

Draft Report

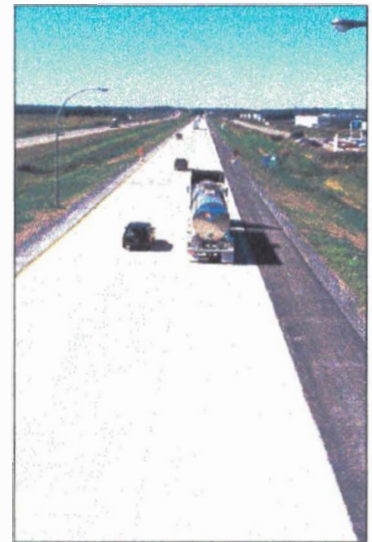
**Interim Report I
Literature Review**

**Development of Portland
Cement Concrete Pavement
Restoration Techniques for
Oklahoma**

ODOT Project Number 2133

Submitted to

**Oklahoma Department of Transportation
Oklahoma City, Oklahoma**



June 1997

Submitted by

ERES
CONSULTANTS, INC.

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16. Abstract Interim Report I presents the results of an in-depth literature review focusing on PCC pavement restoration techniques. Included in the report are general notes on full-depth repairs, partial-depth repairs, diamond grinding and grooving, slab stabilization, load transfer restoration, joint and crack sealing, shoulder restoration, and drainage restoration. Current construction practices as well as an overview of ODOT guidelines and specifications and those of surrounding states are presented.					
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DISCLAIMER

The opinions and conclusions expressed or implied in this report are those of the contractor who is responsible for the facts and accuracy of the data presented herein. The contents do not necessarily reflect the official views or policies of the Oklahoma Department of Transportation. This report does not constitute a standard, specification, or regulation.

REPORT PREPARATION

This project is being conducted under the supervision of Dr. Michael Ayers and Dr. Michael Darter. Other project team members contributing to this report include Joanna Ambrose, Tim Smith, Todd Hoerner, Kelly Smith, Robin Jones, Elizabeth Crow, and Jennifer Miller.

Interim Report I is submitted in draft form and will be continually upgraded over the three year project duration. The information presented in this report includes current practices which are subject to change as new materials, equipment or techniques become available.

METRIC (SI*) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
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LENGTH

in	inches	2.54	millimetres	mm
ft	feet	0.3048	metres	m
yd	yards	0.914	metres	m
mi	miles	1.61	kilometres	km

AREA

in ²	square inches	645.2	millimetres squared	mm ²
ft ²	square feet	0.0929	metres squared	m ²
yd ²	square yards	0.836	metres squared	m ²
mi ²	square miles	2.59	kilometres squared	km ²
ac	acres	0.395	hectares	ha

MASS (weight)

oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams	Mg

VOLUME

fl oz	fluid ounces	29.57	millilitres	mL
gal	gallons	3.785	litres	L
ft ³	cubic feet	0.0328	metres cubed	m ³
yd ³	cubic yards	0.0765	metres cubed	m ³

NOTE: Volumes greater than 1000 L shall be shown in m³.

TEMPERATURE (exact)

°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C
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APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
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LENGTH

mm	millimetres	0.039	inches	in
m	metres	3.28	feet	ft
m	metres	1.09	yards	yd
km	kilometres	0.621	miles	mi

AREA

mm ²	millimetres squared	0.0016	square inches	in ²
m ²	metres squared	10.764	square feet	ft ²
km ²	kilometres squared	0.39	square miles	mi ²
ha	hectares (10 000 m ²)	2.53	acres	ac

MASS (weight)

g	grams	0.0353	ounces	oz
kg	kilograms	2.205	pounds	lb
Mg	megagrams (1 000 kg)	1.103	short tons	T

VOLUME

mL	millilitres	0.034	fluid ounces	fl oz
L	litres	0.264	gallons	gal
m ³	metres cubed	35.315	cubic feet	ft ³
m ³	metres cubed	1.358	cubic yards	yd ³

TEMPERATURE (exact)

°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F
-40	-40		-40	-40
0	0		32	32
100	100		212	212

These factors conform to the requirement of FHWA Order 5190.1A.

* SI is the symbol for the International System of Measurements

Development of Portland Cement Concrete Pavement Restoration Techniques for Oklahoma

Interim Report I Literature Review Draft

ODOT Project Number 2133

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1. INTRODUCTION

Within the past decade, the emphasis on highway pavements has shifted from new construction towards maintenance, rehabilitation, and restoration of existing pavements. With the majority of the interstate and primary/secondary highway system constructed, highway officials are examining alternatives to extend the life of existing pavements. In addition, a decrease in state and federal funding for highways has encouraged the individual state departments of transportation to find the most cost-effective solutions to pavement deterioration. Many states are closely examining the benefits of maintenance, rehabilitation, and restoration tailored specifically to their highway system.

A majority of state and federal highway officials believe that timely restoration is the key to maximizing pavement design life or extending the pavement service life beyond the initial design interval. Restoration refers to the work performed on existing pavements to either restore serviceability or prepare them for an overlay. These techniques may be used to extend the service life of existing pavements or to prevent premature failure of overlays placed on badly deteriorated pavements. The Oklahoma Department of Transportation (ODOT) has contracted with ERES Consultants, Inc. to determine the most cost-effective and long-lasting portland cement concrete (PCC) restoration techniques applicable to Oklahoma.

PCC pavements are subject to load and environmentally induced distresses, material degradation, loss of support, and myriad other factors, resulting in a need for cost-effective restoration/repair. There are numerous references pertaining to restoration techniques for PCC pavements. Application of any of the widely recommended techniques will result in at least partial success or, stated differently, a restoration project with tolerable cost and performance. The fundamental problem associated with the use of generalized techniques is that the recommendations are seldom the most cost-effective or long-lasting for a given region.

Restoration techniques for PCC pavements are highly variable in terms of cost and performance. The suitability of a restoration technique or repair must be based on functional and economic concerns, either or both of which are often difficult to assess adequately. Clearly defined guidelines are often lacking in determining the most appropriate restoration technique and the proper method of construction.

ODOT has monitored PCC pavement restoration test sections for a number of years. However, specific guidelines and implementation strategies, based on highly detailed evaluation and analysis, have not yet been developed. The 1990 ODOT report entitled *Concrete Pavement Restoration in Oklahoma*⁽¹⁾, by Senkowski and Ooten, summarizes the performance of eight restoration techniques monitored on three restoration projects. The results indicate that restoration procedures are a cost-effective means to restore ride quality and the structural integrity of concrete pavements. The current study addresses which restoration procedure results in the lowest life cycle cost for a specific distress type while providing the highest level of performance. In addition, the trigger or threshold

value for initiating the restoration process, the proper construction techniques, and selection of the appropriate materials will be established.

Interim Report I summarizes the results of an extensive literature review focusing on PCC pavement restoration techniques. The literature review includes the following restoration types:

- Full-depth repair.
- Partial-depth repair.
- Diamond grinding and grooving.
- Slab stabilization.
- Joint and crack sealing.
- Load transfer restoration.
- Shoulder restoration.
- Drainage restoration.

State-of-the-art design and construction methods, benefits of the individual restoration methods, a summary of restoration techniques currently employed by neighboring state DOTs, and an overview of current ODOT restoration practices are included for each restoration technique.

2. GENERAL LITERATURE REVIEW

An in-depth literature review was conducted to determine the state-of-the-art practices for the PCC restoration methods listed above. A Technical Reference Information Service (TRIS) database search was used to identify past and current research in PCC restoration techniques. The summary information presented includes both the TRIS-identified references and internal ERES project documentation. The following synthesis is intended to provide brief background information on the techniques.

Full-Depth Repair

Full-depth repairs (FDRs) are placed at deteriorated joints and cracks in concrete pavements to restore rideability, repair isolated structural defects, prevent further deterioration of distressed areas, or prepare the pavement for an overlay. Full-depth repairs are cast-in-place repairs that extend the full depth of the existing slab and are typically a minimum of 6 ft (1.8 m) long and full lane-width wide. It should be noted that it is generally more cost-effective to replace an entire slab if a significant portion is highly distressed.

Full-depth PCC repairs can be designed and constructed to provide excellent long-term performance (10 or more years), although the performance of full-depth concrete repairs on in-service pavements has been inconsistent.^(2,3) The short-term post-construction results of a major PCC pavement rehabilitation project in Ontario showed that the integrity and continuity of the overall pavement structure was improved by full-depth repairs.⁽⁴⁾

The major causes of premature failure of full-depth repairs have been inadequate design, unsuitability of FDRs for the type of distress, and poor construction quality. The severity and extent of the overall deterioration of the pavement will determine whether the full-depth repairs will be cost-effective. The actual construction of full-depth repairs must be carefully controlled through appropriate specifications, guidelines, and construction/inspection practices.

The major considerations in successfully implementing full-depth repairs are as follows:

- Selection of FDR as the most appropriate technique for a given distress.
- Joint design, particularly load transfer.
- Selection of repair locations and boundaries.
- Preparation of repair area.
- PCC placement and finishing.
- Joint sealing.
- Curing and opening to traffic.

The primary design factors influencing the performance of full-depth repairs are the level of load transfer and the repair dimensions required to prevent faulting or rocking, given a specific climatic zone, traffic level, and foundation type. Examination of 5-years of

pavement distress surveys on I-90 in Wisconsin resulted in the following observations about FDRs:

- The full-lane width FDRs where load transfer was provided, either by dowel bars or undercutting, had the best performance.
- The partial-lane width FDRs had higher faulting, deterioration, and failure rates. Approximately 95 percent of the partial-lane-width patches failed due to cracking, settling, and faulting.⁽⁵⁾

Analysis of numerous FDRs in the midwest (pavements with poor drainage conditions and granular bases) has shown that faulting of full-depth repair joints after 10 years will, on average, exceed 0.2 in (5 mm) if 100 or more commercial trucks use the traffic lane each day.⁽⁶⁾ Transverse joint faulting that exceeds 0.2 in (5 mm) is noticeable to drivers.⁽⁷⁾ The faulting potential of FDRs is significantly influenced by climatic conditions, pavement structure, and the design/construction aspects of the FDRs.

In general, the use of mechanical load transfer devices is strongly recommended, because they provide better performance (less faulting, rocking, and other joint-related distresses) than other means of load transfer.^(2,8-12) The FHWA has determined that the only load transfer system that consistently provides acceptable performance is dowel bars with a minimum diameter of 1.25 in (32 mm).⁽¹²⁾ Recent information suggests that virtually all full-depth repairs currently being placed are constructed with dowels.⁽¹³⁾

The major factors in determining the cost effectiveness of FDRs are the identification of specific distresses suited to the technique and selection of the repair boundaries. The repair boundaries are usually determined during the initial distress survey. Structural testing (deflection testing and coring) provides information on the extent of deterioration in the distressed areas. Repair boundaries must be large enough to include all slab and foundation deterioration, but not so large as to unnecessarily increase repair costs. Larger, highly distressed areas should be identified separately since complete removal and replacement of the slab is generally the most cost-effective option under these circumstances.

The following is a list of jointed concrete pavement (JCP) distresses that may warrant full-depth repairs:

- Blowup.
- Corner break.
- Spalling due to D-cracking.
- Deterioration adjacent to existing repairs.
- Deterioration of existing repairs.
- Reactive aggregate spalling.

The following distresses of continuously reinforced concrete pavement (CRCP) may warrant full-depth repairs:⁽³⁾

- Blowup.
- Punchout.
- Spalling due to D-cracking.
- Construction joint distress.
- Deterioration adjacent to an existing repair.
- Transverse crack deterioration (steel rupture).
- Deterioration of an existing repair.
- Localized distress.

Proper construction methods and selection of appropriate materials are critical to the performance of FDRs. PCC removal that causes damage to the surrounding concrete and the support layers will result in rapid deterioration of the repair. Conventional concrete mixtures can be used, as can “fast track” materials for repairs that must be opened to traffic within a few hours.

Partial-Depth Repair

Partial-depth repairs (PDRs) extend the life of PCC pavements by restoring ride quality to pavements exhibiting spalled joints or other shallow distressed areas. PDRs also result in well-defined, uniform joint sealant reservoirs that facilitates joint resealing. When properly placed with durable materials, and combined with effective joint resealing, these repairs can perform well for many years.

Partial-depth repairs are an alternative to full-depth repairs in areas where slab deterioration is located primarily in the upper one-third of the slab and where the existing load transfer devices (if any) are still functional. PDRs should not be constructed in areas where the reinforcing or temperature steel is placed too near the slab surface, the joint spalls are due to misaligned dowels, or where D-cracking or reactive aggregates are a problem.⁽¹⁴⁾ The most common use of PDRs is at joints that become filled with incompressibles during colder portions of the year, and then experience very high point contact stresses as the slabs expand and the joints attempt to close during warmer periods.

When applied at appropriate locations, PDRs can be more cost-effective than full-depth repairs (e.g., when replacing an entire joint to address minor spalling). The cost of partial-depth repairs is largely dependent on the size, number, and location of the repair areas, as well as the materials used. In general, as the number of PDRs on a project increases, the cost per repair falls. Isolated repairs tend to be more expensive than concentrated repairs, and the materials suited to PDRs vary widely in performance and cost.

The major considerations in successfully implementing partial-depth repairs are as follows:

- Selection of PDR as the most appropriate technique for a given distress.
- Selection of repair locations and boundaries.
- Preparation of repair area.

- PCC or proprietary material placement and finishing.
- Joint sealing.
- Curing and opening to traffic.

A comprehensive survey of partial-depth repairs throughout the U.S. found a wide range of performance: many partial-depth repairs were performing well after 8 to 10 years of service, whereas others were exhibiting poor performance in a relatively short time.⁽³⁾ The results of a study conducted on a heavily traveled toll road where several thousand partial-depth repairs had been installed showed that over 80 percent of the repairs were in excellent condition after 5 years of service.⁽¹⁵⁾ It should be noted that inspection and quality control were very stringent on this job.

Generally, the performance of PDRs has been unsatisfactory on projects where quality control and inspection were lacking. Approximately 50 percent of partial-depth repairs failed within 2 years under these circumstances.⁽¹⁶⁾ The most frequent causes of failure include inappropriate use (when deterioration is too deep), lack of bond, compression failure of the patch (due to failure to re-establish the joint), variability of repair material effectiveness, improper use of repair materials, insufficient consolidation, and incompatibility in thermal expansion between the repair material and the original slab.

One study comparing 11 repair materials and 3 preparation techniques concluded that the most important factor affecting performance was squaring of the patch boundaries, because few of the materials could be feathered and held in place.⁽¹⁷⁾ A later study reviewing PDR construction methods and performance noted that most failures resulted from the improper construction and placement techniques, and not from material deficiencies.⁽¹⁸⁾

A wide variety of materials are suitable for use in a partial-depth repair. Material selection depends on available curing time, ambient temperature, cost, size and depth of the repairs, and so on. Increased user costs and the safety hazards to motorists and maintenance crews often necessitate the use of fast-track materials, particularly in high traffic areas. A wide variety of rapid-setting and high-early strength proprietary materials have been developed. Material costs, mechanical properties, workability, and performance vary greatly between the different repair materials.^(19,20)

Arizona reported overall success with partial-depth repairs at the conclusion of a 6-year study. Five different patching materials were evaluated and showed an average failure rate of 2.4 percent overall.⁽²¹⁾ However, Georgia reported that partial depth repairs had a 50 percent failure rate within 2 years. The failures were attributed primarily to point bearing stress build-up and were remedied by using a compressible insert to form a joint that extended 1 inch below and 1 inch beyond the patch. Following this modification to Georgia's standard PDR procedure, the failure rate fell to less than 10 percent after 2 years of service.⁽²²⁾

Partial-depth repairs cannot accommodate the movement of working joints and cracks, load transfer devices, or reinforcing steel without experiencing high stresses and material damage or failure. Thus, they are appropriate only for certain types of distresses that are confined to the top few inches of the slab. Distresses that have been successfully corrected with partial-depth repairs include the following:

- Spalls caused by the use of joint inserts.
- Spalls caused by intrusion of incompressible materials into the joints (typically associated with long reinforced slabs).
- Spalls caused by localized areas of scaling, weak concrete, clay balls, or improperly located temperature steel.

The need for PDRs should be evaluated whenever joint resealing is planned for a project. Effective joint sealing requires repair of spalled joints and establishment of a uniform joint sealant reservoir. On comprehensive concrete pavement restoration projects, partial-depth repairs should be completed after any undersealing or slab jacking, but prior to diamond grinding and joint sealing.

Diamond Grinding and Grooving

Diamond grinding and grooving are used to correct a variety of surface distresses, improve ride quality, and enhance safety. However, diamond grinding or grooving does not add or restore structural capacity to a pavement. These techniques address only surface deficiencies and are commonly used in conjunction with other concrete pavement restoration (CPR) techniques as part of a comprehensive pavement restoration program.

The primary objectives of diamond grinding and grooving are to produce a smooth pavement surface and restore surface texture. A smooth pavement reduces user costs and enhances safety. In addition, smooth roads generally last longer and perform better than rough roads because of the reduced dynamic or impact loads. The magnitude of dynamic loading is in direct proportion to the smoothness of the road and the weight of the vehicle. Consequently, the worst case scenario is a heavy vehicle on a rough pavement. Dynamic loading will cause more rapid deterioration and increased roughness, which will result in a shorter life span for the road.⁽²³⁾ “Diamond grinding has always been a successful CPR procedure for Georgia. Since 1976, Georgia has tightened up the riding quality specification for diamond grinding five times.”⁽²²⁾

The longevity of PCC pavements can be extended by the application of selected CPR techniques including diamond grinding.⁽²³⁾ One study concluded that diamond grinding can extend pavement life by at least 5 years when used alone, and by 10 or more years when used in conjunction with other techniques.⁽²⁴⁾ It should be noted that service life depends on many factors, such as traffic volume (ESALs), pavement design factors (subsurface drainage, joint spacing, base type, subgrade soil type, type of shoulder, and so on), joint sealant effectiveness, climate (freezing index, precipitation), condition of

pavement at the time of restoration, CPR (additional concurrent work), and performance of the existing load transfer system.⁽²⁵⁾

Grooving and grinding have evolved into cost-effective methods for restoring skid resistance and improving ride quality. More than half of the state DOTs have used or are planning to use diamond grinding to correct roughness on either existing or newly constructed pavements. Diamond grooving has proven to reduce wet weather accidents by reducing hydroplaning potential.

Diamond Grinding

Diamond grinding involves the removal of hardened PCC through the use of closely-spaced diamond saw blades. A number of equipment manufacturers have developed diamond grinding equipment that is both efficient and cost effective. These machines can be operated at very close tolerances, thereby promoting a smooth pavement with the desired surface texture.

Diamond grinding was first used in California during 1965 on a 19-year old section of I-10 to eliminate significant faulting.⁽²⁶⁾ In 1983, additional concrete pavement restoration (CPR) was performed on the same pavement, including the use of additional grinding to restore rideability and skid resistance. This project is significant because it was the forerunner of future reconditioning projects on concrete roads and runways throughout the United States, as well as the rest of the world.⁽²⁷⁾ This CPR project included not only diamond grinding, but also slab replacement, spall repair, and installation of edge drains. Since its inception in 1965, the use of diamond grinding has become a major element of PCC restoration projects.

Diamond grinding is a viable option for the following distress types:

- Removal of transverse joint and crack faulting.
- Removal of wheelpath rutting caused by studded tire wear.
- Removal of permanent slab warping at joints (in very dry climates where significant warping has occurred).
- Texturing of a polished concrete surface exhibiting inadequate macrotexture.
- Improvement of transverse slope to improve surface drainage.

The most common use of diamond grinding is to improve rideability through the removal of faulting. A typical vehicle operator can discern faulting of 0.2 in (5 mm) and feels a level of discomfort as faulting approaches 0.25 in (6.4 mm). The International Grooving and Grinding Association (IGGA) and the American Concrete Pavement Association (ACPA) recommend the following guidelines to determine the need for diamond grinding to remove joint and crack faulting:^(25,28)

- If the present serviceability index drops within a range of 3.8 to 4.0, a thorough evaluation of the cause of this loss in serviceability should be conducted. After addressing any functional deficiencies, diamond grinding should be conducted to restore the serviceability to a higher level.
- Grinding should be conducted before faulting reaches critical levels. Such levels are dependent upon many factors, not the least of which is joint spacing. Less faulting is tolerable for pavements with short joint spacings. The highway agencies should establish threshold values of faulting for various pavement configurations.

Georgia has developed an indicator called the faulting index that has proven useful in assessing the severity of faulting.^(2,3) This indicator, referred to as the faulting index value, is a numerical assessment in which a value of 5 represents 1/32 in (0.8 mm) of faulting. For example, a faulting index of 15 translates into average faulting of 3/32 in (2.4 mm). Establishment of appropriate threshold values for different pavement types can then be used to prioritize or schedule diamond grinding projects.

The need for diamond grinding should be based on pavement condition and roughness data. The most important factor in determining the cost-effectiveness of the repair strategy is a thorough evaluation of the collected pavement condition data.⁽²⁹⁾ Structural distress, such as pumping, loss of support, corner breaks, working transverse cracks, and shattered slabs will require repair before grinding is conducted. The presence of widespread distress related to concrete durability, such as D-cracking, reactive aggregate, or freeze-thaw damage, may indicate that diamond grinding is not a suitable restoration technique, and a more comprehensive rehabilitation approach needs to be considered.

The immediate effect of grinding is to provide a smooth pavement surface.⁽³⁰⁾ The pavement roughness after grinding is generally as good or better than what can be achieved during new construction. However, if the cause of the faulting is not treated prior to grinding, faulting will quickly reoccur.⁽²⁸⁾ In New York, the expected service life of grinding operations is only 5 years before faulting will again be a problem.⁽³¹⁾ A recent study of 76 grinding projects in 19 States found that after diamond grinding is performed, faulting tends to develop at an even faster rate than prior to diamond grinding.⁽³⁾ This tendency to fault at an accelerated rate may be offset by concurrent CPR work to improve load transfer, establish slab support, and reduce pumping.

Removal of depressions in the pavement is not cost-effective using diamond grinding. Significant depressions should be corrected by slab jacking prior to diamond grinding. Roughness measurements or longitudinal profiles along the project in each lane are excellent indicators of depressions and swells.

Pavement skid resistance is improved through diamond grinding by increasing the macrotexture of the PCC. The increased macrotexture initially provides high skid numbers, but this improvement may be temporary, particularly if the pavement contains aggregate susceptible to polishing.⁽³²⁾ This effect may be offset by properly spacing the diamond saw blades, creating more land area between the grooves.

Skid resistance is generally measured using either a standard ribbed tire (ASTM E 501) or a standard smooth tire (ASTM E 524). It is recommended that testing be conducted with the smooth tire, since the ribbed tire is not sensitive to the macrotexture improvements created by grinding.⁽³²⁾ Skid values typically decrease over the first few years after diamond grinding; however, an adequate macrotexture will normally be maintained for many years.⁽³³⁾

Minor changes in the pavement cross slope are also facilitated by diamond grinding. Proper cross slope facilitates transverse drainage and reduces the potential for hydroplaning, especially in cases where studded tire wear has produced ruts in the concrete pavement.

Diamond Grooving

Diamond grooving can be performed on both PCC and AC pavements. In this operation, grooves are cut into hardened PCC or AC using diamond saw blades with a center-to-center blade spacing of 0.74 in (18.8 mm) or greater. The equipment used for grooving is essentially the same as that used for diamond grinding. Diamond grooving of PCC pavements has been performed since the 1960s.

The primary objective of grooving is to reduce hydroplaning potential, which can lead to wet weather accidents. Documentation of the effects of grooving have shown a dramatic reduction in wet weather accidents.^(34,35) Grooving may be performed either transversely or longitudinally. Transverse grooving not only provides the most direct channel for drainage of water from the pavement, it also provides enhanced vehicle braking action. However, transverse grooving, although common on runways and bridge decks, is rarely used on highway pavements. This is due primarily to construction difficulties and increased tire noise. Longitudinal grooving has an advantage in that the penetration of the tires into the grooves apparently holds the vehicle in alignment with the roadway, helping the vehicle track around curves.^(35,36)

Slab Stabilization

Loss of support from beneath PCC pavement slabs has long been recognized as a major factor in accelerated deterioration (pumping, faulting, cracking). If significant pumping has occurred and slab support is lost, the pavement will rapidly deteriorate, particularly on heavily trafficked pavements. In many cases, slab stabilization is an effective restoration technique to restore lost support and prolong pavement life.

Slab stabilization has been performed for many years. However, within the past 10 years, these techniques have become highly specialized with improved materials and equipment. Although these methods are commonly used, there is some question as to the effectiveness of slab stabilization, with at least one agency currently maintaining a moratorium against the procedure.⁽³⁷⁾ Several recent studies concluded that slab stabilization results varied so dramatically that performance predictions could not be made with certainty.^(31,38-40)

A study conducted by the North Carolina DOT concluded the following:

- Slab stabilization may lead to increased distress in the slab in some cases. Filling the voids may result in increased temperature-related distress, uneven subgrade support, and differential deformation.
- Following the cracking of stabilized slabs, the rate of slab cracking decreased and followed the same pace as the unstabilized slabs.
- The stabilized slabs investigated had been subjected to poor support conditions for a period of time, which may have resulted in higher fatigue levels and, consequently, a shorter life expectancy.⁽⁴¹⁾

Slab stabilization should be performed only at joints and working cracks where loss of support is known to exist. Stabilizing slabs where loss of support does not exist is not warranted and may be detrimental to pavement performance.^(41,42) To be most effective, it is important that slab stabilization be performed prior to the onset of pavement damage due to loss of support.⁽⁴¹⁾

Deflection testing, in conjunction with visual surveys, is the most effective approach currently in use for locating and estimating the size of underslab voids. Some State agencies use a maximum corner deflection criterion to determine if a void is present. Georgia DOT, for example, uses a 0.025-in (0.64-mm) corner deflection induced by an 18,000 lb (80 kN) single-axle load. Corners that deflect more than this (as measured during the early morning) are considered to have a void, which may be addressed by slab stabilization. However, specifications based on a single corner deflection are not desirable or recommended because variation in load transfer from joint to joint can cause considerable variation in corner deflections.

When applying the corner deflection approach, it is important that similar equipment and loads are applied both during the evaluation phase and after the slab stabilization process. Determining void location and the effectiveness of the stabilization process are critical for long-term effectiveness. The primary weaknesses of this approach are that the size of the void is not determined and that the corner deflection is highly dependent upon the degree of joint load transfer.

A similar procedure uses the profile of both the approach and leave corner deflections.⁽²⁾ As voids first form under the leave corner, it is normal to find that the approach corner deflection is less than the leave corner deflection. If this difference is great, then the presence of a void is likely. The procedure recommends the identification of a reasonable approach corner deflection value above which slab stabilization is required.

Another void detection method is based on measuring the magnitude of the corner deflection at three different load levels. Typically, load levels of 6,000, 9,000, and 14,000 lb (26, 40, and 63 kN) are used to develop load versus deflection plots for each test location. A load versus deflection plot that does not pass through the origin indicates that a void likely exists at that location. Load versus deflection plots that pass through or near

the origin indicate that no loss of support exists. This method of void detection can be conducted concurrently with the stabilization operation, providing close coordination between the void detection and slab stabilization operations. However, because of variations in load transfer, it cannot be used to determine the size of the void.

When conducting a void analysis survey, it is important to assess the percentage of joints and cracks suffering loss of support. It has been found that this percentage can vary from 10 to 90 percent from one project to another. Visual evidence of pumping is directly related to the percentage of joints and cracks affected, with pavements suffering extensive pumping most likely to have the highest percentage of voids.⁽²⁾

The effectiveness of slab stabilization can be determined only by monitoring the subsequent performance of the pavement. The best early indication of the effectiveness is obtained by remeasuring the slab deflections after grouting and determining if the deflection has reduced to the point of full support. One agency determined the effectiveness of slab stabilization by repeating the deflection measurements after initial stabilization.⁽⁴³⁾ If the deflection under an 18,000 lb (80 kN) single-axle load was still in excess of 0.025 in (0.64 mm), the slab was regouted, with the assumption that the existing voids were not entirely filled, or additional voids were formed during the initial stabilization operation. This procedure was not repeated again. Other agencies use different deflection methodologies and may regout up to two times, after which the slab or section would be removed and replaced.

Several recent studies have shown that slab stabilization is an effective technique for filling voids.^(41,43,44) A study in Illinois showed that undersealing of CRCP with both cement grout and asphalt cement prior to the placement of an AC overlay was effective in reducing deflections and subsequent reflection cracking.⁽⁴⁴⁾ An Indiana study showed that slab stabilization using asphalt cement remained effective in restoring slab support after 3 years of service.⁽⁴³⁾ A North Carolina study concluded that slab stabilization was effective at restoring support when performed properly. However, that same study showed that the improper or unwarranted use of slab stabilization could result in slab cracking and the introduction of incompressibles into the joints.⁽⁴¹⁾

The material selected for slab stabilization must be able to penetrate into very thin voids and have sufficient strength and durability to withstand the imposed loads, moisture fluctuations, and temperature extremes. Asphalt cements have been used widely for slab stabilization, although they have been largely replaced by pozzolanic-cement grouts. However, Indiana has continued the use of asphalt stabilization with good results.^(45,46)

Joint and Crack Sealing

Joint and crack sealing are commonly performed pavement maintenance and restoration activities. The primary objective of joint and crack sealing is to reduce the amount of moisture that can infiltrate into the pavement, thereby reducing moisture-related

distresses. Free water entering a joint or crack can accumulate beneath the slab, causing distresses such as loss of support, faulting, and corner breaks.

A second objective of joint and crack sealing is to prevent the intrusion of incompressible materials so that pressure-related distresses (such as spalling) are prevented. Incompressible materials that infiltrate poorly sealed joints or cracks in PCC pavements interfere with normal opening and closing movements, thus creating compressive stresses in the slab and increasing the potential for spalling. If the compressive stress exceeds the compressive strength of the deteriorated pavement, blowups or buckling may occur. Even if blowups do not occur, continued intrusion of incompressibles may cause significant longitudinal expansion of the pavement. This expansion may result in movement of nearby bridge abutments, thereby necessitating expensive bridge rehabilitation.

It has been reported that sealants become ineffective from 1 to 4 years after placement.⁽⁴⁷⁾ However, recent improvements in sealant materials, an increased recognition of the importance of a proper reservoir design, and an emphasis on effective joint and crack preparation procedures are expected to increase the service life of sealant installations.⁽⁴⁸⁾ A 1985 summary of State experience with various rehabilitation techniques showed 45 States conduct joint and crack sealing operations on PCC pavements.⁽⁴⁹⁾

Sealing operations may be performed at both joints and cracks. Most sealing is conducted at transverse joints, although many times the longitudinal joints (lane-shoulder or lane-lane) are sealed simultaneously. Some agencies seal both transverse and longitudinal cracks that develop in their PCC pavements, provided that they are not excessively wide or deteriorated. The sealing of joints, particularly transverse joints, is generally regarded as a more elaborate operation than crack sealing, primarily because more careful preparation and higher quality sealants are needed to ensure good performance.

Critical sealant properties that significantly affect the performance of the sealant material include the following:

- Durability.
- Extensibility.
- Resilience.
- Adhesiveness.
- Cohesiveness.

Durability refers to the ability of the sealant to withstand the effects of traffic, moisture, ultraviolet exposure, and temperature variation. A sealant that is not durable will blister, harden, and crack in a relatively short time. If overbanded onto the pavement surface, a non-durable sealant may soften under higher temperatures and may wear away under traffic.

The extensibility of a sealant is the ability of the sealant to deform without rupturing. The more extensible the sealant is, the lower the internal stresses that might cause rupture

within the sealant or at the sealant-sidewall interface. Sealant extensibility is most important under cold conditions because maximum joint and crack openings occur in colder months. Softer, lower modulus sealants tend to be more extensible, but they may not be stiff enough to resist the intrusion of incompressibles during warmer temperatures.

Resilience refers to the sealant's ability to fully recover from deformation and to resist intrusion of incompressibles. In the case of thermoplastic sealants, however, resilience and resistance to incompressible intrusion are often sacrificed in order to obtain extensibility. Hence, a compromise is generally warranted, taking into consideration the expected joint or crack movement and the presence of incompressibles for specific climatic regions.

As a sealant material in a joint or crack is elongated, high stress levels can develop such that the sealant is separated from the sidewall (adhesive failure) or the material internally ruptures (cohesive failure). Sealant adhesiveness is one of the most important properties of a good sealant. However, cleanliness of the joint or crack sidewalls and proper preparation determines the sealant's bonding ability. Cohesive failures are more common in sealants that have hardened significantly over time.

Typically, higher quality sealants are specified for joint resealing operations than for crack sealing operations. However, it may be more cost-effective to use lower quality sealants in joints or cracks that experience little movement or that will be overlaid or otherwise rehabilitated in the near future.

There are a wide variety of sealants available, each with its own unique characteristics. The general categories used by the American Concrete Institute (ACI) to differentiate among sealing materials are as follows:⁽⁵⁰⁾

- Thermoplastic materials.
 - Hot-applied.
 - Cold-applied.
- Thermosetting materials.
 - Chemically cured.
 - Solvent release.
- Preformed compression seals.

Chemically cured sealants are the predominant type of thermosetting materials used in highway sealing applications. They include polysulfides, polyurethanes, silicones, and epoxies.

The performance of polysulfide and polyurethane sealants is varied. Although these materials seem to retain elasticity fairly well, their adhesive capabilities are questionable (particularly in the polysulfides). In addition, most of these materials are two-component materials, which introduces an additional step in the sealing operation, thereby increasing installation time.

Silicone sealants are one-part, cold-applied materials that have been used in the paving industry since the 1970s. Their properties include good extensibility, resistance to weathering, and low temperature susceptibility. These sealants have excellent bond strength in combination with a low modulus which allows them to be placed thinner than other types of sealants.⁽⁵¹⁾ Because of silicone's thin layer application and lower associated equipment costs, the ratio of in-place cost compared to rubberized asphalt is not nearly as high as the ratio of material costs (for a given volume).

Silicone sealants are available in self-leveling and non-self-leveling forms. The non-self-leveling silicone requires a separate tooling operation to press the sealant against the sidewall and to form a uniform recessed surface. Recently developed self-leveling silicone sealants can be placed in one step because they freely flow to fill the joint reservoir without tooling. Performance of silicone sealants is typically tied to joint cleanliness and tooling effectiveness. Many States, such as Georgia and Kentucky, have developed their own silicone specifications.

Preformed compression seals are premolded strips of styrene, urethane, neoprene, or other synthetic materials that are designed to be placed in PCC pavement joints under compression. Generally, these seals are designed to be compressed 20 to 50 percent of their uncompressed width. Thus, the opening for a joint sealed with a 1 in (25 mm) compression seal should remain between 0.5 and 0.8 in (13 and 20 mm). If the seal is too narrow or the joint opens excessively, the seal, not being in a compressed state, will fall to the bottom of the joint or be pulled out by traffic. If the seal is subjected to compression greater than the 50 percent level for extended periods of time, the seal may take a "compression set." Under these circumstances, the seal will not open to follow the movement of the joint, and the seal will no longer be effective.

Preformed sealants have a good history of performance when used with new PCC pavements; however, because of their expense and the need for vertical sidewalls, preformed compression seals are not commonly used on PCC pavement restoration projects. Standard specifications for preformed compression seals are found in AASHTO M 220 and ASTM D 2628.

Many sealant failures have been attributed to poor or inadequate preparation of the joint/crack and to poor material handling procedures.^(47,52-54) Proper preparation of the joint or crack is essential to ensure that the sealant material can effectively bond to the sidewalls. If dust, water, or other debris remains on the sidewalls, a good bond will not be achieved.

Many of the newer sealant materials are sensitive to application temperatures, and temperature ranges are being recommended by manufacturers.⁽⁵³⁾ The use of supplementary temperature monitoring devices is recommended so that the sealant temperature can be observed closely. Underheating of the material results in poor bonding, whereas overheating of the material destroys its ductile properties.⁽⁵³⁾

When determining the feasibility of PCC pavement resealing, the first priority is to establish the condition of the joints and cracks. If extensive deterioration is present, particularly moisture-related damage, joint resealing may not be warranted without additional CPR procedures.

In instances where the existing joints are in good condition but the sealant is deteriorating, joint resealing should be considered. Pertinent information necessary for planning the resealing operation includes the existing joint spacing, the pavement width, the presence of any working cracks, the existing sealant type, the existing sealant reservoir dimensions, present and future traffic levels, the pavement cross section, and the expected temperature ranges for the area. The presence of any areas of faulting that would require grinding prior to replacing sealant should also be noted.

Load Transfer Restoration

Load transfer restoration consists of retrofitting load transfer devices in jointed concrete pavements. The improved load transfer results in a reduction in deflections across transverse joints or cracks and a reduction in pavement deterioration due to joint pumping, faulting, spalling, and subsequent cracking. The ability of a joint or crack to transfer load from the approach side to the leave side is referred to as the load transfer efficiency (LTE). The LTE is a major factor in the structural performance of a joint or crack and has a profound effect on the smoothness and longevity of the overall pavement structure.

Load transfer restoration may be performed on existing jointed PCC pavements that exhibit poor load transfer across transverse joints or cracks. The most effective means of load transfer restoration is through the use of dowel bars placed in slots cut across the joint or crack, although other devices have been used with limited success. Deformed reinforcing bars can be placed in slots across cracks as well. The deformed bars do not allow longitudinal movement of the slabs as with dowels, but are none the less effective at limiting vertical movement. Load transfer restoration may be expected to increase pavement performance by reducing pumping and faulting and by reducing the number of corner breaks at joints and cracks.

Load transfer efficiency may be expressed as deflection load transfer or stress load transfer. Deflection load transfer is usually defined as the ratio of the deflection of the unloaded side to the deflection of the loaded side of a crack or joint. If complete load transfer exists, the ratio will be 1.00 (or 100 percent), and if no load transfer exists the ratio will be 0.00 (or 0 percent). Some agencies prefer to use the difference between the deflections of the loaded and unloaded slabs rather than the ratio of deflections.

Stress load transfer is defined as the ratio of the stress in the unloaded slab to the stress in the loaded slab (across the joint or crack). Stress load transfer and deflection load transfer are not linearly proportional and are related to the PCC slab properties (thickness, elastic modulus, and Poisson's ratio), subgrade support conditions, and the radius of the load plate used in the deflection testing.

Joints that are doweled during original pavement construction normally maintain adequate deflection load transfer (70 to 100 percent) if adequately sized, corrosion-resistant dowels are used. However, many non-doweled jointed plain concrete pavements have been constructed whose load transfer across the transverse joints is accomplished through aggregate interlock of the abutting joint faces. Aggregate interlock may provide adequate load transfer for a number of years after construction, particularly during hot weather when the joint is held tightly together. However, as the joint opens due to cooler temperature, aggregate interlock is lost and load transfer is greatly reduced. Depending on the size and type (crushed versus rounded) of aggregate used, openings as small as 0.01 in (0.25 mm) can result in reduction of load transfer efficiency. Transverse cracks in both jointed plain and reinforced concrete pavements (where steel has ruptured) also rely on aggregate interlock and may exhibit poor load transfer if the aggregate interlock is not maintained.

Load transfer restoration is recommended for all faulted transverse joints or cracks that exhibit poor deflection load transfer (approximately 0 to 50 percent) when measured in the early morning or in cooler weather.⁽²⁾ Heavy-load deflection testing devices capable of simulating slab bending caused by typical traffic loads, such as the Road Rater or the Falling Weight Deflectometer, should be used for measurements.

It is important that the LTE be measured during cooler temperatures (ambient temperatures less than 80°F (27°C) and during the early morning, when the joints will not be tightly closed. As the temperature rises, the joints close tightly and load transfer efficiency cannot be evaluated adequately. The LTE should be measured in the outer wheelpath, which is subject to the most heavy truck traffic wheel loads. Deflection measurements for the determination of LTE should be taken as close to the joint or crack as possible.

Slab bending effects must be considered in determining load transfer at the joint or crack. In addition to the LTE, the magnitude of the corner deflections should also be considered. It is possible for slab corners to exhibit very high deflections, yet still maintain a high LTE. In this case, even though the LTE is high, the large corner deflections can lead to pumping of the underlying base course material, faulting, and perhaps corner breaks. The corner deflections should be compared throughout a project to help determine if the typical corner deflection values become excessive.

The two most prevalent retrofitted load transfer devices are dowels and the double-vee device. Dowel bars placed in small slots (or kerfs) sawed into the pavement across joints have proven to be an effective method of load transfer restoration.^(2,3,55-57) Although round dowel bars are typically used, I-beams have also been used on some restoration projects in New York.⁽⁵⁸⁾ The dowels are installed in slots formed by multiple saw cuts. The concrete is removed using lightweight hammers or hand tools. A joint-forming medium is used the full depth of the cut to maintain the joint. One half of the dowel is coated with a debonding agent, or an expansion cap is provided on one end of the dowel, to allow for closure of the joint after the dowel bar is installed.

Retrofitted dowel bars generally have performed well.^(2,3) Results of one study show that dowels have performed well after 9 years of traffic, with the effectiveness of the repair material not being as critical as with retrofitted shear devices.⁽³⁾ Dowel bars are the most reliable means of re-establishing load transfer, but their performance is sensitive to the construction and installation procedures. Puerto Rico has installed many miles of retrofitted dowel bars as part of its concrete pavement restoration program. A recent review of over 7,000 dowel bars installed over the last 8 years indicates that less than 0.5 percent of the repairs have failed. Puerto Rico used a slot 1.6 in (41 mm) wide and Set 45 as the filler material.⁽⁵⁹⁾

A critical design consideration for the installation of retrofitted dowel bars is the determination of the number, diameter, and spacing of the bars. Larger diameter dowel bars, an increased number of dowel bars, and closer spacing of dowel bars serve to reduce the bearing stresses on the concrete. The reduction in bearing stress minimizes elongation of the dowel socket and results in reduced long-term faulting. One study determined that stresses and deflections for a joint with as few as 6 dowels (3 in each wheelpath) are similar to stresses and deflections obtained for a joint with 12 uniformly spaced dowels.⁽⁶⁰⁾ Thus, it is expected that concentrating retrofitted dowels in the wheelpaths should provide similar performance and have a lower cost.

The double-vee device is sized to fit in a 6 in (152 mm) diameter core hole. However, the devices are slightly larger than 6 in (152 mm), so they must be compressed before installation. This allows the device to remain in compression as the joint widens, thereby reducing the tensile forces on the bond between the concrete core wall and the repair material. On a number of projects, annular horizontal grooves cut into the core walls have been used to improve the shear characteristics. The double-vee device is designed to accommodate joint opening and closing but to limit differential vertical movement.

The performance of the double-vee shear device has generally been poor. A significant number of failures of this device have occurred, most of which were due to a bond loss between the device and the core wall.^(2,3) Georgia reports that the performance of the double-vee devices is influenced by the effectiveness of the patching materials used with the devices.⁽⁵⁵⁾ Although several modifications have been made to the device over the last several years, the long-term performance capabilities are not known. Results in Florida indicate that the double-vee devices exhibited higher deflections than the retrofitted dowels, although each treatment was effective in reducing faulting when compared to control sections.⁽⁶¹⁾

The success or failure of a retrofitted load transfer system depends on the performance of the load transfer device, the preparation of the PCC kerf faces or core holes, and the repair or filler materials.⁽⁵⁵⁾ The filler material must exhibit minimal drying shrinkage and develop strength rapidly to withstand the inherent stress build-up that exists at joints. The repair material must also exhibit sufficient bond strength between the device/repair material and the existing PCC. A number of materials have proven application to retrofitted load transfer devices, including both proprietary materials and portland cement

based materials. The materials used for partial-depth repairs are generally suited for load transfer restoration.

Other restoration activities should be considered in conjunction with retrofitted load transfer devices. Dowel bars may be installed during full-depth repairs; however, slab stabilization and slab jacking should be performed prior to the retrofit. Diamond grinding, diamond grooving, and joint and crack sealing should be completed after load transfer restoration.

Shoulder Restoration

Shoulders are an important and sometimes overlooked element of a comprehensive highway maintenance and rehabilitation program. Well designed and maintained shoulders are essential for safe traffic operations and serve as lateral structural support for the pavement. Shoulders provide space for emergency stops, recovery space for errant vehicles, clearance to signs and guard rails, space for maintenance operations, and so on.

The methods used in determining the condition of shoulders are essentially the same as those used for mainline pavement. The major items of interest are the visual distress survey, structural evaluation, drainage survey, subgrade and materials evaluation, and an estimate of traffic. As with the mainline pavement, this information can be used to develop rehabilitation alternatives to be applied to the shoulders.

Two mainline pavement-shoulder combinations are discussed below, along with the typical distresses that they may exhibit.

PCC Pavement with Bituminous Shoulder

During the Interstate highway construction of the 1960s and early 1970s, many PCC pavements were constructed with bituminous shoulders. This was often done as a means of reducing construction costs and expediting construction. Current trends in design and construction do not favor this combination. However, there are many existing PCC pavements using bituminous shoulders.

When a PCC pavement is constructed with a bituminous shoulder, the resulting lane-shoulder joint is very difficult to seal adequately.^(62,63) The difference in thermal expansion and contraction characteristics of the two materials can result in large differential horizontal movements at that joint. In addition, relatively large vertical movements can be created at the joint due to differential frost heave that occurs because of the differences in the thickness of the pavement and shoulder and lack of continuity.

The longitudinal lane-shoulder joint must be sealed effectively to reduce the amount of water that infiltrates into the pavement. One study indicated that approximately 70 percent of the water enters the pavement structure through the lane-shoulder joint.⁽⁶³⁾

Excessive moisture in the pavement can lead to cracking, corner breaks, pumping, faulting, settlements, and shoulder separation.

In addition to the difficulty in sealing and maintaining the lane-shoulder joint, a bituminous shoulder does not provide any structural support to the adjacent pavement. Thus, traffic loading at the slab edge can produce very high stresses that can quickly consume the fatigue life of the pavement. Also, fatigue damage due to traffic encroachments can occur in the bituminous shoulder, which creates entry points for water to infiltrate the pavement structure.

Critical distresses occurring in this pavement/shoulder combination are listed below:

- **Pumping:** Pumping is the ejection of water and fines through the lane-shoulder joint or transverse joints or cracks. Pumping results in a loss of support under the pavement and leads to faulting and cracking of the pavement slabs and rapid deterioration of the shoulder.
- **Fatigue Cracking:** Insufficient shoulder thickness or heavy shoulder use will result in excessive stresses in the shoulder, especially when the foundation materials have softened due to moisture intrusion. The increased stress and deformation will result in accelerated fatigue cracking in both the mainline pavement and in the shoulder.
- **Lane-Shoulder Drop-off:** Consolidation of the underlying granular base or subgrade and voids created by pumping will result in settlement of the shoulder relative to the pavement edge.
- **Block Cracking:** Block cracking is caused by restrained thermal movement of the asphalt concrete. It is accelerated by age hardening of the asphalt. The development of block cracking creates entry points for water to infiltrate the shoulder and pavement.
- **Shoving:** Shoving of the bituminous shoulder can occur if the mix is unstable or if there are extremely large shearing forces (e.g., braking or turning vehicles) present.
- **Differential Shoulder Support:** Shoulders constructed with a different, or lesser quality or thickness, base or subbase relative to the mainline pavement can be subjected to differential consolidation, frost heave, or settlement.
- **Weathering and Raveling:** Weathering in this case refers to the oxidation of asphalt cement in the bituminous surface. This oxidation causes the asphalt to harden, after which the aggregates can become dislodged and lead to raveling of the surface.

PCC Pavement with PCC Shoulder

PCC shoulders have been constructed adjacent to PCC pavements for a number of years. These shoulders are either paved after the construction of the mainline pavement or are paved integrally with the mainline pavement. In either case, tiebars are placed across the lane-shoulder joint.

The use of PCC shoulders addresses many of the problems associated with bituminous shoulders adjacent to a PCC pavements. The tied PCC lane-shoulder joint is easily sealed and maintained and the PCC shoulder provides edge support to the mainline pavement. A

ties shoulder reduces critical edge stresses and can increase the life of the mainline pavement substantially as shown in a 1979 study which analyzed the stresses in a PCC shoulder/pavement and the influence on the fatigue life of the mainline pavement.⁽⁶⁴⁾ A load transfer of zero indicates a free edge condition, or a condition where a bituminous shoulder would exist contiguous to the mainline pavement. When the load transfer is low, the edge stresses produced in the slab are high. If good load transfer exists between the slab and shoulder, the stresses in the slab will be decreased.

PCC shoulders are evaluated using the same procedures as used on a mainline PCC pavement. A visual distress survey is typically conducted, the structural history reviewed, and deflection data collected, if applicable. Generally, this is performed in conjunction with the evaluation of the mainline pavement. It is important that the load transfer efficiency be determined at the pavement/shoulder joint similar to the evaluation of the transverse joints in the mainline pavement.

Distresses that occur in a PCC shoulder are virtually the same as those that can occur in a mainline PCC pavement. Some of the primary distresses include the following:

- **Cracking:** Cracking in the PCC shoulder can occur due to fatigue, poor support conditions at corners, and sympathetic cracking from the mainline pavement. Therefore, joints constructed in the shoulder should match those in the mainline. Sawing intermediate joints in the shoulder has been shown to encourage cracking in the mainline.
- **Pumping/Faulting:** Pumping and faulting can occur at the corners of both the PCC shoulder and the PCC mainline pavement. The pumping action can lead to loss of support beneath the slab corners. If good load transfer efficiency exists across the lane-shoulder joint, then the corner and edge deflections will be greatly reduced. However, tied shoulders by themselves are not a substitute for load transfer devices in the transverse joints of the mainline pavement.
- **Spalling:** Spalling of the lane-shoulder joint may occur for a variety of reasons, including inadequate cover of the tiebars, inadequate shoulder thickness resulting in differential vertical movements, and failure of a keyway (if present) at the lane-shoulder joint.

Many of the distresses that may occur in a tied PCC shoulder are believed to be caused by an insufficient tiebar design or by poor construction practices.⁽⁶⁵⁾ Tiebars should be of sufficient diameter to resist shear forces under heavy loading.

Drainage Restoration

The optimum time to address subsurface drainage is during construction, when effective and long-lasting subdrainage systems can be built for minimal added cost over conventional designs. However, in some cases, older pavements without effective drainage can be modified to improve drainage conditions. Because of the significant contribution of drainage to pavement performance and the prevalence of moisture-related

distress, every restoration project design should consider the need for improved pavement subdrainage.

In recognition of the importance of subdrainage, the FHWA has sponsored a study entitled *Performance of Subsurface Pavement Drainage*.⁽⁶⁶⁾ This summarizes the pavement community's current understanding of the role of subdrainage in pavement performance and provides guidelines on the application of subdrainage in both new design and rehabilitation. Factors emphasized in that report include the following:

- The primary source of water in pavements is through nonsealed joints and cracks. Although sealing will not keep out all moisture, it will reduce the amount entering a pavement.
- Pavement subdrainage systems should be used to remove any water that does get into the pavement.
- Adequate pavement and shoulder cross-slopes should be provided to ensure that water does not stand on the pavement surface or at the pavement-shoulder interface. If cross-slopes are inadequate, steps should be taken to improve them through the application of a thin overlay.
- Tight, tied concrete shoulders on concrete pavements provide a joint that is easily sealed and eliminates a major source of water infiltration.

Assessing the need for subdrainage begins with the distress survey, continues with the evaluation of the existing drainage, and culminates, if warranted and feasible, with the design of a subdrainage system to be retrofitted to the existing pavement. The successful completion of these activities requires knowledge of the potential sources of water, its interaction with subdrainage materials, and the basic principles of subdrainage design.

There are several different types of drainage systems that may be placed in a pavement structure; longitudinal edge drains are the most common. These are either circular slotted pipes or a rectangular geocomposite membrane that are placed longitudinally along a project at the pavement edge. They are intended to collect water from the pavement structure and carry it to nearby outlets for discharge into a ditch. Longitudinal drains can be placed during construction or can be retrofitted on existing pavements.

Transverse drains are another type of drainage system that has been employed by some agencies. These are circular, slotted pipes that are placed transversely across the pavement, perpendicular to the centerline of the pavement. Their purpose is to facilitate removal of excess moisture from beneath the pavement. Transverse drains have been used on concrete pavements by some agencies at transverse joints, a primary location of moisture. Transverse drains may be a part of new construction, but are not normally used in rehabilitation (except in reconstruction). However, they are sometimes installed at full-depth repair locations.

Permeable bases provide another means of positive drainage to a pavement structure. These are bases placed below the surface course that is designed and constructed such that excess moisture can rapidly drain through it and to nearby edge drains. An important

factor influencing the effectiveness of a permeable base is its permeability. Permeability is the capacity of a material to conduct or discharge water under a given hydraulic gradient. It is expressed in terms of its coefficient of permeability, k , which is a measure of the rate at which water passes through a material in a given amount of time under a unit hydraulic gradient. Permeable bases are suited only to new construction or reconstruction projects.

The purpose of the pavement drainage system is to remove excess water that infiltrates the pavement structure. A field survey should be performed to determine the condition of the existing pavement. The existence of moisture-related distresses may be an indication that improved drainage is necessary. However, it is imperative that the existing pavement structure be no more than moderately distressed. Studies have shown that if the pavement is severely cracked or has broken slabs, retrofitted edge drains may not be an appropriate rehabilitation technique.⁽³⁾

The FHWA suggests that a suitable pavement for subdrainage rehabilitation be in fairly good overall condition (i.e., no more than 5 percent of the outer lane requiring full-depth repair).⁽⁶⁶⁾ It is also recommended that if the base has greater than 15 to 20 percent fines, the base material may be too impermeable for an effective retrofitted subdrainage installation.

For rehabilitation projects, it is acknowledged that most existing pavements have impermeable layers. The best that can be done for such pavements is to provide means for the rapid, effective removal of water that may accumulate at the slab-base interface through the installation of retrofitted longitudinal edge drains.

The major concern when retrofitting subdrainage to a pavement is the cost-effectiveness of the installation. The lack of drainage is evident in roads where moisture from spring thaw allows loads to deteriorate a pavement many times faster than when the pavement is dry. Thus, the question is whether a retrofitted drainage installation can remove enough moisture such that the pavement life is extended.

A study by the Permanent International Association of Road Congresses (PIARC) investigated the effectiveness of edge drains in reducing pumping when combined with nonerodible materials. The results from this study indicate that care must be taken to ensure that the drains are adequately evaluated and installed in a pavement if the pavement's performance is to be improved. The report emphasizes that drains should not be installed indiscriminately.

A good source of up-to-date information on the performance of retrofitted edge drains on PCC pavements is the FHWA's Experimental Project 12, *Concrete Pavement Drainage Rehabilitation*.⁽⁶⁷⁾ This project is following the experience of 10 States (Alabama, Arkansas, California, Illinois, Minnesota, New York, North Carolina, Oregon, West Virginia, and Wyoming) that have used edge drains in rehabilitation, with experience ranging from 2 to 14 years. Specific studies will be performed on one in-place test section and control in each State.

Most of the drains included in this FHWA study are continuous pipe collector systems, but some still use aggregate-filled trenches (French drains).⁽⁶⁷⁾ At the time of the initial report (1989), the use of geocomposite fin drains was experimental in 8 of 10 projects. It was reported that most States add subdrainage in PCC rehabilitation to extend pavement life. The costs of adding subdrainage ranged from approximately \$1.25 to \$12/lin ft (\$4.10 to \$39/lin m), although they were primarily in the range of \$2 to \$3/ft (\$6.54 to \$9.84/m).⁽⁶⁷⁾ At the time of the report, the greatest controversies included the use of fabric and where to place it and the type of material to use as backfill in the trench.

There is a growing movement toward the use of fin drains. Their primary advantages are that they require a narrower trench than conventional pipe drains and do not require a special backfill, thereby reducing excavation costs, time, and backfill material. The primary disadvantages are that they can clog and be damaged easily during construction.

Kentucky, which has been installing edge drains for over 20 years, has in the past 6 years used almost exclusively geocomposite fin drains. In side-by-side comparisons, they report a number of interesting findings. The fin drains were found to start draining much more rapidly than pipe drains after a rainfall event; a few minutes compared to 24 to 48 hours. However, in studies done by both excavation and borescope, it was found that some damage to the fin drains had occurred as a result of the compactive effort used on the backfill.

On one project where the existing pavement was cracked and seated, widespread failures were reported for fin drains. These were due to a number of causes, including damage to the drains during placement and silting from the fines created during the cracking and seating process. Based on their study, Kentucky then made a number of changes to their specifications for retrofitted subdrainage. They restricted the distance between pipe outlets to either 200 or 450 ft (61 to 137 m), depending on the slope (longer distances resulted in the capacity of the drain being exceeded), and they also learned that they needed to take extra care with edge drains on crack and seat projects.

A drainage survey and evaluation should be conducted to determine the need for improved drainage and to evaluate the potential for improving the drainage. Included in the survey will be the assembly of the available data relative to the existing highway and subsurface geometry, soil and material properties, side ditches, precipitation and frost penetration, and other factors that might contribute to the quantity and effect of water in the pavement.

The existing cross-section must also be examined to determine the best design and location for installing a drainage system. The survey must consider that the design objective is to remove the water as rapidly as possible and that this is best accomplished by shortening the drainage path.

3. STATE-OF-THE-ART DESIGN AND CONSTRUCTION METHODS

The following section presents information on the current industry standards and procedures for the restoration methods addressed in this report.

Full-Depth Repair

Full-depth concrete repairs encompass the removal and replacement of at least a portion of the slab to restore the rideability of the pavement, to minimize vertical deflection, and to prevent further deterioration of distressed areas. Prior to a full-depth repair, a pavement condition survey of the distressed area is an essential step in developing an appropriate rehabilitation strategy.⁽¹¹⁾

Careful design and construction practices of a full-depth concrete patch should allow the repair to provide adequate long-term performance. The source of premature failures in full-depth repairs of in-service pavements has been inadequate design, poor construction, and poor construction quality.⁽²⁾ Accurate design considerations and proper construction practices are fundamental to the installation of a successful full-depth repair. The remaining portion of this section will discuss the design parameters for full-depth concrete repair and proper construction practices.

Design

The critical components of full-depth concrete repair design considerations include pavement type, size and location of repair, load transfer, and concrete repair materials. The condition survey conducted at the beginning of this process not only aids in selecting full-depth repair as a restoration method, but it sets the boundary and condition information needed to develop a repair design. Full-depth repairs are more likely to be needed at the joints, but occasionally they are needed between the joints when the pavement distress type and severity warrant restoration. Current prevailing industry standards identify severity levels of various pavement distress types that merit full-depth repair. Although there are very minor differences among current industry design manuals, a culmination of the type and minimum severity level of distresses that require full-depth repair for jointed and continuously reinforced PCC pavements are presented in table 3-1.

Repair Dimensions

Once the areas needing repair are identified using table 3-1 and the condition survey, the boundaries of the repair must be determined. The distressed portions of the pavement must be removed and replaced for the repair to have a beneficial effect. To ensure that all deteriorated areas are identified for removal, coring and deflection studies should be performed. As a general rule, the deterioration near joints and cracks is greater at the bottom of the slab than at the top, particularly in freeze-thaw climates. The deterioration at the bottom of the slab may extend 3 ft (0.9 m) or more beyond the visible boundaries of deterioration at the surface.⁽⁶⁸⁾

Repairs of transverse distresses should extend the full width of one lane to ease sawing and removal operations. Repair boundaries should be parallel without irregular corners or shapes that may cause additional cracking to develop. A minimum patch length of 6 ft (1.8 m) is recommended to satisfy performance criteria in jointed PCC using dowel bars.⁽¹³⁾ This provides a repair resistant to rocking and faulting and a large enough area to ease construction. For undoweled jointed concrete pavement, a minimum repair length of 8 to 10 ft (2.4 to 3.0 m) is recommended.⁽⁶⁸⁾ Continuously reinforced concrete pavement should have a minimum repair length of 6 ft (1.8 m) in areas containing tied steel and 4 ft (1.2 m) for repair areas containing mechanically connected or welded steel.⁽⁶⁸⁾ A minimum width of 6 ft (1.8 m) is recommended for repair areas in CRCP to provide a large enough area to prohibit rocking and for ease of construction.

Table 3-1 ^(11,12,68) General distress criteria for full-depth repair

Distress Type	Minimum Severity Level Required For Full-Depth Repair
Jointed Pavement :	
Blowup	Low
Corner Break	Low
D-Cracking	Moderate
Deterioration Adjacent to Existing Repair	Moderate
Joint Deterioration	Moderate
Spalling	Moderate
Reactive Aggregate	Moderate
Transverse Cracking	Moderate
Longitudinal Cracking	High
Continuously Reinforced Pavement :	
Blowup	Low
Punchout	Moderate
D-cracking	High
Transverse Cracking (Steel Rupture)	Moderate
Longitudinal Cracking	High
Repair Deterioration	High
Localized Distress	Moderate
Construction Joint Distress	Moderate

It may be necessary to extend the area of full-depth repair prior to construction if any of the following layout situations occur:⁽¹³⁾

- If the patch boundary at minimum width falls within 6 ft (1.8 m) of an existing undoweled transverse joint that does not require repair, extend the patch to the transverse joint.

- If the boundary at the minimum width falls on an existing doweled transverse joint, and the other side of the joint does not require repair, extend the patch beyond the transverse joint by about 1 ft (0.3 m) to remove the existing dowels.
- If the boundary at minimum width falls on a crack in a continuously reinforced pavement, extend the patch beyond the crack by 6 in (152 mm).

If the boundaries of two minimum-width patches are within the distances noted in table 3-2, combine the two patches into one large one.

Table 3-2 ⁽¹³⁾ Guidelines for combining full-depth patches

Slab Thickness in (mm)	Patch Lane Width ft (m)			
	9 (2.7)	10 (3.0)	11 (3.3)	12 (3.6)
7 (175)	17 (5.2)	15 (4.6)	14 (4.3)	13 (4.0)
8 (200)	15 (4.6)	13 (4.0)	12 (3.7)	11 (3.4)
9 (225)	13 (4.0)	12 (3.7)	11 (3.4)	10 (3.0)
10 (250)	12 (3.7)	11 (3.4)	10 (3.0)	9 (2.7)
11 (275)	11 (3.4)	10 (3.0)	9 (2.7)	8 (2.4)
12 (300)	10 (3.0)	9 (2.7)	8 (2.4)	8 (2.4)
15 (375)	8 (2.4)	8 (2.4)	7 (2.1)	6 (2.0)

The cost of placing one large full-depth patch can often be less than repairing two smaller patches. The cost of sawing, removing, reconstructing, and sealing a full-depth patch for a given boundary is a fixed cost that increases with pavement thickness. For example, one larger patch will involve half the amount of repair boundaries as two smaller patches. Therefore, it is possible the costs incurred with the additional area of the larger patch will not be as great as those needed for the additional repair boundaries of the two smaller patches.

Load Transfer

Load transfer is the ability of the pavement to transfer loads and deflections between adjacent slabs. Poor load transfer allows differential movement between adjacent slabs that can cause spalling, pumping, and faulting. Without good load transfer, the full-depth patch will not provide adequate performance and will result in a premature failure of the repair.

The four primary techniques used to provide load transfer across adjacent slabs are dowel bars, tie bars, undercutting, and aggregate interlock. Dowel bars are smooth steel bars anchored into the existing slab and are generally epoxy-coated to prevent corrosion. Dowel bars are used where free horizontal movement of the full-depth patch is desired and are the most reliable method of load transfer. Tie bars are large diameter rebars (typically #8 [25 mm]) anchored into the existing slab. Tie bars are used where no free horizontal movement of the full-depth patch is desired. Undercutting is achieved by excavating

under the existing slab and replacing the excavated material with the monolithic concrete repair. Aggregate interlock is achieved through the friction developed between the faces of a joint or crack that is tightly held together. Aggregate interlock relies on the macro and microtexture developed during the initial drying shrinkage and thermal movement of the slabs and subsequent cracking of the PCC after slab placement.

The FHWA has determined that the only load transfer system that provides acceptable performance is steel dowel bars with a minimum diameter of 1.25 in (32 mm).⁽⁶⁸⁾ It is recommended that for proper load transfer at transverse repair joints where the existing slab are doweled, the repair should also be doweled. In the case that the jointed concrete pavement does not contain dowels, table 3-3 should be used to determine the most appropriate load transfer type.

Table 3-3 ⁽⁶⁸⁾ Full-depth repair load transfer recommendations for nondoweled JPCP

Climate*	Subbase	Average Annual Daily Truck Traffic		
		Light (<100)	Medium (100 - 500)	Heavy (>500)
Wet	Granular	Aggregate Interlock	Dowels**	Dowels
	High Quality Stabilized	Aggregate Interlock	Dowels**	Dowels
Dry	Granular	Aggregate Interlock	Dowels**	Dowels
	High Quality Stabilized	Aggregate Interlock	Aggregate Interlock	Dowels**

* The boundary between wet and dry climates is the zero Thornthwaite Index Contour.

** Recommended if the required future pavement life is greater than 5 years.

The wheel paths are where load transfer is needed most, so it is where the load transfer devices should be located. At least four to five dowels with a minimum diameter of 1.5 in (38 mm) should be placed under each wheel path.⁽⁶⁸⁾

Continuously reinforced concrete pavements should be repaired with rough joint faces and the re-establishment of the continuous reinforcement. The rough joint face provides aggregate interlock with the repair to facilitate load transfer.

Repair Materials

Selecting a durable repair material that is functionally and structurally compatible with the existing slab is an essential aspect of full-depth repair design. Asphalt concrete is considered a temporary repair material and should not be expected to provide adequate service for extended periods of time. Portland cement concrete, numerous proprietary materials, and other similar materials are suited for long-term, durable patches in PCC pavements.

Agencies often want the repair areas opened to traffic as soon as possible to minimize traffic congestion problems. To facilitate early opening to traffic, the repair material must provide adequate strength to accommodate the applied traffic loads and temperature-induced stress without cracking. The recommended minimum compressive strength at the time of opening is 2,000 psi (13.8 MPa); the recommended minimum PCC modulus of rupture is 300 psi (2.1 MPa) center-point loading or 250 psi (1.7 MPa) third-point loading.⁽⁶⁸⁾

The high early-strength needed to achieve early opening of full-depth repairs can be obtained by increasing the cement content, using Type III cement, adding an accelerator, or placing insulating blankets on top of the repairs (in some cases). These measures can reduce opening times to as little as 4 hours. However, they must be used with care to avoid cracking resulting from excessive shrinkage or slab curling. Proprietary rapid-setting materials are also available that can be used to achieve opening times as short as 1 hour, but at a premium price. For most applications, the desirable opening time can be achieved using a conventional PCC mix modified with a higher cement content (and an accelerator, if a very fast opening time is required) to provide high early-strength.

Construction

The six steps in constructing a full-depth repair in concrete pavement are isolating the deteriorated area, removal of the existing concrete, repair area preparation, concrete placement and finishing, curing, and sawing and sealing the repair boundaries. These steps described below.

Concrete Removal

Isolating the deteriorated area of the pavement from the adjacent concrete and shoulder materials is accomplished using full-depth saw cuts. The full-depth saw cuts allow removal of the deteriorated concrete without creating unnecessary damage to the surrounding sound concrete. In hot weather, when the concrete has expanded and compressed the joints, a slanted pressure relief cut may be needed within the repair boundaries to prevent spalling of the adjacent concrete during removal.

To prevent damage to the subbase, the saw cut must not be allowed to penetrate more than 0.5 in (13 mm) into the subbase.⁽¹³⁾ The longitudinal cuts along the shoulder or adjacent longitudinal joints should be cut full depth. After sawing operations are completed, a smooth joint face is created with no joint transfer capacity. It is recommended that the patching be completed within 2 days of sawing operations to avoid pumping and erosion beneath the slab if the pavement is left in service.

Partial-depth saw cuts are made in continuously reinforced concrete pavement at the outer boundaries of the repair area. The partial-depth saw cuts should be located at least 18 in (457 mm) from the nearest tight transverse crack.⁽¹³⁾ Generally, two full-depth saw cuts are made at a specified distance from the partial-depth cuts. The recommended distance is

24 in (610 mm) to tied laps and 8 in (203 mm) for mechanical connections or welded laps.⁽¹³⁾ If inspection of rebar after concrete removal identifies that more than 10 percent of the bars are seriously damaged or corroded, or if three or more of the adjacent bars are broken, the repair boundaries should be extended another lap distance.⁽⁶⁸⁾

It is preferable to use the lift out method of PCC removal because it is less damaging to the subbase and requires less labor than breaking the concrete and removing the pieces. The most general form of removal involves the use of steel chains connected to lift pins drilled into the deteriorated concrete. Saw cuts within the repair area provide additional space for lateral movement of the slab during vertical lift out.

Preparation of the Repair Area

Following the removal of the deteriorated concrete, all subbase and subgrade materials disturbed during concrete removal should be removed and replaced with similar material or a suitable equivalent. The area may need to be dried and a lateral drain placed in cases where excess moisture exists in the repair area. Replacing deteriorated subbase material with concrete is the best performance alternative and is generally cost-effective for repairs less than 10 ft (3 m) long.⁽⁶⁸⁾

The dowel sockets can be drilled rapidly using tractor-mounted gang drills that can drill several holes simultaneously while maintaining proper alignment. Drilling holes with hand-held drills is cumbersome and not recommended because of the likelihood of misalignment. The dowel sockets should be placed on 12 in (305 mm) centers at mid-depth of the exposed face of the existing slab. The drilled holes should be 1/4 in (6.4 mm) larger than the dowels if grout is used as the dowel anchoring material. The holes should be drilled 1/16 in (1.6 mm) larger than the dowels to allow room for epoxy mortar anchoring material.⁽¹⁾ The dowel sockets must be thoroughly blown out with compressed air following drilling.

Quick-setting, non-shrinking cement grout or epoxy resin is injected into the back of the dowel hole. The grout can be placed by using a long flexible tube that places the material in the back of the socket; epoxy-type materials can be placed using a cartridge with a long nozzle that dispenses the material to the rear of the hole.⁽⁶⁸⁾ A thin grout retention disk is placed over the dowel prior to placement to prevent the anchoring material from flowing out of the hole. The dowel should be inserted with a twisting motion to ensure complete coating of the dowel. The exposed part of the dowel should be greased lightly to facilitate horizontal movement and prevent the new PCC from adhering to the “free end.” A dowel sleeve or cap may also be used and is generally preferable.

New reinforcing steel for continuously reinforced concrete pavement repair areas should match the original grade, quality, and number. The new bars should be cut so that their ends are at least 2 in (51 mm) from the joint faces and either tied, mechanically connected, or welded to the existing reinforcement.⁽¹⁾ Depending on the type of splice used, different overlap lengths are required to allow the splice to develop the full bar strength. The

recommended lap length for a tied splice is 18 in (457 mm) for #5 bars (16 mm) and 21 in (533 mm) for # 6 bars (19 mm).⁽¹²⁾ The recommended lap length using a welded splice of 0.25 in (6 mm) is a continuous weld made 4 in (102 mm) long on both sides of the bars, or 8 in (203 mm) long on one side of the bar.⁽¹³⁾

Concrete Placement and Finishing

Adequate consolidation and a level surface relative to the adjacent concrete are critical aspects for successful full-depth repairs. The standard State specifications govern the placement and finishing of the concrete. Attaining good consolidation around dowel bars is very important for adequate load transfer and long term performance.

The addition of water to increase workability of the PCC should be avoided because of the loss in strength and increased shrinkage. It is recommended that the slump of the patching concrete be between 2 to 4 in (51 to 102 mm).⁽⁶⁸⁾ The repair should be struck off in a longitudinal direction to ensure that the surface is flush with the adjacent concrete.

Concrete Curing

Immediately following placement and finishing, the concrete should be covered with a curing compound, wet burlap, polyethylene sheeting, or State-approved equivalent. Proper curing is critical in preventing rapid moisture loss from the PCC leading to the formation of shrinkage cracks.⁽¹⁾

Under certain circumstances, insulation blankets may be placed on the PCC to increase the temperature and accelerate strength gain. Insulation blankets for high early strength concrete are needed for early opening repair areas. However, the insulation blankets should be placed over polyethylene sheeting to prevent excessive moisture loss.

Saw and Seal

The final step in the construction of a full-depth concrete repair is to form or saw transverse and longitudinal sealant reservoirs at the patch boundaries.⁽¹³⁾ Sealed perimeter joints will reduce spalling of the patch and minimize the infiltration of water.

Partial-Depth Repair

Partial-depth repairs extend the life of PCC pavements by restoring ride quality to pavements that have spalled, scaled, or exhibit other forms of surface distress. Partial-depth repairs entail the removal of shallow areas of deteriorated concrete and replacement with a suitable repair material that is comparable both in strength and volume stability to the concrete of the existing slab. The repair material must adequately bond to the sound concrete and become an integral part of the existing slab.⁽⁶⁹⁾

PDRs are an alternative to full-depth repairs where the distresses are limited to the upper one-third of the slab. The load transfer devices (if any) must be functional, and no structural damage must be present. PDRs are well suited for spall repair created by compressive stresses from incompressible materials in joints. In addition, localized surface defects such as scaling, weak concrete due to improper finishing, reinforcing steel placed too near the surface, and so on can be repaired effectively with PDRs.

Generally, PDRs are placed along transverse joints, but they can be located along longitudinal joints or elsewhere in the slab. However, spalls less than 6 in (152 mm) long and 1.5 in (38 mm) wide at the widest point are normally not candidates for partial-depth repair.⁽⁶⁸⁾

Repair Materials

Material selection for PDRs should consider the following factors: mixing time and required equipment, working time, temperature range for placement, curing time, aggregate requirements, repair area moisture conditions, cost, repair size, bonding requirements, and so on.⁽⁷⁰⁾ Patching materials generally fall into three broad categories: cementitious concretes, polymer concretes, and bituminous materials, as discussed below.

Cementitious Materials

Cementitious materials include PCC-based, gypsum-based, magnesium phosphate, and high alumina (calcium aluminate) concretes. These materials differ substantially in performance and cost and are described below.

High-quality PCC is the most common material used for PDRs. Type I or III portland cement concrete with coarse aggregate not greater than half the size of the minimum repair thickness is typical. The concrete mix should be a low slump mixture with a water-cement ratio below 0.44.⁽⁷⁰⁾ Type III cement or the use of an accelerating admixture is used for repairs that need to be opened to traffic quickly. Type III cement is ground more finely than Type I cement and therefore has an accelerated strength gain.⁽¹¹³⁾ Another method for increasing the rate of strength development is to place insulating layers on the hydrating PCC to retain the heat of hydration. PCC can be placed and cured under most conditions by following standardized cold and hot weather concreting practices.

Gypsum-based (calcium sulfate) repair materials, such as Duracal and Rockite, gain strength rapidly and can be used in any temperature above freezing. However, gypsum concrete does not perform well when exposed to moisture or freezing weather.⁽⁷¹⁾ Additionally, the presence of free sulfates in the typical gypsum mixture may promote steel corrosion in reinforced PCC pavements.⁽⁴⁸⁾

Magnesium phosphate concretes, such as Set 45, Eucospeed MP, and Propatch MP are proprietary rapid set materials that produce a high early strength, relatively impermeable patch that bonds well to clean, dry surfaces. However, this type of material is extremely sensitive to water, either on the bonding surface or in the mix. Small amounts of excess

water cause a severe reduction in strength and durability. These materials have shown sensitivity to aggregate type, such as limestones.⁽⁴⁸⁾ These materials can be somewhat difficult to place and finish due to the rapid set time, and they have a narrow range of placement temperatures.

Calcium aluminate concretes (CAC), such as Five Star HP, exhibit rapid strength gain, good bonding properties on dry surfaces, and very low shrinkage. Loss of strength has occurred in some cases from a chemical conversion that typically occurs at elevated curing temperatures.^(3,48,71) The placement and finishing of CAC can be more difficult than conventional PCC because of the rapid set characteristics and the limited placement temperature range.

Polymer Concretes

Polymer concretes are a combination of polymer resin, aggregate, and a set initiator. Aggregate is added to the polymer to provide a wearing surface and to provide thermal compatibility with the pavement and reduce the potential for debonding. Polymers are generally categorized as epoxies, methacrylates, or polyurethanes as described below.

Epoxy resins, such as Burke 88 / LPL, Mark 103 Carbo-Poxy, have excellent adhesion, are impermeable, and are available for a wide range of setting times, application temperatures, strengths, and bonding conditions. Differences in the coefficients of thermal expansion between the repair material and the concrete can cause repair failures. For this reason, the epoxy concrete mix design must be compatible with the concrete in the pavement. Deep epoxy repairs need to be placed in lifts to control heat evolution. Epoxy concrete should not be used to patch spalls caused by reinforcing steel corrosion, as it may accelerate the rate of deterioration of the adjacent concrete.

Methyl methacrylate concrete and molecular weight methacrylate concretes, such as SikaPronto 11 and Degaur 510, are polymer modified concretes with long working times, high compressive strengths, and good adhesion. Many methacrylates are volatile and may pose a health hazard to those exposed to the fumes for prolonged periods of time.⁽¹⁹⁾

Polyurethane concretes, such as Percol FL and Penatron R/M-3003, generally consist of a two-part polyurethane resin mixed with aggregate. Polyurethanes are generally very quick setting (90 seconds), and some manufacturers state that the materials are moisture-tolerant.

Bituminous Materials

Although considered temporary, bituminous patches are often left in place for many years. The most common bituminous patching materials are hot-mix asphalt concretes. Bituminous patches are relatively low in cost and easily placed. Joints cannot be re-established with bituminous patches and are not recommended as a permanent repair.

Construction

The actual extent of deterioration in a concrete pavement may be greater than is visible at the surface. The early stages of joint spalling often develop with no signs of deterioration visible at the surface. “Sounding” techniques, such as those using a ballpeen hammer or chain drag, are used to identify the extent of spall deterioration not detectable at the surface. Dull sounding percussion of the concrete indicates areas of weak concrete, and clear ringing percussion indicates sound areas of concrete. All weak and deteriorated areas of the pavement are marked for removal so that the partial-depth patch will perform effectively. Normally, the area marked for removal is located 2 to 6 in (51 to 152 mm) outside of the deteriorated area.⁽⁷⁰⁾

There are several techniques commonly used to remove the deteriorated concrete in preparation of PDRs. The technique is selected based on equipment availability, contractor experience, available construction time, and cost-effectiveness of the procedure. The recommended procedures include sawing, chipping, high pressure waterblasting (hydrodemolition) and milling.

Concrete Removal and Patch Cleanout

The sawing procedure involves sawing the patch boundaries with a diamond saw blade. The sawed vertical edge faces reduce spalling associated with thin or feathered concrete along the repair perimeter. The deteriorated concrete in the center of the patch is removed toward the marked edge of the patch boundaries. Jackhammers used to remove the unsound concrete should not be operated at more than a 45 degree angle from the pavement to minimize damage to the sound concrete. Hammers and chisels should be used to remove material from the edges of the patch area. Care should be taken not to damage or crack the sound concrete beneath and adjacent to the patch area.

Chipping is a similar procedure except that the boundaries are not sawed. Chipping is quicker than sawing because there are fewer steps involved in the process. The rough surface promotes bonding; however, vertical edges are difficult to obtain at the repair boundaries.

Deteriorated or unsound concrete is removed using a carbide-tipped cold milling machine in the milling procedure. Standard milling machines with a 12 to 18 in (305 to 457 mm) cutting head have proven efficient and economical, particularly when used for large repair areas.⁽⁷⁰⁾ The rough edge surfaces provided by the milling machine promotes bonding, but the milling operation may cause spalling in adjacent pavement edges.

Waterblasting or hydrodemolition involves the use of a high pressure water jet to remove the deteriorated concrete. The waterblasting machine should be capable of producing a stream of water at 15,000 to 30,000 psi (103.5 to 207 MPa) controlled by a mobile robot.⁽⁷⁰⁾ The waterblasting procedure requires less time than the sawing/removal operation and provides an accurate removal with rough vertical edges. However, the

equipment is expensive and leaves a saturated repair area that requires careful cleaning to remove the fine slurry laitance remaining after the procedure.

An adequate bond cannot be obtained unless the bonding surface is free of contamination and has a rough macrotexture. Sandblasting and airblasting follow the removal of the unsound concrete to remove loose concrete, dust, and other debris.

Joint Preparation

Partial-depth repairs placed adjacent to transverse, centerline, or shoulder joints require special construction preparations. High compressive stress is the most frequent cause of failure of partial-depth spall repairs. Non-flexible partial-depth patches placed directly against transverse joints and cracks will be crushed by the compressive forces during thermal expansion of the slabs if there is insufficient space available. Patches have also been known to fail when repair material is allowed to flow into the joint or crack opening below the bottom of the patch. This material in the opening will cure and reduce the movement available to the slab during expansion and create preventable compressive stresses.

Placing a strip of polystyrene, polyethylene, asphalt-impregnated fiberboard, or other compressible material between the repair material and the adjacent slab will reduce the risk of compression-related failures. The strip is referred to as a bond breaker. It is recommended that the existing transverse and longitudinal joints adjacent to the repair be resawed using a double-bladed concrete saw. The bond breaker should extend 1 in (25 mm) below and 3 in (76 mm) beyond the repair boundaries.⁽¹¹³⁾ The extension will prevent the repair material from flowing into the joint during placement. The bond breaker needs to be slightly wider than the joint so that it is slightly compressed after installation.

Partial-depth patches placed at the centerline joint often spall because of curling stresses. To prevent this, place a bond breaker along the centerline joint to prevent the patch from contacting the adjacent lane. The joint needs to be formed using a piece of fiberboard if the repair is at the lane-shoulder joint. Fiberboard is stiffer than other bond breakers and provides the support needed at the lane-shoulder joint when placing the repair material.

Material Placement

Some partial-depth patching materials require epoxy or proprietary bonding agents. Manufacturers' specifications should be followed in regards to bonding agents and the repair materials being used for the patch. The bonding agent is applied after cleaning and just prior to placing the repair material. Thorough coating of the bottom and sides of the repair area is essential and may be accomplished by brushing the grout, epoxy, or other material onto the concrete.

The volume of material required to complete a partial-depth repair is usually small, typically between 0.5 and 2.0 cubic feet (0.01 and 0.07 cubic meters).⁽⁷⁰⁾ Ready-mix

trucks and other large batching equipment cannot efficiently produce small quantities. Therefore, small drum or paddle-type mixers with capacities adequate for partial-depth patching are used for batching from bagged raw or premixed materials.

Placement begins by slightly overfilling the repair to allow for reduction in volume during consolidation. In general, repair materials should not be placed when the air temperature or pavement temperature is below 40° F (4° C).⁽⁷⁰⁾ The repair material should be sufficiently consolidated during placement to remove all voids located at the interface between the repair material and the existing PCC. Vibrators and tamping rods facilitate consolidation. The vibrator is held at a slight angle (15 to 30 degrees) from vertical and is moved at random through the repair material until the entire area has been covered. Avoid overvibrating the material, as it may lead to segregation or a reduction in entrained air (if applicable). Tamping rods are better suited for smaller repairs.

Partial-depth repairs are usually small enough so that a stiff board can be used to screed the repair surface and make it flush with the existing pavement. Hand floating and troweling should originate at the center of the repair and move radially out toward the patch boundaries. This finishing pattern aids in the consolidation and bond at the repair boundary.

Diamond Grinding and Grooving

Diamond grinding and grooving of PCC pavements are separate procedures that have very different objectives. Diamond grinding involves the removal of the hardened PCC surface layer using a series of closely-spaced diamond saw blades. The objective of diamond grinding is to correct irregularities in the pavement surface and improve rideability. Diamond grooving uses a procedure similar to grinding, but the saw blades have a center-to-center spacing of 0.75 in. (19 mm).⁽⁷²⁾ This spacing produces grooves in the PCC surface that improve skid resistance and reduce the incidence of wet weather accidents due to hydroplaning. Cold milling is a separate process typically performed on asphalt concrete pavements. Cold milling chips the surface of the pavement using carbide steel bits. This process is very damaging to concrete pavements because it produces a rough pavement surface, especially near the pavement joints, and may lead to microcracking in the PCC.⁽⁷²⁾

Diamond grinding has been used as a PCC restoration procedure since the 1960s. Innovations in equipment, materials, and processes have made the technique a cost effective and widely accepted restoration method. Diamond grinding improves the ride quality of the pavement and restores the macrotexture of the surface, leading to improved skid resistance. Diamond grinding is not a structural repair method and is suited to a limited number of distress types, as indicated below:

- Transverse joint and crack faulting.
- Wheel path ruts from studded tires.

- Slab warping and curling at joints.
- Polished aggregates.

Distress Indicators

The most widespread use of diamond grinding is to improve the ride quality of PCC pavements exhibiting faulting. Several approaches have been used to quantify a ride quality performance threshold to indicate the most beneficial time to perform diamond grinding to remove joint and crack faulting. The present serviceability index (PSI) of a pavement, used in the AASHTO design approach, is typically used as a trigger for restoration work.⁽⁷³⁾ A faulting index, similar to that developed by Georgia, is also useful in establishing threshold values for diamond grinding.⁽³⁾

The American Concrete Pavement Association and International Grooving and Grinding Association recommend that when the PSI of a PCC pavement falls into the range between 3.8 and 4.0, the agency perform a thorough evaluation to determine the cause of the serviceability loss.⁽⁷²⁾ Once structural deficiencies have been addressed, diamond grinding should be conducted to improve the ride quality. The amount of labor, time, and cost required to improve the ride quality by diamond grinding significantly increases after the PSI drops below the recommended PSI threshold range.

Grinding should be conducted prior to reaching critical levels of vehicle ride discomfort. The generally accepted limit of 0.25 in (6.4 mm) faulting is recognized as the minimum value for vehicle discomfort.⁽⁷²⁾ Joint spacing influences the amount of tolerable faulting. Greater amounts of faulting are tolerated at larger joint spacings than at shorter joint spacings. A faulting index developed by Georgia based on faulting measurements has been proven as a reliable indicator for scheduled diamond grinding. Each faulting index value of 5 represents 1/32 in (0.8 mm) of faulting.⁽⁷²⁾ For example, a faulting index of 25 represents an average fault of 5/32 in (4.0 mm), as shown in table 3-4. The representative number of joints that need to be measured for faulting to accurately characterize the degree of faulting are shown in table 3-5. The average of all fault measurements is used to develop a faulting index value. Diamond grinding is performed at a faulting index of 15 based on the average fault measurements. At a fault index of 15, typically some joints are faulted to the critical level of a 1/4 in (6.4 mm).⁽³⁾

Table 3-4 ⁽⁷²⁾ Faulting Index

Average Fault	Faulting Index	Comments
1/32 in (0.8 mm)	5	No Roughness
1/16 in (1.6 mm)	10	Minor Faulting
3/32 in (2.4 mm)	15	Grinding project
1/8 in (3.2 mm)	20	Expedite project
5/32 in (4.0 mm)	25	Expedite project
3/16 in (4.8 mm)	30	Discomfort begins
7/32 in (5.6 mm)	35	Discomfort begins
1/4 in (6.4 mm)	40	Grind immediately

Table 3-5 ⁽⁷²⁾ Recommended number of fault measurements needed

Joint Spacing	Measure Cracks	Measurement Interval	No. of Fault Measurements per lane mile (per lane km)
<12 ft (<3.65 m)	No	every 9th joint	>50 (>32)
12-15 ft (3.65-4.57 m)	No	every 7th joint	50-63 (32-40)
15-20 ft (4.57-6.10 m)	No	every 5th joint	53-70 (33-44)
20-30 ft (6.10-9.14 m)	Yes	every 4th joint	44-66* (28-42)
>30 ft (>9.14 m)	Yes	every 4th joint	>30* (>19)

* Include transverse cracks with joint fault measurements.

The pavement condition evaluation and ride quality information need to be equally weighted in determining the timing and sequence of diamond grinding with other PCC restoration methods. Diamond grinding is a repair method to improve ride quality and does not address the structural problems that may have caused the decrease in ride quality. Structural and durability problems, such as pumping, loss of support, corner breaks, working transverse cracks, broken slabs, D-cracking, reactive aggregate, and freeze-thaw damage, will require more extensive restoration methods than diamond grinding alone. If structural and durability problems are addressed solely by diamond grinding, the ride quality improvement will be short lived because the cause of the distress has not been remedied. The following factors should be considered in determining the feasibility and sequence of diamond grinding in a typical restoration project:⁽⁶⁸⁾

- If there is evidence that a severe drainage or erosion problem exists, as indicated by significant faulting (> 0.13 in [3.3 mm]) or pumping, appropriate restoration should be performed to alleviate the problem prior to diamond grinding.
- The presence of progressive transverse slab cracking (all severity levels for JPCP and only deteriorated cracks for JRCP) and corner breaks indicates a structural deficiency in the pavement. Slab cracking and the faulting of these cracks will continue after grinding and will reduce the life of the restoration project.
- The hardness of the aggregate has a direct relationship on the cost of the diamond grinding project. Grinding of pavements with extremely hard aggregate (quartzite) takes additional time and effort compared with PCC produced with a softer aggregate (limestone). If an extremely hard aggregate is present on a project, diamond grinding costs may be very high.
- Concrete experiencing durability problems, such as D-cracking or alkali-aggregate reactivity, should not be rehabilitated through grinding.

- Significant slab replacement and repairs may be indicative of continuing progressive deterioration that grinding would not remedy.
- Any significant depressions should be corrected by slab jacking before diamond grinding. It is not cost-effective to remove depressions by diamond grinding.

Design

The three most important factors in the diamond grinding process are the weight of the grinding machine, the horsepower available to the grinding head, and the grinding head itself.⁽⁷²⁾ The progression of a diamond grinding machine is similar to a wood plane. The front wheels of the equipment pass over a fault or bump, the centrally mounted cutting head follows and removes any anomalies, and the rear wheels track in the smooth path that results from the grinding. The weight of the equipment and the horsepower available to the cutting head influence the depth of cut possible and the grinding effort required to compensate for the varying degrees of hardness of the aggregate in the PCC. The cutting head can be adjusted to the desired depth, width, cross slope, and textural pattern depending on the type of equipment used.

Frictional resistance provided by diamond grinding can be altered by varying the “land area” or the raised area between the grooves by increasing the saw blade spacing. The groove is defined as the recessed area created by the saw blade. The height is defined as the depth from the top of the land area to the bottom of the groove. Table 3-6 displays the recommended dimensions for hard and soft aggregate. The recommended dimensions correspond to blade spacing of between 53 and 57 blades per foot (174 to 184 blades per meter) for hard aggregate and 50 to 54 blades per foot (164 to 177 blades per meter) for soft aggregate. The cutting head typically has a width ranging from 36 to 38 inches (910 to 970 mm).⁽⁷²⁾

Table 3-6⁽⁷²⁾ Recommended dimensions

	Range of Values, in (mm)	Hard Aggregate, in (mm)	Soft Aggregate, in (mm)
Grooves	0.09-0.15 (2.3-3.8 mm)	0.10-0.15 (2.5-3.8 mm)	0.10-0.15 (2.5-3.8 mm)
Land Area	0.06-0.13 (1.5-3.3 mm)	0.08 (2.0 mm)	0.10 (2.5 mm)
Height	0.0625 (1.6 mm)	0.0625 (1.6 mm)	0.0625 (1.6 mm)

Diamond Grinding and Grooving Equipment

Usually from 160 to 195 blades per meter are required to produce a level surface with a corduroy-type texture.⁽²⁷⁾ Consequently, fewer blades per meter would be required for diamond grooving. As the grinding machine moves over the pavement, the grinding head rotates and removes from 0.06 to 0.75 in (1.6 to 19 mm) of the surface, leaving a corduroy texture.⁽²²⁾

Before beginning a grinding project, a contractor must make the proper blade selection. There are three factors in selecting a blade: bond hardness, diamond size, and diamond concentration. Each of these factors impacts upon productivity, cost and quality of the ground surface.⁽²²⁾

Bond hardness determines the rate at which support provided by a metal matrix responsible for holding the diamonds is lost as the diamonds become worn. This is why bond hardness impacts on the cutting speed and life of a grinding head. It is important to match the proper bond hardness to the aggregate being ground in order to maintain maximum cutting efficiency.

Diamond size also effects the life and cutting speed of the grinding head. When grinding soft aggregates choose large diamond particles. For harder aggregates use smaller diamonds. Diamond concentration is the most important factor because it can either disguise or overshadow the effects of bond hardness or diamond size. More diamonds make a harder grinding head and allows for more efficient cutting.

Construction

The quality acceptance criteria for diamond grinding varies between agencies, but there are some accepted general criteria. The smoothness specified for newly constructed PCC pavements should be used as the criterion for assessing the ride quality of diamond grinding projects. Roughness can be measured using a variety of devices, such as K.J. Law Profilometer, California Profilograph, or Mays Meter. Skid resistance is generally measured using either a standard ribbed tire (ASTM E 501) or a standard smooth tire (ASTM E 524). It is recommended that skid testing be performed with the smooth tire to recognize the improvements in the macrotexture created by diamond grinding.

The grinding operation produces a slurry of ground concrete and water used to cool the blades. The slurry can be discarded on to shoulder areas or vacuumed into dishrag trucks depending on the location of the project and the local governing legislation regarding grinding waste.

Diamond Grooving

Grooving is a satisfactory solution to low skid resistance on PCC pavements under wet weather conditions. Grooving is mainly completed at interchanges and curves, but it can be performed along the entire length of a project if the number of wet weather accidents is substantial. Grooving will not rehabilitate structural distresses in PCC pavement.

Grooving improves wet weather surface friction by increasing the macrotexture of the pavement and providing a channel for the water to move away from the pavement surface, thereby limiting the potential for hydroplaning. Transverse grooving provides excellent braking action through increased frictional resistance. However, transverse grooving is not feasible on heavily traveled pavements because of the traffic control required to

complete transverse grooving. Longitudinal grooving apparently helps the vehicle track around curves and improves alignment in adjacent lanes.

Grooving equipment is similar to grinding equipment. The cutting head on the grooving equipment can be larger than the grinding head because fewer diamond blades are required. The cutting width of a grooving head can be 5 ft (1.5 m) or more. Typically, the blades are spaced a minimum of 0.75 in (19 mm) apart.⁽⁷²⁾ This spacing increases the land area compared to that of the grinding operation. The depth of the cut ranges from 0.125 to 0.25 in (3.2 to 6.4 mm). The groove width is typically between 0.10 and 0.13 in (2.5 to 3.3 mm).⁽⁷²⁾

Slab Stabilization

The presence of voids under PCC pavements results in rapid development of various distresses and a loss in ride quality. Voids generally occur near cracks or joints, or along the pavement edge, and are a partial function of intruded moisture. The depth of the voids is generally not greater than 0.25 in (6.4 mm), but voids are extremely detrimental to the serviceability of the pavement.⁽⁶⁸⁾ Distresses that are commonly associated with voids include pumping, faulting, and cracking. Slab stabilization is the preferred restoration method for correcting voids if FDRs are not warranted.

Slab stabilization is the pressure insertion of material beneath the slab or stabilized base to restore slab support. The material injected beneath the slab is intended to fill voids and prevent further migration of water and support layer fines. Slab stabilization is also referred to as pressure grouting, undersealing and subsealing. Slab jacking is a similar procedure, but should not be confused with slab stabilization. Slab jacking involves injecting material beneath a slab to raise the profile of the pavement surface to remove a depression and improve ride quality.

Identification of Voids

Slab stabilization should only be performed in areas where voids are known to exist. Injecting material into areas without voids could possibly raise the slab, create rideability problems, and increase the potential for development of additional distresses due to uneven support. Available techniques that are used to detect the presence of voids include visual inspection, deflection testing, and ground penetrating radar (GPR).

Visual Inspection

Visual inspection of the pavement can be used to identify the potential void locations. Faulting of transverse cracks and joints, pumping, and corner breaks are indicative of a loss of support and probable void locations. The presence of ejected fines at or near joints and cracks in the traffic lane or shoulder is a good indicator of pumping and the migration of water and fines within the pavement structure. The accuracy in identifying the amount and location of the voids using only visual inspection is low. Inaccurate estimates of the

quantity and location of voids can result in continued deterioration and problems such as slab lift, broken slabs, insufficient material used for stabilization, and generally poor performance.

Deflection Testing

Deflection testing can determine whether a loss of support has occurred and provide a rough estimate of the quantity of material needed to adequately fill the voids. Deflection testing involves the use of a falling weight deflectometer (FWD) or comparable device. An FWD measures the deflections radially from a dynamic load applied to the pavement surface. Deflection testing is currently the most effective approach to locating and estimating the size of voids beneath concrete slabs. It is recommended that deflection testing be conducted at cool temperatures to avoid problems with slab expansion and increased load transfer at the transverse joints and cracks.

Corner slab deflections are usually the criterion used for void detection. Some agencies have developed a maximum allowable corner deflection criterion to indicate the presence of voids. Georgia DOT, for example, uses 0.25 in (6.4 mm) corner deflection under an 18,000 lb (80 kN) single axle load as the maximum allowable deflection.⁽⁶⁸⁾ Deflections measured at the slab corners that exceed this maximum are considered to have a void that should be addressed through slab stabilization. Variations in load transfer between joints greatly influence the magnitude of the deflections. Therefore, numerical limits placed on the corner deflection can lead to inaccurate estimates.

Another void detection method using the FWD is based on measuring the corner deflection at several different load magnitudes. Typically, load levels of 6,000, 9,000, and 14,000 lb (27, 40, and 63 kN) are used to develop a load versus deflection plot for a given test point. If this linear plot does not pass through the origin or below the origin, it indicates that voids most likely exist at the test location. It is generally believed that the further the plot deviates from the origin, the larger the void.

Ground Penetrating Radar

Ground penetrating radar is gaining popularity in identifying and estimating the extent of voids beneath PCC slabs. GPR works by directing a short pulse of electromagnetic waves into the pavement and receiving the signals that are reflected back from the pavement and underlying layers. Changes in the reflection pattern created by delayed reflection from voids indicate the presence of voids beneath the PCC pavement.

Materials

The most common materials currently used in conventional slab stabilization projects include pozzolan-cement grout and polyurethane. High viscosity or low penetration asphalt cements were commonly used for slab stabilization; however, their use has been largely replaced by pozzolanic-cement grouts. Slab stabilization materials are required to

have sufficient strength to support the slab and yet have the initial fluidity to flow into and fill small voids beneath the pavement. At the proper consistency, the stabilization material should have sufficient consistency to displace free water from under the slab.⁽⁷⁴⁾

Pozzolan-Cement Grouts

Pozzolan-cement grouts are used by most agencies, partly because the materials are readily available and cost-effective. The fineness and spherical shape of pozzolans result in a ball-bearing effect that enhances the flow properties and allows the grout to adequately fill small voids.⁽⁷⁴⁾ The two types of pozzolans used in grout mixes are natural pozzolans (volcanic ash and diatomaceous earth) and artificial pozzolans (fly ash). A typical pozzolan-cement mixture is one part cement and three parts pozzolan. Pozzolans used in a grout mix should conform to ASTM C 618 specifications. The cements typically used in the grout mixes include Types I, II, and III and should conform to AASHTO M 85 specifications.

The amount of water added to the grout mix is determined by the flow cone test. The grout mix used for slab stabilization must be fluid enough to pass through the flow cone in 9 to 16 seconds. For comparative purposes, water flows through the flow cone in 8 seconds. The 7-day compressive strength of the pozzolan-cement grout mix, as measured by AASHTO T 106, should be greater than or equal to 600 psi (4137 kPa).⁽⁶⁸⁾

Polyurethane

Polyurethane is a two-part material that is combined to form a strong, lightweight, foam-like substance. The chemical reaction between the two materials occurs beneath the pavement and causes the polyurethane to expand and fill the voids. Once cured, the polyurethane has a density of about 4 pounds per cubic foot (64 kilograms per cubic meter) and a compressive strength between 60 to 145 psi (0.4 to 1.0 MPa).⁽⁶⁸⁾ The benefits of using polyurethane include its high tensile strength and rapid cure time that allow the pavement to be opened to traffic within 15 to 30 minutes of the repair.

Equipment

Batching and mixing of the grout or polyurethane is generally accomplished by a self-contained, mobile apparatus. The following equipment are required for the slab stabilization process, depending on the materials selected:

- Colloidal mixing equipment provides the best results for pozzolan-cement grouts. Paddle or conveyor belt type mixers should not be used for pozzolan-cement grout mixing because of inadequate mixing.
- A positive-displacement injection pump, or a non-pulsing progressive-cavity pump, capable of maintaining pressures between 25 and 200 psi (0.15 and 1.4 MPa).⁽⁷⁴⁾ A desirable pumping rate is approximately 1.5 gallons per minute (5.7 liters per minute).

- Hand drills or pneumatic drills capable of drilling 1.5- to 2.5 in (38 to 64 mm) holes through concrete and steel reinforcement. Larger holes may break the bottom of the slab, and smaller holes are not efficient for grout injection.⁽⁷⁴⁾
- Grout packers or expanding-rubber packers that can be inserted into the drilled holes to prevent grout extrusion or backup while sealing the hole during injection. A grout return hose should be used to recirculate the grout and prevent it from hardening in the hose.

Injection Hole Location

The injection holes are generally located near the void boundary farthest from the nearby joint or crack. During the grout injection, the grout will progress through the void toward the crack or joint. Hole patterns vary depending on the pavement type, joint spacing, existing slab distresses, and so on. The slab stabilization contractor may relocate the injection holes during the process, depending on the performance of the operation. Each project is different, and flexibility in the hole pattern is necessary to improve stabilization performance.

Typically, four injection holes are used to ensure uniform distribution of the grout. Holes are placed in each wheel path on both the approach slab and the leave slab at the transverse crack or joint. The holes in the approach slab are approximately 8 to 12 in (203 to 305 mm) from the joint and the holes on the leave side are approximately 18 to 24 in (457 to 610 mm) from the joint.⁽⁷⁴⁾ PCC pavements built on stabilized bases need to have the hole extend through the base and into the subgrade, as experience has shown that voids develop beneath stabilized bases in PCC pavements.

Stabilization Procedures

Following hole placement and drilling, the grout packer or expanding-rubber packer is connected to the discharge hose on the pressure grout pump and placed into the drilled holes. The discharge end of the packer is not extended past the bottom of the concrete slab when placed into the drilled hole.

Close monitoring of the slab during stabilization is necessary to ensure that the slab does not raise. Raising of the slab can create additional voids, result in non-uniform support, and ultimately break the slab. Slab uplift should not be allowed to exceed 1/4 in (6.4 mm) for a given slab corner.⁽⁷⁴⁾ Pumping operations should cease when the slab begins to raise; grout flows out of an adjacent hole, joint, or slab edge; grout begins to fill adjacent cracks or joints; or excess water that was being displaced by the grout stops. When pumping time exceeds approximately 2 minutes, the slab stabilization should be stopped because the grout is flowing into a large washout or cavity that will require correction by another restoration method.⁽⁶⁸⁾

Joint and Crack Sealing

The purpose of joint and crack sealing is to prevent the migration of incompressible materials and water into the pavement joint system. The sealant is designed to limit moisture related distresses, such as pumping and faulting, by limiting the infiltration of moisture into joints and cracks. Sealing is also intended to minimize the intrusion of incompressible materials into working joints and cracks that create pressure related distresses, such as spalling and blowups.

Sealing operations should be performed on all joints and cracks in the PCC pavement. Transverse pavement joints are generally more elaborately designed because a properly functioning transverse joint is vital for good performance and limits formation of additional cracks and distresses in the pavement. Joint and crack sealing cannot produce maximum benefits when the pavement is significantly deteriorated. Joint and crack sealing is intended to limit additional severe pavement distresses and not repair these distresses. If severe pavement distresses are present, other PCC restorations methods such as full-depth repairs must be considered.

Historically, relatively rapid deterioration of the sealant material from environmental and traffic conditions reduce the sealant performance and effectiveness. It is generally believed that bituminous based sealants have a service life of 1 to 4 years.⁽⁶⁸⁾ NCHRP Synthesis 98 states that the average effective service life of crack sealing is 3.6 years. Recent improvements in sealant materials and studies performed on proper joint design and preparation have extended the expected service life of joint and crack sealants. New sealant materials and extended service lives have allowed the pavement engineer to select a length of service desired based on given performance and budget criteria.

Sealant Materials

Joint and crack sealant materials must withstand a variety of environmental and traffic conditions. The sealants are subject to horizontal and vertical shear from expanding and contracting slabs, weathering and extreme temperatures, and stone and road material abrasion and penetration.⁽⁷⁰⁾ Under these conditions, the sealant must maintain adhesion to the concrete joint sidewalls to prevent infiltration of foreign materials. There are numerous sealant types available. The proper sealant type must be selected based on the conditions present and the overall objective of the sealing. The American Concrete Institute (ACI) classifies sealants into three categories, thermoplastic materials, thermosetting materials, and preformed compression seals.⁽⁵⁰⁾ A list of the most common sealant types used on PCC pavement are presented in table 3-7.

Table 3-7 ⁽⁵⁰⁾ Common sealant types used on PCC pavement

Sealant Material	Example Products	Applicable Specifications	Design Expansion	Cost Range (\$/L)*
PVC coal tar	Crafco Superseal 444	ASTM D3406	10 - 20%	\$2.10 to \$3.20
Rubberized asphalt	Koch 9005, Crafco RoadSaver 221, Meadows Hi-Spec	ASTM D1190, D3405, AASHTO M173, M301-851, Fed SS-S-164	15 to 30%	\$0.85 to \$1.10
Low-modulus rubberized asphalt	Crafco 231, Meadows Sof-Seal, Koch 9030	Modified ASTM D3405	30 to 50%	\$1.20 to \$1.40
Polyurethane	Mameco Vulkem 300 SSL, Sikaflex, Burke U-Seal	Fed SS-S-200E	10 to 50%	\$6.30 to \$8.40
Silicone (nonself-leveling)	Dow 888, Bayer Baysilone 960, Crafco 902	State specifications	30 to 50%	\$7.10 to \$10.30
Silicone (self-leveling)	Dow 890-SL, Crafco 903	State specifications	30 to 50%	\$7.65 to \$10.55
Preformed neoprene compression seal	DS Brown Delastic, Watson-Bowman WB series	ASTM D2628, AASHTO M220	Compress 45 - 85%	

* Based 1995 costs.

Thermoplastic Materials

Thermoplastic materials are defined as materials that soften upon heating and harden upon cooling without a change in chemical composition.⁽⁶⁸⁾ Thermoplastic sealant materials are bitumen-based and are generally applied in a heated form with the exception of a few cases in which the materials are diluted for application. Hot-applied thermoplastic materials include asphalt rubber, rubberized asphalt, fiberized asphalt and polyvinyl chloride (PVC) coal tar.

Asphalt rubber is a blend of asphalt cement and suspended, solid rubber particles. The unmelted rubber improves the elasticity and cohesiveness of the sealant as well decreasing its temperature susceptibility. Rubberized asphalt is a blend of asphalt cement with polymers and melted rubber. Rubberized asphalt sealants possess the beneficial attributes of asphalt rubber as well as increased workability and performance at low temperatures.

Low-modulus rubberized asphalt sealants incorporate softer grades of asphalt cement that further improve the performance of the sealant at low temperatures. PVC coal tar sealants have a high softening point and bonds well to concrete, which makes them extremely useful in cases where the sealant may be subject to fuel spills or jet blasts.

Cold-applied asphalt based sealants include cutbacks and emulsions. Cutbacks contain asphalt cement that is diluted with petroleum solvents to decrease their viscosity and increase workability. Evaporation of the petroleum solvent allows the asphalt cement to cure, but creates environmental and health hazard concerns that significantly limit their use. Emulsions are a mixture of asphalt cement particles suspended in water and held in suspension by an emulsifying agent. The asphalt cement cures or “breaks” from either dissipation of the emulsifier or evaporation of the water. The emulsion sealants perform reasonably well, but are temperature sensitive and are prone to cracking.⁽⁶⁸⁾

Thermosetting Materials

Thermosetting materials are sealants that are applied and cured through the use of a chemical catalyst or release of a solvent. The performance of thermosetting materials has shown good potential, but they cost four to ten times more than thermoplastic sealants. Thermosetting sealants include polysulfides, polyurethanes, silicones, and epoxies.

Polysulfide and polyurethane sealant performance has varied widely. The retention of elasticity of these materials is good, but they lack adhesion to the concrete joint surface. These sealants require an additional mixing operation thereby increasing overall costs. Silicone sealants have performed well in terms of retained elasticity, improved temperature resistance, and bond strength. Silicone is placed in a thin layer because of its excellent bond strength and low modulus. Silicone comes in two forms, self-leveling and nonself-leveling. The nonself-leveling silicone requires an additional step in its application to press the sealant against the concrete sidewall and create a recessed surface.

Preformed Compression Seals

Preformed compression seals are premolded strips of styrene, urethane, neoprene, or other synthetic materials that are designed to be placed in PCC pavement joints in a state of compression.⁽¹⁾ These seals are compressed to 20 to 50 percent of their uncompressed width and placed within the joint. Precompressed compression seals perform well in new construction projects, but have significant drawbacks and limited areas of use in restoration. If a joint were to expand to the point that the seal loses compression, it falls to the bottom of the joint or is pulled out by traffic. In addition, if the seal is compressed beyond 50 percent for a significant period of time, the seal may take a “compression set” and not expand as the slabs contract.⁽⁶⁸⁾

Joint Design

Horizontal movement at joints is due to the thermal expansion and contraction of adjacent slabs. Slab length is critical in determining the design joint width for a given set of project conditions. The range of horizontal movement of the joint aids in determining the optimum sealant for that particular installation. Joint spacing, the thermal coefficient of expansion of the concrete, extreme or average temperature range, and the coefficient of friction between the slab and underlying layers are factors that influence the joint width. The following equation is used to estimate the average horizontal joint opening:

$$\Delta L = C L (\alpha \Delta T + \epsilon)$$

where:

ΔL = joint opening

α = thermal coefficient of expansion/contraction for PCC

ϵ = drying shrinkage coefficient of the PCC (considered to be zero for resealing projects)

L = joint spacing

ΔT = maximum temperature range

C = coefficient of friction between slab and underlying layers

Thermoplastic sealants and other types to a lesser extent, soften during periods of elevated temperatures and have a tendency to flow further into the joints thus increasing its contact surface area with the concrete joint surface. The increased bonded area increases the stresses in the sealant and may result a shortened performance period. The installation of a backer rod, prevents this movement and allows the sealant to remain where it was originally placed. A secondary purpose of the backer rod is to provide the recommended sealant configuration at the bottom of the joint.

Backer rods, usually made of a polyethylene material, should be compatible with the sealant. There are no universal specifications for backer rod selection and installation even though there are significant variations among products. Backer rod size is dependent on joint width, but they are to be compressed approximately 25 percent during installation to prevent excessive movement and to assure that the correct depth of sealant is achieved.⁽⁷⁵⁾

Backer rods are generally one of the following types:⁽⁷⁵⁾

- Polyethylene Foam: Polyethylene foam is a closed-cell foam that does not absorb water and is moderately compressible. It is better suited for cold-applied sealants since it may melt in contact with hot-applied materials.
- Crosslinked Polyethylene Foam: Crosslinked polyethylene foam is a closed-cell that is compatible with hot-applied sealants. It will not absorb water and is moderately compressible.

- **Polyurethane Foam:** Polyurethane foam is a opened-cell foam that absorbs water, but does not melt when used with hot-applied sealants. It is very compressible, and commonly used with hot-applied sealants.

The backer rod provides a surface that allows the shape of the seal to be formed. Most thermoplastic sealants on the market today are designed to withstand strains roughly 25 to 35 percent of the uncompressed width. Silicone sealants are designed to tolerate strains from 50 to 100 percent.⁽⁶⁸⁾ With these strain limitations, the shape factor (W/D , W =width of seal, D =depth of sealant) for thermoplastic sealants should be 1:1 to 1:2, and silicone sealant shape factors should be 2:1.⁽⁶⁸⁾

Resealing Operation

Proper sealant installation and procedures are vital to the success of resealing operations. Removal of the old sealant, refacing, and cleaning of the joint are vital prior to installation of the new sealant material. Resealing transverse joints consists of the following five steps; sealant removal, refacing of the joint sidewalls, cleaning the sealant reservoir, installation of the backer rod, and installation of the new sealant.

Sealant Removal

Sealant removal procedures must not damage the joint sidewalls or result in additional distresses in the PCC pavement. The following procedures provide adequate removal results with due care.⁽⁷⁵⁾

- **Manual Removal:** Typically, manual removal is used only for preformed compression seals. This method is not feasible for most thermoplastic and thermosetting sealants.
- **Sawing:** The most efficient and common removal method is sawing with diamond blades. It is efficient because the sawing also shapes the reservoir for the new material. Sawing, however, becomes ineffective with extremely sticky materials such as PVC coal tar because the material clogs the saw blade.
- **Plowing:** Plowing can be very effective for removing most of the old sealant. A small plow pulled through the reservoir dislodges the material. Operators must be careful in selecting plow design, because some can easily spall surrounding concrete.
- **Cutting:** Cutting requires that a knife blade be run along the face of the joint to remove the old sealant material. This method is labor intensive and time consuming.

Reservoir Refacing

The refacing operation is performed to provide a clean surface for bonding the new sealant to the joint surface. If sawing is used to remove the old sealant, sawing and refacing can be accomplished in one step. Other methods to remove the sealant needs to be followed with refacing the joints with a water-cooled diamond saw blade. It is suggested that two blades separated by a spacer to the desired width of the joint be used to reface the joint.

Joint Cleaning

Any loose material remaining after the refacing operation must be removed to prevent incompressible materials from entering the joint and creating pressure related distresses. Materials that are typically remaining after refacing include old sealant, water-borne dust, oil or water, dust and dirt, and other debris that entered the joint during or after refacing.⁽⁶⁸⁵⁾ Immediately following refacing, the joints should be cleaned with high-pressure air followed by sandblasting. Two passes of sandblasting should be completed to ensure that both sides of the joint are cleaned. A close inspection needs to be conducted after cleaning to ensure the removal of all foreign matter.

Backer Rod Installation

The backer rod is installed after a thorough inspection to ensure that the joint is free of debris. The backer rod should be compressed 25 percent during installation.⁽⁵⁰⁾ Backer rods are easily inserted with a double-wheeled, steel roller or any smooth blunt tool that will force it uniformly to the desired depth. Care should be taken to ensure that the backer rod is not stretched which may result in shrinkage.

Sealant Installation

The sealant should be installed shortly after the backer rod is in the proper position to prevent the collection of debris on top of the backer rod. Hot-applied thermoplastic sealants should not be installed when the air temperature is less than 50° F (8° C).⁽⁷⁵⁾ The sealant should be applied across the joint in a uniform manner from top to bottom to prevent air bubbles. It is recommended that the sealant be slightly recessed at 0.125 to 0.25 inches (3.2 to 6.4 mm) below the pavement surface.⁽⁶⁸⁾ Some manufacturers suggest that the joint be overfilled with sealant and state that the kneading action of traffic helps retain the elasticity of the sealant. Proper storage and correct application of the sealant should be strictly adhered to in order to prevent damage and loss of sealant performance.

Silicone sealants are not to be placed at temperatures below 40° F (4° C).⁽⁷⁵⁾ Silicone sealants should be placed uniformly across the joint from top to bottom to prevent air bubbles. Nonself-leveling silicone sealants must be forced against the backer rod and joint sidewalls by use of the proper application equipment. A concave sealant surface about 0.25 in (6.4 mm) below the pavement surface is desirable.⁽⁶⁸⁾ Care must be taken when placing the backer rod with self-leveling silicone sealant, since they can easily flow around small gaps in the backer rod.

Joint sidewalls must be perpendicular and uniform width and all spalls must be properly repaired prior to installing compression seals. A lubricant/adhesive needs to be applied to the joint sidewalls prior to inserting the compression seal. The compression seal should be placed about 0.25 in (6.4 mm) below the pavement surface.⁽⁷⁵⁾

Crack Sealing

Crack sealing in PCC pavement is different than transverse joint sealing. Cracks that require sealing are the result of pavement distress. The initial step in crack sealing is to assess the condition of the pavement to determine if crack sealing would be beneficial or whether alternative restoration methods need to be considered in combination with crack sealing. Guidelines for crack sealing of PCC pavements are shown in table 3-8.

Table 3-8⁽⁷⁶⁾ Guidelines for crack sealing on PCC pavements

Crack Condition		Repair Procedures			
Crack Width (in)	Spall Condition	Repair Spalls	Saw Crack	Install Backer Rod	Install Sealant
≤ 0.125	None				No
0.125 - 0.75	Minor		Yes	Yes	Yes
0.375 - 0.75	Major	Yes	Yes	Yes	Yes
>0.75	None		Yes	Yes	Yes
>.75	Major	Yes		Yes	Yes

Cracks less than 0.125 in (3.2 mm) wide are not recommended for sealing. Cracks less than 0.75 in (19 mm) but greater than 0.125 in (3.2 mm) are recommended for sealing. Cracks greater than 0.75 (19 mm) should be evaluated for other PCC restoration methods.⁽ⁿ⁾ Working cracks, especially wider cracks, need to have backer rods placed to maintain the proper shape factor of the sealant. Wider cracks may also require some type of load transfer retrofit. Otherwise, crack sealing is essentially the same as joint sealing.

Load Transfer Restoration

Load transfer restoration refers to retrofitting load transfer devices after initial pavement construction. The purpose of load transfer restoration is to increase LTE and reduce the variation and magnitude of deflection across transverse joints or cracks. Load transfer efficiency is the ability of a joint or crack to transfer load from one side of a joint or crack to the other. Increased LTE will retard further pavement deterioration due to joint pumping, faulting, spalling, and subsequent cracking.

LTE can be expressed in either deflection or stress load transfer. Deflection load transfer is defined as the ratio of the deflection of the unloaded side to the deflection of the loaded side. A ratio of 1.00 or 100 percent is complete load transfer, and if no load is transferred the ratio is 0.00 or 0 percent. Stress load transfer is defined as the ratio of the stress in the unloaded slab to the stress in the loaded side of the slab. Stress load transfer and deflection load transfer are not linearly proportional due to PCC properties, subgrade conditions, and radius of the load plate used in the deflection testing.

Adequate LTE in PCC pavements originally constructed with correctly sized dowel bars is defined to be at least 70 percent. PCC pavements originally constructed without dowel bars achieve load transfer through aggregate interlock. After repeated thermal cycles, the

aggregate interlock efficiency begins to decrease, depending on the type of aggregate used in the PCC mix. Depending on the size and type of aggregate used, openings as small as 0.1 in (0.25 mm) can result in a reduction of LTE.⁽⁶⁸⁾

Load transfer restoration is recommended for all faulted transverse joints and cracks with poor LTE (less than 50 percent). LTE should be measured using heavy load deflection testing devices at cool temperatures to ensure that there is adequate separation between the slab being tested and the adjacent slab. LTE should be measured in the outer wheelpath because it is subject to the heaviest wheel loads and highest number of vehicle passages. Load transfer restoration is also recommended for PCC pavements that are to be overlaid if joints and cracks exhibit poor LTE. Reflective cracking and numerous other distresses in the new overlay can be minimized by repairing the LTE in the pavement to be overlaid.

Load Transfer Devices

There are several types of load transfer devices available on the market today that can be used to restore load transfer across joints and cracks in existing pavements. The list of load transfer devices includes plate and stud, double-vee, dowel bars, and other, less accepted devices.

The plate and stud device consists of two metal plates that are attached to the concrete in a core hole with epoxy. Load is transferred across a joint or crack by a metal stud that serves as a shear connector. The stud is supported by metal plates that are placed in the adjacent slabs at the joint face. These devices have been installed in a few airport pavements and have been effective in the short term in restoring load transfer across joints.⁽³⁾

The double-vee load transfer device consists of two vee devices placed back-to-back and sized for a 6 in (152 mm) diameter core hole.⁽⁶⁸⁾ The center of the device is filled with foam to prevent debris from entering the joint, and a thin foam pad is placed around the outside of the vee to accommodate joint movements. The devices are larger than the 6 in (152 mm) core hole and must be compressed for installation. The initial compression allows the device to remain in compression when the joint widens, thereby lessening the tensile forces on the bond between the device and the existing concrete.

Dowel bars placed in slots sawed into the pavement at joints have proven to be an effective method of load transfer restoration.⁽²⁾ Dowel bars are normally used, but I-beam bars have been used in some projects. Slots are formed using multiple saw cuts, and the material is removed using lightweight hammers and hand tools.

Repair Materials

The repair or filler material used in conjunction with load transfer restoration must have little or no shrinkage and must develop strength rapidly to resist the stress buildup at the joint. The rapid strength gain also allows early opening to traffic, which is often a prime consideration. The repair material must also provide sufficient bond to the load transfer device and the existing concrete.⁽⁶⁸⁾ In general, the repair materials that work well for partial-depth repair methods work equally as well for load transfer restoration. Materials used in load transfer restoration include proprietary materials, polymer concretes, PCC, and epoxy resin adhesives.

Proprietary Materials

Proprietary materials, such as Set 45, and Horn 240 (both magnesium phosphate based materials) and Road Patch (fiberglass-reinforced PCC material) are quick setting and allow early opening of the repair site. However, these materials are very sensitive to temperature, moisture, and installation procedures and generally do not perform as well as polymer concretes and plain PCC when used with the double-vee device.⁽⁷⁷⁾

Polymer Concretes

Polymer concretes, such as methacrylate-based materials, consist of liquid resin, powder filler, and fine aggregate. Polymer concretes usually reach 80 percent of their ultimate compressive strength in 45 minutes to 2 hours after placement in temperatures ranging from 40° to 100° F (4 to 38° C).⁽⁶⁸⁾ The physical properties of the polymer concrete after 3 hours should be specified at a minimum compressive strength of 8200 psi (57 MPa), a minimum flexural strength of 2500 psi (17 MPa), and a tensile strength of 1000 psi (7 MPa).⁽⁶⁸⁾ A short pot life of about 15 minutes requires that polymer concrete be mixed, placed, and finished quickly by qualified personnel.

Portland Cement Concrete

PCC is the most commonly used repair material, since it costs less than other materials, contractors are familiar with the material, and there are no thermal compatibility problems with PCC pavements. Type III cement is generally used because of its rapid strength gain. Sand and an aggregate with a maximum size of 3/8 in (9.5 mm) are commonly used in the PCC mix.⁽⁶⁸⁾ Proper mix design procedures must be used to ensure adequate strength and durability. Bonding admixtures are sometimes added to the mix to provide an adequate bond to the existing PCC although, in many cases, this is unnecessary if the mix design and repair preparation procedures are followed.

Epoxy Resin Adhesives

Epoxy resin adhesives have been used to improve the bond between existing concrete and the repair materials. Epoxy resin adhesives should meet AASHTO M 235 specification

requirements. Close adherence to the manufacturer's recommendations are necessary for good performance.

Dowel Bar Design Considerations

Dowel bar retrofit is the most widely used form of load transfer restoration. Successful installation of retrofitted dowel bars should result in an increase of the LTE to 90 percent or more. The number, diameter, and spacing of the dowel bars are critical design considerations. One study determined that stresses and deflections for a joint with as few as 6 dowel bars (3 in each wheelpath) are similar to stresses and deflections obtained for a joint with 12 uniformly spaced dowels.⁽⁶⁰⁾ This indicates the importance of identifying the proper location and spacing for retrofitted dowel bars. It is believed that concentrating retrofitted dowel bars in the wheelpaths should provide similar performance as past dowel patterns and have the added benefit decreased cost.

The following are recommendations for dowel bar design:⁽⁴⁾

- Dowel bar with diameters of at least 1.25 in (32 mm) should be used, although 1.50 in (38 mm) diameter bars are recommended. The larger dowel bars are more effective at reducing faulting and should be used on most highly trafficked pavements (i.e., 0.5 million or more ESALs per year in the outer lane). Dowels should be at least 18 in (457 mm) long.
- Use three to five dowels in each wheelpath, spaced 12 in (305 mm) apart.
- Locate the outermost dowel a maximum of 12 in (305 mm) from the outer lane edge.
- It is recommended that the dowel bars be epoxy-coated for corrosion resistance.

Dowel Installation

The installation of retrofitted dowel bars is a relatively simple procedure, but can be rather time consuming and expensive due to the labor required for cutting and preparing the dowel slot. The slots for the dowels are created by making multiple saw cuts using a single blade diamond saw and subsequently breaking out the PCC. A 1 to 2 in (25 to 51 mm) wide slot is required for each dowel bar.⁽¹⁾ The slot should be deep enough to position the dowel at mid-depth of the slab, allowing a clearance of approximately 0.5 in (13 mm) beneath the dowel bar for placement on chairs.⁽⁶⁸⁾ Care must be taken during sawing and material removal so as not to damage the surrounding sound concrete.

Once the removal of the concrete is completed and the slot is formed, the slots should be thoroughly sandblasted to remove dust and sawing slurry and to provide a macro-rough surface to which the repair material can bond. The side walls and bottom of the slot are typically coated with epoxy resin prior to the placement of the dowels and patch material. A layer of patch material is then placed at the bottom of the slot immediately before the placement of the dowel bar. This material should not be allowed to infiltrate the crack beneath the joint.

The dowel bars are lightly greased or oiled their full length to facilitate joint movement. An expansion cap is placed on one end of the dowel to allow for joint closure after installation of the dowel. Support chairs in the slot allow the dowel to be positioned in the slot so that it lies horizontally and parallel to the centerline of the pavement at the mid-depth of the slab.

A filler board is positioned at the mid-point of the dowel to maintain the joint or crack. Repair material is then placed in the slot and properly consolidated. After curing, the filler board is removed for resealing operations.

Shoulder Restoration

Shoulders generally are not designed with the same structural capacity as the traffic lanes. Many States use local standards and experience to design shoulders, and there are vast differences in performance. Paved shoulders are required on all Interstate highways. Paved shoulders improve traffic operations, increase safety and service life of the pavement, and reduce maintenance.⁽⁷⁸⁾ Shoulders are generally constructed of the same materials as the mainline, but construction limitations and later additions can result in different materials in the shoulder and the mainline. The shoulder-pavement combinations addressed in this report are PCC pavements with bituminous shoulders and PCC shoulders.

Distresses occurring in the travel lanes can also occur in the shoulders. Tied PCC shoulders (and, to a lesser extent, bituminous or untied PCC shoulders) have an influence on the performance of the mainline pavement, since shoulder distresses can propagate to or result in distresses occurring in the mainline pavement. The cause and extent of the distresses in both the mainline pavement and shoulder must be identified prior to selecting a rehabilitation method.

Shoulder rehabilitation methods are influenced by restoration methods of the mainline pavement. In some instances, the restoration approach for the mainline pavement can be expanded to include the shoulder. Alternatives for shoulder restoration should be formulated at the same time as the mainline. In cases where the shoulder restoration procedures are different from those of the mainline, scheduling accommodations need to be made to ensure that the two operations do not interfere with one another.

Bituminous Shoulders

The outer traffic lane-shoulder joint between a bituminous or asphalt concrete (AC) shoulder and a PCC pavement is one of the most difficult joints to properly seal.^(62,63) The thermal coefficients of PCC and AC are very different, and the horizontal and vertical movements of the two materials can create large openings at the shoulder joint or a shoulder drop-off. A wide and ineffectively sealed shoulder joint can allow large amounts of water to infiltrate the shoulder of the pavement in the mainline. One study indicated

that approximately 70 percent of the water that enters the pavement-shoulder structure enters at the lane-shoulder joint.⁽⁶²⁾

AC shoulders generally are not structurally compatible with the mainline pavement. A PCC pavement has a significantly higher structural capacity than an AC pavement of equal thickness, given the pavements are constructed properly and are not distressed. Therefore, the shoulder does not provide adequate structural support for traffic loading at the edge of the PCC slab. The resulting high edge stresses in the PCC can lead to a reduced service life of the pavement. Excessive traffic loading on the bituminous shoulder can result in fatigue distress such as alligator cracking, which creates additional points of entry for water. Pumping, fatigue cracking, and lane-shoulder drop-off are common distresses in AC shoulders.

In instances where severe shoulder deterioration exists or where drainage improvements are necessary, the AC shoulder may have to be reconstructed. Construction of a PCC shoulder is recommended when the mainline pavement is constructed of PCC. However, a lifecycle cost analysis should be conducted to assess the benefits of PCC shoulders versus AC shoulders. Mainline restoration methods significantly influence shoulder rehabilitation procedures. For example, if an overlay is scheduled for the mainline, it may be cost effective to include a shoulder overlay in the same contract.

When circumstances warrant the reconstruction of an AC shoulder, the design thickness should be related to the anticipated load capacity which is an indirect function of the mainline pavement design. A percentage of the mainline traffic should be used to estimate the loading that may be applied to the AC shoulder. Cross slope and drainage should be considered carefully when designing and constructing an AC shoulder. Rehabilitation of the AC shoulder can encompass all of the accepted restoration methods used for mainline asphalt concrete pavements.

PCC Shoulders

The construction of PCC shoulders has become more prevalent on new PCC construction in the past decade. PCC shoulders are either constructed simultaneously with the mainline pavement or are constructed as a separate construction pass. PCC shoulders are placed with tie bars that connect them to the mainline PCC pavement.

Tied PCC shoulders alleviate the majority of the differential movement that is found with AC shoulders. Tied PCC shoulders provide support to the mainline pavement and limit the critical edge stresses that can reduce service life of the pavement. The longitudinal load transfer provided by the tied shoulders reduces the potential for edge cracking, pumping, and lane-shoulder drop-off. It is recommended that the shoulder be constructed at the same time as the outer driving lane, if possible. This monolithic pour results in a more effective load transfer at the edge/shoulder joint due to the aggregate interlock and tie bars.

Distresses that occur in PCC shoulder are identical to those occurring on PCC mainline pavements. Pumping, faulting, and spalling are common distresses that affect the performance of the shoulder. Tie bar/ joint load transfer efficiency needs to be evaluated and addressed in the same manner as in the mainline pavement.

The restoration techniques used for PCC shoulders are identical to those used on the mainline PCC pavements. If reconstruction of the shoulder is warranted, the shoulder thickness is recommended to equal that of the mainline pavement.⁽⁷⁾ If the shoulder is tapered, the shoulder should be the same thickness as the mainline then tapered to no less than 6 in (152 mm) at the outside edge.⁽⁷⁸⁾ PCC shoulders that are substantially thinner than the mainline pavement sometimes creates a “bathtub effect” that does not allow surface water to drain effectively from the pavement. This trough, formed at the joint, compromises public safety by ponding water and also contributes to the moisture-induced deterioration of the pavement and shoulder.

It is recommended that PCC shoulders be tied to the mainline with 30 in (762 mm) long Grade 40 deformed steel bars, with a diameter 0.625 in (15.8 mm) spaced on 30 in (762 mm) centers.⁽⁷⁸⁾ In instances where the shoulder and pavement were placed separately, the tie bars must be placed in holes drilled into the mainline slab and anchored with epoxy resin or grout. D-cracking or significant edge distress may prevent proper bonding of the tie bar. PCC shoulders may not be an effective solution in this case unless these distresses are remedied.

Deteriorated cracks and joints in the PCC shoulder are rehabilitated using partial-depth or full-depth repairs. If extensive spalling exists along the lane-shoulder joint, examination of the tie bar effectiveness is recommended. The lane-shoulder joint should be sealed and regularly maintained to minimize the infiltration of water into the shoulder and pavement structure. Slab stabilization of the PCC shoulder can be performed, especially at the slab and shoulder corners, where pumping and erosion are most likely to occur.

Drainage Restoration

Drainage restoration should be considered for any restoration project if it will significantly impact the current rate of PCC deterioration and if it can be performed in a cost-effective manner. Several pavement distresses are indicative of excess water within the pavement structure. Pumping, faulting, and to a lesser extent, cracking require moisture to be present in sufficient quantity to either “liquefy” the supporting soil or reduce its bearing capacity. If any or all of these distresses are present in a PCC pavement, drainage restoration should be considered in the overall restoration of the pavement.

Wells suggested the following selection criteria for retrofitting edge drains:⁽⁷⁹⁾

- The pavement age is 10 years or less.
- The amount of first-stage cracking (nonintersecting cracks) is 10 percent or less.

- The amount of third-stage cracking (shattered slabs) is 1 percent or less.
- Accumulated ESALs are 13 million or less.

The FHWA also suggests that in order to be a good candidate for retrofitted edge drains, the pavement should be less than 10 years old and exhibit minimal cracking (less than 5 percent cracked slabs).⁽⁸⁰⁾

Wells and Nokes⁽⁸¹⁾ emphasized the importance of the amount of third-stage cracking on the effectiveness of retrofitted edge drains. Of the 26 retrofitted edge drain projects evaluated, 13 failed prematurely. Among the failed projects, only 1 project had third-stage cracking less than 1 percent, and 10 had third-stage cracking greater than 1 percent. A statistically significant correlation was also found between the heating degree days and the amount of slab cracking prior to the installation of the edge drains.

A considerable amount of current research is underway to develop or refine retrofitted drainage technology. New application criteria, performance estimates, equipment, and materials are being developed which will greatly simplify the design and construction of drainage improvements.

4. SUMMARY OF NEIGHBORING STATE SPECIFICATIONS

The ERES project staff contacted the highway agencies of the States bordering Oklahoma (Arkansas, Colorado, Kansas, Missouri, New Mexico, and Texas) in regards to their current PCC restoration techniques. Table 4-1 presents the PCC restoration methods used in these neighboring states. All of the States responded to ERES's request except for Texas; therefore, no guidelines were included for Texas. The information presented in this section is based on the State highway specification manuals and additional information submitted by the individual State agencies. The information is presented as brief summaries and therefore may differ to some extent from the original specifications. Note that the specifications are not given in SI units. A conversion table is presented at the beginning of this document of conversion is necessary.

Table 4-1. PCC restoration techniques used by neighboring States.

	Arkansas	Colorado ⁽¹⁾	Kansas	Missouri	New Mexico
Full-depth repair	Yes	Yes	Yes	Yes	N/A
Partial-depth repair	No	No	Yes	Yes	N/A
Diamond grinding and grooving	Yes	No	Yes	Yes	N/A
Slab stabilization	No	No	Yes	Yes	N/A
Joint and Crack Sealing	Yes	Yes	(2)	(2)	N/A
Load transfer restoration	No	No	Yes	(2)	N/A
Shoulder restoration	Yes	No	(2)	(2)	N/A
Drainage restoration	(2)	No	Yes	Yes	N/A

(1) The PCC restoration techniques are not included in the CDOT specification manual but may be included in various projects as specification revisions.

(2) No information was submitted for this PCC restoration technique.

N/A = Not applicable.

Full-Depth Repair

Arkansas

The Arkansas State Highway and Transportation Department (AHTD) specifications state that the existing pavement to be restored shall be sawed the full depth of the slab. The patch shall be the full lane width and a minimum of 6 ft long. If necessary and approved by the Engineer, one additional cut may be made to facilitate removal. Overcutting beyond the limits of the area to be removed shall be held to a minimum. All overcuts shall be thoroughly cleaned of saw slurry and other contaminants and completely filled with a low-viscosity epoxy compound.

After sawing, the pavement to be removed shall be carefully lifted out in a manner that will not damage the existing pavement that is to remain or the existing base material. Any damage shall be repaired to the satisfaction of the Engineer at no cost to the Department. Before placing the patch, any loose base material shall be removed. If the existing base material is granular, it shall be recompact as necessary. The Contractor shall take all precautions necessary to ensure that the base material remains dry until the new concrete is placed. The construction methods for PCC pavement patching shall comply with the standard AHTD construction requirements for JCP and JRCP.

Dowel bars and tie bars shall be installed according to details included on the plans. Typically, for transverse joints, 18 in round steel dowel bars are placed mid-slab depth ($d/2$). A 1/4 in thick compressible material is to cover 11 in, including one end of the dowel. The portion of the dowel bar without the compressible material is anchored into the existing pavement. Dowels are to be placed on 12 in centers.

Drills used to make holes for the dowels shall be held in a rigid frame to assure proper horizontal and vertical alignment. The equipment shall be operated so as to prevent damage to the pavement being drilled. The drilling procedure shall be approved by the Engineer. When using the epoxy or polyester resin system, the bars shall be installed according to information provided by the manufacturer. To secure the bars, special care must be taken to ensure that the filling system completely surrounds the bars and fills the holes. The filling system shall be an injection type system approved by the Engineer that will ensure that sufficient material is injected into the hole before the bar is inserted.

Joints shall be constructed according to details shown on the plans. A 1/4 in closed-cell polyethylene foam is placed on the face of the existing PCC surface. Joints that will require sawing and sealing shall be re-established as soon as possible to prevent random cracking. The joints are typically sawed 3/8 to 1/2 in wide and 1-1/2 in deep. A backer rod is placed beneath a type 3, 4, or 5 sealant. Typically, the sealant thickness is between 1/4 and 3/4 in with a 1/4 to 1/2 in recessed surface, depending on the joint design specified.

The areas to be patched will be marked by the Engineer. If there are subsequent pavement or patch failures in the initial patching phase, not due to the Contractor's negligence, they shall be repaired and will be paid for under the appropriate bid item. However, if slab cracking or other damage is caused by the Contractor, then the Contractor must replace the slab at no expense to the Department.

Colorado

The Colorado Department of Transportation (CDOT) does not have a standard set of specifications for PCC restoration. Instead, revisions to the standard specifications are submitted for each individual project. The following information is an example of the revision of the specification for a past CDOT project.

For full-depth patching, the perimeter saw cuts must be full-depth and done using a diamond saw or equivalent. Sawing must go through the existing tie bars or dowel bars, leaving free vertical edges at the limits of the patch. The deteriorated concrete shall be lifted vertically from its position. Pavement breakers and jackhammers shall not be used in the removal process. All loose concrete material shall be removed from the repair area.

If the exposed subgrade is unsuitable, it should be excavated and backfilled with aggregate base course (Class 6). In areas where concrete exists beneath the area to be patched and prior to placing concrete in the patch area, a sheet of 30 lb roofing paper will be placed in the replacement section to serve as a bond breaker, in such a way that the entire exposed area is covered. The roofing paper shall be anchored to prevent movement during concrete placement.

Dowel bars shall be placed to provide load transfer between the replaced slab and the existing slab. To anchor dowel bars, holes shall be drilled into the sawed face of the existing slab, parallel to the longitudinal joint, using gang drills to prevent wandering and misalignment during the drilling process. Deformed tie bars shall be placed to tie the replaced slab to the remaining slab and shoulder. To anchor the tie bars, holes shall be drilled into the existing slab and shoulder perpendicular to the longitudinal joint.

After the holes are drilled, compressed air shall be used to remove dirt and debris from the holes. After cleaning and prior to dowel and tie bar insertion, epoxy or nonshrink grout shall be applied to the back of the hole, in order that this material will be forced forward during insertion, so that it will cover the dowel or tie bar over the entire length of embedment. Each dowel or tie bar shall be twisted a minimum of one full turn during insertion. A grout retention disk shall be placed on each dowel and tie bar used.

The smoothness of the replaced concrete shall conform to CDOT's specifications. All sawed concrete patch joints shall be sawed and sealed. The joints shall be sawed 1/2 in wide by a minimum of 1-1/8 in deep. A 5/8 in diameter backer rod shall be used. The joint seal will be 1/4 in thick and will be recessed by 1/4 in. Sealing of the joints may be done at a later date to coincide with the mainline resealing.

The patched PCC pavement can be opened when a 2500 psi minimum field compressive strength is achieved. This shall not be greater than 24 hours from the time that the paving operation was completed.

Kansas

All full-depth concrete patches will be sawed full depth with a diamond or carborundum saw, making sure not to damage the subgrade. Removal of slabs in one piece is recommended provided damage to remaining concrete does not occur. Sawing in preparation of patching shall not be more than 3 working days ahead of the normal patching operation.

Tie bars and dowel bars shall be fixed in place with an epoxy or portland cement grout in accordance with KDOT specifications. For JPCP, deformed tie bars are to be placed at a distance from the pavement surface of half the width plus 1 in ($d/2 + 1$). Number 4 deformed tie bars, 2 ft long, are to be placed every 18 in throughout the pavement and 9 in from the pavement edge. For doweled jointed pavement, 1-1/2 in by 18 in smooth dowels are to be used. They are placed 12 in from the edge of the pavement, 18 in from the pavement centerline, and with 12 in spacing throughout the pavement section. Dowels are to be placed at pavement mid-depth ($d/2$).

Edges of all patches not receiving an overlay shall be sawed or formed to form a groove 3/8-in wide by 1-1/4 in deep and sealed. Prior to sealing, the joint faces shall be cleaned by high pressure sand blasting followed by high pressure air cleaning free of contaminants. A 1/2-in backer rod of paper rope or Denver foam will be inserted in the groove to form a joint shape factor designated in the plans and then sealed with a sealing compound meeting the KDOT requirements. The sealant shall be recessed 1/8 to 1/4 in and have an overall thickness of 3/8 in.

Patches shall be a minimum of 6 ft measured in the longitudinal direction by the full lane width wide. If the concrete remaining at an individual joint shows deterioration after slab removal as directed by the Engineer, the repair area may be extended to include the deterioration and additional saw cuts shall be paid for at KDOT's expense.

At the time of depositing concrete, the subgrade and exposed surface of existing pavement will be sufficiently moist so that it will not absorb moisture from the concrete, but not to the extent that the subgrade will be muddy or have free water standing thereon. In addition, a bond breaker shall be applied to the surface of the existing PCC face. All edges not abutting remaining concrete pavement shall be formed for the full-depth of the patch.

Normal curing PCC patch material requires a minimum of 24 hours. A minimum of eight sacks (752 lb) of either Type I or II cement will be used. The handling of material, mixing, placing, and finishing concrete will conform to KDOT specifications. In addition, all concrete patching materials shall be air-entrained as defined by KDOT.

Accelerated curing PCC patch material requires a minimum of seven sacks (658 lb) of Type III cement. An amount of calcium chloride consisting of one to two percent by dry weight of the cement will be required to obtain the desired minimum compressive strength before opening the pavement to traffic. The calcium chloride shall be Type II or equivalent as approved by the Engineer and will be added by solution. The solution is considered part of the mixing water. The calcium chloride used shall be subsidiary to other items of the Contract. One percent calcium chloride is required for a minimum curing time of 6 hours at 60° F or above, and 2 percent is required for a minimum of 4 hours curing time.

If the temperature falls below 60° F during the curing period of the normal or accelerated PCC patching material, a Schmidt rebound hammer will be used to determine when the patch can be opened to traffic. The patch may be opened to traffic when the results of the rebound hammer test equal or exceed results obtained on material previously cured under this specification or 60 percent of the rebound on adjoining pavement.

No patching will be performed when the ambient air temperature is below 40° F. The concrete in the patch will be thoroughly consolidated, struck off, and finished with wooden floats or other approved methods.

Missouri

Full-depth patching requires removing all the PCC pavement within the patching area and replacing it with reinforced PCC patching material. The perimeter saw cuts must be full-depth and done using a diamond saw. A rock saw may be used to make a cut through the middle portion of the PCC being removed in order to relieve concrete stress. The full depth of the pavement must be removed without mechanically breaking in place and with minimum disturbance of sound base material. Any aggregate base disturbed during removal must be recompact or removed and backfilled with portland cement concrete. Unstable base aggregate shall be removed and replaced according to Missouri Department of Transportation (MoDOT) specifications.

The 1-3/8-in diameter dowel holes must be blown clean and dried before being injected with an epoxy or polyester bonding agent. The dowel bars used in full-depth patches are 1-1/4 by 18 in and epoxy coated. A thin plastic disk is used at the midpoint of the dowel to prevent the bonding agent from flowing from the hole during placement of the dowel and to create an effective face at the entrance of the dowel hole. The dowel must be inserted into the hole with a twisting motion so the material in the back of the hole is forced up and around the dowel.

Welded wire fabric must be placed 3 in plus or minus 1/2 in below the surface of the concrete patch. When the patch is not resurfaced, the overcut from the sawing operation shall be filled with an expansive mortar, epoxy, polyester, or joint material.

All material, proportioning, air-entraining, mixing, slump and transporting of concrete shall be in accordance with MoDOT specifications, except a minimum cement requirement of 8-1/2 sacks per cubic yard and the maximum slump of 3-1/2 in shall be used. The surface of the repaired area must be finished to provide a smooth ride and shall not vary more than 3/16 in per 10 ft. The area shall not be opened to traffic until the concrete has attained a minimum compressive strength of 3500 psi.

If the repair is to be made and opened to traffic the same day, the concrete shall contain Type III cement and calcium chloride or an approved accelerator. An 8-1/2 sack Type I cement material may be used with an accelerator and other admixtures when approved by the engineer. In addition, the aggregate or water or both can be heated when the ambient temperature drops below 60° F. A minimum of 4 hours curing time and no minimum compressive strength will be required. Both transverse ends of all new portland cement concrete repairs shall be sawed 2 in deep and 3/8 in wide and sealed according to MoDOT specifications.

New Mexico

Due to problems with reactive aggregates which were used during the original PCC construction, PCC restoration is not a cost-effective maintenance solution for New Mexico concrete pavements. New Mexico's only rehabilitation strategy is to mill the distressed surface down to sound concrete and overlay it with a thin bituminous layer until a complete restoration strategy can be applied. The State has found that the most effective restoration method for these concrete sections is to crack and seat/overlay the reactive aggregate pavement sections. They have had good success with crack and seat/overlay projects over 10 years of age and have little or no pavement distress on their high-volume interstate. Because of the success of crack and seat/overlay, there are currently less than 100 miles of exposed PCC pavements remaining under the supervision of the New Mexico State Highway and Transportation Department.

Partial-Depth Repair

Arkansas

The Arkansas State Highway and Transportation Department (AHTD) does not currently use partial-depth patching. AHTD has not found partial-depth patching to be a cost-effective rehabilitation method.

Colorado

No information was submitted for this restoration technique.

Kansas

The limits of the area to be patched shall be delineated at least 1 in outside the area to be patched by a saw and shall be sawed to a minimum depth of 2 in or as indicated on the plans. The connecting edges below the sawed portion shall be cut out and chipped to as nearly true lines with vertical faces as practical. If the depth of repair of an area designated for partial depth-repair exceeds 4 in, the entire area shall be removed and replaced as a full-depth patch when directed by the Engineer.

Sufficient old pavement shall be removed at each location to provide that a patched area shall contain not less than 1 square foot for partial-depth patches. All of the old pavement and old patching material shall be disposed of by the contractor. A portland cement grout consisting of a 1:1 by weight mixture of portland cement and Mortar Sand (FA-M) with a water/cement ratio of 0.60 by weight shall be applied in the area to be patched immediately prior to placing new concrete.

Edges of partial-depth patches will not be sealed; however, where a side abuts an existing joint, a compressible material 3.8 in wide extending the full depth of the patch shall be installed prior to pouring the patch.

Normal curing PCC patch material requires a minimum of 24 hours. A minimum of eight sacks (752 lb) of either Type I or II cement will be used. The handling of material, mixing, placing, and finishing concrete will conform to KDOT specifications. In addition, all concrete patching materials shall be air-entrained as defined by KDOT.

Accelerated curing PCC patch material requires a minimum of seven sacks (658 lb) of Type III cement. An amount of calcium chloride consisting of one to two percent by dry weight of the cement will be required to obtain the desired minimum compressive strength before opening the pavement to traffic. The calcium chloride shall be type II or equivalent as approved by the Engineer and will be added by solution. The solution is considered part of the mixing water. The calcium chloride used shall be subsidiary to other items of the Contract. One percent calcium chloride is required for a minimum curing time of 6 hours at 60°F or above, and 2 percent is required for a minimum of 4 hours curing time.

If the temperature falls below 60°F during the curing period of the normal or accelerated PCC patching material, a Schmidt rebound hammer will be used to determine when the patch can be opened to traffic. The patch may be opened to traffic when the results of the rebound hammer test equal or exceed results obtained on material previously cured under this specification or 60 percent of the rebound on adjoining pavement.

No patching will be performed when the ambient air temperature is below 40°F. The concrete in the patch will be thoroughly consolidated, struck off, finished with wooden floats, or other approved methods.

Missouri

Partial-depth patching requires removing all areas of unsound concrete, not to exceed 4 in deep, and replacing it with PCC or a bituminous material. The perimeter saw cuts must be 2 in deep if a PCC patch is going to be used. No perimeter saw cut is necessary if a bituminous mixture is used. The area must be cleaned to sound concrete and 1) treated with cement slurry and filled with portland cement concrete or 2) primed and filled with an approved commercial bituminous mixture compacted according to MoDOT specifications. When a PCC patch material is used and is not resurfaced, the overcut from the sawing operation shall be filled with an expansive mortar, epoxy, polyester, or joint material.

All material, proportioning, air-entraining, mixing, slump, and transporting of concrete shall be in accordance to MoDOT specifications, except a minimum cement requirement of 8-1/2 sacks per cubic yard and the maximum slump of 3-1/2 in shall be used. The surface of the repaired area must be finished to provide a smooth ride and shall not vary more than 3/16 in per 10 ft. The area shall not be opened to traffic until the concrete has attained a minimum compressive strength of 3500 psi.

If the repair is to be made and opened to traffic the same day, the concrete shall contain Type III cement and calcium chloride or an approved accelerator. An 8-1/2-sack Type I cement material may be used with an accelerator and other admixtures when approved by the engineer. In addition, the aggregate or water or both can be heated when the ambient temperature drops below 60° F. A minimum of 4 hours curing time and no minimum compressive strength will be required. Both transverse ends of all new portland cement concrete repairs shall be sawed 2 in deep and 3/8 in wide and sealed according to MoDOT specifications.

New Mexico

No information was submitted for this restoration technique.

Diamond Grinding and Grooving

Arkansas

The AHTD uses concrete grooving in selected locations to improve the skid resistance of the pavement. The grooves are 1/10 in wide and 3/16 in deep and are spaced 3/4 in apart for the designated distance. PCC grinding is used to substantially eliminate vertical differentials and to restore drainage, riding characteristics, and skid resistance to the pavement surface.

The grinding equipment shall be a power driven, self-propelled machine that is specifically designed to smooth and texture PCC pavement. The construction operation shall produce a uniform finished surface without damaging the existing pavement that is to remain. Grinding shall be accomplished in a manner that eliminates joint or crack faults while

providing positive lateral drainage by maintaining a constant cross-slope. Grinding shall transition as required to provide positive drainage and an acceptable riding surface. The pavement shall be ground in a direction opposite to normal traffic flow.

The entire area designated on the plans shall be ground until the pavement surfaces of adjacent sides of transverse joints and cracks are in the same plane. It is intended that the faulting at joints and cracks be eliminated, that substantially all of the pavement cracks be eliminated, and that substantially all of the pavement surface shown on the plans be textured. Extra depth grinding to eliminate minor depressions in order to provide texturing for 100 percent of the pavement surface will not be required.

The Contractor shall establish positive means for removal of grinding residue. Solid residue including joint material shall be removed from the pavement surface immediately. Residue shall not be permitted to flow across lanes used by traffic. Drainage facilities shall be kept free of accumulated residue.

The grinding process shall produce a pavement surface that is true to grade and uniform in appearance with a longitudinal line type texture. The line type texture shall contain parallel longitudinal corrugations that present a narrow ridge corduroy type appearance. The peaks of the ridges shall be approximately 1/32 in higher than the bottoms of the grooves with approximately 53 to 57 evenly spaced grooves per foot.

The finished pavement surface will be measured for roughness by the Department. The Mays Ride Meter equipped with a PCR 2000 digital recorder will be the measuring device. Roughness must meet a minimum ride rating of 78.4. Vertical misalignment of the planes of the surfaces on adjacent sides of the joints or cracks that is in excess of 1/16 in shall be ground until the surfaces are flush. The transverse slope of the pavement shall be uniform to a degree that no depressions or misalignment of slope greater than 1/4 in in 10 ft are present when tested with a straightedge placed perpendicular to the centerline.

Colorado

No information was submitted for this restoration technique.

Kansas

This work consists of grinding and texturing the existing portland cement concrete pavement longitudinally using a diamond grinder. Grinding shall be performed in the longitudinal direction so that grinding begins and ends at lines normal to the pavement centerline. The entire pavement surface area and adjacent shoulders shall be uniformly ground and textured until the surface on both sides of the transverse joints and all cracks are in the same plane and meet the required smoothness.

The grinding of auxiliary lanes or ramps shall transition as required from the mainline edge to provide positive drainage and an acceptable riding surface. The adjacent shoulders or pavement shall be ground to maintain an adequate cross-slope for drainage.

The surface of the ground pavement shall have parallel corduroy type texture consisting of grooves between 0.090 and 0.150 in wide. The land area between the grooves shall be between 1/16 and 1/8 in. The peaks of the ridges shall be 1/16 in higher than the bottom of the grooves.

The contractor shall provide positive means for removal of grinding slurry or residue by vacuum or other continuous methods. The grinding slurry shall not be allowed to flow across lanes being used by traffic. The pavement shall receive a final sweeping with power equipment before opening to traffic.

The grinding and texturing machine shall be self-propelled with diamond blades mounted on a multi-blade arbor having a minimum cutting head width of 3 ft. Equipment that causes excessive ravels, aggregate fractures, spalls, or disturbance of the transverse or longitudinal joints shall be repaired or replaced.

After completion of grinding and texturing, the pavement surface will be tested for smoothness and shall meet the surface tolerance for new pavement specified in the KDOT Special Provisions. The cross-slope of the pavement shall be uniform and shall not have depressions or misalignment of slope greater than 1/8 in in 10 ft when tested by stringline or straightedge placed perpendicular to the centerline.

Missouri

MoDOT uses concrete pavement grinding to provide good riding characteristics, a surface texture, and proper drainage. All pavement undersealing shall be completed prior to any grinding. The grinding equipment shall be a power-driven, self-propelled machine specifically designed to grind and texture concrete pavement using diamond blades. The effective wheel base must be long enough to minimize vertical fluctuations and must be able to grind a strip at least 3 ft wide. Generally, all of the pavement surface will be textured. It is not necessary to grind extra depth to eliminate minor depressions in order to provide texturing on 100 percent of the pavement surface.

The equipment shall be capable of grinding the surface without causing spalls at cracks, joints or other locations. Grinding should produce a uniform finished surface. It shall be accomplished in a manner that eliminates joint or crack faults and provides drainage by maintaining a constant cross-slope between grinding extremities. A tolerance not to exceed 1/16 in will be allowed for adjacent sides of joints and cracks, except that under no circumstances shall the grinding depth exceed 3/4 in from the top of the original surface. When grinding across faulted joints, a minimum of a 20 ft transition onto the approach side slab shall be used.

The transverse slope of the pavement shall conform to the typical section shown on the plans and shall have no depressions or misalignment of slope greater than 1/4 in in 12 ft when measured with a 12-ft straightedge placed perpendicular to the centerline. Areas of deviation shall be reground. Straightedge requirements do not apply across longitudinal joints or outside the ground area. After grinding, the surface will be straightedged longitudinally by the engineer and all variations exceeding 1/8 inch in 10 ft will be plainly marked and reground.

The grinding process shall produce a final pavement surface that is true to grade and uniform in appearance with a longitudinal line type texture. The line type texture shall contain parallel longitudinal corrugations that present a narrow ridge corduroy type appearance. The peaks of the ridges shall be approximately 1/32 in higher than the bottoms of the grooves with approximately 55 evenly spaced grooves per foot, measured perpendicular to the centerline. No overnight lane closures shall be done for grinding operations.

New Mexico

No information was submitted for this restoration technique.

Slab Stabilization

Arkansas

The AHTD does not use pressure grouting to stabilize faulted slabs. They have determined that attempting to stabilize faulted slabs has not proven very successful.

Colorado

No information was submitted for this restoration technique.

Kansas

This work consists of introducing a cement-fly ash mixture under pressure through holes drilled in the slab to fill the voids and depressions under the slab, displace the water from them, and reduce the damaging pumping caused by excessive pavement deflections. The purpose of subsealing is to stabilize the slab by filling the voids under it with a cement-fly ash mixture without raising the slab, except for areas designated by the Engineer that requires slabjacking to re-establish the profile through area that have settled.

The cement-fly ash mixture used for subsealing shall consist of the following:

- One part (by volume) portland cement (Type I or II).
- Three parts (by volume) fly ash.
- Sufficient water to achieve required fluidity.

All materials to be used in the grout slurry must be submitted to KDOT by prospective bidders prior to letting of the contract. Seven-day strength must be at least 600 psi according to AASHTO Test Method T-106, modified to the extent that fly ash will be substituted for the graded standard sand.

The fluidity of the grout slurry shall be measured by a flow cone method in accordance with ASTM C939. Time of efflux shall range from 9 to 15 seconds or as established by the Engineer. These measurements shall be made at least two times per day. This equipment is to be furnished and tests conducted by the contractor.

The grout injection holes shall be drilled in a pattern determined by KDOT in consultation with the contractor. They shall not be larger than 2 in in diameter, drilled vertically and round, and to a depth sufficient to penetrate any stabilized base and subgrade material. Subgrade penetration shall not exceed 3 in. These holes may be washed or blown to create a small cavity, to better intercept the void structure.

During the subsealing operation, a positive means of monitoring lift to the 0.001 in shall be used. The upward movement of the pavement shall not be greater than 0.125 in , except in those areas designated by the Engineer to be slabjacked. An expanding rubber packer or other approved device connected to the discharge from the plant shall be lowered into the hole. The discharge end of the packer or hose shall not extend below the lower surface of the concrete pavement. Each hole shall be pumped until maximum pressure is built up or material is observed flowing from hole to hole. Maximum allowable pressure shall not exceed 60 psi or other values specified by the Engineer to minimize slab raising, except that a short surge to 150 psi will be allowed when starting to pump the hole in order for the grout to penetrate into the void structure. The discharge pressure shall be monitored by an accurate pressure gauge in the grout line that is protected from the grout slurry. Water displaced from the void structure by the grout shall be allowed to flow out freely. Excessive loss of the grout through cracks, joints, or from back pressure in the hose or in the shoulder area will not be tolerated.

After the designated slabs have been pressure grouted according to the specifications, selected joints shall be retested by the contractor as specified. Slabs that deflect in excess of 0.025 in or as shown on the plans under an 18-kip axle load shall be regouted and retested. Any slab that continues to show movement in excess of that specified after two properly performed grouting may be accepted, or the Engineer may require a third attempt to stabilize the slab.

Upon completion of the subsealing, all drill holes shall be sealed flush with the surface of the pavement with a fast setting sand/cement material or other approved patching material. In the event that the Engineer determines that continued grout injection at any specific location is no longer feasible, he should direct the contractor to cease grout injection at that location. The contractor will be paid at the unit price for the material used up to that point.

Missouri

Pavement undersealing consists of furnishing, heating, hauling and pumping asphalt filler under a portland cement concrete pavement as defined by MoDOT specifications. Holes should be drilled 2 to 5 ft beyond the joint or crack in the direction of traffic and 3 to 6 ft from the edge of the lane being stabilized. Drilled holes shall be a maximum of 1-1/2 in in diameter, drilled vertically and round. Holes shall be drilled with a minimum of break out at the bottom of the pavement. Break out in excess of 1-1/2 in shall constitute an unacceptable hole and shall not be counted for payment. After the hole is drilled it shall be blown clean with air pressure.

Vertical movement of the undersealed pavement slab shall be tested. The contractor shall furnish equipment and personnel necessary to measure pavement lift to the nearest 0.001 in. This equipment shall measure lift relative to the reference points and be of a design satisfactory to the engineer. Pavement raised in excess of 0.20 in and cracked shall be replaced at the contractor's expense.

The asphalt filler shall be injected under the pavement progressively through drilled holes by means of a pressure distributor, capable of handling the necessary hoses, fittings, valves, a satisfactory nozzle for injecting the asphalt filler under the pavement without undue leakage at the point of injection, a pressure gauge to measure pumping pressure, and a recirculating system.

Prior to placing the pumping nozzle in the hole, the pavement around the hole shall be wetted to prevent any leakage of asphalt filler from adhering to the pavement. Pumping shall continue until asphalt filler appears at any longitudinal or transverse joint or crack, the pavement is raised a maximum of 0.20 in, when negative reading occurs, or when 20 gallons of asphalt filler have been pumped into one hole. As soon as the pumping has been stopped, a temporary plug shall be inserted in each hole, sufficiently tight to prevent waste of asphalt filler. Any extruded asphalt filler at cracks or joints shall immediately be wet with water and pumping stopped until the filler has cooled sufficiently to prevent further extrusion. All extruded asphalt filler shall be cleaned from the pavement and disposed of by the contractor.

No asphalt filler should be pumped when the pavement subgrade is frozen or when, in the judgment of the engineer, satisfactory results are not obtained. The temporary plug shall be replaced with a permanent plug as soon as the asphalt filler material has cooled enough to prevent extrusion. Permanent plugs shall consist of approved square or cylindrical wood plugs 4 to 5 in long driven flush with the surface of the pavement.

New Mexico

No information was submitted for this restoration technique.

Joint and Crack Sealing

Arkansas

Joint rehabilitation consists of sawing and cleaning existing transverse and longitudinal joints in portland cement concrete pavement, patches, approach slabs, and bridge decks, and filling and sealing the prepared joints with approved material according to these specifications.

Existing joints shall be sawed to expose a new concrete face, free of any joint sealer, and to provide a sealer reservoir. Joints shall be sawed to a sufficient depth to accommodate the joint sealer and backer rod as shown on the plans. Any existing joint inserts, regardless of type or material, that interfere with joint rehabilitation shall be removed. Any debris resulting from the removal of the inserts shall be disposed of according to AHTD specifications.

No joints, except those for concrete patches, shall be sawed after December 1 and before March 1 without written permission of the Engineer. All joints, except those for concrete pavement patches, shall be sealed within 15 calendar days after sawing. All joints shall be sealed before opening the pavement to traffic.

Within 15 minutes after sawing for joint installation, the joints shall be flushed with water under sufficient pressure to remove all slurry and residue left by the sawing operation. After flushing, the joints shall be blown out with compressed air to remove excess water.

When the joints are thoroughly dry, and just before sealer placement, both vertical faces shall be thoroughly cleaned by sandblasting with a nozzle attached to an aiming device that directs the sand blast at approximately a 45° angle and a maximum of 2 in from the face of the joint. Each joint face shall be sandblasted individually. After sandblasting, the joints shall be blown out with compressed air that has been filtered and is completely free of oil and moisture. The joints shall be thoroughly dry before sealer is placed.

All joints shall be filled and sealed the same day of the final sandblasting. Cleaned joints left open overnight shall be recleaned by sandblasting before filling and sealing. In the event freshly cleaned joints become contaminated before they are sealed, they shall be recleaned as specified above.

Backer material shall be installed in a manner that will result in the planned depth and shape for the sealant. If a primer is required, the primer shall be applied before installing the backer material. AHTD classifies rehabilitated joints into four types. Depending on the selected joint type, the appropriate joint sealant materials are specified.

Colorado

The Colorado Department of Transportation (CDOT) does not have a standard set of specifications for PCC restoration. Instead, revisions to the standard specifications are submitted for each individual project. The following information is an example of the revision of the specification for a past CDOT project.

This revision of the specification includes removing existing joint sealant, sawing, cleaning, and resealing of existing concrete pavement joint, and sawing, cleaning, sealing, or resealing random cracks.

The joint sealant material for sealing existing joints and cracks shall be a one-part, low-modulus silicone sealant designed for use in highway joint sealing applications. The contractor shall remove all of the existing sealant from the sealed joints with a plow, ripping tooth, wire brush, saw, or other equipment; however, no equipment shall be used which will cause spalling of the concrete pavement surface beyond the limits of the proposed joint widths.

The transverse joints, longitudinal joints (excluding joints with plastic parting strip), expansion joints, and random cracks shall be sawed to the widths and depths shown on the plans or as directed by the Engineer with a power-driven saw equipped with diamond blades. Any damage to the concrete pavement, such as spalling or overcutting, shall be repaired by the contractor.

The contractor shall thoroughly clean each sawed joint, random crack, and the adjacent pavement surface immediately after sawing by flushing with a water wash of sufficient pressure and volume to remove all of the cement dust and debris from the sealant removal and sawing operation. Following the initial cleaning of the sawed joints and random cracks with water, no more water shall be used to clean or prepare them for sealing. The use of a high-pressure water blaster to clean the sawed joints and random cracks will not be allowed.

Prior to placing joint sealant, the sawed joints and random cracks shall be sandblasted and cleaned thoroughly with oil-free compressed air. The sawed joints and random cracks shall be completely free of dirt, dust, moisture or other foreign materials that might prevent bonding of the joint sealant materials. No joint sealing will be allowed until the prepared sawed joints and random cracks have been inspected and approved.

The final cleaning operations shall be spaced far enough behind the joint sawing operation to avoid recontamination of the cleaned joints and random cracks with residual water from the sawing operation. On uphill grades, an approved procedure shall be employed which will prevent residual water from the sawing operation from flowing into the previously cleaned and sealed joints and random cracks. Joints and random cracks that are contaminated as a result of the contractor's sawing operations shall be recleaned at the

contractor's expense. No joint sealing will be allowed until the recleaned joints and random cracks have been inspected and approved.

Joint sealing shall be accomplished only when the ambient and pavement temperature is 40° F or higher and the weather conditions are dry. Closed-cell polyethylene foam backer rod is placed in the joints and random cracks to the depths shown on the project plans in order to control the depth and cross sectional shape of the sealant, and to control the bond between the sealant and the concrete. The rod diameter shall be 1/8 in larger than the final saw cut width of the various joint configurations so that it fits snugly in the joint and is not displaced during sealant application. The rod shall be placed in such a manner that the proper depth of sealant material is maintained for all joints. At transverse and longitudinal joint intersections, one of the backer rods shall be cut and butted up against the intersecting backer rod in order to maintain the proper depth of sealant. Care shall be taken not to let the cut backer rod be displaced prior to or during sealing operations.

The joint sealant materials shall be applied and tooled in strict conformance with the manufacturer's recommended procedures. A representative of the sealant manufacturer shall be present at the job site during the initial sealing operations.

Kansas

No information was submitted for this restoration technique.

Missouri

No information was submitted for this restoration technique.

New Mexico

No information was submitted for this restoration technique.

Load Transfer Restoration

Arkansas

To date, AHTD has not used retrofitted dowel bars to restore load transfer at transverse joints.

Colorado

No information was submitted for this restoration technique.

Kansas

Epoxy-coated dowel bars 1-1/2 in by 18 in shall conform to KDOT specifications. All surfaces of the dowel bars, including the ends, shall be epoxy coated. The dowel bars shall have a tight fitting sleeve on one end. The sleeve shall be made of nonmetallic materials. The sleeve shall be approved by the Engineer prior to use.

Chair devices for supporting and holding the dowel bars shall be either epoxy coated or made of non-metallic material. The chair devices shall provide a minimum clearance of 1/2 in between the bottom of the bar and the surface upon which the chair is placed. The chair shall be designed to prevent movement of the bar during placement of the grout. The chair devices shall be approved by the Engineer prior to use.

The caulking filler shall be a silicone sealant. The sealant shall be approved by the Engineer prior to use. The foam core board filler material shall be closed cell foam faced with poster board material on each side. The foam core board filler shall be 1/2 in thick. The foam core board filler material shall be approved by the Engineer prior to use.

The grout placed around the dowel bars shall be one of the following materials: FOSROC-PATCH 10-60, FIVE STAR HIGHWAY PATCH, or MASTERFLOW 928. The Engineer will approve the grout material on the basis of the name brand.

The following construction requirements must be followed to install the dowel bars. Saw cut the existing pavement as required to place the center of the dowel at mid-depth in the concrete slab. Make multiple, parallel saw cuts if necessary to remove existing concrete from the slot. If jackhammers are used to break loose the concrete, avoid the use of hammers weighing in excess of 30 lb.

Sandblast and clean all surfaces of the slot. Sandblast and clean all cracks in the slot. Fill the transverse crack in the bottom of the slot with caulking filler. Use chair devices to support the dowel bars at the depth shown on the plans. Place the dowel bars parallel to the centerline of the pavement and parallel to the pavement surface. Place the dowel bars within 1/4 in of the desired position.

Cut a piece of the foam core board filler material to fit tightly around the dowel bar and against the bottom and sides of the slot. Place the foam core board filler material vertically above the transverse crack in the bottom of the slot. Maintain the material in the vertical position during placement of the grout. Place the grout as recommended by the manufacturer.

Missouri

No information was submitted for this restoration technique.

New Mexico

No information was submitted for this restoration technique.

Shoulder Restoration

Arkansas

The AHTD Standard Specifications for Highway Construction only include specifications for adding a PCC shoulder. The following information pertains to add-on PCC shoulders.

This specification consists of adding a portland cement concrete shoulder to an existing concrete pavement according to these specifications and conforming to the lines, grades, thickness, and typical cross section shown on the plans. Tie bars (#5 x 24 in) are placed at 30 in centers along the longitudinal joint at mid-slab depth. A 6 in coating is required on each tie bar. The coating crosses the new longitudinal joint. A 1/8 to 3/8 in by 2 1/4 in sawed joint is to be filled with a joint sealant. The concrete, joint, and curing materials shall comply with AHTD specifications.

- The construction specifications require that the add-on shoulder meet the AHTD construction standards and the following additions:
- The transverse joints shall match the transverse joints in the existing pavement.
- The longitudinal profile of the concrete shoulder shall match the longitudinal profile of the existing pavement edge.
- The transverse slope of the concrete shoulder shall be specified on the plans. The slope shall vary no more than 1/8 in per foot (10 mm per meter) from the planned slope.
- The final surface finish shall be accomplished using a burlap drag or broom. Concrete corrugations are 4 ft long and are placed on 100 ft centers.

Colorado

No information was submitted for this restoration technique.

Kansas

No information was submitted for this restoration technique.

Missouri

No information was submitted for this restoration technique.

New Mexico

No information was submitted for this restoration technique.

Drainage Restoration

None of the respondents provided specifications pertaining to retrofitted drainage. Several States did include specifications for the installation of new edge drains. However, since these specifications do not directly address PCC restoration policies, they are not included in this report.

The following information was obtained from a survey conducted as part of a separate ERES project regarding the use of retrofitted edge drains.⁽¹²²⁾ The results of that survey indicated that Colorado does not use retrofitted edge drains. Arkansas and Texas did not respond to the survey.

In Kansas, edge drains are placed in the shoulder joint at the bottom of the base in a trench that is 4 in wide and 4 in deep. The unwrapped pipe has a 4 in diameter and is made of PVC or PC, and the opening is specified according to ASTM. An outlet spacing of 500 ft as given. It should be noted that fin drains were not used.

Missouri uses retrofitted edge drains that are placed in the shoulder joint at the bottom of the base. An unwrapped 4 in diameter plastic pipe with AASHTO opening specifications is used. A sand backfill is used, and an outlet spacing of 250 to 500 ft is used.

New Mexico responded that retrofitted edge drains were used at the shoulder joint and that they were placed at the bottom of the slab. No other information was included in the survey.

5. SUMMARY OF CURRENT OKLAHOMA GUIDELINES AND SPECIFICATIONS

Of the eight PCC restoration methods discussed in this report, only diamond grinding is included in the ODOT Standard Specifications for Highway Construction. Included in the ODOT standards are full-depth patching, partial-depth patching, slab stabilization, and joint and crack sealing. Each of these restoration methods is described below.

Full-Depth Repair

A minimum length of 4 ft is specified for full-depth patches. The full-depth patch width options include a full 2-lane patch, a single full-lane patch, an interior edge patch, an exterior edge patch, and a rectangular plug patch.

All damaged PCC pavement must be removed in a manner to minimize damaging the base material or adjacent pavement. No compensation will be made to the contractor for repairing damage sustained during the removal process. If required, undercutting and related backfilling of subbases or subgrade will be shown on the plans.

All transverse expansion joints are formed using a 3/4 in by 7 1/4 in remolded bituminous fiber. The surface of the joint is then edged and sealed with 1-1/2 in of hot poured sealing filler.

The following notes are included as part of the ODOT standards:

- Dowel bar sets (4 bars on 12 in centers) with bond breaker caps) shall be used when a reconstructed full-width joint repair falls within 4 ft of the original joint. When more than one reconstructed joint falls within 4 ft of the original joint (i.e., the patch spans the original joint), then the reconstructed full-width joint nearest to the original joint will be constructed using the 4 dowel design pattern described above.
- If the patch extends beyond 4 ft in both directions, from an original full-width transverse joint, then the original full-width joint will be reconstructed using the 4 dowel pattern described above.
- Full-width reconstructed joints located 4 ft or more from an original joint and not covered by the previous instructions shall be reconstructed using transverse tie bar joints. Overall patch length shall not exceed 7 ft (15 ft jointed pavement) and 15 feet (62 feet jointed pavement), unless otherwise shown on the plans.

The full-depth repair procedure uses both tie bars and dowel bars. Tie bars are used on longitudinal and transverse joints and dowel bars are used on transverse joints.

The specifications for tie bar joints are as follows. Tie bars will be epoxied into drilled holes at mid-slab. Each drilled hole and tie bar shall be placed parallel to the driving surface with sufficient epoxy to completely fill the void between the tie bar and the hole. The specifications for the longitudinal and transverse joints are described as:

- Longitudinal tie bars are #5 deformed reinforcing steel bars that are 30 in long. They shall be epoxied into a maximum hole diameter of 3/4 in and spaced at 30-in centers. Tied longitudinal joints shall be sawed and sealed.
- Transverse tie bars are #10 deformed reinforcing steel bars that are 18 in long. They shall be epoxied into a maximum hole diameter of 1-3/8 in and spaced at 18 in centers. Tied transverse joints shall not be sawed or sealed.

Dowel bars are 1-1/4 in in diameter and 18 in long. They are smooth and coated with a bond breaker cap or a plastic or approved material as a bond breaker on half of the length of the bar. This will ensure that the bond between the dowel bar and the concrete patch is broken.

Dowel bars shall be epoxied (non-capped end) into an 1-3/8 in maximum diameter by 9 in deep drilled hole. The dowel shall be placed at mid-slab and be placed parallel to the driving surface. Sufficient epoxy shall be used to completely fill the void between the dowel bar and the hole.

Partial-Depth Repair

Partial-depth repairs are a minimum width of 6 in and a minimum length of 2 in. The partial depth saw cuts are done at 90° angles with respect to the transverse and longitudinal joints, with nominal overlapping at the corners of 3 in. The entire perimeter of the patch shall be sawed. The saw cuts shall be performed at a minimum setback distance of 2 in and 1 in from the width and length of the pavement distress, respectively.

A maximum 15 lb chipping hammer may be used to remove the debris from the concrete patch up to the perimeter saw cuts. A maximum depth of 4 in horizontal to the existing pavement surface may be removed.

The patch surface must be primed with an epoxy bonding agent. A temporary compressible joint material must be placed in the joint to a depth of 4-3/4 in before placing the patching material. After the patching material has cured the joint shall be sawed and sealed. All patch edges, other than original transverse or longitudinal joints, shall not be sawed or sealed. All overlapping sawcuts at the corners of the patches shall be sealed according to the roadway standard LECS-2.

Diamond Grinding

The grinding equipment shall be a power driven, self-propelled machine that is specifically designed to smooth and texture portland cement concrete pavement with diamond blades. The effective wheel base of the machine shall not be less than 12 ft. It shall have a set of pivoting tandem bogey wheels at the front of the machine, and the rear wheels shall be arranged to travel in the track of the fresh cut pavement. The center of the grinding head shall be no further than 3 ft forward from the center of the back wheels.

The equipment shall be of a size that will cut or plane at least 3 ft wide. It shall also be of a shape and dimension that does not encroach on traffic movement outside of the work area. Equipment that causes excessive ravels, aggregate fractures, spalls, or disturbance of the transverse and longitudinal joints or cracks will not be permitted.

Grinding shall be performed in the longitudinal direction so that grinding begins and ends at lines normal to the pavement centerline. The entire area designated on the plans shall be ground until the pavement surfaces of adjacent sides of transverse joints and cracks are in the same plane. Extra depth grinding to eliminate minor depressions in the pavement to obtain 100 percent texturing will not be required.

The construction operation shall be scheduled and proceed in a manner that produces a uniform finished surface. Grinding shall be accomplished in a manner that eliminates joint or crack faults, while providing a positive lateral drainage by maintaining a constant cross-slope between the edges of grinding operations. Auxiliary or ramp lane grinding shall transition as required from the mainline edge to provide positive drainage and an acceptable riding surface.

The grinding process shall produce a pavement surface that is uniform in appearance with a longitudinal line type texture. The surface shall have grooves between 0.09 and 0.15 in wide, spaced up to 0.125 in apart. The peaks of the ridges shall be approximately 1/16 in higher than the bottom of the grooves.

The contractor shall provide positive means for removal of grinding slurry or residue by vacuum or other continuous methods. Slurry shall not be allowed to flow across lanes being used by traffic.

All ground surfaces shall be profiled by the contractor for smoothness using the profilograph specified on the plans or in the proposal. Profiles will be made 3 ft from and parallel to each edge of pavement and at the approximate location of each longitudinal joint for all pavement areas. Pavement so tested shall have a profile index of 5 in/mi or less using a 0.2 in blanking width. Individual high points in excess of 0.3 in, as determined by measurements of the profilograph, shall be reduced by grinding until such high points, as indicated by reruns of the profilograph, do not exceed 0.3 in.

After grinding has been completed to reduce individual high points in excess of 0.3 in, additional grinding shall be performed as necessary to reduce the profile index to values specified above in any 0.1 mi section along any line parallel with pavement edge.

Additional grinding shall be performed as necessary. All ground areas shall be neat rectangular areas of uniform surface appearance.

Slab Stabilization

Slab stabilization generally is not a stand-alone restoration technique. The following steps outline the standard procedures used for concrete patching, slab stabilization, diamond grinding, and joint rehabilitation (initial and final).

- All areas to be patched shall be removed and replaced using full-depth patching procedures.
- Slab stabilization shall be done using 2 in diameter (2-1/5 in maximum) core holes drilled to a depth of 2 in into the stabilized base material in a manner approved by the Engineer. Once the pressure grouting is completed, the core hole shall be sealed. Pressure grouting of the slab shall be done in accordance with plans or applicable special provisions.
- After the slab stabilization has had time to cure, diamond grinding may begin.
- The initial cut and subsequent sealing shall begin at the high edge of the driving lanes and move toward the low edge.
- The final joint cut shall begin at the low edge of the driving lanes and move toward the initial joint. Installation of the bond breaker and silicone joint sealant shall be from the end of the initial joint to the low edge of the driving lanes.

Joint and Crack Sealing

The following sequence of operations for joint rehabilitation is suggested:

1. Saw existing longitudinal and contraction joints to width and depth required according to Standard LECS-2.
2. Blow out joint with compressed air immediately after sawing.
3. Sandblast joint. Blow clean and immediately place backer rod.
4. Blow joint clean with compressed air and fill clean joint with sealant within 2 minutes.
5. Allow curing time for silicone sealant.

6. RESULTS OF THE ODOT DIVISION SURVEY

A survey was sent to six of the eight ODOT Divisions to determine the current restoration practices employed by the Divisions. The following list summarizes both the questions and the responses. Note that not all Divisions responded to the questionnaire. The questions and responses are divided into the restoration categories detailed in this report.

Full-Depth Repair

How extensively are FDRs used in your division?

- Somewhat.
- Continuously on I-40 and US-69 and intermittently for other highways.
- Rare.
- Sparingly.

What criteria are used to determine if FDRs are required?

- Failure.
- Severity of cracking, joint deterioration.
- Collapsed failures.
- Concrete panels must be fractured.

How are the repair boundaries established?

- Limits of failure.
- Minimum 4 ft long and always full lane width.
- Nearest undamaged surface.
- Cost.

What removal methods are used (e.g., saw cutting, removal of PCC)?

- Saw & break.
- Saw cut and lift out slabs, they do not break-up.
- Sawcutting, 80 lb pavement breaker.
- Sawing and lifting or demolish.

Are base or subgrade repairs made and, if so, how?

- Cut out and use crusher run.
- Rarely. Like material used and tamped with wacker-packer.
- As required, remove and replace.
- Milled, modified, and compacted.

Are load transfer devices (dowels or tiebars) installed and, if so, how?

- Yes, drill.
- Dowels (No. 9 rebar) used at sawed faces (construction joints) and dowel bar baskets used at expansion joints.
- Not consistent.
- Installed with baskets or drill and seat.

What type of PCC materials are used for the patch (e.g., PC type, mix design, aggregate gradation)?

- Class A concrete.
- Standard Specification Class A ready mix.
- Class A high early strength portland cement concrete, Standard ODOT Specifications.
- ODOT Class AA PC paving.

What curing techniques are used and for how long?

- White cure.
- Coated with linseed oil immediately after placement.
- Linseed oil.
- Curing compound and cover with mats.

Are special cold- or hot-weather concrete practices used and, if so, what?

- No.
- No special hot/cold weather practices followed; however, we have tried some fast-track methods in traffic-sensitive areas such as using high-early strength mixes and expediting cure with use of plastic moisture barrier cover and black felt paper (to draw heat).
- Setting retarders or warm water.

What have been the successes and failures with FDRs?

- Mixed.
- Failure: Part or entire patch drops in relation to surrounding pavement.
Success: Patch performing its intended purpose.
- Insufficient experience - N/A.
- When dowels have not been placed, failures began within a short time (3 months).

What suggestions do you have for improving the FDR process?

- Replace more areas.
- None.
- Consider fast track paving materials.
- Full-depths need dowels, underdrain, base repairs, and joints sealed.

Are there any well performing and poorly performing FDRs in your division that would be suitable for testing and long-term evaluation?

- Yes.
- Some of both.
- On I-40 from Choctaw Road east to County Line.

Partial-Depth Repair

How extensively are PDRs used in your division?

- None.
- PDRs are not used.
- Extensive.
- Only on bridge decks.

What criteria are used to determine if PDRs are required?

- Poor ride conditions.
- Design division determines criteria.

How are the repair boundaries established?

- As required to establish acceptable ride.
- By design division.

What removal methods are used (e.g., sawcutting, removal of PCC)?

- Remove loose debris.
- Sawing or chipping.

What surface preparation procedures are used on the underlying concrete?

- None.
- Cleaned.

What type of PCC materials are used for the patch (e.g., PC type, mix design, aggregate gradation)?

- Typically asphaltic concrete mixes.
- High early strength Class AA PC paving.

What curing techniques are used and for how long?

- None.
- Curing compounds and mats.

Are special cold- or hot-weather concrete practices used and, if so, what?

- No.
- None.

What have been the successes and failures with PDRs?

- Temporary.
- Failures, I-40 Crosstown westbound bridge, repairs are potholing.

What suggestions do you have for improving the PDR process?

- Forget them.

Are there any well performing and poorly performing PDRs in your division that would be suitable for testing and long-term evaluation?

- Failures, I-40 Crosstown westbound bridge, repairs are potholing.

Diamond Grinding and Grooving

How extensively are diamond grinding and grooving used in your division?

- Very little.
- Limited, no recent project.
- A lot.

What criteria are used to determine if diamond grinding and grooving are required (faulting, rideability, friction)?

- Friction.
- Faulting and rideability.
- Rideability.

How are the repair boundaries established?

- Usually if a concrete pavement is faulted the entire section is ground.
- Design division.

What are the specific procedures used?

- No specifics.
- Design division.

Is diamond grinding and grooving typically performed only in the outer lane or in all lanes?

- Typical not established, we have done some of both.
- All lanes.

Is load transfer restoration typically performed in conjunction with diamond grinding?

- No.
- Test areas of dowel bar retrofit.

What have been the successes and failures with diamond grinding and grooving?

- Failures: Existing PC that has been doweled into fails below the dowel.
Success: The patch holds up.
- Grinding provides a great ride but results in loss of surface friction.

What suggestions do you have for improving diamond grinding and grooving processes?

- Address load transfer.
- Need a transverse grooving operation that is cost effective.

Are there any well performing and poorly performing diamond grinding or grooving projects in your division that would be suitable for testing and long-term evaluation?

- Yes.
- On I-40 from Choctaw Road east to County Line.

Slab Stabilization

How extensively is slab stabilization used in your division?

- None.
- Intermittently.
- Minimal, typical bridge approaches.
- Frequently.

What criteria are used to determine if slab stabilization is required?

- Slabs dropped or moving greater than 1 in.
- Loss of acceptable ride.
- Broken panels, uneven pavement slabs.

What slab stabilization techniques are used?

- Mudjack, Uretex.
- Mud Jack currently "URETEK" Polyurethane.
- Cement grouts.

What grouting materials are used?

- Soil cement slurry, urethane.
- Past history fly ash or portland cement.
- Cement grouts.

How were the procedures performed?

- Drill holes and pump material.
- By contract.

Have the procedures been successful?

- Yes.
- Marginally.

Were any problems encountered with the procedures?

- Few.
- Time and traffic.

What suggestions do you have for improving the slab stabilization procedures?

- Better injection methods and materials.
- Dowel retrofit and grooving.

Are there any well performing and poorly performing slab stabilization projects in your division that would be suitable for testing and long-term evaluation.

- Yes
- I-40 from Choctaw Road east to County line.

Joint and Crack Sealing

How extensively is crack and joint sealing used in your division?

- Moderate.
- Not used for PCC.
- Have had no active PCC crack and joint sealing procedures.
- Sparingly.

What criteria are used to determine when crack and joint sealing is required?

- Failure.
- Condition.

What preparation procedures are performed?

- Clean.
- Resaw and cleaned.

What types of sealants are used?

- Silicone.
- Poly seals with backer rod.

What installation methods are used?

- Normal.
- Placed rod and pressure sealed.

What have been the successes and failures with crack and joint sealing?

- Very few failures.
- On I-40 from Choctaw Road east to County line.

What suggestions do you have for improving crack and joint sealing procedures?

- Continuous maintenance.

Are there any well performing and poorly performing crack and joint sealing projects in your division that would be suitable for testing and long-term evaluation?

- Yes.
- On I-40 from Choctaw Road east to County line.

Load Transfer Restoration

How extensively is load transfer restoration used in your division?

- None.
- Only in FDRs.
- Sparingly.

What criteria are used to determine if load transfer restoration is required?

- All FDRs address load transfer.
- Need.

How are the repair areas established?

- Same as in #1 above.
- Cost.

What are the specific procedures used?

- Same as in #1 above.
- Pavement removal and replacement or retrofit.

Have load transfer devices other than dowels been used?

- No.
- None.

What have been the successes and failures with load transfer restoration?

- Failure: Existing PC that has been doweled into fails below the dowel.
Success: The patch holds up.
- Great success in stabilizing pavement panels.

What suggestions do you have for improving load transfer restoration processes?

- None.
- Retrofit and surface grooving.

Are there any well performing and poorly performing load transfer restoration projects in your division that would be suitable for testing and long-term evaluation?

- Yes.
- On I-40 from Choctaw Road east to County line.

Shoulder Restoration

How extensively is shoulder restoration performed in your division?

- Very little.
- Intermittently.
- Only performed at total loss with overlay reconstruction.
- Some.

What criteria are used to determine when shoulder restoration is required?

- Failure.
- Shoulder material deteriorated past the point of routine maintenance being effective.
- Condition.

Is shoulder restoration a stand-alone procedure, or is it always performed with other techniques?

- Stood alone.
- Sometimes stand-alone and sometimes in conjunction with overlay.
- Both.

What types of procedures are used?

- Remove and replace.
- Remove and replace.

Are the majority of shoulders AC, PCC, or granular materials?

- AC.
- Majority along PCC is Armor Coat (chip and oil) on soil cement. The rest is split between AC and PCC.
- AC.

Were any problems encountered with the procedures?

- No.
- When removing solid cement shoulders with motor grader, large blocks will sometimes come out, leaving an irregular base for paving operation. Cold milling works well.
- Poor research as to condition of pavement edge and location.

What suggestions do you have for improving the shoulder restoration procedures?

- For Armor Coat over soil cement, cold mill and asphalt overlay.
- Through research.

Are there any well performing and poorly performing shoulder restoration projects in your division that would be suitable for testing and long-term evaluation?

- No.
- Yes.
- On I-40 from Choctaw Road east to County line.

Drainage Restoration

How extensively is retrofitted drainage used in your division?

- Some on new surfaces.
- Sparse.
- Sparingly.

What criteria are used to determine if drainage is required?

- None.
- Obvious need.

What types of drainage retrofit techniques are used?

- Retrofit edge drain.
- Underdrain parallel to pavement at shoulder joint.

Were any problems encountered with the procedures?

- Not involved during installation.
- Pavement edge not smooth.

What suggestions do you have for improving the retrofit drainage procedures?

- None.
- Removing shoulder, install, and repave.

Are there any well performing and poorly performing retrofit drainage projects in your division that would be suitable for testing and long-term evaluation?

- One poorly performing that may be suitable for testing and evaluation.
- Poor research as to condition of pavement edge and location.

7. RECOMMENDATIONS AND CONCLUSIONS

Interim Report I was prepared using current information on materials and techniques. PCC pavement restoration is a rapidly evolving field, and much of the information presented may be outdated at the conclusion of the project. Therefore, ERES will update the literature review prior to inclusion into the final project report.

This report is meant solely as a review of current literature and does not constitute suggested guidelines or specifications. Interim Report II will provide specific recommendations on restoration procedures suited to Oklahoma.

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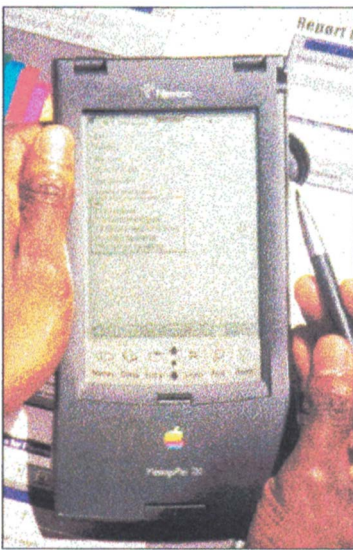
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