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 pavements in good or near new conditions by applying the right maintenance strategies at the right time that are cost-effective and extend pavement life and preserve investment. This section briefly describes the definition, concept, and benefits of pavement preservation, and the importance of treatment selection and the optimum timing for the pavement preservation 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 highway infrastructure. An effective pavement preservation program addresses pavements while they are still in fairly good condition—before the onset of serious damage or distress. By applying a cost-effective pavement preservation treatment at the right time, the pavement can be restored almost to its original, newly-constructed condition. The cumulative effect of systematic, successive preservation treatments is to postpone costly rehabilitation or reconstruction (FHWA, 2005). Pavement preservation treatments restore the function of the existing structural pavement system and extend its life by reducing aging and restoring its serviceability, not increase its bearing 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 approach. 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 treatment stages are also shown in the figure. While the pavement performance curve in the figure is more representative of flexible pavements, the same concept of treatment stages is applicable to rigid pavements as well. It clearly indicates that pavement preservation should be carried out at an early stage of the pavement's life, while it is still in good condition, both structurally and functionally. If the pavement is not maintained effectively, it will eventually deteriorate to a point where the only choice is reconstruction, which is the most costly option.

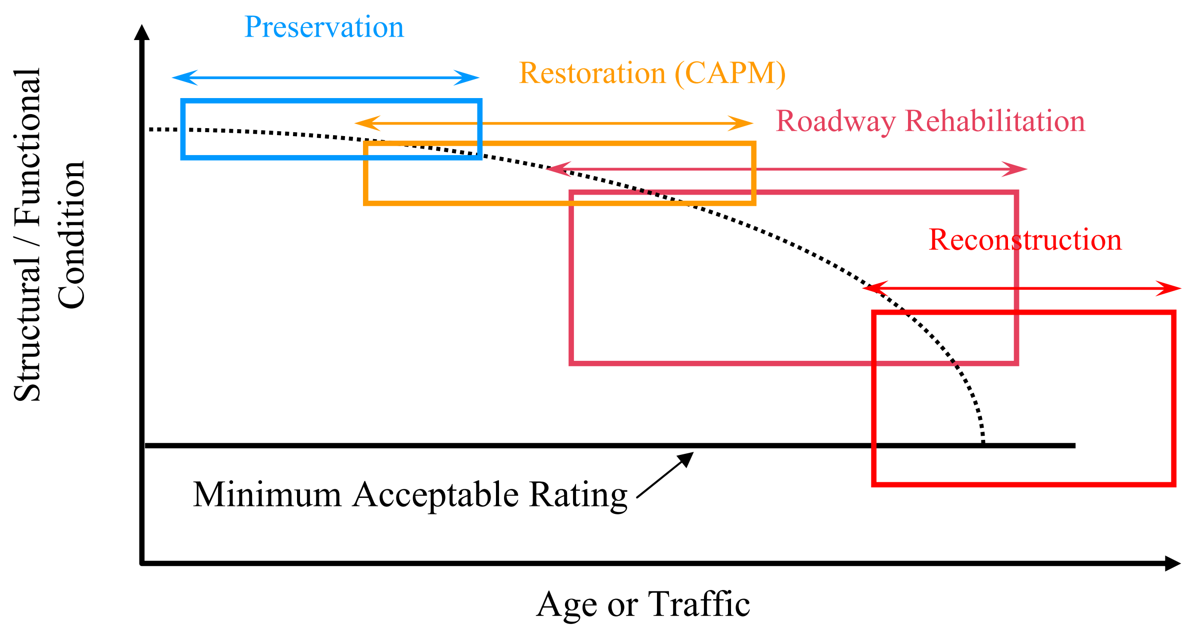

Figure 1-1 Typical pavement performance curve and maintenance/rehabilitation time

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 concept behind *pavement preservation*. As indicated in the foregoing, 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. The timely application of successive treatments can maintain the pavement in good condition and preclude the need for more expensive roadway rehabilitation and reconstruction strategies, as shown in Figure 1-2. This figure illustrates the concept of how the timely application of treatments is paramount in maintaining the existing pavement condition. The frequency of applying these treatments will depend on the type of treatments that have been used and their life expectancy.

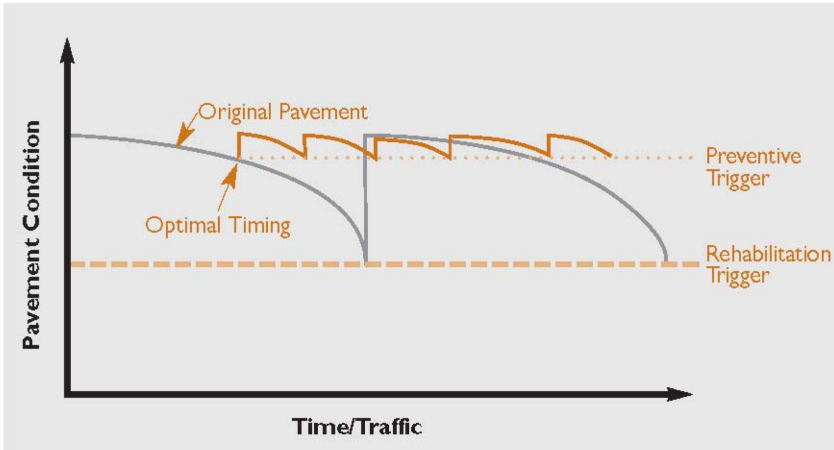

Figure 1-2 Concept of optimal timing for pavement preservation (Galehouse et al, 2003)

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 condition, distress types, traffic, 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 sections of Continuously Reinforced Portland Cement Concrete Pavement (CRCP), California's 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 the 1970's. The design life for rigid pavements was traditionally 20 years and most have out lived their design life with little maintenance. California's rigid pavements on freeways have been functional often far beyond their design life of 20 years, and most of them have not deteriorated as originally anticipated. Current design standards require or encourage a 40-year design life. Currently, an effort is underway at Caltrans to design an improved 100-year design life rigid pavement by using the newest technology, good construction techniques and equipment, and improved materials.

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

- Base support. Initially, 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 a lesser amount of asphalt binder 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, a 9-inch (229 mm) thick slab became common practice. Presently, 10-inch (254 mm) and even some 12-inch (305 mm) thick slabs are used depending on projected traffic.
- Dowels, tie bars, and 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 concrete mixture materials used in the pavement slab have remained fairly constant. One could use 1950's pavement slab materials specifications and be close to current Caltrans Standards. Flexural strengths have also been relatively constant. One notable exception would be the current mineral admixture requirements that were added to address reactive aggregate or alkali-silica reactivity (ASR) concerns. Requirements on strength, curing, batching, mix transporting, slump and penetration have remained relatively constant over the last 50 years.

However, increasing traffic loads and numbers of heavy axle applications have had a significant, detrimental effect on rideability, and eventually durability, of the pavement structure. This was seen as the primary reason that our rigid pavements started showing surface distress.

The foremost distress in California for rigid pavements over CTB was faulting. This distress occurred over time with the up-stream slab rising in relation to the adjacent edge of the down-stream slab, 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 materials on its surface, thus 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 the interface between the base and pavement slab to eliminate the mechanism for carrying fines from the down-stream slabs to up-steam slabs. Edge drains were intended to serve the same purpose. Though faulting may have initially been thought of as a ride issue, its presence became a key to the structural 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 failure that are of interest to maintenance personnel: one general cause is an improper construction practice resulting in the pavement structure not being built as designed; a second is the condition of the project site being incompletely or erroneously analyzed without proper consideration of the "ambient" or environmental impact to the pavement coupled with the inadequacy of a given pavement maintenance schedule.

Such problems are not necessarily due to a flaw or inadequacy in rigid pavement design, but rather not properly transferring theory into practice. Other issues may involve unforeseen changes at the site (such as in increase in traffic loads) after construction. Underestimating wheel loads, improper construction practices, material related distresses, or a changing environment (such as the appearance of ground water after construction) are other examples of unforeseen changes after construction. A couple of real life examples are given below as illustrations of these types of deterioration.

In 1998, a small section of I-5 in Sacramento County near the Pocket Road interchange was in need of replacement. The pavement was designed to be built on a lime treated base course. This section of freeway was failing even 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 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 its designed strength before the PCC slabs were placed, the stability and load bearing capacity of the base would likely be inadequate. Since lime was found in the drainage 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. Rehabilitation included removing the entire pavement structure, lime-treating the base again, and reconstructing a new pavement structure using the latest Caltrans standards.

Another example of premature pavement failure 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 that the 8-inch slab thickness might not be sufficient. Upon further investigation, however, it was discovered the air content in the concrete was as much as 12%. As a result of this high air content, flexural strengths were low. Proper maintenance on this roadway should have considered the fact that the corner cracking was primarily due to weakened concrete.

Fortunately, such examples of premature rigid pavement deterioration are fairly rare. Oftentimes they are due to human error in incorporating sound and established engineering principles. The first example, above, shows how deterioration caused by unforeseen circumstances can have far reaching implications because pavement deterioration becomes inadvertently built into the design. The second example shows how a lack of understanding of how a pavement performs under traffic loads and other factors can affect pavement performance.

1.2.3 Faulting Mechanism and Effort on Addressing Faulting

In California, faulting is 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 that 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 away from the underlying materials. And lastly, the adjacent slabs at the joint must be free to move independently from one another—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 should 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 inches (1.5 mm) or more, 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 and/or drop-off also increase. The ride quality of the roadway becomes poor as the height of the drop-off increases with time and load applications. Although the ride quality can be restored with diamond grinding, this temporary measure will not address the causal deterioration of the pavement structure. As joint faulting continues, the support in the up-stream edge of the slab becomes less and less so the slab functions much like a cantilevered bridge or beam. Eventually, transverse cracks appear near the edge of slab where it is still being supported by the base. As conditions worsen, the slab without adequate base support will crack. 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 can form third stage cracking. At this late stage in pavement deterioration, slab replacement is probably the only viable rehabilitation strategy. As more slabs exhibit third stage cracking, the pavement may need major rehabilitation.

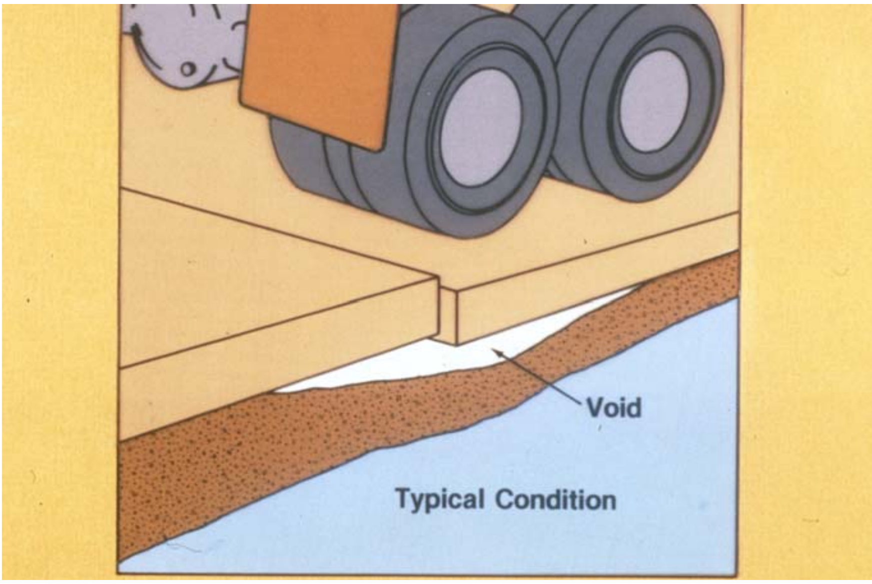

Figure 1-3 Slab drop-off caused by base erosion (Stahl, 2006)

Efforts to enhance the 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 jointed concrete pavements 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 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 a joint or crack. A spall usually does not extend vertically through the whole slab thickness but extends to intersect the joint at an angle. Spalling generally results from one or more of the following root causes:

- 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;
- Disintegration of the concrete from the freeze-thaw action of "D" cracking (for various reasons this distress type does not occur in California, however).

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, thus 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 in 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 material 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 the most prominent failure type in California because Caltrans did not begin building doweled concrete pavements 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 are allowed to infiltrate 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 accumulating incompressible materials and also reduces the amount of water seeping into the underlying 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 slab edges, and the 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 the western states, which have a drier climate than 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 have cracked over twice as often as shorter 12 ft (3.7 m) and 13 ft (4 m) joint 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. 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 stresses.

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 situated a distance less than 6 ft (1.8 m) on each side of the slab, as 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 joints, 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 a pavement slab. These relatively narrow surface cracks often curve around the intersection of longitudinal joints/cracks and transverse joints and 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 far more prominent. ASR is another durability-related distress which typically produces "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 ⅛ to ½ inch (3 to 13 mm) of the concrete slab surface. Map cracking or "crazing" is a series of 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 that may lead to scaling of the surface. Scaling can also be caused by reinforcing steel, such as dowel bars and tie bars placed too close to the pavement surface.

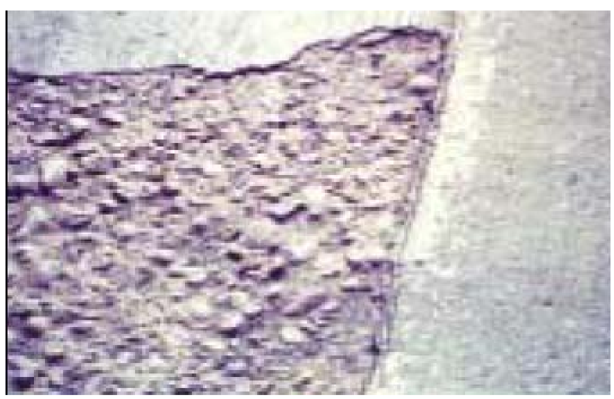

Figure 1-13 Example of scaling (FHWA, 2003)

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

Surface attrition/abrasion – Surface attrition or abrasion is abnormal wear of the concrete pavement (Figure 1-15). It can result from either a poor quality surface material or the 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 the high elevation mountain or desert climatic regions of California, due to the use of tire chains during 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 ½ inch to 2 inches (13-51 mm) in depth.

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

1.3.3 Other Miscellaneous Distresses

Blow-ups – The mechanism leading to blow-ups is excessive compressive pressure at joints or cracks. Infiltration of incompressible materials into the joint or crack during cold periods results in high compressive stresses during hotter periods when slabs expand (Figure 1-17). When this compressive pressure becomes too great, a localized upward movement of the slab and a complete shattering occurs near the joint. Blow-ups are accelerated due to the spalling away of the slab at the bottom, thus creating reduced joint contact area. The presence of "D" cracking (although this distress type does 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 more often it is ejected through the joints and/or cracks (particularly along the longitudinal lane/shoulder joint with an asphalt shoulder). Beneath the slab there is typically particle movement that occurs counter to the direction of traffic across a joint or crack, resulting 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 oftentimes increase joint faulting. Water seepage occurs when water seeps out of joints and/or cracks. Oftentimes it drains out over the shoulder in lower-lying 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 the shoulder (Figure 1-19). Typically, the outside shoulder settles due to a settlement of the underlying granular or subgrade materials or to pumping of the underlying material. This condition is found only in the case of an asphalt shoulder, or as 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.

Figure 1-20 Settlement (Caltrans, 2004b)

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- and load-related and/or climate- and materials-related. The distinction between traffic/load and climate/materials would be important to the selection of treatment.

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

* Does not occur in California.

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

Table 1-3 Structural distresses and possible contributing factors (ACPA, 1998)

Structural Distress	***Contributing Factors ****					
	Pavement Design	Load	Water	Temp.	Pavement Materials	Construct.
Cracking **						
Transverse	P	P	N	C	C	P
Longitudinal	P	P	N	C	C	P
Corner	C	P	C	C	N	N
Intersecting	C	P	C	N	C	N
Possible causes of cracking: Fatigue, joint spacing too long, shallow or late joint sawing, base or edge restraint, loss of support, freeze-thaw and moisture related settlement/heave, dowel-bar lock-up, curling and warping.						
Joint/Crack Deterioration						
Spalling	C	C	N	C	P	C
*Pumping ***	C	P	P	N	C	N
Blow-ups	C	N	N	P	C	N
*Joint Seal Damage ***	C	C	C	C	P	C
Possible causes of joint/crack deterioration: Incompressibles in joint/crack, material durability problems, subbase pumping, dowel socketing or corrosion, keyway failure, metal or plastic inserts, rupture and corrosion of steel in JRCP, high reinforcing steel.						
Punchouts **	P	P	C	N	C	N
Possible causes of punchouts: Loss of support, low steel content, inadequate concrete slab thickness, poor construction procedures.						
Durability						
D-cracking	N	N	P	C	P	N
ASR	N	N	P	C	P	N
Freeze-thaw damage	N	N	P	P	P	C
Possible causes of durability distresses: Poor aggregate quality, poor concentrate mixture quality, water in the pavement structure.						

* *P= Primary Factor C= Contributing Factor N= Negligible Factor*

** *Loss of support is an intermediary phase between the contributing factors and these distresses. Loss of support is affected by load, water and design factors.*

Table 1-4 Functional distresses and possible contributing factors (ACPA, 1998)

Functional Distress	***Contributing Factors ****					
	Pavement Design	Load	Water	Temp.	Pavement Materials	Construct.
Roughness						
*Faulting ***	P	P	P	C	C	N
*Heave / swell ***	C	N	P	P	C	N
*Settlement ***	C	C	C	N	N	C
Patch deterioration	C	C	C	C	C	C
Possible causes of roughness: Poor load transfer, loss of support, subbase pumping, backfill settlement, freeze thaw and moisture related settlement/heave, curling and warping and poor construction practices.						
Surface Polishing	N	C	N	N	P	N
Possible causes of surface polishing: High volumes of traffic, poor surface texture, wide uniform tine spacing, wide joint reservoirs, and wheel path abrasion because of studded tires or chains.						
Noise	P	C	N	N	C	P
Possible causes of noise: High volumes of traffic, poor surface texture, wide-uniform tine spacing, wide joint reservoirs, and wheel path abrasion because of studded tires or chains.						
Surface Defects						
Scaling	N	N	C	C	P	P
Popouts	N	N	C	C	P	C
Crazing	N	N	N	C	C	P
Plastic shrinkage cracks	N	N	N	C	C	P
Possible causes of surface defects: Over-finishing the surface, poor concrete mixture, reactive aggregates, and poor curing practices.						

* *P= Primary Factor C= Contributing Factor N= Negligible Factor*
** *Loss of support is an intermediary phase between the contributing factors and these distresses. Loss of support is affected by load, water and design factors.*

1.4 MATERIAL CONSIDERATIONS

Concrete consists of a blend of cement, coarse- and fine-grained aggregate, water, and some admixtures if appropriate. Admixtures may be included in the mix to entrain air or 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 the desired performance of a rigid pavement. Materials typically used to repair rigid pavements include cementitious repair materials, specialty repair materials, bituminous materials, and joint sealants.

1.4.1 Concrete Constituent Materials

Cementitious Materials

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 "portland" 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 1-5 (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 1-3, have small quantities of air-entraining material ground with the clinker during cement production. In the United States, portland cements are usually governed under the specifications of ASTM C 150.

Table 1-5 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 updates their specifications and test methods to reflect the latest concrete practices. The Caltrans ORPMSC works with the 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 JPCP pavements.

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—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 cement paste; they also must not be susceptible to deleterious chemical reactions (such as alkali-aggregate reaction) 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- and fine-aggregate gradations, as prescribed by Section 90. However, some agencies have been experimenting with the use of a so-called “continuous” aggregate gradation, which is believed to improve the workability and durability of the resulting mixture.

The 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 may be used to make concrete for JPCP (PCA 1992). ASTM C 94 provides acceptance criteria for the use of a questionable water supply. 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-cementitious ratio or the ratio of the weight of total water in the concrete mixture to the weight of cementitious materials in the mix is an important mix design parameter. The water-cementitious ratio is one of the most important factors contributing to the strength of the concrete; however the importance of durability, permeability, and abrasion (wear) resistance should not be overlooked (PCA, 1992). Aggregate quality also affects the strength of the concrete. Typical water-cementitious 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, and set accelerators or 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 workability or to improve handling under otherwise adverse conditions. Other admixtures, such as air entraining agents, are used to enhance the 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 and contract when frozen or thawed. The use of air entrainment is essential to sound concrete constructed in areas subjected to freezing and thawing cycles.

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

Caltrans publishes a list of approved admixtures for use in its concrete projects. This list is updated periodically for reference, primarily by Caltrans and others involved in 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 mixtures. Each mixture is manufactured for its intended usage; therefore, the manufacturer's recommendations must be strictly followed. These materials are typically used for dowel bar retrofit, 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 material: rapid-strength proprietary materials and polymer concretes. Rapid-strength proprietary materials must be used according to the manufacturer's 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 (asphaltic) materials are sometimes used for partial-depth spall repairs on concrete pavements or other surface distress problems. However, they do deteriorate rapidly and are considered only temporary repairs.

1.4.5 Joint Sealants

Sealant materials are typically used in joint and crack sealing applications. The purpose is to minimize infiltration of surface water and incompressible materials into the joint or crack (ACPA, 1991; FHWA, 1990; ERES, 1992). Sealants also reduce dowel bar corrosion potential by inhibiting the incursion 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 a 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.

Joint 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. A detailed description of 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 Caltrans Standard Plans under the heading "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 very long time. Factors that should be carefully thought out during design and construction include traffic applications and their impacts to the pavement, environment conditions, future maintenance and rehabilitation or windows of opportunities for conducting such activities, traffic control during construction, and project staging.

1.5.1 Traffic

Pavements are designed and constructed to withstand the stresses and strains caused by repeated wheel loads that will be imposed over the course of the design life and beyond. Therefore, it is quite important to have a good knowledge of expected traffic loading on a roadway. Proper structural design of a pavement relies upon developing an accurate forecast of future axle 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 a cold winter, the effect of freeze-thaw will also impact pavement performance, since the freeze-thaw cycles 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 the 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 base and subgrade, and any restrained edge conditions, which results in the development of intermittent and continuously changing 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 upwards (nighttime and early morning), either of which can induce high stresses in the concrete. Depending on the time of day, these curling or warping stresses can either add to or subtract from the effect of the load-induced stresses.

Moisture

Variations in moisture content from the top to the bottom of the slab can cause warping stresses to develop in PCC pavements. 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 Opportunity

As illustrated in Figure 1-1, pavements deteriorate under traffic loads and with time. There are periods in a pavement’s 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 exhibits distresses like faulting, cracking, or poor ride quality due to structural deficiencies. If the pavement condition is allowed to deteriorate without any proactive maintenance, the windows of opportunity to keep it in good condition with least expense will be lost. After a favorable window of opportunity has passed, pavement preservation is no longer appropriate since the pavement has deteriorated and a more expensive rehabilitation measure should be considered.

The concept of windows of opportunity can also be applied to a specific treatment. The specific treatment is generally selected based on the pavement condition, distress type, extent and severity of distress(es), and economics. The effectiveness of a treatment is largely dependent on the right time when the treatment is applied. The windows of opportunity for a specific treatment can be defined by trigger and limit values on key distresses. Trigger values define the point when the treatment can still be viable and appropriate. Likewise, limit values define the point when the treatment is not likely to be effective. A structural bearing capacity assessment is also appropriate to find out of any serious structural deficiencies exist before applying a pavement preservation measure. Assuming the load bearing capacity of the pavement is still adequate, the period between the trigger and limit values defines 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 field work, both for safety and the successful completion of the project. Traffic control should be in place before work forces and equipment enter the roadway or 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, item code 193118 is used for concrete backfill and item code 066074 is used for traffic control. Each item code has an appropriate unit of measure. Concrete backfill is measured in cubic meters while traffic control is quoted as a lump sum. 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 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.

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