CONCRETE PAVING *Technology*

The Concrete Pavement Restoration Guide

Procedures for Preserving Concrete Pavements

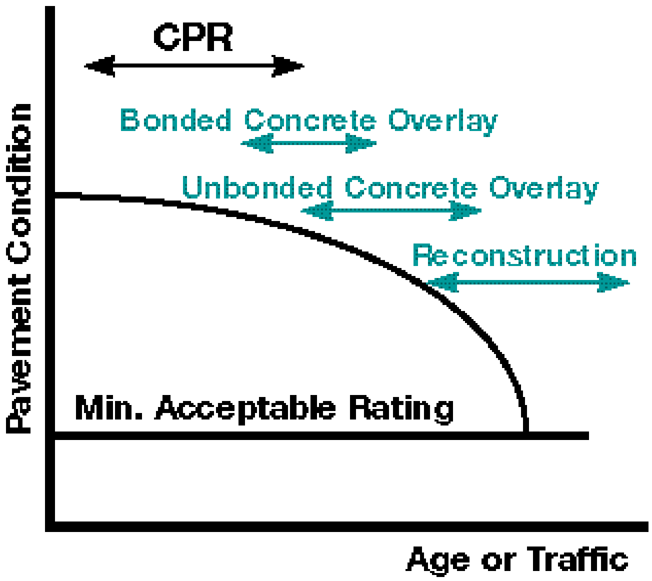

Figure 1. CPR should be the first response to a deteriorating concrete pavement.

Concrete Pavement Restoration (CPR)
An engineered procedure used to manage the rate of deterioration in concrete pavements.

Appropriate and timely CPR maintains a concrete pavement's smooth, safe, and quiet condition, while extending its service life economically.

Introduction

Concrete pavement restoration, or CPR, is a series of engineered techniques developed over the past thirty years to manage the rate of pavement deterioration in concrete streets, highways, and airports. CPR is a nonoverlay option used to repair isolated areas of distress in a concrete pavement without changing its grade. This rational, preventive procedure restores the pavement to a condition close to original and reduces the need for major and more costly repairs later. In fact, recent reports from the Transportation Research Board state that for every dollar invested in appropriately timed preventive pavement maintenance, three to four dollars in future rehabilitation costs are saved.[1]

Ideally, CPR is the first rehabilitation procedure applied to concrete pavement. Figure 1 shows where CPR fits into the overall rehabilitation sequence for concrete pavements. It is usually applied early when the pavement is in reasonably good condition with only slight deterioration. CPR is typically used to replace isolated sections of deteriorated pavement, or to prevent or slow overall deterioration, as well as to reduce the impact loadings on the pavement. If the pavement needs more load carrying capacity or has deteriorated to poorer conditions, other procedures — such as bonded concrete overlay, unbonded concrete overlay, or reconstruction — may be better alternatives.

CPR can also be applied to a mildly deteriorated concrete pavement that already has an asphalt overlay. It is quite feasible to remove the existing asphalt, repair the underlying concrete using CPR, then open it to traffic without a new asphalt overlay.

Table 1: Available Concrete Pavement Restoration Techniques	
Concrete Pavement Restoration Technique	***Used to:***
Full-Depth Repairs	Repair cracked slabs and joint deterioration
Partial-Depth Repairs	Repair joint and crack deterioration and surface distress
Diamond Grinding	Extend serviceability; improve ride and skid resistance; reduce noise
Dowel-Bar Retrofit	Restore load transfer at joints and cracks
Joint and Crack Resealing	Minimize infiltration of water and incompressible material into joint system
Slab Stabilization	Fill small voids underneath the concrete slab
Cross-Stitching	Repair low and medium severity longitudinal cracks
Grooving	Reduce wet weather accidents and prevent hydroplaning
Retrofitting Edge Drains	Add a longitudinal drainage system
Retrofitting Concrete Shoulder	Decrease pavement edge stresses and corner deflections

Table 1 shows the available CPR techniques. Each technique is designed specifically to repair or prevent the recurrence of a certain distress or a combination of distresses. While each technique can be used individually, they are typically more effective when several are used together.

Although CPR does not necessarily increase structural capacity of a pavement, it does extend the pavement's service life. One example is Interstate 475 near Macon, Georgia. This pavement has carried nine times its original design traffic because it has been maintained effectively with CPR.[2]

Advantages

In the past, asphalt overlays often have been used on concrete pavements that have deteriorated. However, CPR has several advantages over asphalt overlays:

1. CPR addresses the cause of a pavement distress, minimizing further deterioration. Covering the distress with an asphalt overlay does not correct the cause of the distress. Eventually, the distress manifests itself again, usually as a larger, more expensive problem. This fundamental difference makes CPR more effective and less costly than asphalt overlays.[3,4]

2. CPR costs less and lasts longer. Georgia has used CPR extensively for more than 20 years, sometimes as many as three times on the same road.[2,5] They have found CPR to be one-fourth to one-third the cost of a 150 mm (6-in.) asphalt overlay. CPR projects in Georgia typically last between seven and 10 years, and some have per formed for more than 17 years before a second CPR.[5] Table 2 compares costs for several comparable CPR and asphalt overlay alternatives.

3. CPR is quicker and causes less traffic disruption. Because CPR maintains the existing grade, features such as curbs and gutters, bridge clearances, approach slabs, and roadside appurtenances do not need adjustment. Furthermore, CPR repairs only those areas that need improvement, such as the driving lane or the keel section of a runway. It does not have to be placed over the entire pavement width, as does an asphalt overlay. This accelerates the entire construction process, requires less traffic control measures, and causes less traffic disruption.

4. CPR preserves the safety of concrete pavements. Concrete does not rut, washboard, or shove. These defects can cause serious safety problems for asphalt pavements at intersections or other locations, where traffic is starting, stopping, and turning. Furthermore, because of their light color, concrete pavements reflect light better than asphalt pavements. This improves vision and makes driving at night and in inclement weather safer.

5. CPR preserves the environmental benefits of concrete pavements. Concrete's light color reduces the number of street lights needed for the same illumination on an asphalt pavement. Studies have

Table 2: Cost comparisons for comparable CPR and AC overlay rehabilitation alternatives			
Location	***Rehabilitation Technique***	***Project Size***	***Cost/Lane km****
North Carolina I-26[9]	CPR	11.3 km	$ 77,640
North Carolina I-26[9]	Crack/Seat and AC Overlay	4.2 km	$ 232,920
Florida I-10[10]	CPR	106.2 km	$ 38,820
Florida I-10[10]	Crack/Seat and 100 mm AC Overlay	51.5 km	$ 117,190
Washington I-90[11]	CPR	53.1 km	$ 73,800
Washington I-90[11]	110 mm AC Overlay	53.1 km	$ 118,300

** 1 km = 0.62 miles*

shown that the number of street lights can be reduced by one-third when streets have concrete surfaces.[6] The light surface also keeps urban areas cool. Concrete pavements and trees can reduce temperatures by ten degrees, which conserves energy in high-energy-use urban areas.[7] Finally, the hard concrete surface makes vehicles more fuel efficient. Because concrete pavements do not deflect like asphalt pavements, they can reduce truck fuel consumption by as much as 20 percent.[8]

Application and Selection of CPR Techniques

Application Considerations —

CPR is very versatile. It allows the design engineer to address specific project problems or develop system-wide programs that provide different levels of improvement. For example, a designer may use a complete CPR program to restore a pavement to a condition similar to a new pavement, or a partial program to extend a pavement's life for a few years. Factors such as fiscal constraints, adjacent pavement conditions, and future agency-programming could make one approach more suitable than another.

CPR can also correct design or construction deficiencies before any distresses develop, or repair a concrete pavement before an overlay is placed. Repairing a design defect or repairing the pavement before an overlay minimizes future distress and maintenance.

Finally, it is feasible to repair a concrete pavement that has been previously overlaid with asphalt. Agencies in the past overlaid many concrete pavements because of roughness. This does not correct the cause of roughness, and the asphalt overlays often deteriorate quickly, requiring a second overlay. In many cases, overlays have to be replaced several times within a short period. With CPR, it is possible to remove an asphalt overlay and repair an underlying concrete pavement to close to its original condition.

Selection Considerations —

In order to determine if a project is a candidate for CPR, then select the best CPR alternative, an agency must look at all relevant information systematically. The information desired includes existing pavement data; initial cost; anticipated maintenance; future rehabilitation requirements; anticipated serviceability; experience; and constructability. Of these, the most important to the pavement engineer is the existing pavement data. The existing pavement data tells the engineer which distresses are present, then helps assess why the distresses developed. The pavement data can be grouped into the following categories: [3]

1. Design Data
2. Construction Data
3. Traffic Data
4. Environmental Data
5. Previous CPR Activities
6. Pavement Condition

Design Data — The primary design information for the existing pavement. It includes the pavement type and thickness, layer materials and strengths, joint design, shoulder design, drainage system design, etc.

Construction Data — Details about the conditions during construction can give insight and may highlight some event or problem that may be the cause the distress.

Traffic Data — Past, current, and expected traffic growth figures help determine the pavement's remaining structural capacity. Knowing the remaining structural capacity may limit the number of options.

Environmental Data — Precipitation, temperature, and freeze-thaw cycles will indicate the drainage adequacy and material durability of the pavement system.

Previous CPR Activities — Along with regular maintenance activities, previous CPR activities can help show the rate of deterioration as well as indicate distresses that may develop. They also allude to how well CPR will work.

Pavement Condition — The condition of the pavement and underlying layers are the most important data needed by the pavement engineer. They tell whether or not CPR can be used to repair the pavement.

After the pavement engineer has all the pavement data, he or she must answer four questions:

1. Which distresses are present?
2. What caused the distresses to develop?
3. What are the viable solutions to correct the distresses in the pavement or prevent their return?
4. Is the timing appropriate for these solutions to be effective and economical?

Applying the proper techniques or procedures for the pavement condition at the proper time is essential for good CPR performance.

Distress Identification and Determination

The best way to identify pavement distresses and determine why they developed is to perform a site-condition survey once a year, preferably in the early spring. The survey should identify the type, severity, and quantity of each distress. It should also try to determine whether the pavement design, applied load, water, temperature, pavement materials, or construction caused the distress. In addition to the visual survey, destructive and nondestructive testing can be used to determine the structural condition and material properties below the pavement surface. Appendix A provides more information on performing condition surveys.

The two goals of the condition survey and the structural assessment testing are to determine the root cause of the pavement's distress and to track the rate of pavement deterioration. Knowing the root cause of the pavement's distress helps determine which CPR techniques are appropriate. Knowing the rate of pavement deterioration helps determine whether a pavement is a good candidate for CPR, or if another rehabilitation technique is more appropriate.

An agency can also use the condition survey to change design or construction practices for new pavements. Changing poor design- or construction-practices may prevent similar distresses in newer pavements. Finally, the condition survey can serve as the basis for a "CPR - Area Management" contract. More information on CPR - Area Management is presented later in this publication.

Distress Classification —

All distresses are either structural or functional. Structural distresses primarily affect the pavement's ability to carry traffic. Cracking and joint deterioration are typical structural distresses. Functional distresses mainly affect the ride quality and safety of the pavement. Some functional distresses are roughness, noise, and surface polishing.[12]

Structural Distresses

Cracks — Any unplanned longitudinal, transverse, corner, or intersecting crack that extends through the depth of a slab is considered a structural crack (Figure 2). Some causes of structural cracking are loading, long joint-spacing, shallow or late joint sawing, base or edge restraint, and joint lock-up. In jointed plain (JPCP) and jointed reinforced* (JRCP) concrete pavements, proper joint design, along with proper construction practices and timely joint sawing,

* In JRCP, the joint spacing is purposely increased, and reinforcing steel is used within the pavement, to hold the mid-panel cracks that develop together. If there is enough distributed steel within the pavement (between 0.10 to 0.25% per cross-sectional area), these mid-panel cracks do not detract from the pavement's performance.[14] However, if there is not enough steel, it can corrode or rupture, and the cracks can start to move and deteriorate.

can eliminate most of this cracking. Pumping of the subbase/subgrade; curling and warping of the slab; or culvert or utility trench subsidence can also cause cracking. For more information on joint designs and sawing procedures, see ACPA publications *Design and Construction Joints for Concrete Highways (TB010P)*[13] and *Design and Construction Joints for Concrete Streets (IS061P)*.[14]

Corner breaks and intersecting cracks indicate that a slab has marginal support (Figure 3). Marginal support develops when heavy loads cause large vertical deflections at the slab edges or corners, and pump fines from beneath the slab. Other causes include curling and warping of the slab because of temperature and moisture gradients; heaving and swelling of frost- or moisture-susceptible soils; and settling of backfill over culverts or underground utility structures.

Cracks that remain tight (hairline), such as plastic shrinkage cracks, do not require any special treatment, sealing, or repair. Many hairline cracks remain very tight and only extend into the slab about 25-50 mm (1-2 in.). These cracks do not allow water to penetrate the pavement substructure and rarely deteriorate or influence the pavement's serviceability.[16]

Joint and Crack Deterioration — Spalling, breaking, cracking, chipping, or fraying of the slab edges are the main types of joint and crack deterioration. They usually occur within 50 mm (2 in.) of joints and cracks (Figure 4).[17] Deterioration starts when incompressibles enter and become lodged in the joints or cracks during cool weather. As the temperature rises, the slabs expand and the joints or cracks try to close; however, the incompressibles keep the joint or crack from closing. This creates high compressive stresses at the joint or crack face that cause it to spall. As the face spalls, it deposits more incompressibles into the joint or crack causing further deterioration. In extreme cases, very high compressive stresses can cause pavement migration and "blowups" or "buckling."

Other contributors to joint deterioration include poor joint sealant maintenance, improper installation or poor maintenance of metal or plastic inserts, high reinforcing steel, subbase-pumping, dowel-socketing, and keyway failure. These are design or construction errors that create locally weak areas that spall easily. In airport pavements, joint and crack deterioration can be espe-

Figure 2: Cracked slabs with low deterioration.

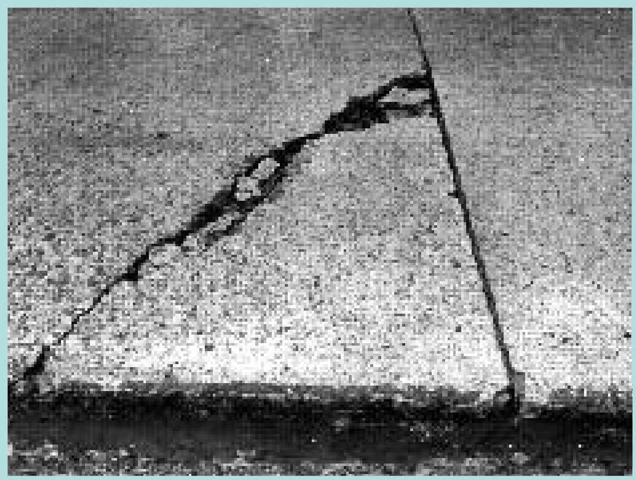

Figure 3: Slab with corner crack.

Figure 4: Slab with moderate deterioration.

cially serious because loose particles may cause foreign object damage (FOD) to jet aircraft engines.

Punchouts — Punchouts are the main distress in continuously reinforced concrete pavements (CRCP). They occur between two closely spaced cracks or at transverse cracks that split into a Y at the longitudinal edge or joint (Figure 5). They develop when high deflections at the pavement edge or longitudinal joint pump subbase material from beneath the slab and cause a loss of support. Further loading creates a cantilever action, which eventually ruptures the longitudinal steel at the crack faces. Continued loading punches the small segment of concrete — no longer with adequate load transfer — into the subbase and causes a punchout.[17,18]

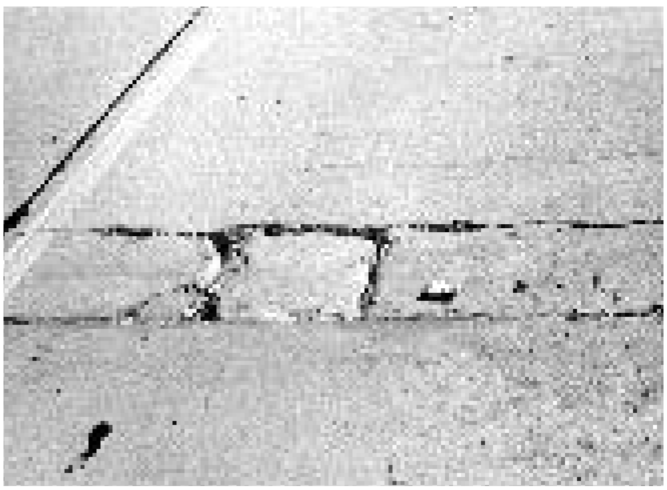

Figure 5: Punchout on a CRCP.

Durability Distresses — These are mainly concrete material problems, such as D-cracking, alkali-silica reactivity (ASR), and freeze-thaw damage. D-cracking is the closely-spaced crescent or D-shaped hairline cracks that occur near joints, cracks, and free edges when certain aggregates in a concrete mixture become saturated, freeze, and expand. This aggregate expansion causes the surrounding concrete matrix to crack.[19]

ASR typically produces a "map-cracking" type pattern with the predominant cracks oriented parallel to the slab-free edges. 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.[19.20]

Freeze-thaw damage occurs in a concrete that has a poor entrained-air system. Entrained air is a system of microscopic air bubbles in the concrete that protects it as it freezes. If the volume and spacing of the air bubbles is not adequate, the concrete matrix deteriorates and cracks when it freezes. Normal concretes should have 4.5% to 7.5% entrained air.[19]

Functional Distresses

Roughness — Faulting is the main cause of roughness. Faulting is the difference in elevation between slabs at joints or cracks[17] (Figure 6). It starts when a heavy truck crosses a joint with poor load transfer.* This induces high deflections at the slab corners and pumps the support material from under the slab (Figure 7) or moves it from one side of the joint to the other. Joints with good load transfer deflect less, which reduces the pumping of the support material and minimizes faulting.

Figure 6: Faulted joint.

* Load transfer is a slab's ability to transfer part of its load to its neighboring slab. A slab with 100% load transfer shares its load (deflection and stress) equally with its neighboring slab. A slab with 0% load transfer shares none of its load. Generally, pavements with poor load transfer have high corner deflections.

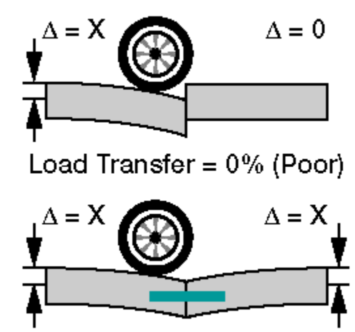

Figure 7: Pumping action due to heavy wheel load.

Roughness can also be built into a pavement during construction or subsequent maintenance operations. However, modern paving equipment and new smoothness specifications, and proper CPR maintenance techniques, have minimized construction and maintenance roughness. Two other sources of roughness are heaving/swelling of frost- or moisture-susceptible soils and settlement over culverts or underground utilities.

Surface Polishing — Surface polishing is the wearing away of the surface texture to expose the concrete coarse aggregate on heavily trafficked pavements. It leaves the surface smooth to the touch and reduces the pavement's skid resistance and surface friction capabilities. Surface polishing can be a safety problem if water cannot escape from beneath tires during wet weather.[4]

Noise — Noise is defined as "unwanted sound" or "sound that is undesired by the recipient."[21] For pavements, it is typically described as a high-pitched "whine." The main source of this "whine" is the surface/tire interaction that develops when the vehicle speed exceeds 55 km/h (35 mph) on pavements with uniformly spaced transverse tining. Surface/tire interaction, and therefore noise, is affected most by the surface texture.[21]

Surface Defects — Examples of surface defects are scaling, popouts, crazing, and plastic shrinkage cracking. Scaling is generally caused by overworking the surface; popouts are due to reactive or absorptive aggregates; and crazing and plastic shrinkage cracking are usually the result of poor curing conditions. Although visually unappealing, these distresses are usually limited to the surface and do not affect the pavement structurally. However, they may affect the pavement's ride and noise characteristics.[22]

Tables 3(A) and (B) summarize the above information.

Concrete Pavement Restoration Techniques

CPR techniques fall into two general categories: corrective activities and preventive activities. Corrective activities repair a given distress and improve the serviceability of the pavement. Full-depth repair and partial-depth repair are corrective activities. Preventive activities are proactive activities that slow or prevent the occurrence of a distress in order to keep the serviceability high. Joint and crack resealing, retrofitting concrete shoulders, and retrofitting edge drains are preventive techniques. Diamond grinding, dowel-bar retrofit, slab stabilization, cross-stitching and grooving can act as both corrective and preventive techniques.

Corrective CPR Techniques —

Full-Depth Repairs — Full-depth repairs (FDRs) fix cracked slabs and joint deterioration by removing at least a portion of the existing slab and replacing it with new concrete. This maintains the structural integrity of the existing slab and pavement. FDRs also repair shattered slabs, corner breaks, punchouts in CRCP, and some low-severity durability problems.

Figure 8 shows the placement of a FDR. It involves marking the distressed concrete, saw cutting around the perimeter, removing the old concrete, providing

Figure 8: Placing concrete during full-depth repair.

Table 3(A) Structural Distresses and Possible Contributing Factors						
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 concrete 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.*

load transfer, and placing new concrete. Each repair must be large enough to replace all significant distress and resist rocking under traffic, yet small enough to minimize the patching material. Typically, patch areas that are full-lane wide and at least a half-lane long meet this requirement. For more information on full-depth repairs, see ACPA publication *Guidelines for Full-Depth Repair (TB002P).*[23]

Partial-Depth Repairs — Partial-depth repairs (PDRs) correct surface distress and joint/crack deterioration in the upper third of the concrete slab. When the deterioration is greater than one-third the slab depth or contacts embedded steel, a full-depth repair must be used instead. Placing a PDR involves removing the deteriorated concrete, cleaning the patch area, placing new concrete, and reforming the joint system. For more information on partial-depth repairs, see ACPA publication *Guidelines for Partial-Depth Repair (TB003P).*[24]

Preventive CPR Techniques —

Joint and Crack Resealing — Joint and crack resealing minimizes the infiltration of surface water and incompressible material into the joint system. Minimizing water infiltration reduces subgrade softening; slows pumping and erosion of subgrade or subbase fines; and may limit dowel-bar corrosion caused by deicing chemicals. Minimizing incompressibles

Table 3(B) Functional Distresses and Possible Contributing Factors						
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, soft coarse aggregate, studded tires or chain wear.						
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.*

reduces the potential for spalling and blow-ups. Joint sealing also can maintain small sliver spalls that can develop into larger spalls if left alone.

It is especially critical to reseal the joint along the pavement/shoulder edge. Most of the surface water that enters the pavement system does so at the lane/shoulder longitudinal joints. For more information on joint and crack resealing, see ACPA publication *Joint and Crack Sealing and Repair for Concrete Pavements (TB012P).*[25]

Retrofitting Concrete Shoulders — Retrofitting concrete shoulders adds a tied concrete shoulder to an existing pavement. It is similar to dowel-bar retrofit because it decreases the critical edge stresses and corner deflections and reduces the potential for transverse cracking, pumping, and faulting. On CRCP, retrofit concrete shoulders can decrease the outside pavement edge deflection and cantilever action, which reduces the potential for punchouts. For retrofit concrete shoulders to be effective, good design and construction practices are essential.

Retrofitting Edge Drains — Adding a longitudinal drainage system to a pavement aids in the rapid removal of water and may prevent pumping, faulting, and durability distress from developing. Despite these potential advantages, the placement of retrofit edge drains must be considered carefully. For some pavements built on fine grained subgrade soils, the addition of edge drains has accelerated the loss of fines from the underneath the pavement. Retrofitting edge drains may not be suitable on distressed pavements that have been in service for more than 10 years and have a silty or clayey subgrade soil.[26]

Corrective and Preventive CPR Techniques —

Diamond Grinding — Diamond grinding improves a pavement's ride by creating a smooth, uniform profile by removing faulting, slab warping, studded tire wear, and patching unevenness (Figure 9). This extends the pavement's service life by reducing impact loadings, which can accelerate cracking and pumping.(27,28)

Diamond grinding's corduroy-like texture also decreases undesirable noise, improves skid resistance, and corrects poor drainage caused by inadequate slope. Correcting skid resistance and drainage reduces the pavement's hydroplaning potential. For more information on diamond grinding, see ACPA publication *Diamond Grinding and Concrete Pavement Restoration 2000 (TB008P).*(4)

Dowel-Bar Retrofit — Dowel-bar retrofit increases the load transfer efficiency at transverse cracks and joints in JPCP and JRCP pavements by linking the slabs together so the load is distributed evenly across the joint.(29) Improving the load transfer increases the pavement's structural capacity and reduces the potential for faulting by decreasing the stresses and deflections in the pavement. Dowel-bar retrofit consists of cutting slots in the pavement across the joint or crack, removing the concrete cleaning the slot, placing the dowel bars, and backfilling the slots with new concrete (Figure 10). For more information on dowel-bar retrofit, see ACPA publications *Dowel Retrofit Restores Pavement Load Transfer (RP335P)*(30) and *Concrete Pavement Rehabilitation Guide for Load Transfer Restoration (JP001P).*(31)

Slab Stabilization — Slab stabilization restores support to concrete slabs by filling small voids that develop underneath the concrete slab at joints, cracks, or the pavement edge (Figure 11). The voids, often not much deeper than 3 mm (1/8 in.), are caused by pumping or consolidation of the subgrade from high corner deflections. Without proper support, the pavement may develop faulting, corner breaks, and extensive cracking. This procedure is sensitive to construction practices, so care must be taken when performing slab stabilization. For more information on slab stabilization, see ACPA publication *Slab Stabilization Guidelines for Concrete Pavements (TB018P).*(32)

Figure 9: Diamond-ground surface.

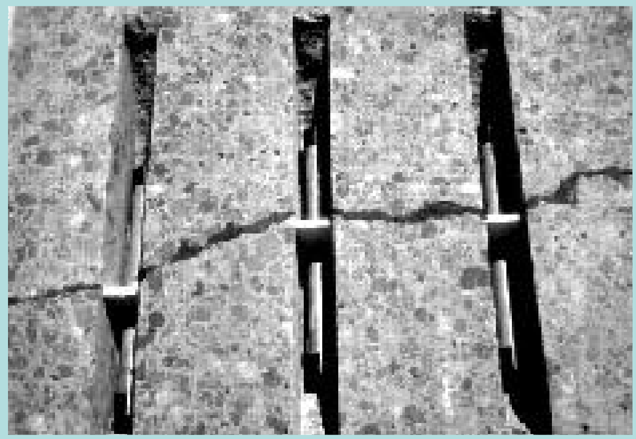

Figure 10: Repairing crack with dowel-bar retrofit.

Figure 11: Slab stabilization.

Cross-stitching — Cross-stitching repairs longitudinal cracks that are in fair (low-severity) condition. It increases load transfer at the crack by adding steel reinforcement to hold the crack together tightly. This limits the crack's horizontal and vertical movement and prevents it from widening.

Cross-stitching is not an alternative for cracks that are severely deteriorated or functioning as a joint. At severely deteriorated cracks, there is too much deterioration to re-establish effective load transfer. Cross-stitching transverse cracks that are functioning as joints may restrain the pavement and may cause a new transverse crack to form. In these cases, dowel-bar retrofit is a better CPR technique. For more information on cross-stitching, see ACPA publication *Joint and Crack Sealing and Repair for Concrete Pavements (TB012P).*[25]

Grooving — Grooving restores skid resistance to concrete pavements. It increases the surface friction and surface drainage capabilities of a pavement by creating small longitudinal or transverse channels that drain water from underneath the tire, reducing the hydroplaning potential.

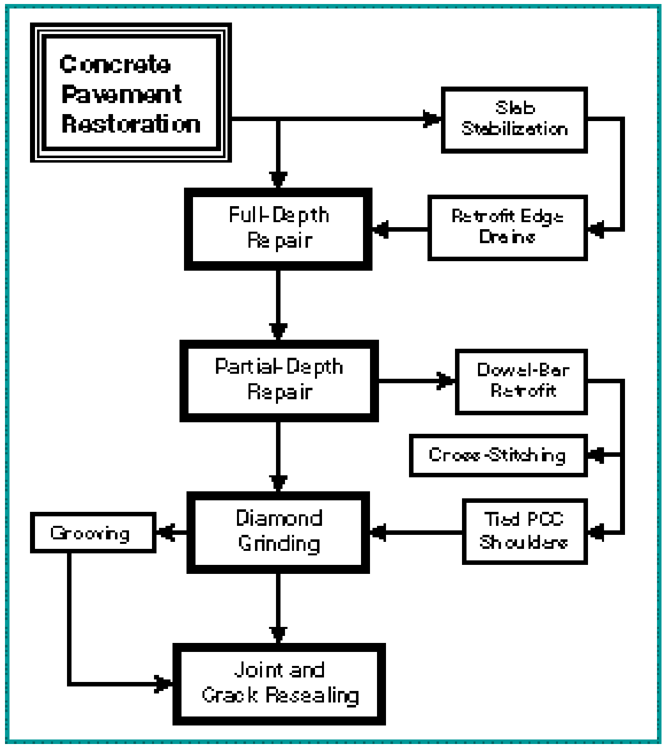

Figure 13: Sequence of CPR techniques. Not all projects will require every procedure, but the sequence should be maintained. The most common procedures are in double boxes.

Relating CPR Techniques to Pavement Distress —

Properly relating the available CPR techniques for the distress or combination of distresses on each project is essential for a good CPR program. Fortunately, knowing the distresses and their root causes narrows the choice of viable solutions substantially. Table 4 and Figure 12 (page 13) show the appropriate CPR techniques for each distress.

In some cases, more than one CPR technique may be applicable, but depending upon the condition of the distress, one technique may be more suitable than another. For example, transverse cracks that are "working cracks" can be sealed early, which helps them perform for many years. Later, it may be necessary to restore pavement integrity with dowel-bar retrofit or full-depth repair if the cracks develop severe spalling, pumping, or faulting.

Sequencing Activities

The sequence of work is very important in a total CPR project (Figure 13).[27,33] Slab stabilization and retrofit edge drains should precede full and partial depth repairs. Full- and partial-depth repairs, dowel-bar retrofit, retrofit concrete shoulders, and cross-stitching must precede diamond grinding. Grooving and resealing joints follow grinding to ensure proper groove- and sealant- depth.

Durability Problems —

Durability problems, such as D-cracking and ASR, are extremely difficult, if not impossible, to repair with CPR. If the rate of deterioration is very slow, full-depth repairs may be used. However, if the rate of deterioration is not slow, another rehabilitation method, such as an unbonded overlay or complete reconstruction will be necessary. Likewise, not many preventive techniques stop the development of durability problems. Joint and crack resealing may slow the development as long as the concrete is sound enough to create a reservoir for the sealant.

Recently, some agencies have tried experimental procedures and materials, such as sealing with high molecular weight methacrylate (HMWM) and lithium, to slow the development of some durability problems. Currently, there is no information to indicate whether these experimental techniques have proven successful.[34]

Table 4: Pavement Distress and Related Repair / Preventive		
Structural Distress	***Repair Techniques***	***Preventive Techniques***
Cracking		
Transverse	Full-Depth Repair Dowel-Bar Retrofit	Joint and Crack Resealing Dowel-Bar Retrofit
Longitudinal	Full-Depth Repair Cross-Stitching Dowel-Bar Retrofit	Joint and Crack Resealing Cross-Stitching Dowel-Bar Retrofit Slab Stabilization
Corner	Full-Depth Repair	Edge Joint Resealing Slab Stabilization
Intersecting	Full-Depth Repair	Cross-Stitching Dowel-Bar Retrofit Slab Stabilization
Joint/Crack Deterioration		
Spalling	Partial-Depth Repair	Joint and Crack Resealing Full-Depth Repair
Pumping	Slab Stabilization Full-Depth Repair Dowel-Bar Retrofit Retrofit Concrete Shoulders	Joint and Crack Resealing Dowel-Bar Retrofit Retrofit Concrete Shoulders
Blow ups	Full-Depth Repairs	Joint and Crack Resealing
Punchouts (CRCP)	Full-Depth Repair	Slab Stabilization Retrofit Concrete Shoulders
Durability *		
D-cracking	HMWM **	Joint and Crack Resealing HMWM **
ASR	HMWM ** Lithium **	Joint and Crack Resealing HMWM ** Lithium **
Freeze-thaw damage		Joint and Crack Resealing
Functional Distress		
Roughness		
Faulting	Diamond Grinding	Dowel-Bar Retrofit Slab Stabilization Joint and Crack Resealing Retrofit Edge Drains Retrofit Concrete Shoulders
Surface	Diamond Grinding	
Heave / Swell	Diamond Grinding	Joint and Crack Resealing
Settlement	Diamond Grinding	
Patch Deterioration	Full-Depth Repair Diamond Grinding	Joint and Crack Resealing
Surface Polishing	Diamond Grinding Grooving	
Noise	Diamond Grinding	Diamond Grinding
Surface Defects		
Scaling	Diamond Grinding	
Popouts	Diamond Grinding	
Crazing	Diamond Grinding	
Plastic Shrinkage Cracks	Diamond Grinding	HMWM **

* *CPR is generally not a reliable rehabilitation strategy for pavements with durability problems*

** *Experimental procedures currently being evaluated (HMWM = High-molecular weight methacrylate)*

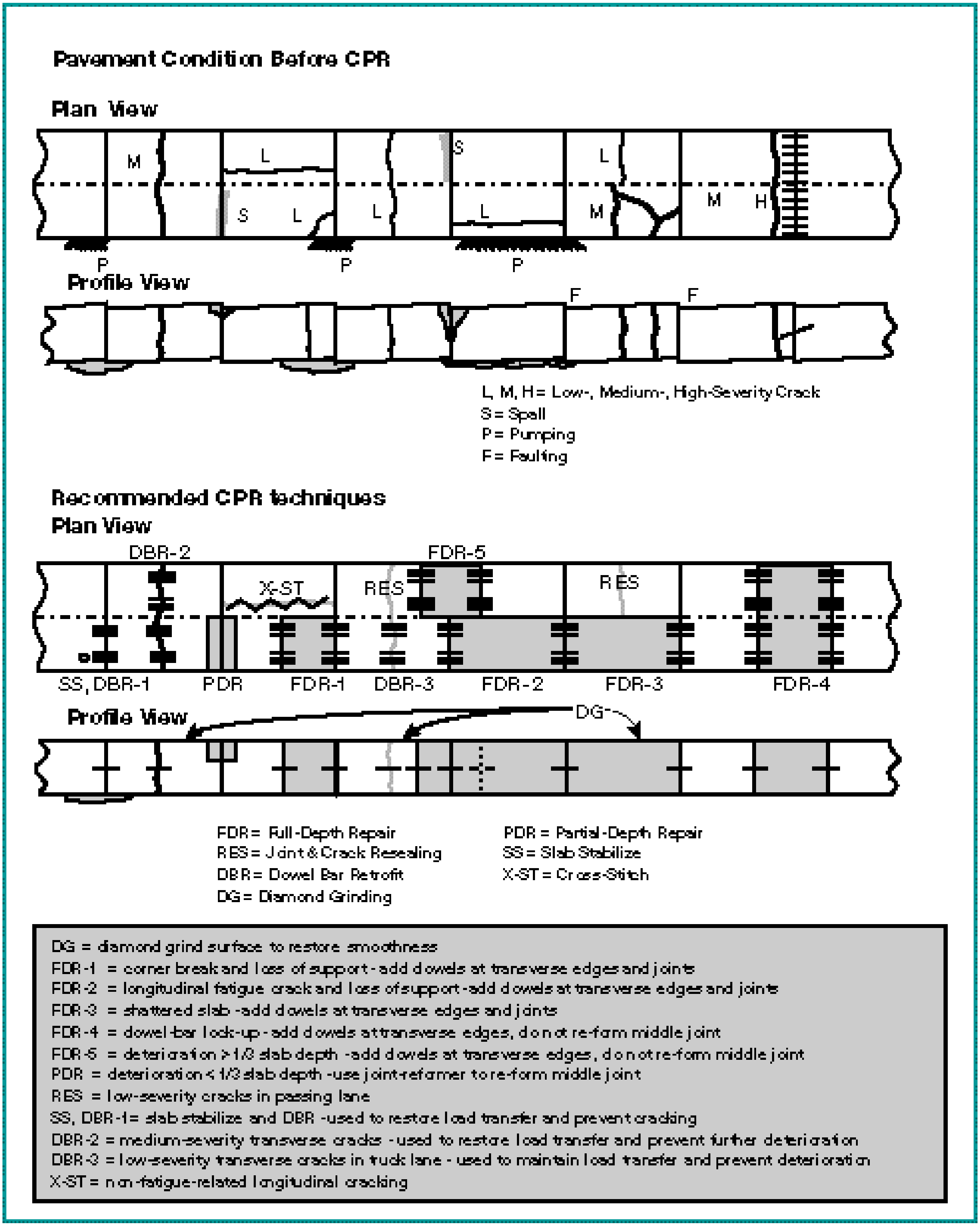

Figure 12: Pavement Distress and Related Repair/Preventive Techniques.

Timing CPR Activities

Determining the appropriate time for CPR is a question of both engineering and economics. Performing CPR too early repairs the distressed areas, but may not produce a significant improvement. Likewise, performing CPR too late may yield a substantial improvement, but at a high cost. Furthermore, the CPR may not perform because the pavement is too deteriorated.

In most cases, CPR is effective and economical when the pavement has only slight deterioration. Repairing the pavement when it shows only slight deterioration slows the rate of deterioration, repairs only those specific areas that are causing problems, and decreases the amount of distress to be repaired later. To determine if a pavement is at this point, an agency can use their annual pavement-condition survey and the "Windows of Opportunity" concept.

Windows of Opportunity —

"Windows of Opportunity" describes the time frame when CPR techniques can be applied so that repairs will perform effectively and economically. The concept uses trigger and limit values to define the opportunity window.

Trigger values define the point when a certain distress or a combination of distresses start to make CPR viable and appropriate. In other words, trigger values open the window. Limit values define the point when the pavement has deteriorated so much that CPR is not likely to be effective. These values close the window. Between the trigger and limit values, the window of opportunity is open and CPR is likely to be effective and economical.[3]

Trigger Values and Limit Values

Trigger and limit values can be based on the structural and/or functional condition of the pavement. Structural-based values define the window of opportunity using distress or performance criteria. Functional trigger and limit values are based on ride quality.

The distresses used to define the structural trigger and limit values are cracking, deteriorated joints, corner breaks, faulting, durability distress, and CRCP failures. Additionally each distress is further broken down by its quantity and severity. The performance criteria used to determine structural trigger and limit values are joint seal damage, load transfer, and skid resistance. The structural-based trigger and limit values are useful because they direct the engineer to appropriate CPR techniques.

The ride-quality indicators used to define the functional-based trigger and limit values are the International Roughness Index (IRI), the Present Serviceability Rating (PSR), and the Profile Index (California profilograph). Functional-based trigger and limit values are useful because they tell when the pavement section has reached some unacceptable condition because of a combination of distresses, even though no distress trigger and limit values have been reached. Functional-based trigger and limit values can also be used to compare different pavement types or rehabilitation alternatives.

Tables 5-7 provide reasonable trigger and limit values for JPCP, JRCP, and CRCP respectively, when no information is available. However, because performance will vary with local traffic and environment conditions, each agency should develop trigger and limit values to reflect their local experience.

Besides being broken down by structural and functional values, Tables 5-7 are further divided into separate values for different traffic volumes (and indirectly, roadway classifcation). This is allows pavements carrying less, or slower, traffic to sustain more damage before being repaired.

The values in Tables 5-7 are set-up so that they can be easily merged into a pavement management system. Furthermore, because all the distress values are in percentages, the same trigger and limit values apply to airports, industrial lots, and large parking areas.

It is recommended that an agency use both the structural- and functional-based trigger and limit values to determine the timing for CPR activites. The functional based values show that a pavement has reached some unacceptable level, but do not tell why it has reached that level. The structural-based values are needed to tell why the pavement has deteriorated and to show what distresses are present.[3]

It is important to realize that these limit values approximate the maximum practical amount of CPR to perform at one time. It is possible to restore a pavement several times and have the actual percentage of pavement repaired be much greater than these limit values.

Table 5: Trigger and Limit Values for Jointed Plain Concrete Pavements

	Jointed Plain Concrete Pavements (Joint Space < 6 m.)*		
	Trigger / Limit Values**		
Traffic Volumes	High (ADT>10,000)	Medium (3000<ADT<10,000)	Low (ADT<3000)
Structural Measurements			
Low to High Severity Fatigue Cracking (% of slabs)	1.5 / 5.0	2.0 / 10.0	2.5 / 15.0
Deteriorated Joints (% of joints)	1.5 / 15.0	2.0 / 17.5	2.5 / 20.0
Corner Breaks (% of joints)	1.0 / 8.0	1.5 / 10.0	2.0 / 12.0
Faulting (avg. - mm)	2.0 / 12.0	2.0 / 15.0	2.0 / 18.0
Durability Distress (severity)		Medium-High	
Joint Seal Damage (% of joints)		> 25 / —-	
Load Transfer (%)		<50 / —-	
Skid Resistance	Minimum Local Acceptable Level / —-		
Functional Measurement			
IRI (m/km)	1.0 / 2.5	1.2 / 3.0	1.4 / 3.5
PSR	3.8 / 3.0	3.6 / 2.5	3.4 / 2.0
California Profilograph	12 / 60	15 / 80	18 / 100

* *Assumed slab length = 4.5 m.*

** *Values should be adjusted for local conditions. Actual percentage repaired may be much higher if the pavement is restored several times.*

Table 6: Trigger and Limit Values for Jointed Reinforced Concrete Pavements

	Jointed Reinforced Concrete Pavements (Joint Space > 6 m.)*		
	Trigger / Limit**		
Traffic Volumes	High (ADT>10,000)	Medium (3000<ADT<10,000)	Low (ADT<3000)
Structural Measurements			
Medium to High Severity Transverse Cracking (% of slabs)	2.0 / 30.0	3.0 / 40.0	4.0 / 50.0
Deteriorated Joints (% of joints)	2.0 / 10.0	3.0 / 20.0	4.0 / 30.0
Corner Breaks (% of joints)	1.0 / 10.0	2.0 / 20.0	3.0 / 30.0
Faulting (avg. - mm)	4.0 / 12.0	4.0 / 15.0	4.0 /18.0
Durability Distress (severity)	Medium-High		
Joint Seal Damage (% of joints)	> 25 / —-		
Load Transfer (%)	<50 / —-		
Skid Resistance	Minimum Local Acceptable Level / —-		
Functional Measurement			
IRI (m/km)	1.0 / 2.5	1.2 / 3.0	1.4 / 3.5
PSR	3.8 / 3.0	3.6 / 2.5	3.4 / 2.0
California Profilograph	12 / 60	15 / 80	18 / 100

* *Assumed slab length = 10.0 m.*

** *Values should be adjusted for local conditions. Actual percentage of total pavement repaired may be much higher than these limit values if restored several times.*

Table 7: Trigger and Limit Values for Continuously Reinforced Concrete Pavements

	Continuously Reinforced Concrete Pavements		
	Trigger / Limit**		
Traffic Volumes	High (ADT>10,000)	Medium (3000<ADT<10,000)	Low (ADT<3000)
Structural Measurements			
Failures (Punchouts and Full-depth Repairs) (No./km)	2 / 6	3 / 15	4 / 24
Durability Distress (severity)	Medium-High		
Skid Resistance	Minimum Local Acceptable Level / —-		
Functional Measurement			
IRI (m/km)	1.0 / 2.5	1.2 / 3.0	1.4 / 3.5
PSR	3.8 / 3.0	3.6 / 2.5	3.4 / 2.0
California Profilograph	12 / 60	15 / 80	18 / 100

** *Values should be adjusted for local conditions. Actual number of total repairs may be much higher than these limit values if restored several times.*

Additionally an agency must realize is that the actual field quantities may be greater than the quantities specified on plans. This is because the pavement continues to deteriorate between the time of the distress survey and the time of repair. Agencies should try to take this into account when developing plans.

Finally, once a pavement passes its CPR opportunity window and deteriorates into a poorer condition, other rehabilitation procedures—such as a concrete overlay or reconstruction—become better alternatives (See Figure 1).

Strategies for an Effective CPR Program

The key to an effective CPR program is commitment to the program. This first involves developing personnel with an understanding and knowledge of CPR. Secondly, it entails designating appropriate CPR funding levels. The consequences of poorly trained personnel or inadequate funding are that expertise or money are not available to apply CPR effectively or appropriately.

Inadequate funding and training can also force an agency to select another rehabilitation strategy based on policies that use the same standard repair for every pavement. Unfortunately, applying the same standard rehabilitation techniques to every situation is neither rational nor economical. The rehabilitation often is under-designed and has poor performance, or over-designed and not cost-effective.
Once an agency commits to a CPR program, balancing proper rehabilitation strategies with available funds becomes a significant challenge. Ideally, each agency would develop a preventive preservation program, both short and long term, with separate, designated funding. This strategy will help an agency apply CPR while it is the most viable option and within its CPR window of opportunity.

Retrofit Smoothness —

One technique that has been very successful in increasing the quality of new pavements is monetary incentives. Incentives encourage quality and develop a sensitivity toward teamwork. They reward excellence and encourage contractors to go beyond typical specification requirements during pavement construction.

Furthermore, the Texas Transportation Institute has found that incentives lead to less costly pavements.[35] Incentives help the quality-sensitive contractor by providing a competitive edge. The quality contractor can, and frequently does, lower the bid value to win the contract, with the aim of receiving the incentive to offset costs. Overall, incentives result in improved pavements that can carry more loads and provide better service to the public.

Based on this success, several states have investigated using incentives for CPR. Most often, the incentive has been based on a percentage of the diamond grinding construction cost — similar to new construction. For new construction, where typical costs are $20 - $30 per square meter, this is reasonable. However, for diamond grinding, where prices are in the range $2-3 per square meter, the same percentage does not cover the additional effort necessary to produce the improved result. For this reason, an additive incentive is preferable to a percentage-based incentive. An additive incentive is an addition to the contract price when the results exceed the specified standard.

Equations 1 and 2* give recommended additive incentive values for a typical retrofit smoothness specification using the 5 mm (0.2 in.) blanking band.** Equation 1 is for pavements with a posted speed greater than 70 km/hr (45 mph). Equation 2 is for pavements with posted speeds less than 70 km/hr (45 mph).

1. Inc. = $ 0.25 x (4 - PI)
2. Inc. = $ 0.15 x (7 - PI)

Where:

Inc. = Incentive in dollars

PI = Profile Index obtained after grinding each section

For agencies using the zero blanking band, Mays Meter, Rainhardt Profilograph, or some other smoothness evaluation equipment, different values are necessary. When setting the incentive, it should be set so that it is obtainable and covers the extra effort expended by the contractor. As a rule, there should be one set of incentive values for pavements with a posted speed greater 70 km/h (45 mph) and another set of values for pavements with posted speeds less than 70 km/h (45 mph).

Isolated sections with a pre-existing settlement problem, such as a roadway over a culvert or utility, or a bridge approach, will prevent a correction to the specified profile. These areas should require that the final profile have at least a 70% improvement, without any consideration for incentive.

* Based on additive retrofit smoothness incentive used in Minnesota and South Dakota. [36,37]

** A typical specified profile index for pavements with posted speeds greater than 70 km/hr (45 mph) is 5-7 per 0.1 mile test section. Pavements with posted speeds less than 70 km/hr (45 mph) typically have specified profile index of 7-10 per 0.1 mile test section.

If any of the completed work does not meet the minimum specified profile index, the work is unacceptable and the contractor must re-grind.

CPR - Area Management —

"CPR - Area Management" is a multiyear contract between a highway or airport agency and a contractor to repair and manage pavement deterioration. The agency contracts for very broad CPR quantities, certain traffic-control windows, and distress surveys. The contractor commits to specific unit prices based on broad quantities, without exact areas or items marked on the pavement or plans.

After the contract award, the agency and contractor jointly conduct a detailed distress survey and agree on the specific repairs for that year. After determining the amount of work, the contractor develops a site-specific work plan and traffic-control scheme. Finally, the agency issues a work order to begin work. The sequence is repeated in successive years.

There are several advantages of the CPR - Area Management contract for both the agency and the contractor. For the agency, some advantages are:

- Fewer contracts.
- Shorter delay's between design and construction.
- More contractor input on constructability issues.
- Fewer claims for overruns and unforeseen conditions.
- Less need to develop and maintain in-house maintenance expertise.

For the contractor, the advantages include:

- Better working relationship with specifying agency.
- Better up-front understanding of the distress survey and repair decisions.
- More flexibility in determining exact construction times.
- Ability to expand or use other professional expertise by contracting with engineering firms for distress surveys.

Performance of an Effective CPR Program

One agency with an extremely successfully CPR program is the Georgia Department of Transportation (GaDOT). The GaDOT has adopted the philosophy that it is better to manage pavement deterioration than to wait until the pavement condition worsens. Essentially for the GaDOT, the question is not when to use CPR, but when not to use CPR.[2,5]

Georgia started its CPR program in the early- to mid-1970s when it noticed that its concrete pavements were starting to crack, fault, pump, and spall. Before 1974, many states were using full- and partial-depth repairs, joint resealing, retrofit edge drains, and diamond grinding individually — but typically not together — to repair their roadways. Between 1974 and 1978, the GaDOT combined these techniques to create a comprehensive program to manage its concrete pavements.[2,5]

Georgia continues to use its CPR program extensively and it has extended the lives of their concrete roadways considerably. One such example is Interstate-475. Originally designed to carry 5 million Equivalent Single Axle Loads (ESALs), I-475 has been restored three times and has carried more than 45 million ESALs, or nine times its design life.

Another recent example is around Atlanta where GaDOT used CPR on approximately 500 lane miles to smooth and extend the concrete pavements for the 1996 Summer Olympics.[2,5]

Overall, CPR has been very beneficial for Georgia. In addition to adding life to its older pavements, GaDOT has used its experiences from CPR to change its standard designs. This has eliminated many of the early distresses experienced on older concrete pavements. However, the biggest benefit is in the condition of their roadways. For the last two years, Georgia has had the smoothest concrete roads in the United States.[2,5]

SUMMARY

Concrete Pavement Restoration is an engineered procedure to manage the rate of pavement deterioration in concrete streets, highways, and airports. Appropriate and timely CPR maintains a concrete pavement in a smooth, safe, and quiet condition and extends its service life. On average, agencies using preventative maintenance for concrete pavements can expect an increase of life of 9-10 years.[1]

Some of the advantages of CPR are:

- It repairs isolated areas of deterioration and reduces the pavement roughness and impact loadings.
- It repairs only the portion of the pavement that needs improvement. This makes it a quick and cost effective operation that causes only minimal traffic disruption.
- It restores the pavement close to its original condition, which reduces the need for major pavement repair.
- It prevents or slows the recurrence of distress development, which keeps the pavement in an acceptable condition longer and extends its traffic-carrying capability.

Furthermore, appropriate and timely CPR lowers the pavement's annual costs to both the agency and the users. Besides costing sometimes as little as 1/3 the cost of other equivalent rehabilitation techniques, each $1 invested in appropriately timed preventative maintenance saves $3 to $4 in future rehabilitation costs.[1] Consequently CPR should be the first response to a deteriorating concrete pavement.

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Appendix A

Distress Survey - Assessment Methods

Pavement Surface Condition —

Windshield Visual Survey — Concrete pavement distress is rated and counted from inside a vehicle that is traveling down the road or along the shoulder. This method can produce a good overall rating of the pavement in question, but determining accurate patching quantities is very difficult. This method can also result in safety or congestion problems in high traffic volume areas.

Manual Visual Survey — Concrete pavement distress is rated and counted by a survey team while walking in either a closed lane or along the shoulder of the road. This method can produce accurate ratings and quantity estimates. If this survey is performed in conjunction with a sounding survey (i.e., chain drag or hammer testing), even more accurate estimates of the patching quantities can be made. This method may also cause safety or congestion problems in high traffic areas.

Automated Visual Survey — Concrete pavement distresses are automatically recorded on video tape or other media, as a vehicle travels along the road at approximately the posted speed. These distresses are then interpreted and identified at office workstations. This method can produce the same results as the Manual Visual Survey method while minimizing the possibility of safety or congestion problems in high traffic areas.

Joint Faulting —

Subjective Estimates — Subjective estimates are made based on the rideability of the pavement, "thumping" of the joints, and visual appearance in rear view mirror as the vehicle travels over the pavement. This method can help determine the presence of joint faulting, but seldom produces accurate enough estimates for CPR type determinations.

Manual Measurement (Straightedge) — A survey team walks down the road and measures joint faulting with a straightedge and ruler. This method produces accurate results but is difficult to perform — and may cause congestion problems — in high traffic areas.

Manual Measurement (Faultmeter) — A survey team walks down the road and measures joint faulting with an automated faultmeter. Typically every seventh to tenth joint (depending on spacing) is measured. This method is more accurate and less time-consuming than the straightedge method; however it still may cause congestion problems in high traffic areas.

Automated Measurement — A vehicle equipped with electronic sensors travels along the road at approximately the posted speed and records the profile of the road. From this profile an algorithm (based on joint spacing) is used to estimate the amount of joint faulting without causing congestion problems in high traffic areas.

Roughness or Rideability —

The roughness or rideability of a pavement section can also greatly influence the type of CPR selected. Roughness is the best representation of the public's perception of the pavement. There are several methods used to measure roughness:

Subjective Estimates — A subjective estimate of the pavement roughness is made based on the perceived ride quality of the pavement as the vehicle travels down the road. This method was used at the AASHTO Road Test and provides a present serviceability rating (PSR) of the roadway surface.

Walking Profilograph Survey — A survey team walks or pushes a profilograph down the road and the profile is recorded. The profile is then interpreted either on site by computer, in the office by computer, or manually. This method can produce very accurate roughness measurements; however, it is time consuming and may cause congestion in high traffic areas.

Automated Profile Survey — A vehicle equipped with electronic sensors travels along the road at the approximate posted speed and records the profile of the road. From this profile, the roughness is automatically calculated. This can produce very accurate measurements and minimizes the possibility of safety or congestion problems in high traffic areas.

Structural Capacity —

Joint faulting and stains from pumping are visual indicators of voids beneath the pavement and/or poor load transfer efficiency. Pavement deflection tests are helpful in estimating the need and bid item quantities for undersealing and/or load transfer retrofit.

Benkelman Beam — A narrow beam is located on the outside shoulder of the road with dial gages near the edge on the outside lane of pavement on either side of the joint. A single axle truck (or a dual axle with front wheels removed) is loaded to 18,000 lb. and stopped one foot before the joint and one foot beyond the joint. Deflection readings are recorded for both the loaded and unloaded slab with the truck wheels in each position. Measurements should be taken when the slab is cool, usually late night or early morning. The deflection is an indication of slab curl, while the difference in deflection is an indication of load transfer and/or voids beneath the forward slab. This method is time consuming and can cause congestion problems in high traffic areas.

Falling Weight Deflectometer (FWD) — A vehicle towing the FWD trailer travels down the road and stops briefly to test at selected locations. The FWD is equipped with several weights that can be raised and dropped from predetermined heights onto a load plate to impact the pavement. The shape of the resulting deflection basin is measured and recorded by a series of deflection sensors located various distances from the load plate. This information is analyzed in the office and produces very accurate information that can assist in determining CPR requirements. This method is relatively quick, easy to perform, and only short term safety or congestion problems should be expected with the proper traffic control.

Metric Conversion Factors

The following table provides metric conversion factors for common English units used in pavement engineering, as well as concrete pavement design and construction. Where possible the values given reflect standard conversions provided by ASTM E 380.

FOR	IF YOU KNOW	MULTIPLY BY	TO GET METRIC UNIT
Angle	degree of curvature	0.0175	radians, (rad)
Area	square inch, (in≤)	645.16	square millimeter, (mm≤)
Area	square feet, (ft≤)	0.093	square meter, (m≤)
Area	square yard, (yd≤)	0.836	square meter, (m≤)
Area	square mile, (mi2)	2.59	square kilometer, (km2)
Area (land)	Acre, (acre)	4046.9	square meter, (m≤)
Density (material)	pounds/cubic foot, (lb/ft≥)	16.02	kilograms/cubic meter, (kg/m≥)
Flow	cubic feet/second, (ft≥/s)	0.028	cubic meter per second, (m≥/s)
Flow (liquid)	gallon/minute, (gal/min)	6.31x10-5	cubic meter per second, (m≥/s)
Flow (liquid)	gallon/minute, (gal/min)	0.063	liter/second, (L/s)
Force	kips (1000 lb), (KIP)	4448.2	newtons, (N)
Horizontal curvature	feet, (ft)	0.3048	meters, (m) round to 5 m
Length	inches, (in)	25.4	millimeters, (mm)
Length	feet, (ft)	0.3048	meters, (m)
Length	mile (U.S.), (mi)	1609.35	meter, (m)
Length	yard, (yd)	0.914	meter, (m)
Mass	pounds, (lb)	0.454	kilograms, (kg)
Mass	ton (U.S. 2000 lb), (ton)	907.2	kilogram, (kg)
Power (engine)	horsepower, (hp)	0.7457	kilowatt, (kW)
Rideability	inches/mile, (in/mile)	15.783	millimeter/kilometer, (mm/km)
Stress (pressure)	pounds/square inch, (psi)	0.00689	megapascals, (MPa)
Subgrade support, k	pounds/square inch/inch, (psi/in)	0.27	megapascals/meter, (MPa/m)
Temperature	degree Fahrenheit, (∫F)	use: t∫C = (t∫F - 32)/1.8	degree Celsius, (∫C)
Velocity (speed)	miles/hour, (mph)	1.61	kilometer/hour, (km/h)
Viscosity	poise	0.10	Pascal second, (Pa∑s)
Volume	ounces, (oz)	29.57	milliliters, (mL)
Volume (liquid)	gallon, (gal)	3.785	liter, (L)
Volume	cubic feet, (ft3)	0.028	cubic meter, (m3)
Volume	cubic yards, (yd3)	0.765	cubic meter, (m3)
Volume, (admixture)	ounces/cubic yard, (oz/yd≥)	22.61	milliliter/cubic meter, (mL/m≥)
Volume, (admixture)	ounces/100 weight (lbs) cement, (oz/100 cwt)	0.015	milliliter/100 kilograms cement, (mL/100 kgc)

The table below provides equivalent metric factors for common U.S. factors in concrete pavement engineering.

Survey station 100 ft	Survey station 1 km
Bag of Cement 94 lb	Bag of Cement (Canadian) 40 kg

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