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Authors:

D. Jones, J. Harvey, and E. Kohler

Partnered Pavement Research Program (PPRC) Contract Strategic Plan Element 4.2:
Evaluation of Rigid Long-Life Pavement Rehabilitation Strategies (LLPRS-Rigid)

PREPARED FOR:

California Department of Transportation
Division of Research and Innovation
Office of Roadway Research

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Abstract: This report summarizes the investigations undertaken by the University of California Pavement Research Center between 1998 and 2005 to assess Caltrans strategies for the construction of rigid pavements, specifically jointed plain concrete pavement. The overall objectives of the study are reviewed and the studies undertaken to meet these objectives, namely desktop studies and laboratory and full-scale experiment are discussed. The reports and recommendations from each study are listed, as well as some details on how the recommendations have been implemented.									
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Signatures: <table border="1" style="width: 100%; border-collapse: collapse;"> <tr> <td style="width: 20%; height: 150px; vertical-align: bottom;"> D. Jones 1st Author </td> <td style="width: 20%; height: 150px; vertical-align: bottom;"> J. Harvey, E. Kohler Technical Review </td> <td style="width: 20%; height: 150px; vertical-align: bottom;"> D. Spinner Editor </td> <td style="width: 20%; height: 150px; vertical-align: bottom;"> J. Harvey Principal Investigator </td> <td style="width: 20%; height: 150px; vertical-align: bottom;"> M. Samadian Caltrans Contract Manager </td> </tr> </table>					D. Jones 1st Author	J. Harvey, E. Kohler Technical Review	D. Spinner Editor	J. Harvey Principal Investigator	M. Samadian Caltrans Contract Manager
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1. INTRODUCTION



Caltrans operates a state highway network of more than 78,000 lane-kilometers (49,000 lane miles), 32 percent of which is rigid pavement (portland cement concrete), mostly on truck routes in urban areas with heavy traffic volumes. In 1995, at the time that this study was being considered, 48 percent of the rehabilitation projects and 41 percent of the lane-kilometers requiring immediate attention were rigid pavements. These pavements were mostly

constructed between 1959 and 1974, and were designed for 20 year lives based on traffic volumes and loads estimated at that time. Consequently, rigid pavements in California are mostly jointed plain concrete on cement-treated bases, have no load transfer devices at the joints (dowels), and usually have asphalt concrete shoulders. Slab lengths vary, and are typically between about 3.6 and 5.8 m (12 and 19 ft). Slab thicknesses are nearly always 200 or 225 mm (8 or 9 in).

Typical rehabilitation strategies for the network include slab replacement, diamond grinding, and asphalt overlays (after crack-and-seat preparation). Prior to commencement of this study, Caltrans engineers and policy makers felt that the existing methods of rigid pavement maintenance and rehabilitation were providing diminishing returns in terms of additional pavement life from each action, due to the damage rate incurred by the pavements under increasing volumes of traffic. Additionally, agency costs of applying lane closures in urban areas are high compared to the actual costs of materials and placement, while safety risks for personnel and property are considerable. The costs to Caltrans' clients, the road users, have also increased due to the increasing frequency of lane closures and deteriorating ride quality.

The *Caltrans Long-life Pavement Rehabilitation Strategy* (LLPRS) identified the need for lane-replacement strategies that would provide more than thirty years of service life with nominal maintenance and minimal disruption to road users. The University of California Pavement Research Center (UCPRC) was requested by Caltrans to conduct research to assess questions about this strategy. Proposed originally by the LLPRS Task Force, this research was of interest to several Caltrans functional units (including Design, Materials, Construction, and Maintenance) in headquarters and the districts. This report is a summary of this research undertaken between 1998 and 2005.

2. STUDY OBJECTIVES



The overall objective of the study was to assess Caltrans long-life pavement rehabilitation strategies for rigid pavements, which aim to add at least 30 years of service life, require minimal maintenance (although zero maintenance is not a stated objective), and allow approximately six lane-kilometers to be rehabilitated or reconstructed within a construction window of 67 hours.

Using this as a framework, the research objectives and outcomes listed in Table 1 were identified for the study. Specifically excluded from the study's objectives were:

- An evaluation of the LLPRS objectives and constraints;
- Development of alternative strategies, unless related to structural load transfer or slab geometry technology;
- Evaluation of drainage; and
- Thickness design (although this was considered as part of the study where pertinent).

The research objectives would be achieved through the following investigations, deemed necessary in 1998 based on the limited California experience with concrete lane reconstruction at that time:

- A desktop study covering design analysis, computer modeling, and estimation of critical stresses and strains within the pavement structure under typical environmental conditions and traffic loading, for comparison with failure criteria;
- Laboratory testing of the strength, fatigue properties, and durability of concrete materials that could be considered for use in LLPRS pavements;
- Heavy Vehicle Simulator (HVS) testing on two experiments constructed on State Route 14 (South and North Tangent) to verify design criteria and failure mechanisms, validate stress and strain calculations, and evaluate performance differences between jointed plain concrete without dowels, jointed plain concrete with dowels and tie bars, and widened [4.3 m (14 ft) instead of 3.7 m (12 ft)] jointed plain concrete with dowels.

Table 1. Objectives and Outcomes

Objective	Outcome	Section*
Evaluate the adequacy of structural design options (tied concrete shoulders, doweled joints, and widened truck lanes) primarily with respect to joint distress, fatigue cracking and corner cracking.	<ul style="list-style-type: none"> • An overview of distresses on concrete pavements in California. • An assessment of the relative performance of the different design options. • An estimate of the traffic that the different design options can carry before failure. 	<p>3.2</p> <p>3.3 & 3.4</p> <p>3.3</p>
Assess the durability of concrete slabs made with cements meeting the requirements for early opening to carry traffic, and develop methods to screen new materials for durability.	<ul style="list-style-type: none"> • A system for classifying and evaluating new products that vendors and contractors may propose for Caltrans projects. • Guidelines for a specification, including test methods and limits, for cements appropriate to both potential materials vendors and Caltrans. • An evaluation of the manufacturing variables that will determine the ability of cement producers to maintain control of the quality of their material, understand sensitivity of different materials to manufacturing variability and overlap with other applications of the same materials • Guidelines for identifying potential adverse reactions between new cements and existing cement-treated bases 	<p>4.2, 4.4 & 4.5</p> <p>4.2</p> <p>4.4</p> <p>4.3 & 4.6</p>
Measure the effects of construction and mix design variables on the durability and structural performance of pavements.	<ul style="list-style-type: none"> • Recommendations towards the setting of construction specifications and mix design requirements that will provide maximum benefit from the materials used and control of quality and performance in the pavements to be built. • Data for mechanistic modeling of concrete pavement structures. 	<p>3.4, 5.2 & 5.3</p> <p>5.3</p>
* Section in this report in which the objective is discussed.		

3. DESKTOP STUDIES

3.1. Introduction



Studies were undertaken to determine the boundaries of existing technology and approaches to testing, design, and construction within the context of the Caltrans long-life rigid pavement strategies (LLPRS). Issues addressed included the limitations of existing design procedures and the load equivalency concept, paving train productivity, concrete fast-tracking, concrete opening strength, and distress in concrete pavements, specifically

longitudinal cracking. Practices and performance over the last fifty years were reviewed to obtain a better understanding of factors that need to be considered in pavement designs with thirty years of service life as well as the implications of incorporating criteria from the existing structures, such as lane delineation, specific joint spacings, and slab thicknesses. Extensive use was made of past and concurrent Caltrans and other Caltrans-sponsored research. In addition to the stated objectives, this research produced many observations of field construction practices that were noted by Caltrans, the concrete paving industry, and the University during initial projects and test section construction between 1996 and 2000. These enhanced practical knowledge for handling the new materials and for lane paving operations as opposed to slab replacements.

3.2. Pavement Distress

The distresses occurring on Caltrans rigid pavements include faulting and transverse, corner, and longitudinal cracking. They are caused by mechanisms that for the most part have been observed and investigated by other researchers in California and in other states, although reliable quantitative models for some mechanisms had not been developed prior to this study. The mechanisms causing longitudinal cracking were also not well understood or documented. Issues relevant to pavement distress mechanisms in LLPRS in California include:

- The most prevalent distress is transverse joint faulting, which occurs throughout the state – with some routes exhibiting the distress over nearly their entire length. Faulting is often severe enough to cause a high level of discomfort to road users. This distress results from poor levels of load transfer across joints and the presence of erodible material in the layers underlying the joints. Past designs

for faulting reduction, including stiffer cement-treated bases (CTB) and skewed joints, have not been effective, although construction of joint sealant reservoirs and use of long-lasting compressible joint sealants has contributed to keeping incompressible materials out of the joints, thereby reducing the potential for joint spalling and possibly longitudinal cracking. The decision not to use dowels for better load transfer across transverse joints was based on construction problems observed in 1949 by Francis Hveem. No further research on the use of dowels by Caltrans had been documented. The implementation of appropriate measures to reduce joint faulting would probably also result in lower occurrence of corner cracking, as both distresses are primarily caused by loss of support under the slab.

- Joint spacing on existing lanes range between 3.6 and 5.8 m (12 and 19 ft). Longer joint spacings lead to faster occurrence of transverse fatigue cracking under truck loads as a result of environmentally induced stresses. Although Caltrans had abandoned long slabs by the early 1980s, there are still many such slabs in the network. Flexural strength is a key component in cracking, and historically, requirements by Caltrans have been less stringent than those of many other states. The use of thicker slabs would, however, require substantial work on the approaches to bridge underpasses (e.g., excavation and reconstruction) to maintain legal height clearances.
- Climate, specifically temperature and rainfall, plays a significant role in rigid pavement distress, but it has not been critically considered in Caltrans design procedures.



3.3. Design Methods



The effects of various design features and design variables on slab thicknesses required to obtain service lives of thirty years or more were evaluated using three rigid pavement design methods:

- Portland Cement Association (PCA) method
- The American Concrete Paving Association (ACPA) version of the American Association of State Highway and Transportation Officials (AASHTO) method
- Illinois Department of Transportation (IDOT) method

Design input variables included expected traffic and axle loads, different levels of base and subgrade support, concrete strength, design features (such as dowels and tied shoulders), design reliability, climate, drainage, and pavement failure modes. Findings relevant to design methods in California include:

- The various design methods produce different results. The ACPA/AASHTO and PCA methods consider both transverse fatigue cracking and distresses associated with loss of support to the slab. The IDOT method considers transverse fatigue cracking only. The PCA and IDOT methods use a mechanistic approach for transverse fatigue cracking analysis, while the ACPA/AASHTO method uses an empirical approach. The current ACPA/AASHTO method is extrapolated significantly beyond the traffic levels encountered in the AASHO Road Test on which it is based, and was developed in a mid-western climate region significantly different from any climate region in California.
- In general, the required slab thicknesses using the ACPA/AASHTO method are much thicker than those calculated using the IDOT method, which in turn are typically thicker than those from the PCA method.
- The inclusion of dowels to increase load transfer at the transverse joints improves resistance to faulting, based on the results from the PCA and ACPA/AASHTO methods. The benefits associated with the use of dowels increase with increasing diameter of the dowels [up to 37 mm (1.5 in)], provided that the concrete slab is thick enough to prevent cracking of the concrete cover around them.
- In all methods where it can be analyzed, the use of widened truck lanes [4.3 m (14 ft)] or tied concrete shoulders to provide good load transfer across longitudinal joints reduces fatigue cracking

and improves performance with respect to the distresses associated with loss of support to the slab.

- In all methods, the use of non-erodible bases improves performance for distresses associated with loss of subgrade support, such as faulting and corner cracking. The use of very stiff bases that cannot accommodate temperature curling may be detrimental to transverse fatigue cracking performance. Retaining existing CTBs should be decided on a project-by-project basis depending on strength and condition. New asphalt concrete bases with relatively high asphalt contents may provide the desired properties of being non-erodible, yet with low stiffness under loading times of several hours. Alternative bases should be considered with respect to structural performance and constructability.
- In all methods, flexural concrete strengths of 4.5 to 5.5 MPa (650 to 800 psi) at 90 days are needed to limit the thickness of the concrete slabs. Flexural strengths less than this will require thicker slabs to prevent cracking. A minimum flexural strength of 2.1 MPa (300 psi) is required to open a 230 mm (9 in) pavement to typical truck traffic. This strength requirement increases if the slab thickness decreases, the subgrade stiffness decreases, or the number of ESALs increases. This was verified in a brief fatigue analysis with the *ILLICON* software program, which also indicated that moving truck wheels away from the edge of the slab would reduce the required opening strength.
- In all methods where it can be analyzed, the coefficient of thermal expansion of the concrete plays an important role in determining tensile stresses in the slab due to temperature curling. The determination of the coefficient of thermal expansion is necessary in order to determine the effect of new fast-setting cements on slab cure stresses. Coefficients of thermal expansion less than 5.4×10^{-6} to 9×10^{-6} mm/mm/°C (3×10^{-6} to 5×10^{-6} in/in/°F) are recommended.
- Axle-load spectra play a role in determining required slab thickness because the heaviest loads in the spectrum generally determine pavement performance with respect to both transverse fatigue cracking (single axle loads) and faulting (tandem axle loads). Caltrans ESALs were compared with AASHTO ESALs and were found to be similar, with differences increasing with axle type (least error for single axle, increasing with tandem and tridem, respectively). Using Southern California traffic volumes and load data, ESALs and load spectra gave the same thickness design, based on fatigue. For individual projects, load spectra analysis should be used to quantify the effect traffic has on the fatigue resistance of the pavement. ESALs should be used to describe the composite effect that traffic and the environment has on overall pavement performance.

Although the three design methods generally did not require the same slab thicknesses for similar design inputs, they were nearly always in agreement as to the benefits and drawbacks of structural design features such as dowels and tied concrete shoulders, concrete flexural strength, thicker concrete slabs, and axle load spectra. The results from the PCA and IDOT methods indicate that it may be possible to obtain thirty-

year design lives using 205- or 230-mm (8- or 9-in) concrete slabs, provided that slab lengths are less than 4.5 m (15 ft), and day-to-night temperature changes do not induce large tensile stresses (areas of concern include the Desert and Valley climatic regions). Pavement structural designs must therefore be considered on a project-by-project basis, rather than applying a uniform structure across a range of climates, joint spacings and base, subgrade, and drainage conditions. Methods for constructing thicker slabs (250 to 300 mm [10 to 12 in]) should be considered for projects with combinations of the heaviest truck traffic, Valley and Desert climates, and slab lengths greater than 4.5 m (15 ft). Mechanistic design permits explicit consideration of these variables.

Axle loads and the number of trucks on the design lanes will undoubtedly increase over the next thirty years. Designs that may have worked in the past may not work in the future and designs that did not provide adequate performance in the past will deteriorate even more quickly under the increased loading. This traffic and loading growth must be adequately accounted for in any pavement designs.

3.4. Concrete Construction Productivity



Each aspect of concrete pavement construction was evaluated in terms of paving lane productivity in a preliminary study. In the late 1990s, it had been proposed that the use of Fast-Setting Hydraulic Cement Concrete (FSHCC) was critical to achieving desired construction productivity objectives, and Caltrans was considering requiring the use of FSHCC for lane reconstruction. The following findings are relevant to LLPRS in California:

- Time required to achieve opening strength of the concrete is typically not the most important variable controlling productivity, and it only has an influence in the last hours of each construction period (fifty-five-hour weekend or continuous closure). Therefore, the use of FSHCC with four- or eight-hour time to meet opening strength was found not to be the most important variable controlling productivity. It was recommended that high early strength portland cement mixes be used for most of each construction period.
- Batch plant productivity is not a limiting factor in pavement construction.
- The concrete paver is most productive when constructing multiple lanes simultaneously.
- Ready mix trucks are less productive than end dump trucks due to their slow offload speed and smaller concrete capacity.

- Other issues that may slow paving productivity include the use of dowel baskets, removal and replacement of cement-treated base, and use of fast-setting cements
- In order to meet the LLPRS objectives of paving six lane-kilometers per weekend, productivity rates higher than those achieved in California PCC at the time of the study would need to be achieved. The time required to pave the six lane-kilometers and demobilize the construction site may be the critical scheduling path for construction rather than the required opening concrete strength for traffic.

Construction productivity for LLPRS was extensively investigated in a subsequent study, which led to the development of the *CA4PRS* software (Construction Analysis for Pavement Rehabilitation Strategies). This can be used to quantitatively identify best practice for LLPRS construction and to optimize productivity.

3.5. Reports

The following reports were prepared for this phase of the study:

1. ROESLER, J., Harvey, J., Farver, J., and Long, F. 1998. **Investigation of Design and Construction Issues for Long Life Concrete Pavement Strategies**. Davis and Berkeley, CA: University of California Pavement Research Center. (Research Report UCPRC-RR-1998-02)
2. HARVEY, J., Roesler, J., Farver, J., and Liang, L. 2000. **Preliminary Evaluation of Proposed LLPRS Rigid Pavement Structures and Design Inputs**. Davis and Berkeley, CA: University of California Pavement Research Center. (Research Report UCPRC-RR-2000-06 and FHWA/CA/OR-2000/02)

4. LABORATORY TESTING

4.1. Introduction



Cements under consideration by Caltrans for rigid pavement construction can be classified into four categories:

- Portland cements and blends
- Calcium aluminate cements and blends
- Calcium sulfoaluminate cements
- Fly-ash based cements

With the exception of portland cements, most of the materials under consideration have not been extensively used for pavement construction in the United States, and little information about their long-term performance and durability under pavement conditions had been documented prior to this study. The calcium sulfoaluminate cements were being used to meet the pre-study specifications for Fast-Setting Hydraulic Cement Concrete (FSHCC). It was thus deemed necessary by Caltrans to characterize the concrete produced from these cements in terms of strength, stiffness, and thermal expansion and shrinkage, as well as long-term resistance to sulfate attack, aggregate-alkali reactions, with a view to their use in long-life rigid pavements in California. The following laboratory investigations were thus undertaken during the course of the LLPRS study:

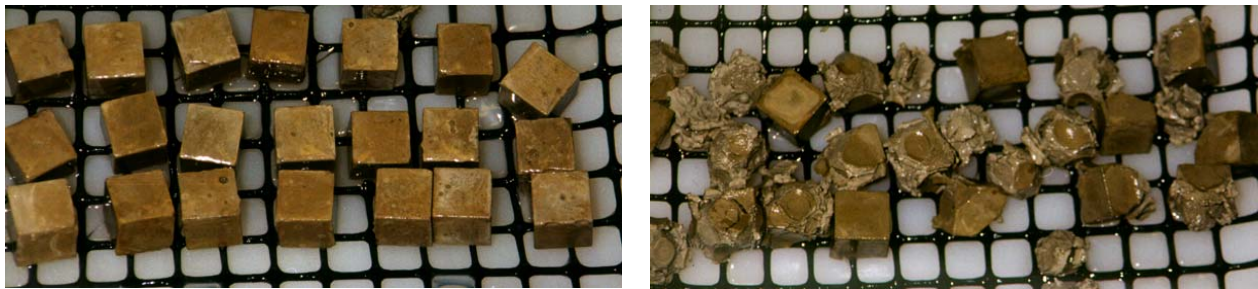
- Resistance to sulfate attack
- Resistance to aggregate-alkali reaction
- Strength
- Stiffness
- Thermal expansion
- Shrinkage
- Flexural fatigue
- Durability of bases

4.2. Concrete Durability

4.2.1 Objectives and Approach

The objective of this phase of the study was to identify the potential durability issues pertinent to concrete pavements in California. Considerable research has been conducted on these topics and thus a literature review was undertaken to identify those issues requiring additional research specific to California. The review focused on sulfate attack, aggregate reactions, corrosion, and freeze-thaw action. Based on the findings of this survey, experimental designs were developed for laboratory investigations to address those issues not adequately covered in the literature, specifically sulfate attack and aggregate reactions.

In the investigation into sulfate attack, four portland cement blends mixed in the laboratory and five proprietary cements submitted by four different manufacturers were subjected to accelerated sulfate testing, which entailed a comparison of cement paste strengths with and without sulfate exposure after 28 and 63 days. In the test, pH (7.2) and sulfate concentration (4 percent Na_2SO_4) were kept constant to simulate field conditions.



In the aggregate reaction study, alkali-silica reactions (ASR) were investigated in an accelerated test (ASTM C1260) in which mortar bar length changes were used to indicate potential reactivity. Two aggregates, granite (mildly reactive) and phyllonite (highly reactive), and five proprietary cements from four different manufacturers were used in the tests. Cements included:

- One Type I/II portland cement
- One Type III portland cement
- Two calcium sulfoaluminate cements
- One calcium aluminate cement

This study was extended to compare results of the ASTM C1260 and C1293 tests, to investigate the reactivity of quartz grains subjected to the two tests, and to determine whether common California cement could be used with the addition of sodium hydroxide to perform ASTM C1293, as an alternative to importing expensive high-alkali content cement from Pennsylvania. Specimens were prepared using aggregates from four different sources, and tested using ASTM C1260, ASTM C1293, and a modified version of ASTM C1293 in which a low-alkali cement was used with added sodium hydroxide.

4.2.2 Findings on Sulfate Attack

Failure criterion was set at 25 percent strength reduction after sulfate exposure. After 28 days, one cement (calcium sulfoaluminate) was considered not to be sulfate resistant. After 63 days, the second calcium sulfoaluminate cement and the calcium aluminate cement failed the criterion, in addition to the one which failed the 28-day test.

4.2.3 Findings on Alkali-Aggregate Reactions

In the first phase of the study:

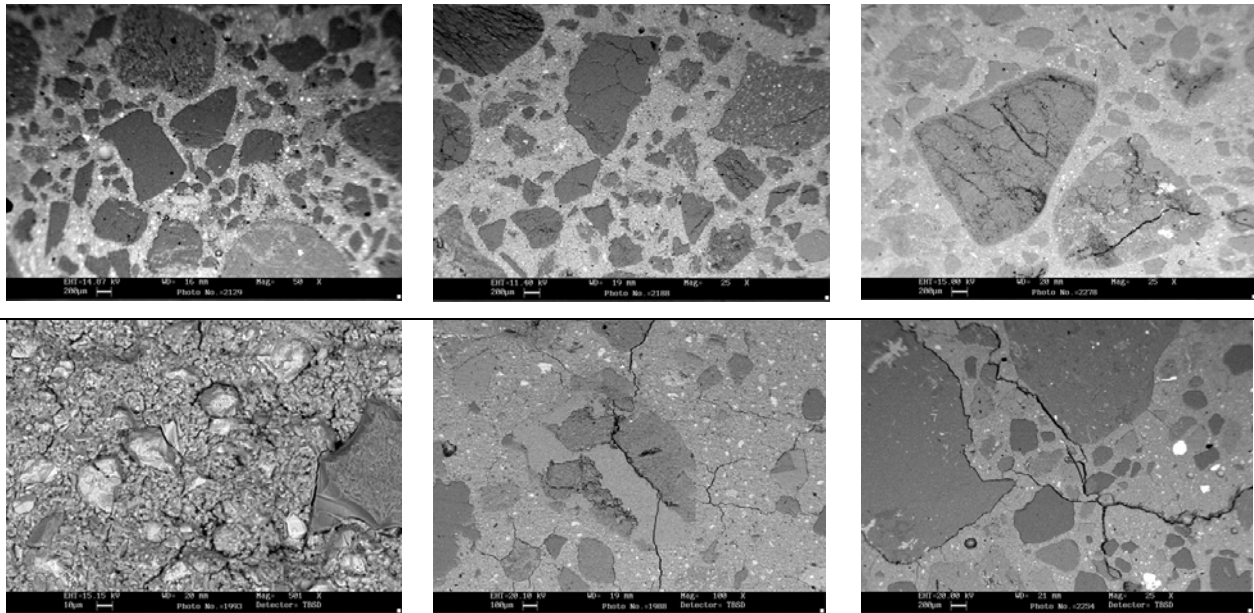
- Calcium aluminate cement was found to be highly resistant to ASR for both aggregates at both 16 and 32 days.
- When using mildly reactive aggregate, both Type I/II and III cements were considered marginal, while the calcium sulfoaluminate cements were considered resistant with an expansion of less than 0.1 percent.
- With highly reactive aggregates, these four cements all exceeded the upper expansion limit of 0.2 percent after 16 days and thus failed. However, the results were not necessarily conclusive given the known severity of the ASTM C1260 test, which is significantly accelerated and not always indicative of field conditions.

Based on the findings of this study, a revised testing specification that accommodates all types of cements was proposed. This includes:

- Revisions to ASTM C1260 to suit California conditions
- Addition of the ASTM C1293 test to the procedure
- Modifications to the aggregate gradings for both tests
- Inclusion of mix design tests as part of the ASR decision process

In the second phase of the study, the following conclusions were drawn:

- The ASTM C1260 test was found to be considerably more aggressive than the C1293 test. A finding of reactivity using the quick and inexpensive ASTM C1260 test should be followed by an evaluation using the more lengthy and costly ASTM C1293. If an aggregate fails both tests it has a high probability of being reactive.
- The microscopy study on aggregates subjected to the two tests revealed that ASTM C1260 and ASTM C1293 cause different phenomena. The high temperature and full saturation used in ASTM C1260 lead to expansion in the aggregate, while the low temperatures and lower hydroxyl content of ASTM C1293 cause cracks to form along the boundary between the aggregate and hardened cement paste, which then propagate through the paste.
- A modified version of ASTM C1293, using low-alkali cement with added hydroxide ions, provided similar results when compared to the standard test. The low-alkali cement also seemed to intensify the expansion value for the reactive aggregate only.



4.2.4 Reports

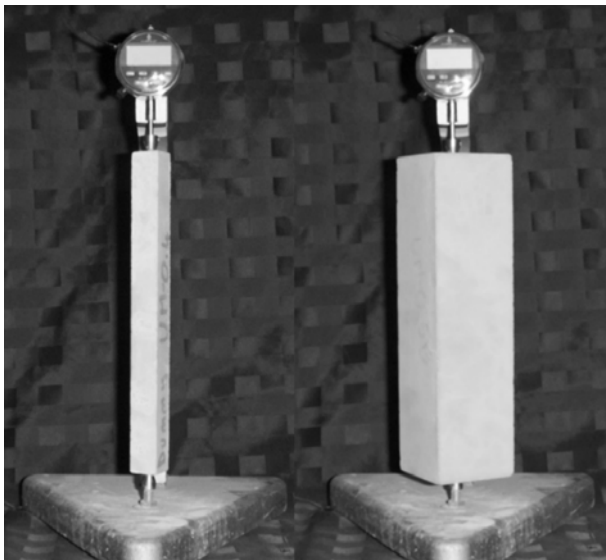
The following reports were prepared for this phase of the study:

1. KURTIS, K. and Monteiro, P. 1999. **Analysis of Durability of Advanced Cementitious Materials for Rigid Pavement Construction in California**. Davis and Berkeley, CA: University of California Pavement Research Center. (Research Report UCPRC-RR-1999-04).

2. MONTEIRO, P., Kurtis, K., Roesler, J., and Harvey, J. 1999. **Accelerated Test Method for Measuring Sulfate Resistance of Hydraulic Cements for Caltrans LLPRS Program**. Davis and Berkeley, CA: University of California Pavement Research Center. (Research Report UCPRC-RR-2000-04)
3. SHOMGLIN, K., Monteiro, P., and Harvey, J. 2001. **Accelerated Laboratory Testing for High Early Strength Concrete for Alkali Aggregate Reaction**. Davis and Berkeley, CA: University of California Pavement Research Center. (Research Report UCPRC-RR-2001-03)
4. CARLOS, C., Mancio, M., Shomglin, K., Harvey, J., Monteiro, P., and Ali, A. 2004. **Accelerated Laboratory Testing for Alkali-Silica Reaction Using ASTM 1293 and Comparison with ASTM 1260**. Davis and Berkeley, CA: University of California Pavement Research Center. (Research Report UCPRC-RR-2004-06)

4.3. Shrinkage and Thermal Cracking of FSHCC

4.3.1 Objectives and Approach



Jointed Plain Concrete Pavement (JPCP) test sections were constructed on the shoulder of SR-14 near Palmdale using Fast-Setting Hydraulic Cement Concrete (FSHCC) for subsequent testing with the HVS. Joint spacings were 3.7, 4.0, 5.5, and 5.8 m (12, 13, 18, and 18 ft.) to match joint spacings in the adjacent state highway pavement. All of the longer slabs [5.5-5.8 m (18-19 ft)] cracked under environmental influences within four weeks of construction and before any traffic load was applied to them. The objective of this phase of the study was to determine and to understand the causes of this

distress. The approach entailed removing and observing cores, and conducting a finite element analysis using field-measured data.

4.3.2 Findings

Cores drilled through the cracks indicated that cracking initiated at the top of the slabs and propagated downward. Finite element analysis using field-measured strains and temperatures predicted high tensile stresses at the top of the test section slabs as a result of the differential drying shrinkage between the top

and base of the slab and the nonlinear nature of the negative temperature gradients through the slab. The findings from this study include:

- Initial strains in the slab were most likely due to thermal contraction of the concrete after construction. After two months, strains at the top of the slabs had increased significantly while the strains measured in the bottom of the slab remained constant. This latter increase was attributed to drying shrinkage and not to thermal contraction.
- The differential strains through the slab thickness from the combined effect of drying shrinkage and nighttime temperature gradients resulted in bending stresses, which exceeded the concrete strength and caused transverse cracking. Laboratory testing performed on the cement (calcium sulfoaluminate) and concrete used showed significantly higher free shrinkage relative to ordinary Type II portland cement and reinforced the findings of the strain measurements. Fine shrinkage measured on specimens made using calcium sulfoaluminate cement from the same manufacturer, but different production lot, had much lower shrinkage. Field measurements across joints showed significant corner curling of the concrete slabs, with as much as 2.5 mm (1.0 in) daily movement under environmental conditions. The corner deflection data suggested the slab corners were permanently curled upward due to the differential drying shrinkage in the slab.
- Corner deflections under daily temperature cycles could be accurately modeled provided the drying shrinkage differential was included in the analysis. The measured data and finite element analyses (using the *ILSL2* program) showed differential drying shrinkage had resulted in the corners of the slab being in a permanently curled up position, resulting in an unsupported corner condition at all times.
- The highest tensile stresses from environmental loading were found to be at the middle of the slab at the surface. This validated the field findings that crack initiation began at the top of the slab and propagated downward.
- The use of FSHCC does not necessarily indicate high shrinkage differentials, as laboratory testing indicated some calcium sulfoaluminate (CSA) cements can have lower shrinkage than Type II portland cements.

4.3.3 Reports

The following report was prepared for this phase of the study:

1. HEATH, A. and Roesler, J. 1999. **Shrinkage and Thermal Cracking of Fast Setting Hydraulic Cement Concrete Pavements in Palmdale, California.** Davis and Berkeley, CA: University of California Pavement Research Center. (Research Report UCPRC-RR-1999-07)

4.4. Strength, Stiffness, Thermal Expansion, and Shrinkage

4.4.1 Objectives and Approach



A comprehensive laboratory study to compare flexural and compressive strength, free shrinkage, coefficient of thermal expansion, and elastic modulus was undertaken on six concrete mixes typical of those used, or considered for use, by Caltrans in LLPRS.

The following objectives were set:

- Evaluate and develop test methods for strength gain, ultimate strength and stiffness, thermal expansion, and shrinkage.
- Develop laboratory data regarding the properties of various high early-strength concrete mixes and compare them with a typical Type I/II mix.
- Develop laboratory data regarding the effects of important mix design and construction variables on mechanical properties.

Two aggregate sources and three categories of cement were used:

- Type I/II portland cement (one cement)
- Type III portland cement (two cements from two manufacturers)
- Calcium sulfoaluminate cement (two cements from two manufacturers)
- Calcium aluminate cement (one cement)

A combination of standard (Caltrans, ASTM, and Army Corps of Engineers) and nonstandard tests were followed. A mix design was developed for each of the six cements, which attempted to optimize the mix properties while obtaining a minimum flexural strength of 2.8 MPa (400 psi) for the construction closure duration applicable to the given cement type. Each mix design was developed by the individual cement manufacturers in the UCPRC laboratory. This strength criterion was developed through mechanistic analysis and was determined to be adequate for opening the pavement to traffic while minimizing the risk that a substantial portion of the concrete pavement fatigue life would be exhausted before the concrete had reached its long-term strength. 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.

4.4.2 Findings

Analysis of the results of testing led to the following conclusions:

- Cement type, curing condition, and water/cement, in this order, are important considerations for assessing strength gain in concrete mix design. A 10 percent increase in water content from the target mix can reduce the strength by more than 10 percent.
- Compressive and flexural strengths respond differently to environmental factors. Cold curing environments cause the greatest reduction in compressive strength while dry conditions are most detrimental to flexural strength; hence there is no 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 scenarios that may be encountered in the field. Although the compressive strength test has less variability than the flexural strength test, they are not interchangeable if precise data are needed.
- The correlation between the elastic modulus and compressive strength conformed to what is given in ACI-318 for the portland cement Type I/II mix at twenty-eight days under standard moist curing. Additional data is needed to extend the conclusion to non-portland cement concrete. The study has shown, however, that the correlation at other ages or under other curing conditions does not conform to ACI-318.
- Curing condition is a more important factor in shrinkage than mix design is. 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 had distinct shrinkage performances, which was attributed to different chemical compositions.
- The tested dry coefficient of thermal expansion ranged from $8\text{--}12 \times 10^{-6}/^{\circ}\text{C}$ for the six mixes. These results conform to the data reported in literature. The Army Corps of Engineers method (CRD) was considered to use a more reasonable temperature range for the measurement. According to the CRD method, portland cement mixes have slightly lower coefficients of thermal expansion than calcium sulfoaluminate mixes made with the same aggregate.

4.4.3 Reports

The following report was prepared for this phase of the study:

1. ZHANG, J., Harvey, J., 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**. Davis and Berkeley, CA: University of California Pavement Research Center. (Research Report UCPRC-RR-2004-01)

4.5. Flexural Fatigue

4.5.1 Objectives and Approach



The objectives of the flexural fatigue investigation were to:

- Study the fatigue characteristics of fast-setting mixes
- Compare the fatigue life of all mixes tested
- Contrast the results with those of similar published studies

The experimental concrete samples included:

- The standard Caltrans mix (using portland cement Type I/II)
- Five fast-setting mixes that used one of three cements:
 - Portland cement Type III
 - Calcium sulfoaluminate
 - Calcium aluminate

Beams fabricated from each mixture and cured for several months under standard conditions were used to determine the materials' flexural strength and fatigue life at stress ratio levels of 0.70, 0.75, and 0.85. Data analyses entailed the following:

- Comparison of the number of cycles to failure of each mix at each stress ratio level
- Regression to compare the fatigue life of each fast-setting mix with the Caltrans standard mix
- Regression to compare this study's results with common models for beam flexural fatigue life found in the literature

4.5.2 Findings

The main conclusions drawn from the study include:

- Fast-setting concrete mixes present similar or higher fatigue resistance than the standard Caltrans type at same flexural stress-to-flexural strength ratios.
- All the mixes presented similar fatigue resistance at a stress ratio of 0.70, but at a stress ratio of 0.85 the Type III portland cement mix displayed the longest fatigue life.
- Linear regression curves generated by the tested mixes compared better to the “zero maintenance” model, the most common fatigue-life model used in concrete pavement engineering, than they did to the NCHRP 1-26 model.
- The results were considered satisfactory, taking into account the high level of scatter usually associated with experimental fatigue research reported in the literature.

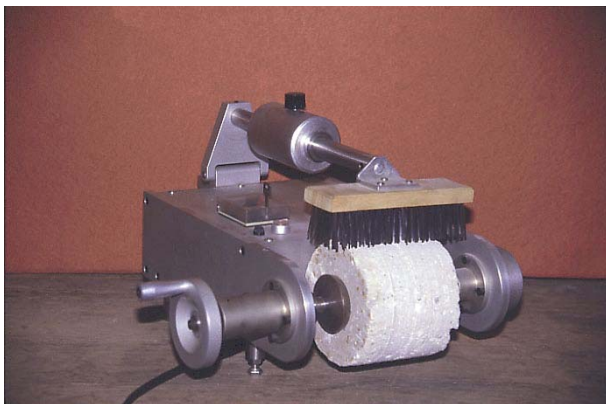
4.5.3 Reports

The following report was prepared for this phase of the study:

1. KOHLER, E., Ali, A. and Harvey, J. 2005. **Goal 4 Long Life Pavement Rehabilitation Strategies - Rigid: Flexural Fatigue Life of Hydraulic Cement Concrete Beams**. Davis and Berkeley, CA: University of California Pavement Research Center. (Research Report UCPRC-RR-2005-04)

4.6. Base Carbonation

4.6.1 Objectives and Approach



The objectives of the carbonation study were to:

- Determine whether the layer of loose material often observed between the concrete slab and the supporting cement-stabilized layer [cement-treated base (CTB) meeting Caltrans specifications of the late 1960s or lean concrete base (LCB) meeting Caltrans specifications of 2000] on faulted concrete pavements could be caused by carbonation of the stabilized layer.
- Determine whether compaction density (using Modified AASHTO and Standard Proctor efforts) influenced durability of the stabilized layer.
- Identify issues for consideration in future stabilization designs.

Two material samples (from Lake Herman and Mission Valley) representative of those commonly used in stabilized bases under concrete slabs were sent to the Council for Scientific and Industrial Research (CSIR) in South Africa for durability testing following South African test methods, but using California cement and designs. Testing included:

- Initial Consumption of Stabilizer (ICS)
- Mechanical and hand wet/dry brushing
- Erosion
- Uncarbonated and carbonated unconfined compressive strength (UCS)

Mechanical crushing of the surface material under the slab was not investigated, although this is a potential cause of the loose layer of material and should be studied.

4.6.2 Findings

- *Cement contents.* Carbonation is unlikely to occur with the cement contents used in California. However, bases with very high cement content and corresponding high shrinkage and cracking could carbonate at these points of distress, leading to further deterioration. Inappropriate construction procedures, specifically curing and intervals between mixing and compaction, could also lead to carbonation.
- *Influence of compaction.* Most test specimens exceeded the compaction density criteria used in South Africa at both compaction energy levels, suggesting that the amounts of cement used are excessive and may be reduced. However, the erosion test indicated that at the lower compaction energy, the CTB materials are likely to erode under concrete slabs, indicating that improved compaction may reduce this problem. It was thus recommended that the required compaction for CTB be increased from 95 percent to either 98 or 100 percent, relative to California Test Method 312 for Class A CTB if this material is still being used. This will increase durability without increasing the risk of shrinkage.
- *Initial Consumption of Stabilizer.* The initial consumption of stabilizer for the Mission Valley CTB and LCB specimens satisfied the South African specification. However, the rates required to meet the South African specification are somewhat lower than the design requirements provided by California. It was recommended that an appropriate ICS specification be developed for California for determining optimal stabilizer contents of treated bases.
- *Brushing.* Samples of the two materials were tested by hand and by mechanical brushing. The mass losses of the Mission Valley specimens were similar for both the CTB and LCB materials. This loss

was attributed to rounded and smooth aggregate, which probably did not bond well with the rest of the mix. Results were acceptable at both compaction efforts and exceeded the South African requirement of a loss of less than 5.0 percent for a stabilized base layer under a concrete pavement and a loss of less than 7.0 percent for A-6/A-7 materials when hand brushed. The Lake Herman LCB proved to be more resistant than the CTB to brushing with the lower cement content. Most specimens had acceptable durability in terms of the test specification limits. This suggests that the cement content may be reduced without adversely affecting the durability of the materials in terms of brushing resistance. This also suggests that LCB is only somewhat better than CTB in terms of durability.

- *Erosion.* The CTB materials proved more erodible than the LCB materials for specimens compacted at both efforts. Both materials with both cement contents exceeded the test requirements for the most demanding traffic loading (erosion index (L) of ≤ 1.0 mm) when compacted at Modified AASHTO effort. However, at Standard Proctor compaction, the CTB materials did not meet the requirements for base or subbase layers under concrete, while the LCB materials at Standard Proctor compaction met the requirements for base layers. It is thus probable that erosion failures will occur if lower cement contents are used or if compaction requirements are not met.
- *Unconfined compressive strength.* The UCS values obtained for both carbonated and uncarbonated specimens at both compaction levels exceeded the minimum South African requirement for the stiffest LCB material [6.0 MPa (870 psi)] for base and subbase layers under a concrete pavement. Some of the values also exceed the maximum suggested value of 12.0 MPa (1,750 psi) at 100 percent Modified AASHTO density, implying that excessive shrinkage and cracking of the treated layer could result. These results suggest that some reduction in cement content could be made without sacrificing the required strength. It was further proposed that the risk of shrinkage cracking could be reduced by consideration of a maximum UCS specification and/or a shrinkage test.

4.6.3 Reports

The following report was prepared for this phase of the study:

1. VENTURA, D.F.C. 2003. **Durability Testing of LCB and CTB Materials Supplied by Caltrans.** Davis and Berkeley, CA: University of California Pavement Research Center. (Technical Memorandum UCPRC-TM-2003-02)

5. HEAVY VEHICLE SIMULATOR TESTING

5.1. Introduction



The Heavy Vehicle Simulator (HVS) testing program was initiated with a pilot study at the UCPRC Richmond Field Station. This included the evaluation of various types of instruments, methods of data recording, and the logistics involved with placing concrete around sensitive instrumentation. After the slab was cast, the HVS was used to evaluate performance of the various instruments as well as the performance of the slab under

accelerated trafficking. Using the experience gained in the pilot study, full-scale pavement experiments were constructed with fast-setting hydraulic cement concrete (FSHCC) on SR-14 near Palmdale and subjected to Heavy Vehicle Simulator Testing following comprehensive test plans. The site was provided and prepared by Caltrans' District 7. The construction was completed under the direction of District 7, with input and assistance from Caltrans Headquarters units. The first group of sections on the southbound side of SR-14 (South Tangent) included jointed plain concrete on aggregate base on which fatigue tests were performed. The second group on the northbound side (North Tangent) included sections with jointed plain concrete on CTB, on which the following tests were performed:

- Two tests on jointed plain concrete slabs without dowels and with asphalt shoulders
- Three tests on slabs fitted with dowels and tied concrete shoulders
- Three tests on sections with slab widths of 4.3 m (14 ft) [instead of the standard 3.7 m (12 ft)] fitted with dowels and with asphalt shoulders.

Studies within the experiment included:

- Construction factors
- The influence of environmental factors (specifically temperature) and dowel bars, tied shoulders, and wider truck lanes on slab curling
- Slab performance modeling.

5.2. Pilot Study



The concrete test sections constructed at the Richmond Field Station (RFS) demonstrated that instrumentation could be successfully embedded in the concrete. The methodologies used to place the instruments were considered adequate given that all gauges functioned correctly throughout the entire test program. The instrumentation and placement methods were developed with help from the US Army Corps of Engineers, Minnesota DOT, and Ohio University.

The use of higher-than-specified concrete strength (approximately 55 percent higher than the minimum Caltrans opening strength), thicker-than-specified concrete [average 28 mm (1.1 in) thicker], and shorter joint spacing in the RFS experiment resulted in a pavement with reduced maximum stresses at the edge and consequently an almost infinite fatigue life. Other failure modes were thus prevalent and included corner breaks, pumping, and joint distress which would need to be considered in future designs through the use of non-erodible base materials, good load transfer across the joints (dowels), and better pavement drainage systems.

By the end of HVS testing both joints were found to have approximately 45 percent load transfer efficiency (LTE), measured with the Road Surface Deflectometer (RSD). This suggests that dowels are necessary to maintain high LTE and to minimize faulting, pumping, and corner breaks. Fatigue analyses using existing mechanistic procedures predicted the test section would never fail in fatigue with a 60 kN wheel load — it ultimately failed after 430,000 HVS repetitions at 60 kN due to a corner break from excessive rainfall and pumping at the pavement edge and joint. This failure mode was anticipated given the use of an aggregate base and the absence of dowels.

5.3. Full-scale Experiments

5.3.1 Construction



Construction of the fast-setting hydraulic cement concrete (FSHCC) test sections in Palmdale was completed in mid-1998 with the successful installation of all instrumentation for later modeling. The contractor selected a blend of 80 percent FSHCC and 20 percent Type I/II portland cement to meet the FSHCC specifications. The South Tangent concrete placement took two days while the North Tangent took three days. Early setting of the concrete in the haul

trucks and paver was noted and some concrete had to be discarded. Tests during construction indicated that:

- None of the beams sampled from the experiments met the eight-hour strength requirements (Caltrans Flexural Beam test) of 2.75 MPa (400 psi) as prescribed in the “Notice to Contractors and Special Provisions.” Furthermore, only 20 percent of the beams met the seven-day strength requirement of 4.15 MPa (600 psi). The average 90-day strength (following ASTM C78 instead of Caltrans Test 523) was 5.2 MPa (750 psi). Although the short-term strengths would not be acceptable in a project opened to traffic eight hours after construction, the 90-day strength (long-term) is acceptable for long-life pavements. Eight-hour and seven-day beam and cylinder strengths correlated well. For 90 day strengths, there was a high variance in the data and no correlation could be established.
- The high FSHCC water/cement ratio at Palmdale was probably the primary reason that the eight-hour strength did not meet specification. Other factors that could have influenced early strengths include curing time and temperature, admixture variability, cement variability, and dry mix batching.
- Cores taken from twenty-four slabs revealed that the average thickness was 215 mm (8.5 in), some 8 percent greater than the 200-mm (8.0-in) design. The coefficient of variation for the core thickness results indicated a high variability in thickness of the pavement from the target value.
- HWD results at different pavement ages indicated that dowel bars at the transverse joints had higher load transfer efficiency (LTE) than the joints with aggregate interlock only. There was no significant difference in LTE across longitudinal joints with and without tie bars, except for a slight improvement at the slab corners.

5.3.2 Environmental Influences

Eight HVS test sections were continuously monitored for vertical and horizontal slab edge elastic movements prior to HVS testing. No loading, apart from the weight of the slab, was applied and the only

forces acting on the pavement were the variable vertical temperature differential, which caused the slabs to curl, and the day-to-night temperature changes, which caused the slabs to expand and contract horizontally. Upward and downward curling movements along the longitudinal edges, caused by cyclic temperature differentials between the top and bottom surfaces of the test sections, were also monitored.

Three temperature regimes were investigated:

- Test sections completely exposed to sunlight;
- Test sections partially exposed to sunlight (HVS parked on the sections); and
- Test sections partially exposed to sunlight, but with controlled temperature [HVS parked on the test sections with a temperature control chamber maintained at approximately 20°C (68°F)].

The following observations were noted.

- The concrete used in the Palmdale sections did not produce a perfectly planar slab and lift-off between the slab and the base was observed along the slab edge. This was attributed to differential shrinkage between the top and the bottom of the slab, which resulted in a permanent upward curl. This warped shape increased with an increasing negative temperature differential.
- Daily temperature variations and the associated temperature differentials (between the top and bottom of the pavement) had a significant influence on slab corner curl. During the day, as the exposed surface heated up, the top of the pavement expanded more than the bottom of the pavement causing the edges of the slab to curl downward. The reverse effect was observed at night with the lower part of the slab retaining more heat than the upper part exposed to colder air, causing the slab corners to curl upwards. The downward curling movement, caused by a positive temperature differential, was more significant than the upward curling movement. This was attributed to the time of testing (early summer and fall) when the positive temperature differential was always greater than the negative gradient. Generally, the surface of the concrete did not cool off to the same extent that it had heated up to during the day.
- On the test sections with controlled temperature, low vertical temperature differentials (typically less than 2.5°C) were recorded. This had a significant effect on the measured responses from the various instruments, and in almost all cases lower movements were recorded compared to those exposed to direct sunlight. However, there was still a good correlation between the recorded trends inside the temperature control chamber and the outside temperature differentials recorded with thermocouples outside the area of influence. This implies that despite good temperature control on the test sections, the temperature changes on the exposed areas of the concrete slabs still influenced concrete behavior inside the temperature control chamber. In certain instances, a distinct lag was observed between the time when a maximum temperature differential was observed away from the temperature control

chamber and the time when an instrument within the temperature control chamber recorded the maximum movement. This lag was typically between two and four hours.

- Strains recorded by the various gauges were generally in the order of $80\ \mu\epsilon$ but strains as high as $300\ \mu\epsilon$, attributed to vertical temperature differentials, were recorded during a twenty-four-hour observation window. Irrespective of their placement within the pavement, the strain gauges exhibited similar tension and compression phases within a twenty-four-hour cycle due to the variation in daily temperature differential. The observed general trend was that the strain gauges were in tension during the day when the pavement was expanding, and in compression at night when the pavement was contracting.

5.3.3 Slab Performance

Slab warping due to differential shrinkage between the upper and the lower part of the concrete layer played a significant role in the measured deflections, even with the application of test loads greater than 90 kN. The following trends were observed:

- Deflections recorded in the base layer were typically less than 0.2 mm compared to between 1.0 and 1.2 mm (0.04 and 0.05 in) on the surface, implying that less than 20 percent of the surface deflection was transferred to the base layer. This was attributed to differential shrinkage, which resulted in a cavity between the bottom of the concrete layer and the base. The high deflections measured at the surface were a direct result of this loss in support from the substructure.
- A significant drop in surface deflections and a subsequent increase in base layer deflections occurred after the appearance of cracks on the undoweled test sections. The cracks caused the slabs to come into full contact with the base layer. This resulted in increased support from the underlying layers and hence an increase in base layer deflections and a subsequent reduction in the measured surface deflections.
- The addition of tie bars and dowels between the slabs had a significant influence on edge curling. Vertical and horizontal movements were normalized in terms of temperature differences and maximum day-to-night surface temperature variations respectively prior to analysis. The sections instrumented with dowels and tie bars were the most successful in terms of restricting slab corner curl and thermal expansion/contraction due to temperature fluctuations. An average vertical corner movement of $81.1\ \mu\text{m}/^\circ\text{C}$ was recorded in comparison with the undoweled, non-tied sections ($161.2\ \mu\text{m}/^\circ\text{C}$), and the widened lane sections ($183.3\ \mu\text{m}/^\circ\text{C}$). Although the sample size was small and there was some variability, it appears that the sections with extra-wide lanes performed the worst in terms of ability to restrict vertical corner movements due to temperature differentials in the slab.

- Edge movements were the smallest in the case of dowels and tie bars ($26.1 \mu\text{m}/^\circ\text{C}$) compared to jointed plain ($86.3 \mu\text{m}/^\circ\text{C}$) and extra wide lane ($118.9 \mu\text{m}/^\circ\text{C}$). Although horizontal slab movement appeared to remain relatively constant regardless of the structure type, the sections with dowels and tie bars produced the lowest average horizontal movement ($29.9 \mu\text{m}/^\circ\text{C}$). It should be remembered that factors such as slab length, the degree and severity of transverse cracks, and daily weather conditions all play an important role in the horizontal movements and hence these results should be considered as indicators of performance only.
- Surface deflections measured at night were at least double those recorded during the day at the same locations. It is clear that deflection measurements were highly dependent on the time of day and that slab curl resulting from temperature variations should be built into any deflection analysis of concrete pavements. Deflection variations caused by daily and seasonal temperature changes generally masked the damaging effect caused by repetitive loading.
- On undoweled joints, edge surface deflections under the influence of a 90 kN test load were between 2.0 and 4.0 mm (0.1 and 0.15 in) before any cracks appeared, and dropped to between 1.0 and 2.2 mm after edge and corner cracks appeared. LTE values started around 99 percent and (0.04 and 0.085 in) dropped to as low as 20 percent after corner cracks appeared.
- On slabs with doweled joints, concrete shoulders, and tie bars, edge surface deflections under the influence of a 90 kN test load were of the order of 0.8 to 1.8 mm (0.03 and 0.07 in) before any cracks appeared. No significant difference in edge deflections was detected after the appearance of cracks. LTE values varied between 80 and 100 percent for the duration of testing and did not drop after the appearance of cracks, even when testing loads were increased to 150 kN.
- On widened slabs [4.3 m (14 ft)] with doweled joints and asphalt concrete shoulders, edge deflections under the influence of a 90 kN test load were between 0.6 and 1.4 mm (0.02 and 0.06 in) before any cracks appeared, and between 0.8 and 1.5 mm (0.03 and 0.06 in) after cracks appeared. LTE values varied between 97 and 100 percent for the duration of testing. The appearance of cracks did not cause any reduction in LTE values.

5.3.4 Slab Performance Modeling

Differential expansion and contraction between the top and bottom of a slab is caused by the combined effects of nonlinear “built-in” temperature gradients, irreversible shrinkage, moisture gradients, and creep, and is referred to as “effective built-in temperature difference” (EBITD). High EBITD results in higher tensile stresses at the top of the slab (curling), which in turn has a major influence on slab behavior, including shorter cracking life. A procedure for estimating EBITD using loaded slab deflections was developed using the HVS results.

The HVS tests were also used to examine Miner’s hypothesis along with various fatigue damage models. Results indicate that the test slabs cracked at cumulative damage levels significantly different from unity. New models that incorporate stress range, loading rate, and peak stresses were thus developed. The models include coefficients for transverse and longitudinal cracking and corner breaks, and can be used for slabs that exhibit high negative EBITD. A procedure to model the influence of slab size and strength reduction from microcracking in slabs susceptible to high shrinkage gradients was developed using nonlinear fracture mechanics principles. A parameter called the “effective initial crack depth” was introduced to characterize the early-age surface microcracking.

Backcalculating EBITD using loaded slab deflection analysis indicated that:

- The Palmdale slabs had high EBITD values [-20°C to -35°C (-4 to -31 F)] for sections with low restraint (undoweled sections) and low to moderate EBITD values [0°C to -20°C (32 F to -4 F)] for sections with higher restraint (doweled sections). The restraints due to load transfer devices appeared to restrict the upward curl of the slabs during early age, probably through tensile creep mechanisms. The high EBITD measured was attributed to the use of a batch of fast-setting high-early-strength concrete with measured high shrinkage. Paving during daytime desert conditions with low ambient humidity and high wind speed also contributed to the high EBITD.
- The slab’s self-weight acts as a restraint to the curling of the slab. Thinner slabs typically had higher magnitude EBITD compared to thicker slabs. However, a reduction in magnitude of EBITD was seen for very thin slabs [less than 100 mm (4 in)], attributed to differential drying shrinkage between the top 50 mm (2 in) of the slab and the bottom of the slab. In thinner slabs, the differential drying shrinkage is reduced, resulting in lower EBITD contribution.
- The presence or absence of the cement-treated base course did not appear to influence curling. However, if the concrete layer had been bonded to the base layer, the type of base might have affected EBITD.
- On all sections, the corners of the slab had a higher magnitude EBITD compared to the mid-slab edge.
- The doweled sections had more uniform restraint at the joints, resulting in similar EBITD for both sides of the slabs. The slabs with undoweled joints may or may not have an asymmetric curvature because the EBITD depends on the aggregate interlock restraint between adjacent slabs, which could vary from one joint to another.
- The dependence of EBITD on aggregate interlock restraint can result in EBITD values that vary from slab to slab.

Miner's hypothesis for accumulation of damage and the applicability of several concrete fatigue transfer functions were tested against the full-scale results from HVS testing, with varying temperature and both fixed and varying load. Peak tensile stresses at critical locations were used to calculate cumulative damage with various fatigue models. The results showed that Miner's approach cannot be used to predict the timing or number of load repetitions corresponding to slab cracking with any level of accuracy. The existing fatigue models, which are based on given sets of data from various studies in the literature, stress calculations, and failure definitions, could not be extrapolated accurately to another loading condition without a "calibration" phase. None of the existing fatigue algorithms or design procedures has been calibrated for longitudinal cracking and corner breaks or for slabs with high negative built-in curl. In order to overcome some of the shortcomings of existing procedures, linear and bilinear models that incorporate stress range, loading rate, and peak stresses were developed.

The linear model assumes EBITD decreases linearly from the top of the slab to the bottom of the slab. The bilinear model assumes EBITD decreases linearly from the top of the slab to the middle of the slab and is zero from the middle of the slab to the bottom of the slab. The models were calibrated for transverse cracking, longitudinal cracking, and corner breaks, and are suitable for slabs that exhibit high negative built-in curl. The models better fit the Palmdale data than existing fatigue models and are more evenly distributed about the expected mean fatigue damage of 1.0. Reasonable correspondence was observed between predicted crack locations and observed crack locations on most of the test sections.

In existing fatigue damage accumulation procedures, the initial damage in the slab is assumed zero for new construction. However, tensile stresses due to restraints from slab weight, slab-base friction, and load transfer devices can result in microcracking and reduction in strength, particularly for slabs built with high early-age shrinkage concrete. Slabs of all thicknesses are also assumed to have equivalent flexural strength in these models. However, fracture mechanics principles suggest that the nominal strength of concrete decreases with increase in thickness. A procedure to model thickness effect and early-age surface microcracking due to restraint stresses based on nonlinear fracture mechanics was developed. A parameter, the "effective initial crack depth" was introduced to model the strength loss due to early-age surface microcracking. This parameter can vary from one slab to another depending on how the restraint stresses in the slab developed during concrete strength gain. However, an overall trend of slabs with higher restraint (thicker slabs and sections with load transfer devices) showed higher effective initial crack depth. Because of the extreme conditions at Palmdale and the excessive shrinkage characteristics of the concrete, the effective initial crack depth was found to be an important parameter affecting the performance of the slabs.

5.4. Reports

The following reports were prepared for this phase of the study:

1. ROESLER, J., du Plessis, L., Hung, D., Bush, D., and Harvey, J. 1999. **CAL/APT Goal LLPRS — Rigid Phase III: Concrete Test Section 516CT Report.** Davis and Berkeley, CA: University of California Pavement Research Center. (Research Report UCPRC-RR-1999-03)
2. ROESLER, J., Scheffy, C., Ali, A., and Bush, D. 2000. **Construction, Instrumentation, and Testing of Fast-Setting Hydraulic Cement Concrete in Palmdale, California.** Davis and Berkeley, CA: University of California Pavement Research Center. (Research Report UCPRC-RR-2000-05)
3. DU PLESSIS, L., Bush, D., Jooste, F., Hung, D., Scheffy, C., Roesler, J. Popescu, L., and Harvey, J. 2002. **HVS Test Results on Fast-Setting Hydraulic Cement Concrete, Palmdale, California Test Sections, South Tangent.** Davis and Berkeley, CA: University of California Pavement Research Center. (Research Report UCPRC-RR-2002-03)
4. DU PLESSIS, L. and Harvey, J. 2003. **Environmental Influences on the Curling of Concrete Slabs at the Palmdale HVS Test Site.** Davis and Berkeley, CA: University of California Pavement Research Center. (Research Report UCPRC-RR-2003-05).
5. DU PLESSIS, L., Jooste, F., Keckwick, S., and Steyn, W. 2005. **HVS Testing of the Palmdale Test Site, North Tangent Sections: Evaluation of Long Life Pavement Rehabilitation Strategies-Rigid.** Davis and Berkeley, CA: University of California Pavement Research Center. (Research Report UCPRC-RR-2005-02)
6. RAO, S., and Roesler, J. 2005. **Characterization of Effective Built-in Curling and Concrete Pavement Cracking on the Palmdale Test Sections.** Davis and Berkeley, CA: University of California Pavement Research Center. (Research Report UCPRC-RR-2005-09)

6. SUMMARY OF RECOMMENDATIONS



Based on the research carried out in the studies detailed in this report, a number of recommendations were made that responded to questions raised by Caltrans and the concrete pavement industry in the period 1996 to 1998. At that time there was little experience in California regarding lane reconstruction of concrete pavements. The research performed by the UCPRC was carried out between 1998 and 2005. The results

of this and other efforts by Caltrans helped to find solutions to most of the issues identified for the Caltrans Long-Life Pavement Rehabilitation Strategy (LLPRS) program.

Observations are presented grouped by the three identified objectives (Table 1), with related recommendations, and minor suggestions derived from observations of construction practices during the investigations.

Table 2 details the status of the recommendations Caltrans has implemented.

Objective 1. Evaluate the adequacy of structural design options (tied concrete shoulders, doweled joints, and widened truck lanes) primarily with respect to joint distress, fatigue cracking and corner cracking.

1. Mechanistic-empirical design procedures should be used for the design of concrete pavements in order to develop the most cost-efficient designs for different environments, materials, traffic levels, subgrades, and structural details such as joint length.
2. The use of axle load spectra instead of equivalent standard axle loads (ESALs) for concrete pavement design should be evaluated as a means of achieving more cost-efficient designs. ESALs are generic measures of traffic across all pavement types, whereas axle load spectra can be used with mechanistic-empirical design to quantify the damaging effects of different axle types and loads specifically for concrete pavement.
3. Dowels were recommended for use in concrete pavements to minimize transverse joint faulting, corner cracking, and associated roughness for all facilities except those designed for very low traffic volumes. The minimum dowel size should be 32 mm, but where possible, larger sizes [up to 38 mm (1.5 in)] should be used, provided that adequate cover can be maintained.

4. It was suggested to limit joint spacing to a maximum of 4.5 m (15 ft). Joint spacings of 5.5 and 5.8 m (18 and 19 ft) used prior to the early 1980s should not be considered as they lead to quicker occurrence of transverse cracking, and reconstructed lanes should not match the longer joint spacings. An isolation joint should be placed between new lanes and existing lanes with the longer joint spacing.
5. The use of widened truck lanes in addition to tied concrete and asphalt concrete shoulders should be considered to improve fatigue-cracking performance.
6. The use of non-erodible treated base types should be continued to minimize transverse faulting and corner cracking. A concurrent study indicates that ATPB (Asphalt Treated Permeable Base) may not be non-erodible.
7. In environments where large temperature gradients and consequent curling occur, very stiff bases may increase tensile stresses in the slab and they should not be considered. In these situations the use of appropriate mechanistic design procedures will assist the designer.
8. The coefficient of thermal expansion (CTE) should be included as a pavement design parameter. Validation of this recommendation should be undertaken in field studies with measurements of CTE as soon as possible for information purposes. The most cost-efficient implementation approach should be determined based on the validation and that database of measured values. This will likely be either a specification of maximum CTE, or adjustment of the pavement design by a factor derived from the CTE of locally available materials.
9. When determining the CTE, a test method with a temperature range similar to that expected of the actual concrete pavement project should be used.
10. If asphalt concrete bases are to be used for concrete pavements, a new mix specification for them should be developed. The current specifications optimize rutting performance; however, bases for concrete pavements need to be optimized for moisture sensitivity and friction between the slab and the base.
11. When designing pavements where non-portland cement concrete will be used, the same design criteria as that followed for portland cement concrete should be applied, provided that all specifications are met. Fast-Setting Hydraulic Cement Concrete (FSHCC) mixes appear to have the same fatigue performance as PCC based on HVS and laboratory testing.

Objective 2. Assess the durability of concrete slabs made with cements meeting the requirements for early opening to carry traffic, and develop methods to screen new materials for durability.

12. The use of flexural strength for the specification of concrete for pavements should be continued. Compressive strength should not be used as this is an indirect measure of pavement performance, and no unique relationship between the two strengths exists.
13. The requirement of a minimum third point flexural strength of 2.1 MPa (300 psi) for rapid-strength gain for traffic opening should be continued. However, an increase in the minimum opening strength to 2.9 MPa (400 psi) should be considered to minimize risk of early cracking due to traffic loading for slabs in the range of 200 to 230 mm (8 to 9 in). Caltrans and industry have developed alternative portland cement concrete materials with high early strength. Mixes of materials with twelve-hour and longer strength gains have been used on LLPRS projects.
14. Ninety-day third point flexural beam strengths of 4.5 to 5.5 MPa (650 to 800 psi) was recommended in 1998 to be considered for adoption as a specification. Flexural strengths less than this require thicker slabs to minimize cracking.
15. Caltrans' practice of using a shrinkage specification of 0.053 percent after seven days (CTM 527) for all cements — including fast-setting, hydraulic cement concrete (FSHCC) — should be continued. Shrinkage testing should be performed on the cement proposed for the construction at the beginning of a project and also during construction, in order to check variability in supply. Curing conditions have a significant effect on shrinkage and appropriate curing should always be performed. Alternatives such as double curing membranes should be investigated. High variability in shrinkage for non-portland cement mixes was noted between different manufacturers and even for the same manufacturer for different dates of production.
16. In 2000, the use of hydraulic cement concrete materials other than fast-setting hydraulic cement concrete was recommended for long-life pavement rehabilitation. The use of hydraulic cement concrete materials other than fast-setting hydraulic cement concrete was recommended in year 2000 for long-life pavement rehabilitation. Concrete construction productivity studies showed that concrete set time is not the most important variable for construction productivity in typical LLPRS closures (e.g., 55 hour weekend closures).
17. The current Caltrans practice of using ASTM C1260 as a screening test for evaluating the reactivity of aggregates, followed by testing with ASTM C1293 if an aggregate is found to be reactive, should be continued.
18. The modified ASTM C1293 test should be assessed using a wider variety of aggregates. If results correlate with the existing method, it should be considered for adoption by Caltrans and submitted to ASTM for approval.

19. The sulfate resistance guidelines for 100 percent portland cement concretes, as defined by ACI Building Code 318/318-95, should be adopted and enforced. This recommends maximum water-to-cement ratios and minimum compressive strengths for different sulfate exposure levels. Since the code only covers portland cements, contractors that propose the use of other types of cementitious material should provide evidence that the material is sulfate-resistant with similar performance to at least ASTM Type I/II cements in accelerated sulfate resistance tests.
20. Caltrans should adopt failure criteria of less than 25 percent loss of strength at 28 and 63 days of sulfate exposure relative to the seven-day strength of the material.

Objective 3. Measure the effects of construction and mix design variables on the durability and structural performance of pavements

21. Bases with a high frictional resistance (e.g., lean concrete bases or open-graded mixes) should not be used without a bond-breaking layer between the base and slab. The high frictional resistance can create significant tensile stresses in the pavement slabs when the concrete cools from a high heat of hydration (as is typical with FSHCC) or when the concrete has a high drying shrinkage. Where feasible, flexible bases should be used as they will deform under long-term environmental loading and thereby decrease stresses in the slabs. Stiffer bases do not allow any relaxation of environmental stresses.
22. When feasible, the construction season, the time of day, and the environmental condition when paving is performed should be considered when planning construction to minimize development of built-in curl. It is usually preferable to pave under cool, moist conditions and not have concrete set during the heat of the day. High built-in curl, measured as equivalent built-in temperature difference (EBITD), results in higher tensile stress and fatigue cracking. The use of dowels will further limit EBITD.

Additional Recommendations

The following recommendations, derived from associated studies, are also considered pertinent:

23. Construction productivity analysis tools, such as *CA4PRS* software, should be used to determine variables controlling the critical path for LLPRS construction. The analyses should generally focus on construction traffic (i.e., the number of trucks hauling old materials out of and new materials into the site and redundancy associated with breakdown of critical equipment such as pavers) rather than actual productivity of equipment, which is usually not the constraining variable.

24. Traffic analysis should be performed and traffic management plans developed for all LLPRS projects to maximize the number of lanes that can be safely taken from traffic. The critical variable controlling construction productivity is the number of lanes behind K-rail that the contractor has available for construction traffic equipment and operations.

Minor Suggestions

These suggestions refer to construction practices observed in the period of 1996 to 1998, and fall outside the original objectives.

25. If a long slab replacement is required then a doveled joint should be placed in the center of the slab.
26. New slabs should be prevented from bonding to adjacent slabs as this will induce tensile stresses during shrinkage in the period after construction. The joints between the new slabs and the adjacent lane slabs should be both cut and sealed immediately after construction or have a bond-breaker placed between them.
27. Strict monitoring of the water/cement ratio of concrete delivered at the site should be continued. Higher than acceptable water/cement ratios result in significant decreases in strength.

Table 2: Summary of Implementation of Recommendations by Caltrans

Project Objectives and Details on Implementation by Caltrans		
Recommendation number	Objective 1: Evaluate adequacy of structural design options and considerations identified by Caltrans in 1998	
	1	M-E design. Currently being implemented for next version of the Caltrans Highway Design Manual (HDM).
	2	Axle load spectra. Implemented.
	3	Dowel bars. Implemented. Use of non-doweled slabs for low-volume traffic is being considered in the new pavement design catalog.
	4	Joint spacing. Recommendation verifies changes in the HDM since early 1990s. Additional studies with regard to reconstruction or addition of lanes adjacent to existing lanes with long joint spacings has since been performed as implementation for specific projects.
	5	Widened truck lane. Implemented in the HDM. Use of non-doweled pavement for low-volume traffic is being considered in the new rigid pavement design catalog.
	6	Non-erodible bases. Confirms Caltrans current designs. A concurrent study indicates that ATPB option (included in the new rigid pavement design catalog) may not be non-erodible.
	7	Stiff bases. Implemented for some projects in District 8.
	8	Coefficient of Thermal Expansion for design. Implemented. CTE currently being measured by construction on most projects.
	9	CTE test temperature. Included in Rigid Pav. Design Guide currently being developed. Considered in AASHTO test protocol (2000).
	10	AC bases for PCC. Implemented.
	11	Structural design with non-portland cement. Implemented.
	Objective 2: Durability of concrete slabs, and material screening methods	
	12	Flexural strength test. Confirmed Caltrans use of modulus of rupture instead of compressive strength for pavements.
	13	Minimum strength for traffic opening. Confirmed current Caltrans. Recommendation for thin slabs not implemented.
	14	Ninety-day strength. Recommendation is being implemented more stringently at 42-days. Implemented.
	15	Shrinkage. Confirmed current Caltrans limit specification. Testing for variability has not been implemented.
	16	Use of non fast-setting cement. Recommendation that not be used unless required for very short construction windows. Implemented.
	17	ASTM C1260, screening for alkali reactivity of aggregate. Implemented.
	18	ASTM C1293, change in test procedure for alkali-silica reaction. Not implemented to date.
	19	Sulfate resistance ACI code. Not implemented to date.
	20	Sulfate exposure strength loss. Not implemented to date.
	Objective 3: Effect of construction and mix design on pavement performance	
	21	Bond breakers on bases. Implemented.
	22	Construction season and time. Considered by Caltrans, but difficult to put into practice. Not implemented.
	Additional recommendations from associated studies	
	23	Construction productivity. Implemented on several projects. Design is implementing use of <i>CA4PRS</i> for LLPRS and similar projects.
	24	Traffic analysis. Implemented on several projects. Design is currently implementing use of <i>CA4PRS</i> for LLPRS and similar projects.