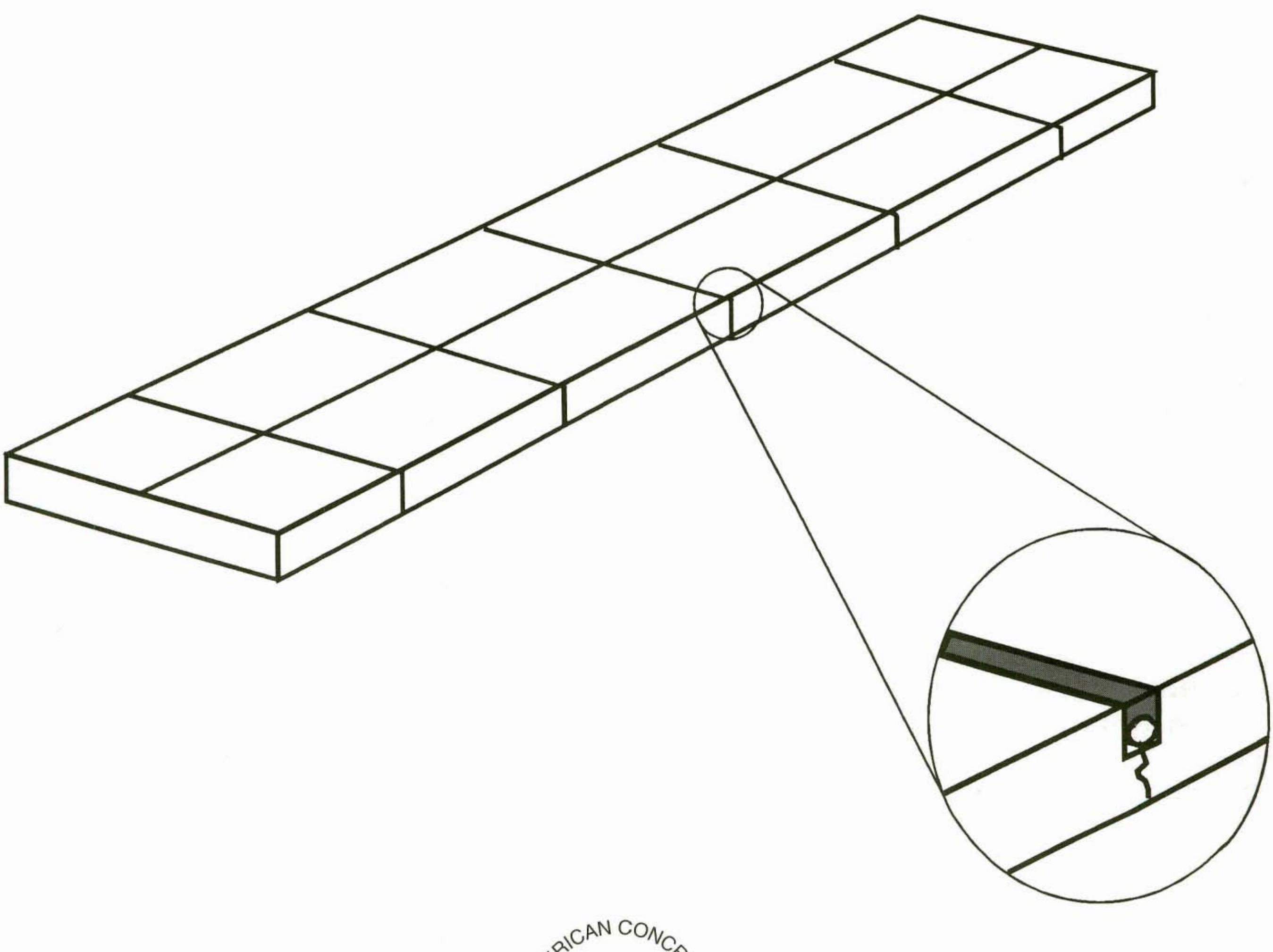
CONCRETE PAVING Technology

Joint and Crack Sealing and Repair for Concrete Pavements



AMERICAN CONCRETE PAVEMENT ASSOCIATION

Purpose

This publication describes the philosophy of concrete pavement joint sealing and outlines the necessary steps in sealing and resealing joints. Recommendations apply to currently acceptable sealant materials for use in roadway and airport facilities. Also described are available methods for crack repair and load transfer restoration of pavement joints.

Introduction

The purpose of joint sealant is to minimize infiltration of surface water and incompressible material into the joint system (1,2,3). Sealants also reduce dowel bar corrosion potential by reducing entrance of de-icing chemicals. Pavement engineers have recognized the need for concrete pavement joint sealants for many years. Sealant use dates back to the early 1900's (4,5). Today, nearly every agency building and maintaining concrete roadways or airports requires joint sealing.

Basic Considerations - Water can contribute to subgrade or subbase softening, erosion and pumping of subgrade or subbase fines. This degradation results in loss of structural support, pavement settlement and/or faulting (3,6,7,8). Unfortunately it is not practical to construct and continually maintain a completely watertight pavement. Therefore engineers use joint seals to minimize passage of surface water through joints.

Sealing prevents incompressibles from entering joint reservoirs. Incompressibles contribute to spalling and in extreme cases may induce "blow-ups" (9). In either case excessive pressure along the joint faces results as incompressibles obstruct pavement expansion in hot weather. Years ago, the term "joint fillers" described materials placed in joints (10). These materials aided more in keeping out incompressibles than minimizing water infiltration.

Many factors play a role in joint and sealant design. Sealant material selection considers: 1) environment, 2) life-cycle cost, 3) performance, 4) joint type, and 5) joint spacing (2,3,4,11,12).

Required sealant characteristics differ for different joint types (1). A sealant for a longitudinal joint does not need to be as elastic as one for a transverse joint. This is because tied joints, like those separating longitudinal lanes and shoulders, undergo virtually no movement. Transverse joints in long-panel reinforced pavements open wide when air and pavement temperatures are cool. Transverse contraction joints of short panels [<20 ft (6 m)] undergo similar but smaller movements. These movements induce larger states of stress and strain within a sealant than typically found in a longitudinal joint. The sealant must be capable of handling these states in order to perform over the range of expected joint movement.

Reservoir dimensioning is a significant aspect of sealant design and performance. Reservoir dimensions are set to help the sealant material withstand joint opening and closure movements. An improperly dimensioned reservoir will not allow the maximum performance from any sealant.

The most critical aspect in sealant performance is reservoir preparation. A considerable investment in joint preparation and cleaning activities is necessary for almost all sealant types. There is little doubt that poorly designed and/or constructed joint sealants will perform poorly.

Some pavement design factors also influence sealant performance despite installation quality. Under high traffic conditions and poor drainage design even traditionally non-erodible base materials can cavitate. Mechanical load transfer and positive pavement structure drainage reduce potential for pumping and joint faulting. Sealants can be damaged by these problems. Slab size design is also critical to negate the impacts of temperature curling and moisture warping.

Use of expansion or pressure-relief joints in concrete pavement may negate the effectiveness of any sealant. In the past, designers placed transverse expansion joints to relieve compressive forces in the pavement and limit blow-ups. However, in many cases the expansion joints allowed too much opening of adjacent transverse contraction joints which led to loss of aggregate interlock and sealant damage (1). By eliminating unnecessary expansion joints, contraction joints will remain tight and provide good load transfer and effective seals.

Necessity—

Debate on the need for joint sealing has raged for many years. The basis for debate hinges on the effectiveness of joint sealants. Widespread belief is that sealing prolongs pavement life by providing protection. This has been substantiated in many field studies (12,13,14,15,16,17,18). However, there have also been studies which show a negligible or even negative impact of joint sealing (19,20,21).

Water is definitely a contributor to pavement distress. For many years, concrete pavement designs included relatively impermeable materials surrounding the pavement layers. These "bathtub" pavement sections were particularly prone to moisture-related problems (8,12,22). The need to minimize water infiltration in these pavements focused increased attention to joint sealing.

To maximize pavement performance the designer must provide a means to control water. Limiting the amount of water that can get to the base and subgrade layers is one key element. Providing a system to efficiently remove water from within the pavement layers is another key. The pavement surface is just one of five points of water entry into a pavement and subgrade (Figure 1) (3). Water present in the soil can migrate to critical locations in a pavement through capillary action and water vapor from the water table. Water may also come from the edge of shoulders, from poorly designed or maintained ditches and from natural high-ground runoff. However, surface water is typically the largest source and has the greatest impact on the pavement system.

Justifiably, much attention is paid to sealant effectiveness because joints are controllable access points for surface water. In the past, some engineers thought sealing was not cost-effective because of poor performance of the most common materials (13). Improvements over the past 30 years have produced effective sealing materials and procedures. Correct sealant application and maintenance can minimize water damage and increase pavement longevity (17,23).

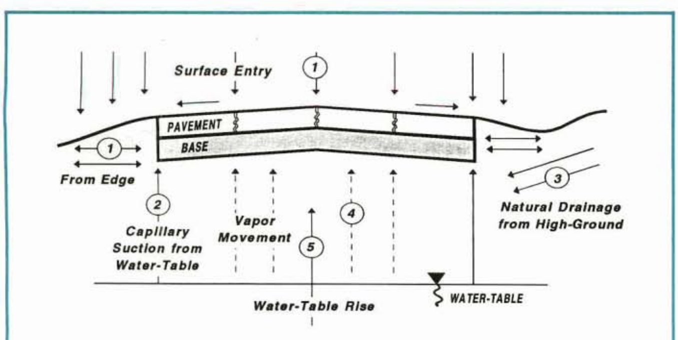


Figure 1 *Avenues for water infiltration into a pavement system (3).*

Recently permeable bases have grown more popular as a means to control water in a pavement system (8). Permeable bases use a uniform gradation which leaves many voids for water passage. Under a pavement, water flows quickly through a permeable base to an edge drain system. The drainage system carries water away from the subgrade to ditches or storm sewer pipes. Many agencies are also successful installing edge drain systems along existing concrete pavement. These outlet systems require frequent maintenance for satisfactory long-term performance.

Joint sealing is still recommended, even on pavements supported by permeable base layers. Some agencies have hypothesized that a permeable base may make sealing unnecessary by negating the need for surface water control. Although this seems logical and some successful field experiments support the idea, significant substantiation is not yet available. An engineer should also consider the impact of incompressibles on the decision to omit joint sealing. Incompressibles that get into open joint reservoirs can cause spalling upon joint closure. This is less likely on slabs less than 20 ft. (6.1 m), because the closure is quite small. However, studies show sealing reduces joint spalling even on short-panel pavements (Figure 2) (17).

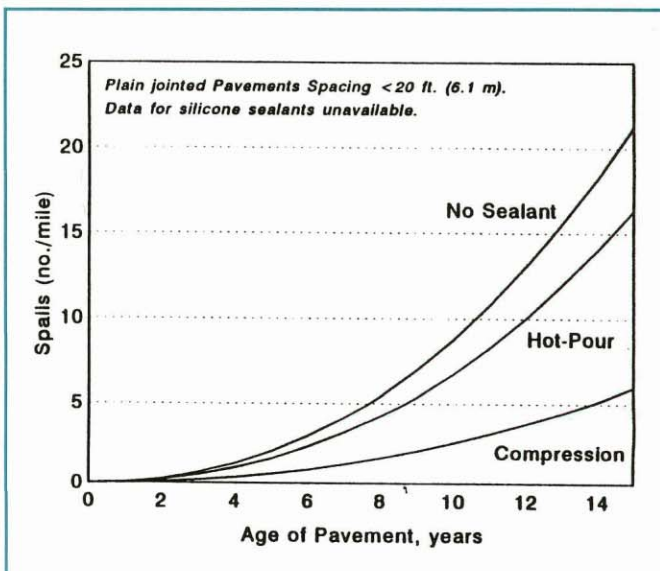


Figure 2 *Transverse joint spalling developed on short panel pavements with and without sealants. Note that the joints were sealed only once at initial construction - maintenance of joint seals would have decreased the development of spalling in joints sealed with hot-pour (17).*

Materials

There are many acceptable materials available for sealing joints in concrete pavements. Sealants are either liquid or preformed. Liquid sealants depend on long-term adhesion to the joint face for successful sealing. Preformed compression seals depend on lateral rebound for long-term success. Table 1 gives descriptions and specifications of the available materials (1).

While many agencies specify single-component cold-pour sealants, there are no standard national specifications for these materials. Each agency must either use the manufacturer's recommendations or develop its own specification.

Sealant properties necessary for long-term performance depend on the specific application and the climatic environment of the installation. Properties to consider include:

- Elasticity: The ability of a sealant to return to its original size when stretched or compressed.
- Modulus: The change in internal stresses in a sealant while being stretched and compressed over a range of temperatures (stiffness of material). A low modulus is desirable and is particularly important in cold weather climates.
- Adhesion: The ability of a sealant to adhere to concrete. Initial adhesion and long-term adhesion are equally important. (Not applicable to compression seals.)
- Cohesion: Ability of a sealant to resist tearing from tensile stresses. (Not applicable to compression seals.)
- Compatibility: Relative reaction of the sealant to materials which it contacts (such as backer rods and other sealants).
- Weatherability: Ability of a sealant to resist deterioration when exposed to the elements (primarily ultra violet sun rays and ozone).
- Jet Fuel Resistance: Ability of a sealant to resist degradation in contact with jet fuel. Some material swelling may occur in contact with jet fuel. Upon evaporation the sealant material must return to original shape and maintain adherence to the reservoir walls.

Specifiers and contractors should always contact the sealant manufacturer and read product literature for warnings of safety and environmental hazards. Project leaders should thoroughly explain potential health hazards to all project personnel. This ensures that inspectors and contractor personnel are aware of any possible hazards before handling a product. Agency designers should also consider the costs of handling and disposing of environmentally hazardous materials in life-cycle cost analysis.

Hot Pour Liquid—

Hot-pour liquid sealants were the first type used for concrete pavement. They have evolved over many years of research and development. Manufacturers have improved their adhesive qualities and now provide low-modulus materials with better elasticity.

The materials require heating temperatures usually from 350 - 400°F (177 - 204°C) for proper application. Most manufactures require melting the material in a double boiler. The inside melting vat is surrounded by a vat of oil. An agitator in the melting vat helps distribute the heat evenly. Both contractor and agency personnel should ensure that the material is prepared at recommended temperatures. Accurate temperature control is important for desired sealant properties (3). Insulated hoses and applicator wands help make sure that the sealant does not lose temperature between the boiler and ejection nozzle.

Some hot-pour sealants contain poly-vinyl chloride (PVC) plastic with coal tar. These sealants are extremely tacky and most are resistant to jet fuel. The PVC coal tar sealants require heating to only about 250°F (120°C) for installation. Polymer (PVC) liquid sealants require a special application nozzle that mixes two-components during application.

Silicone—

Silicone sealants are a field-poured liquid with a base ingredient of silicone polymer. Agencies began using these materials in the 1970's (24). Installation procedures are similar to those for hot-pour materials. Silicone sealants come prepackaged and ready for immediate application. Most manufacturers recommend storing the containers out of the weather until use.

The silicone material is a single component which requires no mixing or heating. The material cures when exposed to the atmosphere during application. Moisture in the air helps the sealant cure to attain its final properties. However, manufacturers caution not

Table 1. **Descriptions and Specifications for Common Sealing Materials (1).**

Sealant Type	Specification(s)	Properties
Hot-Pour Joint Sealant Materials		
Polymeric Asphalt Based	ASTM D3405	Self-leveling
	ASTM D1190	Self-leveling
	AASHTO MO173	Self-leveling
	S-S-1401 C	Self-leveling
Polymeric Low Modulus	ASTM D3405	
	Mod.	Self-leveling
Elastomeric PVC Coal Tar	ASTM D3406	Self-leveling
	SS-S-1614	Self-leveling
Elastic	ASTM D1854	Jet Fuel Resistant
Elastomeric PVC Coal Tar	ASTM D3569	Jet Fuel Resistant
	ASTM D3581	Jet Fuel Resistant
Cold-Pour Single-Component Sealant Materials		
Silicone	N.A.	Non-sag, toolable, low modulus
Silicone	N.A.	Self-leveling (no tooling), low modulus
Silicone	N.A.	Self-leveling (no tooling), ultra-low modulus
Nitrile Rubber Sealant	N.A.	Self-leveling (toolable), non-sag
Polysulfide	N.A.	Self-leveling (no tooling), low modulus
Polymeric Low Modulus	N.A.	Self-leveling (no tooling), low modulus
Cold-Pour Two-Component Sealant Materials		
Elastomeric Polymer	SS-S-200	Jet Fuel Resistant
Preformed Polychloroprene Elastomeric (Compression Seals)		
Preformed Compression Seals	ASTM D2628	Jet Fuel Resistant
	Lubricant	
	Adhesive	ASTM D2835
Preformed Expansion Joint Filler		
Preformed Filler Material	ASTM D1751	Bituminous, non-extruding, resilient
	AASHTO M213	
Preformed Filler Material	ASTM D1752	Sponge Rubber, Cork
	AASHTO M153	
Preformed Filler Material	ASTM D994	Bituminous
	AASHTO M33	

to apply the sealant during rain, frost, or temperatures below the dew point.

Silicone sealants are suitable in climates with wide temperature ranges. Most develop a low elastic modulus which allows good extension and compression recovery. Typical low modulus silicones can undergo at least 100 percent extension and 50 percent compression without detriment. Table 2 provides distinction between the modulus levels of different liquid silicone sealants (25).

Silicones require about 30 minutes curing time before opening to traffic and developing sufficient adhesion. However, the amount of time may differ depending on the manufacturer and environmental conditions. Contact a manufacturer's representative for consultation on curing time needed for particular installation procedures and applications.

Preformed Compression Seals—

Manufacturers introduced compression seals in the early 1960's. They differ from liquid sealants because they are manufactured ready for installation. Compression seals do not require field heating, mixing or curing.

Unlike liquid sealants, which experience both compression and tension, preformed compression seals are in compression throughout their life. Therefore their success depends solely on the lateral pressure exerted by the seal.

The principle compound in compression seals is neoprene. Neoprene is a synthetic rubber which provides excellent rebound pressure under compression. The seals consist of a series of webs. The webs provide the outward force which holds the sealant against the reservoir walls.

If a compression seal is undersized, joint opening may become too wide at low temperatures. The seal will lose contact with the reservoir walls and loosen. Also expansion/isolation joints in the pavement may allow any contraction joints within about 100 ft (30 m) to open too wide. Careful consideration of these factors is essential when sizing compression seals.

Manufacturers provide seals of various nominal widths and depths. The appropriate sealant width is greater than the maximum (coldest weather) joint reservoir width. This is about twice the width of the reservoir. The reservoir depth must exceed the depth of the compressed seal, but does not relate directly to the width of the reservoir. Good performance results when the seal remains compressed at a level between 20 and 50%. Table 3 provides typical compression seal dimensions for standard joint widths and slab lengths (26). Final seal size selection must also consider placement temperature.

Backer Rods—

Backer rods are an important component for liquid sealant installation. Backer rods prevent sealant from flowing out of the bottom of a joint and adhering to the reservoir bottom. The backer rod also helps

Table 2. **Typical modulus levels of silicone sealant classifications (24).**

Modulus Classification	Force Required For 150% Elongation	Ultimate Elongation
High	>100 psi (0.69 MPa)	<500%
Medium	40-100 psi (0.28-0.69 MPa)	500-1200%
Low	<40 psi (0.28 MPa)	>1200%

Table 3. **Sizing recommendations for preformed compression seals (26).**

Joint Spacing [ft (m)]	Minimum Reservoir Width [in (mm)]	Minimum Reservoir Depth [in (mm)]	Relaxed Seal Width [in (mm)]
15 (4.6)	1/4 (6)	1-1/2 (38)	7/16 (11)
20 (6.1)	5/16 (8)	1-1/2 (38)	5/8 (16)
25 (7.6)	3/8 (10)	2 (50)	11/16 (17)
30 (9.1)	1/2 (13)	2 (50)	1 (25)

define the shape factor and optimize the quantity of sealant used.

There are no national specifications for backer rods; however, important considerations for various materials include:

- Polyethylene Foam: Polyethylene foam is a closed-cell foam that does not absorb water and is moderately compressible. It is better suited for cold-pour sealants since it may melt in contact with hot-pour materials.
- Crosslinked Polyethylene Foam: Crosslinked polyethylene foam is a closed-cell foam that is compatible with hot-pour sealants. It will not absorb water and is moderately compressible.
- Polyurethane Foam: This open-cell foam absorbs water, but does not melt when used with hot-pour materials. It is very compressible, and commonly used with hot-pour sealants.

Backer rod size depends on the joint or crack reservoir width. Backer rods are compressed about 25 percent to assure they stay at the desired depth in reservoir. Table 4 provides the proper size for different joint widths.

Backer rods also act as a bond breaker to prevent adhesion to the reservoir bottom. The stresses within the sealant material increase if bond develops along the base of the sealant (2,4) Adhesion loss results because the sealant is constrained from neck down at the reservoir bottom during joint opening.

Reservoir Design

Reservoir sizing is done to permit the sealant to function properly. The first step is selecting a sealant which meets performance and cost criteria for the pavement. This includes consideration of the potential need to reseal the pavement in the future. It is critical that the reservoir is not too wide to inhibit future resealing. Ideally the initial reservoir width should not exceed 3/8 in. (10 mm) for liquid sealants. Initial width for preformed compression seals depends on other design factors.

Expectations of sealant performance and potential resealing need are often neglected. A table or manual which details the year(s) for the expected resealing provides a needed programming tool. It also provides an operation plan for optimizing pavement performance. Such a table is an excellent tool to provide in the original pavement design documents and the pavement management system. It becomes the "Operation and Maintenance Plan" for the pavement. Designers are encouraged to develop and submit this type of plan to the maintenance and programming departments.

Table 4. **Sizing recommendations for backer rods (26).**

Reservoir Width		Backer Rod Diameter	
1/8 in.	(3 mm)	1/4 in.	(6 mm)
3/16 in.	(5 mm)	1/4 in.	(6 mm)
1/4 in.	(6 mm)	3/8 in.	(8 mm)
5/16 in.	(8 mm)	3/8 in.	(10 mm)
3/8 in.	(10 mm)	1/2 in.	(13 mm)
1/2 in.	(13 mm)	5/8 in.	(16 mm)
5/8 in.	(16 mm)	3/4 in.	(19 mm)
3/4 in.	(19 mm)	7/8 in.	(22 mm)
7/8 in.	(22 mm)	1 in.	(25 mm)
1 in.	(25 mm)	1-1/4 in.	(32 mm)
1-1/4 in.	(32 mm)	1-1/2 in.	(38 mm)
1-1/2 in.	(38 mm)	2 in.	(50 mm)

Joint Type & Movement—

The sealant must be capable of accommodating the anticipated joint opening and closing due to temperature changes. Figure 3 provides a pavement

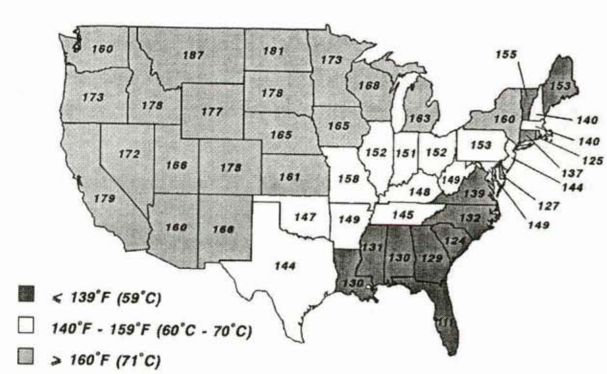


Figure 3 *Pavement temperature differential map for the continental United States (27). Indicates the difference between the maximum concrete temperature at placement minus the minimum ambient temperature in January.*

temperature differential map for the continental United States (27). The map provides statewide averages for the worst case difference between maximum concrete temperature at placement and minimum yearly ambient temperature. It is useful in estimating maximum joint movement where more exact figures are not available.

Most sealant manufacturers recommend calculation of joint movement at transverse joints for proper dimensioning. Joint movement estimates are made with the following equation (1,2,3):

$$\Delta L = C\, L\, (\alpha\, \Delta T + \varepsilon)$$

where:

- ΔL = the expected change in slab length, in. (mm)
- C = the subbase/slab frictional restraint factor (0.65 for stabilized material, 0.80 for granular material).
- L = the slab length, in. (mm).
- α = the PCC Coefficient of Thermal Expansion (see Table 5).
- ΔT = the maximum temperature range (generally the maximum concrete temperature at placement minus the minimum ambient temperature in January, °F (°C).
- ε = the shrinkage coefficient of the concrete (see Table 6). Note: this factor should be eliminated on resealing projects, where shrinkage is no longer a factor).

It is important to remember that there is almost no movement of tied longitudinal and shoulder joints. Tiebars which hold these joints tight will not allow the movement calculated from the formula. Therefore these joints may not require the same material as might be determined based on the calculated movement range. Opening ranges determined from the formula for doweled or undoweled transverse contraction joints will reflect actual field movements.

Tied centerline, highway shoulder or airfield longitudinal joints require sealing even though only small joint opening is likely. These longitudinal joints are often perpendicular to the drainage slope. Therefore they can allow significant access for water. On highways the lane/shoulder joint is the most critical and can let in as much as 80 percent of the total moisture (3,11,17,28). Neglecting to seal and maintain the longitudinal joints will negate the benefit of even excellent transverse joint seals. Figure 4

Table 5. **Typical Values for PCC Coefficient of Thermal Expansion (α) (1,2).**

Type of Coarse Aggregate	PCC Coeff. of Thermal Expansion (x 10^{-6}/degree) °F	°C
Quartz	6.6	11.9
Sandstone	6.5	11.7
Gravel	6.0	10.8
Granite	5.3	9.5
Basalt	4.8	8.6
Limestone	3.8	6.8

Table 6. **Typical Values for PCC Coefficient of Shrinkage (ε) (1,2).**

Indirect Tensile Strength	PCC Coefficient of Shrinkage (strain)
<300 psi (2.07 MPa)	0.0008
400 psi (2.76 MPa)	0.0006
500 psi (3.45 MPa)	0.00045
600 psi (4.14 MPa)	0.0003
>700 psi (4.83 MPa)	0.0002

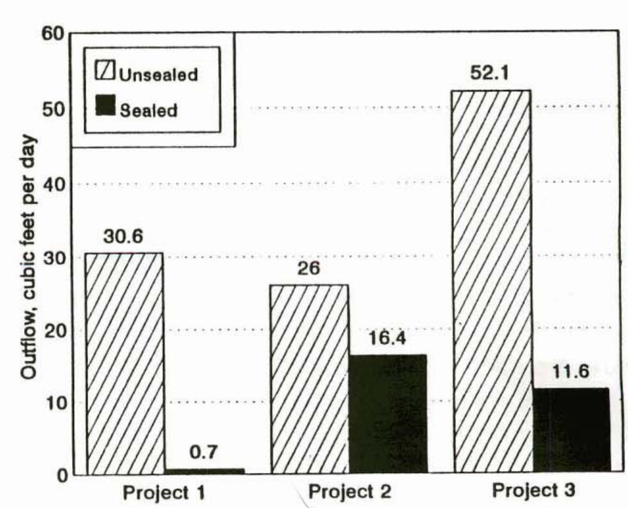


Figure 4 *Difference in water outflow from a pavement drainage system with unsealed longitudinal joints and well-sealed longitudinal joints (3).*

shows the dramatic reduction in water outflow from a pavement drainage system with good longitudinal seals.

Liquid Sealant Reservoir (Shape Factor) - The shape factor is the ratio of depth to width of a field poured liquid sealant. The saw cut width and insertion depth of the backer rod define the sealant shape. The shape factor is critical to long-term success of liquid sealants. The cross section of a joint sealant changes during the expansion and contraction of the concrete pavement. The movement induces strains within the sealant and stress along the sealant/reservoir bond line. These material responses become excessive if the shape factor is not appropriate for the sealant material.

Different liquid sealant materials can withstand different levels of strain. Strain on the extreme sealant fiber depends on the amount of sealant elongation (joint opening) and the shape factor (Figure 5). Most hot-pour liquids can withstand about 20 percent strain of their original width (3). Silicones and some other low-modulus materials can undergo up to 100 percent strain. However, manufacturers recommend designing for total strains of no more than 50 percent and ideally only 25 percent.

Figure 6 shows ideal shape factors for liquid sealants. A shape factor equal or below one induces lower stresses on the joint sealant than a shape factor greater than one. The lower or reduced internal stresses resulting from proper shape factors minimize adhesive or cohesive loss.

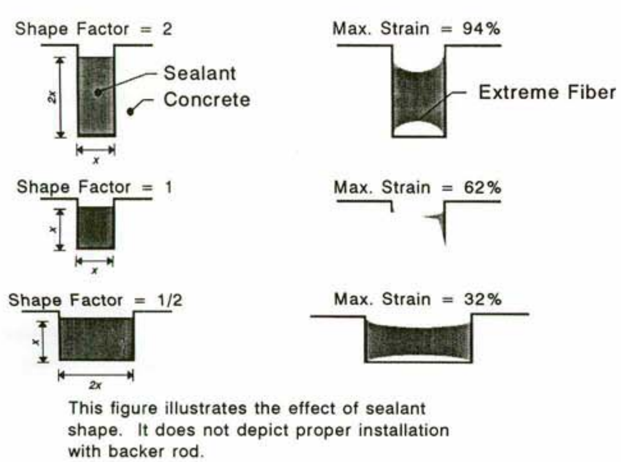


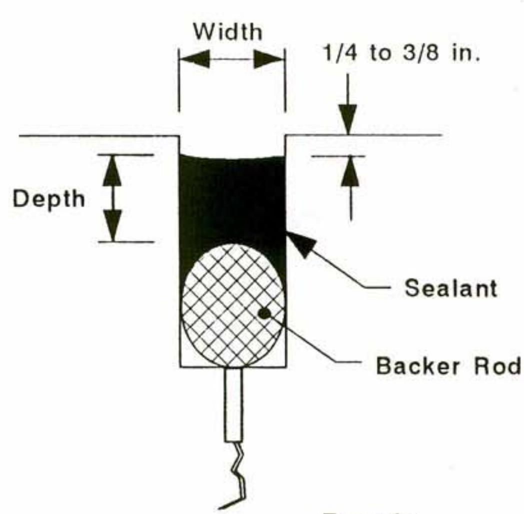
Figure 5 Strain on the extreme sealant fiber for different shape factors (43).

Shape factor design should include recessing the sealant from 1/4 - 3/8 in. (6 - 10 mm). This is important to avoid extrusion problems. Extrusion occurs where joint closure squeezes the seal material up through the reservoir exposing it to traffic.

Preformed Sealant Reservoir—

To size a preformed compression seal requires consideration of pavement temperature at installation and joint movement range (29). The compression seal must work within the compression range (typically 20 - 50 percent).

The first step is to calculate the total range of joint movement using the formula previously discussed. The second step is to select a compression seal with an allowable movement less than or equal to the calculated movement range. If the range exceeds



$$\text{Shape Factor} = \frac{\text{Depth}}{\text{Width}}$$

Liquid Sealant Type	Typical Shape Factor
Hot-Pour	1.0
Silicone	0.5

Figure 6 Typical shape factors for liquid sealants (1).

that allowable for the seal than a larger seal must be chosen. Consideration can also be given to decrease the joint spacing on the project.

The final step is to select a reservoir (saw cut) width to meet seal size, movement range and installation temperature criteria (29). (Only a rough estimate of the pavement temperature is necessary.) Temperature is important so the seal will operate in the 20 - 50 percent compression range. Warmer installation temperatures require more seal compression at installation. Cooler installation temperatures require less seal compression because the joints are at least partially open.

The following equation calculates saw cut width (29):

$$Sc = (1 - Pc) * w$$

where:

Sc =	Joint saw cut width.
w =	Width of the uncompressed seal.
Pc =	Percent compression of seal at installation (expressed as a decimal).
Pc =	$Cmin + \frac{\text{Install. Temp.} - \text{Min. Temp.}}{\text{Max. Temp.} - \text{Min. Temp.}} \cdot (Cmax - Cmin)$
Cmin =	Minimum recommended compression of seal expressed as a decimal (usually 0.2).
Cmax =	Maximum recommended compression of seal expressed as a decimal (usually 0.5).

Of course the actual installation temperature cannot be accurately known during the design process. Therefore designers should calculate sizing for various potential installation scenarios (hot, moderate, cool). The designers should also examine the influence of other design factors on seal sizing requirements. In particular, joint spacing significantly effects total joint movement. Selecting a seal one or two sizes over that required from the calculations can also provide a factor of safety for installation conditions (29).

Evaluation of Existing Sealants

Sealant evaluation usually requires examining three areas: the bonding conditions, the presence of incompressibles and the condition of the adjacent concrete.

Many agencies evaluate sealant as either good or bad, with no middle ground. A problem in any one of the three areas is considered failure of the sealant without regard to overall performance (30).

Distress —

Distress is a more appropriate depiction of the sealant and spall-related problems that occur. A problem may exist in some quantity, but not to such an extent as to consider the joint or sealant failed. Sealant perfection is not a realistic goal and sealant failure is more accurately determined from accumulated sealant distress. Accumulated distress limits effectiveness and may initiate pumping, faulting, spalling, etc.

Sealant distresses include:

- Adhesion loss: the loss of bond between the sealant material and the concrete joint face. Adhesion loss is noted by the physical separation of the sealant from either or both joint faces.
- Cohesion loss: the loss of internal bond within the sealant material. A noticeable tear along the surface and through the depth of the sealant is evidence of cohesion loss.
- Oxidation/Hardening: the degradation of the sealant as a result of natural aging, long-term exposure to oxygen, ozone, ultra-violet radiation and/or the embedment of incompressibles into the sealant material (10). Oxidation/hardening is noted by a crusted surface and the loss of flexibility. The crust or hardening often extends through the entire width and depth of the material. The sealant may be cracked into small segments and missing from the reservoir. Embedded incompressibles produce similar degradation characteristics.

Investigation for spalling of the surrounding concrete is also a necessary in sealant evaluation. Spalling typically arises when material enters the joint during cooler temperatures (3,6). When adjacent slabs expand at higher temperatures, incompressibles inhibit expansive movement that normally results in joint closure. This induces high compressive stresses along the joint face and may break or chip the concrete. Other material that can prohibit joint closure includes dried residue from sawing or patching operations. Small spalls are termed sliver spalls. The width of sliver spalling is typically from 1/8 - 1/4 in. (3 -13 mm) (Figure 7).

Incompressible infiltration results from either spall or sealant-related problems and is not considered a distress mode. The presence of incompressibles indicates other problems. In certain instances the presence of incompressibles can contribute to sealant failure through the working action of traffic. Sealant hardening through incompressible embedment is a good example. Incompressible rating criteria are (31):

- None: No incompressibles are present. Minimal: Some incompressibles are present, but their presence does not appear to affect the joint or sealant performance.
- Moderate: Incompressibles are present and may be contributing to sealant distress and/or spalling exhibited along the joint.
- Extensive: Many incompressibles are present in the joint. Judgement is that they are contributing to significant sealant distress, loss of sealant, and/or joint spalling.

Sealant Condition Survey—

Resealing is necessary when sealant distress affects average sealant condition and results in significant water and incompressible infiltration. The basis of this determination is typically engineering judgement. Consequently, the importance of scheduled reviews by agency personnel to monitor sealant condition cannot be overemphasized (11,12).

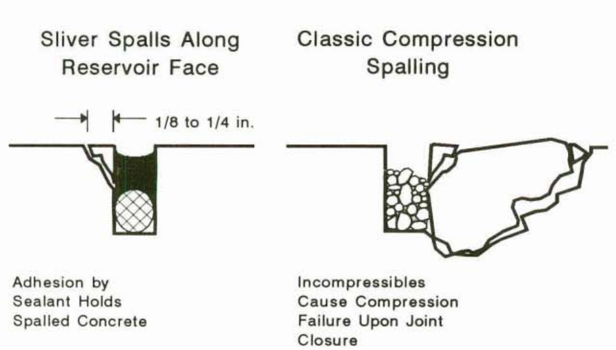


Figure 7 *Minor spalling found on some sealant installations is much smaller than classic spalling and not considered large enough to affect the performance of the pavement.*

An agency may also employ a rational rating system. A system bases the decision to reseal on an average rating of a representative number of joints (32). A survey crew must rate the joints for sealant distress, joint spalling and incompressible presence.

Sealant surveys should consist of basic distress data collection, with concentration at the joints. The crew should take measurements of joint faulting and joint width. The system should require visual and physical examination of the joint and sealant.

Adhesion loss is the most common distress (12,19,21,31). A dull knife blade or thin metal strip provides an excellent tool for checking sealant adherence (Figure 8) (24,31). Four to five penetrations of the knife at random locations along each joint provides a good sample. The feel of the penetration provides a sense of the sealant adhesion. A loose, effortless penetration indicates adhesion loss, while good adhesion provides resistance. Further examination of the knife blade may identify the presence of incompressibles or dust along the joint walls and below the sealant.

Rating cohesion loss and the presence of incompressibles requires visual examination only. On occasion some knife penetration may be necessary to check the depth of cohesion separations seen on the sealant surface.

The surveyors must also check the material for signs of hardening. A sample of the hardened material extracted from the joint can identify the cause. Hardening may be a result of oxidation or incompressibles embedded in the material.

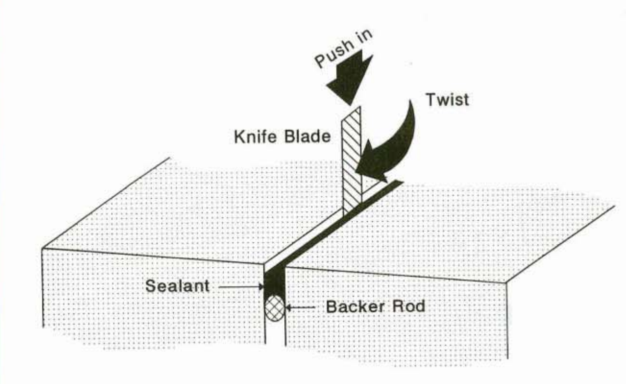


Figure 8 *Checking for sealant adherence with a dull knife blade or thin metal strip (24).*

The presence of incompressibles may sometimes be difficult to assess because some agencies sand roadways for snowy conditions. Road sand mixtures spread across a pavement collect in the joints. A broom may be needed to remove incompressibles in order to view the sealant. This is especially true where seals are properly recessed. Under these conditions, incompressible evaluation requires judgement and should not be influenced by the presence of traction control sand.

The crew should record the presence of spalling for the entire length of each joint. Evaluating spall severity and considering patching needs are important aspects in this effort. Notes of joints needing patching are also important in the final assessment of the pavement condition. Reference 33 provides good guidance to determine the severity of typical spalls.

Be careful in noting sliver spall presence. On occasion popouts have been mistaken for the tiny spalls. Usually the sealant will remain in the joint despite sliver spalling. This makes evaluating the sealant/joint condition difficult. It requires good judgement to determine if these tiny spalls are effecting pavement condition.

Evaluation of a representative number of joints is necessary to accurately characterize the degree of sealant degradation. Table 7 provides random and area samples needed for statistical significance in a sealant/joint survey (34). The average sealant condition from the surveyed joints provides a trigger for resealing necessity.

The length of deterioration defines the severity level of deterioration along each joint (33). A low severity exists if less than 25 percent of the length of any joint seal is damaged. A moderate condition exists with 25 - 50 percent damage. Above 50 percent damaged is considered high severity.

An unexpected increase in joint faulting or spalling may also identify a project in need of sealant replacement. Periodic faulting measurement allows a histogram of joint faulting and/or spalling to convey such changes. An increased faulting rate may be due to the presence of more water or incompressibles from poor joint seals. (Although this identification is effective, it is often made too late after distress inhibits service life.)

Some sealants may remain tight in the reservoir, but still lose adhesion to the side walls (31). Many surveyors would call this failure of the sealant. However, assessment of the joint can often show that little damage is occurring as a result of the bond loss. The incompressibles rating is a good indicator under this situation. Where the rating is minimal to moderate, the sealant is likely still performing satisfactorily.

Researchers in Kansas use a vacuum tester to check seal tightness. They spread a soapy solution on the joint to identify leaks under vacuum. They measure the pressure developed within the tester housing to indicate seal effectiveness. The equipment develops a pressure of 27 in (69 cm) water at no air flow (full seal) and 10 in (25 cm) water at free air flow (no

Table 7. **Random and area evaluation samples needed for statistical significance in sealant/joint survey (34).**

Joint Spacing [ft (m)]	Measurement Interval	Number of Joints	Area
<12 (<3.7)	every 9th joint	+85/mi (+50/km)	20%*
12-15 (3.7-4.6)	every 7th joint	85-70/mi (50-43/km)	20%*
15-20 (4.6-6.1)	every 5th joint	70-50/mi (43-33/km)	20%*
20-30 (6.1-9.1)	every 4th joint	50-35/mi (33-22/km)	20%*
30+ (9.1+)	every 4th joint	35/mi (22/km)	20%*

* *Surveyors should select an area (sample unit) that represents the average condition of the pavement in question.*

seal). Figure 9 shows the average results on different sealants one year after installation (35). Although some sealants have less leakage than others, none provides a complete seal.

Performance –

Hot-pour Liquid - A typical hot-pour sealant provides on average from 3-5 years life after proper installation (17,31). One report discusses good observed performance of low-modulus or PVC coal-tar based products past 8 years (31). Unfortunately, overall hot-pour sealant performance has been inconsistent. The most noted problems are adhesion or cohesion loss, and inconsistent field properties.

Cohesion loss is not unusual in narrow and deep joints. Many agencies provide a single reservoir cut to 1/3 or 1/4 the slab depth. The agency specifies pouring a hot-pour sealant directly into the saw cut. The single cut is difficult to clean and the shape factor (ratio of depth to width) can approach 25. Cohesion loss is not unusual in these situations. At early ages, tensile stresses from joint opening may overcome cohesion in an improperly shaped sealant before overcoming the bond (Figure 10) (31). Hot-pour materials typically perform better with a shape factor of one.

All hot-pour sealants are subject to variances in field preparation. Heating temperature during preparation

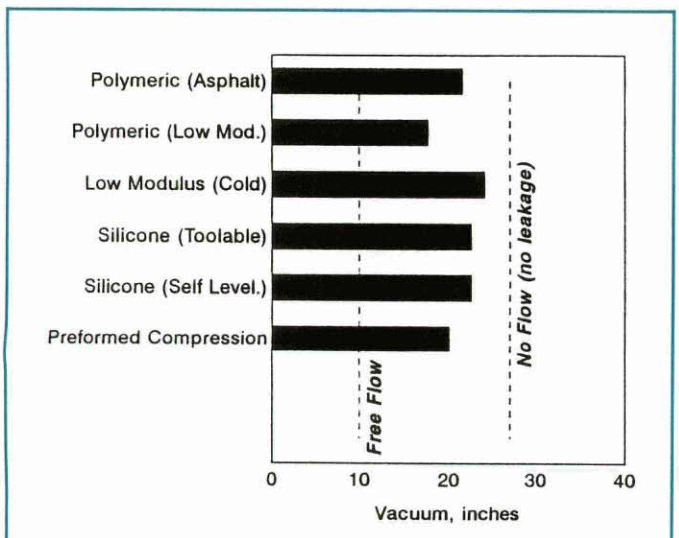


Figure 9 *Average results of Kansas vacuum tests on different sealants one year after installation (35). Note that no sealant provided a completely tight seal.*

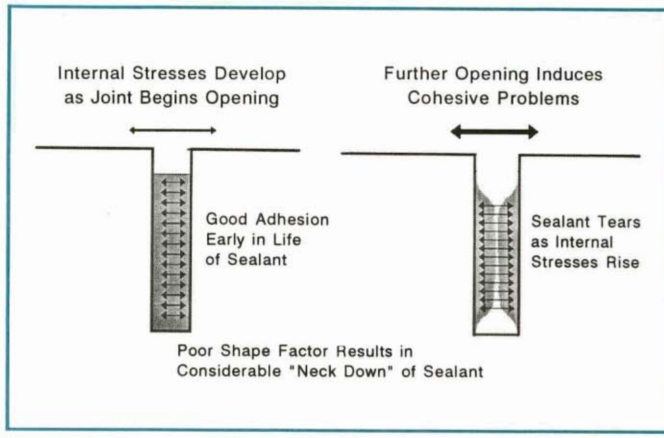


Figure 10 *A large shape factor induces high internal tensile stresses from joint opening and results in cohesion loss. (Also note no backer rod - poor practice).*

is extremely important. Overheating can change sealant properties. Overheating polymeric hot-pour sealants cause the polymers to decompose. Upon cooling the sealant may not have the intended modulus or provide the intended adhesion. Evidence of this can be noted by different performance of the sealant along different locations on a project (31).

PVC coal tar sealants are self healing against small tears (30,36). Observing their condition can be challenging because hot weather may hide adhesion or cohesion loss.

Silicones - Silicone sealants have performed well for periods exceeding 8 - 10 years on roadways (31,37,38). Installations on airports generate similar results. Good performance hinges on joint preparation. Of extreme importance is that the joint be clean and dry at the time of installation.

Poor joint preparation results in inadequate bonding of the sealant to the reservoir walls. Traffic may disturb poorly bonded silicone by pulling it from the joint. In some cases a silicone may recess into the reservoir by suction created by deflection and rebound of joints under load (31).

Sliver spalling has been noted on highway and airport joints sealed with silicone sealants. At one test site, joints sealed with silicone contained 10 times more sliver spalling than the other liquid sealants (31). On that test site, the spalling appeared during the first year of service and did not significantly increase with time. Sliver spalling has not impacted the pavement performance on the test site and will not likely threaten pavement life. Its cause is unknown and requires future research.

In some infrequent past cases, silicone sealants did not cure evenly after installation (38). When this occurred the upper portion of the sealant cured well while the lower portion remained soft and tacky. Consequently the lower portion did not bond well to the reservoir walls. While these cases have been infrequent and have not been observed in many years, it is still advisable to sample sealant within 14 to 21 days after installation (38). Performance of most joints with inadequately cured silicone is still satisfactory (38).

Compression seals - Compression seals provide service for periods often exceeding 15 years and sometimes 20 years (15,17). Five-celled seals provide the most consistent long-term performance. Figure 11 shows a cross-section of a typical five cell seal.

Compression seals require that joint faces be in good condition. Perpendicular faces of uniform width are necessary for optimal performance. A seal can work its way up out of a nonuniform reservoir. A contractor can easily attain the necessary uniformity in new construction, but it may be difficult in rehabilitation.

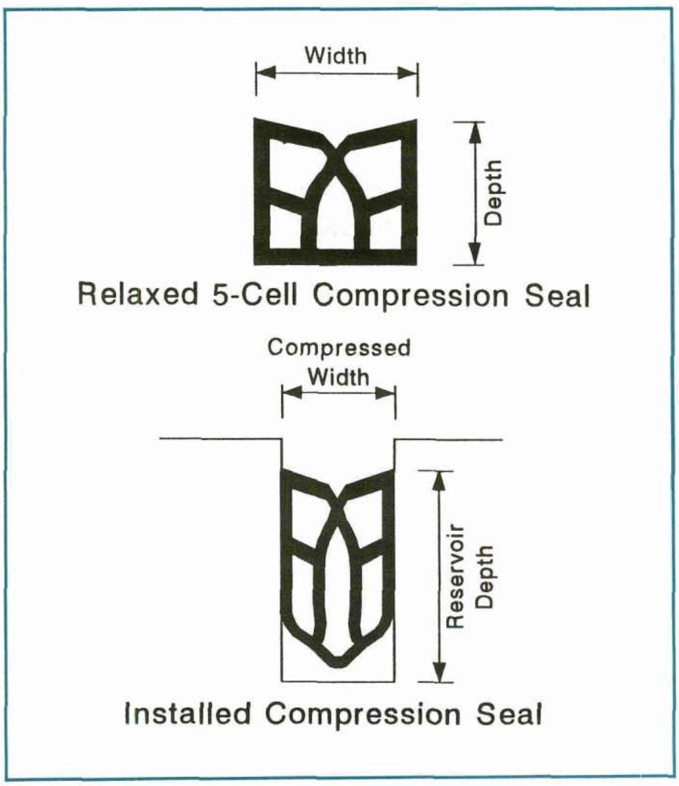


Figure 11 A typical five cell seal cross-section (1).

For this reason, compression seals are not typically used in resealing operations (11).

Preformed seals may lose elasticity and develop compression set over an extended time (36). This occurs when the seal loses its compressive recovery and no longer places outward pressure on the side walls. The seal begins to lose effectiveness and may be dislodged. Avoiding stretch during installation and using a proper seal size reduces compression set potential. Compression greater than 50 percent may induce compression set because webs stick together and prevent rebound (3). In some cases compression set has been attributed to improper chemical formulation during manufacture (36).

Resealing in Restoration

Performed alone, joint resealing is a maintenance activity. However, performed in conjunction with techniques such as patching or surface grinding, joint resealing becomes a necessary part of concrete pavement restoration (CPR).

Good restoration project performance depends on the choice and timing of treatments for the condition of the pavement (2,3,13,51). Techniques may enhance the effectiveness of other repairs performed together. Techniques which may enhance joint resealing include: full-depth repair, partial-depth repair, slab stabilization, diamond grinding, load transfer restoration, retrofit PCC shoulders and edge drain installation. In restoration, resealing joints and cracks is the last technique in the sequence (Figure 12).

Traffic control costs play an important role in resealing operations and sealant selection (12). An optimal rehabilitation design employs sealant that will last at least as long as the restored pavement (15). With many materials, joint preparation will cost more than the sealant material itself (12). That is why it is imperative that a rehabilitation design process consider traffic control and sealant life expectation in life-cycle costing.

Slab Stabilization—

Slab stabilization restores support to a pavement which has developed voids beneath slab corners or edges. Pozzolanic, asphalt or urethane-based materials pumped beneath the slab fill the voids and restore support. Lifting the slabs with the slab

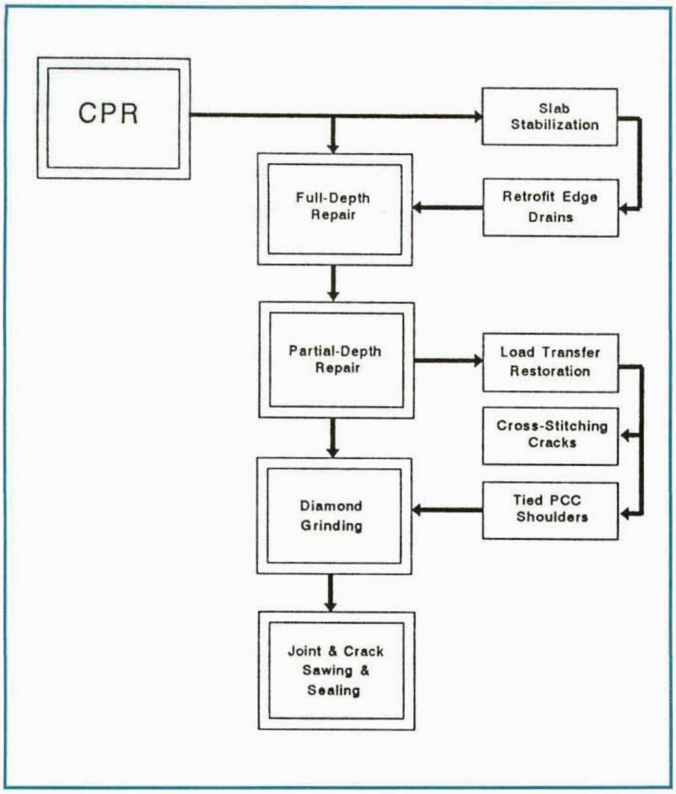


Figure 12 *The sequence of operations in a CPR project (34). Note that the double boxes indicate core activities which almost always are necessary in a typical CPR project.*

stabilization process is not recommended in most cases. See references 4,5,8,9, and 18 for more information.

Patching—

Restoring structural integrity and ride quality may require patching the pavement either full or partial-depth. Partial-depth repairs address spalling and can reestablish the joint reservoir through spalled areas. Full-depth repairs restore load transfer and provide completely new joints. For more information see ACPA bulletins Guidelines for Full-Depth Repair and Guidelines for Partial-Depth Repair (39,40).

Diamond Grinding—

Diamond Grinding restores a smooth pavement profile by removing a small depth of the concrete surface [nominally 0.25 in. (6 mm)]. The operation blends low and high areas and smooths faulted joints. Diamond Grinding is almost always required with a CPR project. For more information see ACPA bulletin Diamond Grinding & CPR 2000 (34).

Retrofit Drainage—

Edge drains along the pavement shoulder provide an avenue to remove water from the pavement system. Installing drains up to one year before rehabilitation helps the pavement seat itself and establish support. Retrofit drains also protect against recurrence of water damage in the future. See references 4,5,8,9 and 18 for more information.

Resealing Applications

Preparation is essential in joint resealing. One demonstration study of airports found a 50 percent savings in the annual cost of joint resealing on projects using proper preparation techniques (14). Successful resealing consists of five steps:

1. Old sealant removal.
2. Shaping the reservoir.
3. Cleaning the reservoir.
4. Installing the backer rod.
5. Installing the sealant.

Anticipating the time of year a pavement will be resealed is an important step in designing a resealing project. The time of year or temperature influences the amount and direction of joint movement after job completion. For example, installing a sealant during a region's warmest weather ensures that the sealant will always be in tension. This is because the joints will be fully closed during installation. However, a sealant installed during moderate regional temperatures will also undergo compression. The designer must verify that the sealant will be capable of handling the full range and direction of movement based on the anticipated installation temperature. Table 8 shows the range of movement placed on a sealant depending on the installation temperature. Probably the most favorable times of year are spring and fall because daily temperatures are moderate (2,3,41).

Another very important component of resealing joints and cracks is construction inspection. Several reports for airports and roadways cite a lack of emphasis on the importance of good joint sealing as a major problem. With the proper emphasis, inspection can lead to vastly improved sealing technique and performance (32,42,43). The inspection process improves the knowledge of contractor and agency personnel. This will heighten the level of competence and overall project quality.

Table 8. **Example Range and Direction of Movement on a Liquid Sealant Placed During Cold, Moderate and Hot Temperatures.**

Temp. At Seal Installation	Expected Movement Range	Movement After Sealing	Reservoir Cut Width	Maximum Expected Width	Minimum Expected Width	Percent Sealant Stretch	Percent Sealant Compress.
	in (mm)		in (mm)	in (mm)	in (mm)		
Cold	0.15 (3.8)	Closure	0.375 (9.5)	0.4 (10.2)	0.25 (6.4)	7	33
Moderate	0.15 (3.8)	Both	0.375 (9.5)	0.43 (10.9)	0.28 (7.1)	15	25
Hot	0.15 (3.8)	Opening	0.375 (9.5)	0.5 (12.7)	0.35 (8.9)	33	7

Old Sealant Removal—

Adhesion will not develop by simply filling over an existing sealant. Removal of the old sealant and joint face cleaning are essential. These processes provide a surface to which a new sealant can bond. It is imperative that methods for removing old sealant do not damage the joint reservoir. The following provide acceptable results (2,3):

- Manual Removal: Typically, manual removal is easy for compression seals. This simple method provides a quick result whenever feasible and does not leave much material on the reservoir sidewalls.
- Sawing: The most common removal and efficient method is sawing with diamond blades (Figure 13). It is efficient because sawing also shapes the reservoir for the new material. However, it may not be effective on sticky sealing materials such as PVC coal tar. Sticky materials clog diamond blades.

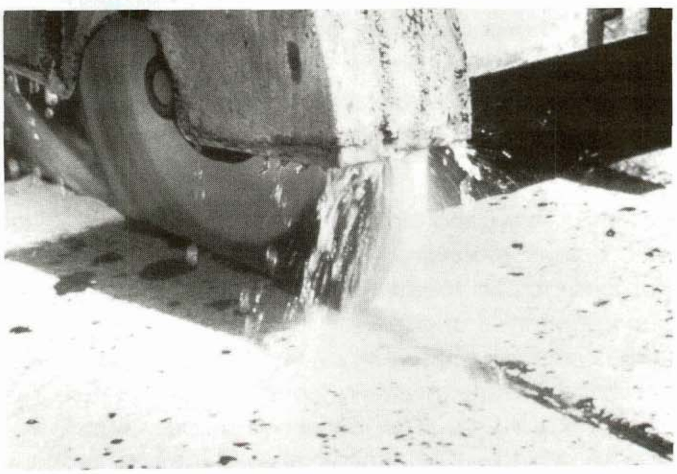


Figure 13 *Sawing/reshaping a sealant reservoir with a wet diamond blade.*

- Plowing: Plowing can be very effective for removing most of the old sealant (44). A small plow pulled through the reservoir dislodges the material. Operators must be careful in selecting the plow design. Avoid vee-shaped plows. The vee-shape tends to scour the reservoir corners and can easily spall surrounding concrete. Very little damage occurs with a rectangular plow.
- Cutting: Cutting requires a laborer to run a knife blade along the face(s) of the joint. Afterward, the sealant easily pulls free by hand.

Shaping the Reservoir—

Sawing/widening shapes the reservoir after sealant removal. Saws with dry or wet diamond blades are acceptable (2,3). The blades remove any remaining old sealant and provide the proper dimensions for the new sealant.

In certain instances eliminating this step may be acceptable. Shaping is unnecessary if sealant removal was by hand and the existing reservoir provides adequate dimensions. Sawing out the old sealant typically provides an adequate reservoir and should not require this step either.

Some minor spalling along the joint face will not inhibit performance of most sealants. However, some patching is likely for larger spalls. The specifications should detail areas requiring patching so that it can be completed before reservoir cleaning and sealant installation operations.

Resealing pavements with plastic or metal joint inserts requires first removing the insert (45). Afterward sawing provides smooth vertical faces for the new sealant.

Cleaning the Reservoir—

Cleaning is the most important aspect of joint sealing. For every liquid sealant, manufacturers require essentially the same cleaning procedures. Likewise the performance claims of any liquid sealant product is predicated on those cleaning procedures.

Reservoir faces require a thorough cleaning to be sure of good sealant adhesion and long-term performance. No dust, dirt or visible traces of old sealant should remain on the joint faces after cleaning. The ability to attain this condition may depend on the reservoir width. Most contractors report that it is easier to consistently get joints clean if they are at least 3/8 in (9 mm) wide. Cleaning 1/8 in (3 mm) or even 1/4 in (6 mm) is very difficult.

Do not use chemical solvents to wash the joint reservoir. Solvents can carry contaminants into pores and surface voids on the reservoir faces (2). Contaminants will inhibit bonding of the new sealant.

Proper cleaning requires mechanical action and pure water flushing to remove contaminants. The following outlines the recommended procedures (1):

a) Immediately after sawing, a water wash removes the slurry from the sawing operation. Contractors perform this operation in one direction to minimize contamination of surrounding areas.
b) After the joint has sufficiently dried, a sandblasting operation removes any remaining residue. Do not allow sandblasting straight into the joint. Holding the sandblast nozzle close to the surface at an angle to clean the top 1 in. (25 mm) of the joint face provides cleaning where needed (Figure 14). One pass along each reservoir face provides excellent results. This not only cleans the joint faces, it provides texture to enhance sealant adhesion.
c) An air blowing operation removes sand, dirt and dust from the joint and pavement surface. Conducting this operation just prior to sealant pumping ensures that the material will enter an extremely clean reservoir. The contractor must provide assurance that the air compressor filters moisture and oil from the air. The compressor should deliver air at a minimum 120 cu.ft./min. (3.4 cu.m./min.) and develop at least 90 psi (0.63 MPa) nozzle pressure (11,45).

Figure 14 *Sandblasting a shoulder joint. Note the angle and close proximity of nozzle to the reservoir.*

Some contractors also use a vacuum sweeper and hand brooms to keep the surrounding pavement clean.

Compression sealants do not require steps b or c.

Backer Rod Installation—

Backer rod installation is made after cleaning and before liquid sealant installation. It must be compatible with the liquid sealant with a diameter about 25 percent greater than the reservoir width. Backer rod inserts easily with a double-wheeled, steel roller or any smooth blunt tool that will force it uniformly to the desired depth (Figure 15). Rehabilitation work with slightly faulted joints may require a single-

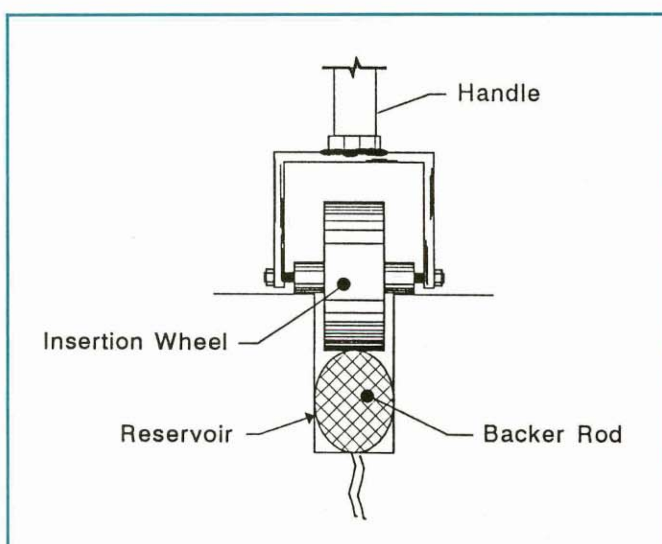


Figure 15 *A double-wheeled, steel roller for backer rod insertion to the desired depth.*

wheeled roller. The tool must not puncture or stretch the material. A steel roller allows exchange of the center insertion wheel for different depths and provides the most consistent results. Ensuring that the backer rod is at the proper depth cannot be over emphasized. Good practice is to roll the insertion wheel over the backer rod twice.

Sealant Installation—

An inspector should not allow a contractor to begin installing sealant until the reservoir meets cleanliness requirements. With a finger the inspector should wipe the reservoir sidewalls to check for dirt and dust (Figure 16). The inspector should require further cleaning with any traces of contamination.

Installation requirements are slightly different for each sealant type. Manufacturers recommend some curing time before opening to traffic for most liquid sealants. Some liquid seal manufacturers also specify limits on the ambient and pavement temperatures for installation. Compression seal manufacturers specify desirable limits on sealant stretch and lubrication. Table 9 provides general recommendations for different sealants. It is important to always consult the sealant manufacturer's particular product recommendations.

Figure 16 Noticeable dust on inspector's fingers.

Liquid - Liquid sealants require uniform installation. Over-filling or completely filling the reservoir is not desirable. Filling the reservoir from the bottom upward avoids trapping air pockets. Remember to recess the sealant at least 1/4 - 3/8 in. (6 - 10 mm) below the surface of the pavement.

It is important that the contractor pumps the sealant through a nozzle sized for the width of the joint reservoir (43,45). The nozzle should fit into the reservoir to allow pumping to the bottom. The injection nozzle forms the sealant bead. Good practice is to draw the

Table 9. **Typical manufacturer's limitations on pavement and ambient placement temperature, and recommended curing periods for common sealing materials.**

Sealant Type	Min. Placement Temperature	Concrete Curing For Non-Fast Track Project	Time To Open Sealed Joint To Traffic
Hot-Pour Materials			
Asphalt Based	50°F (10°C)	7-days(1,2,3)	upon cooling
PVC Coal Tar	50°F (10°C)	7-days(1,2,3)	upon cooling
Polymeric Low Modulus	40°F (4.4°C)	7-days(1,2,3)	upon cooling
Cold-Pour Silicone	40°F (4.4°C)	7-days(1,2,3)	30 min.(4)
Preformed Compression	30°F (-1.1°C)	none	immediate

(1) For new concrete only. The seven days must be free of precipitation.
(2) Assumes the joint reservoir is dry and preparation removes all curing compound, dust, dirt and laitance.
(3) Most manufacturers provide more detailed recommendations and shorter curing time requirements for special applications (ie. Fast-Track paving).
(4) Curing time varies by temperature and humidity. At 75°F (24° C) and 50% relative humidity, the sealant will cure to a tack-free surface in 30 minutes. At 40°F (4°C) it takes 2-4 hours to become tack free.

nozzle toward the operator (Figure 17). Pushing the nozzle may result in voids and nonuniform sealant cross-section (2).

Special attention to the heating temperature is vital at the start of a work day (43). No sealant should be installed before reaching proper installation temperature. About the first 1 gal. (4 liter) of material is unusable because cooled sealant and flushing oil remains in the pumping unit hoses and nozzle. Discard this material and begin pumping only after fresh sealant is ejected from the nozzle at an acceptable temperature.

Low-modulus silicone sealants which are not self-leveling require tooling to provide desired results. After sealant pumping, a laborer draws a tool or backer rod strip over the fresh silicone. This forces the sealant into contact with the sidewalls at the top of the reservoir and produces the desired shape factor (Figure 18) (3,37). Tooling is necessary within about 10 minutes of installation before the sealant begins curing and forms a "skin".

It is extremely important that the reservoir walls be dry before installing any liquid sealant (2,3,45). Moisture will boil in contact with hot-pour materials, forming steam that will bubble the sealant. Moisture will inhibit silicone sealant adherence. Moisture is not as critical for compression sealants. Most silicone manufacturers require a drying time or surface-dry condition before installation. This includes drying after wetting due to water flushing and even rainfall. Follow the manufacturer's guidelines for optimum seal adherence.

Figure 17 *Drawing the nozzle toward the operator during installation of liquid seal.*

Figure 18 *Close-up of low-modulus silicone sealant tooling.*

The sequence of installation is important where transverse joints are sealed with silicone and longitudinal with hot-pour material. It is good practice is to seal transverse joints first. This prevents hot-pour material from flowing into and contaminating the transverse reservoirs. Some contamination of the longitudinal reservoirs will occur while placing the transverse silicone. However silicone is somewhat more viscous than hot-pour and the extent of longitudinal joint contamination is tolerable.

It is important to examine all sealant after installation. An inspector should look at the material and seal characteristics. The simple knife test can indicate how well the sealant adhered to the sidewalls. This early inspection provides assurance that the installation meets requirements.

Testing of silicone sealant curing can only be completed after 14 - 21 days. The inspector can remove small 2-in (5-cm) sample of sealant. Stretching the segment about 50 percent [1 in (2.5 cm)] for about 10 seconds before releasing gives a quick check. A fairly fast and uniform relaxation of the sample indicates adequate curing. Slow rebound and curling of the sample indicates differential curing. The curl results from the upper (cured) seal retracting faster than the lower (less cured) portion. It is important to repair the 2-in (2.5 cm) gap in the sealant where the inspector extracted the sample. Use the same brand of material to take advantage of the good adherence the material has to itself.

Compression - A compression sealing operation requires application of a lubricant/adhesive to the sealant edges and/or reservoir sidewalls. The compression seal is then mechanically compressed and inserted into the reservoir. The lubricant/adhesive material eases sealant insertion, and forms a weak adhesive to help hold the seal in place.

Joint wall inspection before installation will find any suspect areas. Raveling, spalling or other irregularity of the joint walls pose potential problems. These areas could reduce the seal's lateral pressure and allow the seal to extrude or pop from the joint (11). Agreement between the engineer and contractor on potential problem areas will allow repair before the contract is complete and seal damage occurs.

Sealant stretch of three percent or less is desirable. Some neoprene seals are capable of stretching by as much as 50 percent. Stretching reduces the cross-section and compression recovery (36). More than five percent stretch is excessive and could be detrimental. Some sealants can later break into pieces if stretched excessively during installation. Special attention during installation is essential to avoid twisting, nicking or stretching the sealant.

Monitoring sealant stretch is an important check of installation methods. Good specifications require the contractor to lay a length of sealant parallel to a joint and cut the seal to exact length. Excess seal protruding from the joint after the contractor installs the seal is due to stretch. A measurement of this protruding seal provides an accurate number for calculating stretch percentage.

Most compression seal manufacturers make equipment for accurate seal installation (Figure 19). The most common are compress-eject machines. The machines compress and insert a seal to a desired depth in continuous motion. The most advanced equipment automatically applies lubricant/adhesive along the sealant edges. Compress-eject machines remove most stretching and twisting problems that accompany hand installation (3). The machines are usually self-propelled or semi-self-propelled with a guide that keeps them on course over a joint.

Burrs along the sawed joints may make seal installation difficult. Dragging a blunt pointed tool along sawed joints removes sharp edges. A mechanized wire brush will also remove burrs and provides consistent results (46). While this simple step eases seal installation, it may contaminate clean joints and should be done ahead of reservoir cleaning only when needed.

Avoid splicing compression seals as much as possible (45). Splices are discontinuities prone to moisture infiltration and dislodging by traffic. Use only one length of compression seal for transverse joints less than 25 ft (7.6 m) long. For transverse joints on wider pavements one splice is acceptable. For longitudinal joints cut the compression seal at the transverse joint crossings.

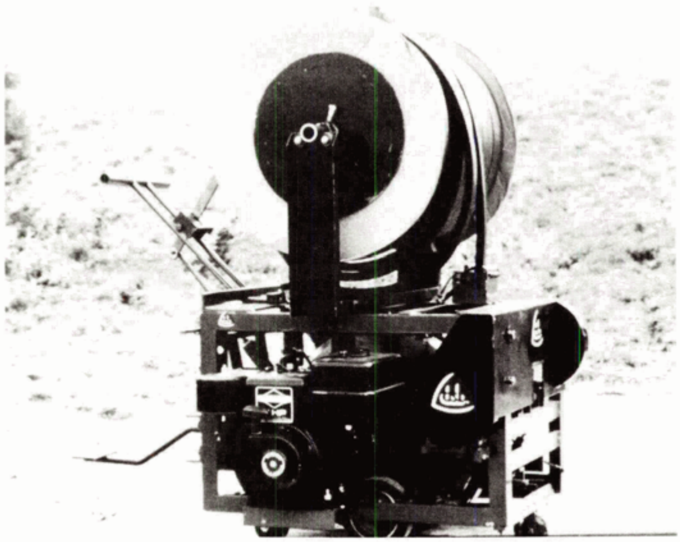


Figure 19 *Compress-eject machine.*

Preparing New Pavement Joints —

The steps for successfully sealing new pavement joints are very similar to those required for resealing joints. Because no old sealant is removed, reservoir shaping is simple. A single or double saw cut forms the reservoir.

Some agencies require contractors to blank-out tining at the location of skewed contraction joints. This prevents minor spalling at the intersection of the tine slots and the skewed reservoir. The blank-out is usually done with a 4 - 5 in (10 - 13 mm) wide piece of astroturf or other rugged fabric. Workers position the blank-out fabric at the joint location. The tining machine or hand tine operator pulls the rake over the blank-out fabric (Figure 20).

New pavement joints must also be clean and dry before installing the sealant. Curing compound on

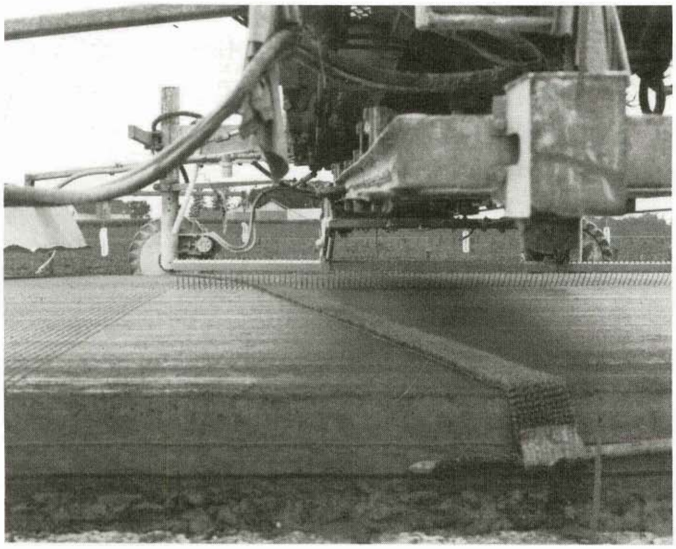


Figure 20 Tining machine running over a blank out strip.

joint faces will inhibit sealant bond and require sandblasting. Airblowing with oil-free compressed air is equally important in sealing joints for the first time. Removal of dirt and other laitance in the reservoirs from construction traffic and dusty conditions is necessary.

Manufacturers of silicone sealants recommend that the standard concrete cure for seven dry days before sealing. For Fast Track operations, most manufacturers make some exception to this requirement. It is important to contact the sealant manufacturer for advice on use of their product in Fast Track projects.

Special Considerations

Nonuniform Joint Cracking—

In plain jointed pavements initial cracking from shrinkage occurs at intervals from about 40 - 150 ft (12 - 46 m) (1). The exact spacing varies depending on concrete properties, thickness, subbase friction and climatic conditions during and after placement. The cracks meet sawed joints at those intervals. The joints between those locations sometimes do not crack for several weeks to months after construction even though saw cut spacing is relatively uniform. As a result, all of the initial shrinkage and thermal movement occurs at the initially cracked joints. Those joints often become much wider than those in intermediate locations. To account for this variability, agencies are encouraged to require the contractor to have several sizes of backer rod or compression seal available.

Expansion/Isolation Joints—

Most steps for resealing expansion/isolation joints are similar to those for contraction joints. However, resealing expansion/isolation joints requires removing the sealant only down to the compressible filler. Compressible fillers are typically directly below the sealing material. The fillers are usually nonextruding and act as a backer rod in the wide reservoir. It may be necessary to place a bond-breaking tape above the filler before installing new sealant (11,41,45). The tape will separate the new sealant from any old sealant that may have been absorbed by the filler. A tape width no more than 1/8-in. (3 mm) narrower than the joint width is acceptable. This ensures adequate separation and also eases installation. Contractors report difficulty in properly placing a tape wider than the actual joint width.

Resealing the contraction joints within 100 ft (30 m) of an existing mainline expansion joint may require special consideration (29). Expansion joint closure allows adjacent contraction joints to open. It is common that the width of contraction joints increase near an expansion joint. To successfully seal these contraction joints it may be necessary to use sealant materials with greater elongation capacity. Other options are to increase the width of preformed compression seals, backer rods and/or shape factor. The project documents should account for these adjustments.

Existing Lane/Shoulder Joints—

Studies show that effectively sealing shoulder joints improves highway shoulder and pavement performance (28). It is simpler to seal the reservoir along concrete shoulders than along asphalt shoulders. Sealing and maintaining concrete shoulder joints requires no further effort than is required for centerline, lane-separation or other tied longitudinal joints. This assures the designer of a good shoulder seal.

Joints between concrete lanes and bituminous shoulders pose a more difficult sealing challenge. Bituminous shoulders tend to settle with time due to water accumulation, traffic encroachment, insufficient support materials and poor soil or bituminous compaction. Often vertical settlement is greater than horizontal thermal movements (28). Some spalling and loss of asphalt material is also common along the shoulder edge of older concrete pavements.

Sealing along bituminous shoulders may require a wide reservoir. One-inch (25 mm) or greater width and depth accommodates the lateral and vertical shoulder movements. This provides a reservoir shape factor of one and is good for most liquid sealants capable of 25 percent strain. Liquid seals for shoulder joint sealing should be capable of adhering well to both materials; rubberized asphalt and specially formulated silicone sealants provide good adherence (37).

As with all sealing, shoulder reservoir preparation is important. Sawing the joint reservoir delivers the most consistent width and depth dimensions (Figure 21). The saw should cut vertically and remove any bituminous material from the edge of the concrete slab. Immediately after sawing a water flush will remove sawing slurry. Both sides of the reservoir require sandblasting. A lighter sandblast along the asphalt face is acceptable. Airblowing just before sealant installation dries the reservoir and removes dust and dirt.

Do not use a propane torch for joint drying and cleaning. Torching has led to concrete spalling and raveling.

Do not seal newly placed bituminous material until it cools to at least ambient temperatures. At higher temperatures bituminous material can ravel, erode

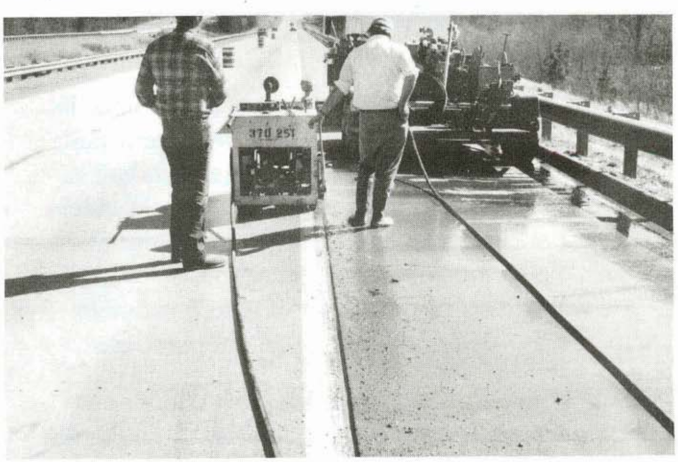


Figure 21 *Worker sawing the lane/shoulder joint reservoir. Note that the blade must remove a small amount of the concrete slab to ensure cleanliness and enable sealant adherence.*

and deteriorate under saw action (28). A cleaner reservoir face results if sawing is delayed until after cooling. Certain mixes may require an extended cooling/aging period.

Joint Load Transfer Restoration

Load transfer describes the distribution of load across a joint or crack. Aggregate interlock, dowel bars and subbase support influence the degree of load transfer (1). The ability of a joint or crack to distribute load is fundamental to its performance and is characterized by joint effectiveness measurements. Reference 3 provides further discussion on load transfer and joint effectiveness.

Restoring load transfer at joints or cracks is necessary to reestablish structural integrity. It may be necessary because a designer omitted dowels in an existing pavement and subsequent joint faulting has become a problem. It may also be necessary where deicing chemicals corrode unprotected dowels. In either case load transfer restoration (LTR) places good mechanical load transfer in the joint.

Joints lose load transfer ability with age and load applications. Determining the rate at which a pavement joint might lose load transfer is very complex. A few simple facts are:

1. Undoweled joints lose load transfer faster than those with dowels under similar traffic.
2. Under heavy truck traffic dowel diameters below 1-1/4 in. (32 mm) may socket the concrete around the bar and reduce load transfer efficiency.
3. Voids from wet and pumping subgrade/base materials provide little support and reduced load transfer.

A joint effectiveness of 75 percent or more is considered adequate for medium and heavy truck loadings (1). It is important that joint effectiveness measurements are taken when actual pavement temperature is cooler than 80°F (27°C). Joint effectiveness is over-estimated with closed joints at high temperatures.

LTR improves load transfer and reduces the rate of future fault development across joints or transverse cracks on in-service concrete pavements (47). Successful LTR requires sound concrete along the joint or crack. Faulted joints and cracks require surface grinding to restore rideability after installing retrofit load transfer. Joints exhibiting high deflections from voids may also require slab stabilization. Do not use LTR on joints with major spalling or material problems. Major deterioration requires full-depth replacement.

The two basic LTR methods are retrofit dowel bars and double-vee shear devices. Dowels are installed in slots cut into the pavement surface across the joint. Double-vee devices are inserted into cores drilled through the joint.

Backfill material must be capable of bonding to the slot/core walls. The thermal expansion characteristic of the backfill material is extremely important for compatibility to the existing concrete. Crushed aggregate is also important for strength. Most mixes employing conventional type I or III portland cement will meet compatibility criteria.

Some proprietary blended-cementitious backfill materials also meet compatibility requirements. Use of some of these materials has been successful as a backfill around double-vee and retrofit dowels. However, laboratory testing is important to ensure they meet recommended criteria (48). Most manufacturers will provide test and verification reports of their products.

One of the first projects in Georgia employed a non-proprietary cementitious backfill material (47,48). The following mix was successful as a load transfer restoration backfill:

Cement -	Type III 94 lb (42.6 kg)
Sand -	125 lb (56.7 kg)
Stone -	220 lb (99.9 kg) [3/8-inch (0.95 cm) top size]
Water -	5 gallons (18.9 liters)
Calcium Chloride -	1.5 lb (0.68 kg)
Expansion Agent -	4.5 oz (127.6 g)

(Expansion Agent - One part aluminum powder to 50 parts filler of inert flyash or pumicite).

A good bond between the backfill and slot/core walls is essential for LTR performance. The bond helps carry the load in shear across the joint. Therefore careful preparation is essential before device installation.

Dowels - Slots for dowels are cut parallel to the pavement centerline and with each other. Careful alignment is necessary for optimum performance. Contractors should employ saws equipped with gang-mounted diamond blades to provide the desired width and location (49). Construct the slots to widths no greater than 2-1/4 - 2-1/2 in (57 - 64 mm). Chipping with light hammers removes the fins that may remain between saw kerfs. Recent tungsten carbide milling technology is now being tested for slot cutting. This is a promising technique that should reduce LTR preparation cost considerably.

Cleaning is critical after the milling or cutting and chipping processes. Sandblasting followed by airblowing provides a roughened surface free of loose particles. The surface must be clean and dry. Similar preparation is described in reference 35 for partial-depth concrete repair.

Good results will require at least three dowels in each wheel path on roadways subject to heavy truck traffic (Figure 22). Airport pavement slabs subject to a variety of gear configurations require evenly spaced dowels. The dowels should be 1-1/2 in (38 mm)

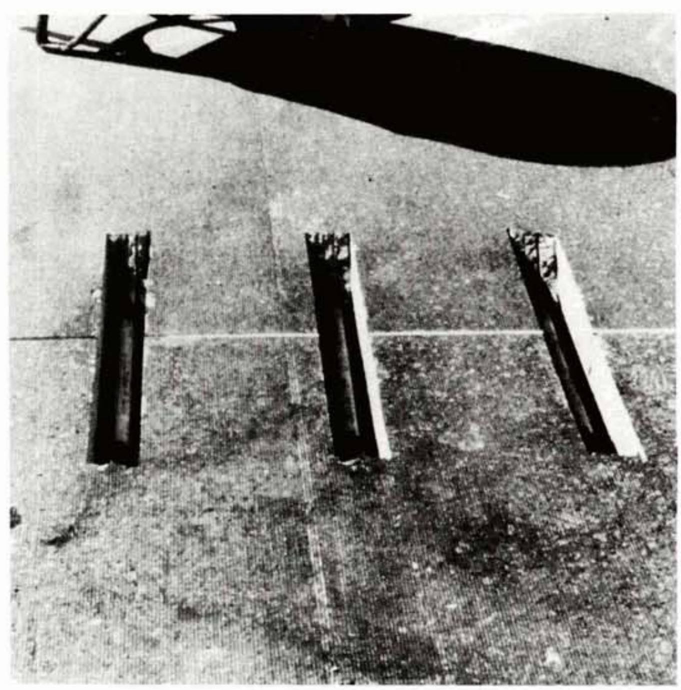


Figure 22 *Slots containing dowel bars. Before backfilling these bars require fillerboards to reform the joint.*

for airports and heavy truck traffic and no less than 1-1/4 in (32 mm) for any application. A dowel embedment depth of about 6-in (15 cm) is adequate to each side of the existing joint. However most installations use a dowel length of 16-in (45 cm). An epoxy or other protective coating is necessary to inhibit corrosion from deicing chemicals. To allow adequate movement, always apply a form oil or other bondbreaker material to dowels protected by epoxy coating. An expansion cap spaced at one end of each dowel will ease joint closure.

Chairs support the dowels in the base of the slot and allow backfill material to surround the bar. At mid-length, a fiber or styrofoam filler-board placed around the dowel forms the joint. The filler-board also prevents patch materials from penetrating the sides or bottom of the existing joint or crack. Each job may require several nominal widths of filler-board for various joint widths. Figure 23 shows recommended orientation, slot size and details for retrofit dowel bars.

LTR with dowel bars is effective in reducing the development of faulting (Figure 24) (3,47,49). Retrofit dowels can increase joint efficiency to between 50 - 80 percent. After five years on one Florida project,

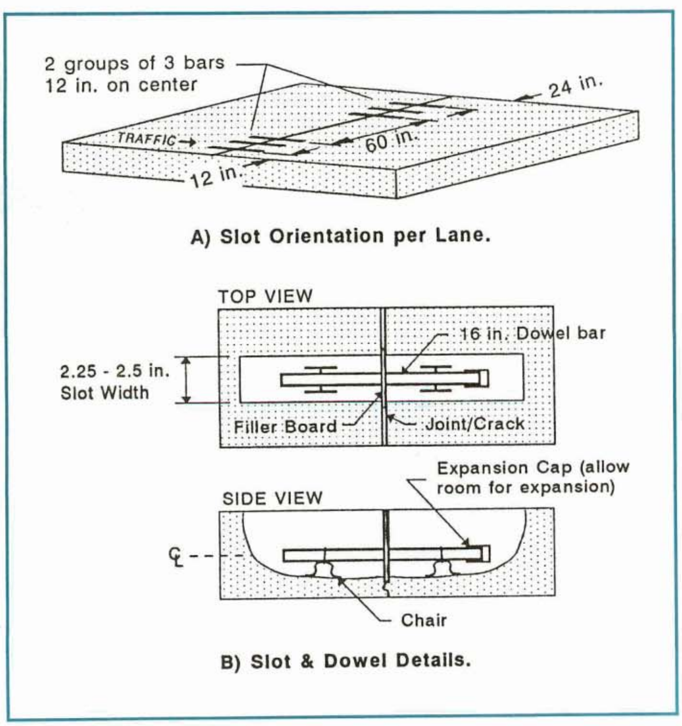


Figure 23 *a) Recommended orientation for retrofit dowel bars (per highway lane). An airport slab requires 12-in. (31 cm) uniform spacing. b) Slot size and details for each retrofit bar.*

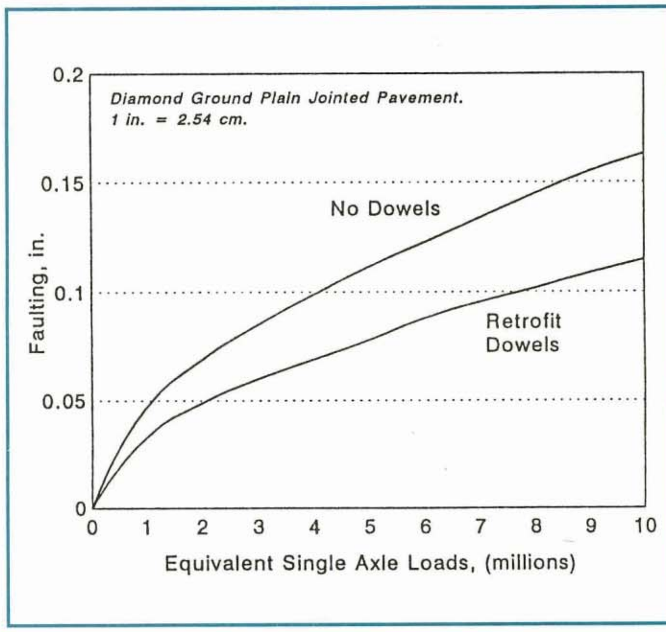


Figure 24 *Predicted effectiveness of load transfer restoration in deterring faulting compared to plain transverse joints on typical CPR projects. (Plain joints contained no mechanical load transfer).*

the dowels are still functioning at efficiencies near post-construction levels (49).

Double-vee Devices - Double-vees are proprietary devices used for LTR in both highway and airport applications. Double-vees require a 6-in. (15 cm) core hole drilled vertically through a slab and oriented across a joint. A laborer compresses the device using a special tool before inserting it into the hole. After insertion, cementitious backfill surrounds the hole and bonds to the device and the core walls. A special coring bit produces a grooved core hole to enhance load transfer. Sandblasting and airblowing are necessary to roughen the core walls for backfill bond. Details for double-vee devices are available from the manufacturer.

Special Considerations for Cracks

Like joints, some cracks also require sealing to prevent moisture and incompressible infiltration. The orientation and type of crack dictates sealing necessity. Cracking in concrete pavement initiates by one or a combination of seven factors:

1) Plastic Shrinkage.
2) Drying Shrinkage.
3) Restrained Thermal Contraction.

4) Thermal & Moisture Gradients.
5) Non-uniform Support.
6) Reflection of Underlying Distress.
7) Load.

Cracks which remain tight usually do not require sealing. These cracks are typically very narrow (hairline) cracks. Table 10 provides guidance to determine where crack sealing, cross-stitching and load transfer restoration are necessary.

Working Cracks —

Once started, a crack may develop full-depth through a slab or traverse only partial-depth (Eg. plastic shrinkage cracks). The crack may also begin moving and functioning as a joint. Cracks which function as a joint are "working" cracks. Working cracks are subject to nearly the same range of movement as transverse joints and therefore require sealing.

Table 10. ***Crack sealing and repair guidelines (33, 52).***

Crack Orientation	Crack Type	Description	Spalling Condition	Faulting	Crack Width	Recommended Repair Procedures
Transverse	Plastic Shrinkage	Partial-depth	None	0	Hairline	Do Nothing.
Transverse	Random	Low Severity	None	0	Hairline	Saw & Seal.
Transverse	Random	Medium Severity	Low [<3 in (76 mm)]	<0.25 in (6.3 mm)	≤0.5 in (12.7 mm)	Partial-Depth Repair, Saw & Seal, Load Transfer Restoration.
Transverse	Random	Medium Severity	Med-High [+ 3 in (76 mm)]	0	≤0.5 in (12.7 mm)	Partial-Depth Repair, Saw & Seal.
Transverse	Random	High Severity	Med-High [+ 3 in (76 mm)]	≥0.25 in (6.3 mm)	>0.5 in (12.7 mm)	Full-Depth Repair.
Longitudinal	Plastic Shrinkage	Partial-depth	None	0	Hairline	Do Nothing.
Longitudinal	Random	Low Severity	None	0	Hairline	Cross-Stitching.
Longitudinal	Random	Low Severity	Low [<3 in (76 mm)]	0	Hairline	Cross-Stitching.
Longitudinal	Random	Medium Severity	Low-Med [<6 in 76 mm)]	<0.5 in (12.7 mm)	≤0.5 in (12.7 mm)	Partial-Depth Repair, Saw & Seal.
Longitudinal	Random	Medium Severity	High [+ 6 in (152 mm)]	0	≤0.5 in (12.7 mm)	Partial-Depth Repair, Saw & Seal.
Longitudinal	Random	High Severity	High [+ 6 in (152 mm)]	≥0.5 in (12.7 mm)	>0.5 in (12.7 mm)	Slab Replacement or Full-Depth Repair.

It may also be necessary to establish pavement integrity at working cracks. Those cracks with significant spalling, pumping or faulting require full-depth repair. Load-transfer restoration can repair cracks with low efficiency levels.

For longitudinal cracks which are in reasonably good condition, cross-stitching is an alternate repair technique. Cross-stitching has been successful on both roadway and airport pavements (50,51). The purpose of cross-stitching is to maintain aggregate interlock and provide added reinforcement and strength. The tie bars used in cross-stitching prevent the crack from vertical and horizontal movement or widening.

Cross-stitching uses deformed tie bars drilled across a crack at angles of 35° (Figure 25). A number 6 bar is sufficient to hold the joint tightly closed and enhance aggregate interlock (50). The bars, spaced 20 - 30 in. (50 -75 cm.) from center to center, alternate from each side of the crack (Figure 26). Heavy truck traffic and airplane traffic require the 20 in (50 cm) bar spacing. A 30 in (75 cm) spacing is adequate for light traffic and interior highway lanes.

Do not stitch a transverse crack which has assumed the role of an adjacent joint. Stitching will not allow transverse joint movement (open and closure). A new crack will likely develop near a stitched working crack or the concrete will spall over the reinforcing bars.

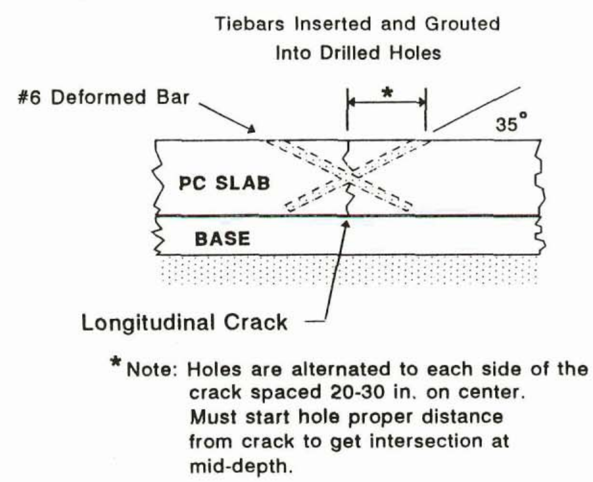


Figure 25 *Cross-section through a longitudinal crack showing the orientation of tiebars for cross-stitching.*

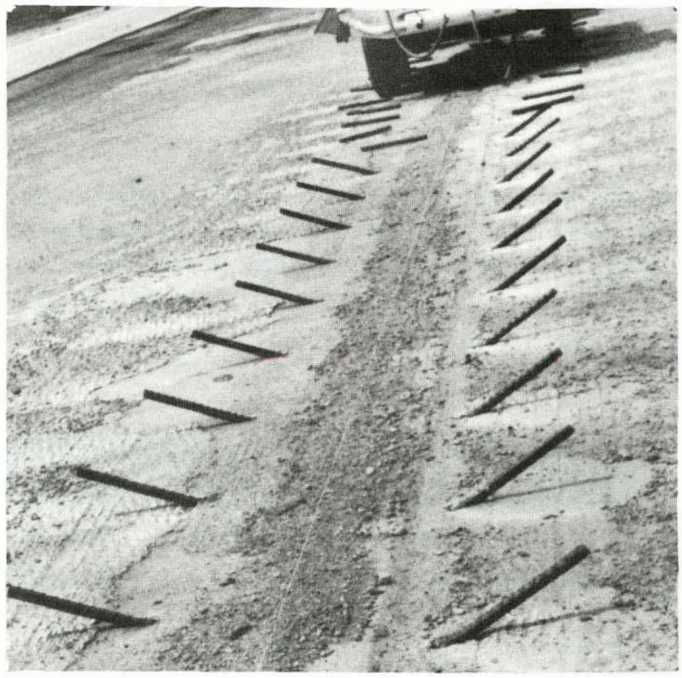


Figure 26 *Cross-stitching tiebars ready for final insertion on an airport pavement.*

Always use smooth dowel bars in repairs of transverse cracks or joints in jointed plain pavement. This includes application in full-depth repair or load transfer restoration. Dowel bars allow necessary movement for proper repair function. In repairing mid-panel cracks in jointed reinforced concrete pavement (JRCP) it may be acceptable to use deformed tiebars. However, the joints on each side of the crack must be handling cyclic temperature movements. If they are not, also use smooth bars in repairing the intermediate crack.

Hairline Cracks—

Most hairline cracks require no special treatment or sealing, mainly because they do not allow significant water to penetrate the pavement substructure. Some hairline cracks, particularly plastic shrinkage cracks, are very tight and do not extend through the full slab depth. Plastic shrinkage cracks rarely deteriorate or influence the ride or life of concrete pavement. Tight cracks held by reinforcing bars, such as those found on continuously reinforced concrete, also do not require sealing.

If a hairline crack begins to deteriorate, remedial treatment may become necessary. Load transfer restoration and sawing and sealing provides the best long-term repair. Using low viscosity epoxy to glue working cracks in pavement is often unnecessary and usually not effective. A slab will eventually crack again near the vicinity of an epoxied crack due to thermal restraint (11).

Crack Sealing/Resealing –

Cracks are not straight and are therefore more difficult to shape and seal (3). Avoid trying to follow crack wander with a standard blade. Manufacturers provide special crack-sawing blades to help the operators follow crack "wander". The special blades with diameter from 7 - 8 in (18 - 21 cm) are also more flexible to aid in crack tracing.

Special crack saws are usually supported by three wheels and are smaller than most joint sawing equipment (Figure 27). A pivot wheel on the saw allows the saw to easily follow crack wander. Even with special blades, a sawed crack reservoir will not be as uniform or clean as a straight joint reservoir. However, it is desirable to attempt to obtain the same shape factor at working cracks that is developed at joints on a project.

Avoid using routers for concrete pavement. Routers were used extensively in the past to create the seal reservoir above cracks (3). Routers use a vertical spinning bit with a diameter and length that produce the desired reservoir dimensions. Most contractors no longer use routers because the they achieve better reservoir results and increased productivity with diamond saws.

After repair and sawing, crack sealing requires all of the cleaning steps used in joint sealing. That includes the use of a backer rod and uniform sealant installation.

Additional Information

Additional information on sealing and resealing joints in concrete pavement is available by contacting the American Concrete Pavement Association.

Figure 27 *Crack sawing equipment. Note the small diameter blade and pivoting front wheel.*

Conclusions

1. Proper joint sealing contributes to good performance on roadways and airports. With proper design and construction joint sealants minimize infiltration of surface water and incompressible material into the joint system.

2. The hypothesis that sealing is unnecessary for pavements with free-draining base materials is logical but currently unsubstantiated. Sealants are needed to reduce incompressible infiltration even in pavements with open-graded base materials.

3. It is not realistic to construct and maintain a completely watertight joint. Periodic surveys and a rational sealant rating system provide the necessary criteria to judge seal effectiveness.

4. Sealant selection considers pavement life expectancy, classification, joint type, climate and cost of traffic control over the economic analysis period. Comparison of different sealant materials based on their individual life expectations is a necessary part of project design and life-cycle analysis.

5. Liquid and compression seals can provide acceptable performance. Proper reservoir sizing and preparation are essential to maximizing performance of any sealant.

6. Joint type and spacing influences the choice of sealant materials and reservoir design. Tied longitudinal joints (centerline or lane/shoulder) do not stress sealant materials as do transverse joints, since their movements are considerably smaller. An agency should optimize project cost by considering this in sealant selection.

7. Longitudinal joints are often perpendicular to the drainage slope providing significant access for water. Neglecting to seal and maintain longitudinal joints may negate the benefits of even excellent transverse joint seals.

8. Resealing joints and cracks requires good preparation to maximize sealant life. The necessary steps include: old sealant removal, reservoir shaping, reservoir cleaning, backer rod installation, and sealant installation.

9. Resealing joints is a necessary maintenance activity for jointed concrete pavement. An Operation and Maintenance Plan developed by the design engineers will provide a tool to engineers charged with maintaining a pavement after construction.

10. Concurrent rehabilitation techniques may be necessary with a joint resealing operation.

11. An agency can establish and maintain pavement integrity at working cracks through full-depth repair or load transfer restoration. Retrofit dowel bars are the most consistent load transfer restoration design.

12. An alternative for longitudinal crack reinforcement is cross-stitching. Stitching has been successful on both highways and airports in otherwise good condition. Cross-stitching is not for transverse working cracks or transverse joints.

References

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

2. "Resealing of Concrete Pavement Joints," Pavement Rehabilitation Manual, Chapter 12 , Federal Highway Administration, Rev. 1990.

3. Eres Consultants, Inc., "Techniques for Pavement Rehabilitation," Federal Highway Administration, 1992.

4. Tons, E., "A Theoretical Approach to Design of a Road Joint Seal," Highway Research Record 211, Highway Research Board, National Research Council, Washington D.C., 1959.

5. "Methods of Forming Joints in Portland Cement Concrete Pavement," Draft Report, Subcommittee on Joint Forming, Highway Research Board, 1961.

6. "Field Inspection Guide for Restoration of Jointed Concrete Pavements," Demonstration Projects Division, Federal Highway Administration, Washington D.C., December 1987.

7. Ray, G.K., "Effect of Defective Joint Seals on Pavement Performance," Transportation Research Record 752, Transportation Research Board, National Research Council, Washington D.C., 1980, pp. 1-2.

8. "Subbases and Subgrades for Concrete Pavements," American Concrete Pavement Association, Portland Cement Association, TB-011.0D, Arlington Heights, IL, 1991.

9. McBride, J.C., Decker, M.S., "Performance Evaluation of Utah's Concrete Pavement Joint Seals," Transportation Research Record 535, Transportation Research Board, National Research Council, Washington D.C., 1975, pp. 35-50.

10. "Joint Sealing a Glossary," Highway Research Board, National Academy of Sciences, Special Report 112, Washington D.C., 1970.

11. "Maintenance of Joints and Cracks in Concrete Pavement," IS188.01P, Portland Cement Association, Skokie, IL, 1976.

12. Peterson, D.E., "Resealing Joints and Cracks in Rigid and Flexible Pavements," Synthesis of Highway Practice 98, National Cooperative Highway Research Program, Transportation Research Board, National Research Council, Washington D.C., December 1982.

13. Gulden, W., Thornton, J.B., "Pavement Restoration Measures to Precede Joint Resealing," Transportation Research Record 752, Transportation Research Board, National Research Council, Washington D.C., 1980, pp. 6-15.

14. "Installing Pavement Crack & Joint Sealants," Facilities Engineering Applications Program, United States Army Engineering Housing Support Center, Fort Belvair, VA, September 1990.

15. Kiljan, J., "Concrete Pavement Restoration Demonstration," CDOH-DTD-R-88-6, Colorado Department of Highways, Denver, CO, February 1988.

16. Brown, D.D., "Effects of Various Sealing Systems on Portland Cement Concrete Joints," Highway Research Record 389, Highway Research Board, National Research Council, Washington D.C., 1972, pp. 28-39.

17. "Performance of Jointed Concrete Pavements," Volume I - Evaluation of Concrete Pavement Performance and Design Features, FHWA-RD-89-136, Federal Highway Administration, McClean, VA, March 1990.

18. "Performance of Jointed Concrete Pavements," Volume II - Evaluation and Modification of Concrete Pavement Design and Analysis Models, FHWA-RD-89-137, Federal Highway Administration, McClean, VA, March 1990.

19. Rutkowski, T.S., "Joint Sealant Study," Wisconsin Department of Transportation, May 1990.

20. Shober, S.F., "Portland Cement Concrete Pavement Performance as Influenced by Sealed and Unsealed Contraction Joints," Wisconsin Department of Transportation, 1974.

21. Hicks, S.E., "Do We Need to Seal Joints?," State Highway Commission of Wisconsin, January 1967.

22. Darter, M.I., Becker, J.M., Snyder, M.B., "Portland Cement Concrete Evaluation Systems (COPES)," National Cooperative Highway Research Program Report 277, Transportation Research Board, National Research Council, Washington D.C., September 1985.

23. Ortiz, D., Barenberg, E.J., Darter, M.I., Darling, J., "Effectiveness of Existing Rehabilitation Techniques for Jointed Concrete Pavement," FHWA/IL/UI-215, Federal Highway Administration, Washington D.C., 1986.

24. Darter, M.I., Carpenter, S.H., Zimmer, T.R., "Field Performance of a Low-Modulus Silicone Highway Sealant," Transportation Research Record 990, Transportation Research Board, National Research Council, Washington D.C., 1984, pp. 31-37.

25. Spells, S., Klosowski, J.M., "Silicone Sealants for Use in Concrete Construction," SP-70, Volume I, American Concrete Institute, 1981.

26. "Guide Specifications for Highway Construction," American Association of Highway and Transportation Officials, Washington, D.C., 1988.

27. Pachuta, J.M., Smith, D.J., "Development of Effective Poured-in-Place Systems for Concrete Pavement Joints," Highway Research Record 287, Highway Research Board, National Research Council, Washington D.C., 1969, pp. 81-86.

28. Barksdale, R.D., Hicks, R.G., "Improved Pavement-Shoulder Joint Design," National Cooperative Highway Research Program Report 202, Transportation Research Board, National Research Council, Washington D.C., June 1979.

29. "Preformed Compression Seals for PCC Pavement Joints," Technical Paper 89-04, Federal Highway Administration, Washington D.C., September 1989.

30. Loza, G.F., Anderson, D.I., "Evaluation of Concrete Joint Sealants Clear Creek Summit to Belknap Interchange," Utah Department of Transportation, March 1988.

31. Voigt, G.F., Yrjanson, W.A., "Concrete Joint Sealant Performance Evaluation," Utah Department of Transportation, July 1992.

32. Brunner, R.J., Kileraski, W.P., Mellott, D.B., "Concrete Pavement Jointing & Sealing Methods," Transportation Research Record 535, Transportation Research Board, National Research Council, Washington D.C., 1975, pp. 24-34.

33. "Distress Identification Manual for the Long-Term Pavement Performance Studies," SHRP-LTPP/FR-90-001, Strategic Highway Research Program, National Research Council, Washington D.C., 1990.

34. "Diamond Grinding & CPR 2000," TB-008.0CPR, American Concrete Pavement Association, Arlington Heights, IL, 1990.

35. Wojakowski, J.B., "Joint Sealant Test Sections - US 36 Doniphan County," NEPT KS-8904, Kansas Department of Transportation, Unpublished Research Data, 1991.

36. Godfrey, K.A., "Pavement Joint Seals," Civil Engineering, American Society of Civil Engineers, March 1972.

37. "Guide Specifications Dow Corning 888 Silicone Highway Joint Sealant," Dow Corning Corporation, 1992.

38. "Silicone Sealant Performance Review," Federal Highway Administration, Pavement Division/Demonstration Projects Division, September 1990.

39. Guidelines for Full-Depth Repair," TB-002.0CPR, American Concrete Pavement Association, Arlington Heights, IL, 1989.

40. "Guidelines for Partial-Depth Repair," TB-003.0CPR, American Concrete Pavement Association, Arlington Heights, IL, 1989.

41. "Street & Highway Maintenance Manual, American Public Works Association, 1985.

42. Lynch, L.N., "Joint Sealant Study and Field Performance Survey," GL-89-3, United States Army Corps of Engineers, Waterways Experiment Station, March 1989.

43. Bugler, J.W., "Rigid Pavement Joint Resealing: Field Application, State of the Art," Transportation Research Record 990, Transportation Research Board, National Research Council, Washington D.C., 1984, pp. 16-21.

44. "Sealing and Resealing Cracks the Crafco Way," Crafco Inc., Phoenix, AZ, 1979.

45. "Guide Procedures for Concrete Pavement 4R Operations," Task Force 23, AASHTO-AGC-ARTBA, 1985.

46. Watson, S.C., "Installation of Preformed Neoprene Compression Joint Seals," Highway Research Record 287, Highway Research Board, National Research Council, Washington D.C., 1969, pp. 53-58.

47. Snyder, M.B., Reiter, M.J., Hall, K.T., Darter, M.I., "Rehabilitation of Concrete Pavements: Volume I - Repair Rehabilitation Techniques," FHWA/RD-88/071, Federal Highway Administration, April 1989.

48. Gulden, W., Brown, D., "Establishing Load Transfer in Existing Jointed Concrete Pavements," Transportation Research Record 1043, Transportation Research Board, National Research Council, Washington D.C., 1985.

49. Hall, K.T., Darter, M.I., Armanghani, J., "Performance Monitoring of Joint Load Transfer Restoration," Draft Report, 72nd Annual Meeting of Transportation Research Board, Washington, D.C., July 1992.

50. "Cross-Stitching - A New Repair Procedure for PCC Pavements," Concrete Pavement Progress Special Report, American Concrete Pavement Association, Arlington Heights, IL, March/April 1986.

51. Burns, C.D., Hutchison, R.L., "Multiple-Wheeled Heavy Gear Load Pavement Tests, Design, Construction & Behavior Under Traffic," Volume II, Waterways Experiment Station, U.S. Army Corps of Engineer, March 1971.

52. Christory, J.P., Nissoux, J.L., "Evaluation and Maintenance of Concrete Pavements," 07.04.B, Permanent International Association of Road Congresses, Washington D.C., 1992.

5420 Old Orchard Road, Suite ACPA, Skokie, Illinois, 60077-1083
(847) 966-2272

TB012P