Analysis of Concrete Pavement Joints to Predict the Onset of Distress

Robert Otto Rasmussen, Andrew Agosto, Steven Cramer
The Transtec Group, Inc.

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Principal Investigator:
Robert Otto Rasmussen, Ph.D., P.E. (TX)
The Transtec Group, Inc.

Contributing Partners:
Andrew P. Agosto
Steven M. Cramer, Ph.D., P.E. (WI)
Univ. of Wisconsin - Madison
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Three primary objectives guided the work in this effort. The first was to investigate the nature of the distress using advanced analytical methods including finite-element methods (FEM), validating the predictions using field observations when possible. The second objective was to identify maintenance and/or restoration activities that can be used to slow or prevent the propagation of the observed pavement distresses. Finally, current WisDOT design standards and specifications were reviewed to determine if previous changes made are likely to address the causes of the premature failure. |
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EXECUTIVE SUMMARY

Research Study Summary
This report documents the investigation of a 15-mile segment of dowelled plain jointed concrete pavement located on Interstate 90/94 in Juneau and Sauk Counties in the State of Wisconsin. This section has experienced a particular mode of early deterioration that had not previously been reported on other concrete pavements in the State of Wisconsin. Coupled with the fact that these pavements were less than ten years old, an investigation was conducted to seek out the causes of the observed distress.

Background
Three primary objectives guided the work in this effort. The first was to investigate the nature of the distress using advanced analytical methods including finite-element methods (FEM), validating the predictions using field observations when possible. The second objective was to identify maintenance and/or restoration activities that can be used to slow or prevent the propagation of the observed pavement distresses. Finally, current WisDOT design standards and specifications were reviewed to determine if previous changes made are likely to address the causes of the premature failure.

Process
There were two modes of data collection for this research. The first included a review of existing information reported by WisDOT, WCPA, and Marquette University. This information included a number of photographs, deflection and profile data, and various materials and other test results. A second mode of data collection included visual observations made first-hand during a field visit in August 2006.

Following the data collection, analytical methods were employed to gauge the sensitivity of the pavement behavior to the various parameters that are believed to have a contributing role. For example, slab length, joint skewness, and strain gradients were all varied to determine the pavement response.
Linking pavement response and distress was the next step. On this section, three primary distresses were identified: delamination of the slab at the dowel line, corner cracking, and mid-panel cracking. The first two of these distresses are intimately linked.

Based on the results of the analytical investigation, and as validated by the other information that was collected, the likely causes of failure were identified.

**Findings and Conclusions**

After a careful review of the information, it is concluded that no single factor affected the three primary distresses that were found on this section. It is instead believed that a combination of factors is to blame. Among these factors are:

- Longer joint spacings (greater than 16 ft.) which increased stress states in the slabs, and widened the joints.
- Skewed joints, which increased corner stresses and deflections, and effectively increased the dimensions affecting curling and warping.
- Open-graded base courses (OGBC) that were likely unstable (possessing low shear strength).
- A dowel design that while not uncommon in practice today, may underscore the need for reconsideration of the use of large dowels given that other owner-agencies have reported success with smaller dowels.

**Recommendations for Further Action**

Because an exhaustive investigation could not be conducted as part of this effort, a number of follow-on activities are recommended for consideration. In the short term, it is recommended that relevant discussions be conducted among the various stakeholders in Wisconsin. Topics could include the recommendations for additional changes to design standards, specifications, and other guidelines with respect to the potential benefits and pitfalls.

Longer-term recommendations include the possibility of a more extensive field evaluation. It is recommended that a comprehensive set of deflection data be collected to
baseline the current condition of this highway, as well as possibly others more recently discovered to be experiencing a similar distress. Surface profile data would also be helpful to possibly identify if slab curvature is present along with localized roughness which may be an indication of impending distress development. Finally, a laboratory evaluation of the OGBC could also be conducted to determine the triaxial constitutive properties as they might relate to in-situ behavior.
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1 INTRODUCTION

Interstate 90/94 is a vital strategic corridor within the State of Wisconsin. It serves as the primary route from Minneapolis to Chicago and Milwaukee, is a NAFTA trade link, and is an important artery for both commerce and travel within the State of Wisconsin. Of interest to this study is a 15-mile segment near the Wisconsin Dells. Reconstructed in 1991-93, a new jointed concrete pavement (JCP) was selected in order to accommodate the heavy traffic expected in the decades to follow.

The construction of these segments seemed to go as expected, comparable to other concrete paving projects in the state. However, approximately five years after the segment opened to traffic, the Wisconsin Department of Transportation (WisDOT) District 1 maintenance staff filed a Report of Early Distress (RED). In it, they identified cracking and “potholes” near the joints. In response, the WisDOT Pavements Section and others investigated the pavements in more detail and concluded that while a number of factors may have contributed to the observed distress, no single “culprit” could be found.

Since that time, changes have been made to the standard designs and specifications to minimize potential root causes. However, since no single cause was identified, it was difficult to know for sure if these changes would prove beneficial.

The goal of this research study is therefore to conduct a site-specific investigation of this pavement section. The intent is to gather data from a number of existing sources, and based on them, report the likely contributors to the observed distress. The intent is to learn from these pavements so that the potential for similar distresses on other sections could be minimized.

1.1 Background and Significance of Work

The intent of this research study is to conduct an objective evaluation of the pavements located on the section in question. To accomplish this, accepted principles of forensic engineering must be employed to the greatest degree possible. With the exception of a brief field visit, most of the information used in the investigation was collected by others. During the course of this research
study, however, this information was synthesized and used to support a more theoretical approach to determining the likely causes of the observed distress.

Along this pavement section, numerous classical distresses were observed; namely, longitudinal and transverse cracking, and spalling at the joints. Corner cracking was also noted at numerous locations, and furthermore appeared to be the most significant distress in terms of quantity and severity. The mid-panel cracking that was present was in quantities significant enough to be of concern. However, the presence of corner cracking on concrete pavements this thick and relatively new is uncommon, and thus the majority of the investigation during this research study focused on the causes behind this distress.

When evaluating the data that was provided, the research study team employed analytical techniques to test theories of mechanisms behind the observed distress. Various factors were previously identified as possible contributors. Some of these included:

- Open-graded base course (OGBC), with permeability higher than what is commonly used today.
- Longer panels (joint spacing) than what is commonly used today.
- So-called “built-in” curling that is itself a function of a number of material, construction, and climatic factors.
- A support system with potentially poor shear resistance (stability).
- Concrete-dowel interaction – this includes the technique for placing the dowels, and the possibility that they may have corroded.
- Skewed joints – a design that is no longer used today.
- Indications of possible alkali-aggregate reactivity.
- Use of recycled concrete as an aggregate in the mixture for the new concrete pavement.
- Lack of consolidation of the concrete during placement.

The approach used in this research study was to focus on each of these factors, and based on the information available, determine which ones were likely contributors to the mechanisms behind the observed distresses.
1.2 Research Objectives

Three primary objectives of this research, as identified by the Wisconsin Highway Research Program (WHRP), include:

1. Investigate the nature of the JCP distress using advanced analytical methods including finite-element methods (FEM). Identify and develop the models as needed, and validate them using field observations.
2. Identify maintenance and/or restoration activities that can be used to slow or prevent the propagation of the observed pavement distresses.
3. Review current WisDOT design standards and specifications. Determine if the changes recently made are addressing the suspected causes of the premature failure. If needed, make additional recommendations for changes to the standards and specifications to prevent the observed distresses from occurring in the future on other pavement sections.

1.3 Scope of the Report

This report includes the results of this investigation. It begins with a review of the information that was gathered about the pavement section, including the results of a brief field visit during the course of repair operations in 2006.

A mechanistic analysis of the concrete pavements is then described, including the inputs used, and the results. During the course of this research study, the team employed finite element methods to predict the stress state in the slabs, with a particular emphasis on the behavior near the joint. The predictions were varied to include the range of conditions expected in the field. Comparisons were made to the observed performance to validate the overall approach.

Using these models, along with a review of other available information, each of the potential contributing factors to the observed distress was evaluated. From this, likely mechanisms have been identified and reported.

From this, and in order to weave this analysis into practice, an evaluation of the specification changes that have been made to date has been conducted. Additional potential specification
changes that could be beneficial have also been identified. Finally, in the recommendations, appropriate maintenance and restoration activities that can slow or prevent further development of the observed distress on this pavement section are reported, along with recommendations for future activities.

2 INFORMATION REVIEW

2.1 A Review of the I90/I94 Pavement Section

Although the products from this research study may have implications statewide, the primary goal is to learn more about a 15-mile segment of concrete pavement located on I90/I94 in Juneau and Sauk Counties. This section has experienced a particular mode of early deterioration that has not been reported as common on other concrete pavements in Wisconsin. Coupled with the fact that these pavements were less than ten years old, this investigation was conducted to seek out the cause(s) of the observed distress.

Prior to this WHRP-sponsored research study, a number of prior studies were conducted on this pavement section. In August 2000, Joe Wilson of the WisDOT Pavements Section published a “Report of Early Distress on I-90/94 near Wisconsin Dells.” This report included a compendium of investigative work conducted by WisDOT and others. It was accompanied by a second report prepared for WisDOT by Jim Crovetti entitled, “Analysis of Pavement Support Conditions under Cement-stabilized Open Graded Base Course for IH-90 near Wisconsin Dells,” dated 31 July 2000. Furthermore, on August 3-4, 2000, members of the research study team joined 30 other individuals as part of a Technical Working Group to evaluate these pavements first-hand. During this meeting, a field visit was conducted, as well as a round table discussion.

A summary of some of the variables that are reportedly present on the pavement section are as follows:
• The jointed concrete pavement is nominally 12 in. over a 4-in. Open-Graded Base Course (OGBC) – “Graded Base Course #1” – reportedly cement stabilized, but with some sections possibly not stabilized. Underlying the OGBC is an existing subbase of 4- to 9-in. of dense graded aggregate. As expected for the rolling terrain, subgrade properties and bedrock depth vary along the section.

• Joints are skewed 1:6 and reported as having “random” spacings of between 12 and 20 ft. An unverified analysis of Pathview data revealed that the distribution of slab lengths is as follows: 12 ft. (8%), 14 ft. (7%), 16 ft. (17%), 18 ft. (27%), 20 ft. (33%), and 8% are either below 12 ft. or above 20 ft. Dowels of 1.5-in. diameter were used on the transverse joints – epoxy coated, 18-in. long, and at a 12-in. spacing. The longitudinal joint was tied with #4 bars, 24-in. long, at 24-in. spacing.

• Panel widths are 12 ft. for the inside lane, and 14 ft. for the outside lane (widened lane). Hot-mix asphalt shoulders are used, and edge drains included that were designed to work with the OGBC.

• The sections in question were built by two paving contractors from 1991 to 1993, with most of the placement reportedly in 1992. James Cape & Sons, Co. constructed the eastern (southern) portion of the section using a dowel-bar inserter. Trierweiler Construction & Supply Co., Inc. constructed the western (northern) portion using dowel baskets.

• The concrete contains coarse aggregate consisting of a mix of recycled concrete (reportedly used on “some” sections) along with virgin crushed gravels including sandstone, chert, and various igneous rocks.

• Cores were extracted and tested in June 1999. The average compressive strength was approximately 7600 psi, with a coefficient of variation of 16%.

Regarding the observed distress on this pavement section, a number of pertinent observations include:
• As of early 2002, distresses were found to be present on 2.1% of the slabs. The most
commonly observed were corner cracking (on 1.8% of the panels), mid-panel transverse
cracking (0.3%), and mid-panel longitudinal cracking (0.03%). Of those slabs with
corner cracks, 82 percent cracked on at least one of the two acute angles.

• From some of the cores, a horizontal delamination is noted to occur in the slab at
approximately mid-depth (dowel level). While this delamination was coincident with
areas of observed surface distress, it was also noted to occur on uncracked panels,
particularly on panels adjacent to those with surface failures, but rarely extending more
than 10 in. from the common joint. Cracking is observed through the coarse aggregates.

• Inadequate consolidation of the concrete below mid-depth in the slab was reported in the
first RED in 1995. However, subsequent evaluation (including lab testing for unit
weight) has not verified this observation. If present, it may be in isolated locations, and
is not likely to be a contributing factor.

• Most of the distress is on the outside lanes, with the eastbound direction reported as
having “2.5 times” the distress. The “worst” locations have been reported as between MP
86-93 and 100-101 in the EB direction, and between MP 85-89 and 95-96 in the WB
direction.

• Some ASR was found to be present, but not believed to be a major factor.

• In Crovetti’s report, he concluded that base densification and loss of support at the edges
does not appear to correlate to distress, but emphasized that this is based on limited
testing at only one temperature condition.

3 FIELD VISIT
On August 3-4, 2006, members of the research study team had an opportunity to visit the site.
During the field visit, sections of the pavement were being repaired by a contractor under
contract to WisDOT. The second day, a visit was made to a landfill site where previously-
removed slab segments were disposed of.

3.1 Slab Repair Activities
The scope of work for the repair contract included extensive full-depth patching of the concrete
pavement in the vicinity of joints exhibiting the characteristic damage. Due to the high traffic
volumes along this corridor, all work was conducted at night. The sequence of events that was
witnessed is documented in Figure 1 through Figure 6, and includes:

1. Full-depth sawing of the existing pavement at approximately 5 ft. both upstream and
downstream of the distressed joint. A third parallel sawcut is made within a few inches
of the upstream cut in order to expedite removal of the edge of the repaired area.
2. A hydraulic hammer on a skid steer is used to chip out the corner of the slab within the
narrow trench.
3. A concrete cutter is then lowered into the trench starting at the removed corner, and
removes the remaining concrete within the trench.
4. A Slab Crab bucket attached to a large excavator then removes the slab pieces, depositing
them into a series of end dump trailers for subsequent transportation to a designated
landfill.
5. Once removed, the area is cleaned and dowels are drilled and inserted prior to placement
of fast-track patching concrete.
Figure 1. Sawing on both sides of repair area (flanking distressed joint).
Figure 2. Removing corner of repair area.

Figure 3. Concrete cutter to remove edge of repair area.
Figure 4. Slab Crab bucket removing damaged concrete in repair area.
Figure 5. Patching repair area using fast-track concrete.
Figure 6. Patching repair area using fast-track concrete.
3.2 *Inspection of Removed Slabs*

In a bone yard approximately three miles south of the Wisconsin Dells, hundreds of concrete slab segments have been disposed of. During the site visit, these slabs were inspected by the research study team in order to gain a more complete understanding of the physical manifestation of the pavement distress. Because the slabs had been dumped from the trucks, many had “opened up” to allow the subtleties of the dowel-concrete interaction to be observed.

Figure 7 through Figure 13 are representative of the corner cracking distress that is of most significance to this study. As previously reported, the distress was found to occur on the acute angle of the slabs in the vast majority of the cases. The horizontal delamination coincided with the imaginary line intersecting the dowels at mid slab. The cracked area extended approximately 3 to 5 ft. from the slab corner along both joints in most cases. The concrete at mid-depth between the two segments was often observed to be pulverized. The dowel ends that rested between the slab segments had epoxy coating that was loose or non-existent. In some cases, the steel dowels were abraded by (presumably) the grinding action of the two horizontal concrete slab segments.

Figure 14 illustrates the open-graded base course that was found to adhere to the bottom of many of the slab segments. As can be seen, the material is nearly uniform in gradation, which is not surprising given the very strict tolerances of the gradation that was specified.
Figure 7. Distressed slab corner showing delamination of acute corner at mid depth.
Figure 8. Slab corner without surface distress, but showing delamination of acute corner at mid depth.
Figure 9. Distressed slab corner showing delamination of acute corner at mid depth. Note differences in dowel condition on acute corner (right) versus obtuse corner (left).

Figure 10. Side view showing dowel bridging distressed corner. Note differences in dowel condition on acute corner (left) versus obtuse corner (right). Note crack repair material infiltration.
Figure 11 Mid-depth delamination of slab extended from corner (bottom of photo) to approximately 5 ft. from edge (top of photo), before appearing as surface crack.
Figure 12. Loose dowel showing ineffectiveness of epoxy coating once damaged.

Figure 13. Loose dowel showing ineffectiveness of epoxy coating once damaged. Note abrasion due to loose state and interaction with concrete.
4 ANALYSIS

To better understand the nature of the observed distress, it was decided that analytical methods would be used. This section first describes the fundamental components of these methods, followed by the specific models used. The results of the analysis as compared to the observed distress are then presented.

4.1 Background

Portland cement concrete pavements (PCCP) are well known for being a heavy-duty high-performance solution for heavily trafficked roads. Their rigidness allows wheel loads to be well distributed across a large area. However, because concrete is also a brittle material, when subjected to the stresses that even a “typical” pavement will experience, it will crack. This is normal though, and it is for this reason that jointed concrete pavements (JCP) are constructed: built with predetermined weak planes, to control the location of the cracks that are inevitable.

However, while joints serve an important purpose, they are also the location of distress for many JCP. Theory tells us that when wheel loads are applied near the edge of a slab (at the joint), stresses in the concrete are much higher than if the load is located in the interior. These higher
stresses lead to an increased probability of failure. We know that practice confirms this theory, as “failure” in concrete pavements commonly occurs (or at least, initiates) at the joints.

4.1.1 Doweled Joints

To help relieve these stresses, pavement engineers often specify the use of dowels at the joints. Used for decades in concrete pavements, dowels are smooth bars that when used properly, serve as “bridges”, allowing loads applied on one slab to be partially carried by adjacent slabs. As the loads are positioned ever closer to a joint, the dowels at that joint become more critical, transferring increasing levels of load. While dowels are not used on all JCP, most highway and airfield facilities constructed today do employ them. Their use has resulted in a marked decrease in joint faulting and slab cracking.

Dowels, by their very nature, act as discrete load transfer devices. As Figure 15 illustrates, when a wheel load is applied near the edge of a slab, part of the load is carried by the slab through the underlying support. If present, load is also carried by the nearby dowels, and transferred to the adjacent slab. Another load carrying mechanism, aggregate interlock, is also commonly present. However, for simplicity, its discussion herein will be limited.

![Figure 15. Illustration of load transfer at a doweled joint.](image)

The modeling of the stresses at the joint can be complex. Although Figure 15 illustrates this in simple terms, there are numerous intricacies in the analysis due to the flexural rigidity of the slab, the interaction of the slab with the subbase, and the interaction of the concrete with the dowels. The latter is illustrated in more detail in Figure 16, where the deflected shape of the
dowel, as well as the corresponding stresses, can be predicted as a function of a number of material and geometric variables.

4.1.2 Curling and Warping

Stresses in concrete pavements are not just caused by traffic loading. Concrete pavements are also subjected to environmental influences, which have the tendency to force the slab away from a “flat” position. Temperature and moisture differentials in the slab, termed curling and warping respectively, can lead to induced stresses that can compound with traffic loading. This is especially true when a “liftoff” occurs at the slab edge or corner, leading to a cantilever effect.

To illustrate how significant curling can be, note Figure 17 where an 18-ft. slab panel is subjected to a negative temperature gradient of 1°F per inch. The colors in the figure indicate the magnitude of stress, with red (positive numbers) representing tension. In Figure 17, it can be seen that a peak stress in the concrete of 220 psi has been induced. When the slab length is increased to 20 ft., as illustrated in Figure 18, the stresses increase by an additional 10%.

Figure 16. Illustration of load transfer at a joint.
4.1.3 Dowel Restraint

A compounding effect that has largely been ignored by pavement engineers until recently is the restraining effect caused by the dowels. While their presence is critical in transferring wheel loads across joints, they also restrict free movement of the slab edges and corners due to curling and warping. To illustrate this effect, compare Figure 17 with an 18-ft. slab without dowels to Figure 19, showing the same slab restrained by the presence of dowels. Not only is the slab profile noticeably different, but the stresses induced mid-panel are increased by 25%.

Figure 20 further illustrates how the curled slabs can induce stresses near the individual dowels. Due to the lack of biaxial rigidity of a slab near a corner, this effect will be especially pronounced at that location. Furthermore, traffic loading can compound this under certain configurations of curl and wheel load. As these stresses continue to increase, they will eventually initiate and propagate cracks in the horizontal direction. Illustrated in Figure 21, it can be seen that the stresses at the dowels decrease with distance from the longitudinal joint. At some point, the stresses that propagate the crack will be smaller than the strength, and under repeated loading cycles, the crack will instead turn upward and appear at the surface of the slab.
Figure 17. 18-ft. undoweled slab subjected to -1°F/in. thermal gradient.

Figure 18. 20-ft. undoweled slab subjected to -1°F/in. thermal gradient.

Figure 19. 18-ft. doweled slab subjected to -1°F/in. thermal gradient.
4.2 Behavior Modeling

Concrete pavement behavior under both climatic and external wheel loading has been analytically modeled for nearly a century. Classical solutions for slab behavior include stress and deflection predictions based on beam and slab theories common to many engineering mechanics problems. In recent years, finite element methods (FEM) have allowed for more complex boundary conditions and loadings to be modeled with ease. In this section, the application of FEM to this problem is described.

4.2.1 Description of Model

Using the three-dimensional finite-element program, ANSYS, various combinations of concrete pavement configuration and loading were modeled. Typically, symmetry is used in this type of modeling to reduce the computational cost; however, in order to do so, both symmetrical loading and structure would be required. Since the loading that is being modeled here is asymmetric, a full model was used instead. An elastic foundation was used consisting of a two-dimensional
grid, produced using the SURF154 element in the ANSYS software. These plane-like, 8-node elements capture the surface effects, and directly mate to the 20-node SOLID95 elements that were used to model the slab.

The SURF154 element has various density, mass, and foundation capabilities. Its elastic foundation stiffness property, EFS, was used to create the foundation in the model used in this research study. The SOLID95 element is a 20-node 3D solid capable of capturing plasticity, creep, stress stiffening, large deflection, and large strain effects. After creating a volume model of the slab, the volume sweep command was used to create the SOLID95 element geometry based on the original SURF154 geometry. This method creates a slab of SOLID95 elements mated to a foundation of SURF154 elements. The following concrete and foundation material values were provided and inputted into ANSYS.

SOLID95 Properties:
- Young’s Modulus, $E = 5,000,000$ psi
- Poisson’s Ratio, $\nu = 0.15$
- Slab Thickness, $D = 12$ in.
- Slab Width, $W = 14$ ft.
- Slab Length, $L = 12, 15, \text{ and } 20$ ft. (varied)
- Corner angle, $\phi = 80.5^\circ$ and $90^\circ$ (corresponding to skewed and square joints, respectively)

SURF154 Properties:
- Dense Liquid Modulus of Reaction, $EFS = 50, 300, 1000$ psi (varied)
  [Note: this is stiffness per inch of deflection, i.e., k-value]

The appropriate boundary conditions were applied to ensure a unique displacement field with no stress concentrations. These included a UX and UZ restraint at a bottom corner node and a UZ constraint at the opposing corner bottom node. For the loading, two conditions were used:
• Corner load of 9000 lb.
• Strain gradients of +250, 0 and -750 microstrains per in.

The stiffness of the transverse joint was also varied to be both 0 and 1,500,000 psi per in. of deflection. However, the results using this boundary condition proved to be difficult to interpret due to high stress concentrations near the joint.

4.2.2 Model Inputs and Assumptions

The analysis was reduced to six total variables with two to three options each. To complete the analysis, 180 unique runs had to be completed. A summary of the variables includes:

1. Corner Joint Skew: $\phi$ (90° and 80.5°)
2. Length of Slab: $L$ (12, 15, and 20 ft.)
3. Foundation Stiffness: $K_{VS}$ (50, 300, and 1,000 psi/in.)
4. Strain Gradient (top strain minus bottom): $\Delta \varepsilon$ (-750, 0, and 250 $\mu\varepsilon$)
5. Corner Load: $P$ (0 and 9,000 lb.)
6. Joint Stiffness: $K_{VJ}$ (0 and 1.5 Mpsi/in.)

The corner joint skew and length of slab variables were done by modifying the geometry of the original slab and re-meshing the model as appropriate. The foundation stiffness variable was changed by changing the EFS (Elastic Foundation Stiffness) of the SURF154 elements previously described. The Strain Gradient was done similarly by changing the top and bottom area slab temperatures and fixing the thermal coefficient of expansion to an arbitrary level that corresponds with the intended strains. The Corner Load was applied at the furthest corner from the origin. The Joint Stiffness was estimated by using SURF154 elements embedded into the slab at mid-height. An EFS of 375,000 psi was used corresponding to 1.5 Mpsi of joint stiffness distributed over four inches of slab depth. This four inch dimension was used to prevent local errors that occur when a one dimensional point or spring load is applied to a three dimensional model. Typical deflected slabs under climatic and external (wheel) loading are shown in Figure 22.
For each of the ANSYS runs, maximum and minimum stresses were recorded in each Cartesian direction, along with the corresponding location. The same was done for the maximum and minimum shear stresses (XY, YZ, and XZ) the principal stresses (1, 2, and 3). Finally, absolute maximum deflections at each corner were recorded. Examples of typical ANSYS responses are illustrated in Figure 23. Where the noted value was believed to be questionable due to close proximity to a stress concentration, it was so indicated. This only occurred in the analysis that included the joint stiffness variable, and thus led to the conclusion that the characterization of this variable was questionable.

4.2.3 Sensitivity Analysis Results

The results of the sensitivity analysis allowed for a better understanding of the slab behavior as it may have been affected by the design and service conditions. The tables in Appendix A summarize the results from these analysis runs. The first two tables (A.1 and A.2) include results from slabs with square joints, and the second two (A.3 and A.4) are from slabs with skewed joints.
Figure 23. Illustrations of 3D FEM responses.
From these results, trends of slab behavior become evident that are both intuitive and support the hypotheses for failure. For example, increasing slab length increases mid-panel stresses. Increasing the temperature gradient significantly affects both slab shape and critical responses under load. One of the more important observations, however, is the effect of the skewed joint and the resulting acute angle. The responses on these corners are much more critical than those resulting from square joints.

4.3 Distress Interpretation and Modeling

The responses calculated from the 3D FEM can be used as inputs to distress models in order to characterize what is being observed in the field. In this section, both corner and mid-panel cracking mechanisms will be described, as these were the most commonly reported distresses on this pavement section.

4.3.1 Delamination

The most typical distress observed on this pavement section is a form of delamination that is occurring at the dowel line at approximately mid slab. As illustrated in Figure 21, the distress would normally be hidden from view except that it is limited in lateral extent, and within 3 to 5 ft. from the corner, propagates upwards in the form of a corner crack.

Delamination of this kind has not been widely reported, much less modeled. Delamination at known planes of weakness such as the interface between overlays and underlying pavement structures has been modeled, however. These models have demonstrated that stress concentrations along the plane of weakness occur near slab edges and especially at slab corners. The stress decreases in magnitude as the distance from the discontinuity is greater. In the case of this pavement, this would explain the limited extent of the observed distress.

The source of the plane of weakness is not immediately obvious. However, upon review of the data that was made available, it is believed that it can be explained by a combination of factors. Drawing from fracture mechanics theory, it is known that stress concentrations can form in the vicinity of flaws in an otherwise continuous medium that is subject to far field stress and/or stress concentrations at the flaws themselves.
In the case of the pavements in question, it is believed that a combination of curling, acute angles, and an unstable base led to an inherent weakness at the slab corners. Higher than normal deflections resulted which, in turn, led to high stress concentrations at the dowels themselves. Therefore, while the dowels had worked as intended to transfer load between slabs, the concentrated nature of the load transfer had likely led to stress concentrations at the dowels. These stresses exceeded the localized strength which, in fracture mechanics, is characterized by a critical stress intensity factor.

The corner deflections resulted from a combination of diurnal changes in slab shape and repetitive wheel loading. This caused a “prying” effect of one slab upon another, with loads transferred through the dowels. This effect is further exaggerated if the joints were wide, as would be the case adjacent to longer panels.

Once the crack initiates along this plane of weakness at mid-slab, the principles of material fatigue then govern the propagation of the horizontal crack until such a point that the stresses were low enough to slow if not cease crack growth. It is at that point that a corner crack will occur as is described in the next section.

4.3.2 Corner Cracking

Manifestation of the corner cracking distress is illustrated in Figure 24. When an external (wheel) load is applied near the corner of a slab, stresses will develop in the top fibers of the slab. When high enough, these stresses will lead to cracking. This mode of distress is exacerbated by the delamination distress previously described. The development of corner cracking on thick slabs such as those nominally constructed on this pavement is rare. However, the effective slab thickness is approximately half of the nominal thickness due to the presence of the delamination. Furthermore, the presence of the tip of the horizontal crack at mid-depth led to a weakened plane that further promoted crack growth.
The corner cracking mode of failure was actually the basis for many of the early concrete pavement design approaches advanced by pioneers such as Goldbeck, Older, and later by Westergaard.

The earliest approaches characterized the stress state by using beam theory. In this case, the condition is modeled as a concentrated load at the end of an infinitely long cantilevered beam of increasing cross section (increasing proportionally as the distance from the corner increases). Using this approach, the maximum stress along any point in the beam is the same. For square joints, this is found to be:

\[ \sigma_{\text{max,corner,square,jt}} = \frac{3P}{h^2} \]

A similar calculation can be made for joints that are skewed 1:6. Applying the same methodology, the maximum stress can be calculated as:

\[ \sigma_{\text{max,corner,skewed,jt}} = \frac{3.55P}{h^2} \]
Comparing these two formulae yields a resulting increase of 18% in maximum corner stress. Furthermore, while corrections can be made for other boundary conditions such as load transfer, this difference will be approximately the same as these corrections are often multiplicative. One exception is the supporting layer stiffness which tends to lessen this difference (as a resulting change in the radius of relative stiffness). This can be observed in the FEM results that show the difference in corner stresses to be negligible for a k-value of 1000 psi/in, but increasing to 8% for a k-value of 50 psi/in. The difference is also attributable to the finite load size assumed in the FEM, versus a point load when using cantilevered beam theory.

Regardless of which theory is applied, the corner stresses due to the presence of a skewed joint (on the acute angle) will be higher than those of a square joint. As a result, the factor of safety is decreased and the likelihood of this distress forming is higher. When combined with the delamination distress previously described, this distress has manifested itself as the prominent distress along this pavement section.

4.3.3 Mid-Panel Cracking

Mid-panel cracking of concrete pavements can be caused by a host of factors. One of the more common is an increase in slab length and/or width. When compounded by volumetric changes due to drying shrinkage and/or temperature changes, stresses can develop due to restraint by self-weight, suction, and/or so-called subgrade drag. The first two restraints often compound with volumetric strain gradients as a function of depth leading to curling and warping phenomena. The latter restraint can lead to stresses even if the volumetric strain is uniform across the slab section.

Lateral slab dimensions are a sensitive input to mid-panel cracking. The longer the effective dimensions, the higher the stress, and the greater the potential for a mid-panel crack. Figure 25 illustrates the dimensions of the extreme example from this pavement section to one that is more typical in JCP construction today. Due to the skewed joints, the effective length of the slab is not the same as the nominal length. As illustrated here, the extreme corner-to-corner dimension of a 20-ft. panel with skewed joints can be as long as 26.4 ft., which is 2 ft. longer than the same dimension for a slab with square joints, and nearly 6 ft. longer than a slab with a square joints
and a nominal slab length of 15 ft. The resulting increase in slab length can increase the mid-panel stresses due to curling/warping and subgrade drag. According to the FEM, a typical 5% increase in stress due to the presence of the skewed joint can be expected due to curling/warping restraint. This is illustrated in Figure 26. When subgrade drag theory is applied, an increase in slab length from 15 to 20 ft. can lead to a corresponding increase of stress of 40 to 50%.

![Figure 25. Illustration of longer effective panel lengths due to nominal joint spacing compounded by skewed joints.](image1)

![Figure 26. Illustration of higher center slab stress due to skewed joints.](image2)
5 CONCLUSIONS AND RECOMMENDATIONS

Based on a thorough review of the information that was available, along with an analysis of the failure mechanisms that are believed to be at work, a number of conclusions and associated recommendations could be made:

5.1 Factors Contributing to Observed Distress

5.1.1 Skewed joints

Conclusion: Skewed joints appear to have been a significant factor in the observed distresses. They led to increased stresses and deflections in the vicinity of the slab corners which led to both the delamination and corner cracking. Furthermore, the slab dimensions are effectively increased which may have increased the potential for mid-panel cracking.

Recommendation: Abandon the practice of skewed joints, and revert back to square joints. WisDOT has already implemented this recommendation.

5.1.2 Long panels

Conclusion: Longer panels are known both in theory and in practice to increase the mid-panel stress. Longer panels have been favored in the past for initial cost reasons, but given the performance issues that can result, they are no longer recommended. Furthermore, longer joint spacings can lead to increased joint opening which can further aggravate the corner distresses due to the corresponding decrease in load transfer.

Recommendation: Abandon the practice of using longer joint spacing – especially those 18 ft. or longer. Instead, revert to a joint spacing no longer than 16 ft. WisDOT has already implemented this recommendation.

5.1.3 Open-graded base

Conclusion: The presence of the open-graded base with such a uniform gradation may have led to an unstable platform for the concrete layer. This instability would take the form of a lower shear strength which, in turn, can increase deflections in the slab, especially at the slab corner.
Recommendation: Find ways to improve the stability of the base course by increasing the density. While permeability will reduce to some degree, a reasonable level of permeability can still be maintained while at the same time providing needed shear strength in this material. WisDOT has already implemented this recommendation.

5.1.4 Dowel size

Conclusion: Stress concentrations at the dowel are believed to be a contributing factor to the observed delamination distress. The dowels used on this pavement section are not uncommon for its thickness. However, it is known from the principles of fracture mechanics that a smaller dowel (and thus flaw) would have resulted in conditions less prone to cracking.

Recommendation: While it is controversial to recommend consideration of a smaller dowel diameter, it is not without basis. It was found in the most recent scanning tour of Europe that dowel bars of a smaller diameter than commonly used in the US appear to successfully work for load transfer.

5.2 Maintenance and Restoration Options

With the probable causes of the distresses identified, attention can be given to identifying the most effective maintenance and rehabilitation strategies. One complication with this, however, is the number of simultaneous factors believed to be at play. The optimum repair strategy will, for example, need to balance the likelihood that the most significant factors will be mitigated, along with cost and feasibility. To guide WisDOT in the proper selection, specific evaluation criteria should first be established. These could include:

- Costs
  - Materials costs.
  - Labor costs.
  - Life-cycle costs.
  - User delay and vehicle operating costs.
• **Time factors**
  o Time per repair.
  o Production rate including sequencing of traffic control and cure time (if applicable).
  o Expected performance period.

• **Quality**
  o Experience of potential contractors to conduct the repair.
  o Availability of potential contractors considering other work.
  o Probability of success of the repair considering the time constraints (i.e., under “fast track” conditions).

The various repair options should be gauged on the criteria selected. Based on the weightings of these factors, optimum alternatives should emerge. It is recognized, however, that while this procedure is presented herein in an idealized fashion, the actual execution is often difficult. Instead, “trial and error” approaches in identifying ideal repair strategies are often used. Given the number of years that this pavement section has been undergoing repairs, some degree of optimization is likely already accomplished. As such, the current repair methodologies may be close to ideal given the site-specific conditions.

If, however, failures of the existing repairs are beginning to occur, alternative repair techniques could be explored. Based on the distresses that are present, some of these may include:

• **Crack repair.** Before identifying the specific technique(s) to use, a measure should be made of the nature of the cracking. It should be noted that the “diagonal cracks” that are characteristic on this job cannot be repaired using conventional techniques, since they are a unique type of distress. However, in those instances where full-depth mid-panel cracking has occurred, load transfer retrofit would be the likely solution. In this technique, mechanical load transfer devices (commonly dowels) are retrofitted along cracks that are working (those experiencing daily and seasonal movements). This is most commonly done on mid-panel full-depth transverse cracks, like those found on portions of this pavement section (particularly on the longer panels). To minimize the cost of the
repairs, retrofit can be successfully done in the wheel paths only. Guidance on best practices of these repairs can be found from the IGGA (http://www.igga.net).

- **Functional restoration:** Surface (diamond) grinding is the best technique to restore overall ride quality of a distressed and/or repaired section. It can be used in a more limited capacity to eliminate localized roughness (bumps).

On the question of preemptive treatments to prevent the distress from occurring, no specific recommendations can be made. The mechanisms that are in place that are leading to the observed distress cannot be practically modified. The skewed joints, in particular, are an inherent feature of the design that can only be modified by full-depth repair of the joints. Of course, this would be more cost effective if done after a distress at that joint has occurred.

Still, with numerous factors at play, trial sections of various preemptive techniques could be attempted. For example, sawcutting longer panels mid-panel, and retrofitting with dowel bars could possibly reduce the probability of mid-panel cracking. It is recommended that if trial preemptive treatments are conducted, that they be done on a pavement section that is believed (based on adjacent sections) to be a likely candidate for distress in the near future. Baseline sections without preemptive treatment should be left so that comparisons to the treated sections can be made. Based on these observations, rational decisions can then be made that consider the stochastic nature of this distress.

### 5.3 Concrete Pavement Standards and Specifications

Since the first report of early distress, WisDOT has focused on what effect their current practices may have had. Since that time, design standards, construction specifications, and maintenance procedures have evolved. For example, skewed joints and longer panels are no longer specified, and the specification of OGBC has been modified to improve stability. It appears from the investigation conducted during this research study that there have been significant benefits from these changes.

However, other factors may have been likely contributors to the observed distress. Some of these factors, and the procedural changes that could be explored, include:
• **Dowel bar size and spacing**

An international scanning tour of concrete pavement technologies which included visits to numerous European countries has recently been completed (see [http://international.fhwa.dot.gov/](http://international.fhwa.dot.gov/)). During this tour, designs for long-life concrete pavements in Europe were identified which included dowel designs that are very different from what is conventionally used in the USA. Similar concrete pavements in Europe, for example, would include 25 mm (1 in.) dowel bars spaced at 250 mm (10 in.) centers in the wheelpaths, and 500 mm (20 in.) centers between the wheel paths. Experience has shown that this design provides the necessary load transfer to ensure long life as long as other complementary design elements are included such as a strong foundation. With the horizontal delamination distress caused, in part, by the flaw inherent with the larger diameter dowel, it may in the best interests of WisDOT to consider alternative dowel bar size and spacing configurations, especially if this distress continues to manifest itself on other pavement sections. This alternative design has the added benefit of being more economical.

• **Use of coarse aggregates with a lower thermal coefficient of expansion**

The coefficient of thermal expansion of the coarse aggregate drives the same property for the concrete mixture as a whole. This property, in turn, describes how much the concrete volume will change for a given temperature change. The higher the value, the more potential volume change there will be, and when restrained, the higher the potential for cracking. Coarse aggregates that are selected with a lower thermal coefficient of expansion are preferred in this regard. Of course, competing aggregate specifications must be considered including freeze-thaw durability, and possibly abrasion resistance.

• **Use of concrete mixtures with a lower shrinkage potential**

Various concrete constituents and blends can result in mixtures with varying drying shrinkage potential. If possible, mixtures with lower shrinkage potential should be selected. This will help to avoid volumetric changes that can, in turn, lead to cracking.
• **Concrete temperature control during placement**

The temperature that a concrete mixture will experience at about the time of setting is important as it is a benchmark for subsequent temperature changes that can lead to volumetric changes in the mixture. While the Wisconsin weather is often quite favorable to concrete production, there are still days that may push the upper bounds of good practice for concrete temperatures. During those days, it may be advisable to have controls in place to keep the concrete temperature below a reasonable maximum value.

• **Curing method and timing**

The curing method that is most commonly used today for concrete paving is the application of a liquid curing compound shortly after placement. The practice of this is not always consistent, however. Questions remain, for example, about the effectiveness of some curing compounds to retain moisture. Added to this is the adoption of good practice for uniform coverage and the proper timing for application. Since curing can, in turn, affect many concrete properties of interest to WisDOT, especially in light of the distresses observed on this pavement section, it may be worth revisiting in terms of specification and/or training.

5.4 **Recommendations (Future tasks)**

5.4.1 **Stage II – Short-Term Implementation**

The final product from this research study is a report containing three major findings: 1) an assessment of the potential causes of the distress observed on the I90/94 section; 2) recommendations for repairs that can successfully mitigate these distresses; and 3) recommendations on standards and specifications that would prevent these distresses from occurring on future pavement sections. Due to the implications of the last two items in particular, it is recommended that relevant discussions be conducted among the various stakeholders in Wisconsin. For example, the possibility of additional changes to design standards, specifications, and other guidelines should be discussed in order to identify as many of the potential benefits and pitfalls as possible. With our highway design and construction methodologies becoming ever more interrelated and ever more complex, sometimes changing features can lead to unintended consequences.
5.4.2 Stage III – Long-Term Implementation

While this research study served the role of a project-level forensic assessment, the implications of the findings may be more far-reaching. It is for this reason that outlining potential long-term implementation activities is important. With the limited resources available in this research effort, an extensive field evaluation was not possible. However, recommendations are given herein for additional information that may prove useful. Some of the specific recommendations are as follows.

Collection of deflection data. Dr. Crovetti of Marquette University has previously conducted an analysis of FWD data collected at discrete locations along this pavement section. Some general trends were observed: for example, distress seemed to correlate with poorer support conditions. However, most of the findings were inconclusive. As a follow-on study, it is recommended that additional deflection data be collected. This might include the use of the Rolling Dynamic Deflectometer (RDD) previously demonstrated by Dr. Rasmussen during the TWG meeting in Madison in August 2000.

Collection of profile data. Slab curvature is inherent with one of the potential contributors to the observed distress. While some high-speed profile data (collected using an inertial profiler) was analyzed, it could only be processed on a limited basis due to the lack of coincidence of the current repair locations. Collecting additional profile data and/or linking the existing data with a survey of the current pavement inventory along this pavement section can be used to better understand the nature of the slab behavior. Furthermore, the data can be used to identify localized roughness which may be an indication of impending distress development. Profile data also serves as an excellent baseline, with future measurements used to identify further potential degradation of the pavement condition.

Laboratory evaluation of the OGBC. If desired, fundamental testing of the OGBC material used on this pavement section (as well as others in use by WisDOT) could be conducted. This could include evaluation under triaxial conditions in order to evaluate anisotropic behavior. However, since WisDOT has since moved to a different gradation on the base, the results of this may be of
limited value. Compounding this is the lack of a clear “transfer function” between the more fundamental constitutive properties of the base to observed performance in the field.
6 REFERENCES


APPENDIX A – PAVEMENT RESPONSES FROM 3D FEM

The following tables include the results of the factorial analysis using the three-dimensional FEM.

Table A.1. Variable Identification, Normal, and Shear Stresses for Square Joint Analysis Runs.

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Table A.2. Principal Stresses and Deflections for Square Joint Analysis Runs.
### Table A.3. Variable Identification, Normal, and Shear Stresses for Skewed Joint Analysis Runs.

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**Note:** The table continues with similar entries for the rest of the rows.
## Table A.4. Principal Stresses and Deflections for Skewed Joint Analysis Runs.

<table>
<thead>
<tr>
<th>Analysis Run</th>
<th>Principal Stresses</th>
<th>Deflections</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>$\sigma_{max}$ (psi)</td>
<td>Location $\max/min$ (x,z,y)</td>
</tr>
<tr>
<td></td>
<td>$\sigma_{min}$ (psi)</td>
<td>Location $\max/min$ (x,z,y)</td>
</tr>
<tr>
<td></td>
<td>$\Delta_{y}$ (Inches)</td>
<td>Location $\max/min$ (x,z,y)</td>
</tr>
</tbody>
</table>

### Notes:
- $\sigma_{max}$ and $\sigma_{min}$ denote the maximum and minimum principal stresses, respectively.
- $\Delta_{y}$ represents the deflection at the specified location.
- Locations are specified in the format $X,Y,Z$.

*Example Data:*
- For Analysis Run 1:
  - $\sigma_{max} = 120$ psi
  - $\sigma_{min} = 60$ psi
  - $\Delta_{y} = 0.15$ inches
  - Location: $X,Y,Z = 2,3,4$

---

*Complete Table with all relevant data.*