Report Prepared for
State of California, Department of Transportation
Sacramento, California

TASK ORDER NO. 56A0315-003

PRELIMINARY ANALYSIS USING DARWIN-ME FOR PRECAST CONCRETE PAVEMENT METHODOGY

DRAFT FINAL REPORT

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June 22, 2012

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CHAPTER 1 – INTRODUCTION

1.1 Introduction

Precast concrete pavement (PCP) technology is of recent origin. The production use of the PCP technology began in earnest during 2001. The PCP systems are used in highway corridors with high volume of traffic and where lane closures are a challenge. Over the last 10 years, several US highway agencies, including California DOT (Caltrans), Illinois Tollway, New Jersey DOT, New York State DOT, and Utah DOT, have implemented the PCP technology and a few other agencies have constructed demonstration projects. The implemented PCP systems include proprietary as well as non-proprietary systems. Because the production use of PCP technology in the US is of recent origin and the information on PCP practices and performance is not well documented, the PCP design processes are not yet fully developed.

The following PCP applications have been implemented by Caltrans at several rehabilitation projects:

1. Intermittent repairs – for full-depth repairs or full slab replacement, generally used on jointed concrete pavements
2. Continuous applications – for longer length or larger area pavement rehabilitation. Two PCP types have been used for this application.
    a. Jointed precast concrete pavement (JPrCP) – these pavements perform similar to conventional cast-in-place jointed concrete pavements.
    b. Precast prestressed concrete pavements (PPCP) – A number of precast panels, typically 10 ft or more in length, are connected together by post-tensioning. This approach results in fewer active joints – at a spacing of about every 100 to 300 ft. The prestressing also allows use of thinner panels compared to the jointed precast concrete pavement systems.

The California PCP projects todate have been designed using a “best practice” approach that considers feedback from the HDM Topic 620, recommendations from pavement designers, and constraints related to existing pavement thickness. However, in order to ensure that future PCP systems are optimally designed, Caltrans is seeking a rational PCP design procedure that allows evaluation of expected performance of the various PCP systems that may be considered in future.

This report, prepared by Fugro Consultants, Inc. (FUGRO), provides a proposed approach to develop the designs for JPrCP systems and PPCP systems which are also referred to as posttensioned precast concrete pavement systems. The report also includes the application of the proposed approach to various sections of Routes 710, 5, and 405 that will be rehabilitated using the PPCP system.

1.2 Scope of Study

The scope of the study includes the development of a PCP pavement design methodology for use by Caltrans that will allow for optimization of key design features for both jointed and posttensioned PCP systems. These design features include the following:

1. Concrete thickness and precast panel size
2. Strength of concrete
3. Modulus of rupture of concrete
4. Steel reinforcement details, including ratio of reinforcement steel to concrete and location of steel in concrete.
5. Prestressing (pre and post tensioning features)
6. Joint configuration (type and spacing)
7. Equivalent Single Axle Loads (ESALs) and Traffic Index (TI)

The thresholds for determining performance life was required to match those found in Highway Design Manual (HDM) Topic 622 or match a set of alternate performance measures with equivalent criteria as mutually agreed with the State Technical Liaison. The methodology is to allow development of a pavement design for an individual project and allow comparison of expected performance of alternate precast systems. The methodology is also to allow the user the ability to optimize the various materials for PCP and PPCP. It should be noted that for PPCP, the methodology is to allow optimization of the design features by balancing the following features:

1. Panel thickness
2. Prestress level (pretension and post-tensioned)
3. Post-tensioned section length
4. Base type (existing or new, typically CTB/LCB)
5. Edge condition (widened panels and/or PCP shoulder)
6. Concrete strength
7. Performance expectation (allowable distress)

CHAPTER 2 – BACKGROUND

2.1 Introduction

The design of PCP is based on the assumption that, once constructed (installed), the overall behavior of the PCP under traffic loading and environmental loading is not significantly different than that of a like cast-in-place concrete pavement. Thus, a jointed PCP (JPrCP) is expected to behave similar to a cast-in-place jointed concrete pavement (JCP) and a PPCP is expected to behave similar to a cast-in-place prestressed concrete pavement. However, the performance of the PCP systems is expected to be better than like cast-in-place concrete pavements because of better quality of concrete used, better control of panel fabrication process and better installation practices.

Concrete pavements are typically designed, constructed, and rehabilitated to provide long-life performance. The U.S. definition for long-life concrete pavements is as follows:

- Original concrete service life of 40+ years;
- Pavement will not exhibit premature failures and materials related distress;
- Pavement will have reduced potential for cracking, faulting and spalling; and
- Pavement will maintain desirable ride and surface texture characteristics with minimal intervention activities to correct for ride and texture, for joint resealing, and minor repairs.

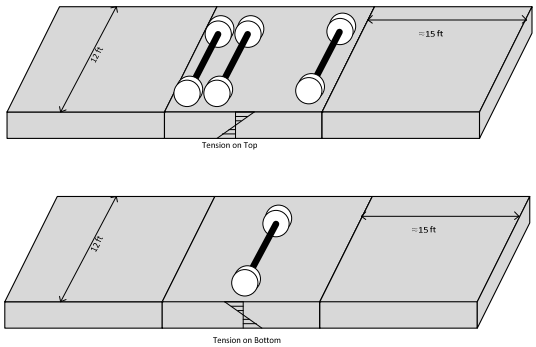
Although PCPs are of recent use and in-service performance information of the oldest U.S. projects is available for about 10 years, PCPs can be designed to provide long-term service. In fact, the warrant for use of PCPs is rapid repair and rehabilitation with recognition of the need for long-term service. The off-site fabrication of PCPs provides certain design-related advantages that include:

1. Design strength of concrete from Day 1 of installation thereby assuring no structural damage due to early traffic loading;
2. No early-age curling and warping issues;
3. No built-in curling to account for since precast concrete panels are typically fabricated flat and remain flat during storage and installation;
4. Precast panels incorporate substantial reinforcement. As a result, any cracks that may develop under traffic loading remain tightly closed and do not deteriorate with time; and
5. The faulting that may develop in PPCP is less critical than faulting in jointed concrete pavements. This is because the PPCP expansion joint spacing may range from about 150 to about 300 feet. The joint spacing for cast-in-place JCP is typically about 15 feet. In addition, PPCP is constructed on good quality stiff bases that results in lower joint deflections under traffic loading and less risk of joint-related distress.

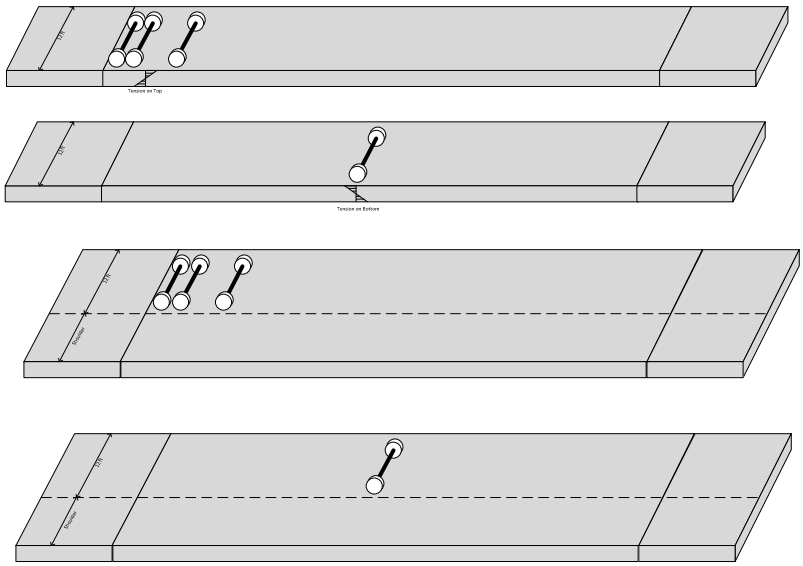
For any pavement system, the structural requirements are defined on the basis of anticipated structural distress (failures) under traffic for a given environmental condition. Typical distresses that can develop in conventional JCP include the following:

1. Cracking - transverse cracking may develop over a period of time due to repeated truck loadings. Cracking is typically referred to as a stress-based distress.
2. Joint Faulting - may develop with or without outward signs of pumping. Faulting is typically referred to as a deflection-based distress. Joint faulting is significantly affected by the type of load transfer provided at transverse joints, base type, and drainage needs.
3. Spalling - may develop along joints or cracks and may develop due to incompressible in joints or cracks and/or poor quality concrete.
4. Materials Related Distress - the more significant materials related distress may include alkali-silica reactivity and D-cracking in a freezing environment. These distresses are mitigated by using the right material for concrete.
5. Roughness - pavement smoothness is affected by the development of various distresses in the concrete pavement. The effect of each distress type is additive and results in increased pavement roughness over a period of time.

The truck loading conditions to be considered for jointed concrete pavements (CIP or precast) and PPCP systems are shown in Figure 2.1. The critical truck axle positions in Figure 1a are for stresses that result in top-down cracking and in bottom-up cracking. These loading conditions are applicable for 12-foot-wide lanes, widened lanes, and for lanes with a tied concrete shoulder. The critical truck axle positions for longer length PPCP segments are shown in Figure 2.1b. As shown, the critical stresses can develop for bottom-up cracking and for top-down cracking for single lane applications. When the PPCP panels are multiple lanes in width, as shown in Figure 2.1b, the loading condition is always an interior loading condition. This is the most efficient design for the PPCP.



a. Truck Axle Loading for Critical Slab Stresses for Cast-in-Place Jointed Concrete Pavement (JCP) and Precast Jointed Concrete Pavement (JPrCP)



b. Truck Axle Loading for Critical Slab Stresses for Precast Prestressed Concrete Pavement (PPCP) - Single and Multiple Lanes

Figure 2.1 - Concrete Pavement truck Loading Conditions

Distress development over the service life of all pavements is expected; however, the rate of distress development is managed by incorporating sound designs, durable paving materials, quality construction practices, and timely preservation activities. In short, structural distress development should take place in accordance with design expectations, but not prematurely.

In order to understand the structural requirements for PCP, it is necessary to understand the loading that a concrete pavement may be subjected to. Pavements are designed on the basis of truck traffic. Without truck traffic, pavements would only exhibit materials related distress. For new concrete pavement systems, the following loading related items need to be considered:

1. Design Traffic - Most new concrete pavements are now being designed for an initial service life of at least 40 years. Assume a roadway carries 50,000 vehicles per day in one direction and the trucks account for 20 percent of the vehicles. The design lane will carry over 100,000,000 trucks over 40 years, without accounting for traffic growth. Most new primary highway system pavements in the U.S. are now routinely being designed for truck traffic in the range of 100 to 200 million trucks over the pavements design period. When precast pavement systems are used for such applications, the precast pavement components need to be designed to accommodate high levels of traffic loading. The allowable truck axle loads range from 20,000 pounds for the single axle, 36,000 pounds for the tandem axle, to 45,000 pounds for the tridem axle. The stresses and deflections in the concrete slab (panel) resulting from the traffic loadings are accounted for in traditional mechanistic-based design procedures, such as the AASHTO MEPDG.

2. Load Transfer at Joints - When fully effective, a doweled transverse joint will have load transfer effectiveness (LTE) of 90 to 95 percent, as constructed. Over a period of time, as a result of traffic loading, the LTE will decrease. For conventional jointed concrete pavements, an LTE of about 70 percent is considered the limit at which some load transfer restoration treatment may need to be provided. The load carried (transferred) by a dowel bar at a joint may range from about 3,000 pounds for the outermost dowel bar with the axle load positioned along the lane edge to about 1,200 pounds with the axle load positioned about 2 feet away from the lane edge. On the primary highway system, these loads are expected to be carried by the dowel bars in excess of 100,000,000 times, assuming most trucks drive along the lane edge.
3. Temperature Related Curling - Temperature variations with depth in the concrete panel induce curling restraint stresses. These stresses vary throughout the day and from day to day and can be very high and are accounted for in traditional mechanistic-based design procedures, such as the AASHTO MEPDG.

In summary, the design of the various components of any new PCP system must take into account the high volume of truck traffic expected to use the facility and the environmental conditions. Design, material, and construction flaws cannot be tolerated under such high traffic loadings. The above discussion is also applicable to intermittent precast repair applications. The only difference is design truck-traffic may be less for such applications if the repairs are designed for a shorter service life.

As discussed previously, specific design procedures have not been developed for PCP systems. Development of reliable pavement design procedures requires a sound understanding of the pavement behavior and validation of the design concepts on the basis of field performance. <u>At this time, there are not sufficient PCP projects available with long service to allow field validation.</u> As a result, the design of PCP systems needs to be based on current design procedures for conventional cast-in-place JCP, such as the recently developed Mechanistic-Empirical Pavement Design Guide (MEPDG) and the associated DARWin-ME software available from AASHTO.

As discussed, the primary difference between conventionally constructed cast-in-place JCP and PCP systems is the method of construction/installation. Once the PCP system has been installed, the behavior of the system should not be significantly different than that of a cast-in-place concrete pavement system. Some differences do exist and are listed below:

1. Less slab warping in the precast panels, if cured properly at the plant;
2. Less variability in concrete strength for the precast panels;
3. More precise embedment of dowel bars in precast pavements;
4. A smoother bottom surface for PCP systems; and
5. JPCP panels have smooth vertical faces at the transverse joints and the installation process can result in a gap of up to 0.5 inches at these joints. Therefore, aggregate interlocking does not develop at these joints.

PPCP systems are typically thinner than JCP. This is a result of the effective prestress in the prestressed pavement. The effective prestress at the mid-location of the post-tensioned segment, typically 150 to 300 feet between expansion joints, needs to be about 150 to 200 psi. This is achieved by properly designing the prestress system for the anticipated slab/base interface condition and consideration of short-term and long-term prestress losses. The effective prestress is additive to the concrete flexural strength and the resulting effective flexural strength is used as the design concrete flexural strength. When using PPCP systems, a caution must be exercised. Because these systems incorporate thinner panels, the panel support (base and foundation) become critical. For heavy truck traffic, the thinner PPCP systems require a non-erodible stabilized base to reduce slab deflections at the expansion joints and along the panel edges (along the shoulder joint), especially for 12-foot-wide outside lane panels.

For repair applications, the precast pavement should be designed with the extended service life of the existing pavement in mind. For new construction, the precast pavement should be designed to achieve a minimum design life of 40 years in accordance to the current version of Caltran's HDM Topic 612 for long-life concrete pavements.

2.2 DARWin-ME Design Process

The concrete pavement design process has evolved over the last one hundred years, beginning with rudimentary design equations based on early road tests and simple analysis procedures. Significant improvements were made in the design process based on the AASHO Road Test and subsequent improvements to the so-called AASHTO Pavement Design Guide, the last version for concrete pavements released in 1993. Up to this time, the AASHTO pavement design procedures were primarily based on empirical data derived from the AASHO Road Test and limited theoretically-based enhancements.

By mid-1990’s, the existing pavement design procedures were considered inadequate to account for the significant increase in truck traffic over the nation’s highway system and to account for new paving materials. In addition, specific site conditions (specifically climatic) and pavement features (joint spacing, lane width, joint load transfer, concrete properties, etc.) could not be properly accounted for. As a result, a major study was initiated by NCHRP during mid-1990’s to develop a more rational pavement design procedure. This procedure, commonly, referred to as MEPDG, was released in July 2008 as an interim guide with companion pavement design software. During 2011, the software was formally released by AASHTO as DARWin-ME.

The MEPDG/DARWin-ME represents a shift in how pavements are designed. The new design process allows consideration of site specific features, traffic load spectra, climatic features, and paving material properties to determine the edge stresses and joint deflections for each axle loading and state of curling throughout a daily period. The computed stresses and deflections are used to determine the damage to the pavement done by the combination of the axle loads and appropriate curling stresses. The

computed damage is then used to determine the expected pavement distress over a period of time for a selected pavement section. If the predicted distresses are acceptable, the pavement section is considered acceptable. An iterative process is used to establish the most optimum pavement section. Details of the MEPDG are given in "Mechanistic-Empirical Pavement Design Guide: A Manual of Practice, July 2008, Interim Edition, published by AASHTO and technical reports delivered as part of the NCHRP 1-47A study.

With respect to jointed plain concrete pavement design, the following are the key attributes of the MEPDG process:

1. Key design inputs
    a. Concrete properties, specifically the coefficient of thermal expansion (CTE)
    b. Bonding characteristic between the concrete slab and the base
    c. Joint spacing
    d. Load transfer (dowel bar) design
    e. Built-in slab warping
2. Key design outputs (outcomes)
    a. Slab cracking
    b. Joint faulting
    c. Roughness

Currently, many highway agencies in the US, including Caltrans, are in the process of implementing the MEPDG/DARWin-ME process by establishing agency-specific design inputs and agency-specific calibration of the MEPDG. In addition, there is continuing effort to improve many of the assumptions and models used to develop the MEPDG. Specifically for jointed plain concrete pavements, these efforts include the following:

1. Improved characterization of the bonding between the concrete slab and the base
2. Revising the distress models to account for corrected CTE values
3. More rational characterization of the built-in slab warping.

<u>It should be noted that the MEPDG/DARWin-ME do not directly address the design of PCP systems. However, as discussed later, the MEPDG/DARWin-ME can be used to extrapolate designs for the jointed as well as the PPCP systems.</u>

2.3 Caltrans HDM Concrete Pavement Design Process

The Caltrans concrete pavement design process is based on Chapter 620: Rigid Pavement of the HDM, dated May 2012 and applicable portions of Chapters 600 and 610 of the HDM. The pavement designs are based on a catalog design approach as detailed in Topic 623 of the HDM. The designs are based on the rigid pavement properties listed in Table 622.1 in the HDM and the performance factors listed in Table 622.2 in the HDM. The designs given in Topic 623 are specific to the climatic region

(nine regions), subgrade type (Type I (SP) or II (CH)), and lateral support. The catalog designs provide the concrete slab thickness for various base/subbase combinations and traffic loading. The catalog designs incorporate the results of pavement design analysis using the MEPDG software (version as of 2005), conducted by the University of California at Davis (UCD) and reported in Technical Memorandum: UCPRC-TM-2006-04: Sample Rigid Pavement Design Tables Based on Version 0.8 of the MEPDG, dated June 2006.

The use of the MEPDG (and the DARWin-ME software) directly to develop pavement designs is currently under evaluation by Caltrans.

2.4 Precast Concrete Pavement Design Considerations

The following categories of the continuous PCP systems have been used or may be used by Caltrans:

1. Precast jointed systems (JPrCP)
    a. Nominally reinforced precast panel systems - These systems simulate conventional CIP jointed plain concrete pavements, except that the panels incorporate reinforcement and possibly higher strength concrete.
    b. Individually prestressed panel systems - These systems are similar to the nominally reinforced precast panels systems, except the panels are individually prestressed (by pre-tensioning. This approach ensures that the desirable level of effective prestress is available in each panel. Site conditions, such as the panel–base friction, do not have an impact on the effective prestress in the panels. Pre-tensioning is required in the pavement longitudinal directions only, but may be used in the transverse direction to provide a more structurally efficient panel. Use of pre-tensioning allows the use of thinner panels with higher structural capacity to fit within an existing pavement profile, especially when single lanes are being rehabilitated.
2. Prestressed systems (PPCP)
    a. Continuously prestressed system (FHWA–University of Texas PPCP system) - This system simulates conventional CIP prestressed concrete pavements and uses posttensioning to connect and prestress a number of reinforced or prestressed panels to form a single-slab section.

The structural requirements for continuous applications of precast pavements focus on reducing both cracking and joint faulting. Cracking is a stress-based distress and joint faulting is a deflection-based distress. Long-term performance necessitates that concrete slab (panel) stresses and slab (panel) deflections be kept as low as possible to accommodate the millions of truck loadings over the expected 30- to 40-plus years of service life.

For continuous applications, long-life performance is expected and needs to be designed for. Therefore, it is essential that PCP systems used in continuous applications be able to meet the requirements for long life.

Design Criteria for Jointed PCP Systems

For continuous jointed PCP systems, the following long-term failure manifestations can result:

1. Structural distress:
    a. Slab cracking.
    b. Joint faulting.
    c. Joint spalling.
2. Functional distress:
    a. Poor ride quality (smoothness).
    b. Poor surface texture (in terms of surface friction and tire–pavement noise).

The design criteria recommended for CIP JCPs for long-life service are considered applicable to the jointed PCPs. However, because the individual panels of the precast pavement are reinforced, any cracks in the panels will be held tightly closed and would not be expected to deteriorate and affect ride quality. As a result, the criteria for cracking can be relaxed. The design criteria recommended by FUGRO for jointed PCPs for long-life service is given in Table 2.1.

Table 2.1. Recommended Design Criteria for Jointed PCP Systems (R = 90%)

Distress	Value
Structural Distress:	
Cracked Slabs, %	20%
Faulting, in.	0.10
Spalling (length, severity)	Minimal
Materials Related Distress	None
Functional Distress:	
Smoothness (IRI), in./mile	160
Surface Texture - Friction	Long lasting, FN > 35
Surface Texture - Noise	No criteria available, but surface should produce accepted level of pavement–tire noise

Note: Caltrans has designated 10% for the Cracked Slabs criteria

Design Criteria for PPCP Systems

For the PPCP system, the following long-term failure manifestations can result:

1. Structural distress
    a. Joint faulting.
    b. Cracking.

   c. Expansion joint or joint hardware failure.
2. Functional distress
   a. Poor ride quality (smoothness).
   b. Poor surface texture (in terms of surface friction and tire–pavement noise).

The design criteria recommended by FUGRO for PPCP for long-life service are given in Table 2.2 and are based on the criteria recommended for JCPs. The criterion related to cracking is not considered directly applicable to PPCP systems and can be relaxed considerably. This is due to the higher level of effective prestress in the posttensioned sections of the PPCP system. The PPCP design is based on the "weakest" panel at mid-length of the posttensioned section, and cracking (failure condition) in such panels would result in one crack every 150 to 250 ft or about 20 to 30 cracks per mile. This level of cracking is still better than an allowable level of about 10% to 15% of slabs cracked for CIP JCP with 13.5 to 15-ft joint spacing (resulting in about 50 to 57 cracks per mile). Thus, the recommended cracking criterion for PPCP is set at 10 to 15 cracks per mile (for 20 to 35 posttensioned sections/mi) or 50% of the sections exhibiting cracking. It should also be noted that the joint faulting criteria is typically based on faulting at shorter joint spacing (typically 13.5 to 15 ft), while for PPCP, an active expansion joint is spaced at 150 to 250 ft. <u>However, even though the faulting criterion is considered applicable at the fewer expansion joints, it is not designed for directly</u>. The faulting reduction is ensured by using a high-quality base for PPCP projects to reduce joint deflections under truck traffic.

Table 2.2. Recommended Design Criteria for PPCP (R = 90%)

Distress	Value
Structural Distress:	
Cracking, % (of sections)	50%
Faulting, in.	Not considered/Not Applicable
Materials-related Distress	None
Functional Distress:	
Smoothness (IRI), in./mile	Not considered
Surface Texture - Friction	Long lasting, FN > 35
Surface Texture - Noise	No criteria available, but surface should produce accepted level of pavement–tire noise

Note: Caltrans has designated 10% for the Cracked Slabs criteria

It should also be noted that the MEPDG cracking criteria is based on fatigue damage due to a combination of top-down and bottom-up cracking. The top-down cracking can be due to flexural stress development at the slab surface that develops as a result of the specific placement of the steering axle and the first tractor axle on a given slab panel. For jointed pavements, this condition can be critical because of the shorter slab length between transverse joints. This condition is not considered critical for the longer PPCP sections. However, the fatigue damage due to both top and bottom tensile stresses are considered in the PPCP design. The MEPDG/DARWin-ME procedure does identify the component of the fatigue damage due to top tensile stresses and bottom tensile

stresses, and it is possible to consider only the bottom-up fatigue damage, but this approach would need to be validated in the field. For now, the use of the total fatigue damage is recommended to develop the preliminary design of the PPCP system and this approach provides an additional level of conservatism. The design criteria recommended for PPCP for long-life service is given in Table 2.

2.5 Alternate PPCP Design Processes

It should be noted that other pavement design approaches have been used for design of PPCP. The approach used for the first PPCP demonstration project in Texas constructed during 2001 and for subsequent PPCP projects constructed in other States, including California, is based on the stress equivalency concept. This concept considers the following three criteria:

1. Elastic Equivalency: the effective prestress for a PPCP with thickness T_i is equal to the bottom tensile stress for the conventional pavement thickness (designed using an established procedure, such as the DARWin-ME (current) or other such as the AASHTP 93 Guide or HDM catalog) less the bottom tensile stress for a PPCP with thickness T_i. This concept is illustrated as follows:

$$\sigma_P = \sigma_{Ti} - \sigma_C$$

Where:

σ_P = minimum effective prestress for a PCP with a thickness of Ti

σ_{Ti} = bottom tensile stress due to design wheel load for a PCP with a thickness of Ti

σ_C = bottom tensile stress due to design wheel load for the conventional design

2. Fatigue Equivalency: fatigue failure is not allowed to develop at the critical location (mid-point of the posttensioned section), after accounting for the maximum load stresses, maximum curling stress, and prestress loss due to panel/base frictional restraint. This concept is illustrated as follows:

$$\sigma_P = \sigma_t + \sigma_c + \sigma_F - f \qquad (2)$$

Where:

f = allowable concrete flexural stress (half of the flexural strength; safety factor of 2.0)

σ_p = minimum effective prestress at the critical location

σ_t = bottom tensile stress due to design wheel load

σ_c = curling stress due to maximum temperature differential in the concrete panel

σ_F = prestress loss due to friction between panel and base

3. Minimum effective prestress level of 100 psi to ensure tight intermediate transverse joints..

The required minimum effective prestress is the maximum value that satisfies the above three criteria.

The above approach, though simple in concept, does not account for project specific axle load spectra, concrete properties, and the diurnal changes in curling stress.

It is the Fugro team recommendation that the design of the PCP systems be based on the MEPDG concepts and as facilitated by the DARWin-ME software. With Caltrans migrating towards the adoption of MEPDG and DARWin-ME in the near future, the use of DARWin-ME, incorporating the PCP specific performance criteria discussed, will provide a systematic approach to evaluating alternated PCP systems and the baseline conventional concrete pavements. The currently recommended design criteria by FUGRO can be revised in future as more performance data become available.

CHAPTER 3 – PROPOSED CALTRANS PRECAST CONCRETE PAVEMENT DESIGN PROCESS

3.1 Introduction

The proposed approach for the design of PCP systems by Caltrans is based on the use of the MEPDG process and the recently released DARWin-ME design software. The use of the MEPDG process is warranted because the current HDM Topic 620 catalog design does not allow consideration of:

1. Higher strength levels of concrete as available in precast concrete panels. The HDM Topic 620 catalog designs are based on a concrete flexural strength of 625 psi.
2. Prestressing available in individual panels or the posttensioned sections
3. Project specific traffic loading (Topic 620 considers only a range of TI values)
4. Project specific concrete properties, primarily, the CTE values
5. Slab-base interface condition.

However, as a new design approach is established for PCP systems, it is necessary that there is a sound basis for comparing the designs developed using the HDM design catalog and using the MEPDG/DARWin-ME process. As a result, FUGRO first evaluated the reasonableness of using the DARWin-ME process as compared to the HDM catalog designs.

1. Establish compatibility between DARWin-ME and the HDM Topic 620 designs
2. Establish adjustments for jointed PCP system inputs for DARWin-ME
3. Establish adjustments for posttensioned PCP system inputs for DARWin-ME
4. Conduct sensitivity analysis to verify PCP system design reasonableness.

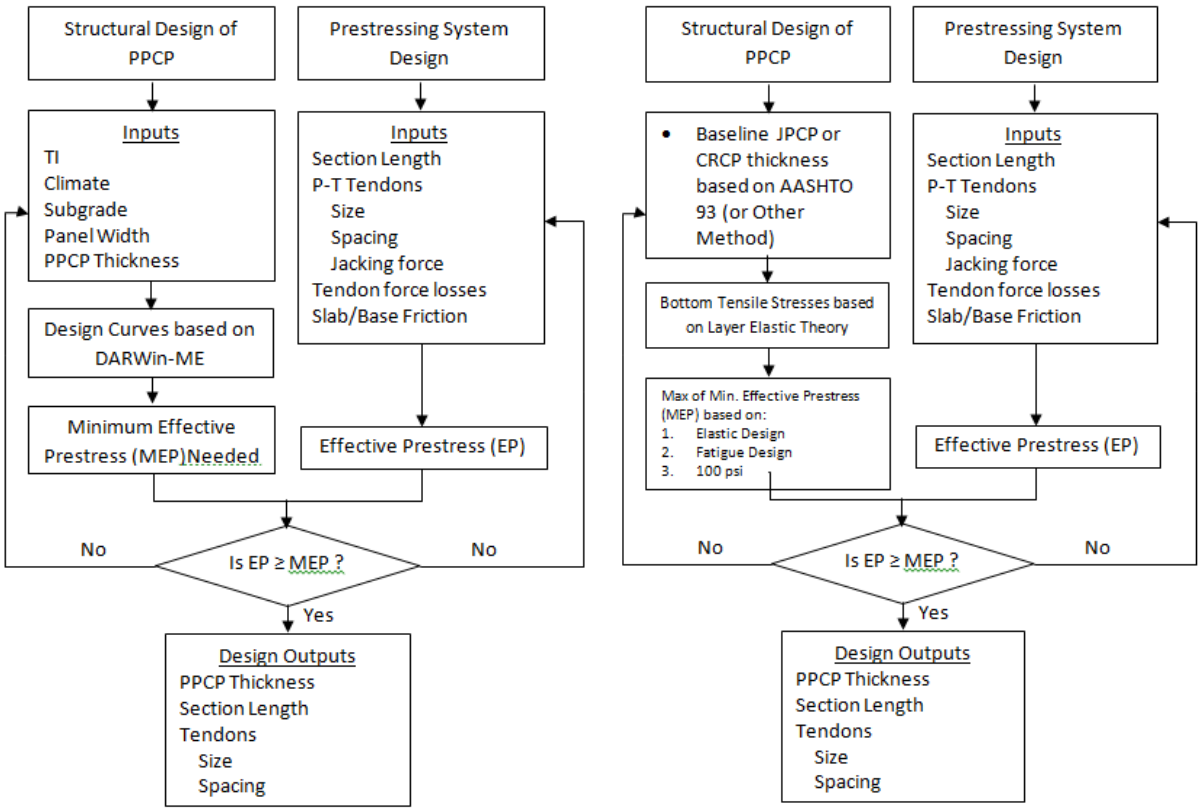
3.2 Summary of Design Approach

As discussed, the proposed PCP design process is based on pavement analysis and design based on DARWin-ME. The DARWin-ME process accounts for pavement damage (based on stress and deflection computation) for each combination of axle load and curling while considering the properties of the paving materials that may change over the analysis period. The proposed design process is illustrated in Figure 3.1. Also, for comparison, the design process used in the past for PPCP design is included in Figure 1. The two design processes are similar except for the computation of the panel (slab) thickness and the effective prestress.

As shown in Figure 3.1, the PPCP design process includes three distinct and parallel steps, as follows:

- Step 1: Determine the minimum effective thickness for a range of panel thickness based on the pavement structural design using DARWin-ME or the University of Texas method.

- Step 2: Conduct the prestressing system design for a range of posttensioned section lengths, panel thickness, tendon spacing (and size, typically 06 in. diameter), prestress jacking force (typically 80% of the ultimate), and consideration of various prestress losses. The prestressing analysis should result in the determination of the effective prestress for each unique set of conditions considered.
- Step 3: Select the panel thickness and the prestressing system details that represent a cost-effective design.



a) Proposed Design Approach b) University of Texas Design Approach

Figure 3.1 – PCP Design Flow Charts

CHAPTER 4 - COMPATIBILITY BETWEEN DARWIN-ME AND HDM TOPIC 620 DESIGNS

4.1 Introduction

The proposed approach for the design of PCP systems by Caltrans is based on the use of the MEPDG process and the recently released DARWin-ME design software. As discussed, as a new design approach is developed for PCP systems, it is necessary that there is a sound basis for comparing the designs developed by using the HDM design catalog and using the MEPDG/DARWin-ME process. This is because, for a given PCP project, the following pavement designs should be developed:

1. Baseline design for a cast-in-place JCP. This design serves as the baseline design to compare the designs developed for JPrCP and/or PPCP systems.
2. Designs for JPrCP and/or PPCP systems

Analysis was conducted to determine the level of compatibility between the HDM Topic 620 catalog-based designs and the designs developed using DARWin-ME for conventional JCPs. This required performing runs for a range of pavement designs given in HDM Topic 620 and incorporating the following design inputs:

1. Traffic level – a range of traffic index values and equivalent axle load spectra for use with DARWin-ME
2. Climatic region
3. Subgrade type
4. Lateral support (edge condition)
5. Concrete properties (a single set of concrete properties as referenced in HDM Topic 620 designs).

4.2 DARWin-ME Design Data

The following key factors and their levels were used for the compatibility assessment study:

1. Climate: Central Coast, Desert, Low Mountain
2. Traffic Index (TI): 9, 10, 11, 12, 13, 14, 15, 16, and 17 (1, 2.4, 5.4, 11, 22, 41, 73, 126, and 210 million ESALs, respectively)
3. PCC thickness: Five consecutive integer thickness values for each TI
4. Subgrade: CH and SP
5. Shoulder Type: Asphalt, Widened or Tied
6. Granular subbase: Yes for CH subgrade, No for SP subgrade

The design inputs related to material properties and pavement design features are given in Appendix A. The performance criteria used for this study are those given in HDM Topic 620 and are as follows:

1. Design life: 40 years
2. Allowable cracking: 10%
3. Allowable faulting: 0.10 in.

4.3 DARWin-ME Analysis

The DARWin-ME analysis was conducted using the bonded and unbonded slab/base interface condition. The unbonded interface condition correlated better with the HDM catalog-based designs and the comparisons to the HDM catalog designs are based on use of the unbonded interface condition for the DARWin-ME analysis.

The comparison of the HDM catalog designs and the DARWin-ME design is given in Table 4.1 for three climatic regions, two subgrade soils, and two edge conditions. It should be noted that the HDM data incorporate 0.36 in. additional thickness for future surface grinding. The DARWin-ME data do not incorporate any additional thickness for future grinding.

Overall, the comparison indicate that the designs developed using DARWin-ME are reasonably in agreement with the HDM catalog designs, although in many cases, there is a difference in excess of 1 in. in favor of the HDM thicknesses, again not accounting for the additional thickness incorporated in the HDM designs to account for future grinding.

Table 4.1 – Comparison of the HDM Catalog Designs and DARWin-ME Designs

Soil	CH
Climate	CC

	12 ft Lane		Widened	
TI	HDM	DARWIN	HDM	DARWIN
09	8.4	7.8	8.4	6.2
10	9.0	8.2	8.4	6.9
11	9.6	8.8	9.0	7. 5
12	10.2	9.0	9.6	7.9
13	10.8	9.6	10.2	8.1
14	11.4	9.9	10.2	8.7
15	12.0	10.3	10.8	9.0
16	12.6	10.8	11.4	9.59
17	13.2	11.3	12.0	10.0

Soil	SP
Climate	CC

	12 ft Lane		Widened	
TI	HDM	DARWIN	HDM	DARWIN
09	8.4	7.6	8.4	5. 8
10	9.0	8.1	8.4	6.5
11	9.6	8.8	9.0	7.4
12	10.2	9.0	9.6	7.9
13	10.8	9.8	10.2	8.3
14	11.4	10.3	10.2	8. 8
15	12.0	11.2	10.8	9.0
16	12.6	12.0	11.4	9.7
17	13.2	12. 9	12.0	10.6

Soil	CH
Climate	DE

	12 ft Lane		Widened	
TI	HDM	DARWIN	HDM	DARWIN
09	9.0	8.6	8.4	7.1
10	9.6	9.0	9.0	7.9
11	10.2	9.8	9.6	8. 5
12	10.8	10.4	10.2	9.0
13	12.6	11.1	11.4	9. 9
14	13.8	11.8	12.0	10.8
15	14.4	12.1	12.6	11.6
16	15.0	13.6	13.2	12.4
17	15.6	14.6	13.8	13.3

Soil	SP
Climate	DE

	12 ft Lane		Widened	
TI	HDM	DARWIN	HDM	DARWIN
09	9.0	8.7	8.4	7.0
10	9.6	9.3	9.0	7.8
11	10.2	10.4	9.6	8.4
12	10.8	11.8	10.2	9.0
13	12.6	12.9	11.4	10.3
14	13.8	13.7	12.0	11.7
15	14.4	14.4	12.6	12.8
16	15.0	15.1	13.2	13.9
17	15.6	16.5	13.8	15.0

Soil	CH
Climate	MO

	12 ft Lane		Widened	
TI	HDM	DARWIN	HDM	DARWIN
09	9.0	8.5	8.4	7.0
10	9.6	9.0	8.4	7.8
11	10.2	9.9	9.0	8.6
12	10.8	10.7	9.6	9.5
13	12.0	11.6	10.8	10.4
14	12.6	12. 7	11.4	11.3
15	13.8	13.5	12.0	12.4
16	14.4	14.1	12.6	13.3
17	15.0	14. 8	13.2	13.9

Soil	SP
Climate	MO

	12 ft Lane		Widened	
TI	HDM	DARWIN	HDM	DARWIN
09	9.0	8.6	8.4	6. 9
10	9.6	9.5	8.4	7. 8
11	10.2	10.7	9.0	8.4
12	10.8	11.8	9.6	9.5
13	12.0	12.7	10.8	10.6
14	12.6	13.3	11.4	11.5
15	13.8	13.9	12.0	12.1
16	14.4	14.5	12.6	12.9
17	15.0	15.0	13.2	14.7

It is expected that when Caltrans implements DARWin-ME, the software will be calibrated based on actual pavement performance of concrete pavements in California. Based on the preliminary analysis of the HDM and DARWin-ME designs, it appears that future local calibration of Window-ME may result in only minor thickness adjustments, from about ½ in. to about 1 in.

Based on the data presented in Table 1, it appears that DARWin-ME can be used to develop baseline concrete pavement designs and by adjusting the design inputs and performance criteria, the process can be applied in the interim to the design of PCP systems.

4.4 Adjustments for Jointed PCP Systems

As discussed, the structural design of the jointed PCP can be developed using the DARWin-ME procedure. Although the MEPDG design procedures are primarily applicable to conventional pavements, use of the MEPDG design procedure for JCPs is recommended for the design of JPrCPs, with modifications to the design criteria discussed previously and with specific adjustments discussed in the following paragraphs.

The current version of the DARWin-ME software can be used to develop the JPrCP designs after appropriate adjustments have been made in the design inputs to account for unique features of jointed JPrCP systems.

For JPrCPs, the following end-of-service distress criteria are recommended by FUGRO:

1. Initial service life - 40 years.
2. Cracking - 20% of panels cracked
3. Faulting - 0.10 in. (Caltrans specified)
4. Smoothness (IRI) – Not considered

It is assumed that as the pavement smoothness deteriorates with time, grinding will be performed to restore smoothness and surface texture. Two cycles of grinding are assumed over the 40-year design life. As a result, any design thickness that is determined should be increased by 0.36 in. to account for the two cycles of grinding.

It should be noted that Caltrans has designated 10% as the cracking criterion for JPrCPs. Therefore, the design results are presented for both 10% and 20% cracking criteria.

Additionally, the following adjustments need to be considered in the DARWin-ME design inputs:

1. Concrete strength – the achieved concrete strength for precast panels is typically higher, exceeding 700 psi, irrespective of the concrete strength specified. In addition, if the panels are pretensioned, the effective concrete strength can be increased by the level of prestress used. For the design analysis presented later, the design flexural strength of 725 is used for JPrCP designs. The design engineer may select any appropriate design flexural strength for a specific project.
2. Permanent curl/warp effective temperature difference (built-in curl) - The default value for conventional JCP is (-) 10 F. Since the PCP panels are fabricated in a plant, there is very little, if any, built-in curl resulting from construction. However, it is assumed that some built-in curl develops during service as a result surface drying of the concrete panels. This feature will require additional review as more field data are collected on PCP performance. For now, the use of the default value of (-) 10 F is recommended.

3. Ultimate concrete shrinkage - 50% of the ultimate value can be used as a large portion of the concrete shrinkage takes place during storage. This is because most precast panels are stored for several weeks or months before installation.
4. Contact friction time - This is the time over which full contact friction is assumed to exist between the concrete slab (precast panel) and the underlying base layer. The MEPDG recommends use of 136-month period over which full contact friction exists. For jointed PCP, the contact friction is considered to be low as the bottom of the precast panels is not expected to bond to the underlying layer because bedding material is used over the existing base and the panel bottom surface is smooth. It should be noted that panel undersealing is performed after panel installation, but is not expected to significantly affect the panel–base interface condition for the jointed PCP systems. This feature will require additional review in the future as more field data are collected on PCP performance and new information is developed on the contact friction condition (as per a new NCHRP study to be initiated during 2012). For now, the use of an unbonded slab-base interface condition is recommended .

4.5 Adjustments for Posttensioned PCP Systems

There are several specific factors which must be considered for the design of a PPCP. These factors are listed below:

1. Slab-Base Interaction - The PPCP systems require placement of the panels on a smooth base/interlayer to ensure that the panel–base friction is as low as possible. Otherwise, a larger portion of the prestressing force is consumed in overcoming the panel–base friction. Precast panels have a smooth bottom surface, which helps to reduce friction between the slab and base. However, a bond-breaking, friction-reducing material, such as polyethylene sheeting, is generally required to further reduce frictional restraint while also preventing bonding between the panel and the base. For examples presented later in this report, the coefficient of slab-based friction of 0.60 is used. The design engineer may select any appropriate coefficient for a specific project.
2. PPCP Support Condition - The base and the foundation need to be of high quality and stiff to minimize slab deflections at the expansion joint.
3. Effective Prestress - The PPCP can be designed to achieve effective prestress of about 100 (minimum) to over 200 psi at midpoint of the posttensioned section. This effective prestress adds to the concrete's flexural strength and <u>allows use of PPCP systems that are about 3 to 4 in. less in thickness</u> than conventional JCPs for the same traffic loading and environmental conditions.
4. Expansion Joints - The PPCP systems can be designed to incorporate expansion joints at about 150 to about 250 ft (45.7 to 76.2 m).
    a. Shorter expansion joint spacing may not be cost-effective.
    b. The longer joint spacing requires use of more prestressing tendons (more prestressing force) to balance the higher prestress losses due to longer prestressing lengths involved.

c. Also, longer joint spacing results in larger movement at expansion joints, which impacts load transfer at these joints. This may require more robust joint hardware and may require more frequent sealant maintenance.

The expansion joint should be designed to allow for large posttensioned section end movements (typically 1 to 3 in., depending on environmental conditions, concrete creep and shrinkage, and posttensioned panel section length) and to provide the desired level of load transfer across the wider joints.

2. Stressing System - The prestressing tendon size (diameter) and spacing should be selected to achieve the desired stress level in the concrete at mid-length of each section of posttensioned panels. The duct spacing can be increased if two tendons are used per duct. The U.S. experience is based on the use of 0.6-in. diameter, Grade 270 7-wire stress-relieved tendons for highway applications for posttensioning and use of 0.5-in. diameter, Grade 270 7-wire stress-relieved tendons for pre-tensioning.
3. Prestress Losses - Prestress losses are an important consideration in posttensioned precast pavements, as the strength of the pavement relies on the effective prestress in the concrete from posttensioning. These losses must be accounted for to ensure that the required prestress level is maintained over the length of the slab over the design life of the pavement. Long-term losses of 40% to 50% of the applied prestress force can be expected for a well-constructed PPCP. A minimum effective prestress level of 100 psi is recommended to ensure intermediate joints remain tight..
4. Intermediate Joints - Attention also needs to be paid to the joints between adjacent panels in each posttensioned section. The prestressing (posttensioning) keeps these intermediate joints tightly closed. The standard method for the design of the intermediate joints uses a keyway system. The panel on one side of the joint has the keyway tongue and the panel on the other side has the keyway groove. The use of the keyway, a coating of epoxy, and the prestressing (posttensioning) ensures a tight and almost monolithic connection at intermediate joints. As a result, there is no need to provide additional load transfer at these joints and these joints do not need to be accounted for in the structural design of the PPCP systems.

As discussed previously, only the cracking criterion is considered applicable for PPCP design. The deflection-related distress (joint faulting) at expansion joints is not directly applicable, and concern with deflection-related distress can be mitigated by specifying a strong, preferably stabilized, base and paying careful attention to the overall foundation support and the load transfer system at these joints.

It should be noted that if there is a failure to attain the minimum level of prestress in the middle portion of the posttensioned section, the affected adjacent intermediate joints may not remain connected under truck traffic and this may result in higher deflections at these joints and cause joint spalling. The failure to attain the minimum level of prestress in the middle portion will also have other consequences, such as panel cracking and settlement at the affected intermediate joints.

4.6 Design of the Prestressing System

The steps used to design the prestressing system are detailed below.

1. Design the prestressing system
    a. Tendon size - typically, 0.6 in. 7-wire tendons used.
    b. Tendon force - 80% of the ultimate load (46,600 lbf).
    c. Tendon spacing - to be determined (12 to 36 in. - depending on posttensioned length (typically 150 to 250 ft) and number of tendons per duct.
2. Assume the posttensioned section length and tendon spacing.
3. Determine end prestress that can be applied. The applied end prestress level for a range of tendon spacing and panel thickness is illustrated in Table 4.2.

Table 4.2. End prestress levels.

Panel Thickness, in.	Applied End Prestress, psi, for Strand Spacing of			
	18	**24**	**30**	**36**
8	299	224	179	149
9	265	199	159	133
10	239	179	143	119
11	217	163	130	109
12	199	149	119	100

4. Determine prestress losses, as discussed previously. The prestress losses during initial posttensioning and during the long term are as follows:
    a. Slab–base friction (largest component)
    b. Concrete shrinkage and creep
    c. Steel relaxation
    d. Tendon friction (within the duct)
    e. Wedge seating

The end prestress levels in the concrete after accounting for short-term and long-term prestress losses, but not including the prestress loss due to slab-base interface friction, are shown in the following figures:

1. Figure 4.2 – for PPCP section length of 75 ft.
2. Figure 4.3 – for PPCP section length of 150 ft
3. Figure 4.4 – for PPCP section length of 250 ft.

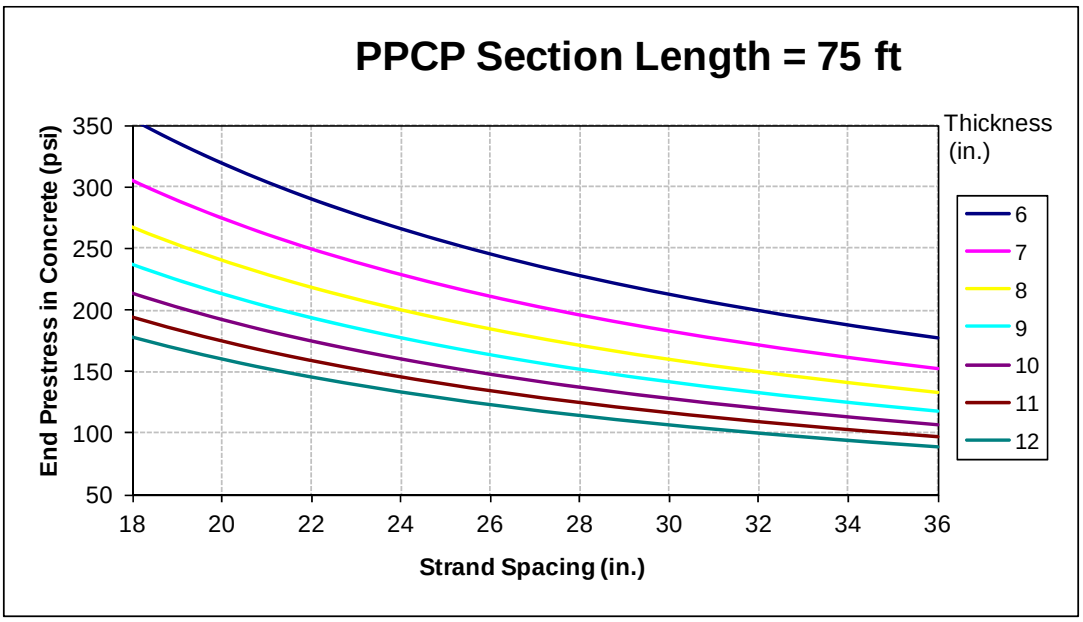


Figure 4.2 – Long-Term End Concrete Prestress for PPCP Section Length of 75 ft.

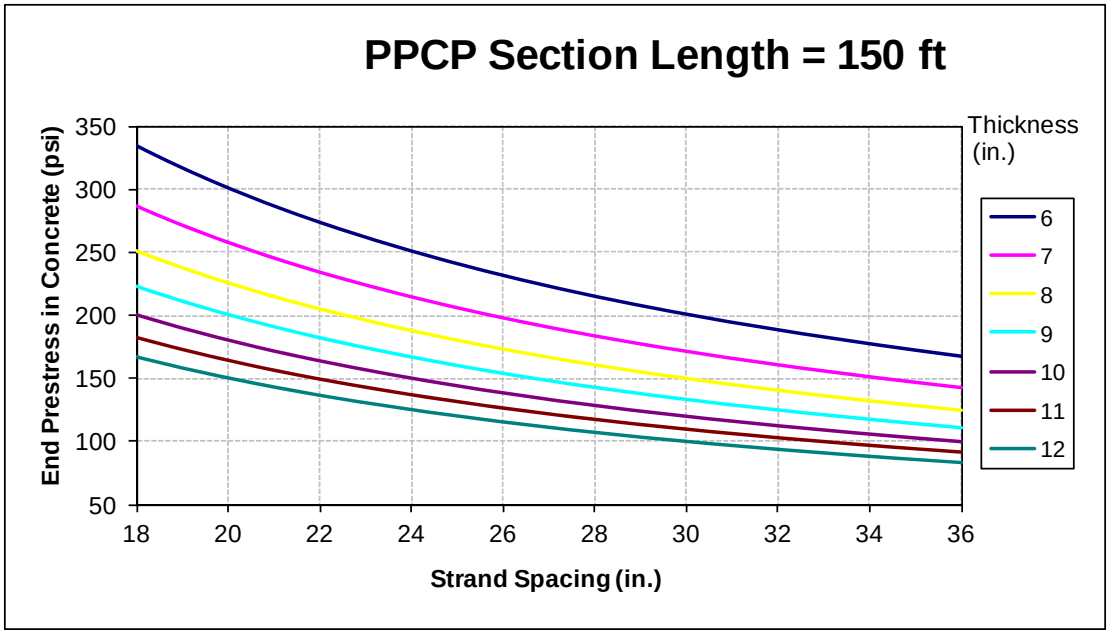


Figure 4.3 – Long-Term End Concrete Prestress for PPCP Section Length of 150 ft.

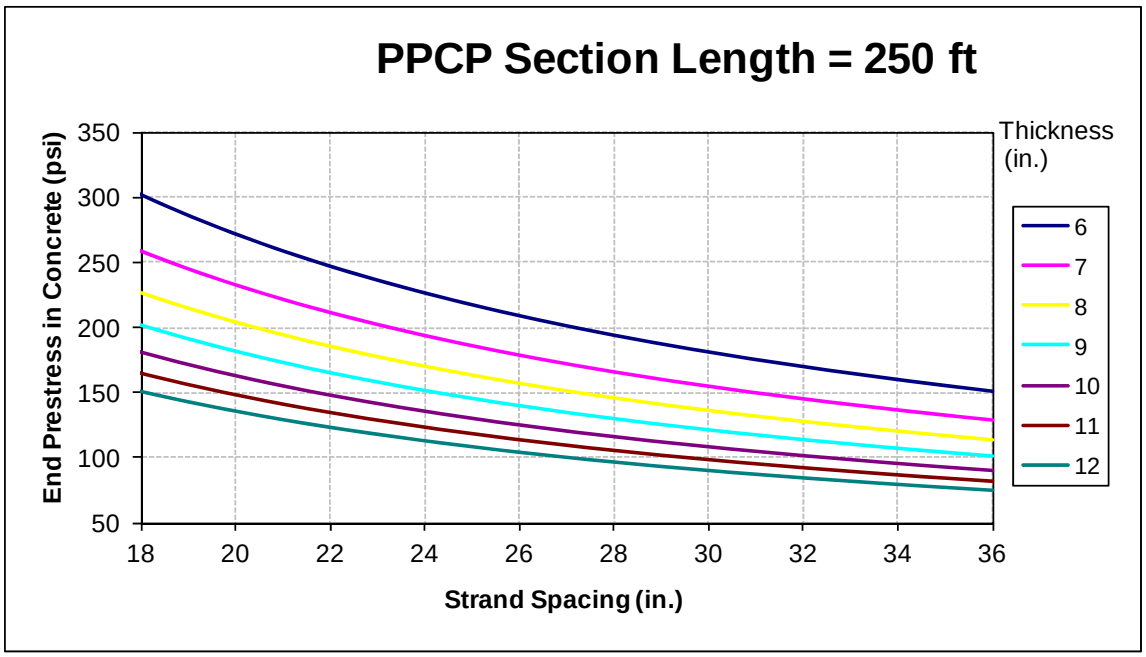


Figure 4.4 – Long-Term End Concrete Prestress for PPCP Section Length of 250 ft.

5. Determine effective prestress at midpoint of the posttensioned section.

   Midsection Effective Prestress ($P_{effective}$) = Applied End Prestress - Prestress Losses

As an example, the long-term midpoint effective prestress levels are shown in Figure 4.5 for a range of panel–base friction factors for a posttensioned section length of 250 ft (76.2 m) and applied end prestress level of 260 psi. A summary of the prestress losses and $P_{effective}$ levels is given in Table 4.2. The prestress losses considered in Figures 4.2 to 4.4 and Table 4.2 are based on a slab-base coefficient of friction of 0.6. As shown in Figure 4.5, the higher the coefficient of friction, the lower the midsection effective prestress level. For design purposes, a project specific coefficient of friction, ranging from 0.5 to about 1.0, should be established considering the base type (typically LCB) and finishing and the interface treatment used.

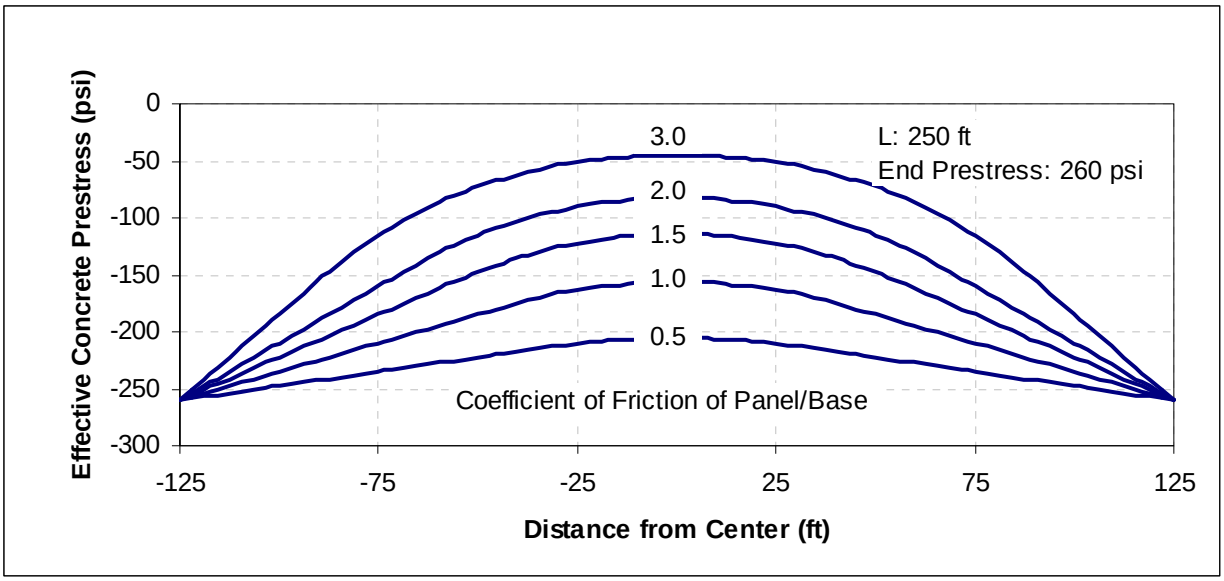


Figure 4.5. Effective prestress levels as a function of panel-base interface friction.

Table 4.2. Prestress losses and effective prestress levels.

Panel thickness, in.	8	9	8	9	8	9
Section Length, ft	75	75	150	150	250	250
Tendon spacing, in.	24	24	24	24	24	24
Prestress Loss due to tendon-duct friction, psi	18	16	34	30	54	48
Prestress Loss due to shrinkage & creep, psi	2	2	2	2	2	2
Prestress Loss due to relaxation, psi	15	13	15	13	15	13
Wedge-Seating, psi	9	8	4	4	3	2
Total prestress loss, psi	43	38	55	49	73	65
Effective long-term end prestress ($P_{effective)}$, psi	200	178	188	167	170	151
Slab/Base friction loss, psi (based on coefficient of friction value of 0.6)	11	9	31	29	56	53
Effective long-term prestress ($P_{effective}$) at midsection, psi	189	169	157	138	114	98

Note: for other design parameters, see the following two tables.

Concrete and Pavement Properties

Concrete Modulus of Elasticity (psi)	E	4,500,000
Concrete Poisson's Ratio	μ	0.15
CTE ($^{o}F^{-1}$)	α	5.00E-06
Concrete Unit Weight (pcf)	γ	150
Concrete Shrinkage Strain (in./in.)	ε_s	0.000000
Concrete Creep Stain (in./in.)	ε_k	0.000075
Coefficient of Friction (Slab-Base)	μ_{max}	0.6
Preliminary Displacement (in.)	PD	0.02

Tendon Properties

Tendon Ultimate Strength (psi)	Ss	270,000
Tendon Elastic Modulus (psi)	Es	28,000,000
Tendon Area ($in.^2$)	a	0.216
Tendon Wobble Coefficient	K	0.002
Design Tendon Strength	DSs	0.8
Relaxation Coefficient	ρ	6.0%
Wedge-Seating (in.)	WS	0.25
Jack Force per Tendon (lbf)	Fjack	46,600

Note: The tendon wobble coefficient is based on reasonably tangent posttensioned section. If the posttensioned section incorporates a curvature, a higher value for the tendon wobble coefficient may need to be established.

4.7 Finalize Structural Design and the Prestressing System

The PPCP design can be finalized and optimized using the following steps:

- Step 1: Determine the minimum effective thickness for a range of panel thickness based on the pavement structural design using DARWin-ME (as discussed in this section) or the University of Texas method.
- Step 2: Conduct the prestressing system design (as discussed in Section 4.4) for a range of posttensioned section lengths, panel thickness, tendon spacing (and size, typically 06 in. diameter), prestress jacking force (typically 80% of the ultimate), and consideration of various prestress losses. The prestressing analysis should result in the determination of the effective prestress for each unique set of conditions considered.
- Step 3: Select the panel thickness and the prestressing system details that represent a cost-effective design.

CHAPTER 5 – ROUTES 710, 5 AND 405 APPLICATIONS

5.1 Introduction

This section details the application of the proposed PCP design process to the Routes 710, 5 and 405 projects located in the Los Angeles area. The design, plans and specifications for use of PPCP along sections of 710, 5 and 405 projects were prepared by Caltrans.

5.2 Design Data

As-designed PPCP Thickness:
The as-designed thickness for the three PPCP projects is summarized below:

- Route 710 project: 11 in.(primary)
- Route 405 project: 8 in.
- Route 5 project: 11 in.

Climatic Region:
The three projects are located in the Los Angeles area. The climatic data for all three projects were determined using the City of Los Angeles as the location (DARWin-ME Weather Station 93134; Coordinates - 118.296, 34.028).

Subgrade and Base Type:
The subgrade type CH was selected for all three projects. The LCB was used as the base for all three projects.

Edge Condition:

1. For CIP JCP, two edge conditions were considered – AC shoulder and widened lane.
2. For JPrCP and PPCP, only AC shoulder use was considered.

Posttensioned Section Lengths:
The as-designed posttensioned section lengths for the Route 710 project only were available and are used for illustration of the design approach. The posttensioned lengths for Route 710 project are about 160 ft and about 240 ft.

Traffic Data:
The traffic data for the three projects are summarized in Table 5.1 for a 40 year design.

Table 5.1 – Traffic Data for the Route 710, 5 and 405 Projects

Project	Section	From	To	ESAL, million	TI	TI (Rounded)
R710	1	18.44	19.73	250	17.4	18
	2	19.73	21.92	303	17.8	18
	3	21.92	23.27	190	16.8	17
	4	23.27	24.63	216	17.1	18
	5	24.63	26.5	119	15.9	16
R405	A	NA	NA	66	14.8	15
	B	NA	NA	33	13.6	14
	C	NA	NA	17	12.6	13
R5	R44.01	North of Junction Rt. 210		126	16	16
	R45.58	North of Junction Rt. 14		126	16	16
	C44.18	North of Junction Rt. 210		339	18	18
	C44.18	South of Junction Rt. 210		209	17	17
	C45.73	North of Junction Rt. 14		209	17	17
	C45.73	South of Junction Rt. 14		339	18	18

Prestress system Design:
According to the project plans for Route 710, the ducts are spaced at 36 ft. It is assumed that two 0.6 in. diameter tendons will be used per duct. The effective end prestress after prestress losses (except those due to the slab-base interface friction) are accounted for and the midsection effective prestress are given in Table 5.2 for posttensioned section lengths of 150 and 250 ft (approximations for the actual section lengths of about 160 ft and about 240 ft).

The complete project plans for Routes 5 and 405 were not available. Limited data available indicate that the duct spacing for the Route 405 project is 24 in.

Table 5.2 – End and Midsection Effective Prestress for Route 710 PPCP sections

Section Length (ft)	Tendon Spacing (in.)	No. of Tendons per Duct	Effective End Prestress (psi)	Effective Prestress at Midsection (psi)
250	36	2	165	109
150	36	2	182	151

PCP Concrete Strength:
For the JPrCP and PPCP design, a higher level of design concrete flexural strength of 725 psi is used. This represents an addition of 100psi to the conventional concrete strength of 625 psi used for the HDM catalog designs. The reason for using a higher level of design strength for PCP systems is that precasters use higher strength concrete mixtures that allow stripping of the forms and lifting of the panels within about 16 hours of casting the panels. The designer has an option to use a lower strength for the concrete (standard strength level of 625 psi) or a strength level higher than 725 psi if that level of strength is specified for the precast panels or can be provided by the precasters.

Other Data:
Analysis to determine the required slab (panel) thickness for each project was carried out using the design data given in Appendix A. The default design data were used as project specific design data were not available. The designs for the baseline CIP JCP, JPrCP and PPCP are presented in the following sections.

Approach Used:
Because all three projects are located in the same climatic region, only a single set of designs were run using DARWin-ME. The designs were developed for a range of traffic loading levels and the following concrete flexural strengths:

1. For baseline CIP JCP: 625 psi
2. For JPrCP: 750 psi (standard 625 psi plus additional strength of 125 psi)
3. For PPCP, a range of flexural strength were used to develop the thickness versus effective mid-section prestress relationships.

5.3 DARWin-ME Analysis – Cast-in-Place JCP Design

The designs determined for the benchmark CIP JCP are summarized in Table 5.3 and incorporates the standard design concrete strength of 625 psi used for the HDM catalog designs.

Table 5.3 – CIP JCP Thickness Requirements for the Route 710, 5 and 405 Projects in the Los Angeles Area

%Cracked <10%; Faulting <0.1 in.; CTE = 6.0 in./in/F

Lane Type	TI	Faulting (in.)	Cracking (%)	IRI (in./mile)	DARWin Slab Thickness, in.	HDM Slab Thickness, in. (CH Subgrade; South Coast)
12-ft	13	0.04	8.1	102	11.0	11.5
	14	0.05	8.8	108	11.5	12.0
	15	0.05	9.4	113	12.5	12.5
	16	0.06	9.0	119	13.5	13.5
	17	0.08	9.9	128	14.0	14.0

	18	0.09	8.2	135	15.0	(14.0+)
Widened	13	0.02	10.0	93	9.5	10.5
	14	0.02	8.5	93	10.5	11.0
	15	0.03	9.1	96	11.0	11.5
	16	0.03	8.2	99	12.5	12.0
	17	0.04	9.6	105	13.0	12.5
	18	0.05	8.3	109	14.0	(13.0+)

Notes:

1. Optimization function from DARWin-ME was used. The slab thickness is rounded up to the nearest half inch.
2. Thickness controlled by the cracking criteria
3. HDM slab thickness includes 0.36 in. sacrificial wearing course for future grinding.

5.4 DARWin-ME Analysis – Jointed PCP Design

The designs determined for the JPrCP system are summarized in Table 5.4 and incorporates a higher level of design concrete flexural strength of 725 psi, an addition of 100psi to the conventional concrete strength of 625 psi used for the HDM catalog designs. The designs are presented for two cracking criteria – 10% (Caltrans designated) and 20% (FUGRO proposed) and use of an AC shoulder.

It is seen from Table 5.4, at the lower traffic level, the cracking criteria determines the slab thickness and for the higher traffic level, the faulting criteria determines the slab thickness, irrespective of the % Slab Cracking level used.

Table 5.4 – Jointed PCP Thickness Requirements for the Route 710, 5 and 405 Projects in the Los Angeles Area

Route 710 Section	Route 405 Section	Route 5 Section	TI	Panel Thickness based on Cracking Criterion		Panel Thickness (in.) based on Faulting Criterion
				10% Slab Cracking (Caltrans)	20% Slab Cracking (FUGRO)	
	C		13	9.0	9.0	8.0
	B		14	9.5	9.0	8.0
	A		15	10.0	9.0	8.0
5		Routes 44.01, 45.58	16	10.0	10.0	9.0
3		Routes CC44.18 – S of Rt. 210, C45.73 – N of Rt.14	17	10.5	10.0	11.0

1, 2, 4		Routes CC44.18 – N of Rt. 210, Rt. 210, C45.73 – S of Rt.14	18	11.0	10.5	13.0

5.5 DARWin-ME Analysis – PPCP Design

The midsection effective prestress required for a range of PPCP slab thickness are summarized in Tables 5.5 and 5.6 for Slab Cracking of 10% (Caltrans designated) and 50% (FUGRO proposed), respectively and incorporate a higher level of design concrete flexural strength of 725 psi, an addition of 100psi to the conventional concrete strength of 625 psi used for the HDM catalog designs. The designs are presented for the case of an AC shoulder (12 ft wide lane) and concrete coefficient of thermal expansion (CTE) of 6.0 millionths in./in./F.

The data presented in Table 5.5 indicate that a minimum slab thickness of 10 in., effectively prestressed, can be used for a range of traffic loading and still meet very conservatively established performance criteria (10% Slab Cracking). Also, if the 50% Slab Cracking criteria were to be used, a slab thickness of 9 in. would be considered acceptable.

Table 5.5 – Midsection Effective Prestress Requirement for the Route 710, 5 and 405 Projects in the Los Angeles Area (% Slab Cracked = 10%)

		Effective Mid-Section Prestress Needed, psi						
		TI for 12-ft Lane						
		12	13	14	15	16	17	18
Thickness (in.)	08	100	124	171	>175	>175	>175	>175
	09	100	100	100	100	101	125	161
	10	100	100	100	100	100	100	100
	11	100	100	100	100	100	100	100
	12	100	100	100	100	100	100	100
	13	100	100	100	100	100	100	100
	14	100	100	100	100	100	100	100

Table 5.6 – Midsection Effective Prestress Requirement for the Route 710, 5 and 405 Projects in the Los Angeles Area (% Slab Cracked = 50%)

		Effective Mid-Section Prestress Needed, psi						
		TI for 12-ft Lane						
		12	13	14	15	16	17	18
Thickness (in.)	08	100	100	100	103	140	174	>175
	09	100	100	100	100	100	100	100
	10	100	100	100	100	100	100	100
	11	100	100	100	100	100	100	100
	12	100	100	100	100	100	100	100
	13	100	100	100	100	100	100	100
	14	100	100	100	100	100	100	100

A minimum 9 in. thickness is recommended for traffic levels in excess to 100 million ESALs to accommodate the prestressing hardware and reinforcement <u>and to mitigate potential deflection related distress at expansion joints</u>.

The prestressing design details given in Table 5.2 indicate that a posttensioned length up to 250 ft can be used with ducts spaced at 36 in. and using two 0.6 in. diameter tendons per duct. This prestressing design provides a midsection effective prestress level of 109 psi and meets the need for a 10 in. slab thickness for all traffic levels. A 9 in. slab, with a midsection effective prestress of 109 psi meets the needs for traffic levels up to TI of 16.

The posttensioned PCP design data discussed above are based on a design life of 40 years. It can thus be extrapolated that thickness in excess of 10 in. will provide an even longer service life if the cracking criteria only is considered.

It should be emphasized that the joint deflection based faulting criteria has not been considered in the analysis. It is recommended that Caltrans establish policies for minimum posttensioned PCP thickness that account for mitigation of joint faulting distress and possible construction-related shortcomings at the expansion joints. For example, a policy decision could be a minimum thickness of 8 in. for ESAL loading up to 100 million, a minimum thickness of 9 in. for ESAL loading between 100 and 150 million, and a minimum thickness of 10 in. for ESAL loading in excess of 150 million.

Additionally, Caltrans will need to establish the values of several design parameters by policy or based on research studies. Some of the key data items that need further refinement include the following:

1. The slab (panel)-base friction. This report used a coefficient of slab-base friction value of 0.6 to illustrate the application of the OCP design approach. A

conservative value of 1.0 is recommended by FUGRO until field data are generated to refine this input data. A higher value of the coefficient can result in an increase in the panel thickness requirement, and/or a limit on the length of the posttensioned section length, and/or a change in the design of the prestressing system (decrease in tendon spacing).

2. Another variable that is not clearly defined at this time is the effect of non-planar slab geometry on the prestress loss due to friction between the duct and the tendon. This aspect will need testing at a test section or at a project site to determine if the non-planar geometry has any significant impact on prestress loss.

5.6 Evaluation of Service Life of As-Designed PPCP

As requested by Caltrans, Fugro evaluated the expected service life of the as-designed PPCP for Projects 710, 405, and 5 using the design/analysis approach discussed above. The as-designed thicknesses for the three projects are as follows:

- Route 710 project: 11 in.(primary)
- Route 405 project: 8 in.
- Route 5 project: 11 in.

The expected service life, it terms of TI, is summarized in Table 5.7. The expected service life was capped at TI of 18 (ESAL = 338,000,000), as it is not expected that the TI would exceed 18. Also, included in Table 5 are the equivalent thicknesses for the CIP and JPrCP sections for the as-expected service life for the Route 710 and 405 projects.

Table 5.7 – Expected Service Life for the As-Designed PPCP Projects

PROJECT	SECTION	TI (Rounded up)	PPCP As-Designed						Alternate PCC Thickness (in.)	
			Thickness (in.)	Nominal Duct Spacing* (in.)	Section Length** (ft)	End prestress (psi)	Effective Prestress for Design (psi)	Life+ (TI)	CIP++	JPrCP++
R710	1	18	11	36	250	165	101	18	15	13
	2	18	11	36	250	165	101	18	15	13
	3	17	11	36	250	165	101	18	15	13
	4	18	11	36	250	165	101	18	15	13
	5	16	11	36	250	165	101	18	15	13
R405	A	15	8	24	250	170	106	15	12.5	10
	B	14	8	24	250	170	106	15	12.5	10
	C	13	8	24	250	170	106	15	12.5	10
R5	R44.01	16	11	NA	Data not available.					
	R45.58	16	11	NA						
	C44.18	18	11	NA						
	C44.18	17	11	NA						
	C45.73	17	11	NA						
	C45.73	18	11	NA						

*Assumption: 2 tendons per duct for Route 710 and 1 tendon per duct for Route 405.
**For Route 710, section length varies from approx. 150 ft to approx. 250 ft. 250 ft was used as it is more critical.
For Route 405, no data is available on section length and 250 ft was used for PPCP life estimation.
+ Based on 50% cracking criterion.
++Based on 10% cracking criterion.

As shown in Table 5.7, the equivalent slab thickness for a CIP concrete pavement to accommodate the expected service life (in terms of TI) of the as-designed PPCP would need to be 4.5 to 5.0 in. greater than the as-designed PPCP thickness. Similarly, the equivalent slab thickness for a JPrCP to accommodate the expected service life of the as-designed PPCP would be 2.0 in. greater than the as-designed PPCP thickness.

CHAPTER 6 – SUMMARY

This draft final report, prepared by Fugro Consultants, Inc. (FUGRO), provides a proposed approach to develop the designs for jointed and posttensioned precast concrete pavement systems. The report also includes the application of the proposed approach to sections of Routes 710, 5, and 405 that will be rehabilitated using the PPCP system.

This report will be finalized after feedback is received from Caltrans.

APPENDIX A – DARWin-ME BASELINE DESIGN INPUT DATA

Climate Data Sources:

Climate Station Cities:	Region
SAN FRANCISCO, CA	Central Coastal
DAGGET, CA	Desert/Valley
SANTA ROSA	Low Mountain

JPCP Design Properties

Structure - ICM Properties	
PCC surface shortwave absorptivity	0.85

Doweled Joints	
Is joint doweled?	True
Dowel diameter (in.)	1.25" for slabs < 8.5" 1.5" for slabs >8.5"
Dowel spacing (in.)	12.00

Tied Shoulders	
Tied shoulders	False for asphalt shoulder True for Widened & Tied
Load transfer efficiency (%)	- 40% for tied shoulder

PCC joint spacing (ft)	
Is joint spacing random?	False
Joint spacing (ft)	13.5

Widened Slab	
Widened Slab width (ft)	14.00

PCC-Base Contact Friction	
PCC-Base full friction contact	True
Months until friction loss	0.00

Sealant type	Preformed

Erodibility index	1

Permanent curl/warp effective temperature difference (ºF)	-10.00

Layer 1 PCC : JPCP Default

PCC	
Thickness (in.)	Variable
Unit weight (pcf)	150.0
Poisson's ratio	0.2

Thermal	
PCC coefficient of thermal expansion (in./in./ºF x 10^-6)	6
PCC thermal conductivity (BTU/hr-ft-ºF)	1.25
PCC heat capacity (BTU/lb-ºF)	0.28

Mix		
Cement type		Type II (2)
Cementitious material content (lb/yd^3)		657
Water to cement ratio		0.42
Aggregate type		Dolomite (2)
PCC zero-stress temperature (ºF)	Calculated Internally?	True
	User Value	-
	Calculated Value	91.3
Ultimate shrinkage (microstrain)	Calculated Internally?	False
	User Value	537.0
	Calculated Value	-
Reversible shrinkage (%)		50
Time to develop 50% of ultimate shrinkage (days)		35
Curing method		Curing Compound

PCC strength and modulus (Input Level: 3)

28-Day PCC modulus of rupture (psi)	626.0
28-Day PCC elastic modulus (psi)	4200000.0

Layer 2 Chemically Stabilized : Cement stabilized

Chemically Stabilized	
Layer thickness (in.)	4.2
Poisson's ratio	0.2
Unit weight (pcf)	150

Strength	
Elastic/resilient modulus (psi)	2000000

Thermal	
Heat capacity (BTU/lb-ºF).	0.28
Thermal conductivity (BTU/hr-ft-ºF)	1.25

Layer 3 Non-stabilized Subbase : A-1-a for CH subgrade

Unbound	
Layer thickness (in.)	Variable
Poisson's ratio	0.35
Coefficient of lateral earth pressure (k0)	0.5

Modulus (Input Level: 3)

Resilient Modulus (psi)
40000.0

Layer 4 Subgrade : A-7-6 (CH Subgrade)

Unbound	
Layer thickness (in.)	Semi-infinite
Poisson's ratio	0.35
Coefficient of lateral earth pressure (k0)	0.5

Modulus (Input Level: 3)

Resilient Modulus (psi)
5000.0

Layer 4 Subgrade : A-2-5 (SP Subgrade)

Unbound	
Layer thickness (in.)	Semi-infinite
Poisson's ratio	0.35
Coefficient of lateral earth pressure (k0)	0.5

Modulus (Input Level: 3)

Resilient Modulus (psi)
28000.0