CHAPTER 1 INTRODUCTION

This chapter presents an overview of and purpose for pavement preservation, a discussion of common distress types found on rigid pavements in the California Department of Transportation (Caltrans) roadway system, a description of fundamentals of materials typically used in PCC pavements, and a discussion of important factors that should be considered during the design phase of pavement maintenance for concrete pavements.

1.1 PURPOSE OF PAVEMENT PRESERVATION

In the simplest term, the purpose of pavement preservation is to keep good pavements in good or near new conditions by applying the right maintenance strategies that are cost-effective at the right time to extend pavement life and preserve investments. This section briefly describes the definition, concept, benefits of pavement preservation and importance of treatment selection and the optimum timing for the treatments used.

1.1.1 Definition

Pavement preservation, as defined by the FHWA, is a program employing a network level, long-term strategy that enhances pavement performance by using an integrated, cost-effective set of practices that extend pavement life, improve safety and meet motorist expectations (FHWA, 2005). A pavement preservation program consists primarily of three components: preventive maintenance, minor rehabilitation (restoration), and some routine maintenance (FHWA, 2005). A pavement preservation program does not include new pavements or pavements that require major rehabilitation or reconstruction. Appendix A of this report presents the FHWA's memorandum on definitions of pavement preservation and terminologies associated with pavement maintenance.

1.1.2 Pavement Preservation Concept

Pavement preservation represents a proactive approach in maintaining the existing highways. An effective pavement preservation program addresses pavements while they are still in good condition and before the onset of serious damage. By applying a cost-effective treatment at the right time, the pavement can be restored almost to its original condition. The cumulative effect of systematic, successive preservation treatments is to postpone costly rehabilitation and reconstruction (FHWA, 2005). The pavement preservation treatments restore the function of the existing system and extend its life by reducing aging and restoring its serviceability, not increase its capacity or strength. Performing a series of successive pavement preservation treatments during the life of a pavement is less disruptive to uniform traffic flow than long closures normally associated with reconstruction projects (FHWA, 2005).

Pavement preservation is not simply a maintenance program, but an agency program. Essentials for an effective pavement preservation program include agency leadership and a dedicated annual budget, and support and input from staff in planning, finance, design, construction, materials, and maintenance.

1.1.3 Benefits of Pavement Preservation

An effective pavement preservation program can benefit Caltrans by preserving the roadway network, enhancing pavement performance, ensuring cost-effectiveness by extending pavement life, and reducing user delays by avoiding rehabilitation or reconstruction. Some of these benefits may be noticed immediately and some may be realized over time (Galehouse, Moulthrop, and Hicks, 2003).

1.1.4 Treatment Selection and the Optimum Timing for the Treatment

Figure 1-1 shows how a pavement would typically perform under traffic and with time (dotted line). Various types of treatment stages are also shown in the figure. Although the pavement performance curve in the figure is more representative of flexible pavements, the same concept of treatment stages should be applicable to rigid pavements as well. It clearly indicates that the pavement preservation should be carried out at early stage of the pavement life while it is still in good conditions both structurally and functionally. If the pavement is not maintained effectively, it will eventually deteriorate to a point where the only choice is the reconstruction which is the most costly option.

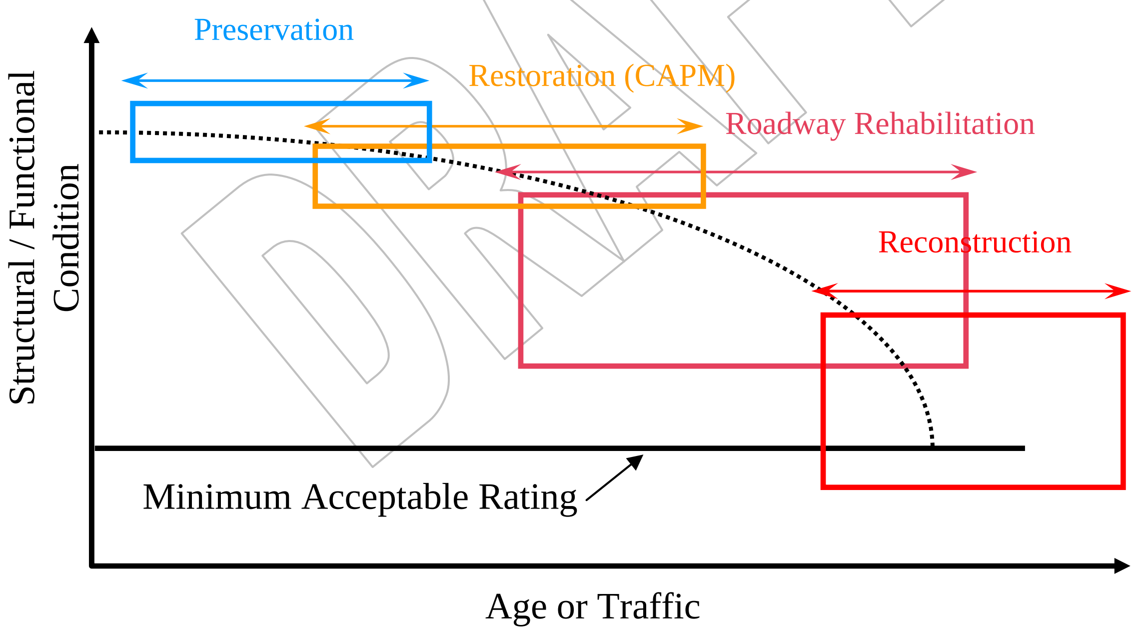

Figure 1-1 Typical pavement performance curve and maintenance/rehabilitation time

The timing of the application of the treatment has a significant influence on the effectiveness of the treatment in prolonging the performance of the pavement; therefore, applying the right treatment to the right pavement at the right time is the core of pavement preservation. As indicated earlier, by applying cost-effective preservation treatments at the right time, the pavement can be maintained close to its original condition for a longer period of time. Timely application of a successive treatment can maintain the pavement in good condition and prolong the need for more expensive roadway rehabilitation and reconstruction strategies, as shown in Figure 1-2. This figure illustrates the concept of timely application of a treatment is important to maintain the existing pavement condition. The frequency of applying treatment will depend on the type of treatment that has been used and their life expectancy.

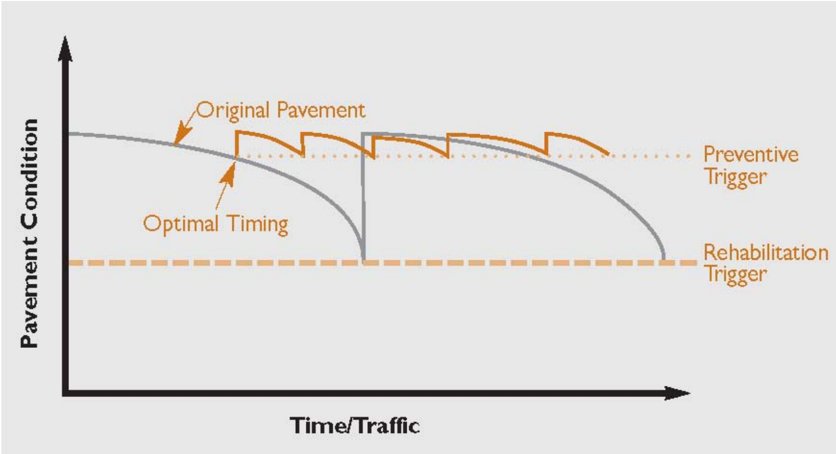

Figure 1-2 Concept of optimal timing for pavement preservation (Galehouse et al, 2003)

Table 1-1 shows examples on the effectiveness of preventive maintenance for selected PCC pavement problems and provides an indication of when an application of preventive maintenance might be appropriate or might be too late. Specific treatment selection and the optimum timing for the treatment are a function of many factors, including pavement conditions, distress types, traffic conditions, constructability, economics, and other factors specific to the project. Chapter 3 provides more detailed guidelines on treatment selection.

Table 1-1 Examples of effectiveness of preventive maintenance (PM)

Example PCC Pavement Problem	Prevented or slowed with PM	Corrected with PM	Indications that it is too late for PM
Crack deterioration	X (minor)		X (severe)
Corner breaks	X (minor)		X (severe)
Blow-ups	X (minor)		X (severe)
Joint spalling	X	X	
Joint faulting		X	
Joint seal damage		X	
Map cracking and scaling		X	
Surface friction loss		X	
Roughness	X	X	

1.2 PCC PAVEMENT DESIGN AND PERFORMANCE IN CALIFORNIA

1.2.1 Design and Performance

With the exception of a few experimental test section of Continuously Reinforced Portland Cement Concrete Pavement (CRCP), California rigid pavements are generally of the Jointed Plain Concrete Pavement (JPCP) variety. Most of these pavements were built from the 1950s through the 1970s.

There has also been a substantial amount of new rigid pavement constructed since then. The design life for rigid pavements was traditionally 20 years and most have out lived their design life with little maintenance. The rigid pavements for freeways have been functional often far beyond 20 years and have not deteriorated as originally anticipated. Current design standards require or encourage 40 year design life.

By taking into account of rigid pavement performance over the years as well as of the continuing advances in paving technology, equipment, and materials, standard structural designs for rigid pavements have also improved over the years. Major design changes included:

- Base support. Initially, a cement treated base (CTB) was used. This material was later replaced by lean concrete base (LCB) which is a low cement content concrete that could be slip-formed or cast in forms. Caltrans has also used cement treated permeable base (CTPB), which is a concrete base batched with no sand to allow water to pass through the base with ease. Caltrans has also used asphalt treated permeable base (ATPB), which is an asphalt concrete (AC) base with lesser amount of asphalt cement than conventional AC.
- Slab thickness. In the 1950s, an 8-inch (203 mm) thick slab was the common practice with a few 9-inch (229 mm) slabs. Later on a 9-inch (229 mm) thick slab became common practice. Presently, 10-inch (254 mm) and even 12-inch (305 mm) thick slabs are used depending on projected traffic.
- Dowels, tie bars, sealed joints were added in 2000.

There were also minor changes with regards to structural performance such as surface texturing, joint spacing and layout, and details for sealing joints.

For the most part, the material for the pavement slab has remained fairly constant. One could use 1950s pavement slab materials specifications and be close to the current Standards. Flexural strengths have been a constant. One notable exception would be the current mineral admixture requirements that were added to address reactive aggregate concerns. Requirements on strength, curing, batching, mix transporting, slump or penetration have remained relatively constant over the last 50 years.

However, the increasing traffic loads and numbers of applications have had a significant effect on the rideability and eventually durability of the pavement structure. This was seen as the primary reason that pavements started showing distress. The foremost distress in California with rigid pavements over cement treated bases (CTB) was faulting. This distress occurred over time with the up-steam slab rising in relation to the adjacent edge of the down-stream creating a rough ride and eventually cracking near the joints. It was noted that when LCB became commonly used, the amount and occurrence of faulting reduced. This was because LCB had no loose or weakly bonded material on its surface, reducing potential pumping caused by the presence of water and fine materials. Extended base width into the shoulder also helped reducing pavement slab faulting. CTPB and ATPB were used to remove water from between the base and pavement slab to eliminate the mechanism for carrying fines from the down-stream slabs to the up-steam slabs. Edge drains were to serve the same purpose. Though faulting may have been thought of as a ride issue at first, its presence became a key to the deterioration of PCC pavements that were constructed on erodible bases such as CTB.

1.2.2 Causes of Rigid Pavement Deterioration

There are several causes of pavement failures that are interest to maintenance personnel: an improper construction practice resulting in the pavement structure not being built as designed, or the condition of the project site being erroneously analyzed without proper considerations of the environmental impact to the pavement, or lack/not adhering of a pavement maintenance schedule. This is not due to a flaw or inadequacy in the design theory, but simply not putting the theory to practice or the assumptions of the theory used to guide the practice or due to unforeseen changes at the site after construction. Underestimating wheel loads, improper construction practice, material related distress, or a changing environment such as the appearance of ground water sometime after construction, are of this first type. A few real life examples are given as illustrations of this first type of deterioration.

In 1998, a small section of I-5 in Sacramento County near the Pocket area was in need of replacement. The pavement was designed to be built on a lime treated base. This section of freeway was failing though it had experienced nowhere near the traffic loads anticipated during the design phase. However, the lime treated base did not behave as anticipated, possibly due to an improper construction practice. Lime was found in the drainage pipes and the base was not intact. This was likely due to inadequate “curing” of the lime treated base. If the lime treated base did not reach designed strength before the PCC slabs were placed, the stability and load carrying capacity of the base would likely not be adequate. Since lime was found in the drain pipes, it is possible that some of the lime leached out of the base. This was believed to be the primary cause of the pavement failure. The rehabilitation included removing the pavement structure, lime-treating the base and reconstructing a new pavement structure using the latest standard.

Another pavement failure example was the repaving of I-80 near Truckee, California. The project is in a freeze-thaw zone and air entrainment was required. After only a one year of service, the pavement began to exhibit corner cracking in almost all the slabs. At first, it was thought the 8-inch slab thickness might not be sufficient. Upon further investigation, it was discovered the air contents of the slabs were as much as 12%. The flexural strengths were low as a result of this high air content. Maintenance on this roadway needed to consider that the corner cracking was due to weak slab concrete.

These examples for the first type of deterioration are rare and due to human error in incorporating established engineering principles. Deterioration of the second kind has much more far reaching implications because deterioration is inadvertently built into the design. The second type is due to lack of understanding of how a pavement performs under traffic loads and of factors that would affect the pavement performance.

1.2.3 Faulting Mechanism and Effort on Addressing Faulting

In California, faulting may be one of the primary and most serious distresses on jointed plain concrete pavements. Understanding its mechanism is important to address this type of pavement deterioration. There are typically four conditions must exist to have pavement faulting. First there must be some curl of the slab. Thermal gradients are the main cause of slab curling. Second there must be fines present that can be moved around by water. Third there must be water present to carry the fines. And last, the adjacent slabs at the joint must be free to move independently at least in one direction from each other. That is the up-stream slab must be able to rebound upward after the wheel load leaves the slabs and depresses the down-stream slab. If any one of these four conditions is not present, faulting will not occur.

When faulting reaches the point where there is a drop-off (Figure 1-3) from the up-stream slab to the down-stream slab of 0.06 inch (1.5 mm), pavement maintenance becomes an issue. The shoulder begins to depress and cracks, mostly on the down-steam side of the joint, begin to appear. As faulting increases, the shoulder deterioration or drop-off also increases. The ride quality of the roadway becomes poor as the height of drop-off increases with time and load applications. Although the ride quality can be restored with diamond grinding, it does not address the other associated deterioration of the pavement structure. As the faulting continues, the support in the up-stream edge of the slab becomes less and less and the slab functions much like a cantilever bridge. Eventually transverse cracks appear near the edge of slab where is still being supported by the base. As the condition worsens, the slab without adequate base support will break. This often occurs 3-6 feet from the transverse joint. This newly formed short slab now has to withstand longitudinal stresses that are increased due to the loss of the cross sectional area on the opposite side of the crack. Additionally, the pavement begins to fault at the crack which is now functioning as a new joint. Further deterioration at this location would form third stage cracking. Slab replacement is probably the only viable strategy. As more slabs exhibit third stage cracking, the pavement will need major rehabilitation.

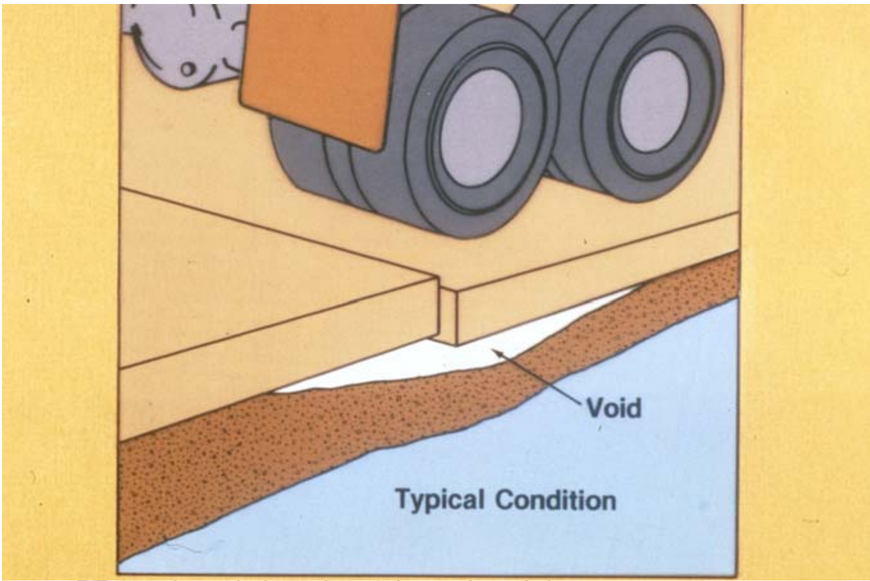

Figure 1-3 Slab drop-off caused by base erosion (Stahl, 2006)

Efforts to enhance durability of jointed plain concrete pavements gradually centered on addressing the faulting of pavement slabs as well as increasing slab thickness. In recent years, some of the efforts to minimize faulting of existing pavement have included adding dowel bars at existing transverse joints, also referred to as dowel-bar retrofit.

1.3 COMMON PCC PAVEMENT DISTRESS TYPES

Distresses commonly found in the California's concrete pavements can generally be grouped into three categories: joint deficiencies and cracking, surface defects, and other miscellaneous distresses (e.g., blow-ups and water pumping).

1.3.1 Joint Deficiencies and Cracking

This group of distress typically includes spalling of transverse and/or longitudinal joints, damage of transverse and/or longitudinal joint seal, transverse and/or longitudinal cracking, durability cracking, and corner breaks.

Spalling – Spalling of cracks and joints is the cracking, breaking, chipping, or fraying of slab edges within 2 ft (0.6 m) of the joint/crack. A spall usually does not extend vertically through the whole slab thickness but extends to intersect the joint at an angle. Spalling usually results from the following:

- Excessive stresses at the joint or crack caused by infiltration of incompressible materials and subsequent expansion;
- Weak concrete at the joint;
- Joint sawing time or insert method during the construction;
- Poorly designed or constructed load transfer device (misalignment, corrosion);
- Heavy repeated traffic loads; and/or
- Disintegration of the concrete from freeze-thaw action of "D" cracking (does not happen in California).

Spalling is typically caused by slab expansion (in warm weather) and contraction (in cool weather). The slab expansion/contraction opens joints and allows incompressible debris trapped in the joint. As joints close, trapped incompressible debris causes fractures of the slab and enlarges the joints permitting larger debris to be trapped and consequently causing greater fractures. Examples of spalled pavements are given in Figure 1-4.

Example 1 Example 2 Example 3

Figure 1-4 Spalling at the joint (Caltrans, 2004a)

Faulting – Faulting is the difference of elevation across a joint or crack (see Figure 1-5). Faulting is caused in part by a buildup of loose materials under the approach slab near the joint or crack as well as depression of the leave slab. The buildup of eroded or infiltrated materials is caused by pumping from under the leave slab and shoulder (free moisture under pressure) due to heavy loadings. The warp and/or curl upward of the slab near the joint or crack due to moisture and/or temperature gradient contributes to the pumping condition. Lack of load transfer devices like dowel bars contributes greatly to faulting. Faulting is most prominent failure type in California because Caltrans did not build doweled pavement until 1998. A detailed discussion on the faulting mechanism is provided in Section 1.2.3.

Figure 1-5 Faulting (FHWA, 2003)

Joint seal damage – Joint seal damage exists when incompressible materials and/or water can infiltrate into the joints (Figure 1-6). This infiltration can result in pumping, spalling, and blow-ups. A joint sealant bonded to the edges of the slabs protects the joints from accumulation of incompressible materials and also reduces the amount of water seeping into the pavement structure. Typical types of joint seal damage are: stripping of joint sealant, extrusion of joint sealant, weed growth, hardening of the filler (oxidation), loss of bond to the slab edges, and lack or absence of sealant in the joint. Poor construction of the joint seal can be a factor in the extent of joint seal damage.

Figure 1-6 Example of joint seal damage (FHWA, 2003)

Longitudinal cracks – longitudinal cracks occur generally parallel to the centerline of the pavement (Figure 1-7). They are often caused by a combination of heavy load repetitions, loss of foundation support, and thermal and moisture gradient stresses. Longitudinal cracking is more prevalent in western States which have a drier climate than it is in the more humid eastern States. Early longitudinal cracks can be caused by improper construction of longitudinal joints, inadequate saw-cut depth, late sawing of longitudinal joints, and/or opening the pavement to traffic before the concrete has achieved adequate strength.

Example 1 Example 2

Figure 1-7 Examples of longitudinal joint crack (FHWA, 2003)

Transverse cracking – transverse cracks are predominantly perpendicular to the pavement centerline and the direction of traffic (Figure 1-8). Typically, JPCP slabs crack when tensile stresses within the slab exceed the slab's tensile strength. Early-age cracking may occur from a combination of restraining forces due to temperature changes, shrinkage, thermal curling, base constraint, and moisture warping, combined with traffic loads imposed on the concrete before it has gained sufficient strength. Transverse cracks that occur in the years following construction are primarily the result of fatigue of the concrete slab caused by repeated heavy axle loads and temperature curling. The cracks develop when the accumulated fatigue damage approaches or exceeds the fatigue life of the JPCP. Note that the potential for transverse cracking increases with increased joint spacing. Old JPCP designs used 18 ft (5.5 m) and 19 ft (5.8 m) spacing which historically has cracked over twice as often as shorter 12 ft (3.7 m) and 13 ft (4 m) spacing. Caltrans now limits joint spacing to 15 ft (4.6 m).

Figure 1-8 Transverse cracking (FHWA, 2003)

Slab cracking - Caltrans classifies slab cracking by stages based on the severity of the cracks (Caltrans, 2004). Figure 1-9 shows examples of cracks at stage 1 and stage 3. The first stage cracking is defined as transverse, longitudinal, or diagonal cracks that do not intersect and that divide the slab into two or more large pieces. Third stage cracks are interconnected cracks that divide the slab into three or more large pieces. Fragmented slabs are characterized by interconnected irregular multiple cracks which divide the slab into several small pieces. Fragmented slabs are a severe form of third stage cracking. Third stage cracking and first stage cracking cannot co-exist in the same slab. However, corner cracking may co-exist with both first stage and third stage cracking. Slab cracking is usually caused by a combination of heavy load repetitions on pavement with weak roadbed support, thermal curling, faulting, shrinkage, or moisture-induced stress.

Stage 1 Crack

Stage 3 Crack

Stage 3 Crack

Figure 1-9 Examples of cracks at different stages (Caltrans, 2004a)

Corner break (or cracking) – A corner break is a crack that occurs in JPCP at the joints a distance less than 6 ft (1.8 m) on each side measured from the corner of the slab. A corner break extends vertically through the entire slab thickness. Corner breaks result from heavy repeated loads combined with pumping, poor load transfer across the joint and thermal curling and moisture warping stresses as shown in Figure 1-10. Corner breaks can also result from a weak or a thin concrete section constructed on a weak base.

Figure 1-10 Corner break/cracking (Caltrans, 2004a)

Durability ("D") cracking – "D" cracking is a series of closely spaced crescent-shaped hairline cracks that appear at a JPCP pavement slab surface adjacent and roughly parallel to transverse and longitudinal joints, transverse and longitudinal cracks, and the free edges of pavement slab. The fine surface cracks often curve around the intersection of longitudinal joints/cracks and transverse joints/cracks (Figure 1-11). These surface cracks often contain calcium hydroxide residue which causes a dark coloring of the crack and immediate surrounding area. "D" cracking is caused by freeze-thaw expansive pressures of certain types of coarse aggregates and typically begins at the bottom of the slab which disintegrates first.

In California, alkali-silica reactivity (ASR) related distress is more prominent. ASR is another durability-related distress which typically produces a "map-cracking" type cracks as shown in Figure 1-12. ASR is caused by a chemical reaction that occurs when free alkalis in the concrete combine with certain siliceous aggregates to form an alkali-silica gel. As the gel forms, it absorbs water and expands, which cracks the surrounding concrete (ACPA, 1998)

Figure 1-11 D-Cracking (Caltrans, 2004b)

Figure 1-12 Map-cracking (FHWA, 2003)

1.3.2 Surface Defects

Scaling – Scaling is the deterioration of the upper 1/8 to ½ inch (3 to 13 mm) of the concrete slab surface. Map cracking or crazing is a series of the cracks that extend only into the upper surface of the slab surface (Figure 1-13). Map cracking or crazing is usually caused by over-finishing of the slab, premature finishing, or early freezing of concrete and may lead to scaling of the surface. Scaling can also be caused by reinforcing steel, such as dowel bars and tie bars, being too close to the surface.

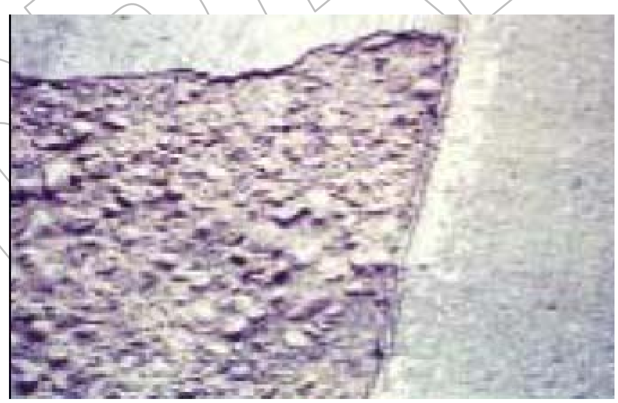

Figure 1-13 Example of scaling (FHWA, 2003)

Surface polish/Polished aggregate – Surface polish is the loss of the original surface texture due to traffic wear. Aggregate polishing occurs when surface mortar and texturing have been worn away to expose coarse aggregate and is caused by repeated traffic applications. An example is shown in Figure 1-14.

Surface attrition – Surface attrition or surface abrasion is abnormal wear of the concrete pavement (Figure 1-15). It can result from either a poor quality surface material, coarse aggregate, or by the action of tire chains and studded tires. Excessive wear in wheel paths may cause “rutting”, a condition which typically occurs in high mountain and high desert climate regions because of the use of chain during the snow storms.

Figure 1-14 Example of surface polish/polished aggregate (FHWA, 2003)

Figure 1-15 Severe surface abrasion with third stage cracking (Caltrans, 2004b)

Popouts – A popout is a small piece of concrete that breaks loose from the surface due to freeze-thaw action, expansive aggregates, and/or nondurable materials. Popouts may be indicative of unsound aggregates and “D” cracking (Figure 1-16). Popouts typically range from approximately 1 inch (25 mm) to 4 inches (100 mm) in diameter and from 1/2 inch to 2-inches (13-51 mm).

Figure 1-16 Example of popouts (FHWA, 2003)

1.3.3 Other Miscellaneous Distresses

Blow-ups – The mechanism for blow-ups is excessive compressive pressure at joints or cracks. Infiltration of incompressible materials into the joint or crack during cold period results in high compressive stresses in hot periods when slabs expend (Figure 1-17). When this compressive pressure becomes too great, a localized upward movement of the slab or shattering occurs at the joint or crack. Blow-ups are accelerated due to a spalling away of the slab at the bottom creating reduced joint contact area. The presence of "D" cracking (although they do not exist in California's rigid pavements) or freeze-thaw damage also weakens the concrete near the joint resulting in increased spalling and blow-up potential.

Figure 1-17 Example of blow-ups (FHWA, 2003)

Pumping and water seepage – Pumping is the movement of material by water pressure beneath the slab when it is deflected under a heavy moving wheel load (Figure 1-18). Sometimes the pumped material moves around beneath the slab, but often it is ejected through joints and/or cracks (particularly along the longitudinal lane/shoulder joint with an asphalt shoulder). Beneath the slab there is typically particle movement counter to the direction of traffic across a joint or crack that results in a buildup of loose materials under the approach slab near the joint or crack. Pumping occurs even in pavement sections containing stabilized subbases. Pumping can often increase faulting. Water seepage occurs when water seeps out of joints and/or cracks. Many times it drains out over the shoulder in low areas.

Example 1 | Example 2 | Example 3

Figure 1-18 Examples of pumping and water seepage (Caltrans, 2004a)

Lane/shoulder drop-off – Lane/shoulder drop-off occurs when there is a difference in elevation between the traffic lane and shoulder (Figure 1-19). Typically, the outside shoulder settles due to a settlement of the underlying granular or subgrade material or pumping of the underlying material. This is found only with asphalt shoulder. This can also be a result of pumping.

Figure 1-19 Lane/shoulder drop-off (FHWA, 2003)

Settlement – Settlement is a local sag in the pavement structural section due to differential settlement, consolidation, or movement of the underlying layer material (Figure 1-20). Sag most commonly occurs above culverts due to the settlement or densification of backfill or at grade points between cut and fill sections. Pavement slippage could also contribute to differential settlement of the pavement and longitudinal cracking.

1.3.4 Summary

Table 1-2 provides a summary of factors that affect the pavement distresses commonly found on JPCP in California. These factors are grouped as traffic/load related and/or climate/materials related. The distinction between traffic/load and climate/materials would be important to the selection of treatment.

Figure 1-20 Settlement (Caltrans, 2004b)

Table 1-2 Summary of factors affecting JPCP pavement distress

Distress Type	Traffic/Load	Climate/Materials
Joint Deficiencies and Cracking		
Spalling		X
Faulting	X	X
Joint Seal Damage	X	X
Longitudinal Cracking	X	X
Transverse Cracking	X	X
Slab Cracking	X	X
Corner Breaks/Cracks	X	
Durability "D" Cracking		X
Surface Defects		
Scaling and Map Cracking		X
Surface Polish/Polished Aggregate	X	X
Surface Attrition (include rutting)	X	X
Popouts		X
Miscellaneous Distresses		
Blow-ups		X
Water Seepage and Pumping	X	X
Lane-to-Shoulder Drop-off		X
Settlement	X	X

The American Concrete Pavement Association (ACPA, 1998) developed guidelines for identifying structural and functional distresses and possible contributing factors. These guidelines are provided in Tables 1-3 and 1-4.

1.4 MATERIALS CONSIDERATIONS

Concrete consists of a blend of cement, coarse- and fine-grained aggregate materials, and water. Various admixtures may be included in the mix to entrain air or to modify certain properties of the fresh concrete (e.g., to accelerate or retard the rate of set). In addition, other cementitious or pozzolanic materials, such as fly ash or slag, may be added to the mix to achieve a specific design objective (e.g., to decrease permeability or to reduce reactive aggregate potential). An understanding of each component used in a concrete mix is essential to achieve desired performance of a rigid pavement. Materials typically used to repair rigid pavements include cementitious repair materials, specialty repair materials, bituminous materials, and sealants.

1.4.1 Concrete Constituent Materials

Cementitious Material

Portland cement is made up of lime, iron, silica, and alumina. These materials are broken down, blended in the proper proportions, and then heated in a furnace at a high temperature to form a product called "clinker." The clinker, when cooled and pulverized, is then ready for use as cement. By varying the materials that are used in the production of cement as well as the fineness of the grinding, different cement "types" are created.

The most commonly used types of portland cement nationally are shown in Table 1-3 (FHWA, 2001). The most common cement type employed in pavement construction in the United States is Type I, although Type III cements are gaining more widespread use, particularly in applications where high early strength is needed (Van Dam et al. 2000). Air-entrained cement, designated with an "a" in table 1-1, have small quantities of air-entraining material ground with the clinker during their production. Portland cements are governed under the specifications of ASTM C 150.

Table 1-3 Most commonly used types of portland cement

Cement Type	Differentiating Characteristic(s)
Type I	Normal
Type Ia	Type I with air entraining agent
Type II	Moderate heat of hydration, moderate sulfate resistance
Type IIa	Type II with air entraining agent
Type III	High early strength
Type IIIa	High early strength with air entraining agent
Type IV	Low heat of hydration, low strength gain
Type V	High sulfate resistance

Caltrans standard specifications (Caltrans, 2006) specify that portland cement shall be either "Type IP (MS) Modified cement, "Type II Modified" portland cement or Type V portland cement. Type III portland cement shall be used only as allowed in the special provisions for locations where traffic needs to be placed on the concrete shoulder after it is placed. Additional requirements for these cements can be found in Section 90 of the Caltrans standard specifications and accompanying special provisions. Cement furnished without a Certificate of Compliance shall not be used in the work until the Engineer has had sufficient time to make appropriate tests and has approved the cement for use (Caltrans, 1999). The Office of Rigid Pavement Materials and Structural Concrete (ORPMSC) is the focal point for Caltrans concrete needs (http://www.dot.ca.gov/hq/esc/Translab/rpsc.htm?id=translab-cd6). Caltrans continuously update specifications and test methods to reflect the latest concrete practices. The Office works with District Materials Engineers (DME) to assist in making recommendations for both new projects and the rehabilitation of existing projects. The ORPMSC has four sections: the Concrete Consultations and Investigations Section, the Aggregate Section, the Cement Section, and the Concrete Section. They provide technical expertise, recommendations and quality assurance testing for the cement, supplementary cementitious materials, admixtures, aggregate and concrete.

Aggregate

Aggregates include both gravels and crushed stone (quarried). Gravels are generally considered to be the most cost effective in concrete mixes, but have the highest coefficient of thermal expansion which negatively affects pavement performance. JPCP is made up of coarse aggregates (those retained by a No. 4 [4.75-mm] sieve), and fine aggregates (those passing a No. 4 [4.75-mm] sieve). Aggregates typically make up between 60 and 75 percent of the total volume of a concrete mix (PCA 1992). Thus, the properties of the aggregate have a significant effect on the durability, behavior, and performance of the JPCP pavement.

The aggregate selected for use in a concrete pavement must meet the requirements of Section 90, although this alone does not ensure that the aggregate will perform well. Perhaps one of the most critical properties of the aggregates is its durability, or its resistance to chemical and physical degradation due to both internal and external forces. That is, aggregates must be able to resist freezing and thawing and moisture cycling without incurring damage to themselves or the surrounding paste; they also must not be susceptible to deleterious chemical reactions (such as alkali-aggregate reactions) that can destroy the matrix of the concrete (Van Dam et al. 2000). Additional laboratory testing is often required to ensure durability.

Traditional grading requirements presented in standard mix design procedures are based on the use of separate coarse aggregate and fine aggregate gradations, as presented in Section 90. However, some agencies have been experimenting with the use of a continuous aggregate gradation, which is believed to improve the workability and durability of the resulting mix.

Caltrans standard specifications require the contractor to submit the proposed gradation of the primary aggregate nominal sizes before beginning concrete work (Caltrans, 2006). If a primary coarse aggregate or the fine aggregate is separated into 2 or more sizes, the proposed gradation shall consist of the gradation for each individual size, and the proposed proportions of each individual size, combined mathematically to indicate one proposed gradation. The proposed gradation shall meet the grading requirements described in the specifications (Caltrans, 2006).

Water

In general, water that has no pronounced taste or odor can be used to make concrete for JPCP (PCA 1992). ASTM C 94 provides acceptance criteria for the use of questionable water supplies. Caltrans requirements on water quality vary depending on type of work. Allowable amount of chlorides as Cl, sulfates as SO4, and impurities in the water are specified in Section 90 of the Caltrans standard specifications (Caltrans, 2006).

The water-cement ratio or the ratio of the weight of total water in the concrete mix to the weight of cementitious material in the mix is an important mix design parameter. The water-cement ratio is one of the most important factors contributing to the strength of the concrete, but the importance of durability, permeability, and wear resistance should not be overlooked (PCA 1992). Aggregate quality also affects the strength of the concrete. Typical water-cement ratios for concrete paving materials are between 0.40 and 0.50 (Van Dam et al. 2000).

Admixtures

Admixtures are added to plastic (still wet) concrete in order to obtain specific desirable characteristics. These include air entraining agents, water reducing agents, set accelerators, and set retardants. Each of these admixtures alters a specific property of the plastic mix. Some admixtures, such as accelerators, retardants, and water reducing agents, are used to obtain specific results during placement. These materials are added to increase concrete's workability or to improve its handling under otherwise adverse conditions. Other admixtures, such as air entraining agents, are used to enhance concrete's long-term properties. Air entraining admixtures introduce a matrix of air bubbles into concrete so that water trapped in the pavement has room to expand when frozen. Their use is essential to sound concrete constructed in areas subjected to freezing.

Section 90-4 of the Caltrans standard specifications, along with the project special provisions, describes what admixtures and the amount of admixtures allowed or not allowed for use, what ASTM Designations should be conformed, and approval process to use admixtures. The specifications must be carefully followed to achieve intended, desired characteristics of adding admixtures.

Caltrans publishes a list of approved admixtures for use in concrete. This list is updated periodically for reference primarily by Caltrans and others involved in the Caltrans projects. The approved list of admixtures may be found at the Caltrans website at the following address:

http://www.dot.ca.gov/hq/esc/approved_products_list/

1.4.2 Cementitious Repair Materials

Cementitious repair materials can generally be classified into two categories: normal concrete mixtures and high-early-strength PCC mixtures. Each mixture is manufactured for its intended usage; therefore, manufacturer's recommendations must be strictly followed. These materials are typically used for dowel bar retrofit and isolated partial and full depth repairs and slab replacement. Details can be found in chapters 6 and 7 of this report.

1.4.3 Specialty Repair Materials

There are two major types of specialty repair materials: rapid-strength proprietary materials and polymer concretes. Rapid-strength proprietary materials must be used according to the manufacturer recommendations concerning suitable temperature ranges for placement, bonding, curing, and opening time. Some proprietary materials are very sensitive to temperature and construction procedures (ACPA, 1998). Polymer concretes are a combination of polymer resin, aggregate, and a set initiator. Polymer concretes are categorized by the type of resin used, such as epoxies, methacrylates, and polyurethane (Patel, Mojab and Romine, 1993; Smith et al, 1991). Details can be found in chapter 7 of this report. Polyester concrete has sometimes been used in overlays and it consists of polyester resin binder, dry aggregate, and an initiator.

1.4.4 Bituminous Materials

Bituminous (asphalt) materials are sometimes used for partial-depth spall repairs of concrete pavements or other surface problems. However, they do deteriorate rapidly and are considered only temporary repairs.

1.4.5 Sealants

Sealant materials are typically used in joint/crack sealing applications. The purpose is to minimize infiltration of surface water and incompressible material into the joint/crack (ACPA, 1991; FHWA, 1990; ERES, 1992). Sealants also reduce dowel bar corrosion potential by reducing entrance of de-icing chemicals. Required sealant characteristics differ for different joint types (ACPA, 1991). A sealant for a tied longitudinal joint does not need to be as elastic as one for transverse joint. This is because tied joints undergo virtually no movement (ACPA, 1991). However, most longitudinal joints in older rigid pavements are not tied. Transverse joints undergo larger movements which induce larger states of stress and strain within a sealant than typically found in a longitudinal joint; therefore, the sealant used in transverse joints must be capable of handling these stresses to perform over the range of expected joint movement.

Sealants are either liquid or preformed. Liquid sealants depend on long-term adhesion to the joint face for successful sealing. Preformed compression seals depend on lateral rebound for long-term performance. Sealant properties necessary for long-term performance depend on the specific application and the climatic environment of the installation. Detailed description on sealant materials can be found in chapter 4 of this report.

1.4.6 Dowel Bars and Tie Bars

Dowel bars are smooth round bars that act as load transfer devices across pavement joints. Dowel bars are typically placed across transverse joints or cracks. Tie bars are deformed bars (i.e., rebar) or connectors that are used to hold the faces of abutting rigid slabs in contact. Tie bars are typically placed across longitudinal joints. Further details regarding dowel bars and ties bars can be found in the Standard Plans and Pavement Technical Guidance on the Caltrans website: http://www.dot.ca.gov/hq/oppd/pavement/guidance.htm.

1.5 DESIGN CONSIDERATIONS

When properly designed, constructed, and maintained, concrete pavements are expected to last for a long time. Factors that should be carefully thought out during the design and construction include traffic applications and their impacts to the pavement, environment condition, future maintenance and rehabilitation or windows of opportunities for conducting such activities, traffic control during the construction, and project staging.

1.5.1 Traffic

Pavements are designed and constructed to withstand the stresses and strains caused by repeated wheel loadings that are sustained over the course of their life. Therefore, it is important to have a good knowledge of the amount of traffic loading expected on a pavement. The proper structure design of a pavement relies upon developing an accurate forecast of future loadings. Details on traffic analysis and rigid pavement structural design can be found in the Caltrans Highway Design Manual (Caltrans, 2004c).

1.5.2 Environment

There are primarily two major environment-related factors that affect the performance of rigid pavements: temperature and moisture. For pavements located in areas with cold winter, the effect of freeze-thaw will also impact the pavement performance since the freeze-thaw cycle can cause stresses in a pavement due to variation in temperatures. To address climatic effects, Caltrans has developed a pavement climate map which can be found in Caltrans Highway Design Manual Topic 615 or at Caltrans website: http://www.dot.ca.gov/hq/oppd/hdm/hdmtoc.htm#hdm.

Temperature

The variation of temperature causes the slabs to expand or contract. As ambient temperatures change throughout the day, the temperature of concrete pavement also changes. This temperature cycling creates a temperature gradient in the slab, i.e., a difference in temperature between the top and bottom of the slab. As the slab tries to respond to these temperature differences, it is resisted by the weight of the slab, the support of the subgrade, and any restrained edge conditions, which results in the development of slab stresses. During the day the temperature at the top of the slab is greater than the temperature at the bottom of the slab, while at night the opposite is true. The temperature gradient causes the slab to curl downward (daytime) or curl upward (nighttime), either of which can induce stress in the pavement. Depending upon the time of day, these curling stresses can either add to or subtract from the effect of the load-induced stresses.

Moisture

Variations in the moisture content from the top to the bottom of the slab can cause warping stresses to develop in PCC. Generally, when the top of the slab is drier than the bottom, it causes the pavement to warp upward as a result of a moisture gradient. When these movements are resisted by the weight of the slab, subgrade support, and end conditions, stresses in the slab develop.

Other Factors

There are other key stresses that can develop in concrete pavements that affect performance. Among these are drying shrinkage stresses, which are due to the volume change due to water loss during curing and resistance from the subgrade as it shrinks. Temperature shrinkage stresses are another type of stress occurring in concrete pavements, and these develop because of the resistance of the subgrade to the expansion and contraction of the concrete slab as it responds to daily temperature changes. Dowel bar bearing stresses are also important to the performance of the pavement, particularly in the development of joint faulting.

1.5.3 Windows of Opportunities

As illustrated in Figure 1-1, pavements deteriorate under traffic loads and with time. There are periods in a pavement life during which pavement preservation is an economical option. Pavement preservation should be considered early on in the life of a pavement when it is still in relatively good condition. Pavement restoration should be considered when the pavement is expected to initially exhibit distress like faulting, cracking, or ride quality issues. If the pavement condition is allowed to deteriorate without any proactive maintenance, the windows of opportunities of keeping it in a good condition with least expense would be lost. The pavement preservation is no longer appropriate since the pavement has deteriorated and a more expensive rehabilitation measure would have to be considered.

The concept of windows of opportunities can also be applied to a specific treatment. The specific treatment is generally selected based on the pavement condition, distress type, distress extent, distress severity, and economics. The effectiveness of the treatment is largely dependent on the right time when the treatment is applied. The windows of opportunities for a specific treatment may be defined by trigger and limit values on key distresses. Trigger values define the point when the treatment is viable and appropriate. Limit values define the point when the treatment is not likely to be effective. The period between the trigger and limit values is the window of opportunity where the treatment is likely to be most effective and economical. Guidelines on trigger and limit values for various treatment strategies are provided in Chapter 3 of this report.

1.5.4 Traffic Control

Adequate traffic control must be provided during the field work for safety and successful completion of the project. Traffic control should be in place before work forces and equipment enters onto the roadway or into the work zone. Typical traffic control includes construction signs, construction cones and/or barricades, flag personnel, and/or pilot cars to direct traffic flow. Details on traffic control may be found in the Caltrans Traffic Manual (Caltrans, 1996) or at the website:

http://www.dot.ca.gov/hq/traffops/signtech/signdel/trafficmanual.htm.

1.5.5 Item Codes

Caltrans uses item codes along with estimated item quantities to develop project construction costs. An item code is a six digit code used to describe a specific item or activity in a project. For example, the item code 193118 is used for concrete backfill and the item code 066074 is used for traffic control. Each item code has a unit of measure. Concrete backfill is measured in cubic meters and traffic control is a lump sum unit. The engineer must determine what work items and/or activities are expected in the project and develop estimated quantities for bidding purpose. Caltrans Standard Materials and Supplemental Work Item Codes can be found at the following web site:

http://i80.dot.ca.gov/hq/esc/oe/awards/#item_code.

For each treatment type discussed in this guide (joint resealing and crack sealing, diamond grinding, dowel bar retrofit, and isolated partial and full depth concrete repair), typical item codes are provided in the corresponding chapters.

1.6 KEY REFERENCES

ACPA, 1991. *Design and Construction of Joints for Concrete Highways*, American Concrete Pavement Association, Portland Cement Association, TB-010.0D, Arlington Heights, IL, 1991.

ACPA, 1998. Guidelines for Partial-Depth Spall Repair, American Concrete Pavement Association, TB003.02P, 1998.

Caltrans, 1996. *Caltrans Traffic Manual*, Sacramento, CA, 1996.

Caltrans, 1999. *Standard Specifications*, California Department of Transportation, July 1999

Caltrans, 2004a. *Slab Replacement Guidelines*, Sacramento, CA, January 2004.

Caltrans, 2004b. *Interim PCC Pavement Rehabilitation Guidelines – Pavement Tech Notes,* Caltrans, Sacramento, CA, Revised July 28, 2004.

Caltrans, 2004c. *Highway Design Manual*, Caltrans, Sacramento, CA, September 2006.

Caltrans, 2006. *Update of Section 90: Portland Cement Concrete, Standard Specifications*, Caltrans. 2006.

ERES Consultants, Inc., 1992. *Techniques for Pavement Rehabilitation,* Federal Highway Administration, 1992.

FHWA, 2001. *PCC Pavement Evaluation and Rehabilitation Reference Manual*, National Highway Institute Course No. 131062, Federal Highway Administration, October 2001.

FHWA, 2003. *Distress Identification Manual for the Long-Term Pavement Performance Program*, Publication No. FHWA-RD-03-031, FHWA, June 2003.

FHWA, 2005. *Memorandum on Pavement Preservation Definitions*, FHWA, September 12, 2005.

Galehouse, L., J. Moulthrop, and R.G. Hicks, 2003. *Principles of Pavement Preservation*. TR News, Transportation Research Board, September-October, 2003.

Patel, A.J., Mojab, C.A.G. and Romine, A.R., 1993. *Materials and Procedures for Rapid Repair of Partial-Depth Spalls in Concrete Pavements - Manual of Practice*, Strategic Highway Research Report No. SHRP-H-349, National Research Council, Washington, D.C., 1993.

PCA, 1992. *Design and Control of Concrete Mixtures*. Engineering Bulletin EB001.13T. Portland Cement Association, Skokie, IL, 1992.

Rao, C., E.J. Barenberg, M.B. Snyder, and S. Schmidt, 2001. *Effect of Temperature and Moisture on the Response of Jointed Concrete Pavements*, Proceedings, Seventh International Concrete on Concrete Pavements, Orlando, FL, 2001.

Smith, K.L. et al, 1991. *Innovative Materials and Equipment for Pavement Surface Repair – Final Report*, Volume 1 and II, Strategic Highway Research Report No. SHRP-M/UFR-91-504, National Research Council, Washington, D.C., 1991.

Stahl, Kirsten, 2006. *PCC Pavement Preservation and Maintenance*, Presented at the Southern California Pavement Preservation Conference, April 25-26, 2006, Diamond Bar, California.

Van Dam, T. J., M. J. Wade, K. D. Smith, and L. L. Sutter. 2000. *Guideline III - Treatment, Rehabilitation, and Prevention of Materials-Related Distress in Concrete Pavements*. FHWA Project No. DTFH61-96-C-00073. Federal Highway Administration, McLean, VA, 2000.