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Guide for Optimum JOINT PERFORMANCE of Concrete Pavements





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16. Abstract

The purpose of this guide is to help practitioners understand how to optimize concrete pavement joint performance through the identification, mitigation, and prevention of joint deterioration. It summarizes current knowledge from research and practice to help practitioners access the latest knowledge and implement proven techniques. Emphasizing that water is the common factor in most premature joint deterioration, this guide describes various types of joint deterioration that can occur. Some distresses are caused by improper joint detailing or construction, and others can be attributed to inadequate materials or proportioning. D cracking is a form of joint distress that results from the use of poor-quality aggregates. A particular focus in this guide is joint distress due to freeze-thaw action. Numerous factors are at play in the occurrence of this distress, including the increased use of a variety of deicing chemicals and application strategies. Finally, this guide provides recommendations for minimizing the potential for joint deterioration, along with recommendations for mitigation practices to slow or stop the progress of joint deterioration.

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Guide for Optimum

JOINT PERFORMANCE

of Concrete Pavements

JULY 2012

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About This Guide

This guide will help practitioners optimize concrete pavement joint performance by preventing, identyfing, and mitigating premature joint deterioration.

While the majority of concrete pavements are not affected by premature joint deterioration, the problem is common enough to have triggered research efforts to identify causes and preventive measures. Current projects include a Federal Highway Administration (FHWA) Transportation Pooled Fund Study TPF 5(224): Investigation of Jointed Plain Concrete Pavement Deterioration at Joints and the Potential Contribution of Deicing Chemicals. With the Iowa Department of Transportation (DOT) as the lead state, TPF-5(224) is a collaborative effort among the National Concrete Pavement Technology Center (CP Tech Center) at Iowa State University, Michigan Technological University, and Purdue University and is sponsored by the state departments of transportation in Indiana, Iowa, Michigan, Minnesota, New York, South Dakota, and Wisconsin. Other efforts include individual projects at state departments of transportation in Iowa, Michigan, Minnesota, and South Dakota, to name a few. As a result of all these efforts, knowledge about the causes of joint deterioration is growing significantly.

In recent months, the CP Tech Center has been synthesizing and supplementing best practices to date based on the latest research and using data and photographs provided by local authorities in multiple states, numerous visits and investigations at sites (mostly in Iowa, Minnesota, Wisconsin, and Michigan), as well as laboratory testing. Now, instead of waiting for "all the answers" to questions that still remain, the CP Tech Center has developed this guide under TPF 5(224) to help practitioners access the latest knowledge and implement proven techniques for identifying, mitigating, and reducing the risk of premature joint deterioration.

Acknowledgments

The authors appreciate the support of the FHWA (DTFH 61-06-H-00011 (Work Plan 26)) and of the Transportation Pooled Fund (TPF) 5(224) sponsored by state DOTs in Indiana, Iowa, Michigan, Minnesota, New York, South Dakota, and Wisconsin, which has made it possible to develop this guide. They would also like to acknowledge the contributions of numerous organizations and individuals referenced herein, particularly Purdue University, Michigan Tech University, and the cities of Ankeny, Iowa, and West Des Moines, Iowa.

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Executive Summary

Users of this guide will learn why joint deterioration occurs, how to address deterioration that may already be evident, and how to prevent it from occurring on future projects.

A particular focus in this guide is joint distress due to freeze-thaw action of saturated concrete. Deicing practices currently in use appear to be increasing the degree of saturation of concrete at the joints; thus, the concrete must be higher quality to be able to resist this environment.

Emphasizing that water is the common factor in most premature joint deterioration, this guide describes various types of joint deterioration that can occur. Some distresses are caused by improper joint detailing, inadequate drainage, or poor construction practices, and others can be attributed to inadequate materials or proportioning.

1 Why Now – What's New?

Concrete pavements are constructed with joints to accommodate concrete shrinkage and control crack locations.

While the majority of concrete pavements are not affected by premature joint deterioration, problems have been reported in several northern (cold weather) states. Pavements affected include state highways, county roads, city streets, and parking lots.

The question of why premature joint deterioration is happening now is raised because none of the mechanisms that appear to contribute to the problem are new to concrete practitioners. The deterioration is likely a result of a combination of many factors. Indeed, it is likely that most concrete is acceptable for the environment it is exposed to, but very close to the cliff edge of failure, therefore small changes in mixture quality, and construction or salting practice **may** result in localized distress:

- Concrete that is saturated with trapped water is at higher risk of failure. Such saturation is more likely in joints than at the slab surface.
- Deicing salts currently in use are prone to increasing the risk of saturation because they do not dry out readily.
- Some joint details appear to trap water.
- Air void systems are less stable due to changing chemistry of mixture ingredients, increasing the risk that in-situ air contents are less than ideal.
- Increased water-cementitious materials (w/cm) ratios to reduce cost and improve placement, while still achieving minimum strength.
- Mixtures containing supplementary cementitious materials (SCMs) that are known to be more sensitive to poor curing.
- Lack of curing applied to the concrete within the saw-cut faces.
- Construction that is being pushed further into the cold season. The result is reduced concrete maturity before it is exposed to freezing conditions.

It is common to observe sections of a roadway experiencing joint deterioration near other sections that are in excellent condition. It appears that even small differences between concrete batches or in construction-related activities lead to differences in joint performance. For example, hand-placed sections are more prone to distress than slipformed sections in the same roadway, likely because water is added to improve workability of the hand-placed sections.

While all of these factors are important, quite possibly the most significant change is related to de-icing practices. Pavement owners are becoming increasingly aggressive in their deicing and anti-icing activities, with the goal of improving safety. In addition to using greater quantities of salt, alternatives to sodium chloride (NaCl) such as calcium chloride (CaCl2) and magnesium chloride (MgCl2) are now being used both in solution and as dry powders. Unfortunately, these alternatives have been shown to increase the saturation of the concrete at a saw cut, which is a significant contributor to the observed joint deterioration. Concrete pavements will have to be engineered to resist this added stress.

Given the variety of concrete pavement design details, construction scenarios, materials and climate factors, detailed causes of distress will vary between locations. Likewise, suggestions for repair will have to be thought though keeping in mind all of the factors in play. There is no one-size-fits-all solution to the issue.

2 Types and Mechanisms of Joint Deterioration

No single mechanism can account for all reported occurrences of joint deterioration. Contributors can include frost or freeze-thaw damage, mechanical damage, early-age damage, and D-cracking, each of which is discussed below. The focus of this document is on frost related distress in the paste as other mechanisms are discussed in detail elsewhere.

2.1 Saturated Frost Damage

Saturated frost damage is due to expansion of water in the saturated capillaries of the concrete as it freezes causes cracking. Cycles of freezing and thawing open these cracks allowing more water to penetrate, and as a result the concrete deteriorates incrementally. Concretes that are highly saturated are prone to accelerated damage. This is different from D-cracking because frost damage occurs in the paste and not the aggregates

Common characteristics of or practices on pavements with frost-damaged joints include the following:

- Pavement saturated for long periods, regardless of the source of water.
- Pavement with marginal air-void systems (total air content, spacing factors, and specific surface).
- The use of significant quantities and/or potentially aggressive deicing salts.
- Secondary ettringite deposits that fill the air-void system under saturated conditions.
- The damage appears as thin flakes of mortar that form parallel to the exposed surface (Figure 1)

2.1.1 Mechanisms

Water is the common factor in frost damage. Water can be present in a pavement system because of inadequate surface or subsurface drainage, a high water table, or because it is trapped behind a seal above an un-cracked or non-draining joint. Weiss and Nantung have modeled how a joint face can be saturated when a seal fails to prevent water ingress (1) (Figure 2). Figure 3 illustrates how inadequate subsurface drainage can be a contributor, especially when coupled with excessive roadside irrigation.

Figure 1. Typical slivers from freezing and thawing cycles

Weiss has also shown that increasing the saturation of a concrete sample will decrease its ability to resist freezing because there is more water in the system than can be accommodated when freezing occurs (2). Concrete that is less than 85 percent saturated can survive, while saturation greater than this will likely result in damage.

Deicing salts can aggravate frost damage. Based on findings by Weiss, the primary driver behind this acceleration is likely the increased saturation due to the tendency of some salts (most notably magnesium chloride [MgCl2] and calcium chloride [CaCl2] to retain water (2). Additional mechanisms may also include expansion of crystallizing salts as water evaporates and/or solutions freeze as well as osmotic pressures induced by salt concentration gradients (3).

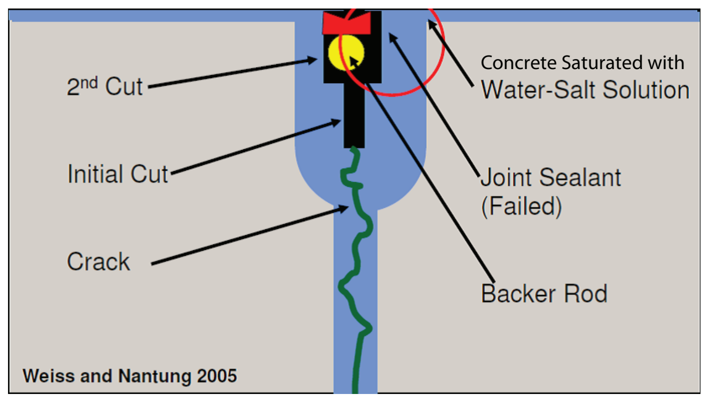

Figure 2. Schematic of poor joint sealant leading to saturation (3)

Figure 3. Saturated soils due to inadequate drainage and roadside irrigation (left) leading to joints showing frost damage (right) (Source: Snyder and Associates)

The chemical decomposition of calcium silicate hydrate in contact with some salts (magnesium chloride [$MgCl_2$]) is also possible; however, this is a relatively slow process and may not be a significant contributor compared to other effects (5).

Current deicing practices are tending to increased volume and concentration of products used, along with selection of more aggressive compounds, therefore increasing the risk of distress of the concrete. In addition, some agencies are using anti-icers that are applied before a snow event to make snowplowing easier. Typically these are applied as solutions rather than as dry salts. Again these activities are believed to be more aggressive to the concrete.

2.1.2 Presentation

Deterioration is sometimes first observed as shadowing or darkening of a zone a few inches on either side of a joint. This effect is the result of a fine network of microcracks that develop near and parallel to the joint. The cracks trap water, which lead to the darker color. Over time significant loss of material may occur (Figure 4). In most cases where shadowing is observed the system is not well drained (Figure 5), and the air-void system is often marginal or poor. It is also common to observe evidence of secondary ettringite deposits in the air voids (Figure 6). This indicates abundant water within the concrete, although the exact mechanisms and effects of this ettringite are still not resolved.

If the joint does not crack out, then salt solution can collect in the saw-cut. Freezing and thawing of this trapped fluid leads to the creation of what appears to be a tunnel through the slab at the level of the bottom the saw-cut (Figure 3).

When the pavement is placed on a non-draining base and/or when the water table is above the bottom of the slab, the top of the pavement may appear to be in reasonable condition, but coring reveals concrete that has been seriously damaged in the joint (Figure 7). Interestingly, the damage is more pronounced in the saw-cut than in

Figure 4. Evolution of joint deterioration from shadowing (left) to high severity (right)

Figure 5. Typical saturated foundations under a shadowed section (Source: Snyder and Associates)

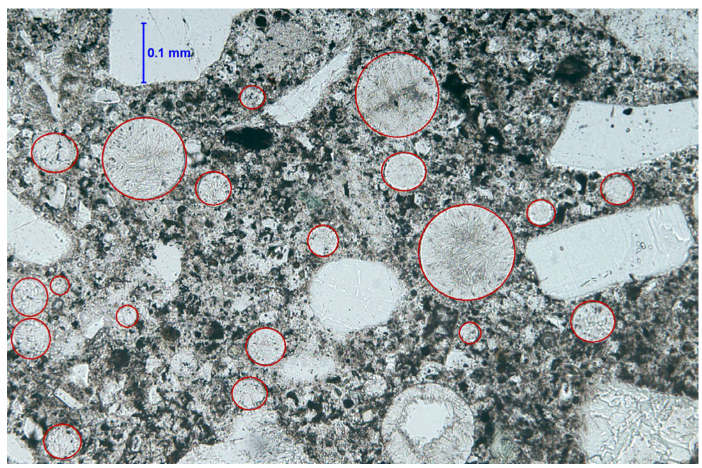

Figure 6. Secondary ettringite deposits in air voids (Source: American Engineering Testing, Inc.)

Figure 7. Three cores illustrating progression of distress from bottom-up moisture

the crack, presumably because a significant amount of water can collect in the saw-cut while cracks tend to be tight. Figure 8 illustrates the site where these cores were extracted, showing the clear signs of abundant water flow.

2.1.3 Prevention

There are three primary strategies for preventing or reducing frost damage to concrete joints: preventing saturation, ensuring adequate air entrainment and reducing concrete permeability. Limiting the use of aggressive deicing salts would also reduce the risk of problems but may be impractical from a safety point of view.

Saturation. Attention to detail in how water will be prevented from collecting and staying in a joint is critical. This will include if and how the joint is sealed, and whether water that penetrates into the joint may be drained away. If the base or support layer is impermeable consideration may be given to using a geotextile that is daylighted at the edge to provide some drainage. Note that the volume of water penetrating a joint from above will be small, so high permeability (and thus low stability) systems are not required.

Figure 8. Water flow through joints from a high water table (bottom-up moisture); note staining on surface

Air entrainment. Concrete is provided with deliberately entrained small air bubbles that provide pressure relief for expanding water when it freezes. It is therefore important to ensure that the concrete has an adequate air-void system. A spacing factor of 0.008 in. in concrete behind the paver in sufficiently low w/cm mixtures should provide satisfactory performance; however, work is continuing to establish whether this value is sufficient for concrete that is saturated for extended periods.

Low permeability. It is recommended that the permeability of concrete be low, particularly if it is likely to be wet for extended periods. Reducing permeability can be achieved by the following:

- Limiting the maximum w/cm ratio consistently to below 0.42. Ideally, the w/cm ratio should be close to 0.40.
- When possible, using appropriate supplementary cementitious materials at appropriate dosages.
- Implementing rigorous curing techniques inside the joint.
- Potential use of surface or impregnating sealants at and in the joint. Work continues to quantify the specific benefits and limitations of this approach.

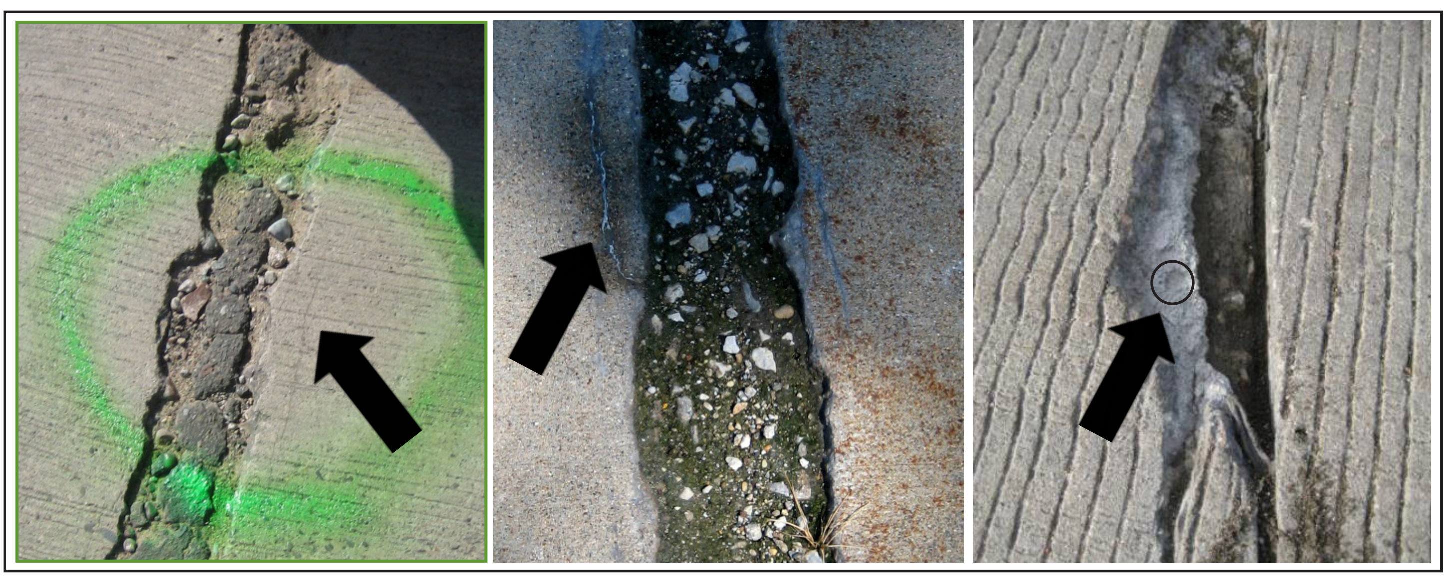

Figure 9. Typical incremental cracking: Note (left to right) the crack parallel to the already patched face, the signs of water passing through the crack, and the exposed aggregate remaining in the concrete

2.2 Incremental Cracking

Joint deterioration is also seen as parallel cracks that form at approximately one-inch increments starting from the joint face (Figure 9). The concrete between the crack and the free face is normally sound, as is the remaining concrete next to the crack; which is not typical of normal frost damage. The coarse aggregate still embedded in the concrete is often free of adhering mortar on the exposed face (Figure 10) and the joint is often filled with loose aggregate. This indicates a mechanism that is attacking the paste alone.

When a joint is patched or filled, it is common to observe new cracks that form an inch or so beyond the boundaries of the repair. Furthermore, staining and carbonate deposits, indicating water transport through the crack, are common.

It is hypothesized that this distress is a result of the interfacial zone around coarse aggregate particles being exposed by the saw cut. Water preferentially penetrates the zone when the joint is flooded, and jacks the aggregate away from the paste when frozen (Figure 11 and 12)

Work is ongoing to investigate the validity of this hypothesis and to assess preventative approaches.

2.3 Mechanical Damage

Joint damage can occur from stresses caused by incompressible materials (sand, rocks, other debris) trapped in the joint (Figure 13). This is not considered significant.

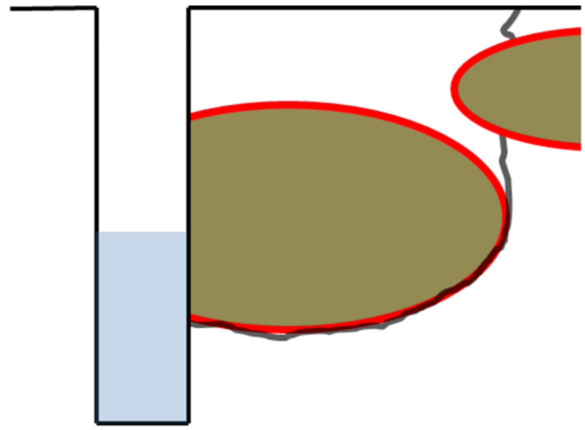

Figure 11. Illustration of crack development through the interfacial; zone leading to so-called incremental cracking

Figure 12. Photograph of a crack around an aggregate particle

Figure 10. Coarse aggregate exposed by damage to the paste

Figure 13. Incompressibles causing mechanical damage, which can lead to further distress

Raveling of a saw cut can also be caused by aggregate particles being dislodged during sawing, typically because the concrete strength is too low when conventional sawing is conducted. Alternatively, raveling is observed when the shoe on an early-entry saw is not functioning properly (Figure 14). Such spalling is typically found at the surface and will rarely extend through the depth of the slab.

Figure 14. Raveling due to poor sawing practice (Source: Iowa Department of Transportation)

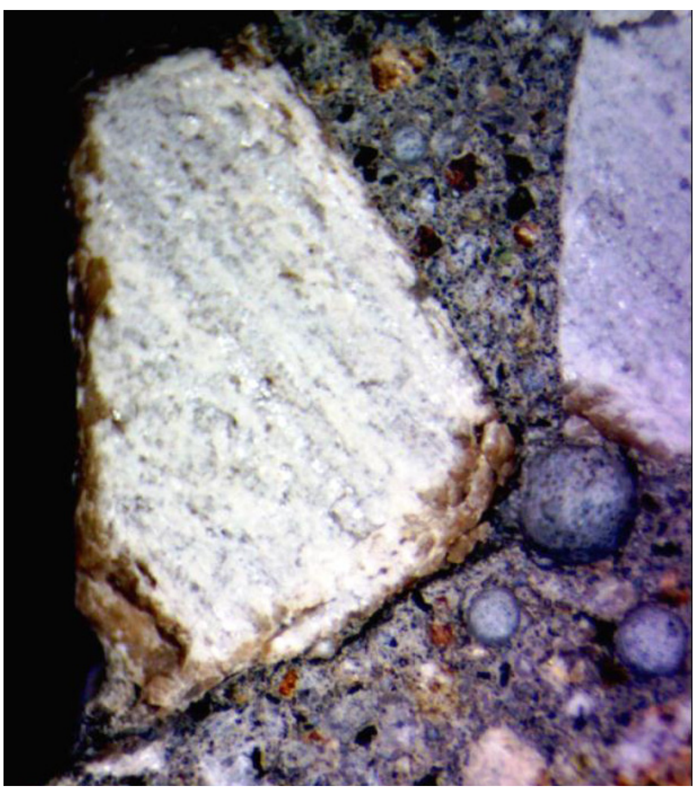

Figure15.Photographofanaggregateparticledislodgedbyinappropriate sawing (Field of view 5mm)

Concrete at the bottom of a saw cut may become damaged during sawing using machines with worn bearings or an inappropriate blade, or when cutting on a curve (Figure 15). Erosion and/or a zone of microcracking is possible, which can lead to water being trapped, thus increasing the risk of damage from frost action.

Traffic loading has been considered as a mechanical cause of joint deterioration, but the shear stresses imposed at the edges of saw cuts by wheel loads are low. Unless heavy traffic is allowed on a pavement a few hours after placement, loading is unlikely to be a significant contributor.

2.4 D-cracking

D-cracking is a type of deterioration caused by expansive freezing of water trapped inside some types of aggregate particles. The damage normally starts near joints and forms a characteristic crack pattern (Figure 16). The damage is generally worse at the bottom of a slab than at the top. As long as freeze-thaw cycles continue, the distress cannot be stopped.

D-cracking can be prevented by choosing aggregates that are not susceptible to freeze-thaw deterioration. Alternatively, where marginal aggregates must be used, reducing the maximum aggregate size has been found to be beneficial. Improving drainage to reduce the potential for saturation of the concrete aggregates can have a marginal benefit.

This form of distress can easily be distinguished from the others that are the focus of this publication in that the distress starts in the aggregate as opposed to occurring in the paste.

2.5 Early-Age Drying Damage

Another potential mechanism for joint deterioration begins with drying conditions during concrete placement although the damage may not become evident until years later. High evaporation rates during placement results in large differences in moisture content through the depth of the concrete slab. These differences may lead to stresses high enough to cause fine horizontal cracks and delamination. In areas where these horizontal cracks intersect vertical cracks or joints, concrete material can break free, and “flat bottom” or delamination spalling can occur. The severity and timing of delamination spalling varies with the severity of moisture loss at an early age, along with traffic and climate factors McCullough et al. (5). This

Figure 16. D cracking of low severity (top) and high severity (bottom) (Source: The Transtec Group)

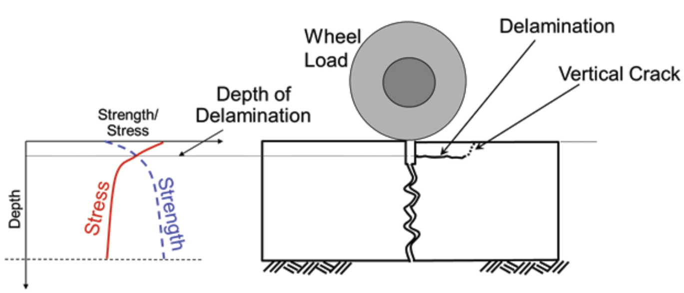

Figure 17. Early-age drying stresses (left) and resulting horizontal cracking and delamination spalling (right) due to high moisture loss during placement (2)

process is illustrated in Figure 17 and the result is shown in Figure 18.

2.6 Summary of Joint Deterioration Observations

Basic forms of joint deterioration are shown in Figure 19 through Figure 24. Following are the critical factors:

- Water has to be prevented from saturating the concrete.
- Water penetrating from the top surface must be prevented from ponding in the joint.
- Water must be prevented from penetrating from the base.
- Permeability of the concrete should be as low as practically feasible.
- The air-void system in the in-place concrete must be adequate.

Figure 18. Example of delamination spalling (Source: Washington State)

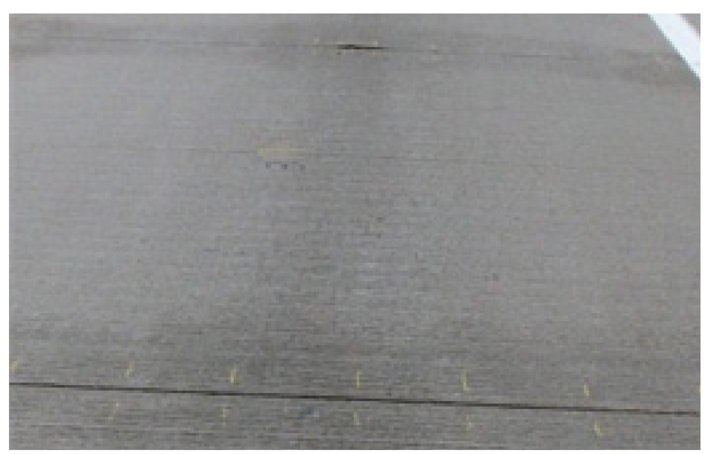

Figure 19. Shadowing at the joints, which is commonly followed by loss of material

Figure 20. Top-down joint distress, with vertical edges and shallow depth

Figure 21. Joint deterioration evident below the joint sealant

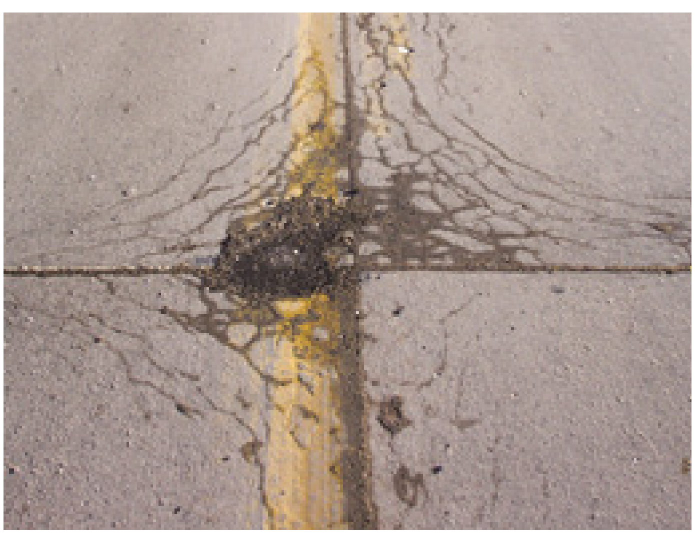

Figure 22. Deterioration due to D cracking

Figure 23. Deterioration due to bottom-up moisture

Figure 24. Joint deterioration due to raveling from improper saw-cut procedures

3 Joint Deterioration Investigation

Before mitigation or preventive measures can be identified, it is important to assess the form, amount, and probable causes behind the pavement joint damage (7). Questions to be addressed are the following:

- Are saturation and salting likely to be issues?
- What is the quality of the concrete with respect to its ability to resist severe conditions?
- Are there differences between distressed and nearby non-distressed pavements that may flag potential causes?

To help assess the causes, it is best to begin by collecting information about the design and construction of the pavement. A field review can then be conducted and. in many cases, complemented by sampling and testing of the pavement. Together, these steps will yield significant insight about the probable joint deterioration mechanisms.

3.1 Design and Construction

When possible, historical information about the pavement should be collected. Specific information that can be helpful includes the following:

- Design details
  - Foundation system including aggregate gradation
  - Drainage system
  - Design life
  - Specified mixture parameters (air, w/cm ratio)
- Construction information
  - Weather
  - State of the foundation system
  - Compaction of the subbase as the result of construction equipment
  - Equipment used (paver type, sawing technique)
  - As-built mixture parameters including water added on site
  - Records of problems encountered
- Operation and maintenance information
  - Pavement age
  - Salting practices (type and timing)
  - Joint sealing
  - Sealant maintenance
  - Historical pavement condition data (structural and functional)
  - Drainage conditions (subsurface and surface)

3.2 Field Indicators

Prior to making a decision about the best repair approach, two questions must be answered:

- Is the distress at the top, bottom, or all the way through the slab?
- Will damage continue to develop after the repair has been completed?

The first question can only be reliably addressed by coring since nondestructive methods cannot reliably identify voids inside a joint.

The second question is more complex. The short answer is that if water can be trapped adjacent to a marginal concrete mixture, damage will indeed continue to develop.

3.2.1 Mechanical Damage and Early-Age Drying

Both of these distresses occur early in the life of a pavement, so the root causes can no longer be mitigated. Often, however, damage caused by these early-age mechanisms provides places for water to collect and thus becomes a starting point for frost damage. For example, it is common to see distress starting at intersections of longitudinal and transverse saw cuts (Figure 25). It is likely that some "bruising" due to sawing of the concrete at the joints can become a zone where water is trapped, thus accelerating subsequent frost damage.

Figure 25. Damage starting at joint intersections

3.2.2 D-cracking

D-cracking is typified by crack patterns parallel to saw cuts extending several inches from the joint (Figure 16 and Figure 22) after about 20 years. The damage is normally caused by moisture migrating from the bottom up and leaves behind loose, unbound material.

Damage is progressive, meaning that repairs will likely fail unless they can straddle the loose material.

3.2.3 Shadowing

Pavements that have exhibited shadowing due to saturated freezing and thawing are often found to be damaged through about one-third the depth of the slab.

To mitigate the source of the distress, repairs may have to include retrofitting a drainage system. Penetrating sealers may slow the rate of damage but only if applied early enough. It has been reported in Iowa that reduction of salt brine application rates on shadowed roadways can reduce the rate of deterioration.

3.2.4 Incremental Cracking

Typically, incremental cracking is seen in systems that have some form of cut-off layer in the foundation. Distress is typically top down, meaning that partial depth repairs are an option.

Filling the voids with asphaltic materials does not appear to help because new cracking appears outside the patch (Figure 9). It is likely that an intimate bond is required between the repair material and the existing concrete to prevent the entrapment of water between them.

3.2.5 Bottom-Up Moisture

Distress can be caused by the presence of moisture near the bottom of the slab. Because such damage is likely to be progressive, long-lasting repairs are feasible only if adequate drainage is provided.

3.2.6 Drainage

During the field investigation, it should be noted if distress is related to surface drainage. For example, is damage more pronounced to one side of the lane (i.e., adjacent to the shoulder) or possibly confined to the edge drains?

It should also be noted if, after a rain event, the joints are drying faster than the slab or vice versa. On urban pavements, observations in cleanouts and intakes can indicate whether the sub-drains are flowing.

3.3 Sampling and Testing

Field-testing via coring may be conducted to further characterize joint deterioration and identify its possible causes (Figure 26).

Cores can provide information about where the damage is occurring. If necessary, cores can also be sent to a laboratory for petrographic examination to assess the following:

- The quality of the air void system.
- The w/cm ratio.
- D-cracking.
- Whether salts are being deposited.
- Other distress mechanisms.

Ideally, cores should be extracted from several locations:

- Over a distressed area of a joint.
- Over the same joint, but at the end of the distressed area in an attempt to identify damage early in its development.
- In the slab, a few inches from the joint, in order to characterize the concrete near the joint.
- At the center of the slab, to assess variability in the mixture and placement.
- From a nearby section that is not exhibiting distress in order to determine why one section is distressed and the other is not.

4 Preventing Joint Deterioration in New Pavements and Overlays

The following approaches can be recommended as a means of reducing risk of paste deterioration at joints.

Figure 26. Coring at deteriorated joints to help identify causes of failure

These recommendations are based on the fundamental damage mechanisms discussed in this guide. Decisions about which recommendations are implemented and how they are implemented should be based on industry best practices and local needs.

The recommendations are targeted at three primary areas:

- Prevent moisture from remaining in contact with the joint face.
- Reduce permeability of the concrete as a preventive measure against the ingress of moisture.
- Provide an adequate air-void system within the concrete paste.

4.1 Drainage of the Pavement System

It is clear that moisture trapped in the joint is a significant factor in the distress observed. Design, construction, and maintenance practices must all ensure that water is allowed to leave the joint. This means that subsurface drainage should be designed to transport water away from the concrete slab, and surface drainage should be designed to quickly shed water from a pavement surface. This may be achieved through combinations of the following activities:

- Provide stable and drainable base layers (evidence of the lack of this is shown in Figure 27). It should be noted that because the amount of water that penetrates a joint is small, very high permeability rates are not required in the base, which improves its stability.
- Avoid bathtub designs that trap water under the pavement.
- Provide underdrain systems, particularly in urban environments where it is not possible to drain the pavement structure to an open ditch.
- Detail sufficient cross-slopes and profile grade lines that facilitate water to the edge of pavement or gutter where applicable.
- Avoid low spots that can hold water for extended periods ("birdbaths").
- Avoid saw-cut details that can become reservoirs for trapped water. An example is that a transverse saw-cut that is shallower than the longitudinal saw cut may lead to water being trapped in the longitudinal cut.

4.2 Reduced Concrete Permeability

The permeability of a concrete mixture determines how easily moisture can infiltrate the paste structure of the concrete. A lower permeability is desirable to slow the rate at which concrete will become saturated.

Recent work led by the South Dakota Department of Transportation includes recommendations to achieve durable, dense, and impermeable concretes that withstand the deleterious effects of deicing chemicals (4) and prevent or reduce joint deterioration caused by water saturation at the joints. Recommendations include the following:

- Low w/cm ratio.
- Appropriate use of SCMs.
- Well graded aggregates.
- Adequate curing.
- Application of penetrating sealers.

Target permeability at 56 days should be less than 1500 coulombs when tested in accordance with the rapid chloride permeability test (ASTM C 1202) or 25 kΩ-cm when tested using resistivity measured with a Wenner probe.

It has been noted that agencies that have demanded more rigorous quality control have observed a reduction in problems.

4.2.1 Low w/cm ratio

The permeability of a concrete mixture is primarily governed by the amount of water in the concrete at the time of mixing. Permeability will decrease as less water is used. The w/cm ratio should not exceed 0.45; ideally, the w/cm ratio should be between 0.38 and 0.42. Recent testing has shown that a pavement with a w/cm estimated in the range 0.40 to 0.45 was performing satisfactorily, while a short section in the same pavement with w/cm in

Figure 27. Example of a poorly draining pavement

the range 0.42 to 0.47 was not. Pavements constructed in Minnesota using mixtures specified at below 0.40 are showing slower damage accumulation than mixtures specified above 0.40.

There are a number of ways to achieve uniformly lower w/cm ratios while retaining satisfactory workability including combinations of:

- Using SCMs in appropriate dosages.
- Using water-reducing admixtures.
- Using aggregate systems with a good gradation.
- Controlling concrete temperature.
- Water should not be added to a ready-mix truck at the point of delivery.

4.2.2 Appropriate Use of SCMs

Replacement of some portland cement with SCMs in well-cured concrete has multiple benefits ranging from improved workability to reduced permeability of the hardened concrete. Typical replacement rates with SCMs are 15 percent to 35 percent depending on the chemistry of the system. Commonly used SCMs include Class C fly ash, Class F fly ash, and ground granulated blast furnace slag (GGBFS).

Setting times for concrete may be retarded when SCMs are used, especially in cool weather conditions, which can cause difficulty in sawing joints before random cracking occurs. Therefore, use caution when using SCMs during periods of extended cool weather ensure that the strength gain of the mix is compatible with the sawing plan. Mixtures containing SCMs must be well cured.

More information is available in the Integrated Materials and Construction Practices for Concrete Pavement (10).

4.2.3 Well Graded Aggregates

The use of well graded aggregates helps to improve permeability in several ways. Firstly, mixtures made with well graded systems tend to be more workable, which in turn means that less water is required to achieve the same workability, allowing use of a lower w/cm ratio.

In addition, well graded systems allow use of higher aggregate and lower paste contents. Because paste is more permeable than aggregate, reducing paste content while maintaining workability will lead to reduced permeability (11).

Thirdly, better workability will lead to better consolidation of the mixture, also improving (reducing) permeability (12) and reducing the risk of over vibration and the attendant problems.

4.2.4 Curing

Curing is the practice of ensuring that the concrete is moist and warm enough to promote hydration. The most common means of curing pavements is to apply curing compound.

When properly applied, a high quality curing compound slows the loss of moisture from the pavement to the atmosphere. This allows for improved hydration, which in turn decreases the permeability of the concrete. Improper curing will result in a loss of moisture, which leads to larger capillary voids in the pavement structure and higher permeability.

It is suggested that curing compound be applied to the inside faces of saw cuts, in addition to the pavement surface, shortly after sawing. Although applying curing compound to the internal sawed faces is not common practice, it is desirable to ensure that the quality of concrete exposed inside the joint is as good as that on the surface of the slab. It is possible that this practice may make it more difficult for a seal to bond to the joint faces, if used.

It is reported that curing compounds based on poly-alpha methylstyrene (AMS) are effective.

4.2.5 Penetrating Sealers

An additional approach to improving impermeability of concrete is to apply penetrating sealers to reduce the rate of ingress of water into the concrete at the joint.

Siloxane-based materials have a history of reportedly reducing permeability of concrete systems. They have to be replaced periodically—approximately every 5 to 7 years (4).

Other sealant types and when they should be applied are being investigated (2).

4.3 Adequate Air-Void System

Freeze-thaw durability is primarily affected by the environment (wet freezing conditions) and the air-void system of the concrete. An air-void system consisting of many small, closely spaced voids is a common means of providing protection against freeze-thaw damage.

An adequate air void system in the as-placed concrete is vital. Air void systems can be affected by varying the composition of concrete constituents, placing techniques, and finishing activities.

Well graded aggregates

Concrete mixtures produced with well graded, dense aggregate matrix tend to

- Reduce the water demand.
- Reduce the cementitious material demand.
- Reduce the shrinkage potential.
- Improved workability.
- Require minimal finishing.
- Consolidate without segregation.
- Enhance strength and long-term performance.

Gap-graded aggregates

Concrete mixtures produced with a gap-graded aggregate combination may

- Segregate easily.
- Contain higher amounts of fines.
- Require more water.
- Require more cementitious material to meet strength requirements.
- Increase susceptibility to shrinkage.
- Limit long-term performance.

(Source: FAA [10])

For concrete that is exposed to deicing chemicals or high water saturation (which is considered "severe exposure"), PCA Bulletin EB001.15 recommends a minimum of 5 percent to 8 percent air content in the in-place concrete to prevent damage (8). In addition, a spacing factor equal to or below 0.008 in. (0.2 mm) is recommended, along with a specific surface area of air voids equal to or greater than 600 in²/in. (24 mm²/mm). Sutter has reported that these values are still appropriate based on recent laboratory work (9).

Test procedures to determine air content in fresh concrete include the pressure method (ASTM C 231 / AASHTO T 152), volumetric method (ASTM C 173 / AASHTO T 196), and the gravimetric method (ASTM C 138 / AASHTO T 121). The spacing factor and the specific surface can be determined in hardened concrete by microscopical measurements (ASTM C 457)

The air content should be checked in samples taken in front of paver, and periodically from behind the paver to quantify how much air is lost during placing.

By periodically comparing air content difference between samples, taken from the same hauling unit both before and after the paver, the stability or quality of the air system can be estimated. When the difference between the two test results is less than 2% the hardened air determined spacing factor is usually acceptable. If the difference is greater than 2% then admixture dosage of the mixture should be adjusted to ensure adequate protection of the in-place system.

Concrete performance can be assessed in the laboratory (during design stage) using ASTM C 666/AASHTO T 161.

4.4 Sawing and Sealing Joints

4.4.1 Sawing Joints

There is window to saw contraction joints in new concrete pavements (Figure 28) (6, 10, 13). The window begins when concrete strength is sufficient for sawing without excessive raveling along the cut. The window ends when random cracking starts to occur. The risk of random cracking increases as joint sawing is delayed.

Sawing too early can cause the saw blade to break or pull aggregate particles free from the pavement surfaces along the cut. The resulting jagged, rough edges are termed raveling. Some raveling is acceptable, especially where a second saw-cut would be made for a joint sealant. If the raveling is too severe, it will affect the appearance and/or the ability to maintain the joint. Figure 29 shows different degrees of raveling.

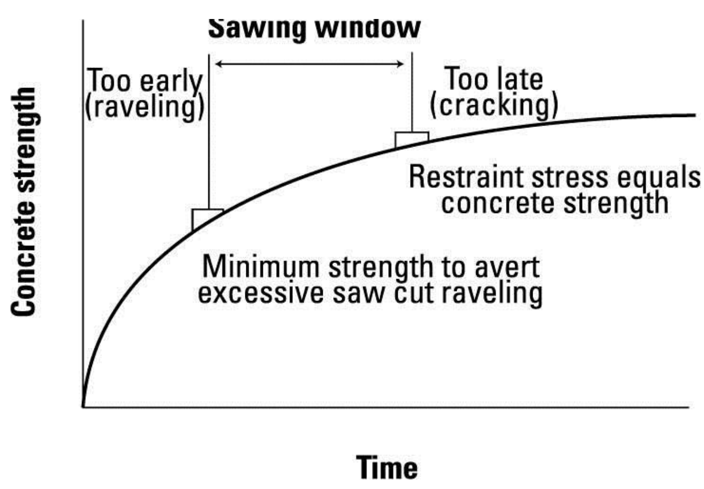

Figure 28. Definition of the sawing window (9)

When using early-entry saws, it is recommended that temporary spacers be inserted where cuts intersect existing cuts, in order to prevent corner damage and the subsequent risk of other joint deterioration mechanisms (Figure 30).

Ensure that sawing equipment is well maintained and that appropriate blades are selected for the aggregate in the mixture.

4.4.2 Sealing Joints

The purpose of sealing joints is to minimize infiltration of surface water, deicing solution, and incompressible material (13).

There have been examples of pavements exhibiting premature joint deterioration where water has been trapped in the joint, particularly below a seal in a tight or un-cracked joint, as illustrated in Figure 31. It is critical that water be prevented from ponding at the sawn surface. Approaches to consider include either:

- If seals are used they must be applied and maintained in accordance with industry best practices to ensure their effectiveness (13).
- Avoid the use of a backer rod and rather fill the saw kerf with a hot poured material to avoid an open area where water can pond (Figure 32).
- Saw contraction joints as narrow as practical and leave all joints unsealed.
- Ensure sure that the crack forms below the saw cut. This may require the saw cut depth to be increased.

Neither of these activities will address water penetrating from below the pavement, which can only be remedied by providing adequate drainage below the pavement.

4.5 Summary

In summary, new concrete pavements must be specified to be of adequate quality:

- Air content, in place, greater than 5 percent.
- Maximum w/cm ratio of 0.45, preferably 0.40.
- Appropriate amounts of SCMs.
- Durable aggregates.
- Thorough curing (not optional)
- Joints that can dry out periodically.

Figure 29. Different degrees of joint raveling caused by sawing (9)

Figure 30. Using temporary joint spacers to protect and minimize damage due to early entry sawing (Source: Husqvarna)

Figure 31. Evidence of saturation within joint beneath seal (Source: Purdue)

5 Maintenance Activities to Reduce Joint Deterioration Risk

5.1 Routine Maintenance

5.1.1 Joint Cleaning and Filling

It is recommended that joints be refilled in existing pavements only when they were originally filled during construction. Proper selection should consider the environment, cost, performance, joint type, and joint spacing. Refilling joints is most effective when the joints are not severely deteriorated and when refilling is combined with other maintenance activities such as joint repairs and grinding (14).

Typically, fillers have to be replaced every 8 to 10 years. Fillers are either placed in a liquid form or are preformed and inserted into the joint reservoir. Fillers installed in a liquid form depend on long-term adhesion to the joint face for successful filling.

Several factors regarding concrete material or filler installation technique can affect joint filler performance:

- Silicone fillers are known to have poor adhesion to concrete containing dolomitic limestone. A primer application to the reservoir walls will help ensure that the silicone adheres.
- Chemical solvents used to clean the joint reservoir may be detrimental. Solvents can carry contaminants into pores and surface voids on the reservoir faces that will inhibit bonding of the new filler.
- For cleaning joints, the air stream must be free of oil. Many modern compressors automatically insert oil into the air hoses to lubricate air-powered tools. New hoses or an oil and moisture trap prevents contamination of the joint face from oil in the compressor or air hoses.

The process for refilling transverse joints involves removing the old filler, joint re-facing, reservoir cleaning and new filler installation. For more specific information on joint refilling, consult the ACPA's Technical Bulletin TB012P (13) and the Concrete Pavement Preservation Workshop Reference Manual (14).

5.1.2 Surface Drainage

Maintenance activities to enhance surface drainage include cleaning drainage structure grates/drains (to prevent clogging from roadway debris, ice, or snow), grinding to increase the cross-slope, and refilling joints.

If there are water accumulation problems due to inadequate surface drainage, such as inadequate cross slope (Figure 33), then grinding to increase the cross slope is a possible solution.

5.1.3 Subsurface Drainage

Proper maintenance of drainage systems is critical. This includes both regular inspection and cleaning. Maintenance of edge drains involves cleaning and replacing outlets. Figure 34 shows the typical components of edge drain systems, which include a trench filled with filter-graded aggregate wrapped with a geotextile, longitudinal (perforated) pipe, and outlet (non-perforated) pipe (15).

Figure 32. Joint filled with hot pour sealant (Source: The Transtec Group)

Figure 33. Failing transverse joint associated with poor drainage at gutter

If the existing pavement is beginning to show signs of joint deterioration and a subsurface drainage system is not present, then potential sources of excess water should be identified. Common sources include landscaped islands/ shoulders with irrigation systems, shallow ditches, high groundwater tables and pavement systems without effective outlets. If a source of excess water is identified and cannot otherwise be mitigated, edge drain retrofit can be considered. A retrofit is shown in Figure 35. It should be noted that this process requires careful project evaluation, design, installation, and maintenance. The presence of existing utilities can be particularly problematic during the retrofit process. Retrofitting edge drains is not recommended for sections exhibiting severe joint deterioration. More guidance on this topic can be found in the Concrete Pavement Preservation Workshop Reference Manual (14).

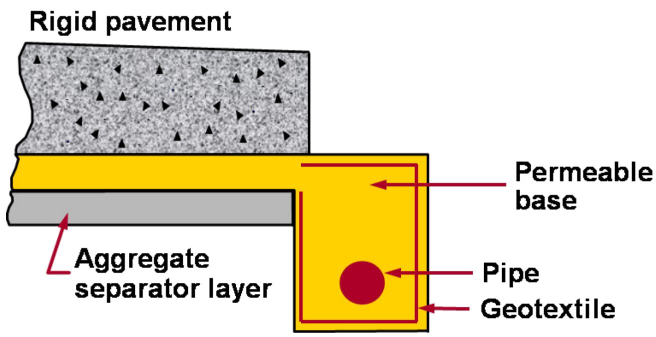

Figure 34. Typical components of an edge drain system (Source: NHI 131008) (16)

Figure35.Subdrainretrofitoperationincludingcleanout(TheTranstec Group)

Figure 36. Example of effective drainage of unsealed joints

One technique to determine if there are drainage issues is to observe the pavement surface immediately after a rain event, noting whether the joints or the rest of the slab dries first. Figure 36 shows a pavement with unsealed joints after measurable rain. It can be observed that the water is effectively exiting the system and the joints are drying before the rest of the slab.

If the joints remain wet and the rest of the slab dries, this is an indication that water is not effectively leaving the system and further investigation is necessary to identify measures, such as joint sealing or drainage improvements.

5.2 Winter Maintenance

Winter maintenance activities to remove snow and ice on highway pavements include sanding, snow plowing, and application of anti-icing or deicing solutions.

A Transportation Pooled Fund Study TPF 5(042) (7), led by South Dakota DOT investigated the effect of commonly used anti-icing and deicing solutions on concrete pavements. The study concluded that concentrated brines of magnesium chloride (MgCl2) and calcium chloride (CaCl2) have the most deleterious effects on concrete samples. It was also found that deicer concentrations have an impact on the rate/amount of distresses, and that concrete surface sealants are effective at slowing the ingress of chemicals into the concrete. Following are the main recommendations from this study:

- Use less deicing chemicals (the lowest possible concentration levels).
- Use sodium chloride (NaCl) brines whenever possible.
- Use concrete sealants and concrete mixture designs incorporating SCMs to slow deicer ingress.
- Employ a minimum 30-day or one-winter “drying period” before applying deicing chemicals to new concrete (Figure 37).

6 Treatment of Pavements with Joint Deterioration

Several techniques may help mitigate joint deterioration. Selection of the technique is primarily governed by the following:

- The extent of the damage.

- Whether the damage is developing from the top or the bottom or has progressed through the full depth of the slab (Figure 38).
- The number of joints that are distressed.

6.1 Concrete Surface Sealers

As with new pavements, surface sealants may be applied to the faces of and near existing joints to reduce ingress of water and deicing solutions into the concrete. At present, there is little guidance available on when such materials should be applied or how to specify them. Work is continuing to develop more specific guidance.

6.2 Partial-Depth Repairs

Partial-depth repairs are defined as the removal of small, shallow areas of deteriorated concrete that are then replaced with a cementitious repair material (14). Partial depth repairs are not recommended when the main cause of joint deterioration is D-cracking or other material-related distress, or where damage is more than one-third to one-half the depth of the slab (Figure 39).

Guidance on installing partial depth repairs is available in Partial-Depth Repair of Concrete Pavements (16). Other references include the Concrete Pavement Field Reference: Preservation and Repair manual (17), and the Concrete Pavement Preservation Workshop Reference Manual (14).

6.3 Full-Depth Repairs / Slab Replacement

In cases where deterioration has occurred through more than one-half the depth of the pavement, a full-depth repair is required. As shown in Figure 40, a full-depth repair is a cast-in-place concrete repair that extends through the full thickness of the existing concrete slab.

Like partial-depth repairs, full-depth repairs are not recommended when the principal cause of joint deterioration is D-cracking. However, an unbonded overlay may be an option. The following are considerations when evaluating the viability of full-depth joint repairs:

Figure 37. Signage to help avoid salting of new pavement

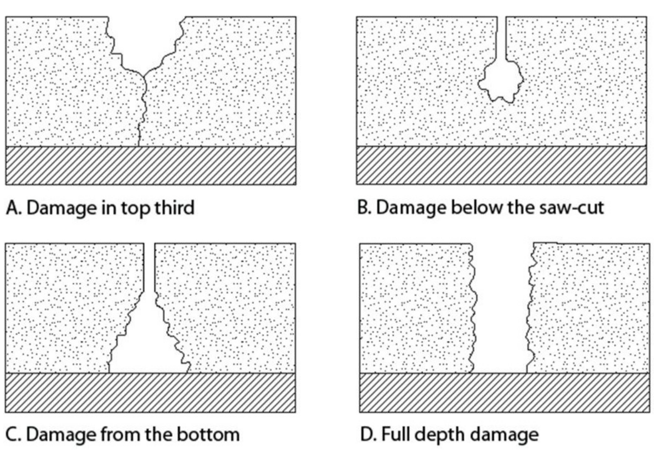

Figure 38. Typical forms of damage that require different repair approaches

Figure 39. Completed patch (Source: The Transtec Group)

Figure 40. Full-depth patching

- Full-depth repairs are effective if deterioration is limited to the joints or cracks.
- Full-depth repairs are effective if the deterioration is not widespread over the entire project length; otherwise, a structural overlay or reconstruction is more suited.
- Diamond grinding should be considered after the repairs are made to produce a smooth-riding surface.
- If every joint requires repair, economics may demonstrate that an overlay or replacement is more effective than full-depth repairs.

Other references include the Pavement Preservation Workshop Reference Manual (14), Concrete Pavement Field Reference: Preservation and Repair manual (17), and Concrete Pavement Rehabilitation—Guide for Full-Depth Repairs (18).

6.4 Overlays

Asphalt overlays may not perform well in some cases because continued deterioration under the overlay will reflect through the overlay, reducing ride quality. However, concrete overlays may be a viable option.

Items to consider when assessing the suitability of an overlay include the severity and extent of joint deterioration, risk of continued deterioration under the overlay, pre-overlay repairs required to prevent reflective cracking, design life, and related costs.

Partial-depth repairs may be required to address damage before bonded or unbonded overlays are placed.

More guidance on this topic is available in the CP Tech Center Guide to Concrete Overlays (19).

Additional guidance on the use of concrete overlays for the repair of concrete pavements exhibiting joint deterioration is being developed at the CP Tech Center.

6.5 Reconstruction

Pavements exhibiting severe joint deterioration throughout the entire length of the section and at a majority of the joints may be more suited for reconstruction, particularly if the geometry prevents the use of a concrete overlay.

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For information about obtaining any of these references, contact the National Concrete Pavement Technology Center, or visit www.cptechcenter.org.

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