macroscopic *[FREQ]*, and microscopic *[PARAMICS]* traffic simulations), and agency cost.

---

[7]Supported by Caltrans and the Asphalt Pavement Alliance through the PPRC.

Table 9 shows the results of these analyses. As seen in this table, compared to traditional ten-hour nighttime closures, the single-roadbed continuous closure scenario requires 81 percent less total closure time, 39 percent less road-user cost due to traffic delay, and 51 percent less agency cost for construction and traffic control.

2.3.2.3 Summary

In both the I-710 and I-15 projects, results of analyses, laboratory testing, and HVS test programs were utilized. As described earlier, for the I-710 project, the design of asphalt mixes and full-depth sections took advantage of mix and pavement design methodology developed during the Strategic Highway Research Program (SHRP) and which subsequently calibrated with HVS tests.

For the I-15 project, the use of widened concrete truck lanes (validated on the SR-14 HVS tests) and asphalt shoulders, rather than tied concrete shoulders, resulted in shorter construction times. In addition, the decision to use HMA as the base resulted from an evaluation of both construction time and environmental stress effects, considerations of which resulted from analyses of the SR-14 test sections.

Table 9. Integrated Comparison of Construction Schedule and Traffic Delay for the I-15 Devore Project

Construction Scenario	Schedule Comparison		Cost Comparison ($M)			Maximum Peak Delay (min.)
	Total Closures	Closure Hours	Agency Cost	User Delay	Total Cost	
72-Hour Weekday Continuous	8	512	16.0	5.0	21.0	50
55-Hour Weekday Continuous	10	550	17.0	10.0	27.0	80
1 Roadbed Closure	2	400	15.0	5.0	20.0	80
10-Hour Night-time Closures	220	2,000	21.0	7.0	28.0	30

2.4 Mechanistic-Empirical Pavement Design and Rehabilitation (SPE 4.1)

While mechanistic-empirical (M-E, or analytically based) pavement and rehabilitation analysis and design developments have been utilized in specific situations, e.g., the I-710 (54) and I-15 (53) freeway rehabilitation projects, there has been a systematic, ongoing effort to develop an improved pavement and rehabilitation design system for both flexible and rigid pavements for Caltrans. Elements of this framework are now in place and training of selected Caltrans staff in the use of this methodology is now underway.

The flexible pavement and rehabilitation design methodology has been programmed by Dr. Per Ullidtz and draws on the extensive knowledge that has been developed in this area over the years. The framework for new design includes both fatigue and rutting considerations utilizing the linear sum of cycle ratios concept (Miner's criterion). The cumulative damage concept for fatigue is similar to that incorporated in the proposed NCHRP 1-37A Design Guide (AASHTO 200X) currently (2004) under evaluation. The methodology being developed in the PPR Program has been directed specifically to California conditions; e.g., AC mix characteristics, traffic load spectra, and environmental conditions. Moreover, the results of the HVS test program as well as the WesTrack Study (49) have played a significant role in development to ensure that the analysis procedure produces "reasonable" results.

Considerations of rutting in the AC layer differ from that in the proposed NCHRP 1-37A Guide (AASHTO 200X). It is based on methodology which had been developed during SHRP and extended based on WesTrack test results and those obtained from rutting tests in the HVS under controlled loading and temperature conditions (55).

The rigid pavement design procedure is patterned after the proposed 1-37A Design Guide (AASHTO 200X) utilizing the traffic, environmental, and mix characteristics for conditions encountered in California by Caltrans. In addition, provision is made, depending on the environment and potential slab curling, to analyze for both bottom-up and top-down cracking not only in the transverse direction at mid-slab, but also in the longitudinal direction and at slab corners. Provision is included for doweled transverse joints, tied concrete shoulders, widened lanes with asphalt shoulders, and various base types (e.g., asphalt concrete as well as lean concrete base). Results of the HVS tests at Palmdale and Ukiah have provided key data to aid in the development of the design methodology (as described in Section 2.3.2.2).

As a part of the M-E program, a number of software programs are under development or evaluation by PPRC staff. These are summarized in Table 10 together with their planned use in the M-E design and rehabilitation methodology.

Table 10. Summary of Software Programs Under Development or Evaluation by Partnered Pavement Research Center (PPRC) to Support Caltrans Pavement Operations

Software Program	What the Program Does	Results and Reports Produced	Information Needed to Run Program NOT Available in Software	Current Status of Programming Validation, Calibration
CA4PRS Ver. 1.0 Programmer: N. Sivanaswaran (consultant)[1]	Analyzes pavement rehabilitation projects for construction productivity	Deterministic and probabilistic estimates of lane-km rehabilitated per closure for different scenarios and constraints	Project geometry; pavement rehab cross-section; process production rates; resources available	Program complete, validated, field calibrated
CalME Ver. 1.0 Programmer: Per Ullidtz (Dynatest)[1]	Design tool for flexible pavement new and rehab design; includes mechanistic-empirical and Caltrans empirical methods	1. Set of designs meeting R-value or Flexible Rehab Manual criteria; check of designs by same criteria 2. Designs meeting simple ME requirements; check of expected life of designs by same criteria 3. Prediction of expected life of designs using incremental ME analysis 4. Prediction of expected life and distress during life using recursive ME analysis	1. Information required for R-value or Flex Rehab Manual design 2. Stiffness, thickness, Poisson ratio for each layer; design life; mix design; field compaction; 3. same as 2, with options to use more complex data 4. same as 2, with options to use more complex data	1, 2 programmed, review, validation, calibration with field data underway 3,4 algorithms and programming under development
2002 Design Procedure Ver. 1.0 Programmers: EREs, Arizona State University[5]	Design tool for rigid and flexible pavement new and rehab design	Prediction of expected life of designs using incremental ME analysis for each distress. Different levels of precision of output depending upon complexity of input data	Flexible and rigid pavement materials properties for each layer, field construction information, damage equations, for each material, axle load spectra, design criteria. Data varies in complexity depending upon level of design, 3 levels of input data.	Programmed. Some review and validation performed. Some calibration on sites distributed across US, few in California

Software Program	What the Program Does	Results and Reports Produced	Information Needed to Run Program NOT Available in Software	Current Status of Programming Validation, Calibration
RadiCal Ver. 1.0 Programmers: J. Roesler, J. Hiller University of Illinois[4]	Rigid pavement damage analysis tool	Prediction of expected fatigue damage of designs at longitudinal edge and transverse joint using incremental ME analysis.	Geometry of structure, shoulder type, temperature gradient, effective built-in temperature difference from FWD, traffic load, and geometry	Programming done for a partial factorial; review, validation, calibration with field data underway
CalBack Programmer: Per Ullidtz (Dynatest)[1]	Tool for analysis of Falling Weight Deflectometer data	Test data from FWD, pavement layer types and thicknesses, temperatures	Elastic stiffnesses of each layer; load transfer efficiency for rigid pavement joints and cracks	Programming done, review and validation underway.
EverFE Ver. 2.3 Programmer: W. Davids (University of Maine)[2]	3-D finite element analysis tool for calculating stresses, strains and deformation in rigid pavements caused by traffic and environment	Stiffness, geometry, thermal contraction coefficient for each pavement layer and dowels, tie bars, thermal gradient, load geometry and mass.	Stresses, strains and deformations in pavement structure.	Programming complete, software reviewed, field validation underway.
LEAP2 Programmer: Shmuel Weissman (Symplectic)[3]	Layer elastic theory analysis tool for calculating stresses, strains and deformation in flexible pavements cause by traffic	Stiffness, geometry for each pavement layer. Load geometry and mass.	Stresses strains and deformations in pavement structure.	Programming complete, software being reviewed.
CDIM Programmer: Ala Mohseni (Pavsys)[1]	Climate databases with user interface to provide probabilities of various rainfall and temperature events	Climate data summarized in a variety of formats and reports, using data from 1960 to 1991. Also creates input files for the Enhanced Integrated Climate Model to predict pavement temperatures.	User selects location and report type desired, no other inputs required.	Programming nearly completed, software being reviewed.
WIMANA Programmer: Qing Lu (PPRC)[1]	Takes raw binary Weigh-In-Motion station data and performs operations to put	WIM data organized spectra for truck types, axle types, axle spacings. Also calculates	Raw WIM data.	Software has been used as a research tool to create WIM databases. Results have been

Software Program	What the Program Does	Results and Reports Produced	Information Needed to Run Program NOT Available in Software	Current Status of Programming Validation, Calibration
	into a format that can be used with 2002DG, CalME and RadiCal	growth rates, lane distribution factors, directional distribution factors.		reviewed. Software intended for use by Traffic Ops to create databases for general use.
Programming Languages: 1. Visual Basic 2. Tickle TK 3. Java 4. MS *Excel* 5. C++ shell with Fortran subroutines				

2.5 Databases

From the outset of the project, it has been necessary to establish databases to filter and store essential results of the laboratory and field investigations (e.g., 56, 57, 58)]. Table 11 lists the databases in use and under development (as of 2004) by the PPR Program Staff. These include:

1. *Heavy Vehicle Simulator Database (PRC-HVS)* contains the results of seventy-four HVS tests completed as of June 2004 (Table 2) and includes a summary of the various measurements taken during the course of each test. This database is an important part of the calibration/validation of the M-E design methodology (Section 2.4) under development.
2. *Seasonal Monitoring Database (Fieldsites.mdb)* includes the results obtained from eleven seasonal monitoring stations [Long Term Pavement Performance (LTPP) type] located throughout California. Data from this database, like the HVS database, provide useful site specific climate data for the pavement design and rehabilitation methodology and permits evaluation of the program *CDIM* listed in Table 10.
3. *Falling Weight Deflectometer (FWD) Database (PRC_FWD.mdb)* includes: (1) results for FWD tests conducted on the various HVS test sections both at the RFS and at the various field sites (SR-14, US-101, SR-89); and (2) special studies such as SR-138 (pavement noise study) and the I-710 postconstruction evaluation.
4. *Laboratory Test Database (Fatigue.mdb, shear, PCC-lab)* contain summaries of the various laboratory tests conducted on the materials used in the HVS test program as well other programs in which the PRC has been involved, e.g., WesTrack Test Road and the Pacific Coast Conference on Asphalt Specifications asphalt concrete fatigue study.
5. *Weigh in Motion Database (WIMData)* contains Caltrans ASC II weigh-in-motion (WIM) data for the period 1991–2003. [N.B. It is planned to transfer this database to the Caltrans Traffic Division Together with the analysis program (Table 10, WIMANA) in September 2004].

Table 11. Databases in Use or under Development by Partnered Pavement Research Center to Support Caltrans Pavement Operations

Database	Software	Contents	Information Included
PRC-HVS	MS-*Access* and *Oracle*	Stores all the HVS test data for all test sections from 1995 to 2004. Has functions that perform: -data quality checks at the time of data loading (check for outlier data, data filtering and data smoothing algorithms); -data summaries, data analysis.	Test section structures, mdd, rsd, profilometer, jdmd, strain gauge, temperatures at different depths in tested sections
FieldSites.mdb	MS-*Access*	Stores information from the 11 weather stations installed in different climatic regions in California. Has functions that check for outlier data when data is loaded. Data is downloaded every 2 months from each site.	Information collected includes: -collected from all sites: wind speed, wind direction, solar radiation, rainfall, relative humidity, atmospheric pressure, air temperature; -PCC sites: strains (Carlson strain gauges), slab corners and joints movement (JDMD), temperature at different depths in the slab, maturity data collected for the first …. days from construction; -Seasonal Monitoring Sites: subgrade pore pressure, subgrade water content, temperature at different depths in the AC layer and 2 depths in the subgrade, FWD tests spring/fall.
PRC_FWD.mdb	MS-*Access*	Stores the Falling Weight Deflectometer data from seasonal monitoring sites, Modified Binder project, Goal 1, Goal 3, Goal 5, I710, SR395, SR138. Data quality check is performed at the time the back calculation is done.	Contains the deflection basins of each point tested within a selected section and the applied loads, temperature measured at the surface of the pavement, section structure, climatic region, route, post mile
Fatigue.mdb	MS-*Access*	Stores the fatigue test data and the fatigue frequency sweep data of Goal 1 and Goal 3 tests.	Information included: repetitions, phase angle, tensile strain, tensile stress, dynamic modulus, dissipated energy, mean strain, initial stiffness, repetitions to

Database	Software	Contents	Information Included
			failure, initial phase angle, cumulative energy, specimen air voids, rice max specific gravity data, test temperature, test strain.
Shear	MS-*Access*	Stores the Repetitive Simple Shear Test at Constant Height data and the shear frequency sweep test data of Goal 1 and Goal 3.	Information contained: Specimen name, air-void content, asphalt content, test temperature; -Shear frequency test data include: frequency, shear stress, shear strain, complex shear modulus, phase angle; -RSST-CH data include: repetitions, plastic shear strain, plastic shear stress, axial stress, resilient shear strain, resilient modulus, no of repetitions at 1%, 2%, 3%, 4%, 5% strain, complex shear modulus at 100 reps, no. of reps to failure.
PCC-Lab	MS-*Access*	Stores the flexural and compressive laboratory test results of the Goal 4 study for different PCC mix designs as well as the shrinkage experiment results.	Information contained: mix designs, compressive strength, flexural strength, load, modulus, mix temperature, aggregate temperature, water temperature, air temperature, humidity, slump, unit weight, air (%), shrinkage data.
WIMData	MS-*Access*	Stores the summary results of the WIM data analysis; based on sampled WIM raw data files processed using the Fortran application *WIMANA*	Information contained: summary of AADTT for each truck type, for each WIM station, for each direction from 1991 to 2001; the axle load spectra on each lane for each truck type at each WIM site; the truck factor (ESALs per 1000 trucks) information for each truck type on each lane at each WIM site; the ratio of truck volume in the daytime to that in the whole day; the lane distributions of truck traffic volume; the left/right side wheel load deviance ratio (SWLDR) of each axle group in each direction at each WIM site; the averaged axle load spectra for each truck type at each WIM site; the averaged truck factor for each truck type at each WIM site; the percentage of each truck type in the total truck traffic volume.

2.6 Deep In-Situ Recycling (DISR) (SPE 2.4.2, Goal 10 [SPE 4.12])

The DISR activities have included two separate projects:

- DISR using recycled AC as unbound base (59)
- DISR using foamed asphalt (60)

The project using recycled asphalt concrete as unbound base has been listed as SPE 2.4.2 in Table 3 in the category of *Research Services Special Forensic Investigations*. Similarly, the foamed asphalt study was listed initially as SPE 2.4.3 in this same category. This latter project was expanded through the partnership with Transportek into Goal 10 in the 2003–2004 period (SPE 4.12) to include mix and structural design and construction guidelines. Both studies include extensive laboratory testing as well as field evaluation.

2.6.1 DISR Using Recycled Asphalt Concrete as Unbound Base (SPE 2.4.2)

The purpose of this study has been to evaluate the rehabilitation strategy involving recycling the in-place asphalt concrete and a portion of the untreated aggregate, and using the combined materials as the base for a new AC layer. Three projects in District 2 are included in the study:

- U.S. 395 approximately ten miles south of Alturas, CA; two-lane, two-way highway with a project length of three miles.
- SR-70 in Plumas County at Beckwourth; two-lane, two-way highway with a project length of 12.8 miles.
- SR-44 in Lassen County near Poison Lake; two-lane, two- way highway with a project length of seventeen miles.

Objectives of the study include: (1) evaluation of the performance of the recycling process in the field by analyzing destructive and nondestructive data before and after the recycling process; (2) characterization of the recycled asphalt concrete material using standard and triaxial laboratory tests; (3) comparison of the laboratory performance of the recycled materials with typical Class 2 aggregate base materials; and (4) development of a gravel equivalent or gravel equivalent factors, G_f, for this type of material.

The study includes field monitoring of the projects for five years. This section includes only summary results for the US 395 Project. All of the initial test data have not been completed for the other projects as of June 2004 (59).

For the US 395 Project, the recycled asphalt concrete material was tested and characterized using field and laboratory testing and compared with two California Class 2 aggregate base (AB) materials. Field tests (DCP and FWD testing) indicated that the recycled base was stiffer than the base existing before the recycling process. (A stronger/stiffer base reduces the elastic deformations in the pavement that cause fatigue cracking in the asphalt concrete and reduces the potential for rutting in the unbound layers.) Continued field evaluation is required, however, to support the initial improvements observed.

The laboratory data indicated that the recycled material exhibited a higher resilient modulus and slightly higher shear resistance than the two California aggregate Class 2 base materials used in the study. Some laboratory tests also indicated that the modulus and shear resistance of the recycled material can be further improved by increasing the field compaction effort above that currently used by Caltrans as discussed in Section 2.1.3. A limited laboratory study using lime suggested that the admixture improved the performance of the pulverized material. This will be investigated in more detail as the project progresses.

Some conclusions drawn from this study are as follows:

1. Based on the preliminary results of the pilot project, Caltrans staff concluded that the pulverization strategy provides cost savings and an improved product. Cost savings were

achieved in terms of time, material, and better performance; i.e., (1) the overall speed of the process made it more competitive than the conventional rehabilitation strategy; (2) the digout process was eliminated, which in turn eliminated the need to import material to the project location to fill the digout areas; and (3) the potential for reflection cracking is eliminated, and the improved base results in lower deflections (reducing potential for early fatigue cracking) and lower stresses in the underlying unbound layers (reducing potential rutting).

2. Based on field testing, the results indicated that the pulverization process produced a better pavement than the pavement that was present before the pulverization process. Lower DCP penetration rates and higher moduli were obtained in the new rehabilitated pavement.
3. Estimates of the pavement life indicated that the pulverization process produces a pavement structure that exceeds the pavement life provided by the overlay rehabilitation process. These initial estimates need to be verified through long-term monitoring.
4. Based on laboratory testing, the results indicate that the pulverized material from US 395 exhibited better performance than the two Class 3 aggregate base materials. Higher shear strength and resilient modulus were obtained for the pulverized material than for the conventional Class 2 aggregate bases.
5. Laboratory results also demonstrated the benefits of increased compaction levels on the performance of unbound layers. Higher strength and resilient moduli were obtained at increased compaction levels. These improvements should reduce the fatigue cracking in asphalt concrete layers and rutting in unbound materials. Performance of the pulverized material from District 2 also showed improved resilient response and performance when treated with lime.

2.6.2 DISR Using Foamed Asphalt (SPE 4.12) (60)

As noted earlier, while this study started as a current experimental strategy under evaluation by Caltrans, it is now included as a Strategic Plan Element (from Goal 10 to SPE 4.12).

By June 2004 HVS loading on the four test sections on SR-89 at Calpine were completed. The test sections were constructed in the shoulder area next to the southbound lanes. Results of a Level 1 analysis (61) produced the following conclusions and recommendations. More detailed analyses will be included in subsequent reports.

Results from field surveys done prior to, during, and after HVS testing show that the pavement structure of the HVS test sections on State Route 89 is not representative of the mainline and foamed bitumen treated, recycled asphalt concrete in general. The base layer thickness on the HVS test section varies between 74 and 100 mm. The base is supported by a weak clay-like layer and decomposed granite subgrade. A very weak support layer was identified in the vicinity of Section 595FD and test-pit results show that the moisture content in the subgrade of Section 595FD exceeded 20 percent.

The mode of distress of the test sections differs between the favorable conditions in summer and fall and unfavorable conditions in winter. The mode of distress before the onset of winter consisted of gradual deformation of the pavement resulting in a terminal surface rut with limited fatigue cracking. After the winter, the mode changed to a more rapid rate of rutting, and on Sections 595FD and 596FD testing during spring, shear failure of the base layer occurred in certain locations. These sections also showed extensive fatigue cracking but this is probably caused by a combination of a soft base layer (low resilient modulus) and large plastic strains in the base layer generating high tensile strains in the asphalt surfacing layer.

The pavement structure of the HVS test section on SR-89 showed sensitivity to high moisture contents in terms of elastic and plastic response. The resilient modulus of the base layer decreased during winter and spring and the rut rate increased. Although not to the same extent, a reduction in base layer resilient modulus on the mainline was also observed from FWD results. Accordingly it is recommended that FWD surveys should be done in each of the four seasons of the year to track changes in pavement condition. If the reduction in base layer resilient modulus is permanent, it may lead to early fatigue of the asphalt surfacing layer.

The pavement bearing capacity in the HVS test sections only exceeds the design value under favorable conditions in fall and early winter. The pavement structure of these sections is, however, not representative of the mainline pavement structure and therefore not representative of the bearing capacity of foamed asphalt-treated, recycled asphalt pavements. The bearing capacity of the pavement is subject to seasonal effects and cannot be estimated from a single HVS test result. It is recommended that a seasonal simulation should be done using the results from the HVS tests in each season and seasonal traffic data in a 2nd level analysis of the HVS data. The bedding-in parameter was highest during spring and it is recommended that pavements of similar construction should not be opened to traffic in spring.

2.7 Other Technical Activities

In addition to the specific projects described in the previous sections, there are a number of activities that involve the PRC staff working with Caltrans staff. While most of the reported research would be considered short term there are also longer-term activities which have been included in the program. Two examples of the Caltrans/PRC staff collaboration to be discussed are: (1) pavement management activities and (2) construction-related activities. An example of the longer-term research to be described is related to the permanent deformation response of asphalt concrete.

2.7.1 Pavement Management Activities

The PRC staff has worked with Caltrans staff in identifying databases in the areas of materials, design, construction, traffic, and maintenance, which can be linked to the Caltrans Pavement Management System. This activity has, among other items, required the identification of variables needed for M-E pavement design and rehabilitation as well as QC/QA data associated with performance-based pay factors for asphalt concrete construction.

These activities have been formalized into two SPE's: (1) SPE 3.2.4, "Development of Integrated Databases to Make Pavement Preservation Decisions;" and (2) SPE 4.5, "Calibration of Mechanistic-Empirical Design Modules."

Project objectives for SPE 3.2.4 include the following:

- Identify Caltrans pavement data business practices.
- Identify elements of the databases that already exist.
- Work with Caltrans pavement organizations, primarily the Pavement Standards Team but also other pavement data users not represented on the PST, to perform a needs analysis for Caltrans pavement data, including the precision of the linear referencing system, and to identify Department initiatives and regulations for databases and linear referencing systems.
- Develop recommended changes to pavement data business practices. Develop recommended tables and dictionaries for these databases. Identify variables that are missing or that are currently being collected but are not necessary. In addition identify key issues that must be resolved before databases can be integrated such as linear reference system and Caltrans information technology requirements.
- Recommend changes in a report to management — for review, approval, and implementation — based on the findings of the four objectives listed above.
- Populate databases with existing data, and perform preliminary analyses.
- Develop recommendations for ongoing collection and database management procedures to be implemented and operated by Caltrans functional units.

The ME design procedures being developed for Caltrans need calibration with field data as well as HVS and laboratory testing and analysis. The two primary sources of long-term pavement performance data for Caltrans pavements are test sections on mainline pavements and information stored within the Caltrans pavement management system and construction databases. The objectives of SPE 4.5 are:

- Obtain data not only from Caltrans databases but also from the Arizona and Washington State PMS databases.
- Provide Caltrans with a list of all known field test sections in the state and categorize the sections according to pavement deterioration mode (this objective was completed prior to June 2000). During the 2000–2004 period the PRC staff have received some structural and materials information on sections identified from this list collected by another Caltrans Research contractor. These data will be evaluated for possible integration into the Caltrans database.
- Perform laboratory testing on the material samples. This work has been completed for the WesTrack project. The other Caltrans Research contractor is performing tests on asphalt concrete specimens taken in the field and measuring the thicknesses of underlying layers, but is not collecting or testing any other materials in the pavement structure. The laboratory and field deflection test results obtained from that contractor will be included in the databases.
- To the extent possible, use the laboratory, field performance, and PMS data to calibrate mechanistic models for key distresses.

A report has been completed (62) describing the development of a single database containing pavement and condition information based on fixed sections. This database covers the period 1978 to 1992 in the Caltrans PMS. The report suggests that a more comprehensive and rigorous approach to Caltrans data collection, storage, access, and usage is required to improve the efficiency of Caltrans business practices for pavement data and pavement management.

Work performed on SPE 4.5 during the latter part of the 2000–2004 period utilized the databases of both Arizona and Washington DOTs for evaluating reflection cracking models, and a report based on these analyses in preparation at the date of this report.

2.7.2 Construction-related Activities

In addition to the work described in Section 2.3 there are two additional research goals in which projects in construction-related areas are underway. These are: (1) SPE 4.14, “A Framework for Implementing Innovative Contracting Methods for Transportation Infrastructure Rehabilitation/Reconstruction;” and (2) SPE 4.15, “Development of Integrated Pavement Strategy Decision Support System.”

The objective of SPE 4.14 is to develop an analysis framework which can:

- Assist Caltrans in determining optimal contracting method for a specific project
- Evaluate the impacts of implementation
- Adjust the contracting methods to specific environments
- Determine the best practices for each contracting method
- Build specific contracting strategies, and
- Develop an analysis tool (program) based on the framework

The current the projects concerned with urban freeway rehabilitation involving the use of concrete and asphalt pavements concentrate on the following contracting methods:

1. warranty (C);
2. cost + schedule (A+B) + incentive/disincentive, and pay factors; and
3. combinations of these (for example, A+B+C)

SPE 4.15 has as its objectives the following:

- Develop at the project level a support system for Caltrans (and other state transportation agencies) that models and optimizes a project's life cycle cash flow in its decision-making process. The system would include: (1) key pavement design concepts (e.g., materials and component pavement thicknesses); (2) timing of construction (e.g., accelerated or conventional); (3) various combinations of project financing (federal, state, private, tolls); and (4) segments being planned for construction or rehabilitation.
- Expand the project-level concepts to the network level, which would include: (1) establishment of alternative pavement design strategies for the analysis period; (2) establishment of typical "project templates"; (3) identification of alternative strategies considering initial design and maintenance options; (4) a study of performance deterioration behavior of concrete and asphalt pavements, and provision of pavement condition curves during their periods of performance for all alternatives; (5) identification of scope and timing of reconstruction in each alternative depending on the developed pavement condition curve; (6) estimation of user costs for all alternatives; (7) study of the user cost items and identification of the factors representing the value of each user cost item; (8) application of the California data to measure the user cost numerically; (9) evaluation of reconstruction designs with related user costs; (10) definition of the major design factors affecting user costs during reconstruction and maintenance periods; and (11) estimation of the tradeoffs between the pavement performance improvement and incurred user costs during the performance period (life) for alternative values in design factors.
- Develop economic analyses to: (1) identify revenue sources used to finance different projects, including their key terms and conditions (e.g., fixed versus adjustable interest rates, prepayment options and penalties, call provisions); (2) identify the typical operations and maintenance cash flows associated with different project types; (3) unify these different input variables into a process model that allows calculation of the project's discounted life-cycle cash flow; and (4) develop a model which will assemble the process into a software test platform (MS *Excel* or *Access*, to be determined) and test its viability by examining examples from both asphalt and concrete projects.

Studies have been initiated to develop costs for a number of Caltrans Long-life Rehabilitation Projects (LLPR) including: (1) I-710 Freeway, Phase 1 Rehabilitation (Long Beach); (2) I-10 Freeway Rehabilitation (Pomona); and (3) I-80 Freeway Rehabilitation (Boca/Floristan).

2.7.3 Permanent Deformation Response of Asphalt Concrete

This study has focused on the formulation of an accurate constitutive law for asphalt concrete mixes at elevated temperatures where ruts are the primary failure mechanism. It is based on the concept that the development of effective pavement design procedures hinges on the availability of accurate predictions of the pavement system response to different loading conditions. This predictive capability depends on the availability of material models that accurately represent the behavior of the various materials. The closer the material is to the surface of the pavement the more accurate the model required. Since rutting has a significant impact on asphalt concrete performance and since load magnitudes, tire pressures, and load repetitions continue to increase, attention to rut depth is essential.

Building on previous work, a fully nonlinear constitutive law for the behavior of asphalt concrete mixes at elevated temperatures has been developed that is suitable for the modeling of both rut initiation and rut evolution phases (63). To this end, the model has been formulated within the realm of large deformations and permits large strains accompanied by large rotations. This feature is needed because large rotations have been measured near the edges of the ruts as they develop. For example, measurements in HVS tests at the RFS indicated rotations as high as 45˚ and about 10 percent vertical compressive strain near the center of the rut. Such large rotations and moderate strains indicate that the use of small strain theory, commonly used in modeling pavements, cannot be used for the post-rut initiation phase. Instead the approach adopted here has been considered essential to achieve a suitable representation of asphalt concrete rutting behavior.

The model consists of a viscoelastic fluid acting in parallel with an elastoplastic solid. The current model is designed to account for key aspects of the observed behavior of asphalt concrete mixes. Some of these aspects are included as follows: (1) the two components acting in parallel are motivated by the different observed response to slow- and fast-moving loads; (2) the elastic component of the elastoplastic branch is endowed with an explicit volumetric-deviatoric coupling; and (3) the yield surface in the elastoplastic model is different under hydrostatic tension and compression.

The model has been used to study the simple shear at constant height test, which provides the basis for evaluating the rut resistance aspects in the mechanistic–empirical design of asphalt concrete pavements in California. The analysis performed in this report clearly demonstrates that despite the non–homogenous state of stresses in the specimen, the test is accurate in predicting "shear" properties as long as the length-to-height ratio of the specimen is greater than three. This study has demonstrated the usefulness of employing constitutive laws in the analysis of laboratory tests, and the ability to use the model to identify critical laboratory tests.

3. IMPLEMENTATION AND TECHNOLOGY TRANSFER

For the PPR Program to be successful, it is necessary that intensive effort be made by the research program participants (including the principal staff of the two universities together with the DRI staff) to expeditiously implement significant results obtained.

During this period the universities have attempted to do this by means of the following activities:

1. Extensive interactions with both Caltrans and asphalt industry personnel;
2. Working side by side with Caltrans staff on specific projects;
3. Continuous and timely reporting of research results and the preparation of special publications;
4. Conducting short courses and special seminars; and
5. Participating with Caltrans staff in the State Pavement Technology Consortium (SPTC).

Results of the program have also been presented to both the national and international pavement engineering communities through papers in various technical journals. Lists of the various reports to Caltrans and other clients as well as papers in the various technical journals are available at the following Web site: *http://www.its.berkeley.edu/pavementresearch.*

3.1 Interaction with Caltrans and Asphalt Industry Personnel

Members of the PPR Program Staff have served as members of a number of joint Caltrans/Industry task groups and committees. Examples include the following:

1. *Moisture Sensitivity Asphalt Concrete Group (MSACTG).* A joint committee consisting of co-chairs and member representatives from Caltrans and the Asphalt Pavement Industry was assembled in 2001 to address the perceived moisture sensitivity problem in the State. PPR staff served on MSACTG subgroups that focused on: Problem Identification, Mix Design and Laboratory Testing, and Implementation. In addition, UCPRC staff was heavily involved in the Caltrans-supported workshop on "Moisture Sensitivity of Asphalt Pavements" held in San Diego February 4–6, 2003 (64). Through the Implementation subgroup, representatives of the UCPRC together with staff from the pavement engineering firm MACTEC, and with Caltrans support, developed a one-day course on the state of the practice relative to moisture sensitivity. The course content incorporated much of the information contained in the Workshop report (64) and the course is intended for both public (state and local government) and asphalt industry personnel. The first two offerings of the course were held in February 2004 in San Diego and in April 2004 in Sacramento.
2. *Long-life Flexible Pavement Rehabilitation Task Group*. This is a joint committee with Caltrans, industry, and UCPRC representatives. The initial purpose of the task group was to provide guidance for the design and construction of the LLPR for the I-710 freeway in Long Beach, California. This project was successfully completed in November 2003. Results of the UCPRC's role have already been summarized in Section 2.1, "Asphalt Mixes—Materials and Flexible Pavement Studies," and in Section 2.3, "Construction-Related Activities."

3.2 Working Side by Side with Caltrans on Specific Projects

Two examples of this working together are:

1. *I-15 Devore Pavement Reconstruction Project.* PRC staff worked directly with Caltrans District 8 Staff to select the final design features and the closure plan (as described in Section 2.3) for the rehabilitation of the I-15 Freeway in the vicinity of Devore, California.

2. *I-710 Long Beach Pavement Rehabilitation Project.* PRC staff worked directly with District 7 Design, Construction, and Traffic staff on various aspects of design, construction scheduling, and traffic monitoring. In the construction scheduling area, PRC staff was on-site for three of the eight weekend closures collecting data for calibration of *CA4PRS* and the associated traffic model.

3.3 Reports and Special Publications

Formal reports and technical memoranda (TMs) have provided a continuous record of developments in both the asphalt and concrete areas to Caltrans DRI staff. Table 3 provides for each Goal or SPE (Strategic Plan Element), a listing of numbers referring to the publications on the list included at the end of the report.

During this period a brief summary of results for specific projects has been developed in a four-page format termed *Roadway Research Notes*. These brief publications are intended to highlight results of the PPR Program in specific areas and are distributed within Caltrans to key staff in pavement- and materials-related areas. Examples include:

1. "*MultiCool* – Asphalt Concrete Pavement Cooling Simulator Program," June 2002
2. "Performance of Rubberized Asphalt Concrete Gap-Graded (RAC-G) versus Dense-graded Asphalt Concrete (DGAC) Overlays under Accelerated Pavement Testing."
3. "Performance of Caltrans 'Drained' Flexible Pavement Structures with Asphalt Treated Permeable Base"
4. "*CA4PRS*, Combining Pavement Engineering Construction Productivity Analysis and Traffic Simulation to Expedite Major Freeway Reconstruction Projects"

3.4 Short Courses and Special Seminars

Results of the developing research are incorporated into short courses developed under the auspices of the Technology Transfer (T^2) Program of the Institute of Transportation Studies of UC Berkeley. Examples of the short courses include:

1. Asphalt Pavement Fundamentals: Design, Construction, and Rehabilitation (three days)
2. Asphalt Mix and Structural Pavement Design (three days)
3. Concrete Pavement Fundamentals (three days)
4. Compaction, Stabilization, and Drainage of Asphalt Pavement Layers (two days)
5. Controlling Moisture Damage in Asphalt Pavements (one day)

Information on these and other courses can be found on the Web at: *http://www.techtransfer.berkeley.edu.*

In addition, a special one-week *Materials Academy* has been developed to introduce and to train recently hired Caltrans engineers in pavement engineering. The course consists of modules in: (1) pavement materials, mix design, and testing; (2) pavement and rehabilitation design; (3) pavement construction, maintenance, and rehabilitation; and (4) quality control / quality assurance. While the course has been specifically related to Caltrans methodology, results of the PPR Program have been introduced where appropriate.

Recently, because of budget stringencies, new ways of packaging materials for technology transfer have been and are under development. One methodology, recently introduced, has been to take four-to-six-hour segments, termed "roadshows," from the five courses listed above and to prepare instructional materials that can be delivered at a specific site requested by Caltrans or other public agencies and industry groups. Information on these roadshows can also be found at the Web site listed above.

4. SUMMARY

This report has attempted to provide a summary of the results of the various studies completed during the period of 2000–2004. In addition, preliminary findings of investigations initiated but not yet completed during this period are also included. These results are based on a program which has combined the results of analytical developments, laboratory testing of pavement materials, and the HVS testing of carefully planned, full-scale pavement test sections to provide information to Caltrans to assist its staff in moving forward toward the goal of improved pavement performance. The program has benefited not only from the partnering between the Pavement Research Center, Caltrans, Dynatest Consulting, and the CSIR, but also with many organizations listed in the *Acknowledgments.* Table 1a provides a complete listing of the HVS tests completed as of June 2004. Table 4 contains a summary of the results of a number of the studies listed in Table 3, a tabulation of the Strategic Plan Elements according to which the program operates.

4.1 Asphalt Mixes — Materials and Flexible Pavement Studies

Results of the Goal 3 laboratory fatigue studies on RAC-G and AR dense-graded mixes provide useful information for the mechanistic-empirical design procedure (SPE 4.1) under development. In the near term it also provides useful data to develop Gravel Equivalent Factor(s) for AR hot mixes for rehabilitation design alternatives using current methodology.

Results of the Goal 5 study suggest that improved structural pavement design and construction practices (e.g., improved AC compaction) reduce the necessity for the use of ATPB to drain water entering from the pavement surface.

If ATPB is used directly beneath the AC layer, improved mix design of the ATPB is required, e.g., increased binder content, use of a modified binder, and the use of an additive to improve mix moisture sensitivity resistance. Also, a properly designed geotextile (or soil filter) between the ATPB and AB should be incorporated in the pavement structure to preclude clogging of ATPB from the fines of the untreated aggregate base (AB). Systematic cleaning of edge and transverse drains adjacent to the ATPB is a necessity to prevent water being trapped in the ATPB.

Results of studies of the performance characteristics of AB emphasize the importance of improved compaction. It is recommended that AB be compacted to a relative compaction of 100 percent based in the Modified AASHTO Compaction Test (T 180) test. This test is recommended to replace the current CTM 216 procedure since the relationship between field and laboratory compaction test results, both water content and dry density, corresponds more closely to results of the AASHTO T-180 test.

The mix designs for the I-710 Freeway rehabilitation using the simple shear test were subjected to HVS tests prior to construction. Results of these tests indicate that the RSST-CH provides a “reasonable” mix design for the mix containing the PBA-6a* (modified) binder. At 50°C this mix was able to accommodate a significantly larger number of load repetitions (approx. 200,000 to a rut depth of about 8 mm) than a conventional DGAC with a stabilometer “S” value of 43 (approximately 20,000 to a rut depth of 12.5 mm).

A few months after completion of construction of the I-710 project, postconstruction interviews were conducted by members of the Caltrans/Industry Long Life Pavement Rehabilitation (LLPR) Flexible, Task Group. Results of the interviews stressed the importance of partnering between Caltrans and the Contractor on projects of this type. In addition, the other “lessons learned” resulting from the interviews provide a useful set of recommendations to expedite subsequent LLPR projects.

In the Goal 9 Project (SPE 4.10) to develop improved designs for reflection cracking, the MB Test Road pavement was constructed with a DGAC surface course about 75 mm (3 in.) thick. HVS testing on this pavement provided the cracked AC surface that served as the test sections for the investigation. Overlays were placed using mixes containing AR-4000 asphalt cement (DGAC), asphalt rubber (RAC-G), and three different modified binders containing rubber. By June 2004, rutting studies of the various overlay mixes were completed.

Results of the rutting study, as compared to the results of the earlier Goal 3 study, indicated that the various mixes containing the MB materials exhibited less resistance to rutting than the two Goal 3 overlay mixes. These results suggest that an improved mix design procedure will likely be required, e.g., like that used for the I-710 mixes.

The PCCAS-supported study was conducted to evaluate the influence of the binder parameter $G^* \sin\delta$ in the AASHTO PG binder specification (currently AASHTO M320-04) on pavement fatigue performance. Results showed that this parameter as well as the *SSV* and *SSD* parameters (used in the Caltrans PBA Specification) did not differentiate mix performance for the range of binders and asphalt pavement structures analyzed for representative regions in the area encompassed by PCCAS. Based on the results of the study, the recommendation was made to continue using the current specification requirement since there are no data to support its deletion. This finding likely contributed to the decision of Caltrans to adopt the PG binder specification to replace the AR binder specification, effective January 1, 2006.

The AC moisture damage investigation (SPE 4.9), though still in progress, has provided a few preliminary observations. For example, analysis of data from *the field survey of projects* phase suggests that high air-void contents in the mixes, permitting water retention, contributed significantly to moisture-related distress.

From the laboratory part of the test program, preliminary results of tests using the Hamburg Wheel Tracking Device (HWTD) indicate that the test procedure selected does not clearly distinguish between mixes with different degrees of moisture sensitivity.

4.2 Concrete — Materials and Rigid Pavement Studies

Results of the Palmdale (SR-14) test program provided an evaluation of concrete pavement sections constructed using fast-setting hydraulic cement concrete (FSHCC). This investigation provided information on the fatigue response of the FSHCC, and the influence of dowels, tied shoulders, and widened traffic lanes on pavement performance.

Prior to completion of the SR-14 study, HVS 2 was moved temporarily to Northern California to a site on US-101 in Ukiah. The purpose of this test program was to evaluate the efficacy of dowel bar retrofitting of joints (and cracks) in an existing PCC pavement that had been subjected to traffic ($>4.0 \times 10^6$ ESALs) over a period of about thirty-four years (1967–2001). The project included participation of staff from the Washington State DOT (WSDOT). In this case, the PPR Program utilized the expertise of WSDOT in this area to carry out the study. At the same time, it provided WSDOT with information on the expected longer-term loading performance of this method for concrete pavement rehabilitation (an example of the value of partnering).

In the *concrete pavement design area*, results of pavement analysis studies, together with the results of HVS tests (including those on US-101 at Ukiah and SR-14 at Palmdale) stress the importance of the use of dowels, non-erodible bases, and tied-shoulders or widened outside lanes for heavily trafficked, jointed concrete pavements. Results from the SR-14 site have also demonstrated the effectiveness of dowels in restricting curling movements along transverse joints from daily temperature changes associated with the high desert environments of Southern California. Tie bars produce similar benefits for longitudinal joints.

Performance data obtained from the SR-14 experiment suggest the following to increase the lives of pavements using FSHCC:

1. Shrinkage must be controlled (Caltrans SSP requirements $\leq$ 0.053 percent at seven days) and monitored during construction;
2. Control of curing is important;
3. It is necessary to minimize friction between concrete and base;
4. Flexible (e.g., AC) bases are preferred over rigid bases (e.g., LCB) to permit relaxation of environmental stresses;
5. Joint spacing should not exceed 4.6 m; and

6. It is necessary to take measures to prevent bonding of new slabs placed adjacent to existing slabs.

Analyses of the SR-14 sections have also demonstrated that built-in curl can lead to either bottom-up or top-down load-associated cracking. This curl contributes to load associated longitudinal and corner cracking (versus mid-slab bottom-up transverse cracking — the normal mode assumed for design purposes). While the proposed NCRHP 1-37A Design Guide (AASHTO 200x) for rigid pavements considers the latter form of cracking, concrete pavement design in California must incorporate considerations of built-in curl to mitigate longitudinal and corner cracking as well.

From a concrete materials standpoint, higher flexural strength (4.5 Mpa [650 psi]) than currently used for design purposes (3.8 Mpa [550 psi]) by Caltrans is extremely desirable. Strengths at this level will reduce the propensity for both load-associated and environmentally induced cracking.

The performance of the dowel bar retrofitted pavement on US-101 as well as test sections on SR-14 have demonstrated the significant improvement in resistance to step faulting under traffic. Substantial increases in ESALs were obtained for these pavements as compared to similar pavement sections without dowels.

For *concrete mixes* the laboratory investigations have included:

1. Studies of the behavior of FSHCC, including strength, stiffness, fatigue, shrinkage, thermal expansion, and durability characteristics;
2. Evaluation of the program *HIPERPAV*; and
3. Evaluation of the concrete maturity concept.

The mix durability study included evaluation of sulfate resistance (already reported in Reference [1]) and aggregate silica reaction (ASR). The latter study included an evaluation of two tests for ASR, ASTM C 1260 (quick and inexpensive), and ASTM C 1293 (requires one year to complete). For the ASTM C 1293 test, an evaluation of the use of a locally available low-alkali cement with added hydroxide ions suggested that it might be used in lieu of a standard high-alkali cement (not available locally).

The following recommendations resulted from this study:

1. Continue to use ASTM C1260; if aggregate is found reactive, perform ASTM C 1293.
2. Continue the evaluation of the “modified” ASTM C 1293 with a wider range of aggregates; if the similar results are obtained with the additional aggregates, replace current C 1293 with the modified test.

Results of the fatigue test program indicate that the FSHCC exhibits about the same response as conventional PCC. Also, the SR-14 mix exhibited significantly higher free shrinkage relative than mixes containing Type II PCs. These results support the findings from the *in-situ* strain measurements. It should be emphasized, however, that the use of FSHCC does not necessarily result in higher shrinkage differentials since some of the FSHCCs can have lower shrinkage then Type II PCs. Thus, when using FSHCCs it is important to test the shrinkage characteristics not only initially, but also periodically during the construction process.

From the initial studies using the *HIPERPAV* software, it shows promise in providing guidance for making decisions to reduce the risk of early age cracking. *HIPERPAV*, however, is not a substitute for good construction practices, which include proper joint sawing and slab curing. Moreover, for California, the studies have indicated that the risk of early-age cracking is larger in the desert climate than in the coastal regions. Mix design is also important in that aggregate type selection should be carefully evaluated for each region, and higher strength concrete will definitely reduce the potential for shrinkage cracking.

The results of the *Maturity* study indicate the there is a reasonable correlation between the maturity indices (TTF and t_e) and flexural strengths measured in the laboratory for the range of mix types studied. At early ages the flexural strength predicted from laboratory curves were similar to measured flexural strengths on field beams for mixes containing Type II cements but were higher than field-measured strengths for mixes with Type III cements. The use of laboratory determined compressive strength versus maturity curves is not recommended to estimate flexural strength. A limited study also suggested that the maturity approach using flexural strengths is probably applicable to mixes with special cements and/or chemical admixtures. It is recommended, however, that field-testing of beams and cylinders should be continued to further validate the procedure.

4.3 Construction-Related Activities

An optimal solution for reconstruction of heavily trafficked freeways, particularly in urban corridors in California, has required combining developments in pavement engineering, construction productivity analysis, and traffic simulation. Used together they can provide a solution which balances traffic delay and construction schedule for the rehabilitation while considering different construction windows.

The *CA4PRS* (Construction Productivity Analysis for Pavement Rehabilitation Strategies) software was developed to meet constructability considerations while an existing program, *PARAMICS,* has been utilized to assess traffic impacts. *CA4PRS* has been designed to estimate the length of freeway that can be rehabilitated or reconstructed within a set of constraints. It considers “what-if” scenarios for major parameters and constraints such as:

- Construction windows: seven- and ten-hour nighttime closures; fifty-five hour weekend closures; continuous weekday closures; and other closed windows required for a specific project;
- Lane closure tactics: partial closures; full closures (counterflow traffic);
- Strategy type: concrete (portland cement concrete or fast-setting hydraulic cement concrete) slab replacement strategies; crack, seat, and asphalt overlay and full-depth asphalt concrete replacement strategies;
- Material constraints: mix design and curing time (concrete) and cooling time (asphalt). (The *CA4PRS* program incorporates the program *MultiCool* to determine cooling rates for HMA as a function of the environment and layer thickness.)
- Pavement structural section profile: thickness of concrete slab or asphalt concrete layers;
- Concrete pavement design: widened truck lanes, various base types (lean concrete base or asphalt concrete base);
- Resource constraints for the contractor: location, capacity, and available pavement equipment; and
- Scheduling constraints: mobilization, demobilization, and traffic control.

The proposed work plan, CPM schedules, resource availability, and traffic pattern of the construction equipment are the main inputs to the analysis. Resource availability and construction traffic patterns are treated as constants in a deterministic analysis module, and treated as random variables in a probabilistic (stochastic) analysis module, which considers variability of the inputs.

Integrating *CA4PRS* with the traffic simulation program to analyze potential construction and traffic scenarios permit development of quantitative estimates of the optimal (most cost-effective) construction management and traffic control plans. The software also evaluates different pavement structures and construction windows for construction duration. When combined with traffic delay simulation, pavement structures that maximize construction speed without creating unacceptable traffic delays are determined. Evaluation of the impact of various traffic-handling tactics on construction duration can define a procedure to minimize total traffic delay. These data are vital to achieve the three competing goals of longer-life pavement, faster construction, and less traffic delay during freeway reconstruction and rehabilitation projects.

During this four-year period the *CA4PRS* program has been used for the I-710 project in Long Beach, CA, where long-life asphalt pavements were used for rehabilitation in a series of fifty-five-hour weekend closures. The original time Caltrans estimated for completing the 4.4 km (26.3 lane-km) project required ten weekend closures. The contractor actually completed the project in eight closures; use of the *CA4PRS* program was instrumental in producing this time savings.

CA4PRS has also been used in the planning of the reconstruction of I-15 at Devore (near San Bernardino, CA). This highway has an average daily traffic of about 110,000, 9 percent of which is trucks, and a total length of 17 lane-kilometers (4.2 km × 2 lanes × 2 directions). The project includes two segments: the first consisting of four lanes and the second three lanes. The existing pavement is 200 mm (8 in.) of concrete with 100 mm (4 in.) of cement-treated base. The new pavement will consist of 290 mm (12 in.) of Type III high early strength concrete with 150 mm (6 in.) of asphalt concrete base.

Evaluation of the total cost (construction cost + traffic handling cost + total user delay cost) based on the construction productivity and traffic analyses were utilized. A number of alternatives were considered; based on the overall comparison and justification, Caltrans District 8 selected continuous closures during weekdays, with durations of seventy-two hours.[8]

In both the I-710 and I-15 projects, the results of analyses, laboratory testing, and HVS test programs were utilized. For the I-710 project, the design of asphalt mixes and full-depth sections took advantage of mix and pavement design methodology developed during the Strategic Highway Research Program (SHRP) and calibrated with HVS tests.

For the I-15 project, the use of widened concrete truck lanes (validated on the SR-14 HVS tests) and asphalt concrete shoulders, rather than tied concrete shoulders, resulted in shorter construction times. In addition, the decision to use the HMA as the base was based on both construction time and environmental stress effects, the latter resulting from analyses of SR-14 test sections.

Currently, Caltrans makes use of *pay factors for asphalt concrete construction* on QC/QA projects. These factors have been established on the basis of experience. As noted in Reference (1) an investigation was initiated into the development performance of related pay factors. This latter approach utilizes performance equations developed for fatigue cracking from the PPR Program and for rutting from the WesTrack program. The performance equations, in turn, permit determination of performance-based pay factors for AC construction. For rutting, the performance equation includes the influence of asphalt content, air-void content, and aggregate gradation. The performance equations for fatigue include the influence of air-void content, asphalt content, and asphalt concrete thickness.

Costs are established considering only agency cost consequences of delaying or accelerating the time to the next rehabilitation. For the as-constructed mix, the relative performance (RP) — the ratio of off-target ESALs to target ESALs — is determined for both fatigue and rutting. The smallest combined RP of the two distress modes permits determination of the pay factor from the cost model.

To establish the feasibility for the use of this approach, pay factors determined by the methodology were compared with those used by Caltrans. Comparisons were established for approximately eighty projects constructed in the period January 1997 to June 2000. Only a limited number of these projects contained measured rutting and fatigue-cracking data that had been incorporated in the Caltrans Pavement Management System (PMS). Accordingly, a "shadowing" study is underway and awaits the results of additional detail performance data from the PMS.

This blending of the results from the HVS and WesTrack programs provides an example of the synergistic effects that can result from the PPR group being involved in other related projects.

4.4 Mechanistic-Empirical Performance Design and Rehabilitation

While mechanistic-empirical (or analytically based) pavement and rehabilitation analysis and design development have been utilized in specific situations, e.g., the I-710 and I-15 freeway rehabilitation projects,

---

[8] This decision was changed subsequently because of local public concern with anticipated traffic delays. However, the use of the *CA4PRS* resulted in a new and mutually acceptable solution to all parties involved.

there has been a systematic ongoing effort to develop an improved pavement and rehabilitation design system for both flexible and rigid pavements for Caltrans. Elements of this framework are now in place and training of selected Caltrans staff in the use of the methodology is now underway.

The flexible pavement and rehabilitation design methodology has been programmed by Dr. Per Ullidtz and draws on the extensive knowledge that has been developed in this area over the years. The framework for new design includes both fatigue and rutting considerations utilizing the linear sum of cycle ratios concept and the cumulative damage concept reflecting both the effects of traffic loading and environment. It should be noted that for fatigue, the procedure is similar to that incorporated in the NCHRP 1-37A Design Guide (AASHTO 200x) currently under evaluation. The methodology, however, reflects California conditions; e.g., AC mix characteristics developed in the PPR Program, Caltrans-measured traffic load spectra, and environmental conditions based on California weather station information. Moreover, the results of the HVS test program have played a significant role to ensure that the analysis procedure produces “reasonable” results.

Considerations of rutting in the AC layer differ from that in the new design guide. Estimates of rutting are based on methodology that had been developed during SHRP and refined using WesTrack test results and those obtained from rutting tests in HVS tests under controlled loading and temperature conditions.

The rigid pavement design procedure is patterned after the new design guide making use of traffic, environmental, and mix characteristics for California conditions. In addition, provision is made, depending on environment and potential slab curling, to analyze for both bottom-up and top-down cracking not only in the transverse direction at mid-slab (as in the new design guide), but also in the longitudinal direction and at slab corners. Provision is included for doweled transverse joints, tied concrete shoulders, widened lanes with asphalt shoulders, and various base types (e.g., asphalt concrete as well as lean concrete base). Results of the HVS tests at Palmdale and Ukiah have provided key data to aid in the development of design methodology.

As a part of the M-E program, a number of software programs have been developed or are under development. Table 10 of the report contains a summary of these programs and their expected usage in the M-E design and rehabilitation methodology.

4.5 Databases

From the outset of the project, it has been necessary to establish a database or databases to filter and store essential results of the laboratory and field investigations. Table 11 contains a summary of the current databases that are maintained. These include:

1. *Heavy Vehicle Simulator Database,* which contains the results of the completed tests listed in Table 2.
2. *Seasonal Monitoring Database* includes results for eight seasonal monitoring stations established through the PPR Program.
3. *Falling Weight Deflectometer (FWD) Database* includes FWD tests from HVS test sections and field sites.
4. *Laboratory Test Database* contains a summary of the various laboratory tests conducted on the material used in the HVS test program as well as other programs in which the PRC was involved, e.g., WesTrack Test Road and the Pacific Coast Conference on Asphalt Specifications asphalt concrete study.
5. *Weigh-in-Motion (WIM) Database* contains Caltrans ASCII WIM data for the period 1991–2003. This program will be transferred to the Caltrans Traffic Division in September 2004.

4.6 Deep In-Situ Recycling (DISR)

DISR activities include: (1) use of recycled AC as untreated aggregate base (AB) and (2) use of foamed asphalt to stabilize a mix consisting of recycled AC and unbound aggregate from the existing pavement.

Working with District 2, three projects using the recycled AC as AB are being evaluated. Initial results from the study on US 395 near Alturas suggests that this is a viable rehabilitation strategy resulting in cost savings and, from initial field measurements, may provide a longer pavement life than the conventional overlay strategy.

For DISR using foamed asphalt, PPR Program staff has been working with District 3 staff to evaluate this alternative. HVS tests were completed on a series of test sections on SR 89 near Truckee. The tests were constructed on a shoulder section; results of the tests indicated that the test sections were not representative of the traveled way. Analyses are underway, however, to evaluate the performance of these sections. Preliminary analyses suggest, for example, that the test sections exhibited seasonal variations that should be considered in any future performance evaluations of foamed asphalt DISR.

4.7 Other Technical Activities

The PRC Staff has worked with Caltrans Staff in the development of an *enhanced pavement management system (PMS).* This activity has included the identification variables required for databases for M-E pavement design and rehabilitation (SPE 4.1, 4.5) and QC/QA reports (SPE 3.1.5) which can be linked to the Caltrans PMS. A report on QC/QA data, for example, will permit validating or modifying the performance-based pay factors for asphalt concrete construction (SPE 3.1.5). Similarly, in order to assess the validity of the M-E system (SPE 4.5), monitoring of pavements designed according to new methodology is essential.

Development of effective mix and pavement design procedures depends on accurate predictions of the pavement system response to different loading conditions. This predictive capability depends on the availability of material models that accurately represent the behavior of the various materials. Thus a longer term study has focused on the formulation of an *accurate constitutive law for rutting for asphalt concrete mixes at elevated temperatures*. To this end a nonlinear constitutive law for the behavior of asphalt concrete mixes at elevated temperatures has been developed that is suitable for the modeling of both rut initiation as well as rut evolution phases. The model consists of a viscoelastic fluid acting in parallel with an elastoplastic solid and has been designed to account for key aspects of the observed behavior of asphalt concrete mixes. In the longer term this model will be useful to evaluate the rut resistance of mixes for use in heavy duty pavements.

4.8 Implementation and Technology Transfer

Implementation activities during this period have included:

1. Interactions with Caltrans and the pavement industry;
2. Working directly with Caltrans Staff on specific projects; and
3. Short courses and special seminars

Members of the PPR Staff have served as members of a number of joint task groups and committees including the following:

1. Moisture Sensitivity Asphalt Concrete Task Group
2. Long-Life Flexible Pavement Rehabilitation Task Group

Results of the developing research have been incorporated in short courses developed under the auspices of the Technology Transfer (T^2) Program of the Institute of Transportation Studies of UC Berkeley. Examples of the short courses include:

1. Asphalt Pavement Fundamentals: Design, Construction, and Rehabilitation (three days)
2. Asphalt Mix and Structural Pavement Design (three days)
3. Concrete Pavement Fundamentals (three days)
4. Compaction, Stabilization, and Drainage of Asphalt Pavement Layers (two days)
5. Controlling Moisture Damage in Asphalt Pavements

Information on these and other courses can be found at the following Web site: *http://www.techtransfer.berkeley.edu.*

Recently, because of budget stringencies, new ways of packaging materials for technology transfer have been and are under development. One methodology, recently introduced, has been to take four- to six-hour segments from the first four courses listed above and prepare instructional materials that can be delivered at a specific site requested by Caltrans or other public agencies and industry groups.

5. REFERENCES

1. Harvey, J. T., J. Roesler, N. F. Coetzee, and C. L. Monismith. June 2000. *Caltrans Accelerated Pavement Test (CAL/APT) Program Summary Report Six Year Period: 1994-2000.* Report prepared for California Department of Transportation. Report No. FHWA/CA/RM-2000/15. Pavement Research Center, CAL/APT Program, Institute of Transportation Studies, University of California, Berkeley. UCPRC-RR-2000-08

2. Harvey, J. T., M. Bejarano, A. Fantoni, A. Heath, H. C. Shin. December 2000. *Performance of Caltrans Asphalt Concrete and Asphalt-Rubber Hot Mix Overlays at Moderate Temperatures--Accelerated Pavement Testing Evaluation.* Draft report prepared for the California Department of Transportation. Pavement Research Center, Institute of Transportation Studies, University of California, Berkeley. UCPRC-RR-2000-09

3. Tsai, B. W., J. T. Harvey, and C. L. Monismith. *Goal 3 Fatigue Report.* Draft report completed June 2004. Prepared for the California Department of Transportation, Pavement Research Center, Institute of Transportation Studies, University of California, Berkeley. June 2004.

4. Bejarano, M. O., Harvey, J. T., Ali, A., Russo, M., Mahama, D., Hung, D., and Preedonant, P. December 2001 (Revision February 2004). *Performance of Drained and Undrained Flexible Pavement Structures under Wet Conditions Test Data from Accelerated Pavement Test Section 543-Drained.* Draft report prepared for the California Department of Transportation. Pavement Research Center, Institute of Transportation Studies, University of California Berkeley, University of California Davis. UCPRC-RR-2001-06

5. Bejarano, M. O., J. T. Harvey, A. Ali, D. Mahama, D. Hung, and P. Preedonant. December 2001 (Revision May 2004). *Performance of Drained and Undrained Flexible Pavement Structures under Wet Conditions Test Data from Accelerated Pavement Test Section 544-Undrained.* Draft report prepared for the California Department of Transportation. Pavement Research Center, Institute of Transportation Studies, University of California Berkeley, University of California Davis. UCPRC-RR-2001-05

6. Bejarano, M. November 2001. *Evaluation of Recycled Asphalt Concrete Materials as Aggregate Base.* Technical Memorandum prepared for the California Department of Transportation, District 2 Materials Branch. Pavement Research Center, Institute of Transportation Studies, University of California, Berkeley. UCPRC-TM-2001-04

7. Bejarano, M. O., Harvey, J. T., Ali, A., Mahama,D., Hung, D., and Preedonant, P. 2003. *Performance of Drained and Undrained Flexible Pavement Structures in Accelerated Loading under Wet Conditions -- Summary Report Goal 5 Partnered Pavement Performance Program*. Draft report prepared for the California Department of Transportation. Pavement Research Center, Institute of Transportation Studies, University of California, Berkeley. UCPRC-RR-2003-04

8. Harvey, J., B-W Tsai, F. Long, and D. Hung. Draft submitted July 1997; Final submitted June 1999. *CAL/APT Program: Asphalt Treated Permeable Base (ATPB), Laboratory Tests, Performance Predictions and Evaluation of Caltrans and Other Agencies Experience.* Report prepared for the California Department of Transportation. Pavement Research Center, CAL/APT Program, Institute of Transportation Studies, University of California, Berkeley. UCPRC-RR-1999-05

9.Wells, G. *Evaluate Stripping of Asphalt Treated Permeable Base (ATPB).* Minor Research Report No. 65332-638047-39303, F93RM01, California Department of Transportation, Sacramento, CA June 1993.

10. Heath, A. C., J. M. Pestana, J. T. Harvey, and M. O. Bejarano. November 2002. *Normalizing the Behavior of Unsaturated Granular Pavement Materials.* Draft report prepared for the California Department of Transportation. Pavement Research Center, Institute of Transportation Studies, University of California Berkeley.UCPRC-RR-2002-05

11. Hveem, F. N. “Maximum Density and Optimum Moisture of Soils.” *Highway Research Bulletin 159,* Highway Research Board, Wash., D. C. 1957, pp. 1–19.

12. Turnbull, W. S., and Foster, C. R. “Stabilization of Materials by Compaction,” *Transactions,* American Society of Civil Engineers (ASCE), Vol. 123, 1958, p. 1.

13. Highway Research Board. Factors that Influence Field Compaction of Soils. Bulletin 272, 1960.

14. *Standard Specifications for Public Works Construction,* “Greenbook.” Public Works Standards, Inc. BNI Publications, Anaheim, California. 2000 Edition.

15. Pavement Research Center. June 1999. *Mix Design and Analysis and Structural Section Design for Full Depth Pavement for Interstate Route 710.* Technical Memorandum prepared for the Long Life Pavement Task Force. Pavement Research Center, CAL/APT Program, Institute of Transportation Studies, University of California, Berkeley. UCPRC-TM-1999-02

16. Monismith, C. L., and F. Long. September 1999. *Overlay Design for Cracked and Seated Portland Cement Concrete (PCC) Pavement--Interstate Route 710.* Technical Memorandum prepared for the Long Life Pavement Task Force. Pavement Research Center, CAL/APT Program, Institute of Transportation Studies, University of California, Berkeley. UCPRC-TM-1999-03

17. Monismith, C. L., J. T. Harvey, T. Bressette, C. Suszko, and J. St. Martin. “The I-710 Freeway Rehabilitation Project: Mix and Structural Section Design, Construction Considerations, and Lessons Learned.” *Proceedings*, International Symposium on Design and Construction of Long Lasting Asphalt Pavement, National Center for Asphalt Technology, Auburn University, Auburn, Alabama. June 2004. pp. 217–262.

18. Sousa, J. B., J. A. Deacon, S. Weissman, J. T. Harvey, C. L. Monismith, R. B. Leahy, G. Paulsen, and J. S. Coplantz. *Permanent Deformation of Asphalt-Aggregate Mixes.* Report No. SHRP-A-415, Strategic Highway Research Program, National Research Council, Washington, D.C., 1994.

19. Bejarano, M., B. Morton, and C. Scheffy. Summary of Construction Activities and Results from Six Initial Accelerated Pavement Tests Conducted on the Modified Binder–Asphalt Concrete Pavement Section. Draft Report. Pavement Research Center, PPR Program, Institute of Transportation Studies, University of California, Berkeley, December 2003.

20. J. A. Deacon, J. T. Harvey, A. Tayebali, and C. L. Monismith. “Influence of Binder Loss Modulus on the Fatigue Performance of Asphalt Concrete Pavements.” *Journal,* Association of Asphalt Paving Technologists, 1997, pp. 633–668.

21. Tsai, B. W. and C. L. Monismith. “Influence of Asphalt Binder Properties on the Fatigue Performance of Asphalt Concrete Performance,” *Journal*, Association of Asphalt Paving Technologists, 2005, pp. 733–789.

22. Harvey, J. T., J. A. Deacon, B-W. Tsai, and C. L. Monismith, C. L. January 1996. *Fatigue Performance of Asphalt Concrete Mixes and Its Relationship to Asphalt Concrete Pavement Performance in California.* Report prepared for the California Department of Transportation. Report No. RTA-65W485-2. Pavement Research Center, CAL/APT Program, Institute of Transportation Studies, University of California Berkeley. UCPRC-RR-1996-01

23. Institute of Transportation Studies, Technology Transfer Program. “Controlling Moisture Damage in Asphalt Pavements.” *Course Notes (IDM-10)*, University of California, Berkeley.

24. Kurtis, K., and P. Monteiro. Draft report submitted September 1998; Final report submitted April 1999. *Analysis of Durability of Advanced Cementitious Materials for Rigid Pavement Construction in California.* Report prepared for California Department of Transportation. Pavement Research Center, CAL/APT Program, Institute of Transportation Studies, University of California, Berkeley. UCPRC-RR-1999-04

25. Monteiro, P., K. Kurtis, J. Roesler, and J. Harvey. Final report submitted April 2000. *Accelerated Test Method for Measuring Sulfate Resistance of Hydraulic Cements for Caltrans LLPRS Program.* Report prepared for the California Department of Transportation. Pavement Research Center, CAL/APT Program, Institute of Transportation Studies, University of California, Berkeley. Draft report submitted June 1999. UCPRC-RR-2000-04

26. University of California at Berkeley, Dynatest Consulting Inc., and CSIR, Division of Roads and Transport Technology. April 1998. *Test Plan for CAL/APT Goal LLPRS-Rigid Phase III.* Test Plan prepared for California Department of Transportation.

27. Roesler, J., C. Scheffy, A. Ali, and D. Bush. Final report submitted April 2000. *Construction, Instrumentation, and Testing of Fast-Setting Hydraulic Cement Concrete in Palmdale, California.* Report prepared for California Department of Transportation. Pavement Research Center, CAL/APT Program, Institute of Transportation Studies, University of California, Berkeley. Draft report submitted March 1999. UCPRC-RR-2000-05

28. Heath, A. and J. Roesler. December 1999. *Shrinkage and Thermal Cracking of Fast Setting Hydraulic Cement Concrete Pavements in Palmdale, California.* Draft report prepared for California Department of Transportation. Pavement Research Center, CAL/APT Program, Institute of Transportation Studies, University of California, Berkeley. UCPRC-RR-1999-07

29. Du Plessis, L., Bush, D., Jooste, F., Hung, D. Scheffy, C., Roesler, J., Popescu, L., and Harvey, J. T. July 2002. *HVS Test Results on Fast-Setting Hydraulic Cement Concrete, Palmdale, California Test Sections, South Tangent.* Draft report prepared for the California Department of Transportation. Pavement Research Center, Institute of Transportation Studies, University of California, Berkeley.UCPRC-RR-2002-03

30. Du Plessis, L. and Harvey, J. T. 2003. *Environmental Influences on the Curling of Concrete Slabs at the Palmdale HVS Test Site.* Draft report prepared for the California Department of Transportation. Pavement Research Center, Institute of Transportation Studies, University of California. UCPRC-RR-2003-05

31. Rao, S. and Roesler, J. 2004. *Analysis and Estimation of Effective Built-In Temperature Difference for North Tangent Slabs: Data Analysis from the Palmdale, California Rigid Pavement Test Site.* Draft report prepared for the California Department of Transportation. Pavement Research Center, Institute of Transportation Studies, University of California Berkeley, University of California Davis. UCPRC-RR-2004-03

32. Rao, S. and Roesler, J . 2004. *Palmdale South Tangent Built-In Curling and Cracking: Preliminary Analysis Report.* Draft report prepared for the California Department of Transportation. Pavement Research Center, Institute of Transportation Studies, University of California Berkeley, University of California Davis. UCPRC-RR-2004-04

33. Zhang, J., Harvey,J. T., Ali, A. and Roesler, J. 2004. *Goal 4 Long Life Pavement Rehabilitation Strategies--Rigid: Laboratory Strength, Shrinkage, and Thermal Expansion of Hydraulic Cement Concrete Mixes.* Draft report prepared for California Department of Transportation. Pavement Research Center, Institute of Transportation Studies, University of California Berkeley, University of California Davis. UCPRC-RR-2004-01

34. Kohler, E., Ali, A., Harvey, J. August 2005. *Goal 4 Long Life Pavement Rehabilitation Strategies-Rigid: Flexural Fatigue Life of Hydraulic Cement Concrete Beams.* Draft report prepared for: California Department of Transportation Division of Research and Innovation Office of Roadway Research. Davis and Berkeley, California. UC Pavement Research Center. UCPRC-RR-2005-04

35. Carlos, C. Jr., M. Mancio, K. Shomglin, J. T. Harvey, P. Monteiro, and A. Ali. 2004. *Accelerated Laboratory Testing for Alkali-Silica Reaction Using ASTM 1293 and Comparison with ASTM 1260.* Draft report prepared for the California Department of Transportation. Pavement Research Center, Institute of Transportation Studies, University of California Berkeley, University of California Davis. .UCPRC-RR-2004-06

36. University of California at Berkeley Pavement Research Center, Dynatest Consulting, Inc., Washington State Department of Transportation, University of Washington Seattle. August 2001. *Goal 7 Test Plan: Dowel Bar Retrofit Rehabilitation of Rigid Pavements.* Partnered Pavement Research Test Plan prepared for California Department of Transportation.

37. Harvey, J. T., Ali, A., Hung, D., Uhlmeyer, J., Popescu, L., Bush, D., Grote, K . Lea, J., and Scheffy, C. 2003. *Construction and Test Results from Dowel Bar Retrofit HVS Test Sections 553FD, 554FD and 555FD: US 101, Ukiah, Mendocino County.* Draft report prepared for the California Department of Transportation. Pavement Research Center, Institute of Transportation Studies, University of California. UCPRC-RR-2003-03

38. EverFE, Version 2.3, 3D Finite Element software program, Rigid Pavement Analysis; W. Davids, University of Maine, 2004.

39. Yu, H., M. Darter, K. Smith, J. Jiang, and L. Khazanovich. “Performance of Concrete Pavements, Volume III — Improving Concrete Pavement Performance,” Final Report, Contract No. DTFH61-C-00053, Federal Highway Administration, McLean, Virginia, 1996.

40. Lee, E. B., Lamour, V., Pae, J. H., and Harvey, J. 2003. Analysis of Sensitivity of Plain Jointed Concrete Pavement in California to Early-Age Cracking Using HIPERPAV. Draft report prepared for the California Department of Transportation. Pavement Research Center, Institute of Transportation Studies, University of California Berkeley, University of California Davis. UCPRC-RR-2003-06

41. Mancio, M., Harvey, J. T., Ali, A., and Zhang, J. 2004. *Evaluation of the Maturity Method for Flexural Strength Estimation in Concrete Pavement.* Draft report prepared for the California Department of Transportation. Pavement Research Center, Institute of Transportation Studies, University of California Berkeley, University of California Davis. UCPRC-RR-2004-02

42. State of California Department of Transportation. “Theoretical Maximum Specific Gravity and Density of Bituminous Paving Mixtures,” California Test Method 309. June 2004, 13 pp.

43. Deacon, J. A., C. L. Monismith, J. T. Harvey, and L. Popescu. February 2001. *Pay Factors for Asphalt-Concrete Construction: Effect of Construction Quality on Agency Costs.* Technical Memorandum prepared for the California Department of Transportation. Pavement Research Center, CAL/APT Program, Institute of Transportation Studies, University of California, Berkeley. UCPRC-TM-2001-01

44. Monismith, C. L., L. Popescu, and J. T. Harvey. 2004. “Performance-based Pay Factors for Asphalt Concrete Construction; Comparison with a Currently Used Experience-based Approach.” *Journal,* Association of Asphalt Paving Technologists. Vol. 73: 147-194.

45. Lee, E. B., Ibbs, C. W., Harvey, J. T., and Roesler, J. R. June 2001. *Constructability and Productivity Analysis for Long Life Asphalt Concrete Pavement Rehabilitation Strategies.* Draft report prepared for the

California Department of Transportation. Pavement Research Center, Institute of Transportation Studies, University of California, Berkeley. . UCPRC-RR-2001-02

46. Lee, E. B., Roesler, J. R., Harvey, J. T., and Ibbs, C. W. 2001. *Case Study of Urban Concrete Pavement Reconstruction and Traffic Management for the I-10 (Pomona, CA) Project.* Report for the Innovative Pavement Research Foundation, Falls Church, VA by the Pavement Research Center. UCPRC-RR-2001-01

47. *Partnered Pavement Research Center Strategic Plan 2004/2005.* December 2004. Prepared for the California Department of Transportation by the Pavement Research Center. UCPRC-SP-2004-01.

48. Deacon, J. A., C. L. Monismith, and J. T. Harvey. *Pay Factors for Asphalt-Concrete Construction: Effect of Construction Quality on Agency Costs.* TM-UCB-CAL/APT-97-1. Pavement Research Center, Institute of Transportation Studies, University of California, Berkeley, 47 pp., April 1997.

49. Monismith, C. L. J. A. Deacon, and J. T. Harvey. June 2000. *WesTrack: Performance Models for Permanent Deformation and Fatigue.* Pavement Research Center, University of California, Berkeley, 373 pp.

50. Hudson, W.R., Monismith, C.L., Dougan, C.E., and W. Visser. 2004 "Evaluating Superpave Using Performance, Materials, and Construction Data for Task Order 34 Final Report." Agile Assets, Inc. (formerly TRDI). Austin, TX, to Federal Highway Administration.

51. Lee, E. B., Lee, J. H., and Harvey, J. T. February 2004. *Impact of Urban Freeway Rehabilitation on Network Traffic: Measurement and Simulation Study.* Technical Memorandum prepared for the California Department of Transportation. Pavement Research Center, Institute of Transportation Studies, University of California Berkeley, University of California Davis. UCPRC-TM-2004-1

52. Lee, E. B., Ibbs, C. W., and Thomas, D. February 2004. *Minimizing Total Cost for Urban Freeway Reconstruction with Integrated Construction/Traffic Analysis.* Technical Memorandum prepared for the California Department of Transportation. Pavement Research Center, Institute of Transportation Studies, University of California Berkeley, University of California Davis. UCPRC-TM-2004-2

53. Lee, E. B., Harvey,J. T., and Thomas, D. February 2004. *Integrated Design/Construction/Operations Analysis for Fast-track Urban Freeway Reconstruction.* Technical Memorandum prepared for the California Department of Transportation. Pavement Research Center, Institute of Transportation Studies, University of California Berkeley, University of California Davis. UCPRC-TM-2004-3

54. Lee, E. B., Lee, H., and Harvey, J. T. 2004. *Fast-Track Urban Freeway Rehabilitation with 55-hour Weekend Closures: I-710 Long Beach Case Study.* Technical Memorandum prepared for the California Department of Transportation. Pavement Research Center, Institute of Transportation Studies, University of California Berkeley, University of California Davis. UCPRC-TM-2004-4

55. Deacon, J. A., J. T. Harvey, I. Guada, L. Popescu, and C. L. Monismith. “Analytically Based Approach to Rutting Prediction,” Transportation Research Record No. 1806. *Transportation Research Board.* Washington, D.C., 2002. pp. 9–18.

56. Lea, J. and L. Popescu. 2003. *The Design and Implementation of the Pavement Research Center Heavy Vehicle Simulator Database.* Draft report prepared for the California Department of Transportation. Pavement Research Center, Institute of Transportation Studies, University of California. UCPRC-RR-2003-01

57. Lu, Q., Harvey, J., Lea, J., Quinley, R.,Redo, D., and Avis, J. June 2002. *Truck Traffic Analysis using Weigh-In-Motion (WIM) Data in California.* Report produced under the auspices of the California Partnered Pavement Research Program for the California Department of Transportation. Pavement Research Center, Institute of Transportation Studies, University of California, Berkeley.UCPRC-RR-2002-01

58. Ongel, A. and Harvey, J.T. 2004. *Analysis of 30 Years of Pavement Temperatures using the Enhanced Integrated Climate Model (EICM).* Draft report prepared for the California Department of Transportation. Pavement Research Center, Institute of Transportation Studies, University of California Berkeley, University of California Davis. UCPRC-RR-2004-05

59. Bejarano, M. November 2001. *Evaluation of Recycled Asphalt Concrete Materials as Aggregate Base.* Technical Memorandum prepared for the California Department of Transportation, District 2 Materials Branch. Pavement Research Center, Institute of Transportation Studies, University of California, Berkeley. UCPRC-TM-2001-04

60. Theyse, H., Long, F., Harvey, J. T., and Monismith, C. L. 2004. *Discussion of Deep In-Situ Recycling (DISR).* Technical Memorandum prepared for the California Department of Transportation. Pavement Research Center, Institute of Transportation Studies, University of California Berkeley, University of California Davis. UCPRC-TM-2004-6

61. Theyse, H. and F. M. Long. July 2004. First-level Analysis Report: HVS Testing of the Foamed Bitumen Treated Sections on State Route 89, California. Draft. CR-2004/XX, Volume 1, CSIR Transportek, Pretoria, S.A. 101 pp.

62. Lea, J. and Harvey, J. T. August 2002 (Revision December 2004). *Data Mining of the Caltrans Pavement Management System (PMS) Database.* Draft report prepared for the California Department of Transportation. Pavement Research Center, Institute of Transportation Studies, University of California, Berkeley. UCPRC-RR-2002-04

63. Weissman, S. L. and J. L. Sackman. June 2005. "A Finite Strain Constitutive Law for Asphalt Concrete Mixtures at Elevated Temperatures Based on Multiplicative Decomposition of the Deformation Gradient." Report prepared for the Pavement Research Center by Symplectic Engineeering Corporation. 86 pp.

64. Transportation Research Board. *Moisture Sensitivity of Asphalt Pavements, A National Seminar,* February 2003, San Diego, California, Washington, D.C. 2003, 360 pp.